Statens haverikommission
Swedish Accident Investigation Board

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Report RL 2010:01e

Accident to aircraft SE-IVF at the northern basin of Falsterbo canal, Skåne County, on 26 October 2006

Case L-27/06

SHK investigates accidents and incidents with regard to safety. The sole objective of the investigations is the prevention of similar occurrences in the future. It is not the purpose of this activity to apportion blame or liability.

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Statens haverikommission
Swedish Accident Investigation Board

2010-02-22 L-27/06

European Aviation Safety Agency
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Report RL 2010:01e

The Swedish Accident Investigation Board has investigated an accident that occurred on 26 October 2006 at the northern basin of the Falsterbo canal, Skåne county, involving an aircraft with registration SE-IVF.

In accordance with section 14 of the Ordinance on the Investigation of Accidents (1990:717) the Agency herewith submits a report on the investigation.

The Swedish Accident Investigation Board will be grateful to receive, by August 1, 2010, at the latest, particulars of how the recommendations included in this report are being followed up.

A translation of the report into English is appended.

Göran Rosvall Henrik Elinder

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ABBREVIATIONS

Abbreviation	**Nomenclature**
AC	Advisory Circular
AFM	Aircraft Flight Manual
AD	Airworthiness Directive
AIP	Airport Information Publication
AOC	Air Operators Certificate
AOL	All Operators Letter
ARCC	Aeronautical Rescue Coordination Centre
ATA	Air Transport Association
ATPL	Airline Traffic Pilot License
BCL	Bestämmelser för Civil luftfart (Civil aviation regulations)
CASA	Construcciones Aeronáuticas, S.A.
CIAIAC	Comisión de Investigación de Accidentes e Incidentes de Aviación Civil
CPCP	Corrosion Prevention and Control Program
CPL	Commercial Pilot License
CVR	Cockpit Voice Recorder
DGAC	Spanish Civilian Airworthiness Authority
DGAM	Spanish Military Airworthiness Authority
DHB	Drifthandbok (Operating Manual)
EASA	European Aviation Safety Agency
ELT	Emergency Locator Transmitter
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FDR	Flight Data Recorder
FFV	Förenade Fabriksverken (Swedish United Military Workshops)
FMV	Försvarets Materielverk (Swedish Defence Materiel Administration)
GPS	Global Positioning System
GVI	General Visual Inspection
IAS	Indicated Air Speed
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
IPC	Inch Per Second
LVD	Airworthiness Directive (Swedish)
MEL	Minimum Equipment List
MMC	Metal Matrix Composite
MCC	Multi Crew Cooperation
MPa	Megapascal
MRCC	Maritime Rescue Coordination Centre
MSS	Maritime Surveillance System
MUST	Militära underrättelsetjänsten (Swedish Military Intelligence Service)
NDT	Non Destructive Testing
OSC	On Sceen Commander
KBV	Kustbevakningen (Swedish Coastguard)
PC	Proficiency Check
PFT	Pilot Flight Training
QAR	Quick Access Recorder
PSE	Principal Structural Element
QNH	Q-code
ROV	Remotely Operated Vehicle
RM	Route Manual
RPM	Route Performance Manual
RVR	*Runway Visual Range*
SAR	Search And Rescue
SB	Service Bulletin
SEM	Scanning Electron Microscope
SHB	Standards Handbook
SID	Supplemental Inspection Document
SLAR	Side Looking Airborne Radar

SMHI	Swedish Meteorological and Hydrological Institute
S/N	Serial number
SSRS	Svenska Sällskapet för Räddning av Skeppsbrutna (Swedish Sea Rescue Society)
STOL	Short Take Off and Landing
TFHS	Trafikflyghögskolan vid Lunds Universitet - Lund University School of Aviation
UTC	Coordinated Universal Time
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VMCA	Minimum Control Speed Airborne
VMCG	Minimum Control Speed Ground
VMS	Vessel Monitoring System

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Report issued 2010-02-22

Aircraft; registration and type	SE-IVF, CASA C-212-CE
Class, airworthiness	Normal, valid Certificate of Airworthiness
Registered owner/Operator	Kustbevakningen (KBV – The Swedish Coastguard), Box 536, SE-371 23 Karlskrona, Sweden
Time of occurrence	26 October 2006, at 13:26 in daylight Note: All times are given in Swedish standard time (UTC + 1 hour)
Place	Northern basin of Falsterbo canal, Skåne county, (posn. 55° 25' N 012° 56' E; at sea level)
Type of flight	Surveillance flight
Weather	According to SMHI's analysis: Wind south-west 18 knots with gusts of up to 25 knots, good visibility, no cloud below 5000 feet[1], temp./dewpoint +14/+11 °C, QNH 1004 hPa
Persons on board:crew members Passengers	4 -
Injuries to persons	All on board were fatally injured
Damage to the aircraft	Completely destroyed
Other damage	Fuel and oil leakage into the sea
Commander: Sex, age, licence Total flying time Flying hours previous 90 days Number of landings previous 90 days	 Male, 41 years, ATPL 4424 hours, of which 4192 hours on type 149 hours, all on type 25, all on type
Co-pilot: Sex, age, licence Total flying time Flying hours previous 90 days Number of landings previous 90 days	 Male, 33 years, CPL 638 hours, of which 421 hours on type 210 hours, all on type 35, all on type
System operators	Two males

The Swedish Accident Investigation Board (SHK) was notified on 26 October 2006 that an aircraft with registration SE-IVF had an accident at 13:26 hours on that day at the northern basin of the Falsterbo canal, Skåne county.

The accident has been investigated by SHK represented by Carin Hellner, Chairperson until 28 February 2007 and Göran Rosvall thereafter, Henrik Elinder, Investigator In Charge and technical investigator, Stefan Christensen, operations investigator, Gerd Svensson, Human factors investigator and Patrik Dahlberg, Rescue services investigator.

SHK was assisted by Hans Landström as operational expert, Sven-Åke Karlsson, as metallurgical expert, and by Liselotte Yregård, as medical expert.

The investigation was followed by Max Danielsson of the Swedish Transport Agency, Civil Aviation Department, until 1 October 2008, and Nicklas Svensson thereafter.

Accredited experts were José Sala from CIAIAC (Spain) up to and including 24 March 2008 and Juan Antonio Plaza thereafter, along with Jennifer Kaiser from the NTSB (USA). Analyses of the FDR and CVR data were carried out by Mark Ford from the AAIB (Great Britain).

[1] 1 *foot = approx. 0.3 metres (unit of measurement)*

The investigation was carried out with factual support from EADS/CASA, Saab AB and the Royal Institute of Technology in Stockholm.

Summary

One of the Swedish Coastguard aircraft, of type CASA C-212 with call sign KBV 585, took off at 11:09 from Ronneby airport for a routine maritime surveillance flight. The crew consisted of two pilots and two system operators.

During the flight the crew received a message from the co-ordination centre concerning a request that had been received for a fly by over the Falsterbo canal, where the Swedish Coastguard has a base. The pilots accepted this and revised the final part of their flight plan so that a demonstration of the aircraft could be performed.

At 13:23 KBV 585 came in over the coast at Falsterbonäset on a north-north-westerly course along the canal. The aircraft then continued out over the sea and after a left turn returned to approach the base. The aircraft then performed another fly by at low speed over the base and along the canal in the opposite direction. Beyond the end of the canal the aircraft turned back to the left and flew for the last time towards the base.

As the aircraft neared the base once more it made some wing tipping. After tipping its wings two or three times a loud bang was heard, and the entire left wing separated from the aircraft. The aircraft then rolled over on to its back and fell, along with the left wing, into the harbour basin, where it disintegrated on impact. All on board were killed.

The technical examination showed that the cause of the wing separation was a fatigue fracture, about 84 cm long, which was present in the wing lower skin, where the wing was attached to the aircraft fuselage. The crack in the wing lower skin, which forms part of the wing’s load-bearing structure, meant that the strength of the wing was severely compromised.

In connection with the wing tipping that was performed, momentary lift and mass forces were applied to the wing, which resulted in a final fracture in the left wing that bent upwards and separated from the aircraft fuselage.

The same type of fatigue crack was found in a similar location in the right wing, but this was far less developed. The initiation and development of these left and right wing cracks were similar. The metallurgical examination showed that they had been initiated at an early stage, and that the fatigue cracks had grown for a long time without having been detected. The location of the cracks under doublers meant at they were not visible from the outside of the wing.

SHK considers that the design of the wing attachment to the aircraft fuselage was unsuitable, since the fairings between the aircraft fuselage and wing can transmit vertical loads for which they are not intended. The design means that a considerable proportion of such loads can, in certain circumstances, be transferred to the lower wing skin in a band at right angles to the primary load path of the skin.

The characteristics of the fatigue cracks that in the left wing resulted in wing separation are typical of Multiple Site Damage (MSD).

The fatigue cracks could have come about as the result of residual stress in the wing lower skin, that could have existed since the wing was manufactured or

that arose due to some momentary overload while in service. Nothing in the investigation indicates so, although this possibility cannot be excluded.

SHK considers, however, that it is more likely that the fatigue cracks arose during normal flight operations in combination with some form of additional vibration and/or oscillating loads at some period of time in the history of the accident aircraft. The damage sequence had progressed over a long time, and some form of combination of the above factors cannot be excluded.

It is the assessment of SHK that the manufacturer underestimated the material stress and the risk of crack formation in that particular area, and thereby overestimated the fatigue strength of the wings.

The maintenance system that the manufacturer has prepared for this type of aircraft, and that SHK understands was complied by the maintenance organisation, was not able to detect and prescribe relevant measures to prevent the growth of these particular fatigue cracks.

Nor did the manufacturer utilise the possibility of using the accident aircraft, which was the operating time leader in respect of coastguard flying operations, for crack growth inspection, as a sample, with the intention of identifying possibly critical areas concerning fatigue cracks.

After this accident, the manufacturer and authorities prescribed special inspections of the affected areas in the wings, in respect of fatigue cracks. About 1/3 of the aircraft of this type in service have so far been reported as inspected, without finding any similar cracks.

The operations of the Swedish Coastguard have sometimes subjected the flight equipment to high loads, but the operations have, in the opinion of SHK, taken place within the permitted limits for this type of aircraft.

The demonstration flight along the Falsterbo canal took place with a deviation from the applicable internal rules and without operational instructions.

The accident was caused by an inadequate maintenance system in respect of inspections for fatigue cracks. Contributory to the crack formation has been an unsuitable design of the attachment of the wings to the aircraft fuselage.

Recommendations

It is recommended that EASA:

- takes the necessary measures to ensure that fatigue cracks of the type that caused the wing fracture on the accident aircraft cannot occur in any CASA C-212 aircraft that is in service *(RL 2010: 01 R1)*,
- evaluates the need for modification to the wing attachment to the fuselage so that the material stress situation along the critical row of rivets will be conclusively defined for all in-flight cases *(RL 2010:01 R2)*, and to
- take steps so that the existing flight recording systems on board large aircraft, such as FDR, QAR, etc., are developed further so that they can also be used to inform pilots, while recording the data, about possible overloading during operation *(RL 2010:01 R3)*.

It is recommended that the Swedish Transport Agency should:

- develop an applicable set of regulations for KBV flying operations, taking into account the unique tasking profile of the operations and their increased risk level *(RL 2010:01 R4),)*, and to
- review the current set of requirements in the BCL in respect of self-checking systems in operations that are similar to the KBV operations *(RL 2010:01 R5)*.

1 FACTUAL INFORMATION

1.1 History of flight

1.1.1 Conditions

Kustbevakningen (The Swedish Coastguard), henceforth called KBV, intended on that particular day to perform two routine maritime surveillance tasks with flights over the southern Baltic Sea and along the south and west coasts of Sweden, including a flight over the Kattegatt. The flights would be carried out by the aircraft registered SE-IVF, with call sign 585. The crew consisted of two pilots and two system operators.

The first flight of the day would take off from Ronneby, with Malmö/Sturup as the landing airport. According to the submitted flight plan the flight from Ronneby would depart north-east outwards across the southern tip of Öland, via reporting point KOLJA and onwards to a point south of Gotland. Thereafter the route would be via KOLJA back on a south-west course to a point south of Smygehamn in the southern Baltic Sea and then directly to Malmö/Sturup airport.

1.1.2 The take off from Ronneby

When KBV 585 taxied out for take off, route clearance had been obtained for take off in accordance with the submitted flight plan. The flight would be undertaken in VFR (Visual Flight Rules) weather conditions. The flight plan did not state the desired altitude, so at the initiative of air traffic control KBV 585 was assigned the altitude band "1500 feet or lower" in connection with the flight clearance.

Take off was at 11:09 on runway 19. Immediately after take off the crew requested a "360", i.e. to make a complete turn from their current position. This request was accepted by air traffic control and KBV 585 performed a circuit at about 500 feet in a left turn around the airfield. No comments or explanations were offered by the crew during this manoeuvre.

In an interview with SHK the air traffic controller stated that he thought that the aircraft had suffered a technical fault and/or the crew wanted to carry out some form of check. It later transpired that the reason for the extra circuit may have been to show off the aircraft to a practical work experience student who was at the KBV as part of work experience training.

After the completed left hand circuit the pilots returned to their original flight plan and continued, with an initial climb to the south, to then turn left and follow the planned flight route.

1.1.3 The first phase of the flight

During the continuing climb the pilots received an instruction to change radio frequency from Ronneby air traffic control tower to Ronneby control, i.e. the air traffic control section covering the Ronneby terminal area, that normally includes radar surveillance. As KBV 585 continued to climb, the air traffic controller noted that it continued to climb above the maximum altitude of 1500 feet that the stated flight clearance had included. At about 2000 feet while still climbing the pilots requested permission to climb to and maintain 2500 feet, which was granted.

When the aircraft left the Ronneby terminal area the pilots changed radio frequency without reporting this to the air traffic control area controller. The air traffic controller on duty on that particular day at Ronneby stated that this was unusual behaviour by the KBV pilot, both to climb through the cleared altitude and to depart from the radio frequency without reporting it.

The flight continued to the north-west in accordance with the flight plan. Apart from the routine tasking order concerning environmental and fishing surveillance, the tasking included instructions to search for traces from a previously sunken barge. The flight was performed without any problems being reported. During the flight the pilots were in radio contact both with air traffic controllers and the KBV co-ordination centre.

As the aircraft was en route south-west after having turned at the southern tip of Gotland, the crew received a message from the co-ordination centre concerning a request they had received to perform a fly-by over Falsterbo.

KBV has a base at the Falsterbo canal, which on that particular day was hosting a study visit by two school classes. Therefore a request came from the base to ask whether the pilots could consider performing a fly-by as they were on their way to Malmö/Sturup, so as to demonstrate the aircraft. The pilots accepted this and revised the final part of their flight plan so that a demonstration of the aircraft over the Falsterbo canal could be performed.

1.1.4 The fly-by over the KBV base

At 13:23 KBV 585 came in over the coast at Falsterbonäset on a north-north-westerly course along the canal. The aircraft then continued out over the sea and after a left turn returned to approach the base.

The aircraft then performed another fly-by at low speed over the base and along the canal in the opposite direction, i.e. south-south-east, at low altitude. The route of the flight was partly over the canal, partly over the strip of beach and the buildings along the north-eastern shore. Beyond the far end of the canal the aircraft performed a 180 degrees left turn, first climbing and then descending.

On its last approach to the base the aircraft came over the beach at the north-eastern side of the canal, on a north-westerly course, which was later altered to north-north-westerly as it once again came over the canal.

1.1.5 The accident

As the aircraft neared the base once more it began wing tipping. After two or three wing tippings, by which time the aircraft was approximately above the bridge at the north-west entrance to the canal, a loud bang was heard and the entire left wing separated from the aircraft, to fall into the basin. The aircraft then rolled over on to its back and also fell into the basin, somewhat further out.

The impact created a huge cascade of water. The remains of the aircraft and wing then quickly sank to the bottom. The whole sequence of events took place quickly and afterwards various pieces of wreckage could be seen floating on the surface at the point of impact. All onboard were fatally injured.

The accident took place at position 55° 25' N 012° 56' E; at sea level.

1.1.6 Information from the witnesses

The accident was witnessed by a large number of people who had been watching the aircraft as it flew in the area and over the Falsterbo canal at a low altitude. Many of these were interviewed as witnesses in connection with the investigation.

Apart from the fact that the flight over the Falsterbo canal took place at low altitude and with relatively steep turns at the ends of the canal, none of these witnesses perceived anything abnormal concerning the flight or any signs of technical faults. The engines sounded normal.

There was unanimous information that the accident sequence began with no warning whatsoever with a loud bang when the aircraft was more or less above the bridge and on a north-north-westerly course.

Several witnesses saw the aircraft wing tipping just before and in connection with the bang. Some of these witnesses thought that the wing tipping was powerful, i.e. accompanied by fierce banking.

Apart from the fact that the subsequent events happened very quickly and ended with the aircraft and an object appearing wing-like impacting into the basin, some details of the event sequence were perceived differently by the witnesses.

Most believed that it was one of the aircraft wings that broke off upwards. On the other hand there were different conclusions as to whether it was the left or the right wing that separated. Some people thought that it was the aircraft tail plane or tail fin that separated.

It was a unanimous perception that immediately after the bang the aircraft quickly rolled over on to its back before hitting the water. Some thought that the roll was to the left, while others thought it was to the right.

1.2 Injuries to persons

	Crew	Passengers	Others	Total
Fatal	4	–	–	4
Serious	–	–	–	–
Minor	–	–	–	–
None	–	–	–	–
Total	4	–	–	4

The commander
The commander was killed in the accident. The pathological investigation showed that the commander had suffered multiple internal and external injuries as a result of the body being subjected to extreme blunt trauma.

Co-pilot
The co-pilot was killed in the accident. The pathological investigation showed that the co-pilot had suffered multiple internal and external injuries as a result of the body being subjected to extreme blunt and possibly penetrating trauma.

System operator 1
System operator 1 was killed in the accident. The pathological investigation showed that the system operator had suffered multiple internal and external injuries as a result of the body being subjected to extreme blunt trauma.

System operator 2
System operator 2 was killed in the accident. The pathological investigation showed that the system operator had suffered multiple internal and external injuries as a result of the body being subjected to extreme blunt trauma.

Forensic chemical analysis of drugs and medicine, taken on samples from the pilots and system operators, gave negative results, i.e. no substances were found.

The pilots, in the cockpit, suffered more extensive injuries than the system operators, who were located further back in the aircraft.

1.3 Damage to the aircraft

Completely destroyed.

1.4 Other damage

About 700 litres of aviation kerosene and a lesser amount of oil leaked out into the northern entrance to the Falsterbo canal.

1.5 Personnel information

1.5.1 The commander

The commander, male, was 41 years old and had a valid Airline Transport Pilot Licence.

Flying hours			
Latest	24 hours	90 days	Total
All types	8	149	4424
This type	8	149	4192

Number of landings this type previous 90 days: 25.
Flight training on type carried out on 15 August 1997.
Latest PC (Proficiency Check) carried out on 7 June 2006 on a CASA C-212.
Latest PFT (Periodic Flight Training) carried out on 6 January 2006 on a CASA C-212.

The commander entered employment with KBV in 1993 and was trained in 1997 to become a commercial pilot at Trafikflyghögskolan vid Lunds Universitet (TFHS - Lund University School of Aviation), with the intention of serving as a pilot for the Swedish KBV aviation division. Apart from this period of flying training his entire flying experience was with KBV.

The commander served as the station manager (manager of the work place) at the base located at Stockholm/Skavsta airport.

1.5.2 *Co-pilot*

The co-pilot, male, was 33 years old and had a valid CPL (Commercial Pilot Licence).

Flying hours			
Latest	24 hours	90 days	Total
All types	8	210	638
This type	8	210	421

Number of landings this type previous 90 days: 35.
Flight training on type carried out on 13 March 2006.
Latest PC (Proficiency Check) carried out on 13 March 2006 on a CASA C-212.
Latest PFT (Periodic Flight Training) carried out on 28 September 2006 on a CASA C-212.

The co-pilot completed commercial pilot training at TFHS and then became employed by KBV in 2004. Apart from this period of flying training his entire flying experience was with KBV.

1.5.3 *System operators*

Operator 1, male, was 47, employed by KBV from 1981 and trained as a system operator in 1995.

Operator 2, male, was 30, employed by KBV from 1999 and trained as a system operator in 2003-2004.

1.5.4 *The crew members' duty schedule*

The day before the accident flight the aircraft had landed at Ronneby airport at 22:25, after which the crew spent the night in a hotel. The whole crew therefore had a normal night's rest up to the start of their duty period the next day at 09:00.

1.6 The aircraft

1.6.1 *General*

The aircraft	
Manufacturer	CASA (Construcciones Aeronáuticas, S.A.)
Type	CASA C-212-CE
Construction serial number (S/N)	346
Year of manufacture	1986
Flight mass	Max. authorised take-off/landing mass 7,700/7,450 kg, actual 6,769 kg
Centre of gravity	Permitted limits: Index 18.6 (front) to index 44.0 (rear). Actual index: 22.1
Total flying time (TT)	17048 hrs
Number of cycles (TC)	7389
Flying time since latest inspection (TSI)	88 hrs
Fuel loaded before event	Jet A1
Engine	
Manufacturer	Honeywell
Model	TPE 331-10R-513C

Number of engines	2	
Engine	No. 1	No. 2
S/N	P-37529	P-37511
Total operating time (TT)	14385 hrs	15465 hrs
Operating time since overhaul (TSO)	2038 hrs	3177 hrs
Cycles since overhaul (CSO)	798	1203
Propeller		
Manufacturer	Dowty	
Model	R334/4-82-F/13	
Propeller	No. 1	No. 2
S/N	DRG/7405/89	DRG/0679/86
Total operating time (TT)	10576 hrs	11886 hrs
Operating time since overhaul (TSO)	4110 hrs	4291 hrs

The aircraft had a valid Certificate of Airworthiness.

Unless otherwise specified, the A/C individual will hereafter in this report be identified by its serial number, S/N 346.

The CASA C-212 is a small transport aircraft manufactured in Spain by aircraft manufacturer CASA (now EADS-CASA), henceforth called “the manufacturer”. This type of aircraft has STOL characteristics and is intended for both civil and military operation. It is equipped with two turboprop engines and does not have a pressure cabin. The first flight of this type was in 1971. By the end of 2006, 470 CASA C-212 aircraft in various versions had been delivered to operators in over 35 countries.

The passenger versions of the aircraft have room for 21-28 passengers depending on the configuration. Military use is primarily for the transport of soldiers and materiel, but in certain cases armament is also fitted. This type of aircraft is approved for Rough Field Operation[2].

With additional equipment this type of aircraft is also used for environmental and maritime surveillance from the air. The CASA C-212 aircraft used by KBV are of the version called “200 Series”.

Figure 1. The accident aircraft

[2] Rough Field Operation – Operation on unprepared landing strips

1.6.2 Certification

The aircraft type was certificated by the Spanish Certification Authority in 1977 (Certificate Number 01-82) in accordance with FAR-25 and by the US FAA (Certificate Number A43 EU). FAR-25 specifies the applicable Airworthiness Standards for aircraft in the Transport Category Aircraft.

The Swedish Civil Aviation Authority (now the Swedish Transport Agency) issued on 11 May 1988 Modification Certificate No M 2/87, for this aircraft type, including the special equipment that is installed in aircraft belonging to the KBV (see Section 1.18.3).

At the time of the accident this aircraft type in civilian operation, regardless of the type of use, was initially approved for 20,000 flying hours or 20,000 landings (number of cycles), whichever occurred first. Continuous operation beyond these limits required special inspections according to the manufacturer's instructions (see Section 1.6.10).

1.6.3 Wing attachment

The wing in this type of aircraft consists of three sections, a central wing and two outer wings, which are held together by two bolted joints. In the centre wing, which extends out about two metres from the aircraft fuselage, there are among other things hard points for the two engine mounts and four wing attachments to secure the wing to the fuselage. The outer wings contain four separate fuel tanks. The outer wings include flaps and ailerons for controlling roll movements.

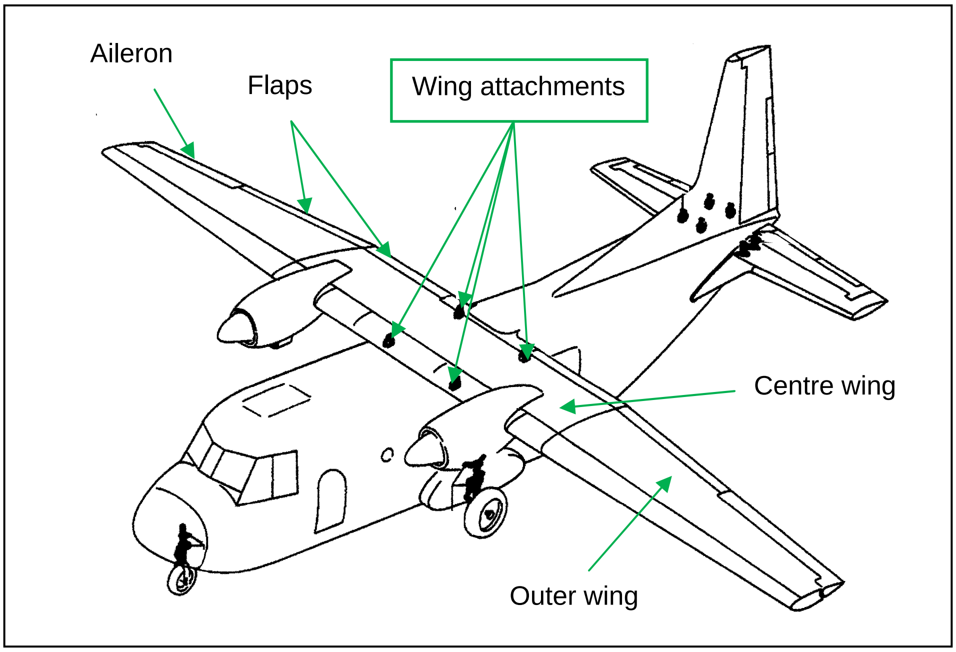

Figure 2. Wing with wing attachments

The wing attachments consist of four wing bolts that join attachment lugs in the wings to equivalent lugs in the upper part of the aircraft structure.

In addition to these fittings the wing is secured to the aircraft structure by two fairings on each side, beneath the wings. Each fairing is butt-fastened to an angle bracket on the underside of the wing and to a strip secured to the outside of the fuselage by a total of 22 screws and sealing compound.

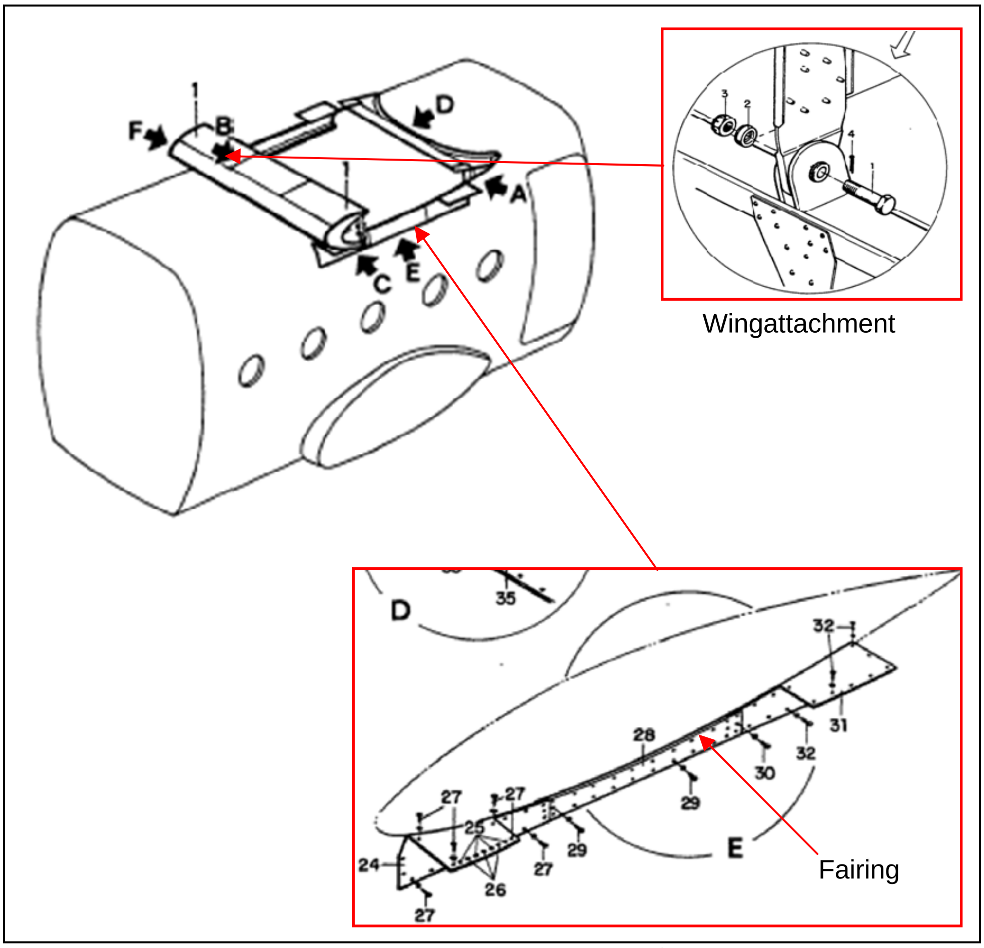

Figure 3. Wing attachments and fairings

Figure 4. Left side front wing attachment

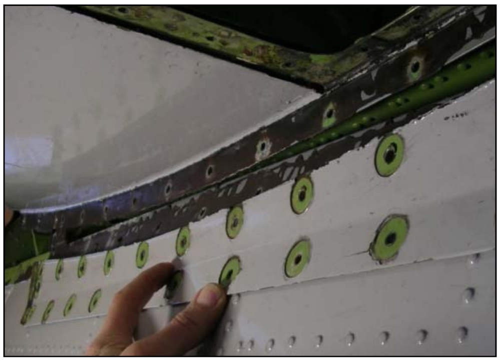

Figure 5. Left side fairing

1.6.4 *Wing attachment load carrying*

According to the manufacturer the intention is that the bolted attachments shall transfer loads between the wings and aircraft fuselage in the Z and Y axes (vertical and lateral to the direction of flight) and that the two fairings shall transfer loads in the X axis (the direction of flight).

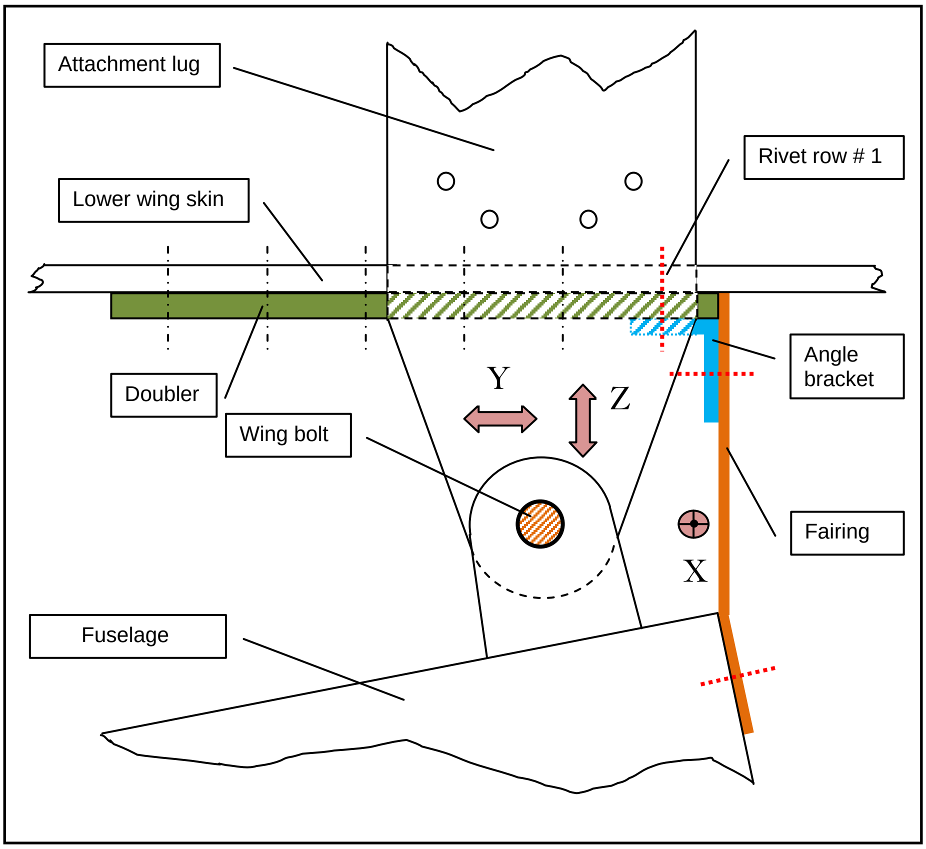

Figure 6. Load distributions in the wing attachments and fairings
(Seen from the rear in the direction of flight
- load directions are marked by arrows)

1.6.5 Centre wing

The load-carrying part of the centre wing consists of a wing box made of sheet aluminium made up of two beam webs in the span axis and intermediate upper and lower wing skins with longerons, which form the unit flanges, and bulkheads at each end.

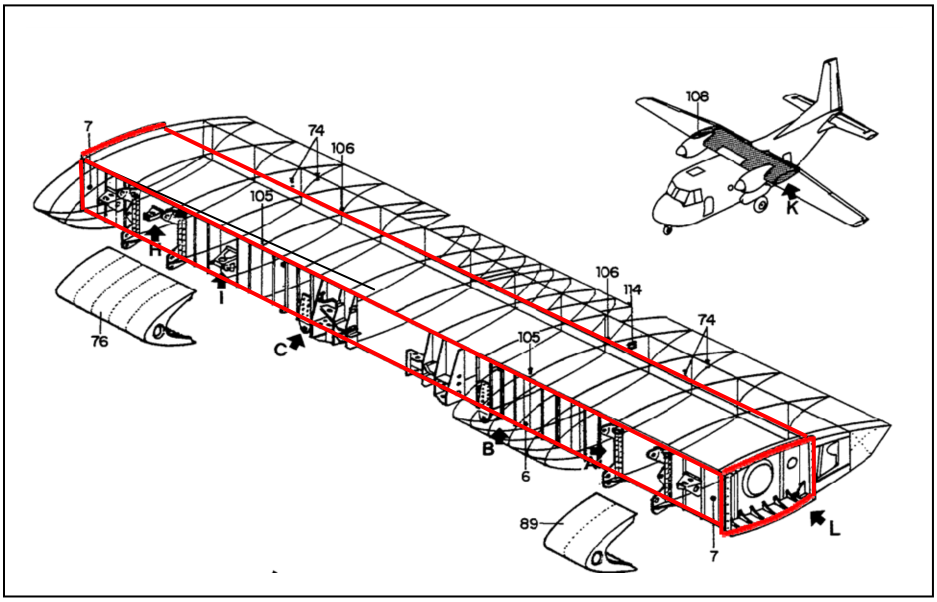

Figure 7. Centre wing wing box (marked in red)

This assembly, that is mostly manufactured using an aluminium alloy (AA-2024), is reinforced by, among other things, 14 internal ribs and 6 internal longerons above and below the box. Most of the joints are riveted. The riveted joints are in most places sealed with sealing compound.

On the underside of the centre wing, 15 cm wide doublers are secured at each side extending from the front to the rear wing spars. The doublers are riveted to the underside skins of the wing box, at the level of each inner rib, by more than 200 rivets, divided into six rows of rivets. On the accident aircraft these were not implemented with sealing compound. (See further in Section 1.16.12.)

The lugs for securing to the fuselage are mounted on the wing spars in attachment with the above-mentioned ribs.

At the respective doubler "outer" row of rivets (rivet row # 1, nearest the wing tip) the rivet row includes an angle bracket, which in turn provides the attachment for the previously mentioned fairing. See the Figure below.

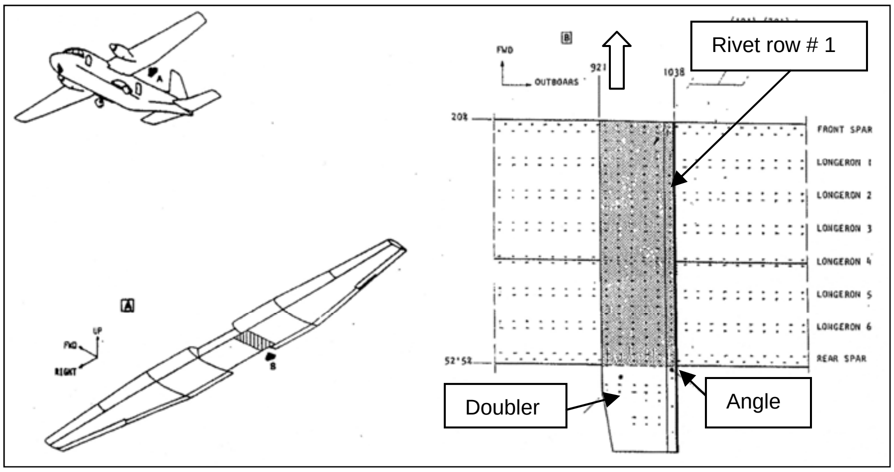

Figure 8. Doubler and angle bracket

1.6.6 *De-icing system*

This type of aircraft is equipped with a de-icing system for such components as the wings, tail plane, fin, engine air intakes and propellers.

De-icing of the wings, tail plane and fin takes place pneumatically by means of cyclic inflation of rubber boots at the affected surfaces, which crack and shed any ice that may form.

De-icing of the propeller blades takes place electrically by heating the leading edges of each propeller in two sections. In order to prevent overloading of the aircraft electrical system not all the propeller blades and their sections are supplied with electric current simultaneously when the system is activated, instead there is automatic alternation between different blades and sections in a symmetrical manner.

De-icing of the engine air intakes takes place with the aid of hot air that is tapped off from the engine compressors.

1.6.7 *Stall warning system*

This aircraft type can be equipped with a stall warning system that has the task of warning the pilots if the aircraft angle of attack becomes too great, thus risking a stall and loss of lift.

Stall warning devices were not installed on the first two KBV CASA C-212 aircraft until after delivery, in accordance with CASA Service Bulletin No. 212-31-12 on the following dates:

S/N 343	26 May 1988,	at a total flight time of 390.45 hours.
S/N 346	22 June 1988,	at a total flight time of 555.05 hours.

1.6.8 *Flight control system*

The CASA C-212 was designed to have a conventional type of flight control surfaces system, with elevators, rudder, ailerons and flaps. The elevators and ailerons are controlled by the pilot by means of a control column in the cockpit, and there are pedals to control the rudder. Transfer of the control movements from the cockpit to the flight control surfaces is mechanical, with cables and push-rods.

The ailerons are used to control the roll of the aircraft. These are located furthest out on each wing (see Section 1.6.3). When performing wing tipping the ailerons are used to tilt the aircraft alternately from side to side. In order for wing tipping to be clearly perceived, according to information from pilots who were interviewed, large aileron movements must be applied.

In order to avoid the risk of structural damage to the aircraft while manoeuvring, a maximum permitted speed is defined when full flight control surface movements are applied; Max. Manoeuvring Speed (VA). According to the AFM (Aircraft Flight Manual) for the CASA C-212, the VA is defined as 146 knots indicated air speed (IAS).

1.6.9 *Maintenance system*

The KBV CASA C-212 aircraft, which have now been phased out from the operation, were continuously technically maintained in accordance with a maintenance programme which is documented in the operator's maintenance manual, (UHB) CASA C-212. The UHB CASA C-212 is based on the manufacturer's C-212 Aircraft Maintenance Manual and was approved by the Swedish aviation authority.

At the time of accident the following was valid:

<u>Daily Inspection</u>
The Daily Inspection was carried out before the first flight of the day in accordance with the "Daily Inspection CASA C-212" checklist. The Daily Inspection was valid for 24 hours from the moment of being signed for, and was to be performed by a flight technician or other authorised person. Authorised personnel, without flight technician certification, were to perform a maximum of six Daily Inspections during any 14-day period.

Pre-flight inspections (Line Checks) were carried out before each of the other flights of the day in accordance with the "Line check CASA C-212" checklist. Pre-flight inspections were to be performed by a flight technician or other authorised person.

<u>Periodic maintenance</u>
Periodic maintenance was carried out in accordance with a specified maintenance programme at intervals of 150 flying hours. An inspection cycle covered 3,600 flying hours and was then repeated periodically. According to the programme specific checks were carried out and maintenance actions are

taken at intervals of 150, 300, 600, 1,800 and 3,600 flying hours. Before 1997 this system was based on 100 hour intervals.

In addition specific checks were carried out and maintenance actions are taken at calendar intervals of one, two, four and eight years.

The requirements in the C-212 Aircraft Maintenance Manual, regarding inspection in the wing area where the actual fatigue cracks were found, are specified in Chapter 5, Section 5-20-00, Sections 57.05 and 57.06 as listed below. These tasks are to be performed at intervals of eight years.

Sec.	*Access*	*Item*	*Task*
57.05	*All wing upper surface access*	*Wing internal structure*	*Detailed visual inspection for corrosion, component security and biological contamination.*
57.06	*All wing access*	*Wing: Access panels*	*Detailed visual inspection of hinges, fairings and adjacent structure for corrosion, adjustment and general condition.*

These requirements had been incorporated into the maintenance programme described above. According to the technical documentation for the accident A/C, S/N 346, the most recent inspection before the accident was performed on September 5, 2002 at A/C TT 12,232 hrs.

Apart from these inspections and corrosion checks of CPCP C-212-PV01 as described below, no specific inspection is required of the insides of the wings in the area where fatigue cracks were found.

Special maintenance measures

Apart from the above-mentioned system there are various types of directives from the materiel manufacturers and authorities concerning special checks and maintenance actions that must be carried out (Service Bulletins, Service letters, Airworthiness Directives, etc.) to maintain airworthiness. In certain cases these are once-only measures, and in other cases they are measures that have to be repeated.

1.6.10 *Life extension*

AC 91-56

On 6 May 1981 the FAA published the document AC 91-56, which required that aircraft manufacturers must prepare instructions concerning how older transport aircraft with take off masses exceeding 34 tons must be inspected to ensure their strength for the whole of their life. The programme was called "A/C Type Service Life Extension Program" and is summarised by the following points:

- *Manufacturers and operators to develop a continuing structural integrity program to ensure safe operation of older airplanes throughout their operational life.*
- *Development of Supplemental Inspection Document – SID.*
- *In accordance with principles in current FAR 25.571 standards.*

C-212-PV-01-SID / C-212-PV-02-SID
Based on this document, the manufacturer issued document C-212-PV-01-SID on 1 June 1987 for this type of aircraft. The document was issued voluntarily as the CASA C-212 weighs less than 34 tons.

The latter document specifies that a detailed inspection programme must be carried out on each individual aircraft before it reaches 20,000 flying hours or 20,000 flights (cycles), whichever comes first. The inspection covers all Principal Structural Elements (PSE) in the aircraft where the strength could have degenerated due to corrosion, fatigue, etc.

C-212-PV-01-SID was replaced on 1 June 1997 by C-212-PV-02-SID, which became mandatory on 4 February 2004 in accordance with the Spanish civil aviation authority, DGAC, by means of AD No. 02-88 Rev.3. AD No. 02-88 Rev.3 was approved by EASA on 9 February 2004.

One of the measures that, according to C-212-PV-02-SID, must be performed, is an external and internal inspection of the undersides of the wings, at station Y=±978 using NDT in accordance with the special instructions, NDT section ref. 57-10-03. This area is the place where the fatigue cracks discovered in the wings of the accident aircraft were found and that in the left wing led to wing separation. Appendix 4 is a brief description of the particular NDT method to be used.

Correspondence between the manufacturer (EADS-CASA) and the maintenance organisation, SAAB Aerotech, concerning C-212-PV-02-SID
In DGAC AD No. 02-88 Rev.3 it states that the manufacturer must be contacted in the case of individual aircraft which fly for more than 10 % of their flying hours at altitudes of less than 3,000 feet and where the average flight time is more than 80 minutes, for special assessment of the relevance of the threshold time.

The CASA C-212 aircraft of KBV operated in such conditions and the maintenance organisation therefore contacted the manufacturer concerning this issue on 29 July 2004 in respect of the individual aircraft in the KBV fleet with the highest flying hours, S/N 343 and S/N 346 (the accident aircraft).

The manufacturer then asked the following supplementary questions about the operational conditions:

In order to evaluate the applicability to these aircrafts of the established inspection requirements, it is necessary for us to know some key information regarding the operation for these aircrafts.

More specifically, for the different mission profiles under which the aircrafts are being operated, any information about the following parameters is of interest:

- *Average fuel and payload weights.*
- *Typical altitudes and flight speeds.*
- *Average flight times.*
- *Relative frequency (percentage) of the different missions.*

We understand that some of the requested data may be difficult to gather for you. Therefore, even a rough estimation would be much appreciated.

These were answered as follows:

- *Average fuel 1400 kg and payload MTOW.*
- *Typical altitudes 1500 ft and flight speed 150 kts.*
- *Average flight times 2.5 hours.*
- *Relative frequency of different missions is 90 % surveillance, 7 % training, 3 % other.*

In response the manufacturer sent a document, ICS-SE-MP-A410-032/05, dated 25 February 2005, with the information that the operational use had been analysed and that the original threshold value of 20,000 flying hours would apply to the individual aircraft S/N 343 and S/N 346 in accordance with the text:

- *EADS-CASA has concluded that your applicable threshold for fatigue inspections is 20000 flight hours, according to Spanish DGAC AD 02/88 Rev 3.*
- *According to Spanish DGAC AD 02/88 Rev 3, a conformity document will be provided before the aircraft reach 20000 flight hours.*
- *Please contact EADS-CASA before the aircraft reach 20000 flight hours in order to adjust the inspection requirements established in the CASA Document C-212-PV-02-SID.*

No further correspondence concerning this measure had been exchanged before the accident.

1.6.11 Corrosion check CPCP C-212-PV01

On 31 March 1995 the manufacturer published the Corrosion Prevention and Control Program, (CPCP) C-212-PV01, which was followed by an Airworthiness Directive, AD 01/96, from the Spanish civil aviation authority, DGAC, on 30 April 1996 and another Airworthiness Directive, AD 98-18-21, from the American civil aviation authority, FAA, on 20 October 1998.

The programme means that operators of this aircraft type must prepare inspection procedures, adapted to suit their own flying operations, which shall ensure that serious corrosion does not occur in load-bearing structural elements without being detected and that can be corrected in time.

In C-212-PV01 the manufacturer has set a deadline, before which the programme must be initiated. The starting point and period of time for this deadline depend on which part of the aircraft is involved.

The starting point varies from two to eight years after the year of manufacture. The period of time until the deadline varies from two to eight years, and is the same as the subsequent inspection intervals. In areas where the deadline had already passed, the inspection programme was to be initiated within one year, counted from the issue date of the document, 31 March 1995.

The requirements stipulated by the authorities for the initiation of CPCP C-212-PV01 are not completely harmonised. DGAC AD 01/96 set a deadline of one year to start the programme, from the issue date of the document, namely 30 April 1996. FAA AD 98-18-21 set a deadline of one year to start the programme, from the issue date of the document, namely 20 October 1998.

Three levels were set for the scope of the inspection, as follows:

- *General Visual Inspection* *(GVI)*
- *Detailed Inspection* *(DET)*
- *Special Detailed Inspection* *(SDET)*

After the first inspection recurring corrosion checks must be carried out at intervals of one, two, four and eight years.

In respect of corrosion checks on the lower skin of the centre wing, in the area where fatigue cracks were found (centre wing internal structure between central spar and rear spar, Zone 920) the inspection interval is eight years.

The cracks were localised in an open structure accessible from the adjacent inspection hatch, but behind an inner wing rib in relation to the hatch. In order to inspect the complete area a mirror or other device for GVI has to be used.

The inspection level for this area is GVI, which is the lowest of the three inspection levels and is to take place in accordance with the following instructions:

A visual check that will detect obvious unsatisfactory conditions/discrepancies in structure and system/power plant installations. This type of inspection may require removal of fillets, fairings[3] access panels, doors, etc..., to gain access. The use of ladders, work stands, etc, may be required to gain access to the area.

In the technical documentation relating to the accident aircraft, S/N 346, there are the following remarks concerning corrosion checks in accordance with CPCP C-212-PV01:

1998-12-18 "*Corrosion insp. PV01 – 1Y/-2Y/-4Y done.*" According to the maintenance authority this means that corrosion checks on this occasion were carried out in the areas of the aircraft where inspections are to take place at one, two or four year intervals.

2001-09-03 "*1A/1Y insp. done at 5096 ldgs. PV01-1Y insp. done i.a.w FAA AD 98-18-21 option 1. Ref Saab Nyge Wo C2653.*" According to the maintenance authority this means that corrosion checks on this occasion were carried out in the areas of the aircraft where inspections are to take place at one year intervals.

2002-09-05 *"PV01 -1Y / 2Y / 4Y / 8Y Inspection carried out in accordance with DGAC AD 01/96 and FAA AD 98-18-21, option 1."* According to the maintenance authority this means that corrosion checks on this occasion were carried out in the areas of the aircraft where inspections are to take place at one, two, four or eight year intervals.

A note in the maintenance log for the aircraft, dated 15 May 2004, states the following: *"From date 2003-05-15, PV-01 is inc. in UHB i.a.w. FAA AD 98-18-21 Option 2 and DGAC AD 01/96"*. The maintenance manual states that from

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[3] "Fairings" - Here means all types of skinning that is associated with airflow.

that date CPCP C-212-PV01 is included in the maintenance authority's normal inspection programme.

According to information obtained by SHK no serious corrosion or other abnormality were found during any of the inspections that were carried out in accordance with the above-mentioned programme.

1.6.12 Dowty SB 61-1119-R4.

The propeller manufacturer, Dowty, published on 15 September 2005 Service Bulletin (SB) 61-1119-R4 (obligatory) in which it was prescribed that a special inspection of that aircraft type propeller must be carried out every 300 flying hours to check for fatigue cracks around bolt holes.

During such inspections cracks were found on the accident aircraft on three occasions. These all occurred on the left side but on different engines and on different propeller hubs.

Cracks were also found on two occasions on one of KBV's other CASA C-212 aircraft, also on the left side but on the same engine and propeller hub.

An inspection in accordance with SB 61-1119-R4 was carried out on this particular aircraft on 18 August 2006, 248 flying hours before the accident. No cracks were found.

1.6.13 Operational restrictions

The operational restrictions concerning the CASA C-212 that relate to the aircraft structure are stated in the AFM. In the following, a review of such applicable restrictions is given:

<u>Mass</u>
- Maximum permitted take off mass – 7,700 kg.
- Maximum permitted landing mass – 7,450 kg.
- Maximum permitted ramp mass[4] – 7,750 kg.

The total amount of usable fuel is 2,000 litres (equivalent to approx. 1,550 kg), carried in the outer and inner fuel tanks in each wing. Landing is permitted with full fuel tanks. Interviews with pilots have revealed that operations often took place with the maximum permitted take off mass. The structural mass limitation is frequently reduced in respect of performance limitations.

Remarks
In an undated continuation sheet in the AFM concerning KBV operations, it is stated that the maximum permitted landing mass is 7,400 kg.

<u>Speed</u>
- Maximum permitted speed (VMO) – 200 knots
- Maximum permitted manoeuvring speed (for full flight control travel) (VA) – 146 knots.
- Maximum flap extended speed (VFE) – 115 knots.
- Lowest speed for full controllability of the aircraft with a single engine (VMCA (in the air) and VMCG (on the ground)) – 88 knots.

<u>Wind</u>
- Max. demonstrated side wind component – 20 knots.

[4] Ramp mass – Total mass at parking and taxiing

- Maximum permitted tail wind component is 10 knots.
- Maximum permitted wind for take off and landing (including gusts) - 50 knots.

Maximum permitted G-loading (Nz)

- With flaps retracted - +3.0 to -1.2 G
- With flaps fully extended - +2.0 to ±0.0 G

Note:
G-force is a term that is used to measure the loading exerted on an object in various conditions, for example on an aircraft in heavy turbulence, steep pull up or turn. The normal positive loading is 1.0 G, which is equivalent to the gravity exerted on a person on the ground, or an object at rest or during constant movement.

If an opposite force of 1.0 G is applied, 0.0 G is exerted, commonly called weightlessness. This aircraft type has no instrument for this (G-indicator) in the cockpit to show the amount of G-force being applied to the aircraft.

Other
Aerobatic manoeuvres and spins are not authorized.

Checklists
The AFM also includes the manufacturer's checklists for various stages of flight operations and the external inspections, of "Line check" type, that must be performed before flight. The checklist part contains sections that cover normal and abnormal situations and emergency actions. The checklists from the manufacturer are however recommendations and KBV had modified these in order to adapt them to the actual operations.

1.7 Meteorological information

According to the SMHI analysis of the Falsterbo canal area at the time of the accident:

Wind southerly 18 knots with gusts of up to 25 knots (decreasing), good visibility, no cloud below 5000 feet, temp./dewpoint +14/+11 °C, QNH 1004 hPa. The wind between 200 and 500 feet was assessed as southerly to south-westerly at 20-25 knots with moderate mechanical turbulence.

1.8 Aids to navigation

In its original state the aircraft was equipped for instrument flying. It was equipped with additional radar and navigational equipment for use in KBV operations.

1.9 Communications

1.9.1 The take off

The radio communications between KBV 585 and air traffic control at Ronneby airport were normal and included a request and granting of operational clearance to taxi out and take off, and route clearance to continue the flight. The only deviation from the expected procedures was a request to make a left-hand circuit round the airport immediately after take off.

1.9.2 *Maritime surveillance*

After KBV 585 had left the Ronneby air traffic control radio frequency the pilots went over to a local frequency for communication with the southern KBV surveillance region. The pilots also had direct radio contact with the base at the Falsterbo canal, from which the request later came concerning the fly-by that took place.

Also communications between KBV 585 and the other units during the surveillance flight to the southern tip of Gotland and back were normal. Information that was exchanged included the planned arrival time at the Falsterbo canal. The base relayed that they would advise those concerned so that they would be ready at the time the aircraft would pass by.

1.9.3 *The fly-by*

During the approach to the northern end of the Falsterbo canal, radio communications from KBV 585 were limited to single contacts with the base. No further communications with the aircraft were recorded.

1.10 Aerodrome information

Not applicable.

1.11 Flight recorders and voice recorders

1.11.1 *Handling of the FDR and CVR*

The aircraft was equipped with an FDR of Honeywell type, part number (P/N) 980-4100-FWUS and a CVR of Fairchild type, P/N 93-A100-83.

The aircraft's CVR was found during wreckage recovery, while the FDR was found over a week later embedded in the bottom silt after an extensive search carried out by KBV personnel.

Both units were damaged and water had entered through their casings. Immediately after recovery they were packed into fresh water filled containers and transported by courier to the Air Accidents Investigation Branch (AAIB) in Great Britain for analysis.

In both cases the data storage media consisted of magnetic tape, which was damaged. Using advanced technology the AAIB succeeded in saving and downloading all the information that was stored in the memory modules of the units.

1.11.2 *FDR-data*

Apart from some short interruptions it has been possible to read out relevant data from the entire flight, including True Heading, Pressure Altitude, Indicated Airspeed and Normal Acceleration. Based on this information the bank angle, climb and descent rates and course have been calculated.

The recorded and calculated performance parameters for the final part of the flight have been collated in Appendix 1 as a function of time.

This information can be summarised as follows:

During the first fly-by, on a north-north-westerly course, the altitude was about 534 feet and the IAS about 152 knots. After this the flaps were extended (CVR information). During the subsequent left turn over the sea the speed reduced to about 110 knots. The G loading momentarily peaked at about 1.6 G and the angle of bank to about 45°.

The next fly-by, on a south-south-easterly course, took place at about 180 feet altitude at a speed of about 100 knots. After this the altitude reduced to 136 feet and the flaps were retracted at the same time.

The final left turn, before the accident, took place without flaps while climbing to about 420 feet altitude and with G loading of up to about 1.8 G.

The final fly-by was with retracted flaps at a altitude of about 240 feet and at a speed increasing to just over 160 knots.

The final part of the flight was graphically drawn on to the vertical photograph shown below of the Falsterbo canal. The relevant parts of the audio recording in the CVR are also shown on the graphic.

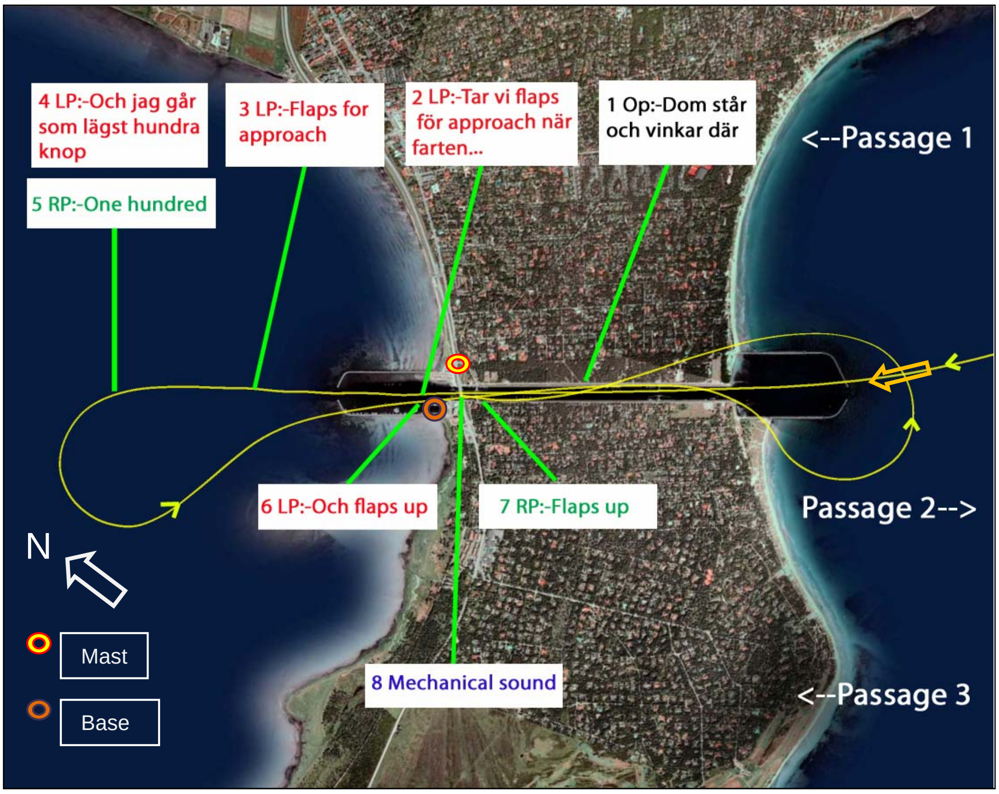

Figure 9. The flights along the Falsterbo canal
(Commander -LP, co-pilot -RP, operator –Op.
For translation see Appendix 2)

1.11.3 Radar data

The whole of the accident flight was recorded by the Swedish Armed Forces and plotted on the map picture below. A comparison of the radar data against the FDR data was carried out for the final part of the flight, which verified the performance calculations that had been made as mentioned above from the FDR data.

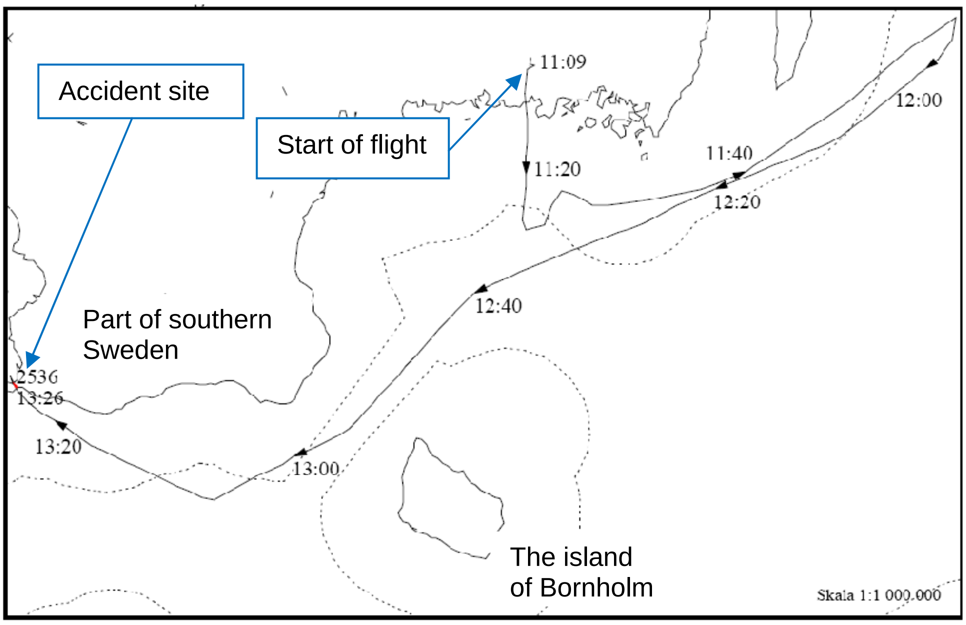

Figure 10. The accident flight

1.11.4 Available recorded flight profiles

In order to get some idea of how this type of aircraft is operated by KBV, all the recorded FDR data from both the accident aircraft and the other KBV aircraft of the same type, i.e. S/N 343 and S/N 229, was analysed. The analysis was focused on examining the numbers and levels of typical G-loadings that were applied during normal flying tasks as a result of, for example, turbulence, steep pull-ups and stationary turns.

Three G-loading levels were defined:

- Level 1: +1.13 G
- Level 2: +1.4 G
- Level 3: +2.0 G

The numbers of traverses through these levels and the total times at each respective level were counted.

In total from these three aircraft there were about 3 x 25 = 75 hours of recorded data from the most recent flights. Not all data was however used for the analysis, as some of the recordings were from ground movements or were of poor quality.

It must be noted that this amount of data only represents a very small part of the total flight times of the aircraft concerned. It is also difficult to draw comparisons between the different individual aircraft as each task profile is different.

Summaries for the respective individual aircraft.

S/N 346 (the accident aircraft)
The quality of the FDR data was for the most part good.

Number of analysed flights: 38
Above level 1: 68, totalling 1,042 seconds
Above level 2: 39, totalling 97 seconds
Above level 3: None

The data indicates flight cases with positive loading up to +1.8 G and down to +0.4 G. These flights involved turns and in some cases climbing with "unloading" at the tops of climbs.

S/N 343
The data quality was sometimes poor and impossible to analyse.

Number of analysed flights: 10
Above level 1: 18, totalling 489 seconds
Above level 2: 20, totalling 302 seconds
Above level 3: 4, totalling 9 seconds

The data indicates flights with loadings up to +2.3 G. No negative G loadings or "unloading" were recorded.

S/N 229
The data quality was sometimes poor and impossible to analyse. A large proportion of the data had been recorded on the ground.

Number of analysed flights: 7
Above level 1: 15, totalling 89 seconds
Above level 2: 11, totalling 5 seconds
Above level 3: None

In the recordings that could be read out no abnormalities were found.

Summary
The recorded FDR data from the three individual aircraft indicated that during their most recent recorded 75 flying hours, totalling 70 cases and for a total of 404 seconds, they were operated in a manner that could have included turbulence, climbs and stationary turns with bank angles up to 45° or combinations of these. The aircraft registered S/N 343 had also on four occasions and for a total of nine seconds been subjected to G-loadings exceeding +2.0 G.

The recordings also included some cases with first a positive loading closely followed by "unloading" to a value of less than +1.0 G. (Ref. 1.16.13)

1.11.5 CVR data

The CVR in the aircraft receives and records all internal and external communication on board, along with other sounds and audio signals. On behalf of SHK the recorded data from the accident flight has been listened to and written out by a sound laboratory.

The audio data from the flight was recorded from 12:53:18 up to the instant of the accident at 13:26:30. Relevant communications from the last part of the recording have been summarised in Appendix 2.

The conversation that occurred between the crew members included both the pilots and the operators. Most of the conversation was between the two pilots. The content varied between normal chatting of a private nature to flight operations communications or radio messages.

In the analysis of the operational parts of the communications it was noted that no approach briefing took place before the requested fly-by at the Falsterbo canal. Such a briefing normally contains a review by the pilot who is flying the aircraft, as to how and where the approach will take place, in what aircraft configuration, and what altitudes and speeds are intended to be maintained. In the DHB there are however requirements for briefings only on approaches that are intended to precede landings.

In the analysis of the tapes and their written accounts, SHK has not found any signs of faults or abnormalities that could have affected the continued sequence of events. Nor has it been able to find anything abnormal in the communications between the members of the crew that could refer to any observed or suspected faulty function in that particular aircraft.

1.12 Accident site and aircraft wreckage

1.12.1 Accident site

The Falsterbo canal is a waterway, about 1400 metres long and 80 metres wide between Höllviken and the Kämpinge bay just east of Falsterbo. There is an artificial basin at each entrance.

Near the southern entrance there is an approximately 22 metres (72 feet) high navigation marker on each of the canal breakwaters. Close to the northern entrance to the canal, on the northern shore, there are two telecommunications masts, about 27 and 35 metres high respectively (89 and 115 feet). An opening bascule bridge carries a road across the canal at the northern opening.

Next to the north basin, which measures approximately 550 x 200 metres and is enclosed by two stone piers, KBV has a base (Höllviken) with jetties and buildings for vessels and materiel storage.

The aircraft came down into the northern basin of the Falsterbo canal.

Most of the aircraft ended up at about the centre of the basin, where on impact with the water it broke into a large number of pieces that sank to the bottom. Wreckage that did not sink floated in towards the northernmost pier.

The separated wing with the engine went into the basin about 100 metres from the bridge and soon thereafter sank to the bottom.

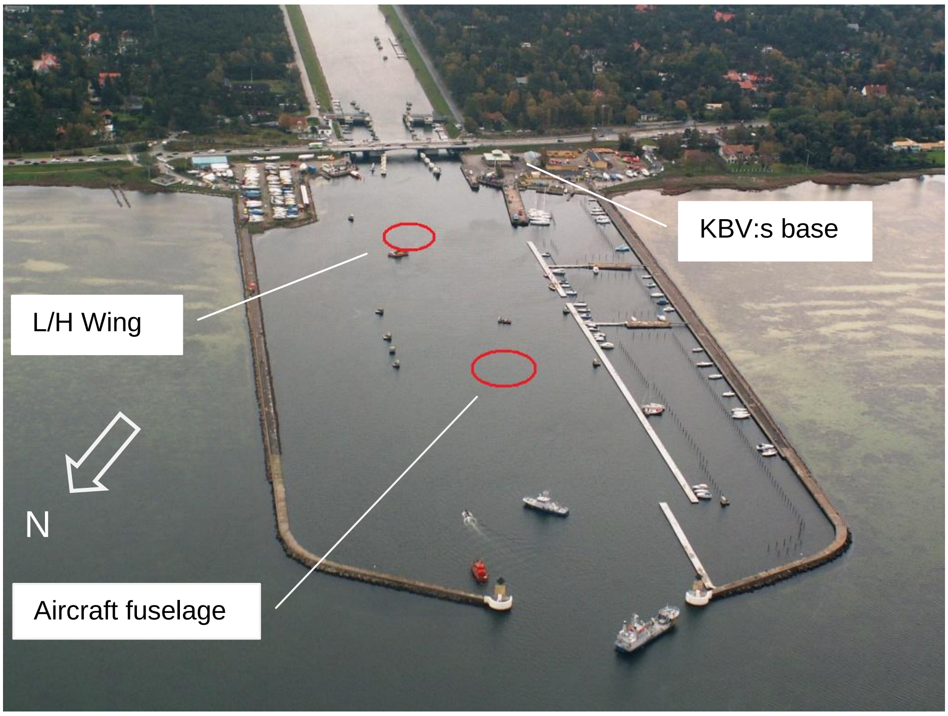

Figure 11. The approximate impact locations shown by ellipses

1.12.2 The search for and mapping of pieces of wreckage

The aircraft wreckage was located at the bottom of the basin by a search and rescue helicopter soon after the accident occurred. With the aid of KBV resources that were on site the search then began for the crew and wreckage on the bottom. The depth of water in the basin is about six metres and the search was performed by divers and with the aid of a ROV.

In connection with the search and recovery of the parts of the aircraft, all the larger parts were identified and documented, the positions being defined with the aid of GPS. Most of the aircraft parts were lying grouped on the bottom in three main areas, the locations and main parts being as follows:

Area 1, Concentrated and located about 100 metres from the canal bridge
Left wing, parts of the left wing, left engine and left propeller.

Area 2, Concentrated and located about 325 metres from the canal bridge
The tail section, right wing, parts of the right wing, right engine, right propeller, cockpit, instruments and nose wheel.

Area 3, Spread out and located about 400 metres from the canal bridge
Fuselage, CVR, main landing gear, doors and hatches.

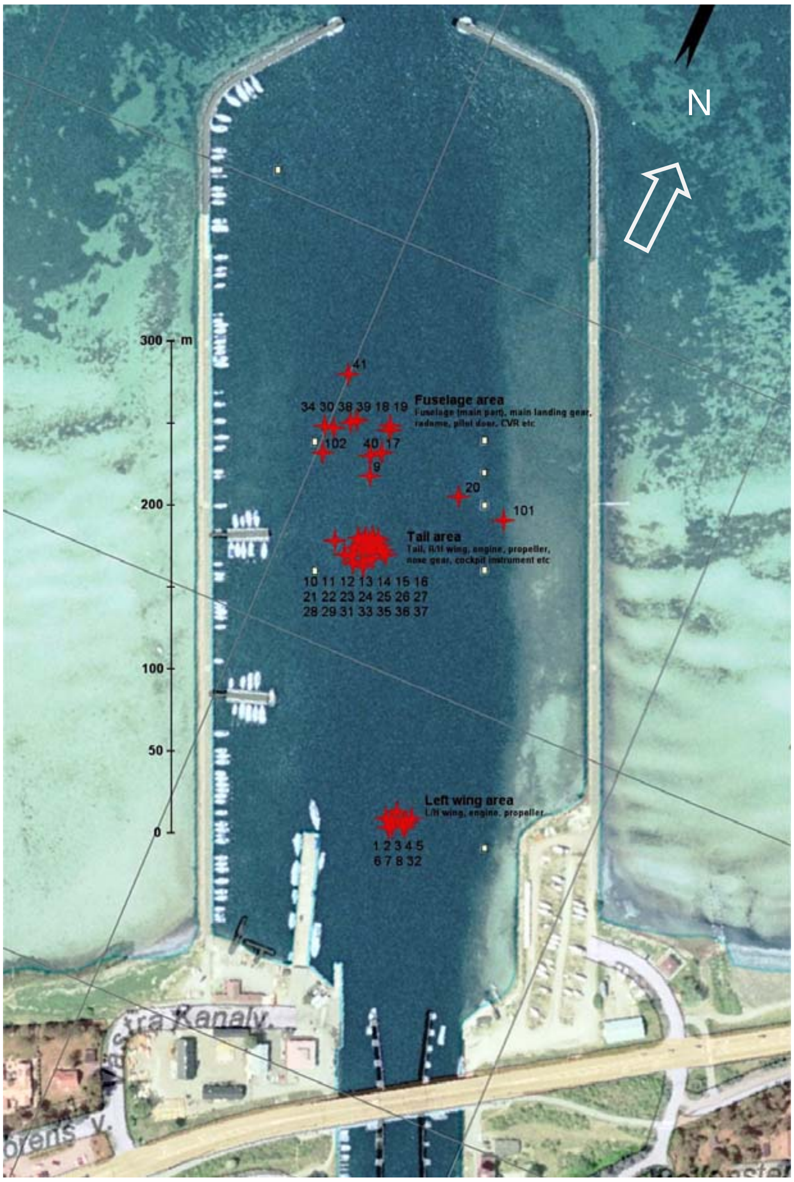

Figure 12. Plot of the pieces of wreckage

1.12.3 Recovery of the aircraft wreckage

Recovery was carried out with the aid of KBV personnel and equipment. For the recovery of all the larger pieces of aircraft wreckage one of the KBV oil decontamination vessels was used. Large pieces of wreckage were documented and rinsed with fresh water before further examination.

1.12.4 The aircraft wreckage

The aircraft was severely damaged and had broken into a large number of pieces.

Figure 13. The aircraft fuselage

The entire left wing with its engine had separated from the aircraft while in flight and impacted with the water, leading to major damage. The left engine with its propeller had broken free from the wing.


Figure 14. Left wing

On impact with the water the centre part of the wing, with the right outer wing and the tail section broke off from the fuselage, which broke up.

The right engine with its propeller had broken free from the right wing.

The tail section suffered extensive damage to the tail plane and fin. The attachment of the fin to the aircraft structure broke.

After recovery the aircraft wreckage was taken to a hangar at Malmö/Sturup airport for further examination.

1.13 Medical information

1.13.1 The commander

The commander had undergone the prescribed medical examinations with approved results.

1.13.2 The co-pilot

The co-pilot had undergone the prescribed medical examinations with approved results.

1.14 Fire

There was no fire.

1.15 Survival aspects

The damage to the aircraft indicates that the impact forces in the accident were considerable. The chances of surviving this type of accident are almost negligible, and all the indications are that those on board died immediately on impact. The pilots were wearing seat belts at this time. It has not been possible to determine whether the operators wore seat belts.

The aircraft’s ELT became unusable on impact.

1.16 Tests and research

1.16.1 General

At an early stage of this investigation it was clear that the left wing, including the left engine, had separated from the aircraft during flight.

This section describes a summary of the results of the comprehensive metallurgical investigations that were carried out on the wing fracture itself, the aircraft wings and its attachments to the fuselage. This section also deals with the investigations that were carried out on other systems and parts of the aircraft, and presents relevant factors that it was assessed could have had a bearing on the occurrence of the wing fracture and the accident sequence.

1.16.2 The aircraft structure – general

As mentioned above, the aircraft was completely destroyed on impact with the water and broke apart into a large number of large and small pieces. As far as it has been practically possible the aircraft structure has been examined in respect of possible defects in the aircraft before the accident that could have been related to the wing fracture.

No such defects were found. The examination indicated that the aircraft structure, including the internally and externally mounted additional equipment, was intact when the wing broke off.

Apart from fatigue cracks in the left and right wings, and a crack in the left propeller hub, all the important materiel damage is believed to have occurred in connection with the accident. In cases of doubt this was verified by metallurgical examination.

The attachment points for the fin and tail plane showed no signs of play or abnormal wear.

The mechanism and bearings for movement of the flying controls and flaps were in good condition.

No signs of corrosion that could have contributed to the accident were found.

1.16.3 *Instruments*

The aircraft's instrument panels and associated systems were severely damaged and found spread across the accident site. Certain instruments had detached from the panels. As far as practically possible the instruments, warning lamps and controls were examined in respect of possibly abnormal positions before the accident. Nothing indicated other than that the aircraft was in normal flight when the accident occurred.

The aircraft was equipped with two mechanical gyro horizon attitude indicators. These instruments were severely damaged but on the moving horizon panels of both the instruments there was a clear "impression mark" from the aircraft symbols of the instruments. Experience shows that such marks can occur on flight instruments as the result of high G-forces associated with a collision.

The location of these marks is approximately the same on both instruments and indicates that at the moment of impact with the water the aircraft was about 40° from a completely inverted attitude and in a dive at an angle of almost 40°. This attitude is equivalent to the aircraft rolling to the left at 140° or rolling to the right at 220° before impact.

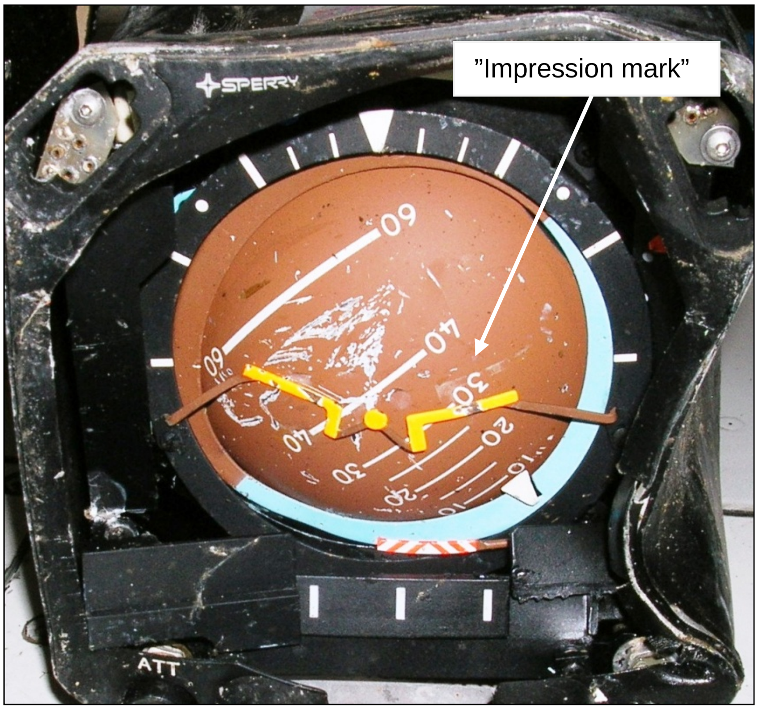

Figure 15. Left gyro horizon

1.16.4 Engines

Both the aircraft engines were inspected by a representative of the engine manufacturer under the supervision of SHK. Both engines suffered extensive damage that occurred in connection with water impact. The damage to the engine compressor blades differed significantly between the engines.

The damage to the left engine compressor (impeller) was limited and it was possible to turn the rotor, which indicates that the rotor speed was low and that the left engine was not delivering much power at impact.

All the compressor blades in the right engine were bent and it was not possible to turn the rotor, which indicates that the rotor speed was well above idling and that the right engine was delivering a certain amount of power at impact.

Apart from the impact damage no faults or abnormalities were found in the engine mounts or its flexible engine pads.

Two drainage pipes on the left engine were worn at their lead-throughs in the engine casing which could be a sign that there was a certain amount of engine vibration during flight.

1.16.5 Propellers

The propellers, which had separated from their engines, were inspected by a representative of the propeller manufacturer under the supervision of SHK.

The propellers had separated from the engines due to momentary overload fractures of their connection flanges.

In the fracture surface of the left propeller hub one of the bolt holes had a fatigue crack measuring approximately 10 x 5 mm. (See also Section 1.6.12.)

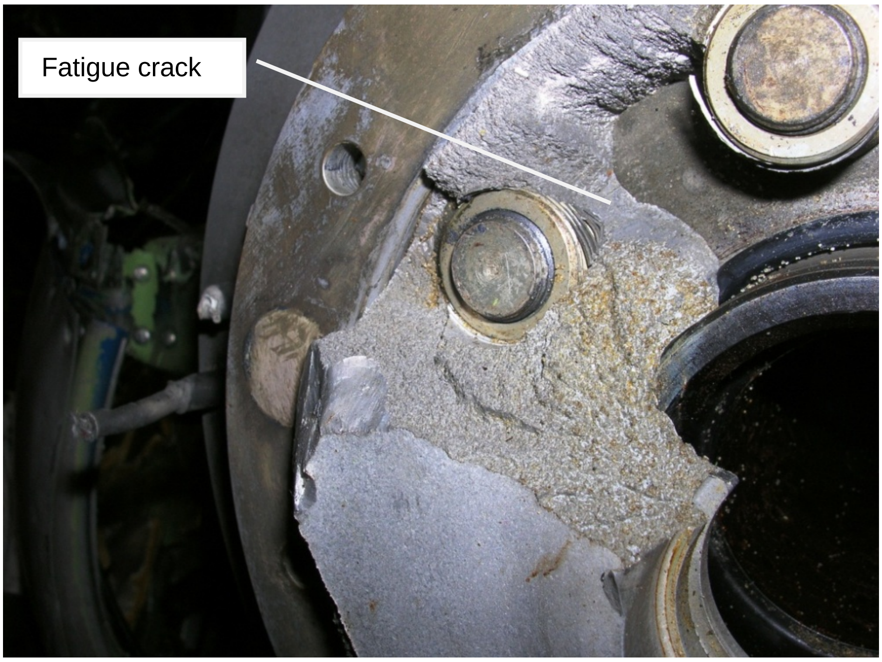

Figure 16. Left propeller hub

Because of the crash damage it was not possible to determine for certain the propeller blade angle at impact. Nothing in the examination of the propeller pitch adjustment mechanism however indicates other than that it was operating as designed at the moment of impact.

All the blades of the left propeller had remained on the hub and were deformed in such a way that indicates that the propeller speed was low and that the propeller was not producing any thrust at impact.

All the blades of the right propeller had remained on the hub and were deformed in such a way that indicates that the propeller speed was low and that the propeller was producing only low or no thrust at impact.

1.16.6 The wing fracture

The left wing broke off at the wing root during the accident flight. The fracture occurred at the central wing box adjacent to the fuselage. Damage to the upper part of the wing structure shows that the wing, while separating from the aircraft, bent upwards.

Figure 17. Location of the fatigue cracking

1.16.7 Left wing

After separation the left wing and engine installation went into the water. On impact the left engine was torn off and extensive damage occurred to the left wing section of the wing box. The other part of the wing received severe compression damage at the front edge. The outer part of the wing broke upwards and split. The flap and aileron remained comparatively intact.

An approximately 840 mm long fatigue crack that led to the wing fracture was found in the lower supporting wing skin between the wing spars. The crack was localised in the longitudinal plane of the wing, along the outermost row of rivets (rivet row # 1 closest to the wing tip) in the riveted attachment for the lower doubler, that at the same time forms the riveted attachment for the angle bracket to which the fairing is screwed (Station 1030). Within the same length 6 longerons and both wing spars had fatigue cracks which had penetrated between 5 and 95 % of their cross-sections.

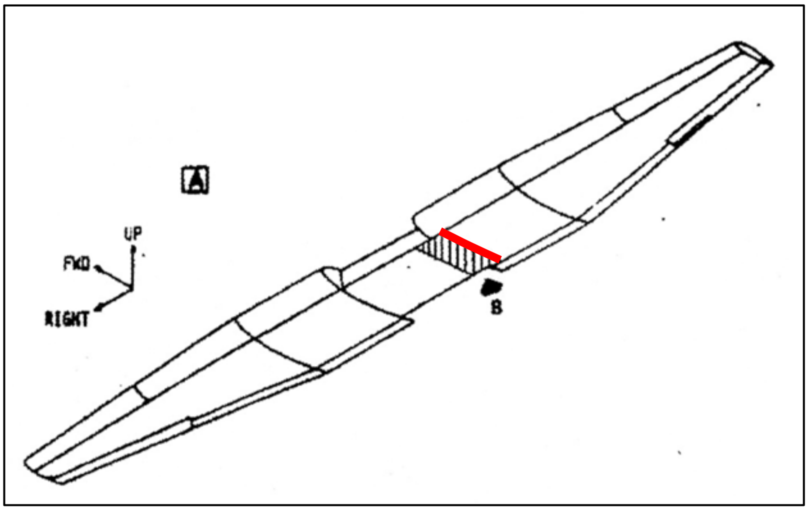

Figure 18. Location of the cracks in the underside wing skin

The location of the cracks under the doubler meant that they were not visible from the outside of the wing.

During the examination colour changes were noted in the primer on the inside of the wing, which could indicate that the anti-corrosion treatment had been applied at different times.

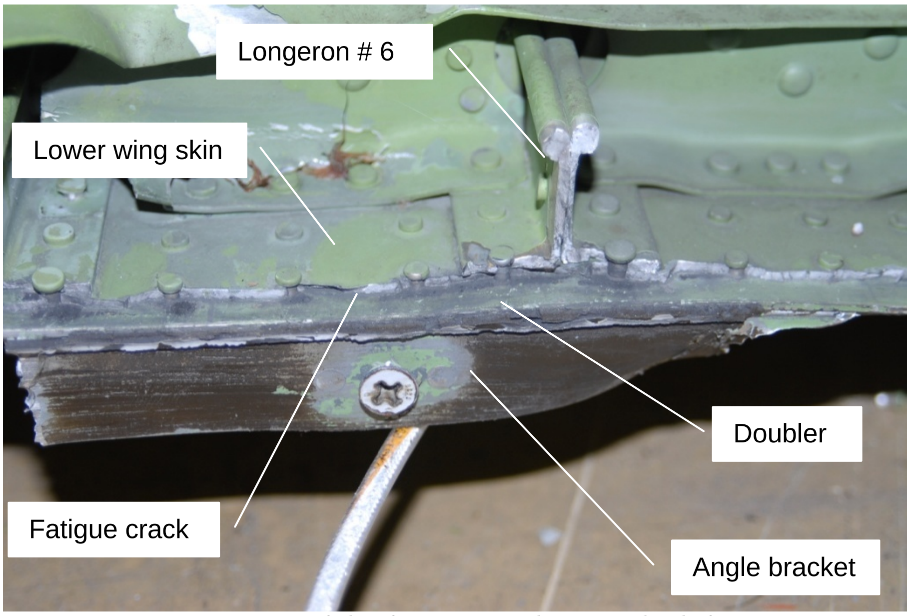

Figure 19. Part of the fatigue cracking in the left wing.

1.16.8 Right wing

The right wing struck the water with the leading edge first, together with the aircraft fuselage. On impact the right engine was torn off and extensive damage occurred to the right wing section of the wing box. On contact with the water the upper and lower skins peeled off from the front, so that most of the wing split. The flap and aileron remained comparatively intact.

Along the row of rivets that were equivalent to the row of rivets at which the wing fracture occurred on the left wing, there were found several complete fatigue cracks between the rear wing spar and the two rear longerons. Some of these had grown together to become 55-60 mm contiguous cracks. The total crack length was estimated as being about 200 mm. Concerning the emergence of the fatigue cracks, see below.

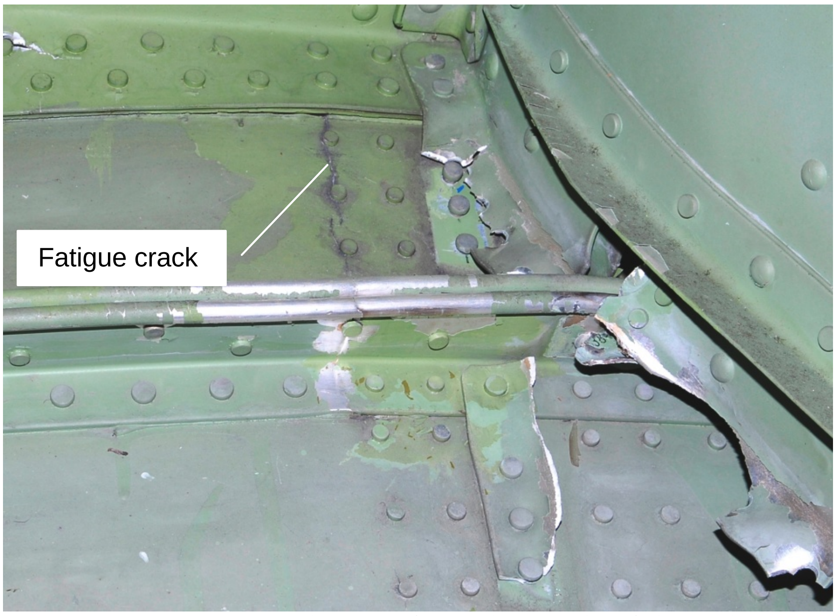

Figure 20. Fatigue cracks seen from the inside of the right wing

During the examination the same type of colour difference was seen in the anti-corrosion primer as in the left wing.

1.16.9 Metallurgical investigations

General
Extensive metallurgical investigations were carried out on the parts of the wings where fatigue cracks had been found, with the aim of clarifying the reason for their initiation and the mechanism behind their growth. The investigations were carried out on affected parts from both the left and right wings and on other parts of the aircraft where wear patterns were of interest. Comparisons were also made with other individual aircraft of the same type while in operation.

The work was performed by the Bodycote materials laboratory in Linköping in conjunction with an SHK metallurgy expert, on behalf of SHK. The results of the metallurgical investigations are summarised in the reports TEK07-0059 and Technical report SE-IVF no. 06.

In parallel with the SHK investigation, the same wreckage materiel was examined by the manufacturer's materials laboratory in Madrid, and to some extent by experts from the Accident Investigation & Research Inc. consultancy (AIR) in Canada, on behalf of the manufacturer. The results of the manufacturer's investigation are presented in the Technical Report NT-2-ID-06015.

Affected areas in both wings have been examined and compared. In general it can be said that the circumstances surrounding the initiation and growth of the cracks are almost identical in respect of both the left and right wings. The difference is that the fatigue process in the left wing had at the time of the accident progressed further and this was why the cracking in that wing first resulted in the wing fracture.

In order to facilitate the understanding of the metallurgical section of this report, the following factual information is appended:

Appendix 3	The mechanical characteristics of metals
Appendix 4	Non-destructive testing (NDT)
Appendix 5	Internal stress in metal alloys
Appendix 6	Riveted lap joints and Multiple Site Damage (see also Section 1.18.8)
Appendix 7	Fracture analyses
Appendix 8	Summary of Report NT-2-ADF-08002

Affected riveted joints

The aluminium alloy quality and physical characteristics met the specifications in accordance with AA 2024 T3 clad for all the affected parts. The sheet thicknesses agreed with the specified dimensions in the drawings.

Rivets with diameters of both 3.2 mm and 4.0 mm were used, depending on their locations. The diameter of the rivet head is normally a measure of the squeeze force that has been applied. In the case of the 3.2 mm rivets the head diameters varied from 4.4 mm to 6.0 mm. In the case of the 4.0 mm rivets the head diameters varied from 6.0 mm to 6.8 mm. According to information from the manufacturer, the diameters were checked by a gauge during manufacture.

The distance between rivet holes deviated in certain cases by 2-3 mm from the defined drawing distance, which meant that the rows of rivets were not always straight. However, the distances between rivets were never less than the minimum distance, 5 x the rivet diameter, which is a non-mandatory design standard.

Some rivet holes had manufacturing damage and some were deformed in conjunction with riveting. In several cases it was found that the rivets did not completely fill the rivet holes. Liquid anti-corrosion protection had entered in between the rivets and rivet holes in a number of cases.

It was found that a marginally greater squeeze force had been applied to the rivets in the left wing than the right wing.

According to the manufacturer the quality of the examined rivet joints was "normal" for the time when this particular aircraft was manufactured.

Processing of the lower load-bearing wing skin

The lower wing skin at the rivet joint in question is 2.0 mm thick. In order to save weight, material was milled away from the underside of the skin about from rivet row # 1 so that at the junction of the respective outer wings the thickness was 1.4 mm.

As part of the manufacturing process, after milling the ground surface was surface finished with a rotating tool. The finishing resulted in a pattern of concentric finishing marks. The finished surface is also present beneath the doublers and penetrates at some places up to about 50 % of the skin cladding[5], which is about 50 µm[6] thick.

[5] Clad – Corrosion protection

[6] 1 µm – 0.001 mm

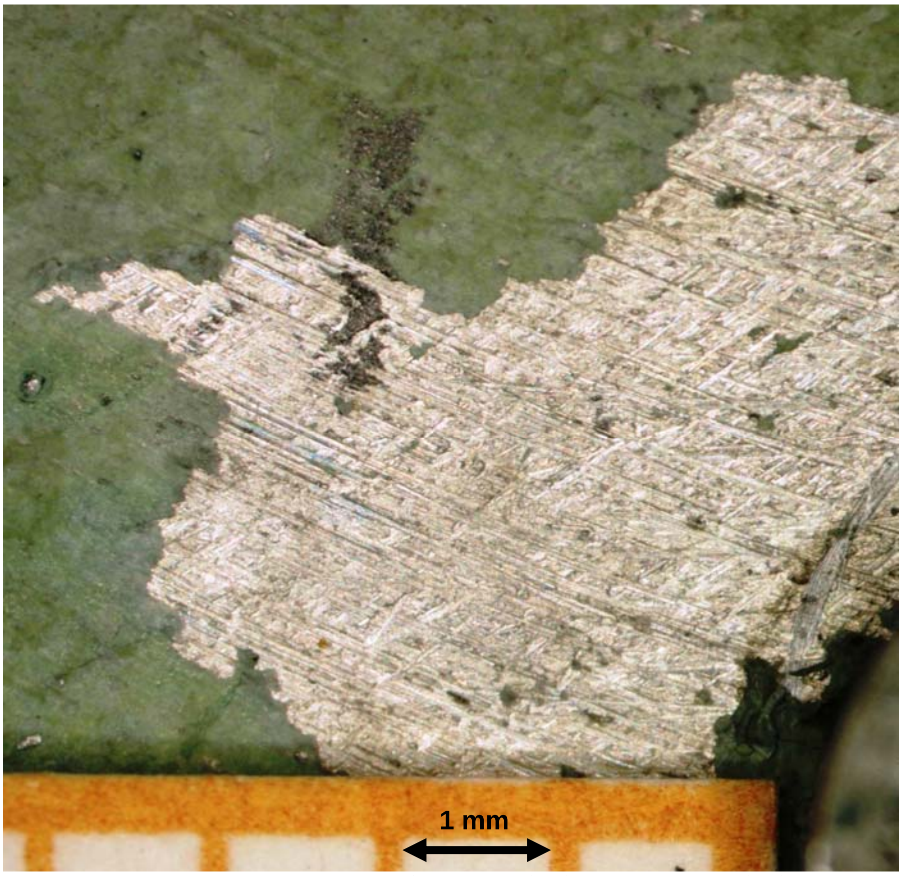

Figure 21. Finishing marks between rivet holes

<u>Fatigue cracks</u>
The development of the fatigue crack along rivet row # 1, that finally led to the wing fracture, can be described in five phases:

Phase I – A great number (thousands) of micro-cracks, less than 50 microns deep, developed in the Alclad layer.

Phase II - Some hundreds of those micro-cracks grew as fatigue cracks into macro-cracks.

Phase III – A number of macro-cracks coalesced into continuous fatigue cracks that penetrated the lower wing skin.

Phase IV – In a zipper opening effect the joining of the continuous crack with individual fatigue cracks created a major crack along the rivet row. Along the same row fatigue cracks of different size were developed on all the longerons.

Phase V – When the major fatigue crack had reach a length of about 840 mm the wing ruptured. See the following sketch.

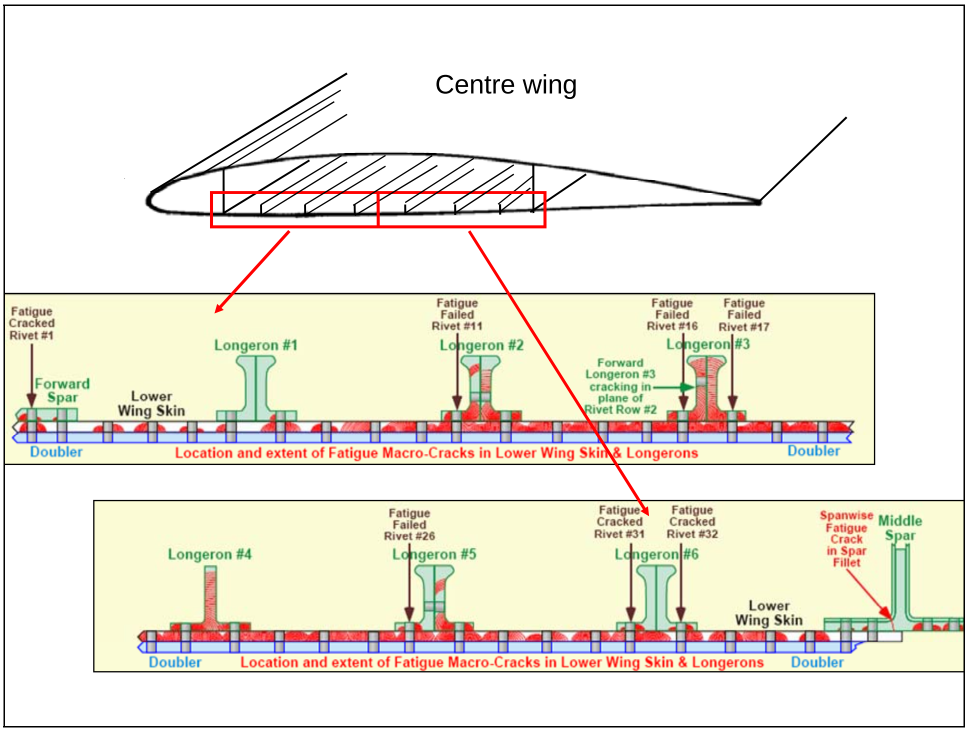

Figure 22. Fracture, with fatigue cracks marked in red

The cracks initiated both from the edges of the rivet holes and from micro-cracks in the underside of the skin along the rivet rows # 1.

<u>Micro-cracks</u>
In a band that extends about 4 mm inside to 12 mm outside the centre line of the rivet row, hundreds of micro-cracks were found on the underside of the skin. Some of these were only 0.1 mm deep and 1 mm long, and could not be seen by the bare eye or with any of the usual NDT methods. Such cracks only become apparent during visual inspection with magnifying glass (x 10) or when the sheet is bent.

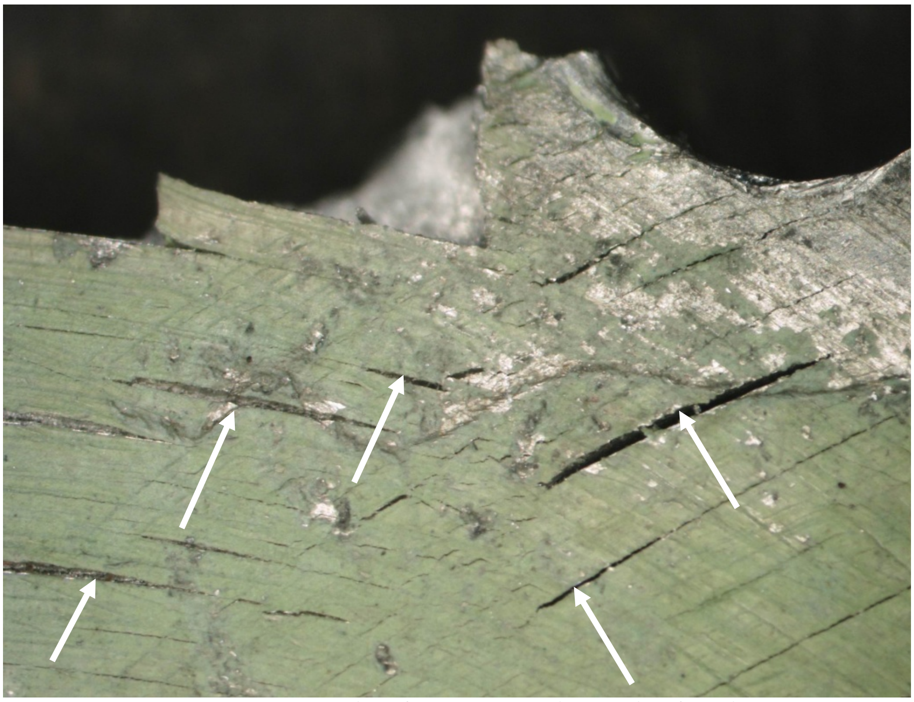

Figure 23. Example of micro-cracks in the finishing

In most cases the micro-cracks arose at the bottom of the above-mentioned finishing marks and are of typical fatigue character. With the aid of a scanning electron microscope clear striations[7] could be seen from each respective starting point (see Appendix 8). The concentric finishing marks cross each other which mean that the angles between cracks in some places reach 45°.

The fracture surfaces of many of the micro-cracks show no sign of mechanical fretting against the opposing fracture surfaces. (See the illustration below, taken using a sweep electron microscope.) This may be because there was internal stress in the material or that the normal forces that arose in the wing during flight tended to hold the cracks "open".

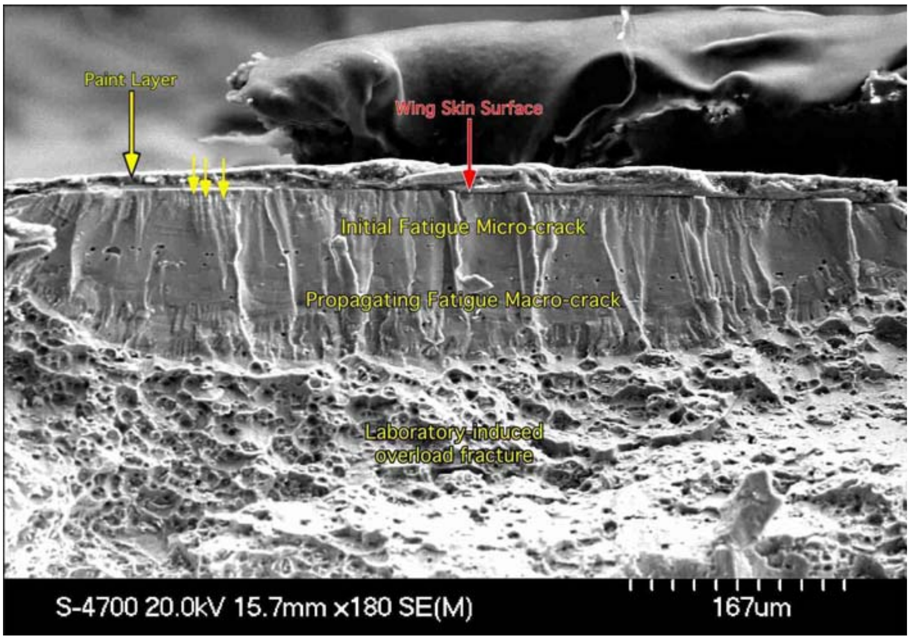

Figure 24. Undamaged fracture surface in micro-crack

Crack growth

Fatigue cracks have grown from the many initiation points along the rivet row. The arrow at the left in the illustration below shows how a crack has grown from a starting point between the rivet holes. On the surface of the crack can be seen typical curved beach lines. The arrow at the right indicates a starting point from the corner of a rivet hole.

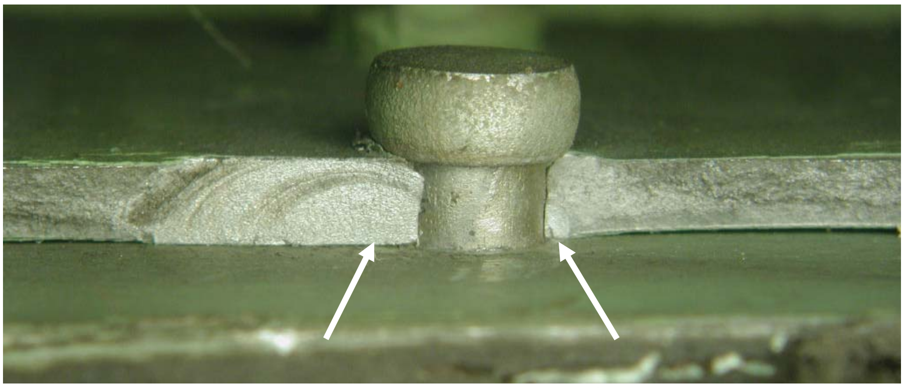

Figure 25. Fatigue cracks in the left wing skin.

Growth was upwards and to the sides. The cracks have eventually grown together with other cracks to form longer cracks. The fatigue cracks that began

[7] Striation – Concentric curved line patterns in fatigue cracks

in the areas between the rivet holes were mainly initiated by the micro-cracks in the finishing marks. In several cases the cracks have also initiated in the corners between the rivet holes and the lower wing skin. This meant that the growth of the fatigue cracks between the rivet holes largely followed the finishing marks.

The picture below shows different stages in the growth of fatigue cracks that have started from micro-cracks between the rivet holes, seen in a cross-section of the skin.

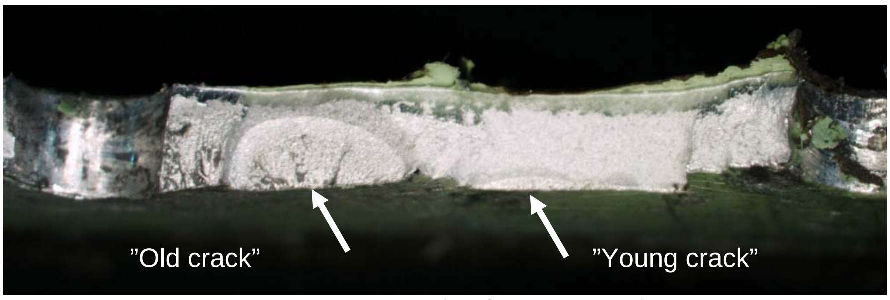

Figure 26. Growth of micro-cracks

In many cases a crack has “jumped over” to another crack that has thereby been lengthened. (See the picture below.)

Figure 27. Example of crack growth by “jumping”

Fretting damage on many of the crack surfaces and the presence of aluminium oxide indicate that some cracks are old and that crack growth developed over a long time, probably several years.

Fretting[8]
At several places along the doubler, fretting damage has, to different extents, occurred along the crack. This has not always reached the edge of the crack, and may have been due to the presence of internal stress in the wing, or that the forces that arose in the wing during normal flight tended to hold the cracks “open”.

[8] Fretting – Wear phenomenon occurring between two surfaces. (See Attachment FF)

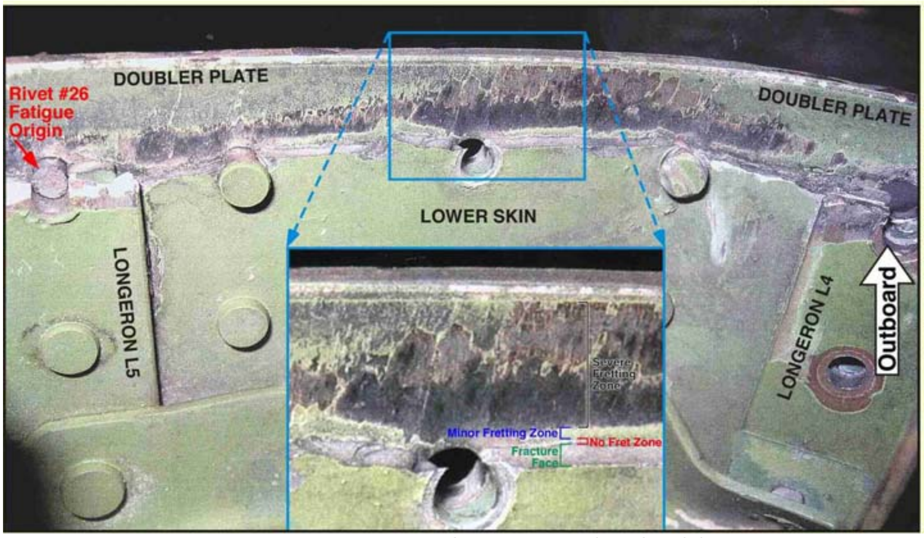

Figure 28. Fretting damage at the doubler

<u>Fracture analysis</u>
Extensive metallurgical investigations were carried out into the character and fracture surfaces of the fatigue cracks. Important parts of these are described in Appendix 7. The following is a summary.

<u>Summary of fracture analysis</u>

- The number of partial cracks in the wing fracture is very large, in the order of hundreds. Not all these cracks were initiated at the same time, since oxidation and fretting show internal age differences.
- A large number of small cracks have grown together and formed cracks of great combined length along a row of rivets.
- During growth, in certain cases cracks have “jumped” from one fatigue crack to another.
- The characteristics of the fatigue cracks in the left and right wings are similar.
- In all there are a very large number of striations, indicating in the order of millions of load changes for the entire crack sequence.
- In an initial stage of the fatigue sequence, i.e. with little crack depth, the stress level in the load spectrum was low and with similar internal size.
- According to the fracture mechanics calculations in both the Bodycote report BMT TEK07-0059 and the manufacturer’s report CASA MEMO MM-2ADF-07002A, it was found that the stress load was about 115 Mpa, i.e. 1/3 of the yield strength, which for this particular skin sheeting amounted to 365 Mpa. This infers that oscillating loads had been present, but that random loads, of a type caused by turbulence or by maneuverings, had dominated.
- At deeper crack depths, in a developed stage of the fatigue sequence, the load spectrum is different, with high peaks, often with varying amplitudes. Here the crack propagation has often taken place in jumps and partial cracks have successively linked up to become a connected main crack that grew to the final fracture.
- There are four types of notch that have contributed to localisation of the initiation points of cracks:
  - The sharp corner between a rivet hole and the underside of the wing skin.
  - Fretting between the skin and doubler.
  - Mechanical damage in rivet holes.
  - Scratches in the skin cladding, arising during manufacture when surface finishing with a rotating tool.
- None of these notches were assessed as being so great as to be considered as the only reasons for fatigue crack generation, but they have contributed to localised crack start points.

- These notches were adjudged as being usual and complying with the manufacturing standard and quality applying to aircraft at that particular time period.
- The fatigue cracking status of the accident aircraft shows very strong similarities to a commonly occurring fatigue phenomenon in “Ageing aircraft”; Multiple Site Damage, MSD.

Non-destructive testing (NDT)
Sample pieces from the area along rivet row # 1 taken from both the left and right wings were examined in laboratory conditions using radiographic, inductive, ultrasound testing and visual inspection. (See Appendix 4.) The aim was to obtain more detailed information about the extent of the cracking and the possibility of detecting cracks using NDT, i.e. the kind of inspection that could be carried out on aircraft that are in operation. In certain cases comparative tests were performed on other individual aircraft.

It was found that none of these methods seem able to find all cracks that are present. To detect these it was necessary to bend the sheet metal. In addition, the design is in many places complex and practical problems arise in getting access to the surfaces that have to be examined. Certain cracks can be detected by the NDT method, but not with a different method, and vice versa. The previously mentioned micro-cracks are in some cases so small that they cannot be detected by any of the methods.

It has become apparent that the methods prescribed in the EASA Airworthiness Directive AD No. 2006-0365-E, issued on 4 December 2006 due to this accident, would not have found all the cracks in the affected area. Using the methods prescribed by the manufacturer in CASA C-212 SID C-212-PV-02-SID, C-212 SIP C-212-PV-02-SIP and EADS-CASA AOL 212-018, revision 1, dated 1 December 2006, less than half of the continuous crack length in the right wing could be found. Some of the cracks that were not detected using this method were up to 5.0 mm long. EASA has been given information about this.

The investigation verified that certain rivets did not completely fill the rivet holes, so that gaps between the rivet shank and the rivet hole of up to 0.2 mm existed.

In March 2007 AOL 212-018 revision 2, was published, which includes initial and repetitive inspections of affected area with several redundant NDT methods such as X-ray, HF eddy current, ultrasonic and visual inspection with a boroscope or videoscope.

Comparison of the affected riveted joint with equivalent joints in aircraft that were in operation
In order to get an idea of rivet joint conditions, comparisons were made between X-ray images taken on all the CASA C-212 aircraft operated by KBV and the Swedish Armed Forces. In this investigation it transpired that gaps were found to about the same extent in all the CASA C-212 aircraft operated by KBV. Equivalent gaps were not found in aircraft S/N 139, which was operated by the Swedish Armed Forces, which is older but has less flying time.

It was further noted that gaps were mainly only present in joints that connected loaded elements such as ribs, longerons, angle brackets, etc. The illustration below shows a section of the rivet joint on the sister aircraft, S/N 343, where rivet row Y-1030 (rivet row # 1) also secures the angle bracket, while rivet row Y-995 only secures the doubler.

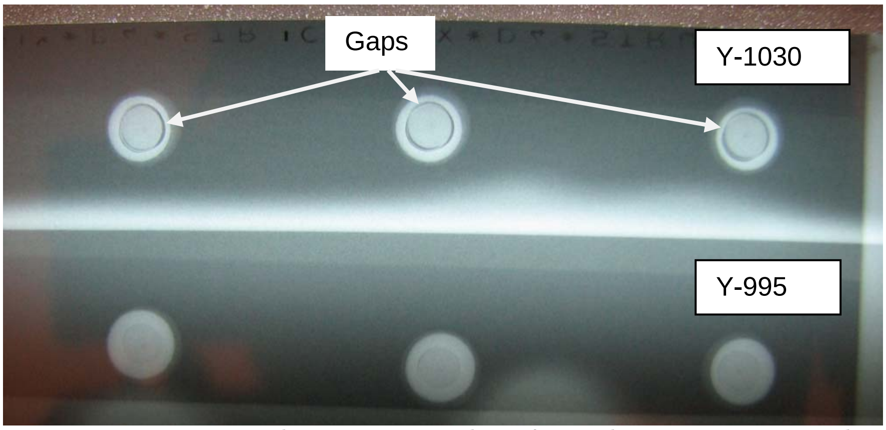

Figure 29. X-ray image showing examples of gaps between rivets and rivet holes *(Aircraft S/N 343)*

<u>Cracks in rivets</u>
In rivet row # 1 of the left wing on the accident aircraft six rivets were missing. Two of these were found. One was 100 % fatigued and the other 30 % fatigued. During the investigation 8 rivets were removed and suspected cracks were confirmed by bending up the skin. Three of these had small fatigue cracks.

On the right wing there were two broken rivets caused by 100 % fatigue. These were located on each side of the rear wing spar. The cracks had initiated from the side that faced out to the wing tip and propagated "inwards". (See the illustration below.)

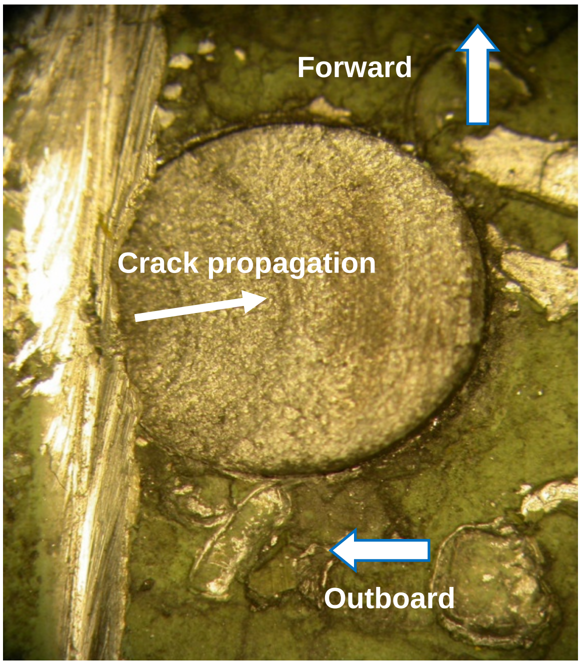

Figure 30. Fatigue fracture in a rivet shank

Riveted joints are in the first place designed to take up shear loads. The location and appearance of the cracks showed that the rivets in this case had been subjected to axial loads beyond those that were normal. This damage probably occurred at a late phase, when the structure had been loosened up by the fatigue cracks.

Signs that axial movement had occurred in the joint in question were also present on the sister aircraft, S/N 343, where black aluminium oxide had leaked out from some rivets. So far, rivets have been found to be missing on two other aircraft individuals in operation.

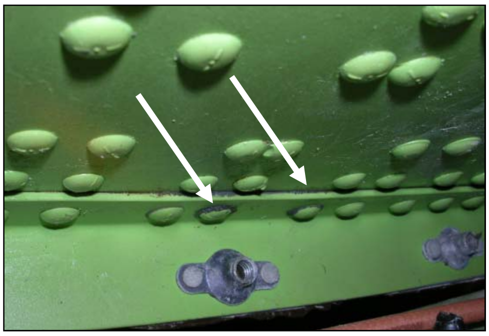

Figure 31. Signs of movement in a riveted joint, in aircraft S/N 343

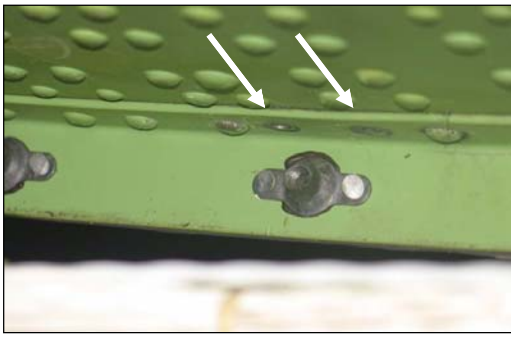

Figure 32. Missing rivets in a Spanish-registered operational aircraft
(Manufacturer's picture)

Wing bolts with attachments
Each wing attachment consists of two lower attachment lugs that are secured to the fuselage structure and an upper attachment lug that is secured to the central wing section, which are joined by wing bolts with castellated nuts. The attachment lugs have pressed-in bushings with jointly drilled holes for the attachment bolts. Inspection or exchange of the wing attachment components have not taken place during the aircraft's use, nor is it a requirement in the maintenance programme.

Wear in the aircraft wing bolts and bushings have been investigated. It was found that wear on the wing bolts from aircraft S/N 346 was greater than normal, and greater than in aircraft S/N 343.

The wear damage consisted of a type of fretting and the beginning of cutting. Also purely mechanical deformation was present. The two front bolts were more worn than that at the rear, but no great difference in wear was apparent between the left and right sides. The wear was fairly evenly spread around the circumference but not so great that a gap was present in the attachment.

Figure 33. Wing bolt from the accident aircraft S/N 346, right front position

Figure 34. Wing bolt from sister aircraft S/N 343, unknown position

Angle bracket and fairing
After the wing separated the left side fairing remained securely screwed to the fuselage, without any relative movement taking place. At separation all the

screw holes at the attachment to the angle bracket tore up, while all the screws in the plate remained in place.

Four of the rivets that secured the angle bracket to the doubler and the wing underside skin had broken. The fracture surfaces of two of these rivets, those that also secured the angle bracket to longeron # 3, showed that the fractures had been preceded by fatigue cracks. In the rivet hole in the angle bracket for one of these two rivets, two fatigue cracks were found.

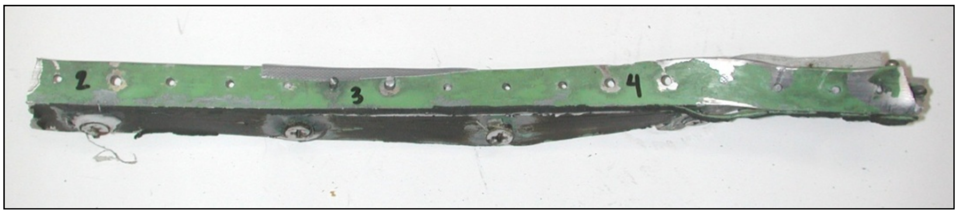

Figure 35. Part of the angle bracket from the left wing.

The appearance of these parts indicates that before the accident the fairing had been firmly mounted between the wing and the fuselage and that no relative movement had occurred between the fairing and the angle bracket, or between the fairing and the fuselage.

1.16.10 Fatigue testing and flight tests

As part of the investigation the manufacturer has performed material fatigue tests and flight tests to simulate the actual circumstances. Among other things the aim was to obtain further knowledge of the factors that could have contributed to the initiation of the fatigue cracks along rivet row # 1 in the lower skin of the wing.

The manufacturer's investigations have not yet been completed but a preliminary report: "C212 AIRCRAFT. ANALYSIS – TESTS CORRELATION", NT-2-ADF-08002" was published in November 2008. A summary of the contents of the report and the manufacturer's own conclusions, without evaluation by SHK, is presented as Appendix 8.

The report states among other things that the tests that were carried out were not on their own able to explain the early initiation of fatigue cracks in the accident aircraft that were assessed as arising after about 3,500 flights, i.e. when the cracks could have been detected using an NDT method. Taking into account the loads applied, the use of the aircraft, its design and production standards, etc. it was considered that the calculated fatigue life of the wing had been adequate.

According to the opinion of the manufacturer some further factor must have been applied to explain the early crack initiation. It is considered possible that the centre wing lower skin, at some time during the initial use of the aircraft, could have been subjected to a very high compression load which caused plastic deformation close to rivet row # 1, resulting in a persistent local internal stress.

It is thought that this could have reduced the fatigue life along the row of rivets and would explain the initiation of micro-cracks which formed the starting points for all the fatigue cracks that later grew together and finally resulted in the wing fracture.

SHK remarks
Before the above-mentioned flight tests, SHK verbally requested that measurements should also be taken with loads near to the maximum permitted limits and during various types of “asymmetric flying”. This takes place, for example, when flying on one engine, with incorrect trimming, etc., which are practised, among other things, when converting to type.

The reason for this request was that SHK considers it important to obtain information on whether during this type of flying there could arise exceptional loadings and material stresses along the critical row of rivets as a result of the effect of the fairing.

However the flight tests did not include this type of flying. The calculations by the manufacturer of the forces and material stress in such flight cases are therefore extrapolations based on the assumption that forces and stresses increasing linearly in the case of loads in these parts of the flight envelope.

Detailed verification of these calculations is time-consuming and requires expertise, including access to complete construction drawings and the manufacturer’s own software. SHK has therefore decided not expending resources and time for such verification.

SHK has, however, with the aid of expertise from the Kungliga Tekniska Högskolan (KTH - the Swedish Royal Institute of Technology), looked through the report and its conclusions, and found that the tests and analyses on which it is based were to a great extent performed using accepted methods. However, the stress analysis using the finite element method was performed with simple shell, beam and bar elements which lead to results that may contain large errors in computed local stresses.

1.16.11 Comparisons with sister aircraft S/N 343

The sister CASA C-212 aircraft registered S/N 343 was largely manufactured in parallel with the accident aircraft and delivered to KBV at the same time. Also the installation of the electronic maritime surveillance equipment after delivery to Sweden was also done in parallel and was identical. Both the aircraft S/N 343 and S/N 346 were used for the ground and airborne testing of the equipment.

Thereafter both aircraft were operated in the same manner by KBV and by the time of the accident had more or less accumulated a similar number of flying hours and numbers of flights.

During thorough examinations of aircraft S/N 343 and S/N 229 (the latter having been delivered later to KBV and having fewer flying hours) with pertinent methods, no fatigue cracks were found in the critical areas on the undersides of the wings along rivet row # 1. On aircraft S/N 229 the inspection was performed with the doublers installed.

Apart from aircraft S/N 346 initially being used more frequently for flight training (see section 1.17.13) than aircraft S/N 343, SHK has not found any significant difference in the histories of these three aircraft nor usage that would clearly explain the difference in crack generation in the wings.

1.16.12 Sealing of riveted joints

Sealing of riveted joints with an air-hardening sealing compound is a usual method within the aircraft industry for corrosion protection and to reduce the risk for fatigue cracks. This latter effect has been demonstrated by several practical fatigue tests and documented by such papers as H. Vlieger & H.H.Ottens Uniaxial and Biaxial Tests on Riveted Fuselage Lap Joint Specimens, DOT/FAA/AR-98/33, NLR.

In respect of the particular doublers that were riveted to the undersides of the wings, at the time of manufacture of the accident aircraft there were no special instructions for the use of sealing compound. As a general rule it was stated that sealing compound should be used when riveting together joints with "load-bearing construction elements".

The use of sealing compound thus depended to some extent on which assembly worker performed the work. According to the manufacturer's follow-up, the wings of all the aircraft manufactured before S/N 474 were assembled without the use of sealing compound.

In the case of aircraft individuals S/N 343 and S/N 346 it was found that sealing compound had not been used. In the case of aircraft S/N 229 it has not been possible, for practical reasons, to be able to establish whether sealing compound was used or not.

The calculations that were performed in respect of the fatigue tolerance of this particular riveted joint were, according to the manufacturer, "conservative", i.e. based on the joint not having been sealed with sealing compound.

1.16.13 Fatigue cracks in alloy AA 2024 T3

The wing skin on the accident aircraft is made of aluminum alloy AA 2024 T3 which is clad on both sides for corrosion protection. It is well known that the fatigue life of clad alloy is much shorter than that of unclad alloy. If clad alloy is exposed to oscillation loads initiation of so-called multiple micro-cracks is common, and the first crack can be initiated in the clad already after 1 % of the fatigue lifetime.

1.17 KBV organisation and management

At the time of the accident

1.17.1 General

KBV is an authority with the task of undertaking maritime surveillance and providing rescue services along with preserving the environment at sea. Maritime surveillance involves being responsible for providing other authorities with supervision, crime prevention operations, checking and inspection. These operations are carried out with the aid of aircraft and vessels.

From the mid-1970s the aviation side of KBV was implemented by small aircraft, equipped with sideways looking airborne radar (SLAR) and scanners, mainly for recording releases of oil. In the 1980s KBV, together with Försvarsmakten (the Swedish Armed Forces) via Försvarets Materielverk (FMV), negotiated for the procurement of CASA C-212 type aircraft. The first of this type of aircraft for KBV, S/N 343 and S/N 346, came into operation in 1986, and in 1990 a further aircraft of this type was procured.

KBV originally operated its aircraft from bases at Bromma, Sturup and Säve, but in the 1990s all flight operations were based at Skavsta airport.

1.17.2 KBV's flying operations

General

The flying operations carried out by KBV are defined as national aviation and are not therefore subject to authorisation in accordance with JAR OPS 1. The authority that grants authorisation, the Swedish Civil Aviation Authority (now the Swedish Transport Agency) that also acts as an inspectorate for operations, bases its authorisation on national regulations.

The part of the national regulations that governs KBV operations is called "Specialised aviation" and is regulated by LFS 2007.47 (former BCL D 2.2) and BCL D 3.1.

Authorisation and special rules

The operational authorisation for KBV was issued in accordance with paragraph 89 § of the Civil Aviation (Act 1986:171) with a validity up to and including 31 March 2007 (applicable at the time of the accident) and includes: "The exercise of aviation operations of special type covering monitoring and surveillance".

The authorisation was issued by the Swedish Civil Aviation Authority (now the Swedish Transport Agency) and contains, apart from a request to comply with the applicable civil aviation regulations, in addition a reference to the associated "Special rules".

The "Special rules" appendix defines those persons approved by the authority to manage and take responsibility for the flight operations.

These types of operations require, in accordance with the special rules, approved personnel in the following posts:

- Responsible for aviation operations
- Flight Manager
- Technical Manager

The document also contains information about the headquarters (Karlskrona) and its base of flight operations (Skavsta airport). The rules give permission for KBV to conduct its operations with aircraft of the type CASA C-212 along with certain single-engined aircraft as determined by the Flight Manager.

The operations must be performed in accordance with an Operating Manual (DHB) prepared by KBV and approved by the inspectorate. In addition, for technical services, there must be workshop manuals with maintenance manuals for the respective aircraft types.

The special rules in the authorisation give KBV permission, among other things, to perform take off and landing even when the runway visual range (RVR) has decreased to 550 metres.

1.17.3 Operational documentation

The aviation operations of KBV are based on operational documentation, which at the time of the accident consisted of:

Operating Manual (DHB)

The KBV Operating Manual was produced internally and approved by the Swedish CAA and contains the general rules and regulations for flight operations within KBV. In this document the detailed description of operations has been divided into two main areas, surveillance and checking, and rescue services, as follows.

Surveillance and checking

- General border and maritime surveillance
- Customs surveillance
- Inspection of protected areas
- Hunting inspection
- Fishery inspection
- Environmental protection inspection
- Maritime traffic surveillance
- Sea bottom surveillance
- Certain general police inspections
- Vessel safety inspections
- Historical maritime monument inspections

Rescue services

- Air sea rescue
- Actions to deal with oil leakage at sea
- Action to deal with other maritime pollution

The document defines the organisation and responsible decision-makers, also the aims and quality policy for the aviation operations. The DHB foreword by the Director-General states:

A basic principle for the aviation operations shall be an effort on every occasion to achieve maximum efficiency without jeopardising safety.

In the section dealing with aims and quality policy, it states that flight safety shall have the highest priority. A description is given of the system of self-checking in the organisation, covering among other things a system for the reporting of abnormalities and other events relating to flight safety.

It also describes the organisational procedures for analysis, evaluation and the following up of reports. The DHB is defined as a system of manuals that includes other documentation such as BCL, AIP, etc. Allied to the issuance of operational authorisation for aviation operations, is included a review of the DHB with associated documentation, this being a part that the authorisation authority checks.

After the accident, SHK requested a copy of the DHB for inspection. The copy that was received was found not to contain the issued revisions and/or applicable revision status. The explanation from KBV was that the DHB that was supplied was an electronic copy of an Operating Manual that did not contain any revision information.

Each pilot had his own DHB and was responsible for ensuring that revised pages were replaced in his own copy.

<u>Standards Handbook (SHB)</u>

The KBV SHB (Standards Handbook) is an internal document that forms part of the Swedish Coastguard system of manuals. The SHB, as with the other publications that are counted as "included" in the DHB (such as NOTAMs, AIC, AIP, etc.) are, according to the Swedish Transport Agency, not subject to separate approval for operational authorisation.

The SHB contains detailed descriptions of how coastguard flights are to be carried out. This document also contains descriptions of the operational training programme for pilots, both practical and theoretical type training, such as introductory route training.

The SHB also contains detailed operational tips in respect of various special areas, such as flying in abnormal weather conditions and low flying. In respect of low flying it is stated in the SHB that the lowest permitted flying altitude is 150 feet. The DHB states that the lowest permitted flying altitude is 100 feet.

Route Manual (RM) and Route Performance Manual (RPM)
These manuals form the operational basis, where the RM consists of route and approach flight planning maps and the RPM a performance basis for the CASA C-212 aircraft type. These documents were prepared by an external company that also deals with revisions, via subscription.

Each pilot has his own RM and is himself responsible for incorporating the revisions.

Aircraft Flight Manual (AFM)
The AFM was prepared by the manufacturer and approved in conjunction with the certification of the aircraft type. It forms an important part of the basis for flight operations and the way that flights are performed. Changes and revisions to the manual are distributed by the manufacturer.

The AFM contains information concerning the operational limitations of the aircraft (see Section 1.6.13) within the intended area of use, and procedures that must be followed in both normal and emergency situations. The manual also contains basic data for performance calculations, which are also in the RPM, along with information and limitations concerning the mass and balance of the aircraft.

The copy of the AFM received by SHK for review had a change date of 8 January 1991, without any subsequent revisions. The manual did not contain any notes concerning temporary revisions. According to KBV this manual was an unregistered surplus copy that was not in use and therefore not current.

At the time of the accident there had, according to the manufacturer, since 8 January 1991, been issued three new revisions (the latest being on 17 September 2004) and five temporary revisions (the latest being on 5 November 2003). The pilots did not have personal copies of the AFM, these were kept on board the aircraft and in the flight operations premises.

General regulations
In addition to the above-mentioned manuals the KBV aviation division had access to general regulations concerning aviation activities of a type such as BCL, AIP, etc. These manuals were kept in the flight operations premises at Skavsta airport.

1.17.4 Management

During the period 1985 to 2005 the head of the KBV aviation division, responsible for the finances, staff and administration, was also the Flight Manager with operational responsibility. He was mainly located at Karlskrona. The Director General was, according to the special rules in the authorisation, responsible for the aviation operations.

Due to the high workload on the Flight Manager the tasks were eventually shared between the Flight Manager and the Chief Pilot. The Flight Manager undertook the administrative part of the work and the Chief Pilot the more practical part, which also meant that there was a link between the pilots and the Flight Manager and that flight safety was monitored on site.

In connection with the procurement of new aircraft types, a reorganisation took place in 2005. A new Flight Manager was appointed, to be based at Skavsta. The previous Flight Manager, who had dual responsibilities as both Manager of the Coastguard aviation division and Flight Manager, remained in his post as Manager of the Coastguard aviation division. The CASA C-212 Chief Pilot also remained in post.

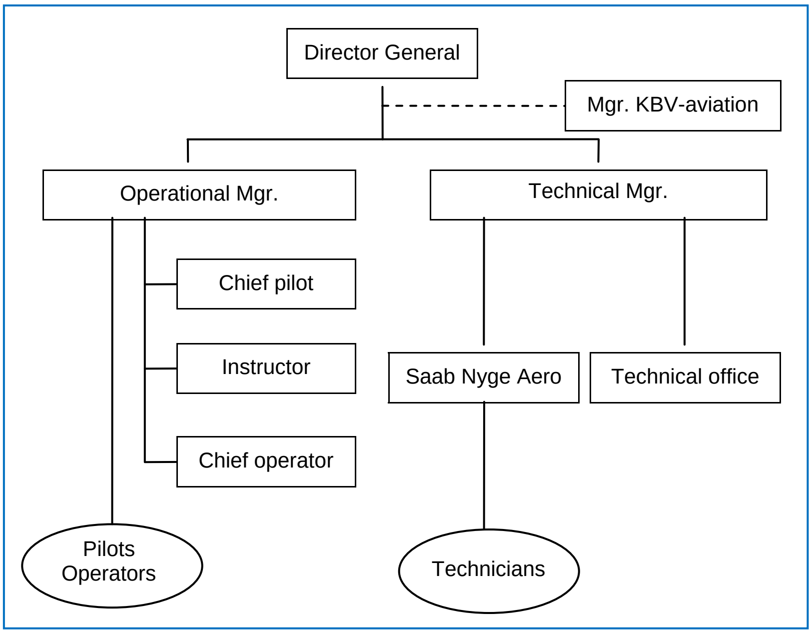

Figure 36. The KBV aviation division organisation according to the DHB at the time of the accident. (The manager of KBV aviation was however not part of the aviation organisation according to the DHB.)

1.17.5 Procurement of the CASA C-212

After having earlier performed maritime surveillance tasks with smaller aircraft, KBV recognised in the mid-1980s the need to be able to operate with larger aircraft, with the capacity to carry more technical equipment and a larger crew. The decision was made to procure three aircraft and equip these with the necessary technical maritime surveillance equipment.

SHK has not been able to obtain any written specification with the requirements that were laid down for the type of aircraft. However it was determined that what was wanted was a robust and spacious aircraft that was suitable for operation in difficult conditions at low altitude and often over water.

These requirements were put forward during negotiations with the manufacturer, and SHK has formed the view that the manufacturer’s representative in the sale of the three CASA aircraft was well aware of how KBV intended to use them. In the marketing of this aircraft type it had been specially proclaimed as having robust and “tough” characteristics and being suitable for such tasks as maritime surveillance. Most of the CASA C-212 aircraft that were manufactured were used for various types of transport operations.

1.17.6 Flight mission profiles

General

As detailed above, KBV has a wide field of tasks for its operations. In addition to individual events that require special missions, the flight operations however largely concern fishery and environmental monitoring in both Swedish and international waters.

The initial phase of KBV flight operations was mostly based on visual monitoring with manual detection and identification of vessels. With the CASA C-212 the agency was offered the chance to tailor the aircraft for monitoring using radar surveillance at sea. Identification was however still manual, i.e. a radar echo had to be identified and photographed by means of visual contact.

This normally took place by the aircraft, after detecting a target, flying a number of circuits around it to enable positive identification and photography. At times these manoeuvres could require relatively tight turns to keep the target in sight, which for brief periods could lead to increased G-loadings on the aircraft. Such identification actions could sometimes involve repeated climbs and descents, with rapid changes between positive and negative G-loads on the aircraft.

The procedures were eventually modernised by the introduction of the Automatic Identification System (AIS). AIS is a GPS-based system that makes it possible from vessels, aircraft or land to identify and track a vessel's movements.

For the monitoring of various fishing activities a similar system was introduced for fishing vessels of a length exceeding 15 metres, called the Vessel Monitoring System (VMS). This system, which is also based on GPS, means that both Swedish and foreign fishing vessels can be monitored.

For KBV operations the introduction of AIS and VMS considerably facilitated the identification of vessels. Operationally this has meant a reduction in the need to perform tight turns around vessels in order to identify them, and that KBV aircraft are now subjected to less G loading than before.

Flying environment

Most of KBV's operations take place over the sea or over large lakes. Most of the missions are of supervisory character and take place in VMC. When covering an area the normal flying altitude is 1500-2000 feet. Identification and photography of maritime targets normally takes place at altitudes of 300 – 500 feet.

In general, flying at low altitude involves increased turbulence caused by the underlying terrain. When flying at a low altitude over the sea outside archipelagos the turbulence is normally less than over land.

Sometimes KBV is engaged in special tasks that may require flying in demanding meteorological conditions. An example of this was taking stock of the damage to woodland after the "Gudrun" storm, which involved flying through powerful turbulence.

1.17.7 *Special flight conditions*

Flying in icing conditions
Most KBV flights are carried out in VMC, which normally does not lead to ice accretion on the aircraft. However, flying at a low altitude over the sea in most cases means operating in heightened humidity, with the risk of ice accretion in certain temperature conditions.

A lesser part of KBV flight operations has also included purely transport flying (ferry flights) and training flights. For such flights the aircraft has been operated in "all weather conditions", i.e. also flown in IMC where there is an occasional risk of icing.

Aircraft that are certified for flying in icing conditions are equipped with various systems for protection against or removal of ice. Apart from a general deterioration in aircraft performance and flying characteristics if ice builds up on the wing and tail surfaces, ice accretion can also cause vibrations of various types.

The propeller blades are equipped with electrically heated elements to prevent and melt off ice. In the case of extreme ice accretion or a fault in one of the de-icing elements, the ice can cause imbalance in a propeller which can sometimes generate severe vibration.

Low flying
Low flying refers to flying at less than 500 feet when this is not associated with take off or landing. As previously mentioned, temporary low flying is a normal part of KBV flight operations. According to BCL D 2.2, KBV flights are permitted to fly at less than the minimum flight altitudes that are specified in BCL-T. This may not however take place over tightly grouped communities, large gatherings of people, etc. The Flight Manager is authorised to train, issue authorisation and order low flying for individual pilots.

According to the DHB such training as authorisation for low flying is included in aircraft commander training. It is also stated in the DHB that flying must not take place at an altitude less than of 100 feet (30 m) over water or land, and that "Low flying may only be carried out when necessitated by the implementation of the task".

In the SHB it states that 150 feet (50 m) is the lowest permitted flying altitude. The regulations in BCL D 2.2 do not define any minimum flying altitudes, except in the case of airborne photography, in which case the lowest permitted flying altitude is 75 m.

The flights over the Falsterbo canal were a special flying case that was performed at low altitude and where the pilots had been requested to show off the aircraft.

STOL operations
The CASA C-212 is an aircraft with STOL characteristics, meaning that the take off and landing distances in certain conditions can be made very short. The distances required for take off and landing depends however to a great extent on different factors, such as flight mass, flap position, wind and other meteorological conditions. The AFM states in respect of the take off and landing distances: "Take off/Landing distance 900 m".

Several pilots have said that training in short field landings with the KBV CASA C-212 had regularly taken place. Such landings were made with full flap and sometimes with a firm touch-down. Air traffic control at certain airports have been aware of the short landing capability of KBV aircraft and sometimes asked the pilots to "land short".

Short landings with firm touch-downs give rise to momentary peaks in both positive (at the instant of touch down) and negative (as the wings rebound) loads on the aircraft. (The loadings on the wings have an opposite relationship.)

There was originally on the KBV CASA 212 aircraft an indicator on the landing gear for abnormally hard landings. This consisted of a red-painted colour band round the landing gear oleo legs. A hard landing would leave a mark on the red colour band. This indicator has disappeared or was removed from the KBV aircraft. SHK has not managed to obtain any information as to when and why this took place. The manufacturer has not issued any special requirement regarding the indicator.

1.17.8 *Training*

KBV pilots have usually undergone basic civilian flying training that in recent years has been carried out by TFHS. After basic flying training the pilots were type-trained on the CASA C212 aircraft type under the aegis of KBV itself.

For type training KBV has a syllabus for the CASA C-212 - Company Training Manual (CTM-Casa 212). An equivalent training syllabus has been obtained from the manufacturer – "Training Manual C 212". When comparing these manuals it was found that they were very similar, and that there were no deviations in the KBV manual in relation to the manufacturer's recommendations.

The flight training of KBV's first CASA C-212 pilot took place in Spain by the manufacturer. Among the first pilots were the former Flight Manager and Chief Pilot, who were trained by the manufacturer's Chief Pilot and Test Pilot.

After this the KBV Chief Pilot gave type training to the other pilots, apart from some cases where the manufacturer's personnel carried out the training. He had this flying instruction role for almost 25 years up to about two years before the accident, when two new instructors were trained.

He underwent instructor's flying training at the beginning of the 1990s and since than trained about 30 different pilots within KBV aviation. In addition he received authority to act as the official flying inspector for the CASA C-212, and thereafter worked in that post.

1.17.9 *Technical responsibility and performed maintenance*

The flight operation of KBV has its own technical manager with technical responsibility for the operation, but does not have its own personnel to perform technical maintenance. This work has instead been brought in from outside. Apart from the daily and the pre-flight inspections, which are performed by the pilots, with certain limitations, all other maintenance therefore has been carried out by external aircraft servicing establishments.

When KBV purchased the CASA C-212, the agreement included technical maintenance for the first five years. In 1989 CASA appointed Nyge Aero of Nyköping as an authorised Service Centre for this type of aircraft in Scandinavia. When the maintenance agreement with CASA expired in 1991, Nyge Aero was engaged for the task. In 1998 Nyge Aero became Saab Nyge Aero and in 2006 Saab Nyge Aero became Saab Aerotech.

The applicable maintenance agreement with KBV included technical follow-up, performance of periodic inspections, implementation of modifications, installation of new equipment and technical training on the type for pilots.

1.17.10 Particular historical events and notifications

As far as practically possible, SHK has tried to map out the operational history of the accident aircraft in respect of events that may have had some influence on the initiation and growth of the fatigue cracks. The technical documentation pertaining to the aircraft has been reviewed for this, and also the affected operational and technical staff has been interviewed.

The following is a summary of the results of these investigations.

Documented events and actions
Since the delivery of the aircraft in 1986 its technical logs have been inspected in respect of reported problems, faults found and action taken regarding the landing gear (ATA 32), aircraft fuselage (ATA 53), tail plane (ATA 55), wings (ATA 57), propellers (ATA 61) and engines (ATA 72). Similar mapping was carried out in respect of the other KBV aircraft, S/N 343 and S/N 229, for comparison.

No particularly serious event or action that could have affected the strength or fatigue tolerance of the aircraft was found. Apart from normal notifications and actions that can be expected for this particular type of operation, it was found that the aircraft had been subjected to a bird strike, one reported hard landing and that the leading edge of the left wing was damaged by a loading pallet during a storm.

Similar problems were reported for the sister aircraft, and apart from the vibration described below the results of the reported problems and actions were more or less equally divided between the three aircraft.

In respect of reports concerning vibration, the results were higher for the accident aircraft. At 10,000 flying hours there had been a total of nine reported cases of vibration. Most of these reports were in respect of the first five years of the aircraft’s operation. Six of these reports concerned the left engine and three the right engine.

One of these notifications concerned vibration from the left engine and was reported on 6 October 1998. No fault was found and the report was closed after the propeller had been balanced.

On 2 June 2000, 1,735 flying hours later, there was another report of vibration from the left engine. Extensive attempts were made to balance the propeller without success. It was later found that there was a fatigue crack in the propeller hub, so the propeller was changed, 74 flying hours after the notification was written.

After 10,000 flying hours for the two sister aircraft there were two and one notifications respectively concerning vibration.

Interviews
In connection with interviews conducted by SHK with KBV staff and Saab Aerotech technicians, specific questions were asked whether anyone had been

part of or heard about any "extraordinary" events or overload of the accident aircraft that they thought could have affected the strength of the wings.

Several incidents, thanks to these interviews, came to the attention of SHK and were followed up as far as possible. Of these many could be attributed to other aircraft than the accident aircraft.

Questionnaire
In order to obtain information about the accident aircraft possibly being subjected to overload that for some reason had not been reported in the usual way, SHK sent a questionnaire to all pilots, system operators and technicians who work with or have worked with the KBV CASA C-212 aircraft.

In the questionnaire, which could be answered anonymously, the recipients were encouraged to supply information about possible events or special conditions that in their opinion could have affected the strength of the wings.

In all 88 people were sent the questionnaire. The response rate was about 86 %, i.e. 76 sent replies, and most of these were done openly.

The questionnaire did not produce any information of value to the investigation apart from statements that the KBV CASA C-212s were generally sometimes operated under "demanding" conditions, which subjected the materiel to severe loading.

Some new occurrences with possible overloading came to light via the questionnaire, however these did could not be tied to any specific aircraft individual.

To sum up, it was not possible to relate any single event or incident to the accident aircraft that could explain why this particular aircraft suffered from crack generation, but the other aircraft did not.

1.17.11 Operational flying culture and environment

Introduction
With the intention of gaining an impression of the operational culture and work environment within KBV aviation a total of 24 people in various posts in the organisation were interviewed.

Impressions of this type of aircraft
Most pilots perceived this type of aircraft as being generally very robust and able to withstand stress. Some pilots were not aware of the maximum permitted G-loading on this type, i.e. +3.0 G to -1.2 G. One pilot believed that the type was approved for up to +6.0 G.

Flight training
Flight training on this aircraft type was described by pilots as adapted to the KBV need for maritime low flying, with the accent on being able to manoeuvre the aircraft in all situations. The interviews showed that pilots had been trained in short landings with full flap, and for the purposes of demonstration were able to experience the characteristics of the aircraft close to its operational limits. This was perceived as being "tough flying".

The Chief Pilot, who had type-trained most of the interviewed pilots, was said to be a very skilled pilot who knew the aircraft "like the back of his hand".

The pilots' descriptions of how the aircraft flew

The general impression among KBV pilots was that the aircraft was normally operated well within the permitted flight envelope.

There were some differences between views of the pilots and the system operators in respect of how the aircraft flew. The system operators in general described the flights as being harder than the pilots' descriptions. There were system operators who admitted to being sometimes uncomfortable or afraid.

Some pilots and system operators felt that there was a kind of "macho culture" among their colleagues, mainly among the older pilots. Although some thought that this was only expressed verbally, others felt that it was shown in the way that they flew.

As examples of flying that could have imposed severe stress on the aircraft were named flying in severe turbulence and ice accretion, bunting manoeuvres (with G-loadings less than +1.0), crosswind landings in strong winds, steep turns with high G-loadings and repeated short field landings with full flap that can lead to hard touch-downs.

It was said that display flights, similar to that which was performed on the accident flight, occurred regularly. These usually ended with wing tipping.

In order to perform certain KBV tasks it was reported that the operational rules were sometimes infringed. Vessel identification sometimes had to be done while flying at low altitude in VMC when the conditions otherwise were IMC. When transitioning between these conditions with different rules, sometimes several times during a single flying task, it could be difficult to comply with all the applicable rules.

According to some pilots it happened that the MEL requirements, lowest permitted flying altitude, aircraft take off mass with account taken of RPM calculations and recommendations, and maximum permitted ramp mass were not always respected. Some pilots considered that civilian regulations and procedures were not suitable for the operations of the KBV surveillance flights.

Several thought that the total produced flying time was seen by the management as the most important yardstick of quality in the KBV aviation operations. They felt under pressure to complete the flying time quota, since the appropriated funds for the work risked otherwise being reduced. The pressure to complete the quota was declared by some to be greatest at the end of the year, i.e. during the time of year when the flying weather is often worst in Sweden. Some saw this as being a flight safety problem.

Reporting of deviations

KBV has a system for reporting deviations in respect of events that could affect flight safety. Impressions of how the system works varied. Some thought the system was good and that they had been well instructed on how it should be used. Others had the opposite opinion and stated that they had not written many reports, since they thought that they did not get any response.

Drawing the line between what should and what did not need to be reported was experienced by some pilots as being difficult on occasion. It happened, according to some, that mistakes were not reported since the affected persons did not want to "expose themselves".

Other comments
Certain pilots thought that the KBV aviation Multi Crew Cooperation (MCC) had deficiencies and was not fully applied, and that more education and training were needed for this. The ability of commanders to set a good example and to maintain sufficiently tight control in this respect varied according to some.

Some told of how pilots who had been trained in a two-pilot system and standard practice for commercial heavy aviation could face difficulties when they began to fly in KBV aviation. There they confronted a different reality to what they were trained for and were used to.

According to the staff, in recent years there had been positive moves in the direction of development and an increased use of prescribed operational procedures.

1.17.12 SHK participation in KBV flying

With the aim of getting an insight into the operational conditions and the crew working environment SHK took part in flights with KBV. The flying task was a normal surveillance mission over the southern Baltic Sea.

SHK found that the working environment and the operational conditions described in interviews with KBV personnel agreed well with the actual conditions. Despite the fact that AIS and VMS facilitated such aspects as identification, relatively steep turns were sometimes necessary to, for example, photograph certain targets.

1.17.13 The use of SE-IVF for flight training

During flight training there occur manoeuvres that to some extent subject the aircraft to different and sometimes greater stresses than during normal flying. Examples of these are steep turns, stalls, short landings, single engine flying, etc. Each type training flight involves a total of 20-30 minutes of single engine flight.

SHK has determined to what extent the accident aircraft was used for training purposes in relation to the other KBV CASA C-212 aircraft. During the first five years the accident aircraft, S/N 346, was used for training flights more than the other aircraft. By 1991 S/N 346 had accumulated about 140 training flight hours, while its sister aircraft, S/N 343, had accumulated about 90 hours. Over the subsequent years this difference reduced, and by the time of the accident S/N 346 had accumulated a total of about 425 training flight hours, and S/N 343 about 395 hours.

1.18 Other aspects

1.18.1 Manufacture of the CASA C-212 - general

The three major wing assemblies were manufactured in calibrated jigs to ensure dimensional accuracy. According to the manufacturer the rivet holes were drilled while the components were in the jig before riveting. The inserted and squeezed rivets were checked by gauges after riveting.

There were no special instructions concerning the use of sealing compound in riveted joints in the manufacturing drawings. It generally applied that sealing compound had to be used in all riveting of joints of securing elements of any type.

The fixtures in the wings and aircraft fuselage have built-in bushings for the four wing bolts. The bolt holes in the bushings were made undersized and then jointly drilled in conjunction with the assembly of the wings to the fuselage in order to obtain an accurate fit between the bolts and bolt holes. This joint drilling of the bushings took place before the engines and outer wings had been fitted.

The same conditions applied to the two fairings, whereby the screw holes were drilled in place in conjunction with the assembly of the wing. Joint drilling of the fairing holes took place before the engines were installed, sometimes before and sometimes after the outer wings had been fitted.

There is no prescribed order in relation to the joint drilling of the bushings. The joint drilling of the fairings is performed after drilling of the bushings.

1.18.2 Manufacture of the accident aircraft

According to the documentation from the manufacturer that was supplied to SHK, and the verbal information given by the manufacturer, the accident aircraft was manufactured in complete accord with the normal procedures. In the understanding of SHK there is no indication in the information provided that the work was done other than in the ordinary jigs, by ordinary assembly workers and inspectors.

On request from KBV the wings on aircraft S/N 343 and S/N 346 were modified before delivery from the Series 200 pattern to Series 300. Series 300 wings are identical to Series 200 wings except that Series 300 wings are equipped for pressure refuelling.

This modification work was carried out after the wings had been installed and jointly drilled for each aircraft. In respect of the installation of the fairings, joint drilling on the accident aircraft, S/N 346, was carried out with the outer wings installed, and on sister aircraft, S/N 343, without the outer wings installed. After manufacture, the wings on the accident aircraft had never been detached from the fuselage.

It was also found that these particular aircraft, S/N 343 and S/N 346 were during manufacture parked outdoors without engines for ten months while waiting for a purchaser. They were parked together with a number of other aircraft of the same type on the manufacturer’s premises in Seville.

These were the only deviations found by SHK in respect of manufacture.

1.18.3 Modifications after delivery

Immediately after delivery to Sweden, aircraft S/N 343 and S/N 346 were put into a workshop for modifications in accordance with a KBV directive and for installation of a Maritime Surveillance System (MSS). The equipment consisted of an advanced navigation and radio monitoring system which among other things could perform detection and recording of the sea areas both in front of and at the sides of the aircraft.

The system was built into two securely mounted instrument desks in the aircraft cabin and included two system operator positions. On the outside of the aircraft the system included a permanently installed radar scanner in the nose and radar antennas on each side of the cabin. The installation resulted in an increase in aircraft tare weight by a total of about 700 kg.

The MSS was developed by Rymdbolaget and the installation of the system into the aircraft was prepared by FFV Aerotech in accordance with FFV Aerotech report FF 82/88:008, being approved by the Swedish Civil Aviation Authority in accordance with Modification Evaluation report No. M 2/87, FFV.

FFV Aerotech was also responsible for the AFM Supplement, the maintenance manual for the system and the necessary drawings.

The physical modification of the aircraft including the installation of the MSS, etc. was mainly carried out by FFV Aerotech, which was also responsible for flight testing after installation and testing of the system. The flight and system tests accumulated a total of 350 flying hours, shared between aircraft S/N 343 and S/N 346.

The flight testing resulted in the preparation of Supplement S 5/88 concerning minor changes to the aircraft performance in relation to their original design.

1.18.4 *CASA C-212 operating statistics*

By the end of 2006, a total of 470 CASA C-212 aircraft in various versions had been delivered to operators in over 35 countries. Of these, over 350 were still in use at the time of the accident. At the time of the accident the fleet leader was around 27,000 flight hours and around 48,000 cycles.

There were about five operators using this type of aircraft for maritime surveillance. Of the individual aircraft employed for this task the three CASA C-212 aircraft operated by KBV had achieved the greatest number of flying hours. The accident aircraft and its sister, S/N 346 and S/N 343, had the most, over 17,000 hrs.

In the later part of year 2009 the leaders of the fleet have more than 29,000 hrs and 53,500 cycles.

1.18.5 *CASA C-212 accident statistics*

Since this type of aircraft came into operation in 1976, according to the manufacturer’s statistics, 88 aircraft have been written off in various types of accident. Out of these the causes of 31 of these accidents (20 military and 11 civilian) were classified as “Unknown” or “Controlled Flight Into Terrain” (CFIT). Of the six accidents classified as “Unknown", two occurred during commercial operation and four during military operation.

In 14 cases the aircraft fell into the sea or were never found. It is uncertain whether the aircraft wreckage in these cases could be examined.

According to the manufacturer the relatively large number of accidents with unknown causes was due to the aircraft being operated in a variety of tasks and by many different operators, mainly military, and often in geographically isolated areas. This has meant that complete accident investigations have not always been carried out after the accidents.

The manufacturer has stated not being aware of any other wing fracture on this type of aircraft, other than the one which the accident aircraft suffered.

1.18.6 *Feedback from completed inspections*

After the accident there were demands from the aircraft manufacturer and the authorities for all CASA C-212 aircraft in service to undergo an NDT inspection of the area along the critical row of rivets, see Section 1.18.10 below. In the instructions for these inspections there is a requirement for reporting back that the inspections had been completed or whether any cracks had been found.

At the time of issue of this report, inspections had been reported as completed on about 1/3 of all CASA C-212 aircraft in service. No cracks had been found in any of these inspections.

1.18.7 Ageing aircraft

The term "Ageing aircraft" is now a familiar problem within the aviation industry. This phenomenon garnered a great deal of attention in connection with the "Aloha incident" in 1988, when a Boeing 737 lost a major part of the upper part of the fuselage in flight as a result of extensive fatigue cracking in the hull.

The problem has arisen due to the fact that many aircraft are in service for long periods, and are subject to more flying hours and cycles than was foreseen at the time they were manufactured. The applicable maintenance programmes are based on crack scenarios with single major cracks and not the extensive multiple crack initiation that is the case in some structures at the end of their lifetimes. In some studies cracks have been found already after 1 % of the lifetime.

In some cases it is also a matter of older aircraft being used for various types of tasks that they were not originally designed for. An example of this is older transport aircraft that are rebuilt and used for water bombing of forest fires.

For this category of aircraft there is also seldom access to the information that is nowadays collected by full scale tests of complete aircraft in test rigs that simulate long term stress of various types.

The result has been that various types of age-related defects have arisen during service that are not always detected and rectified in the applicable maintenance programme. Such defects have resulted in several cases of total destruction.

In order to deal with this problem, the manufacturers and inspection authorities for certain aircraft types have introduced special inspection programmes that must be implemented on older aircraft that are in service (see Section 1.6.10).

One of the many problems that can arise in older aircraft is the formation of fatigue cracks in riveted joints constructed of an aluminium alloy such as, for example "AA 2024 T3 clad" material. This often concerns crack formation in the pressure cabin structure or in the lower wing skin and longeron flanges. Many of these cracks have the characteristics of Multiple Site Damage (MSD), as described below.

1.18.8 Multiple Site Damage

Multiple Site Damage, (MSD), is a known phenomenon, characterised by the simultaneous development of multiple fatigue cracks in a number of similarly designed and loaded structural elements.

The cracks initiate from small flaws in the riveted joint and develop along the same row of rivets. When they reach a certain length several cracks coalesce into a main crack, which can continue to grow into a fracture.

The problem area has led to extensive investigations. See Appendix 6, Riveted Lap Joints and Multiple Site Damage.

The research has included extensive fatigue tests on large riveted panels that simulate typical cabin structures. A simplified table showing the results of such a test, which was presented at the 9th Joint/DoD/NASA Conference on Ageing Aircraft, held in Atlanta in 2006, is shown below:

Start	Cracks detectable by NDT	Visible cracks	First crack jump	Unstable crack growth (fracture)
	35,000 cycles	80,000 cycles	106,000 cycles	107,458 cycles

Figure 37. Schematic presentation of fatigue in a cabin structure

As can be seen in the table, most of the life is taken up by the initiation of cracks and their growth until they become visible. The time from the first crack jumping to another and then progress until unstable crack growth (fracture) takes place is however very short. (In terms of loading cycles 1,458, i.e. about 1 % of the total test period.)

Characteristic for MSD is:

- Many small fatigue cracks are initiated along a row of rivets.
- Initiation takes place at hole edges, fretting damage and surface defects.
- The cracks first grow separately but join up later with other fatigue cracks and form longer continuous cracks.
- In certain cases crack growth takes place by a crack “jumping over” to another crack due to a localised overload fracture.
- The striation density is initially high and relatively constant along the length of the crack.
- The crack sequence progresses for a very long time.
- The growth rate of fatigue cracks is at the start very slow, but accelerates considerably towards the end.
- When small cracks have begun to link up with larger cracks the continued growth towards unstable crack growth in the joint (fracture) is very rapid.
- The total fatigue crack has a considerable age.

Below is a summary of some more results taken from the literature:

- When MSD is established in an aircraft it will probably appear in other aircraft of that type that have been subjected to a similar number of cycles.
- The presence of cracks has not been indicated by analysis and tests, but has been confirmed by the inspection of aircraft that have been in service.
- The first crack, detectable by inductive testing (NDT-method), has already shown up at about 10 % of the total number of counted load cycles.

- The effect of clamping forces during riveting and defects have been studied with variable results. The spread is so great that it has hardly been possible to draw significant conclusions. The clamping force can however be said to affect the localisation of the start of a crack. A high clamping force provides a crack origin from the sheet metal faying surfaces, while a low one tends to start cracks from the edge of the rivet hole.

1.18.9 The Swedish Civil Aviation Authority (now the Swedish Transport Agency) inspection work

As previously mentioned the authorisation for KBV aviation activities was issued in accordance with the BCL D regulations (see Section 1.17.2). This authorisation (AOC) was issued on an initial audit and a review of the provided documentation.

An AOC is only valid for a stated time period and is renewed on application by the head of the organisation for an extension. During the period of validity any changes and/or supplements to operations are to be reported to or sought from the appropriate inspection authority.

In connection with the issue of an AOC the inspection authority names a special inspector, the Principal Inspector, (PI), who bears the responsibility for the aviation operator in question. This inspection work includes carrying out inspections on the particular operator, with the purpose of checking the compliance of the operations with the authorisation that has been issued. These inspections are performed in the form of system inspections with the purpose of checking the operations as a whole, without going into detail.

System inspections are performed in the form of auditing of a particular operator every second year, whereby the PI, during a visit lasting one or two days would go through an agreed part of the operations. These audits would not perform detailed inspections of the operations. This area was intended to be covered by the operator's self-checking system.

In an interview with the PI who was responsible for KBV operations it transpired that those inspections that had been carried out did not result in any serious notifications regarding the operations. Those deficiencies that had been noted stemmed from quality problems in certain parts of the documentation.

For the authorisation category relating to KBV operations there was no requirement that the organisation should contain a quality manager or equivalent, only that a self-checking system had to be set up. Interviews with the PI also revealed that the inspection authority participated in strengthening and developing a quality and self-checking system for the KBV aviation division.

1.18.10 Measures taken due to the accident

<u>SHK</u>
On 22 November 2006 SHK, in conjunction with CIAIAC, delivered preliminary information about the accident to the Swedish Civil Aviation Authority (now the Swedish Transport Agency), DGAC and EASA which stated that the left wing broke off in flight as the result of a fatigue crack in the lower wing skin.

On 5 March 2007 SHK, in conjunction with CIAIAC, delivered updated information about the investigation into the accident to the Swedish Civil Aviation Authority, DGAC and EASA. The information stated among other things that the inspection instructions CASA C-212 SID C-212-PV-02-SID, C-212 SIP C-212-PV-02-SIP and EADS-CASA AOL 212-018, revision 1, dated 1 December 2006, were unable to discover all the types of cracks that could occur in the critical area in the lower wing skin.

On 3 March 2009 SHK sent to EASA and the Swedish Transport Agency information concerning the status of the investigation. This stated among other things that the fatigue cracks in the accident aircraft wings were characteristic of Multiple Site Damage and that there were no signs that the accident aircraft had been subjected to overload.

The Swedish Civil Aviation Authority

The Swedish Civil Aviation Authority published on 22 November 2006 LVD No 2-3366 whereby all Swedish-registered CASA C-212 aircraft were temporarily banned from flying. The next day the ban was withdrawn, with reference to EASA AD No.: 2006 – 0351-E.

The manufacturer

On 22 November 2006 the manufacturer published a Directive, “All Operator Letter (AOL) 212-018 Rev 0” (One-time inspection of the centre wing lower skin), which prescribed one-time inspection for cracks using ultrasonic NDT of the centre wing lower skin in that particular area on all CASA C-212 aircraft that had accumulated more than 5,600 flying hours or 2,400 landings.

In AOL 212-018 Rev. 1, that was published on 1 December 2006, this inspection requirement was extended and X-ray NDT examination or a detailed visual inspection from inside, was introduced as an alternative to ultrasonic NDT.

In AOL 212-018 Rev. 2, that was published on 20 March 2007, a requirement was issued that the inspections must be supplemented by an additional High Frequency Eddy Current (HFEC) NDT inspection from the interior of the wing torsion box. The inspections were to be carried within the next 200 flying hours or before 100 landings after issue of the AOL, whichever came first.

In the case of aircraft that had achieved 8,000 flying hours or 3,600 landings, the above inspections, must, according to AOL 212-018 Rev.2, be regularly repeated every 600 flying hours or every 250 landings, whichever came first. The requirement for any further inspection measures has not been introduced.

In parallel with the ongoing investigation, the manufacturer prepared a possible modification of the attachment of the wings to the fuselage called “C-212. Modification of Wing Fuselage Longitudinal Load Fittings Certification Program, DT-07-2001”.

The purpose of the modification was that loads in the X axis, between the wing and the fuselage, would no longer be taken up by the previously mentioned fairings but instead via four newly designed attachment fittings secured between the centre wing and the top of the fuselage (see the Figure below).

This modification has been incorporated on aircraft S/N 343 in accordance with Service Bulletin (SB) 212-57-40 as a test. With the issue of new inspection requirements the manufacture does not consider it necessary to implement this modification on other CASA C-212 aircraft in operation.

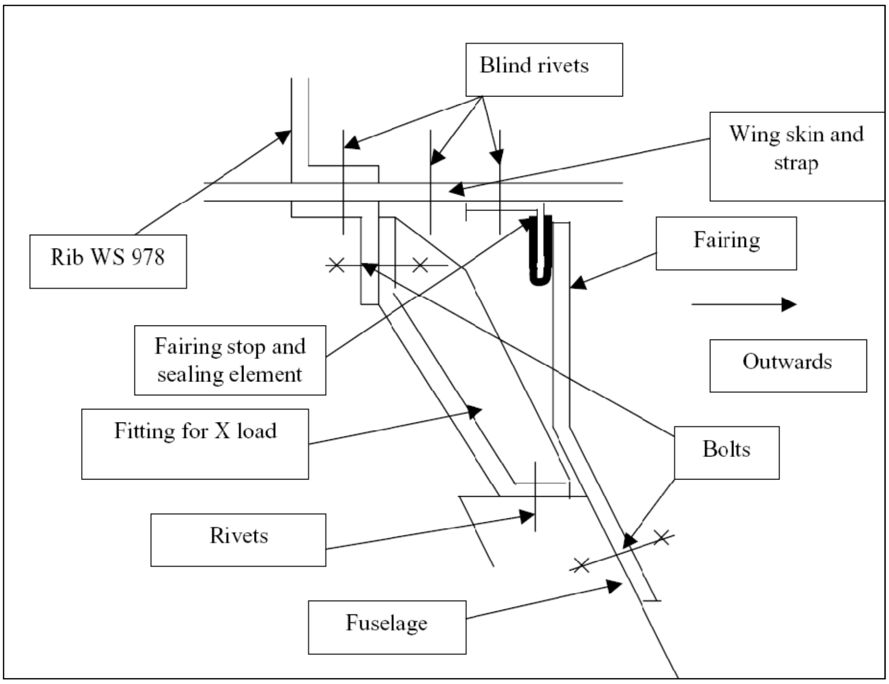

Figure 38. Modified wing attachment according to manufacturers drawing (Compare with Figure 6)

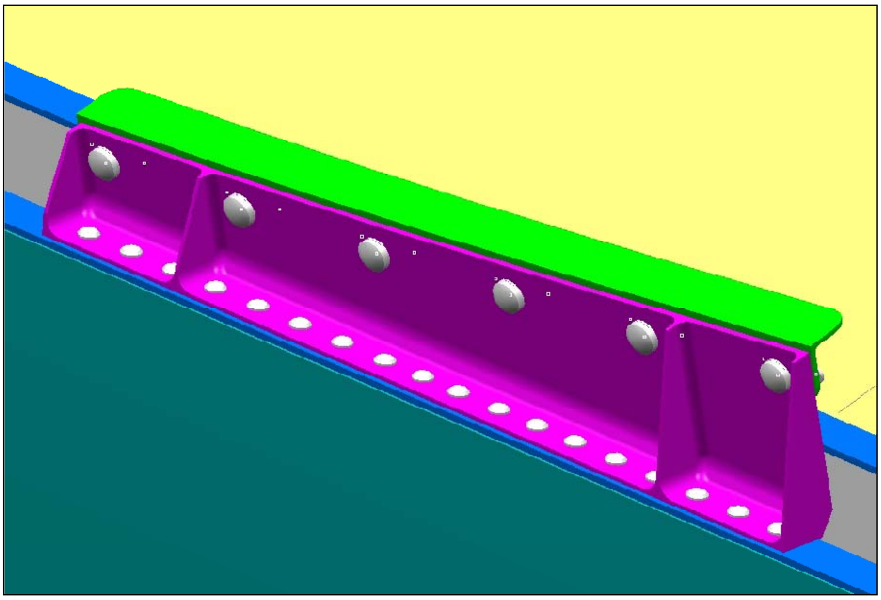

Figure 39. New attachment fitting – left rear

EASA

EASA published on 23 November 2006 EASA AD No. 2006-0351-E, which prescribed measures in accordance with AOL 212-018 Rev.0.

On 4 December 2006 EASA replaced AD No. 2006-0351-E by EASA Airworthiness Directive No. 2006-0365-E, which to a large extent prescribed measures in accordance with AOL 212-018 Rev.1.

On 18 April 2007 EASA replaced AD No. 2006-0365-E by EASA Airworthiness Directive No. 2007-0108-E, which to a large extent prescribed measures in accordance with AOL 212-018 Rev.2.

FAA
The American aviation authority, the Federal Aviation Administration (FAA), published on 14 March 2007 Airworthiness Directive (AD), 2007-05-01, which on 13 March 2008 was replaced by AD 2008-06-13. AD 2008-06-13 to a large extent prescribes the measures contained in EASA AD No. 2006-0365-E

KBV
Immediately after the accident all the KBV CASA C-212 aircraft were grounded, and at the same time personal care resources were provided to support the flight crews. The grounding was lifted after about two months, since the fatigue cracks in the accident aircraft had been found and the wings of the other aircraft had been inspected for cracks in accordance with C-212-PV-02-SID in advance.

On inspection of the wing on aircraft S/N 343 the wing was removed from the aircraft and the doublers were demounted from the wing. This work was performed under supervision from representatives from the manufacturer.

In addition, several organisational changes had been carried out within the operational and technical areas. A Quality manager for the operational and technical departments was added. The procedures and manuals were supplemented and updated taking into account the Bombardier Dash 8 aircraft type that had been procured and were new to KBV operations.

The decision was taken to change the current dark green and dark blue crew overalls to overalls with a colour providing better contrast to the sea.

1.18.11 FAA Memorandum FEB 19, 2008

The United States civil aviation authority, the Federal Aviation Administration (FAA), addressed on 19 February 2008, via its local offices, a general "Memorandum" to a number of specific major aircraft manufacturers and manufacturers of aircraft materiel. This concerned the need to evaluate and supplement existing routines and procedures for inspections to be carried out on transport category aircraft (FAR 25) after overload. ("Evaluation of Aircraft Maintenance Manual Special Inspection Procedures, Transport Category Airplanes").

The basis of this measure was five recommendations from the National Transportation Safety Board (NTSB), based on the investigation into an accident on 31 July 1997, and two incidents on 17 and 18 November 2002.

According to the NTSB and the FAA there was a need to evaluate and possibly supplement the prescribed inspection measures that were carried out after the occurrence of overload. There was a risk that the existing maintenance system would not catch and repair all the structural damage that could arise in aircraft and that was associated with overload, which could pose a flight safety risk.

As examples of overload were mentioned hard landings, strong turbulence, extreme manoeuvres with high positive and negative G-loads and abnormally fast changes in the pitch or roll axes. Special inspections can in certain cases be justified even after high load stresses that are still within the aircraft type permitted limits.

As a preliminary to this memorandum the FAA tasked the aircraft and aircraft operators' interest organisations, the Aerospace Industries Association (AIA) and the Air Transport Association (ATA) to set up a working group with a remit to go through the applicable practices for these inspections and to provide recommendations for improvements.

On 1 September 2005 the working group published a final report on this work entitled "Review of Inspection Processes Following High Load Events". The report dealt with the NTSB recommendations and provided a number of recommendations itself concerning how the prescribed inspection procedures could be improved.

The report also pointed out the importance of having functioning procedures for the reporting of overloading that may occur since this forms the starting point of such inspections. The meaning is that in certain situations it can be difficult for pilots to assess whether an operational event has been so "obvious" that it should be classified as an overload which must be reported.

The report therefore supported, among other things, the increased use and development of existing flight recording systems on board the aircraft, such as FDR, QAR, etc. so that the operator could be more certain of catching overloads that have occurred and take suitable action.

Along with the final report there was appended a proposal for a procedural description, "Best Practices Guide – Inspection Processes Following High Load Events (BPG)", to be used when evaluating and supplementing existing inspection regulations.

In the FAA memorandum aircraft manufacturers and aviation materiel manufacturers were challenged within a year to come back with details of how evaluation and the associated inspection rules were being taken into account and what additions had been made. The aircraft types affected were transport aircraft (FAR 25) that were still being manufactured as new, or where at least 100 were still in service.

The aircraft manufacturer CASA, which is part of the inspection responsibility of EASA, was not on the FAA list and has not undertaken any measures regarding CASA C-212 as a result of this memorandum.

1.18.12 Rescue services

<u>Requirements</u>
By rescue services the Protection Against Accidents Act (LSO) refers to the rescue services that the government or district councils are responsible for in the event of accidents and considerable danger of accidents, to prevent and limit injury to people or damage to property or the environment.

Each district council must, on the basis of the local risk picture, prepare an action programme that will contain the aims for the local district efforts and risks concerning accidents that could lead to rescue efforts. The action programme must also define the geographical area of responsibility for the local district rescue services.

In the case of rescue efforts using divers it is of vital importance that the diving proceeds in such a way that divers are not injured. This is regulated by the Arbetsmiljöverkets Författningssamling, AFS 1993:57 Dykeriarbete (Swedish Work Environment Authority Statutes, AFS 1993:57 Diving work).

The geographical location of the impact area of the accident aircraft was in the Falsterbo canal in Vellinge District. Rescue Services Trelleborg has a civil rights agreement with Vellinge District Council, which means that Rescue Services Trelleborg was responsible for the District rescue services at the crash site.

Alarms

An emergency call from a private person who had seen the aircraft accident was received via the mobile telephone network by SOS Alarm at 13:27. The information was that a grey and yellow aircraft had crashed into the Falsterbo canal. SOS Alarm made contact with MRCC and ARCC and at the same time sent out an alarm to the District rescue services, the ambulance services and the police.

While en route to the accident site the commander of the District rescue services contacted SOS Alarm and requested that divers be sent to the site. The basic direction and main decision was life-saving efforts by surface searching (with boats) and the pinpointing of the impact location so that divers could begin searching and life saving below the water surface. It was decided that there would be a reporting point on road number 100 just north of the Falsterbo canal.

En route they were told by ARCC via SOS Alarm that it was a KBV aircraft with at least four crew members on board. ARCC called out a rescue helicopter from Denmark and SAR helicopter 997 from Ronneby. In addition police helicopter SHA 947 was called out from Malmö to search for possible places where there could have been objects the aircraft could have struck before it entered the water.

The first unit from the rescue services arrived at the site at 13:38 and launched their boat. It was at that time reported that a boat from KBV was already there and searching the area. At the same time they were informed that divers were on the way.

Surface life-saving and searching

Surface life-saving commenced soon after the aircraft had crashed. To a large extent it was characterised by self initiative. The KBV personnel on site went out immediately in a small rubber boat and patrol boat KBV 286, and marked the impact location at 13:33. KBV 048 also arrived at an early stage and launched a RIB boat[9] so as, together with the District rescue services, which also had RIB boats, take part in the surface search and also later in the diving work. KBV 048 carried out a search beyond the piers.

SSRS, with a station in the Falsterbo canal, brought all its units to help in the search for survivors and to collect pieces of wreckage. A pilot boat from Helsingborg also received an alarm call and participated in the work.

Ambulance, police and rescue services personnel helped to search on land and along the piers. At the same time two rescue helicopters searched the area for the aircraft fuselage. SAR helicopter 997 searched the basin and the SAR helicopter from Denmark, R278, searched for people in the water outside the piers.

[9] RIB-boat – Rigid Inflatable Boat, an advanced rubber boat with an engine

Diving
At 13:41 the rescue services boat was launched and took with it ambulance personnel, Sjukvårds Insats Till Sjöss (SITS – Medical Aid at Sea) equipment and divers from Trelleborg Rescue Services to commence diving. KBV 286 on site had according to ARCC seen the impact and marked the site. When divers came out to the vessel it however turned out that KBV did not know where the impact had been. The divers therefore waited until the exact position could be established.

The fuselage was found at 15:12 by SAR helicopter 997, which then hovered over the basin at a low altitude. This was reported to the commander via ARCC. The divers went to the defined location and started diving. However not the entire fuselage was found at that location.

Eventually one of the crew was found on the bottom outside the aircraft wreckage, strapped into a seat.

In co-operation with the diving managers it was later agreed that divers from Malmö would continue to dive on the aircraft fuselage and that divers from the Trelleborg Rescue Services would dive on the "plume[10]". The search was performed by having a diver pulled by a boat, similar to searching with a horizontal otter board[11].

By 16:05 the life saving phase of the rescue effort was over. However the rescue effort did not end, as the diving continued for ethical reasons. The rescue services continued with recovery and one more person was found at 17:20 in the "plume", also sitting in an aircraft seat on the bottom. He was not strapped in.

Diving ceased as it became dark. The rescue efforts stopped at 17:50 with the accident site being handed over to the police for guarding.

Remains of the other crewmembers were later found.

Command
It was apparent to ARCC at an early stage that the Falsterbo canal event was within the local district's area of responsibility. This information was on the digital nautical chart in Gothenburg, where the ARCC and MRCC share premises together with KBV.

At 13:50 the head of the local district rescue services and the rescue commander from ARCC were linked together via SOS Alarm. Since the aircraft impact point had not been determined and the fuselage had not been found, it was jointly decided that it was a matter for the national rescue services which would be led by ARCC.

The ARCC directed SAR helicopter 997, rescue helicopter R278 from Århus in Denmark and police helicopter SHA 947. Since it was only a matter of directing three units for ARCC, no-one was assigned to be the Aircraft Co-ordinator.

[10] Plume – Expected wreckage spread area
[11] Horizontal otter board – Diving aid for underwater searches

MRCC directed the vessels that on their own initiative had gone out to search the waters inside the piers. At 13:50 KBV 268 took on the role of On-Scene Coordinator (OSC) and co-ordinated the surface in their part of the search.

At 14:55 the responsibility for the rescue services was handed over to the local district rescue services. The head of services there took over as the rescue commander and led the units from the Vellinge and Trelleborg rescue services, along with the diving units from Trelleborg and Malmö.

At the command post that had been set up in the kiosk at the entrance to the KBV station there were also the medical group and their leader with six ambulances and the police incident commander who, apart from assisting in the search along the piers, cordoned off the area to keep out unauthorised spectators. Also at the command post was a press chief from the police who dealt with the issue of information and the mass media.

Rearguard management support was set up at the fire station in Trelleborg. The commander there was given the task of ensuring readiness, providing reliefs and other logistics.

Communication and co-ordination

Communication between the units that were led by the ARCC and MRCC took place on the maritime VHF channel 67. The Danish rescue helicopter, R278, communicated via maritime VHF channel 16. KBV 286, in its post as OSC was given the task of handling orders to R278 from ARCC, which was done with a certain amount of difficulty.

The connections between the local district rescue services and ARCC/MRCC were set up via telephones and via SOS Alarm. The local district rescue units communicated with each other on channel 39 and with SOS Alarm by telephone or radio.

Communication between the surface units and the local district rescue services took place by telephone or verbally. It was often difficult to communicate between the boats due to the helicopter hovering overhead.

The divers suffered the consequences of this when other surface units passed directly over divers who were underwater. This was despite the activity being marked correctly with the diving flag “A” as a warning that diving was in progress.

1.18.13 Environmental aspects

Aircraft fuel and oil entered the water in connection with the impact. Environmental protection could not be carried out after the life saving phase. The great amount of activity with the many surface units made it impossible to encircle and deal with the fuel and oil release.

The district rescue service was responsible for any environmental clean-up services that may be necessary. No measures were taken to inspect the beaches in case they needed to be cleaned. The district council environmental office and the Skåne County Administrative Board were not contacted in respect of the releases. The KBV resources for environmental clean-up services were accessible on site.

1.18.14 Equal opportunities aspects

This event has also been examined from the point of view of equal opportunities, i.e. against the background that there are circumstances to indicate that the actual event or its effects were caused by or influenced by the women and men concerned not having the same possibilities, rights or obligations in various respects. Such circumstances were however not found.

2 ANALYSIS

2.1 The accident flight

2.1.1 Flight planning

The flight planning on that particular day was routine and did not contain any additional tasks that could make the mission more difficult. The weather was good and the crew were well acquainted with the planned route and the area involved.

The crew had spent the night at Ronneby after having been on duty together the previous day. Both the pilots and the system operators on board had previously flown together, and could, as far as SHK could learn be described as a well functioning crew without any known problems in working together.

According to the information that is available everything indicates that the crew were in good health. The aircraft that was assigned to the task had been flown by the same crew the day before, and any faults or abnormal conditions in the case of that particular aircraft should therefore have been known by the pilots.

The operational planning in respect of flight time, fuel, weight and balance state, has, after being checked by SHK, not been found to deviate from standard. The flight planning for KBV 585 can therefore be considered as completely normal for KBV flight operations.

2.1.2 The flight

SHK has not found any explanation as to why KBV 585, after taking off from Ronneby, penetrated the cleared altitude and departed from the radio frequency without any report. However, this deviation has been assessed as having no effect on the subsequent events.

The continued flight to the north-east to the southern tip of Gotland and back again proceeded normally. When the request was received by radio for a fly-by at the Falsterbo base the crew were on their way to Malmö/Sturup. Even though the crew were proceeding towards their lunch stop, the fly-by was only a minor change of route and an assessment of the CVR recording gave the impression that the crew almost thought that this would be a welcome intermission in the otherwise relatively monotonous flight.

Near the Falsterbo base there are relatively high trees and several masts, of which the highest were about 35 metres (115 feet), which involved an increased risk in the case of low flying.

In all low altitude operation it is very important that all parts of the planned flying are carefully briefed to the crew. During the approach to the Falsterbo base and before the fly-by however no such briefing took place.

One reason for this could be that the KBV operational documentation did not contain any instructions as to how display flying should be conducted. This type of operating instructions only applied to take off and landing.

A further reason why the programme was not discussed among the crew was that the pilots had probably performed similar flying displays previously and probably were well versed in which manoeuvres would be carried out.

In hindsight it can be assumed that the commander had planned a programme that would demonstrate the aircraft performance and characteristics to the spectators at close quarters, probably with the following content:

- Low level flying along the canal, probably with photography.
- Steep turns when turning back to the base.
- A low speed run with flaps extended.
- A high speed run with flaps retracted.
- Prominent wing tipping as a final manoeuvre.

2.1.3 The fly-bys

The first overflight on a north-westerly course was performed at above 500 feet. During the turn back to the base the flaps were extended and the speed reduced to about 100 knots. On passing the base the altitude was about 180 feet, but reduced to about 135 feet at the lowest along the canal.

The final fly-by took place with flaps retracted at about 240 feet. The speed was gradually increased, at the same time as the aircraft began a series of wing rocks.

On analysing these flights SHK could determine that the clearance over the tops of the masts at the bridge ends was between 20 and 65 feet (6 to 21 metres).

The area at the tip of Falsterbo (Falsterbonäset) and along the canal has small houses with pathways and must be considered a tightly grouped community. According to the interpretation by SHK of the BCL regulations, and the internal regulations on the KBV DHB, Section 2.10.2.1, flying lower than 500 feet is not permitted in this area.

As a supplement to these regulations it can be added that the reason for the flying was a study visit by two classes of schoolchildren, which in terms of numbers could be defined as a “large gathering of people”. Therefore it was not permitted to fly over them at less than 500 feet according to the BCL.

Seen only as the altitude regulations that exist in KBV’s internal regulations, the lowest altitude that was flown was permitted according to the DHB, but not according to the SHB.

The understanding of the pilots was probably that the flying altitude “was permitted” since that type of flying had taken place several times previously.

Since demonstration flights at low altitude are repeatedly carried out by KBV, SHK considers that it is a deficiency in the operational procedures that the issue of permission is not clear and that there are no detailed instructions as to how such flights are to be performed.

2.1.4 The wing separation

So that wing tipping during the last fly-by should be clearly seen, it is reasonable to assume that the commander applied substantial aileron input. The speed just before passing over the bridge had by then increased to over

160 knots, which is above the maximum speed that is permitted for full aileron, i.e. 146 knots.

In connection with these wing tipping manoeuvres a final fracture occurred, in the wing that had been weakened by cracks, which resulted in the left wing bending upwards and separating from the aircraft.

After wing separation the pilots lost the ability to control the aircraft. Loss of the left wing resulted in the aircraft entering an uncontrolled dive and at the same time rolled to the left, which ended when the aircraft collided with the water surface in the basin about four seconds later.

Analysis of the CVR printout has shown that the wing fracture came as a total surprise to all on board. Nor in the information from the FDR was there anything to show any change in the aircraft characteristics that could have warned the pilots.

The analyses that were carried out of the area in the wing where the fracture occurred have shown that the extent of the fatigue cracks and their growth were to such an extent that it was only a matter of time before a wing fracture would occur. It is probable that the low flying along the canal, combined with wing tipping, was the peak loading which triggered the wing fracture just at that moment.

2.1.5 The impact

On the evidence of the impression markings seen on both the gyro horizon attitude indicators of the aircraft it can be deduced that the aircraft impacted the water surface in an inverted position with an approximate impact angle of 40° at an angle of bank of about 40°. The impact with the water surface was very severe and the aircraft broke up into a large number of pieces.

The aircraft came down into the centre of the basin and the separated wing fell about 100 metres from the bridge. On the evidence of the spread of the wreckage, where pieces including the right wing and right engine were found at the principal impact point, most indications are that the aircraft struck the water right wing first, whereupon these parts were torn off. The fuselage then continued further some metres in the direction of flight.

The inverted position of the aircraft at the point of collision with the water meant that the nose section and cockpit windscreen struck the water early and were smashed. The dynamic pressure of the incoming water then tore the fuselage at several locations. Everything indicates that those on board died immediately on the impact.

2.2 KBV's flying operations

2.2.1 Flight mission profiles

It can be said that the tasks placed on KBV involve a range of areas that in most cases have no equivalent within Swedish aviation. Some of the task profiles are much more similar to areas within military aviation.

The principal operating areas for KBV flights have – both now and historically – consisted of monitoring in various ways, where the maritime part has naturally been dominant.

The requirement specification when the CASA C-212 type of aircraft was introduced was therefore directed at meeting the requirements set by airborne monitoring operations at low altitude in a maritime environment. According to both the manufacturer and KBV the CASA C-212 met these requirements.

In the analysis of KBV flight profiles it has become apparent that the identification and photographic requirements associated with the operational targets sometimes necessitate periods of flying that place varying degrees of load on the aircraft. Such loads, involving both positive and negative G-loads to various degrees, can arise for example during steep turns and/or altitude changes close to vessels.

Flying at the altitudes where KBV normally operates can to a certain extent also require flying in turbulence, which has contributed to the accumulation of load cycles for the aircraft. Operations in a maritime environment also bring an increased risk of ice accretion that can, among other things, impose vibrations and additional loads on the aircraft structure.

2.2.2 G-loads

Because of this particular accident, SHK's review of KBV flying operations has focused on the possible exposure of the aircraft to abnormally high G-loads. The collection of facts in respect of this has covered:

- Consequence analysis of the tasking profiles.
- Interviews with the flight crews.
- Questionnaires sent to employed – and previously employed – flight crews.
- FDR analyses from a limited number of flights.
- SHK participation in KBV flying missions.

The collective result of these analyses shows that KBV flight operations are associated with flight profiles and types of flying that sometimes involve G-loadings that are greater than normal for transport flying. This is however necessary in order to be able to perform the tasks that have been assigned to the KBV aviation division.

Nothing has emerged that indicates that the KBV aircraft have thereby been operated outside the aircraft type operational limits, or in a way that the aircraft manufacturer did not intend.

The C-212 aircraft was designed and certified as per FAR-25 which requires that it must be able to withstand positive vertical G-loads of not less than +2.5 G. However the aircraft type is designed and approved for manoeuvring load factors +3.0 (max) and –1.2 G's (min).

For calculations of strength in this respect the safety factor 1.5 shall be used according to present regulations, i.e. the aircraft type shall be able to withstand vertical loads of up to +4,5 G and down to –1,8 G without suffering damage.

The manufacturer has marketed this type of aircraft as a very robust and "tough" aircraft, and that is how the KBV flying staff have understood and operated it.

2.2.3 Operational procedures

KBV flight operations are of a unique kind in Sweden and cannot therefore in all respects be compared to operations by a civilian operator of equivalent size.

Since this is a matter of commercial aviation with large aircraft, one must however expect that the operations will be carried out to a flight safety standard that can be compared to those of other commercial operators.

In reviewing the documentation that had been prepared for these operations and via the interviews with pilots concerning how the flight operations were carried out in practice, SHK has found deficiencies in the operational flying and in the operational documentation.

The deficiencies that were found – some of which were noticed during the audits by the inspection authority – were not detected by the operator's self-checking system. This can indicate that the regulations that were currently applicable – in which the requirements concerning a quality manager were not present in the applicable authorisation category – were probably inadequate.

These deficiencies may be an indication that the operations management were not completely clear concerning at what level these parts of the operations should lie. Even though initiatives were taken to improve the situation, there is reason to further analyse the most common flight manoeuvres in the operations with the purpose of preparing relevant procedures for an optimal two-pilot system. These procedures must be documented correctly and ingrained into the affected personnel.

Instead, in the process of preparing such procedures for formal reasons by copying the systems and viewpoints that are present in major commercial operators, SHK considers that in terms of flight safety they should be adapted to suit the special operational circumstances of KBV.

2.2.4 *Operational culture*

In the analysis of the operational culture of KBV, a model has been used consisting of risk control, understanding and behaviour. These three aspects interact with each other and all need to be taken into account[12].

Risk control – objectives and priorities

Swedish KBV aviation has had a high ambition to respond to the requirement to deliver the flying hours that it has promised its management to supply annually, with the risk that otherwise there would be a reduced appropriation in the future. This ambition has been clearly pronounced by the operational management. The production of flying hours has been understood by several among the staff as being the most important quality aspect.

At the same time the roles of Flight Manager and Manager of the KBV aviation division, with its financial responsibility, have rested on the same person up to about a year before the accident. This in SHK's opinion may have made it unclear for the staff as to whether they were addressing the manager as a Flight Manager or the person responsible for the finances of the operations.

The extent to which safety is prioritised as a goal in relation to other goals, such as production, is an important dimension of the culture in a business with heavy operational requirements. If the demand for production is too great, there may be a risk that the work is done with smaller safety margins and that both staff and materiel are exposed to greater strain. In the DHB for KBV the priorities are reflected in the Director-General's foreword, with the

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[12] References: - Skriver, J. A Simple Model of Safety Culture. I D.d Waard, K.A. Brookhuis and C.M. Weikert (Editor) Human Factors in Design. Maastricht, NL: Shaker Publishing, 2004.

text: “A basic principle for the aviation operations shall be an effort on every occasion to achieve maximum efficiency without jeopardising safety."

In all flight safety work the procedures must be founded on the management understanding the priorities that are required to run a safe business. Without signals from the business management that flight safety has the highest priority, the risk arises for other prioritisation, with possibly reduced flight safety levels as a result. SHK considers it is a weakness in the overriding KBV risk control that the primary objective of the operations is defined in terms of efficiency instead of flight safety.

Risk control - Operational procedures

Safe procedures also includes the ability of the organisation to make its flight personnel aware that safety and quality work not only consists of regulations, but is to a high degree a living process that must be constantly maintained in order to function. This safety work must try to encourage personnel to work in such a way and at levels of safety that the flight operations documentation prescribes.

In order to have the intended effect it is obviously unsatisfactory if the operations documentation is deficient or incorrectly revised. As an example of this it can be mentioned that a so fundamentally important regulation as the lowest permitted altitude during low flying differs depending on which manual one reads, and that there are no regulations for briefings before low flying manoeuvres.

It is also a failure in risk control that there are no prescribed standard operating procedures (SOP) for when KBV is demonstrating an aircraft.

SHK is of the opinion that this has no direct connection to this particular accident, but exposes a risk that the crews believe that this documentation has been prepared just to satisfy the requirements of the inspection authority rather than to be practical manuals necessary to undertake safe flying.

If the management of the operations does not continuously ensure that the operations are adapted to the regulations that exist, the consequences can be that in some respects the pilots make up their own rules or have their own interpretations of the existing regulations.

One example of this is the low altitude flying over the Falsterbo canal associated with the accident. This flying took place with deviations from the applicable regulations and meant that there was a real danger due to the small margin from obstacles along the canal. It is probable that the planning shortcomings and the execution of this flight were not a one-off occurrence with these pilots, but rather reflected the general deficiency in the ability of the management of flight operations to ensure awareness in respect of basic flight safety.

Risk control - the previous Flight Manager’s dual role

That the roles of Flight Manager and Manager of the KBV aviation division were held by the same person for many years can, in the opinion of SHK, have led to a lack of clarity in the guidance and follow-up of the work of safety. This carried the risk that safety was not given a high enough priority. It also meant a high work load on the Flight Manager and that his tasks were delegated to the Chief Pilot. SHK considers that this could have carried with it the risk that the Flight Manager for all these years was not fully informed of all the issues that were important for flight safety within the operations.

About a year before the accident the KBV aviation division had split the roles. Contributory to this was probably the difficulty in uniting the dual roles of the Flight Manager in the organisation.

Understanding and behaviour
It is worth taking very seriously that the interviews showed that the pilots expressed the need for good examples and they added that there was not enough insight of the importance of this. To set an example and to establish and maintain standards and regulations for good flight safety behaviour is a leadership question and is of central importance for the safety culture.

An important instrument to develop operations is to learn from events that have occurred and to evaluate one's own actions. The pilots made use of a reporting system in order to report events and problems. An impression gained by assessing what had been reported as flight safety-related events was that relatively few human errors had been reported in comparison with experience of similar military reporting systems.

This could have several reasons, such as the fact that reporting was not confidential and people did not want to expose themselves, that mistakes that were caught by the two-pilot system were not considered worthy of a report and that the organisation did not regard mistakes and deviations as the consequences of problems more deeply embedded within the organisation. The recurrent forum for the discussion of safety questions that has started should also be able to be a forum to further develop the organisation's ability to learn from experience.

Summary
According to SHK´s judgment some shortcomings in the flight safety culture have been present within the KBV organisation. These have not contributed to the wing fracture but are still issues that the KBV needs to take care of as a part of its improvement work.

2.2.5 *Training flights*

Most of the type training for new pilots was carried out in KBV's own aircraft. Flight training can subject the aircraft to loads that are greater and different to normal flight tasks. These arise for example during take off and landing practice, stalls, steep turns and single engine flying.

In the case of the loss of an engine there is training in emergency drills for that particular event, such as the ability of the pilot to safely manoeuvre the aircraft with only one engine operating. Since the drag forces in that case are only on one side, there arises an asymmetric load on the aircraft. This results, among other things, in powerful turning moments in the horizontal plane between the wing and the fuselage, which have to be taken up by the wing attachment structure.

Type training usually also includes demonstration of and training in the aircraft's maximum performance, in the form of short landings and cross-wind landings, which can stress the aircraft structure.

SHK's assessment is however that the flight training that was carried out with the KBV CASA C-212 aircraft took place within the permitted operational limits.

It may however be noted that the accident aircraft, S/N 346, was for the first five years in KBV service used for flight training to a considerably greater extent than the other aircraft.

2.2.6 Previous events

As stated in Section 1.17.10, extensive investigation was carried out to try to trace any overload or events in the operational history of the accident aircraft that was assessed as being of such a nature that it could have resulted in residual damage to the aircraft. This means damage that possibly could have contributed to the fatigue cracking initiation and growth.

No such overload or individual event was found in respect of the accident aircraft. The verified events of this type were instead found to have affected the two sister aircraft in the KBV CASA C-212 fleet.

The action taken and scope of the subsequent research that was carried out should, in the opinion of SHK, have revealed all such events. Contributory to this assessment was that KBV normally operated with a crew consisting if three to four personnel, which increases the likelihood that such a possible "extreme" event should have come to the attention of SHK somehow.

However it can be difficult to decide an event being so significant it can be considered as an overload (see Section 1.18.11). In addition possible events during the first years after delivery of the aircraft may have been forgotten.

2.2.7 Operational inspections and regulations

The responsibility for the issue of operational permission, and the responsibility for checking the main operations of KBV, i.e. the monitoring task, rest upon the inspection authority, the Swedish Civil Aviation Authority. Most of the shortcomings in such areas as operations documentation that were revealed in the review by SHK had also been highlighted by the inspections carried out by the inspection authority.

SHK can however say that the operations carried out by the KBV aviation division are of special character and do not have any relevant comparison in Sweden. Supervision of the operations has not functioned as intended in all areas, so that deficiencies in the operations documentation have not been rectified.

It cannot be substantiated that the inspection authority was aware of how low altitude flying was applied within KBV aviation, where demonstration flying was carried out without operational instructions for safe implementation.

Taking into account the difficulty of finding within the country's borders comparable operations, there is a risk that inspection of operations such as those conducted by KBV aviation would be dealt with in a special way, where the regulations to a certain extent would be adapted to the requirements of the operations instead of vice versa. SHK therefore finds it important from a flight safety viewpoint that a review is carried out in respect of the authority's supervision of KBV aviation.

Based on this SHK considers that the Swedish Transport Agency should prepare a national set of regulations adapted to suit the KBV aviation flying operations and that in applicable areas follows the same demands that are placed on civilian operators in respect of organisation, responsible decision makers, documentation, internal regulations, training, self-checking, etc.

2.3 The wing fracture

2.3.1 Design of the wing securing structure

This type of aircraft was designed at the end of the 1960s and approved at the beginning of the 1970s, in accordance with the knowledge and requirements set by the authorities that applied at that time.

The following analysis presents the SHK view that the way the wings were attached to the fuselage was by means of an unsuitable design and that this was probably decisive for the localisation of the cracks at the wing lower skin.

According to the manufacturer the intention was that all loads between the wing and the fuselage in the Z and Y planes (vertical and sideways) would be taken up by the four wing bolts and attachment lugs. The two fairings between the centre wing and the fuselage would only take up the loads in the X plane (horizontal in the direction of flight). These loads consist of, among other things, engine thrust, aerodynamic drag, mass forces and acceleration/retardation of the aircraft.

As stated in Section 1.6.3 the fairings were rigidly attached to both the centre wing and the fuselage. This means that the fairings could also transfer vertical loads to the undersides of the wings.

As can be seen in the following sketch (Figure 40), the vertical force consists mainly of the wing lifting force (FL + FL) that among other things is to balance the mass force (mg) of the aircraft fuselage. The four attachment lugs are fitted between the aircraft fuselage and the centre wing, just inside the fairings. The geometry of the rigid attachment structure means that loads in the vertical plane can take two different directions, both via the attachment lugs and via the fairings.

In order to calculate the distribution of these forces in different flight conditions detailed computer simulations are required which are dependent on many parameters.

The structure is statically indeterminate making the load distribution sensitive to how the fairing is attached to the fuselage and the wing.

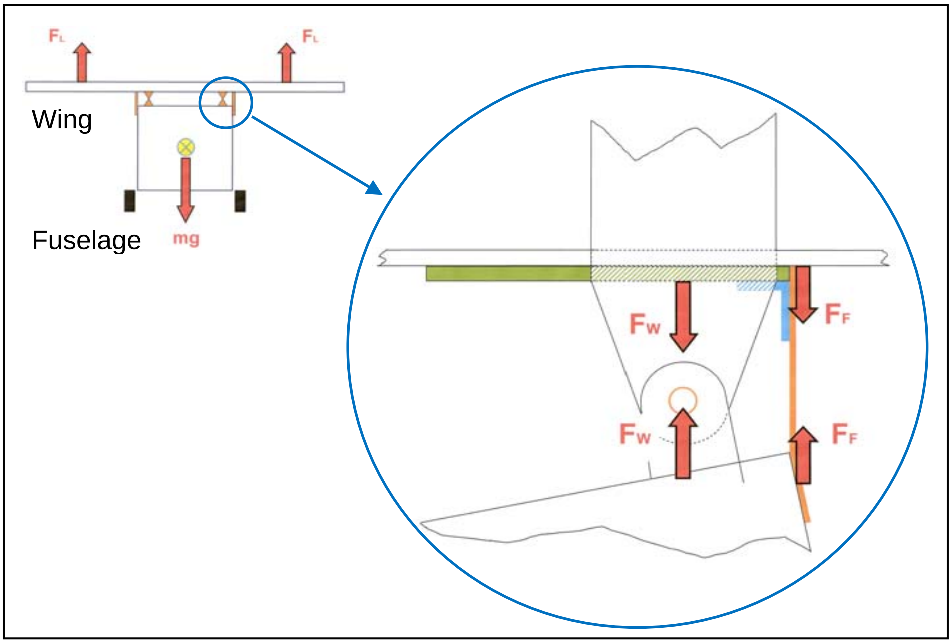

Figure 40 Force distribution in the wing attachment

The consequence of this design is that also very small deviations in parameters, that affect the stiffness in the wing attachment area, can be of major importance to which path the forces take. The mutual position of attachment points is one example of such a parameter."

Such deviations can for various reasons take place already during manufacture, but arise above all during flight as a result of the static and dynamic forces that then apply.

Additional loads can also arise caused by the normal deformation of the wings during flight, which contribute to the complex loading along rivet row # 1.

The fact that the fairings transfer vertical loads is reinforced by the flight tests and ground tests that were carried out by the manufacturer. Measurements during refuelling, with and without the fairings in place, showed that the tensile stress in the critical area (station 1132) changed by about 30 % (the tensile stress is however low, so that completely different values may arise in the case of higher wing loadings, such as during flight).

The flight tests also showed an inexplicably large difference between the tensile stresses measured on the right and left fairings respectively, and that the front part of the fairing on the right side was more loaded than the rear part, whilst the opposite was found in the left fairing, i.e. in that case the rear part was more heavily loaded than the front part.

These large differences in load transfer cannot be explained, but it cannot be ruled out that it depends on the assembly, and thereby be a basis for the differences between individual aircraft. The available measured results thus show that the fairings affect the stress in critical areas. However the extent of this is not clear.

These flights were not conducted to the maximum permitted +3.0 G and did not include the asymmetric flying that had been requested by SHK. On calculating the forces and material tensions in such in-flight cases, the manufacturer instead assumed a linear increase under load, which is an approach that SHK doubts and discusses below.

It is apparent from the above discussion that a considerable proportion of the vertical loads between the wings and the aircraft fuselage can, in certain circumstances, be transferred via the fairings to the angle bracket.

These undefined loads are then transferred via the angle bracket directly to rivet row # 1 in the lower skin of the centre wing. The loads are probably unequal in the chord direction, which can lead to local stress concentrations in the skin. The normal X-axis loads must be added to these loads.

This design means that on the centre wing lower skin, where the material stress is high in the span-wise direction, loads of undetermined size and resultant direction are added in a band at right angles to the primary load path (span-wise). This must be seen as a very unsuitable design in terms of fatigue.

Riveted joints are normally used to transfer various types of shear loading. The angle bracket attachment to the lower skin means that with this design the rivets, during positive G-loads on the aircraft, are subjected to axial pulling loads.

As can be seen in the following sketch (Figure 41) these loads will in addition be increased as a result of the "levering effect" that arises in the joint. The consequence will be that the axial tension force on the rivets becomes roughly twice as large as the downward directed forces from the fairings. ($F_R \sim F_1 + F_2$)

This condition is confirmed by the broken rivets and movements in the rivets along rivet row # 1, which were seen on the accident aircraft and on other aircraft in service. The damage indicates that they were subjected to abnormal axial loadings.

The fracture surfaces of the broken rivets showed that they are fatigue fractures that started at the "outside" and propagated in the direction towards the fuselage, i.e. as the result of vertical forces that arose in connection with oscillating positive G-forces.

This design also means that with such loads there arises a local bending moment (M) in the wing lower skin just inside rivet row # 1, which further complicates the stress situation in the wing skin. (See simplified load-sketch in Figure 41 and Figure 42 below)

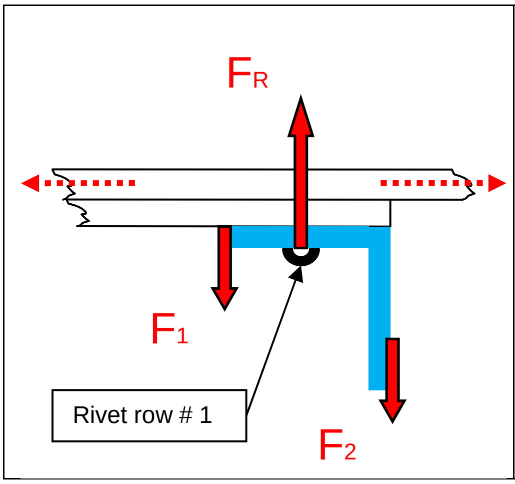

Figure 41. Axial forces on the rivets

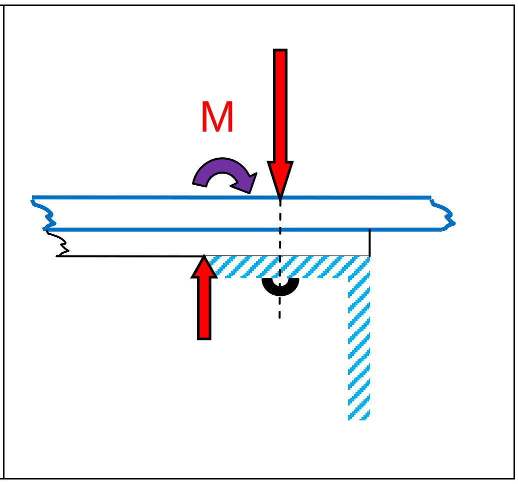

Figure 42. Bending moment in the lower skin

Taken together the above-mentioned design deficiencies mean that the material stresses in the wing lower skin along rivet row # 1 are very complicated and difficult to calculate.

No full scale fatigue tests were performed on the CASA C-212 wing in connection with its development, and the possibility of detecting its critical areas has therefore been limited.

SHK notes that the manufacturer and the certification authority have accepted this design. However SHK questions if the strength and fatigue tolerance calculations that were carried out for this critical area were relevant for all possible flying conditions such as asymmetric flight and flying close to the permitted limits.

The flight tests performed by the manufacturer after the accident seems to be extensive and well performed. However no measurements were made of the material stress directly on the lower skin along rivet row # 1, but only in the adjacent area and on the fairings. The measurements were performed in “normal” flights with G loadings well within the permitted load limits.

It is unfortunate that the flight tests did not cover measurements directly on the critical skin sheet surfaces and those measurements were not made for all possible flight cases. This would have provided valuable knowledge concerning the true loads and material stress that could occur.

In summary, it is the impression of SHK that the manufacturer, at the time of design, probably did not fully realize the consequences of the manufacturing deficiencies and underestimated the complexity in respect of the forces and material stresses in this area. There is therefore a risk that the calculations made of the forces and material stresses in the riveted joint arising in certain flight cases are not reliable and that the calculations of the fatigue life were therefore too optimistic.

The assessment of the design and the consequences of its deficiencies were carried out in consultation with highly qualified aviation technology expertise. SHK has not considered it to be meaningful to assign the time and resources that would be necessary to calculate in detail a verification of this opinion.

2.3.2 *Manufacture of the accident aircraft*

Based on the information provided by the manufacturer, SHK has not found anything to show that the accident aircraft was not manufactured in accordance with the manufacturing procedures and quality requirements that applied at the time of delivery. No single deviations of any significant importance have emerged, but it can naturally not be completely excluded that something happened during manufacture of just this particular aircraft that was not documented and that could have had some effect on the damaging sequence.

It has however been discovered that the joint drilling of the fairings between the fuselage and the centre wing on the accident aircraft, S/N 346, was carried out with the outer wings installed, while joint drilling of the fairings on sister aircraft, S/N 343, was done without the outer wings installed.

There were no particular instructions for this, but practical production factors probably decided whether the joint drilling was performed with or without the outer wings installed.

As a result of the mass of the outer wings, during joint drilling, the wings were flexed further downwards on the accident aircraft than those of the sister aircraft. During normal flying, when the wings due to the lifting force bend upwards, it could have been that the fairings on the accident aircraft had to transfer greater vertical loads to the centre wing lower skin than those on the sister aircraft. The possible consequences of this are discussed further in Section 2.4 below.

As shown in Section 1.16.9, a number of deficiencies were discovered during manufacture, which could have contributed to the initiation and spread of the fatigue cracks. These are reviewed in terms of metallurgy in Section 2.4 below.

The rows of rivets in this particular riveted joint are not straight, and some rivet holes have manufacturing defects and hole diameters that are too large. There are also variations in the striking power that was used while riveting. According to the manufacturer the work met all the applicable requirements and is probably representative of the manufacturing standard that applied in general at that time.

The gaps in certain rivet holes could have come about during the drilling and riveting operation in manufacture, but could also have arisen during operation. If the gaps are the result of large forces during operation, a systematic direction dependency should be visible in the form of ovalization, but this is not the case. This, and the fact that primer is present between the hole and the rivet indicates that the gaps originated during manufacture.

It is the opinion of SHK that these deficiencies are not however enough on their own to be able to explain the crack sequence in the wings of the accident aircraft.

SHK considers that there was a shortcoming in the applicable procedures during the manufacture of the centre wing to the effect that there were no detailed instructions for the use of sealing compound in the various riveted joints and that the process was not documented. It is well known that using sealing compound has a favourable effect on fatigue life. The fatigue tests that the manufacturer performed on sample pieces of riveted joints that were similar to the critical riveted joint on the accident aircraft showed that the fatigue life can increase by up to 88 % with the use of sealing compound.

This omission in the manufacturing work documentation has meant that the level of fatigue strength in the riveted joints was left to chance in the wings that were manufactured. This situation strengthens SHK's opinion that the manufacturer underestimated the risk of fatigue in the riveted joint in question.

The initiation of the fatigue cracks on the accident aircraft would most probable have taken place later and their growth been slower if these riveted joints had been sealed with sealing compound.

As can be seen in Section 1.16.9, the crack initiation between the rivet holes mainly occurred in the finishing marks that were seen on the wing lower skin surface. The finishing marks could therefore have contributed to crack initiation. The tests carried out by the manufacturer have however shown that they had no decisive effect on the fatigue tolerance of the joints, which can be interpreted as these tests not representing the true situation at rivet row # 1.

This “manufacturing defect” seems to have been standard in the manufacture of all the centre wings, which means that this also cannot be judged as being of decisive importance to the sequence of damaging events.

The fact that the accident aircraft and its sister aircraft were equipped with Series 300 -wings, which enabled pressure refuelling, and that they during manufacture were parked outdoors without engines for ten months is adjudged not to have had any effect on the eventual damage.

Nor are the modifications and installations of the maritime surveillance system, that were carried out on all KBV CASA C-212 aircraft after their delivery to Sweden, assessed as having any importance in this respect.

Even though deficiencies have been found in the manufacture of the accident aircraft that contributed to the damage sequence, these are not enough, in the opinion of SHK, on their own to explain why fatigue cracks appeared on just that particular aircraft.

2.3.3 *The wing fracture*

As stated in Section 1.16.9, the growth mechanism for the final fatigue cracking in the lower wing skin could be mapped. The mechanism behind the initiation itself of the many micro-cracks and the first crack growth are discussed in Section 2.4.

When the ability of the lower skin to withstand loads in the Y axis (span-wise) was reduced along the row of rivets, the load increased on the six longerons, whereby fatigue cracks began to appear in these too.

The large differences that were found in the characteristics of the fracture surfaces indicate that the cracks had been growing for many years. The growth had probably at the beginning been very slow. As the total crack length gradually increased, the load on the remaining load-carrying cross-sectional surfaces increased, whereby the crack growth started to accelerate.

The fatigue cracks in the lower wing skin, which is a part of the wing’s load-carrying structure, finally became so large that the remaining structure was no longer able to carry the loads to which it was subjected during the accident flight. In connection with the wing tipping that was performed, momentary lift and mass forces were created which on the left wing resulted in a final fracture of the wing that broke upwards and separated from the rest of the aircraft.

The similarities between the fatigue cracks in the left and right wings are striking and show that there was a symmetric system failure and that the mechanics behind the initiation of the cracks and their growth were the same. The difference is that the cracks in the left wing had at the time of the accident progressed further and that the total crack length became critical there first.

Since the growth was initially very slow, it has not been possible with any certainty to determine when the first fatigue cracks were initiated. Those particular rows of rivets in both wings had never been inspected. The original initiation could therefore have taken place already during the first years that the aircraft was in service.

Later the growth rate of the cracks increased and at the time of the wing fracture was probably very high. It can therefore be assumed that it was sheer coincidence that the wing fracture occurred during that particular flight. If it had not happened then, it would probably have occurred during a flight soon afterwards.

The fact that no signs of similar cracking was found on the sister aircraft, S/N 343, which had a very similar history, both technically and operationally, or on any other aircraft in service that have so far been inspected for this is dealt with in Section 2.4.

2.4 Initiation and growth of fatigue cracks

2.4.1 Multiple Site Damage

Despite extensive technical examinations and material analyses SHK has not been able with any certainty to establish why the initiation of hundreds of micro-cracks took place along the critical rivet rows in the accident aircraft, but not in the sister aircraft nor in any of the other CASA C-212 aircraft that have so far been inspected. It cannot therefore be totally excluded that some other factor, that has not so far been identified, could have contributed.

As stated in Section 1.18.8, crack initiation and crack growth, in the form of Multiple Site Damage, (MSD), is a well-known phenomenon that is characterised by a large number of minor fatigue cracks initiating and propagating along a row of rivets, in various positions and at different times.

The appearance of the fatigue cracks along the critical row of rivets on the centre wing of the accident aircraft generally agree with all the points that are characteristic of MSD.

A question in this investigation has been why no similar case of crack formation has been found in any other in-service CASA C-212 aircraft. Nor in the case of the sister aircraft, S/N 343, which was of more or less the same age and had a similar number of flying hours as the accident aircraft, had any sign of cracks been found in that particular area, despite the use of advanced NDT methods.

So far, however, only about 1/3 of the CASA C-212 fleet has been inspected. It is therefore possible that this type of crack could appear in one or more of the aircraft that have not so far been inspected.

Since crack detection also required qualified personnel and advanced equipment, and that the cracks at their beginning are extremely small and their growth very slow, existing cracks may have continued to be undetected. Practical tests have shown that some cracks at the outset can be so small that they cannot even be detected by normal NDT-methods and only become apparent at optical inspection with a strong magnifying glass or when the skin sheets are bent.

Nor can it be excluded completely that some of the six total losses that have affected this type of aircraft, where the accident cause has been classified as “unknown”, could have hidden similar types of wing fracture.

2.4.2 Fatigue life

As can be seen in Appendix 5, the fatigue life of a structural element is, apart from its shape and material, dependent on the applied basic loading and the presence and type, amplitude and frequency of additional oscillating loads, i.e.

the load spectrum. These loads give rise to equivalent material stresses in the structural material.

The resulting material stress is the sum of the basic stress (or residual stress) and the applied stress. As a guideline in the design of aviation materiel the aim is to ensure that the resulting material stress shall have a given margin to the yield strength of the material.

Based on the above information and the information concerning the expected use of this type of aircraft the stress conditions, in the critical structural elements and material data, the probable life span up to the point that fatigue cracks risk appearing can be calculated. Such calculations are verified and supplemented by various kinds of full scale testing and by the acquisition of data from those aircraft in operation that have the highest number of flying hours.

Original calculations in combination with updated information from such inspections performed on aircraft in service then form the basis for the development of a maintenance system that will ensure that any eventual cracks are detected in good time before they reach a critical size. See further section 2.5.

If a significant change takes place in any of the factors mentioned above, this can influence the fatigue life.

SHK sees two possible alternatives for how such factors would have been able to affect the accident aircraft in such a way as to speed up crack initiation and reduce the accident aircraft fatigue life.

1. Initiation may have been caused by the basic stress level in the wing lower skin, along the critical row of rivets, for some reason being increased, so-called residual material stress.
2. The initiation could have been the result of normal, but for the aircraft heavily loaded flying, in combination with some form of additional oscillating load during a period early in the aircraft's history.

Some form of combination of these alternatives cannot be excluded.

Common to these alternatives is, in the view of SHK, that the main reasons for the location of the fatigue cracks in the lower wing skin were the complicated loading situations along rivet row # 1, that could have caused unknown and high material stresses in the area. In addition static and oscillating loads, of varying frequency and amplitude, were present for a long time.

In general it also applies that multiple micro-cracks easily arise in the skin sheet surface of the alloy AA 2024 T3 used for the wing skinning.

Initiation has also been encouraged by the presence of finishing marks, fretting damage on the sheet metal surface and sharp edges and manufacturing defects in the rivet holes. The absence of sealing compound in the joint has also contributed, even though the manufacturer's calculated fatigue life was based on sealing compound not being used.

2.4.3 Residual material stress

If the basic stress on the structure for some reason was greater than calculated, the additional oscillating loads would take place at a "higher level".

The material stress in the structure will then approach more closely the material yield point, as shown in the following sketch, thus shortening the fatigue life.

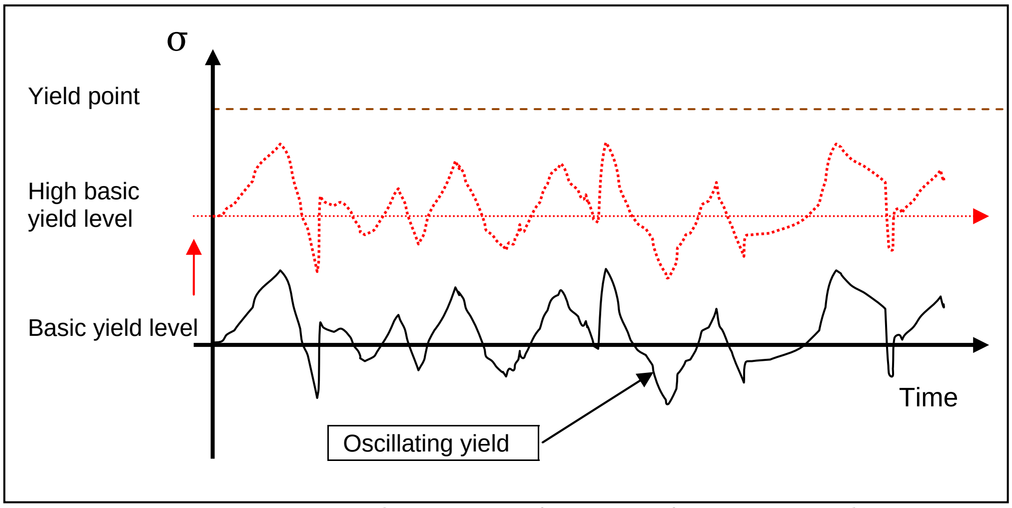

Figure 43. Material stress as a function of time (Example)

It is possible to consider two possibilities as to why the structural basic stress in that particular area would have been higher than normal.

A. Manufacturing defect or deviation

Some defect or deviation could have already arisen at the time the centre wing was constructed. The manufacture was manual, using jigs. A dimensional error could have come about in a jig, or an assembly error could have been made during the manufacture of that specific wing. It cannot therefore be excluded that a residual built in stress existed in that particular riveted joint as soon as the aircraft went into service.

According to the documentation and information that SHK received from the manufacturer concerning the manufacture of the accident aircraft there is no indication in it that the manufacture took place other than completely within the normal procedures.

It is possible however, that a rise in the basic stress could have occurred in the area as a result of the joint drilling of the fairings between the fuselage and centre wing being performed with the outer wings already installed.

B. Overloading while in service

Another possible reason why increased basic stress could have occurred in the riveted joint is that the accident aircraft was at some time subjected to an extremely high negative G-load.

Under negative G-loading during flight the wings are loaded “downwards”. It is possible to imagine that such a loading could be so high that a local compression with resulting plastic deformation of the metal then occurs in the centre wing lower skin.

Such a deformation would have resulted in the lower skin “shrinking” in the span-wide direction whereby a permanently increased material stress (residual stress) would have been left in that area when the other structure of the centre wing forced the wing to regain its original shape.

Such a local deformation, with subsequent residual stress could be exacerbated by high stress concentrations, e.g. in units with loosely fitting securing elements, which were in fact found in the accident aircraft wings in the form of rivets with poor hole filling.

Examples of events that could possibly result in such overloading are:

- Violent manoeuvring
- Hard landing
- Powerful turbulence

Violent manoeuvring
A manoeuvre that would result in a negative G-loading, beyond the permitted -1,2 G, is very improbable during normal flying, and would therefore assume that the pilot, for some unknown reason, consciously manoeuvred the aircraft in such a manner.

The manoeuvre would be experienced as very unpleasant for both the pilots and the system operators and mean that they would hang in their safety belts, while all loose articles in the cabin would end up on the cabin ceiling.

Hard landing
Involuntary hard landings can occur during normal flying operations, but above all in connection with the type training of new pilots. The accident aircraft was used more for training during its first years than the other two aircraft, which could have meant that it was at first more exposed to the risk of hard landings.

Only one case of a really hard landing was reported from KBV operations with the CASA C-212. On this occasion there occurred easily visible and extensive damage to the aircraft cabin skin, which had to be repaired. However this event happened to another aircraft that did not have cracks in the wings.

SHK finds in this context that it is unfortunate that the landing gear indication of hard landing, that was present on the aircraft at delivery, has disappeared or was removed. With this system in operation a better follow-up of hard landings would have been facilitated.

Powerful turbulence
The KBV CASA C-212 aircraft have been operated in weather situations where powerful turbulence could have occurred. If the aircraft on any such occasion entered an area with local, very powerful air flows that were both ascending and descending – which there can be in strong thunder clouds – the centre wing could have been subjected to abnormally high loadings.

In this context it can however be said that the sister aircraft operated in very strong turbulence after the storm “Gudrun” without any wing cracking or other damage occurring in the aircraft.

<u>Summary</u>
Common to the above-mentioned alternatives is that a possible event so violent as to cause permanent damage to the centre wing structure should have been so disturbing that reasonably someone in the crew would have noticed it and either reported it or at least mentioned it to a colleague.

As stated in Section 1.17.9 and 1.17.10, SHK has carried out several very comprehensive surveys with the aim of finding such a possible event. Nothing in the technical documentation that has been reviewed, nor from all the interviews conducted with the pilots, system operators and technicians indicated that such an event had taken place. Nor in the anonymous questionnaires either that were carried out was any event of this type mentioned.

Such a possible event should also, experience tells us, have caused other damage to the aircraft, in the form of broken rivets, creases in the skin, etc.

No such damage has occurred and SHK therefore in summary adjudges these alternatives as less probable even if the possibility could not be excluded.

In this context SHK would like to refer to the FAA Memorandum FEB 19, 2008, which emphasises the fact that structural damage can occur in aircraft in connection with overloading taking place that for various reasons is not always reported.

SHK supports therefore the issued recommendation concerning the increased use and development of existing flight recording systems on board, so that the operator could be more certain of catching such events that have occurred and take suitable action.

2.4.4 *Demanding operations with added oscillating loads at times*

If additional oscillating loads have greater amplitude, stronger load changes, higher frequency or unfavourable formats relative to what is normal, this can also result in a reduction of the fatigue life.

The relationship is illustrated in a simplified form in the following sketch, where it can be seen that the resulting material stress with such an unfavourable load spectrum among other things more often comes closer to the material yield strength.

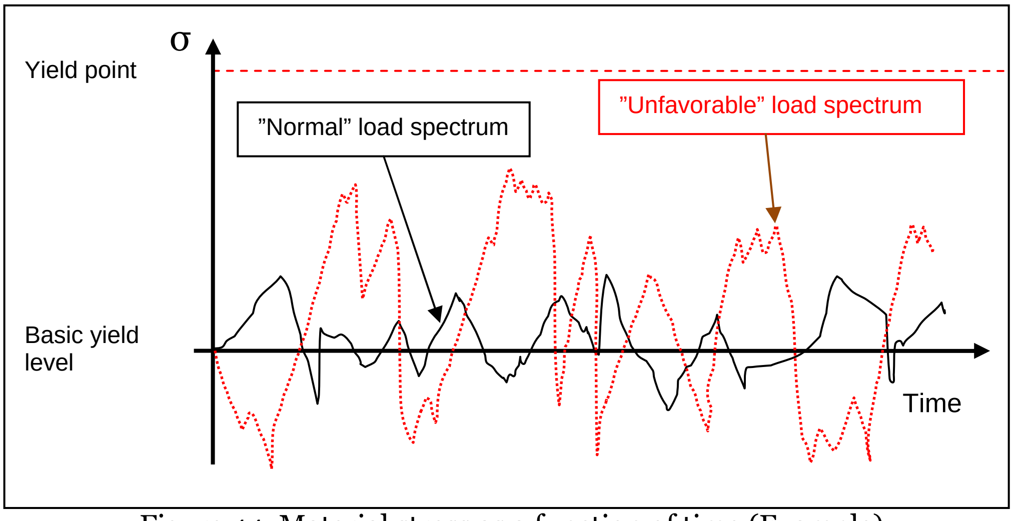

Figure 44. Material stress as a function of time (Example)

If the aircraft has been subjected to such an “unfavourable load spectrum”, even for a limited period of time, this means that the built-in fatigue margin is “consumed” more quickly.

Even though the operating conditions for the accident aircraft and its sister aircraft were similar, the investigation has uncovered conditions that indicate that the accident aircraft, for a certain time period, probably at an early stage in its service, operated with an unfavourable load spectrum in the form of vibration or oscillating loads.

After 10,000 flying hours there had been a total of nine reported disturbances concerning vibration, while sister aircraft, S/N 343, had at that time only two reported vibration disturbances and S/N 229 one reported disturbance.

Most of these vibration disturbances in the accident aircraft occurred during the first five years of the aircraft's operation. Six of these reports concerned the left engine and three the right engine. In the case of some of these disturbances the fault tracing took a long time and the aircraft was sometimes operated in parallel with attempts to rectify the problem.

On a later occasion the aircraft was operated for probably at least 74 hours with a fatigue crack in the left propeller hub. Even though propeller balance, according to the manufacturer's investigation, only had a marginal effect on the fatigue life in the critical area, such an imbalance can generate natural oscillations in the aircraft, of a different amplitude and frequency, which can increase the risk of fatigue.

After the accident a further fatigue crack was found in the left propeller hub. Since similar cracks had been found on three previous occasions on the accident aircraft, although on different propeller hubs and engine installations, and on only two occasions found on sister aircraft, in those cases on the same propeller hub and same engine installation, these cracks could be an indication that the accident aircraft generated a different vibration profile, which increased the risk of this type of damage.

Bearing in mind that KBV flight operations quite often took place in an "unsteady" environment, it is reasonable to assume that the pilots' "threshold level" for reporting abnormal roughness and vibration were generally at a high level. Deviations in the form of imbalance and vibration problems could therefore have occurred without being reported.

During the first two years of operation of the accident aircraft it was used about 50 % more than its sister aircraft for training. As mentioned in Section 2.2.5, flight training can subject the aircraft to loads that are greater and different to normal flight tasks. Since KBV flight operations can generally be characterised as demanding it can be assumed that the training of new pilots took place in a similar manner.

The two first CASA C-212 aircraft in KBV service were also operated for almost two years before stall warning devices were installed. During that period type training flights were carried out without access to the "warning system" for abnormal, and sometimes load-incurring, manoeuvres of the aircraft which the stall warning system to some extent provides.

The wing bolts on the accident aircraft were more worn than the bolts on the sister aircraft and more so than the manufacturer considers normal. The bolts had never been detached from the wing attachment. This wear could therefore be a physical indication that the aircraft, periodically during its life, had been subjected to some kind of different loading between the wing and the fuselage, in the form for example of vibration or oscillating loads.

It is the view of SHK that probable and unfavourable load changes as described above, which via the fairings were transferred to the centre wing lower skin, in combination with flying conditions that were generally demanding in terms of load, sufficed entirely to be able to explain why fatigue cracks along the critical rows of rivets have so far been found only in the accident aircraft.

Experience has shown that there is also a wide statistical spread in the number of load cycles after which fatigue cracks begin to be initiated in otherwise identical structures.

The fact that the cracks managed to grow further in the left wing than in the right wing is probably due to the left wing being subjected to torque and gyroscopic forces from the engine, which try to bend the wing upwards, while equivalent forces from the right engine try to bend the right wing downwards. This is a phenomenon that is well known in the aviation industry.

2.4.5 Summary

The character of the fatigue cracks in the wings of the accident aircraft, and that in the left wing resulted in the wing breaking off, are typical of Multiple Site Damage (MSD).

The fatigue cracks could have arisen as a result of a residual stress in the wing lower skin that occurred since the manufacture of the wing or in connection with some momentary overload during operation. Nothing in the investigation has been discovered to indicate this, although the possibility cannot be excluded.

SHK considers, however, that it is more likely that the fatigue cracks arose during normal flight operations in combination with some form of additional vibration and/or oscillating loads at some period of time in the history of the accident aircraft. However nothing has emerged to indicate that the aircraft was exposed to any operational loads that were outside the permitted limits for the aircraft type.

The damage sequence had progressed over a long time, and some form of combination of these factors cannot be excluded.

The basic reason for the location of the fatigue cracks, in the opinion of SHK, been the statically undefined load situation in the wing fastening that probably meant that the material stress along rivet row # 1 has, in certain flight conditions, been greater than that calculated by the manufacturer. To this should be added a long period of exposure to static and oscillating loads, of varying frequency and amplitude.

The initiation and propagation have been encouraged by the presence of finishing marks, fretting damage and manufacturing defects in the rivet holes, along with the absence of sealing compound.

The possible deviation from a normal load spectrum that the aircraft was probably subjected to is not greater than that which other aircraft, with similar operational profiles, of that type could also have experienced. This means, according to SHK´s opinion, that there is a risk that similar fatigue cracks could arise in the wings on other CASA C-212 that are now in operation.

So far only 1/3 of the aircraft of this that are in service have been inspected in accordance with the applicable regulations. This makes it important that the manufacturer and affected authorities set a high priority on taking measures to ensure that these inspections are in fact carried out on all aircraft in service, by qualified personnel and with usage of the correct NDT equipment.

2.5 Maintenance system

2.5.1 Maintenance instructions

It is the responsibility of aircraft manufacturers and the inspection authorities to ensure that a functioning maintenance system is available for all operational aircraft. These must include clear maintenance provisions that, when followed by operators must ensure the long term reliability of flight materiel and contribute to flight safety.

In this particular case SHK has found no divergence from the fact that all the prescribed inspections, in respect of searching for cracks in the specified areas of the wings of the accident aircraft, were carried out by the maintenance organisation in compliance with the applicable regulations.

The accident therefore shows that deficiencies were present in the manufacturers' maintenance system in respect of CASA C-212 aircraft as far as checking for fatigue cracks was concerned.

The maintenance system has not succeeded in catching and recommending relevant action to stop the growth of serious fatigue cracks in one of the most critical areas of the wings. Growth that continued for several years and in the end resulted in the wing fracture.

These deficiencies in the maintenance system have been a major contributing factor to the accident and show, as mentioned previously, that the manufacturer underestimated the risk of fatigue in that particular area.

The only regulation concerning strict inspection of crack formation in this area was the document C-212-PV-02-SID in respect of lengthening life. According to the analysis performed by the manufacturer, in respect of KBV aircraft S/N 343 and S/N 346, this inspection was not however deemed necessary before reaching 20,000 flying hours. Since the average flight time for KBV aircraft was little more than two hours per flight, the limit of 20,000 cycles would never be reached.

A total flight time of 20,000 hours is equivalent to about 23 years in KBV type operation, which must be considered a very long time – both in terms of flying time and calendar time – to be completely without specified crack inspection in the critical area.

The area where the cracks arose is in a way covered by inspections in accordance with the requirements in C-212 Aircraft Maintenance Manual, Chapter 5, Section 5-20-00, Sec. 57.05/57.06 and directive CPCP C-212-PV01, but these instructions deals primarily with corrosion control, component security, biological contamination, adjustment and general condition and do not mention anything specific regarding cracks.

If one also takes into account that the prescribed inspection level in directive CPCP C-212-PV01 that particular area (Zone 930) is at the lowest of three levels – "General Inspection" – and that the inspection interval is the longest of four – eight years – it is clear that the manufacturer's assessment was that the risk of corrosion was also low in that area.

In respect of the implementation of CPCP C-212-PV01, SHK has found that this inspection initially did not take place in accordance with the applicable regulation. The first documented check was not carried out on the accident aircraft until 18 December 1998, over three years after its publication.

Documentation is missing for the three prescribed checks between the documented checks on 18 December 1998 and 3 September 2001. Either they were not performed or were not documented correctly. None of these however affect the space in the wing where the fatigue cracks occurred. The checks that were possibly missed are therefore adjudged as not being worth anything in this case.

The last documented checks in this particular area, in accordance with AMM Chapter 5, Section 5-20-00 Sections 57.05 and 57.06 and regulation CPCP C-212-PV01, were carried out on 5 September 2002 at 12,232 flying hours. During these checks no corrosion or otherwise abnormal condition was found. The next checks prescribed in accordance with these regulations would have fallen due some eight years later, i.e. just under four years after the accident.

These inspections were performed as visual checks in accordance with the applicable instructions, with the aid of a portable inspection lamp and a mirror. At this time it is probable that many of the fatigue cracks in the wings had already initiated and growth had begun.

The checks were carried out 4,816 flying hours before the wing separation, which is equivalent to about 28 % of the total flying time of the aircraft at the time of the accident. As can be seen from the table in Figure 37, most of the aircraft lifetime is taken up by the initiation and propagation of a fatigue cracks until it became visible. The time from a crack becoming visually detectable to what is called unstable crack growth (fracture) is on the other hand relatively short.

The assessment by SHK is therefore that the actual cracks at that time were probably still so small that they had not broken through the lower skin corrosion protection and were hardly likely to be detected by a mere visual check as described above.

The cracks were in addition localised behind an inner wing rib in relation to the inspection hatches which means that the technician would have had to search precisely the right surfaces to detect them.

After the accident the manufacturer and the inspection authority involved had prescribed, among other things, that this particular area must be checked for cracks periodically with the aid of two different NDT methods at 600 flight hours or 250 cycles' intervals respectively on all aircraft that had reached 8,000 flying hours.

2.5.2 *Flight operation profiles*

During the design of aviation materiel calculations are used for dimensions of elements and different types of full scale tests are employed to verify the calculations. Such tests, of among other things, strength and fatigue tolerance form the basis for determining the maximum permitted flying life and/or the number of permitted landings. Experience has shown that despite this it is sometimes difficult to identify all critical areas in an aircraft regarding fatigue.

In such determinations it is the absolute number of load factor changes and their amplitudes that are of primary importance.

However aircraft are operated in different ways. Certain aircraft are subjected to greater loads and a larger number of load factor changes than others. This affects the built-in margin to the initiation and growth of fatigue cracks. Some types of aircraft have therefore been assigned different flying life and cycle limitations, depending on what type of flying operations they are principally used for.

The CASA C-212 aircraft type is used for many different types of flights, and therefore subjected to great differences in loading and load factor variations. For example coastguard operations often generally subject the aircraft to greater loads than normal transport flying, something that the manufacturer also was well aware of.

SHK therefore considers that it is unfortunate that the manufacturer, to a greater extent, has not prescribed differentiated flying life limitations and inspection intervals based on the tasks that the aircraft is primarily used for.

The normal communications that over the years took place between the manufacturer and KBV should have provided the manufacturer with a good knowledge of what loads the flight materiel was subjected to in practice during its usual coastguard operations.

2.5.3 Leading aircraft

As stated in Section 1.17, the aircraft operated by KBV are regularly subjected to high loads, although within approved limitations. This particularly applied at the beginning of their use when the on board technical surveillance equipment was less advanced than it later became.

The manufacturer’s statistics show that the accident aircraft and its sister aircraft were, at the time of the accident, the two aircraft, among the world population of CASA C-212 used for KBV duties, those which had accumulated the greatest number of flying hours, over 17,000. This was about 70 % of the flying time for the aircraft of that type that at the time had the largest accumulated total (Leading Aircraft) of flying hours within other transport service.

Considering the great age and flying time of the accident aircraft and its sister, and the demands made on them, these particular aircraft were natural candidates to suffer possible fatigue cracks at critical areas of the structure.

The manufacturer was well informed about the flying time status and usage of these particular aircraft. Despite this the possibility was not taken of using these as sample candidates for a general fatigue crack inspection in accordance to the principle described in Section 1.4.2 below, for example according to C-212-PV-02-SID, in good time before the flying time of 20,000 hours or 20,000 cycles were reached.

2.5.4 Ageing aircraft

To some extent the CASA C-212 aircraft type is representative of the term “ageing aircraft”. It was built almost 40 years ago and there has not been a full scale test with an aircraft that has accumulated more simulated flying hours and number of cycles than any aircraft in service which was not a requirement at this time.

The type was marketed in its time as an extraordinarily robust utility aircraft, and has therefore been used for a wide range of demanding service all over the world, coastguard flying being one of these tasks.
This aircraft type is also being used by many categories of operators, civil and military, probably with varying quality of technical maintenance and follow-up of the materiel. The relatively high incidence of accidents may be a result of this, among other things.

The wide range of uses for the aircraft type and its availability on the market mean that it will probably remain attractive to many operators for many years to come. It could well be that new areas of use will also be found, so this aircraft will to an increasing level be represented in the category of “Ageing aircraft”.

This raises great demands on the manufacturer and the affected authorities to, based on knowledge of this problem, prepare a complete maintenance system for the CASA C-212 that will ensure flight safety for all the aircraft of this type in service.

2.6 The rescue services

In spite of the fact that there were a large number of witnesses at the site it was difficult to obtain reliable information about the point of impact. The location that KBV 286 marked was found to be incorrect. The search in the wrong place for the fuselage delayed the diving efforts for life saving by about an hour and a half. In this case it made no difference, but in the case of life saving it can be decisive for victims to be found as quickly as possible.

The fuselage was eventually found visually from the air. The rescue units which participated did not know what technical aids were available in the other rescue organisations. If the risk analysis, performed by the local rescue service, had included an aircraft accident as a risk, this need could have been highlighted in the local district council action programme. There are reasons to update the risk analysis and the possible need for special resources.

There were failures in the co-ordination between the diving units and the surface units. On several occasions boats entered the area where diving was in progress. It is of vital importance that diving can be carried out safely so that divers are not injured.

In AFS 1993:57 Dykeriarbete (Diving work) 34 § it is prescribed that a special co-ordination diving leader must be assigned. In this operation the diving leader would have acted as a sector commander under the rescue leader in the same way as OSC and ARCC. This in turn would have facilitated the overall co-ordination and the various search areas would not have been in conflict.

One of the divers was responsible for the diving efforts, but was not formally assigned as the diving leader. The rescue services should review their organisation so that there is a contingency plan to control major diving operations optimally.

The command structure with the individual who had the responsibility for the rescue efforts was clear from the start. ARCC started off as the rescue commander until the fuselage had been located, whereupon the responsibility was transferred to the local district rescue services. The various units were on the other hand not informed of what work was being done within the various sectors.

With a better picture of the situation at the command post concerning which sectors and search areas the various units had, the problem between the diving and surface units could probably have been avoided.

By carrying out joint exercises procedures can be determined and such difficulties as communication under the hovering helicopter and the use of different radio channels solved.

SHK considers in summary that the deficiencies in the rescue service are not of the nature that there is a need to issue a recommendation.

3 CONCLUSIONS

3.1 Findings

3.1.1 The accident

a) The crew were qualified to perform the flight.
b) The aircraft had a valid Certificate of Airworthiness.
c) The fly-bys were performed without an approach briefing by the crew.
d) The fracture in the left wing occurred without warning in association with wing tipping.

3.1.2 The aircraft type

a) According to SHK´s judgment the design of the wing attachment to the fuselage is unsuitable.
b) The fairings can transfer vertical loads between the fuselage and wing, which they are not intended.
c) A considerable part of the vertical loads between the wing and the aircraft fuselage can, in certain conditions, be transferred to the lower skin of the wings.
d) Loads of unknown size and resultant direction are introduced into a band at right angles to the primary load route in the lower wing skin.
e) The material stress in the wing lower skin along rivet row # 1 is, according to SHK: judgment, complicated and difficult to calculate with certainty.
f) Fatigue fractures and movements of the rivets in rivet row # 1 on the accident aircraft and on other aircraft in service indicate that they have been subjected to abnormal axial loads.
g) According to SHK´s judgment the manufacturer has underestimated the material stress and the risk of crack formation in that particular area, and thereby overestimated the fatigue strength of the wings.
h) There is a risk that the calculations made for fatigue life are too optimistic.
i) The manufactures maintenance system for this type of aircraft was unable to detect, and prescribe relevant measures to stop the growth of the fatigue cracks.
j) The manufacturer did not take advantage of the chance to use one of the leading flying time coastguard aircraft for a general crack seeking inspection (as a sample aircraft).
k) About 1/3 of the aircraft of this type in service have so far been reported as inspected, to check for this particular type of fatigue cracking, without finding any cracks.

l) On the sister aircraft, S/N 343, with a similar operational history, no similar cracking was found.

m) Approximately 2/3 of this type of aircraft that are still in operation have not so far been reported as having been inspected.

n) There is a risk that similar types of cracking are present in aircraft of this type in service.

3.1.3 *The accident aircraft*

a) The strength of the left wing was considerably reduced as the result of an extensive fatigue crack along rivet row # 1 in its lower skin.

b) The crack is characteristic of Multiple Site Damage (MSD), which had developed over a long period of time.

c) The same type of crack was found in the right wing, but less fully developed. Initiation and propagation were similar.

d) Nothing was found to indicate that the accident aircraft had been subjected to momentary overloading or any other extreme event, although this possibility cannot be excluded.

e) There were signs that the accident aircraft had at some time been operated with an unfavourable load spectrum in the form of vibration or oscillating loads.

f) Wear on the wing bolts from aircraft S/N 346 was greater than normal, and greater than in aircraft S/N 343.

g Manufacturing defects in the wing were found.

h) With correct instructions and suitable equipment it would have been possible, at the time of the accident, to detect the cracks visually from the inside of the wing.

i) Corrosion checks in accordance with CPCP- C-212-PV01 were initially not performed according to prescribed directives.

3.1.4 *Flight operations*

a) KBV aviation flying operations have sometimes subjected flight material to high loadings, but in the opinion of SHK these have taken place within the permitted limits for this type of aircraft.

b) The operations management have prioritised production efficiency.

c) Demonstration flights, similar to the fly-by involved here, have formed part of the routine flying in the KBV flight operations.

d) Flying along the Falsterbo canal took place with a deviation from the applicable internal rules and without operational instructions.

e) There are deficiencies in the operational documentation.

f) There are deficiencies in the technical documentation in respect of corrosion checks that were carried out.

g) The self-checking system was unable to detect the deficiencies in documentation that were found.

h) Those deficiencies that have been identified in the flight operations as described above have partly been highlighted by the inspection performed by the authority.

3.1.5 *The rescue services*

a) Deficiencies are present in the national and local district rescue services which however in this case did not affect the survival of the crew.

3.2 Causes of the accident

The accident was caused by an inadequate maintenance system in respect of inspections for fatigue cracks. Contributory to the crack formation has been an unsuitable design of the attachment of the wings to the aircraft fuselage.

4 RECOMMENDATIONS

It is recommended that EASA:

- takes the necessary measures to ensure that fatigue cracks of the type that caused the wing fracture on the accident aircraft cannot occur in any CASA C-212 aircraft that is in service *(RL 2010:01 R1)*,
- evaluates the need for modification to the wing attachment to the fuselage so that the material stress situation along the critical row of rivets will be conclusively defined for all in-flight cases *(RL 2010: 01 R2)*, and to
- take steps so that the existing flight recording systems on board large aircraft, such as FDR, QAR, etc., are developed further so that they can also be used to inform pilots, while recording the data, about possible overloading during operation *(RL 2010:01 R3)*.

It is recommended that the Swedish Transport Agency should:

- develop an applicable set of regulations for KBV flying operations, taking into account the unique tasking profile of the operations and their increased risk level *(RL 2010:01 R4),)*, and
- review the current set of requirements in the BCL in respect of self-checking systems in operations that are similar to the KBV operations *(RL 2010:01 R5)*.

APPENDICIS
1 - 8

APPENDIX 1
FDR-DATA

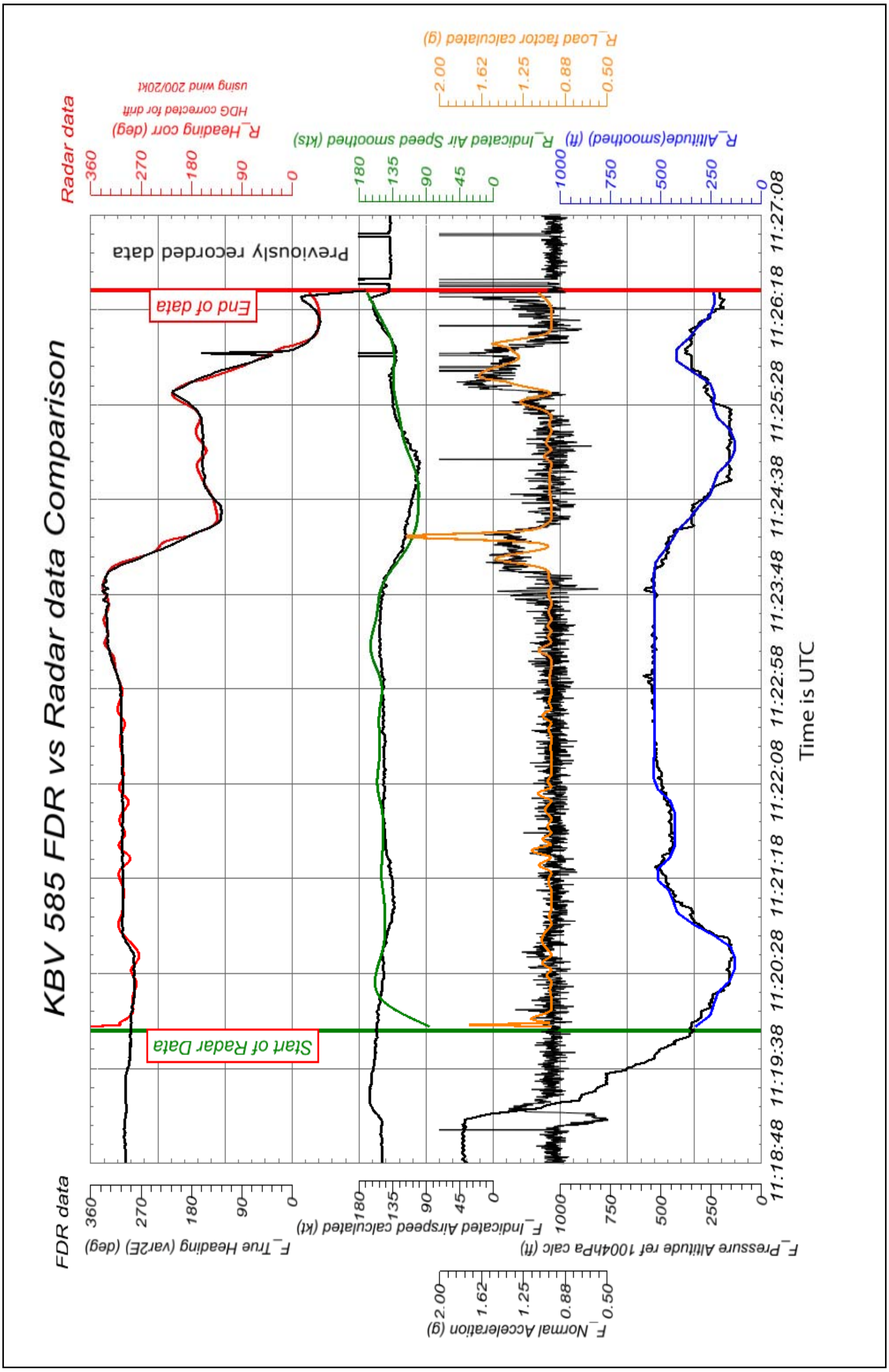

Figure B1. FDR-data

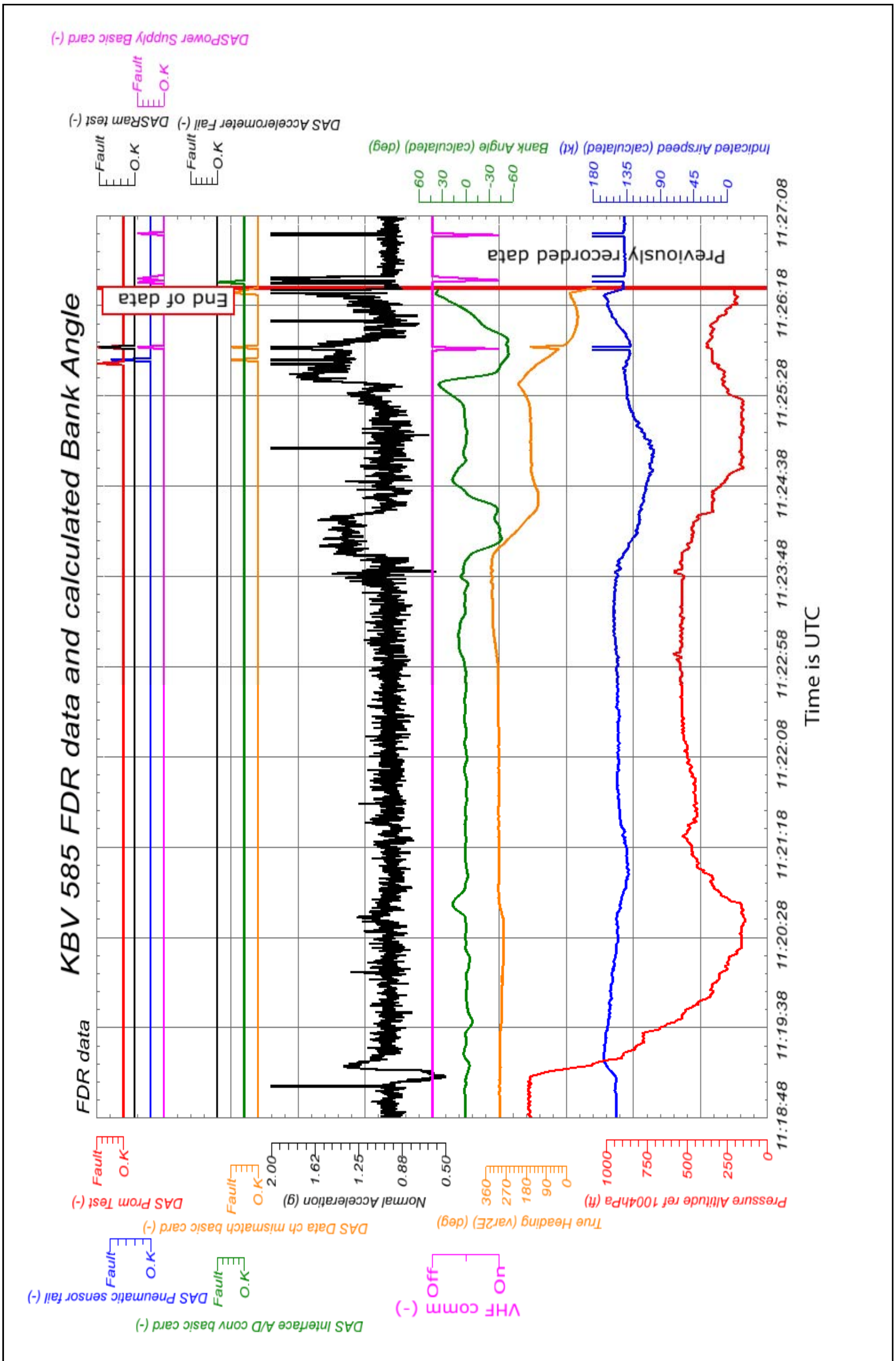

Figure B2. FDR data with calculated roll angle

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APPENDIX 2

RELEVANT INFORMATION FROM THE CVR PRINT-OUT

KBV 585 CVR

Time: Universal Time Coordinated (UTC).
Local time = UTC + 2 hours. The time is set according to the radar data, on the assumption that the last radar recording, at 13:26:28 local time, was at two seconds before the CVR stopped.

From: Source:
LP - Left Side Pilot
RP - Right Side Pilot
OP1 - Front system operator
OP2 - Rear system operator
LC - Coastguard Co-ordination Centre
GÄ - Ground station “Gäddan”
ST - Ground station “Storken”

Remarks Traffic
VHF - VHF radio
UHF - Coastguard UHF radio
& - Internal KBV 585

Comments:
[Parentheses] - Translator’s comments or other information.
(Brackets) - Information that could not be completely understood. Also indicates where names have been removed from the text.
?? - Marks information that could not be understood or that was lost in interference.
? - Marks questions or that the information is uncertain.

Time	From	Note	Information
11:20:22	RP	VHF	And Storken, we just passed GG597.
11:20:29	(ST)	VHF	??.
11:20:30	RP	&	Under way.
11:20:35	OP2	&	What was her course then? She had two... zero.
11:20:39	LP	&	Two four... two four zero, perhaps.
11:20:43	RP	VHF	Storken 585.
11:20:53	OP2	&	Storken [whistling]. Please, Storken, listen to me now.
11:21:02	LP	&	Didn’t get contact with 48 again (name)?
11:21:04	OP1	&	I didn’t try again.
11:21:07	RP	VHF	Storken, coast 585.
11:21:14	OP2	&	Is Storken answering?
11:21:16	LP	&	Here is Storken answering [jokingly]
11:21:20	OP2	&	Yes, what food is there today, then?
11:21:23	LP	&	I forgot to look.
11:21:25	OP1	&	Pancakes and pea soup.
11:21:28	RP	&	Dangerously close to pea soup and pancakes.
11:21:30	LP	&	Yes, they usually always...
11:21:31	OP2	&	Yes, it’s standard, but... otherwise.
11:21:35	OP1	&	The proper meal.
11:21:38	LP	&	Now we have two minutes left until passing.
11:21:41	OP2	&	Two minutes to passing, yes.

11:21:44	RP	&	[Private]
11:21:47	OP2	&	[Private]
11:21:50	??	&	[Private]
11:21:56	LP	&	Fly along the canal till we get there.
11:21:57	RP	VHF	Storken 585.
11:22:00	??	&	The canal.
11:22:02	OP2	&	[Private]
11:22:08	??	&	[Private]
11:22:17	OP2	&	Yup.
11:22:28	OP2	&	No contact.
11:22:29	LP	&	That was a really good time estimate there, (name).
11:22:32	OP2	&	You think so?
11:22:33	LP	&	Yup.
11:22:34	OP2	&	Yes, great, you know.
11:22:42	OP2	&	Now let's see, we had more, we had 286, we had there at...
11:22:49		UHF	[Tone lasting 1.06 seconds. SELCAL transmission]
11:23:15	LP	&	I only see 286.
11:23:17	RP	&	Yes, it's not there any more.
11:23:20	OP1	&	048?
11:23:21	RP	&	No.
	OP1	&	Where are they then?
11:23:23	LP	&	Not a soul on the quay either.
11:23:26	OP2	&	Maybe they've already finished that... spectacle.
11:23:29	LP	&	Ah, there's a whole group, you see them.
11:23:31	OP1	&	They're standing there waving.
11:23:34	OP2	&	Standing and waving at their proud coastguard. Yehaa.
11:23:42	LP	&	Well use flaps for the approach when the speed...
11:23:49	OP2	&	Shall we see if we get any AIS contact with the...
11:23:53	LP	&	Flaps for approach.
11:24:01	LP	&	And I'll go down to minimum hundred knots.
11:24:05	RP	&	One hundred.
11:24:22	OP2	&	Shall we see where the hell 48 is somewhere, then.
11:24:25	OP1	&	She is somewhere, she aimed for us before.
11:24:28	OP2	&	Yes, they are up you know where, south of Klagshamn. Those bloody hooligans. [pretending to use a local dialect]
11:24:52	OP1	&	Goodbye.
11:24:57	LP	&	And flaps up.
11:25:01	RP	&	Flaps up.
11:25:07	OP1	&	Very nice houses here too.
11:25:10	OP2	&	Yup. Wasn't it, (name) who had a place in this neighbourhood?
11:25:14	LP	&	Yes, only it wasn't her. It was some company, wasn't it?
11:25:15	OP1	&	Really.
11:25:18	OP1	&	[Private]
11:25:19	OP2	&	Yup.
11:25:24	LP	&	Yes, she did.
11:25:29	LP	&	So I flash past one more time and say "Cheerio" then I go and eat lunch.
11:25:32	OP1	&	That sounds great.
11:25:33	OP2	&	[Simulating vomiting sound]
11:25:37	OP1	&	What are you doing, throwing up? [pretending to use a local dialect]
11:25:40	OP2	&	I'm just burping. [pretending to use a local dialect]

11:25:48	LP	&	Dammit, so early??.
11:26:08	OP2	&	Yes, real nice places some of these here. That one with the green roof was beautiful.
11:26:13	OP1	&	Yup.
11:26:14	OP2	&	Nice, you know.
11:26:16	LP	&	There's no job more amusing than this.
11:26:19	OP1	&	Really?
11:26:25.8			[Mechanical sound lasting 0.8 seconds]
11:26:26.1			[Sound of reducing propeller speed (?) < 1 second]
11:26:26.8	RP	&	No, no.
11:26:27.6	??	&	Ooh
11:26:27.7			[Two tones at 0.3 seconds interval at the same pitch. The first lasting 0.1 seconds, the second 0.3. Stall warning]
11:26:28.4			[Brief clicking sound]
11:26:28.8	LP	&	Hell!
11:26:29.9			[Brief sound in channels 1, 2 and 4]
11:26:30.3			[Brief sound in channels 1, 2 and 4. end of propeller/engine sound in channel 3]

Figure B3. CVR printout

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APPENDIX 3

THE MECHANICAL CHARACTERISTICS OF METALS

General

Mechanical characteristics is an inclusive term for all the characteristics shown by a material when it is subjected to mechanical stress in the form of tension or deformation.

The most important mechanical characteristics can be described with the aid of the following terms:

- Tensile strength
- Fatigue resistance
- Creep resistance
- Hardness
- Toughness, impact strength, fracture toughness
- Stiffness

Only the first two characteristics are discussed below.

Tensile strength

The tensile strength of a material is determined by tensile testing, whereby a test piece is pulled at a constant strain rate until it fractures, while at the same time recording the material tension, σ (N/mm² =MPa) and elongation, ε (%), as shown in the figure below.

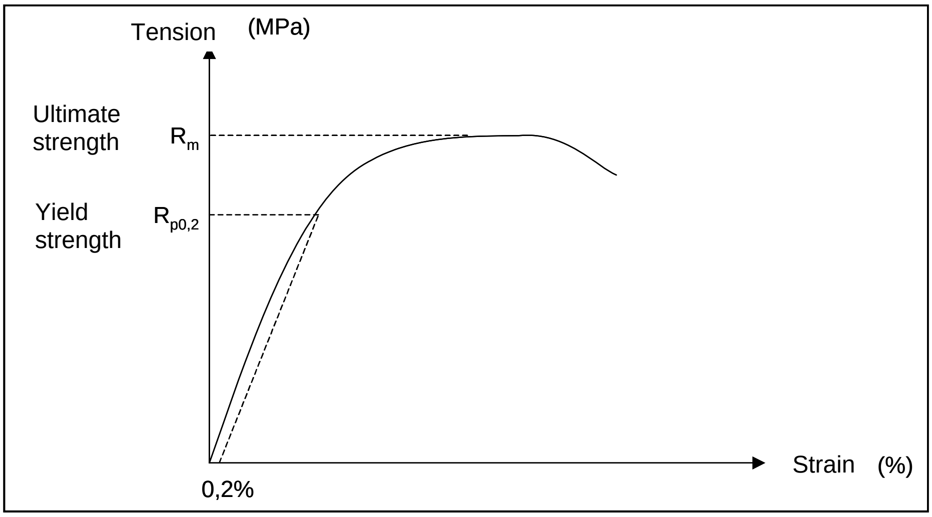

Figure B4. Tension and elongation diagram during tensile testing

As a measure of the tensile strength, characteristics of the material are defined:

- Yield strength (extension limit), $R_{P\ 0,2}$ (N/mm²) which is the tension at which the material begins plastic deformation.
- Ultimate strength, R_m (N/mm²), the maximum tension that is required to pull the material to fracture point.
- Elongation after rupture A (%), defines the percentage of elongation of the test piece at the point of rupture.

$$A = \frac{\text{Length after rupture} - \text{Original measured length}}{\text{Original measured length}} \times 100$$

Fatigue resistance

Fatigue in metals refers to the structural change that takes place as the effect of a pulsating load, and that gradually gives rise to a successively growing crack which finally leads to fracture. Fatigue fractures are without doubt the most common cause of accidents concerning metallic structures and have been estimated as accounting for 80-90 % of all accidents.

Characteristic of fatigue fractures are:

- A fracture can take place at a tension that is considerably less than the ultimate strength and even the yield strength of the material during tension testing.
- The fracture occurs without macroscopically detectable deformation.
- For a given tension amplitude the fracture takes place after a given number of load changes, however with a considerable spread.

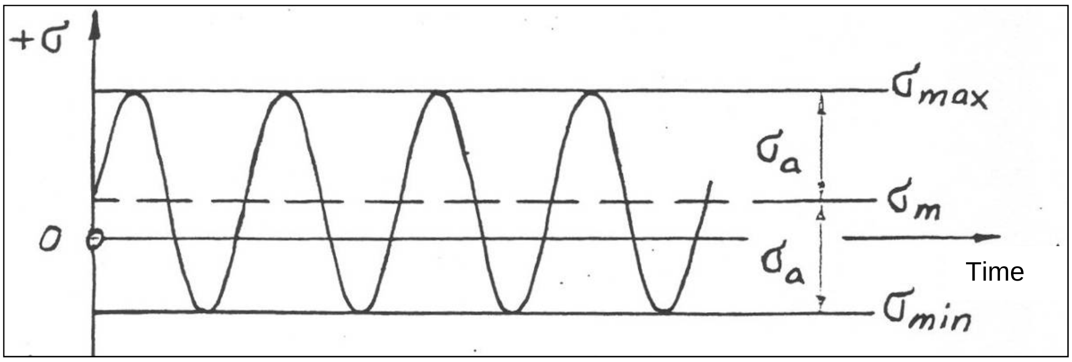

Figure B5. Oscillating tension

σ_m	= Average tension = ½ x (σ_{max} - σ_{min}) + σ_{min}
σ_a	= Tension amplitude = ½ x (σ_{max} - σ_{min})
σ_{max}	= Upper tension limit
σ_{min}	= Lower tension limit
$\Delta\sigma = 2\sigma_a$	= Tension range

Fatigue crack initiation and growth

Fatigue cracks can be initiated in many different ways. The most usual, however, is to be nucleated at the free surface. Irregularities in the surface act as notches and locally increase the tension amplitude at the bottom of the notch. In the case of rolling contact surfaces (e.g. train wheels on rails, or ball bearing balls on races), the greatest value of shear stress is below the surface. In this case phase boundary surfaces against hard slag inclusions often serve as the starting point for fatigue cracks.

The growth of fatigue cracks mainly takes place in two stages.

<u>Stage 1</u>
In stage 1 the crack grows along the failure plane with the greatest shear tension, i.e. generally a plane which is close to 45° from the greatest principal tension direction, and is governed mainly by the crystal structure of the material. The lower the amplitude of the tension, the longer the growth continues. Normally stage 1 ends when the crack meets the first grain boundary, and the crack growth then translates into stage 2.

<u>Stage 2</u>
The main direction of the crack in stage 2 is at right angles to the largest main tension direction, and is controlled by the applied tension. Characteristic for the crack growth is

the emergence of striations in the fracture surface. (Also see Appendix 7, Fracture surface analyses.) For each load cycle the crack grows a little and makes a new striation.

During stage 2 crack growth is much faster than in stage 1. The distance between two adjacent striations at a low tension amplitude is in the case of the order of size 0.1 µm ($0.1 \cdot 10^{-6}$ m). In the case of high tension amplitudes the distance between striations may be as large as 5 -10 µm, and thus the life will of course be much shorter.

Stage 2 ends when the fatigue crack has reached its critical size. In the case of brittle material the crack spreads at right angles to the direction of the greatest tension, i.e. “stage 2” – the lengthening of the crack. In the case of ductile material the final fracture takes place when the remaining cross-sectional area can no longer withstand the applied tension and then by shearing at an angle of 45° relative to the direction of the greatest tension. Since different criteria apply to fractures in ductile and brittle material respectively, the critical crack size in stage 2 is determined by the ductility of the material.

Regarding aluminium alloy AA 2024 T3

The sheet metal covering the aircraft wings consists of aluminium alloy AA 2024 T3, which is clad on both sides. It is well known that cladding (a layer of pure aluminium) provides less good fatigue characteristics than unclad sheet metal of the same alloy composition. The effects of cladding have been studied in several fields, where quantitative values of the fatigue characteristics have been shown, as has information concerning crack initiation and crack growth. Fatigue testing has been carried out at a constant amplitude with axial tension loads.

Some results:

A fatigue limit of 10 million cycles was found at a tension of 42 MN/M^2 for non-clad sheet metal. At this tension clad sheet metal lasted 300,000 cycles before fracture. The reason for this was stated as being that the cladding layer, consisting of 10% of the sheet thickness, became locally plastic and would not tolerate any further load, so that the entire tension had to be borne by the core material. The tension in the core material was thus 10% higher that for the cladding material. Other factors could also have played a part.

In unclad material inclusions form the starting points for fatigue cracks, and here there are almost no indications of multiple nucleation.

In clad sheet metal the crack initiation is localised in the pure aluminium layer, where multiple nucleation was seen. Here there are no cracks initiated by particles, but nucleation takes place at the surface.

Metallographic examinations of sections taken from the test pieces showed the presence of micro-cracks throughout the samples. These were multiple cracks with depths from a few µm up to 67 µm, i.e. almost the whole depth of the cladding. Some images of typical micro-cracks are shown below:

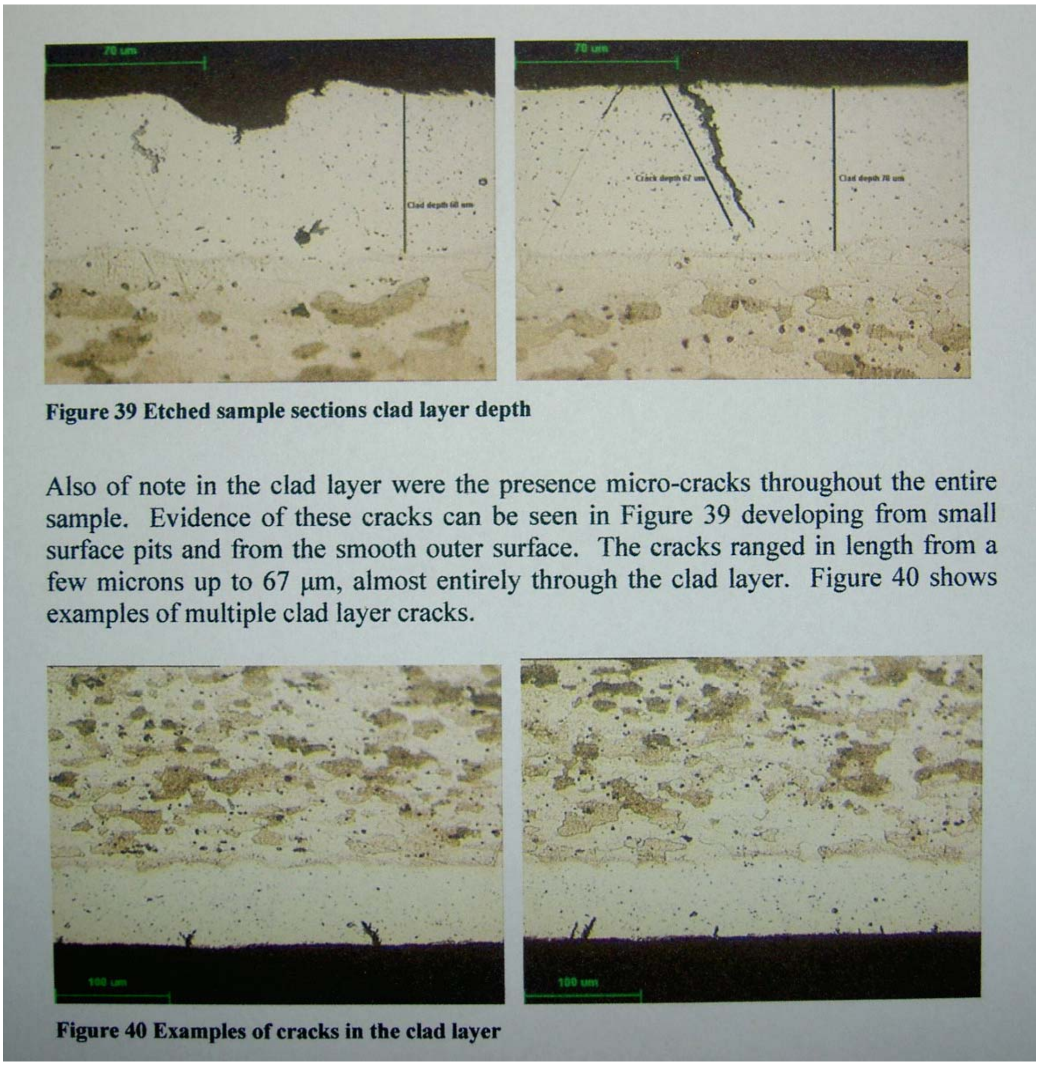

Figure 39 Etched sample sections clad layer depth

Also of note in the clad layer were the presence micro-cracks throughout the entire sample. Evidence of these cracks can be seen in Figure 39 developing from small surface pits and from the smooth outer surface. The cracks ranged in length from a few microns up to 67 μm, almost entirely through the clad layer. Figure 40 shows examples of multiple clad layer cracks.

Figure 40 Examples of cracks in the clad layer

Figure B6. Micro-cracks

To summarize, it can be said that clad sheet metal 2024 T3 has a much shorter fatigue life than unclad material. Multiple crack initiation in the cladding layer is commonly present, and the first cracks can arise as early as 1 % of the total life.

References:

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APPENDIX 4

NON-DESTRUCTIVE TESTING (NDT)

General

The purpose of NDT is in the first place to detect material failure of various kinds without destroying or damaging those parts that are to be examined. Material failure can arise during the manufacture or processing of material but also during operation due to fatigue. The five most common NDT methods are:

- Testing using penetrant (PT)
- Radiographic (X-ray) testing (RT)
- Ultrasonic testing (UT)
- Inductive (eddy current) testing (ET)
- Magnetic powder testing (MT)

Depending on the kind of defect that is being sought in the material, the most appropriate method is used. Often several methods are combined in order to achieve high detection confidence. Each method has a minimum limit for the size of material defect that it is practically possible to detect. ("It is not a matter of the smallest defect that can be found, but the largest defect that could be missed.")

All these methods require special test equipment that must be correctly calibrated, along with trained and qualified staff to perform the work, in order to obtain reliable results.

Testing using penetrant

The method of finding discontinuities that are open to the surface in non-porous material. This method can reveal faults such as cracks with gaps of as little as a few µm. The technology is based on how capillary action works. A liquid is drawn more deeply in, the smaller the gap.

The aim of this method is to allow a liquid with special penetrating characteristics, such as fluorescing or with a bright colour, to enter into discontinuities in the material. The liquid can then be made to force its way out to the surface and become visible ("developed").

X-rays

This method finds such discontinuities as cracks, inclusions, pores or holes and similar either on the surface or inside the material. This method can be used on most materials (even those that are biological). This method is also suitable for checking material thickness and the condition of riveted joints.

In the case of technical X-ray testing there is a requirement for special approval of staff and equipment, which in Sweden is administered by Statens Strålskyddsinstitut (SSI – the Swedish Radiation Protection Authority).

Ultrasonic testing

This method finds cracks, creases, pores, slag inclusions and similar either on the surface or inside the material. This method is also suitable for determining thickness, elasticity, assessment of structure, etc. Discontinuities with a length of a few hundredths of a millimetre and widths of several µm can be detected. This method is also used in, for example, medical contexts.

Inductive testing

This method finds cracks, creases, pores, inclusions and similar in electrically conductive material. Inductive testing is also suitable for the assessment or determination of dimensions (e.g. layer thickness), variations in structures, grain size, hardness, chemical composition, resistivity, etc. Discontinuities with a length of a few tenths of a millimetre and widths of several µm can be detected in normal conditions.

An eddy current is a circulating electrical current generated by a magnetic field that is alternating in an insulated conductor. A specially wound electrical coil is placed on the test object so that eddy currents are induced in the electrically conducting material. If a crack or an inclusion are present in the tested area the eddy current will be broken, and this registers on a measuring instrument connected to the coil.

Magnetic powder testing

This method can only be used for magnetic materials, which does not include aluminium alloys.

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APPENDIX 5

INTERNAL STRESS IN METAL ALLOYS

The resultant material stress in a defined direction is the algebraic sum of the applied and residual internal material stress.

$$\sigma_{resultant} = \sigma_{applied} + \sigma_{residual}$$

Stress may be tensile (positive) or compressive (negative). This means that the resultant stress may be 100 % applied, 100 % residual or something in between.

The residual internal and local stresses in a metal structure (with volume) are one of the least understood areas within metallurgy. This is because it is difficult to prove and to measure, also being complicated to calculate.

Damaging residual stress can result in spontaneous fractures or crack formation in metal parts, even without any external load at all. Some common types of cracks caused by residual stress are heat cracks, hardening cracks, grinding cracks, welding cracks and thermal fatigue. Also distortion from welding, heat treatment and machining can be caused by residual stress.

Favourable residual stress can lengthen the life of fracture-prone components. This is utilised in many industrial processes for a large number of parts, for example case hardening, surface hardening, shot peening, pressure rolling and similar processes.

A large number of stressed parts, especially those exposed to fatigue fractures and stress corrosion, are routinely treated with such processes in order to create favourable residual stress in such parts.

The above describes how applied tension results in residual compression stress, when the load is removed. The opposite, with negative effects, can arise if temporarily applied compression stress results in damaging residual tensile stress.

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APPENDIX 6

RIVETED LAP JOINTS AND MULTIPLE SITE DAMAGE

Introduction

A search on the Internet for “Riveted lap joints” and “Multiple Site Damage (MSD)” resulted in more than 20 papers with over 200 references. These papers cover:

- FEM[1] modelling
- Prediction of fatigue crack growth
- Fretting fatigue
- Multiple site damage
- Effects of manufacturing process parameters
- Fractographic investigations
- Characterisation of defects and damages in rivet holes
- Simulation of multiple site damage growth
- Repair

Over 70 fatigue test panels have been fabricated and subjected to uniaxial or biaxial cyclic testing and examination of crack patterns.

Fractographic investigations of panels removed from retired aircraft have been carried out on Boeing 707, 727, 737 and 747 and Fokker F28 and F100, and BAC 1-11. In all these cases the cracks were located in longitudinal rivet rows in pressure cabin skins.

Link-up of Multiple Site Damage cracks at the outer skin was the cause of failure for the 1988 Aloha 737 accident.

One accident in June 2002 with a wing fatigue failure in the centre wing on a Hercules C-130 is reported. (7). As a consequence an accident with C-130 N135FF in 1994 was re-investigated and a similar cause was found.

The present paper will review only results with an estimated interest for the CASA C-212 accident in Sweden.

Content

- Introduction
- Content
- Summary
- Brief descriptions of actual damage types
  - Multiple Site Damage
  - Fretting
  - Fretting corrosion
- Abbreviations
- Load transfer through rivet joints
- Fractographical examination of panel from fatigue tested fuselage
- Examination of skin panels from in-service aircrafts
- Effect of rivet squeeze force
- Multiple Site Damage formation and growth
- References

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[1] FEM – Finite Element Method

Summary

The phenomenon of fatigue cracking in riveted lap joints in 2024 clad material is obviously a common problem in transport aircraft. It is a well investigated area with research work on laboratory test panels as well as examination of panels from in–service aircraft. Most reports are related to narrow body aircraft with pressure cabins.

Multiple Site Damage is the simultaneous development of fatigue cracks at an array of similar structural details, which considerably reduces fatigue life.

The initiation, growth, and interaction of MSD in lap joint fuselage panels was investigated by constant amplitude fatigue loading to 157,458 cycles (5). Cracks developed in the outer skin layer along the upper critical rivet row.

Sub-surface crack indications along the rivet row were recorded by eddy current after 12,600 cycles. The first visual damage occurred after 51,500 cycles.
The life from first linkup to failure was less than 5 % of the total fatigue life.

A comprehensive study by Delta Air Lines reports: “There was significant variability among similar components, but there was little variability among airplanes as to when repair was necessary. Once MSD was detected in the first aircraft, MSD was found during inspection of most aircraft of the same cycle age”.

The effect of rivet squeeze force and effects of defects have been studied with varying results.

Brief descriptions of actual damage types

Multiple Site Damage

MSD: Multiple Site Damage is the simultaneous development of fatigue cracks at an array of similar structural details.

MSD fatigue cracks tend to initiate at several sites near or at rivet hole corners and grow in directions varying from transverse, (through thickness) to longitudinal. (2).

Previous studies conducted by the FAA on stiffened fuselage panels with lead cracks showed that Multiple Site Damage resulted in 37 % reduction of fatigue life:

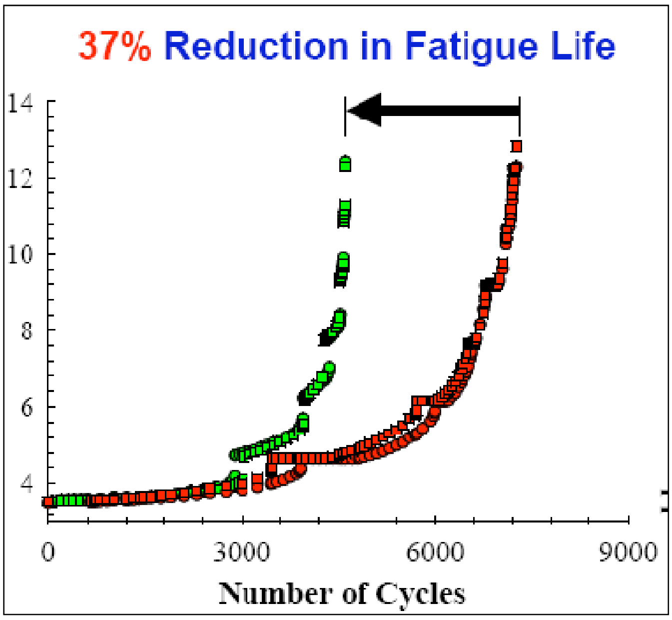


Figure B7. Fatigue life

Fretting

The American Society for Testing and Materials (ASTM): “a wear phenomenon occurring between two surfaces having oscillatory relative motion of small amplitude”. (9).

“When at least one of the fretted components also experiences fatigue loading, the process is called fretting fatigue. The effects are synergistic, with the component life possibly being reduced by an order of magnitude or more as a result of fretting fatigue when compared to fatigue without fretting.” (9).

Fretting corrosion

ASTM: “A form of fretting wear in which corrosion plays a significant role”.

Load transfer through rivet joints

The actual load transfer in the riveted joint is a very complex, nonlinear analysis problem. The stress analysis behaviour includes the interaction between the rivet bearing contact, clamp- up and friction effects, interference fit stresses, bending effects, and crack growth. (6).

Fractographical examination of panel from fatigue tested fuselage

This NASA study forms the basis for the analytical methodology to predict the onset of widespread fatigue damage. (6).

Fatigue cracks were present at virtually every rivet hole in the top row of rivets, from 50 μm to several centimetres. Crack initiation mechanisms included high local stresses, fretting along mating surfaces and manufacturing defects formed during the riveting process. (6).

The lengths of all the fatigue cracks at link-up were approximately the same, which suggests that the long crack behaviour is somewhat independent of the initiating mechanism. Data strongly suggest that the fatigue behaviour of the long cracks is deterministic and predictable. (6).

Examination of skin panels from in-service aircraft

Ramakrishnan, Delta Air Lines, examined lap joints from skin panels of the fuselage on an A/C near its DSG (Design Service Goal). NDI (Non-Destructive Inspection) revealed more than 150 rejectable findings along one fastener row on one side of the A/C. (3).

The crack findings were characterized regarding density, length and location of the cracks at each fastener hole.

Rivet fit condition was recorded by measuring maximum tail height and minimum tail diameter. The measured dimensions were used to classify the fit as:

- Significantly under driven
- Marginally under driven
- Within specification - lower limit
- Within specification
- Within specification - upper limit

A large majority (90 %) of the cracked holes had rivets which were under driven, or on the under driven side of the specification.

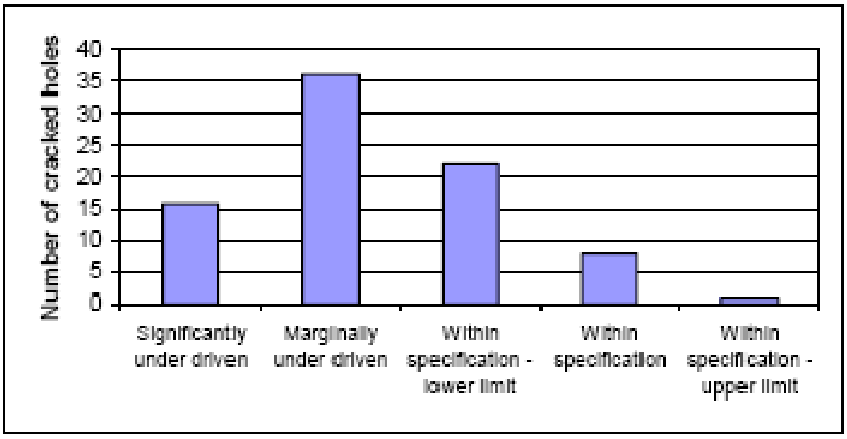


Figure B8. Number of cracked holes by rivet fit condition

After removal of the rivets the condition of the holes was characterized.

Types of distress:

- Fretting/galling
- Faying surface defects, scratches and gouges
- Hole edge deformation
- Circumferential gouge in hole

In order to get a single parameter, each defect was assigned a numeric value which increased with increasing severity.

Table 2. Assigned values for qualitative characterization.

Fretting/Galling

No appreciable	1
Mild galling	2
Heavy galling	3
Mild fretting, with or without galling	4
Heavy fretting	5

Edge Deformation

Clean, no deformed edge	1
Edge deformation like a volcano, no overflow	2
Edge deformation with little metal overflow	3
Edge deformation with significant overflow	4

Faying Surface Defects

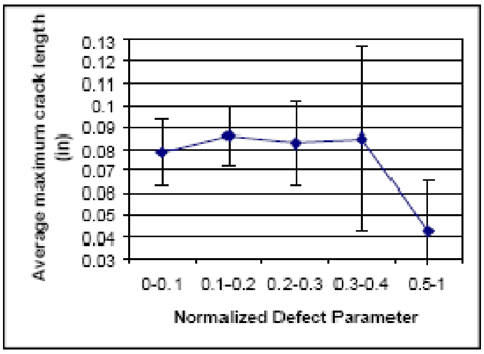
Clean	1
Light scratches	2
Heavy scratches	3
Light gouges	4
Heavy gouges	5

Hole Quality

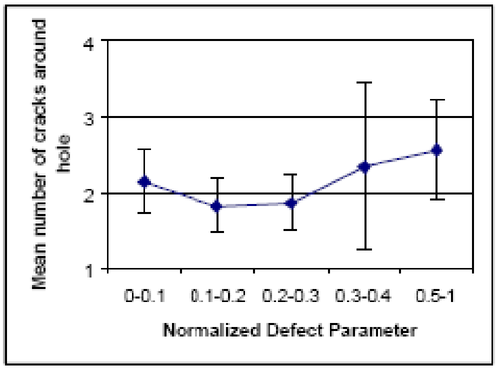
Clean	1
Circumfe rential gouge	2

Figure B9. Qualitative characterization

The extent of cracking, (crack length and density) appeared to be independent of the severity of defects.



Mean maximum crack length vs. normalized defect parameter. Error bars are 90% confidence limit on the mean.



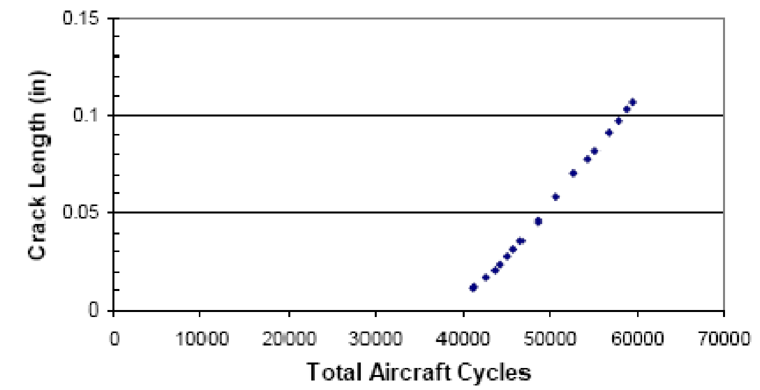
. Mean crack density vs. normalized defect parameter. Error bars are 90% confidence limit on the mean.

Figure B10. Crack length and density

Striations on one crack were measured and related to distance from origin, crack length and number of fatigue cycles.

Based on striation spacing, measurements and the integration of crack length versus striation spacing, a plot was obtained. The crack growth history in terms of aircraft flight cycles was obtained by taking the last reading and combining it with A/C cycles at the time it was retired (59,497 flight cycles).

Some of the results are shown below:



Example of backtracked crack length as a function of total aircraft cycles for the crack

Figure B11. Crack Length

Another study by Delta Air Lines on fleet aircraft focused on MSD progression. (2). A striation count was performed to determine crack growth rate at several locations along the fracture surface. Calculations based on these data gave following crack sequence as a percentage of the design service goal:

22 %	First crack initiation at one hole
27 %	Crack initiation at adjacent hole
83 %	Outward MSD crack initiations at two holes
93 %	Crack discovered; 500mm long with all holes cracked

Some conclusions:

- The first crack initiated at a hole in the high stress area at the bay centre. Each subsequent crack initiated adjacent to the previous.

- All holes were cracked before the lead crack linked through them, many from both sides of the hole. The MSD cracks continually returned the lead crack to the longitudinal direction, counteracting the tendency to “flap” safely.
- The outer skin restrained the inner skin after link-up. The crack growth arrested temporarily when the crack tips reached a frame fastener.
- MSD was found on in-service aircraft prior to being identified by test or analysis.

Most important:

“There was significant variability among similar components, but there was little variability among airplanes as to when repair was necessary. Once MSD was detected in the first aircraft, MSD was found during inspection of most aircraft of the same cycle age”.

“Fleet inspection programs may be required as early as 50 % DSG”.

Effect of squeeze force

A large squeeze force, resulting in a large head diameter, might cause a large clamping force in the two parts. This would decrease load transfer through the rivet and increase load transfer by friction. In that case, crack initiation on the faying surface is more likely. (4).

Small squeeze forces increase load transfer through the rivet and crack initiation in the hole is more likely.

It appears difficult and possibly impossible to relate fatigue crack initiation location directly to riveting squeeze force indicated by rivet head diameter.

Another study, (10), shows that fatigue life increased with increasing rivet interference. No significant difference in fatigue life was noticed at medium to high rivet interference. Based on hole quality under-driven rivets show maximum difference in life.

The study by Ramakrishnan, (5), indicates a strong dependence on rivet fit condition.

Multiple Site Damage formation and growth

The initiation, growth, and interaction of MSD in lap joint fuselage panels was investigated by constant amplitude fatigue loading to 157,458 cycles (5). Cracks developed in the outer skin layer along the upper critical rivet row.

Subsurface crack indications along the rivet row were recorded by eddy current after 12,600 cycles. The first visual damage occurred after 51,500 cycles.

The first MSD link-up occurred after 106,217 cycles, forming a lead crack. Subsequently the lead crack grew very rapidly, along the outer rivet row, eventually forming a 400mm long crack after 107,458 cycles.

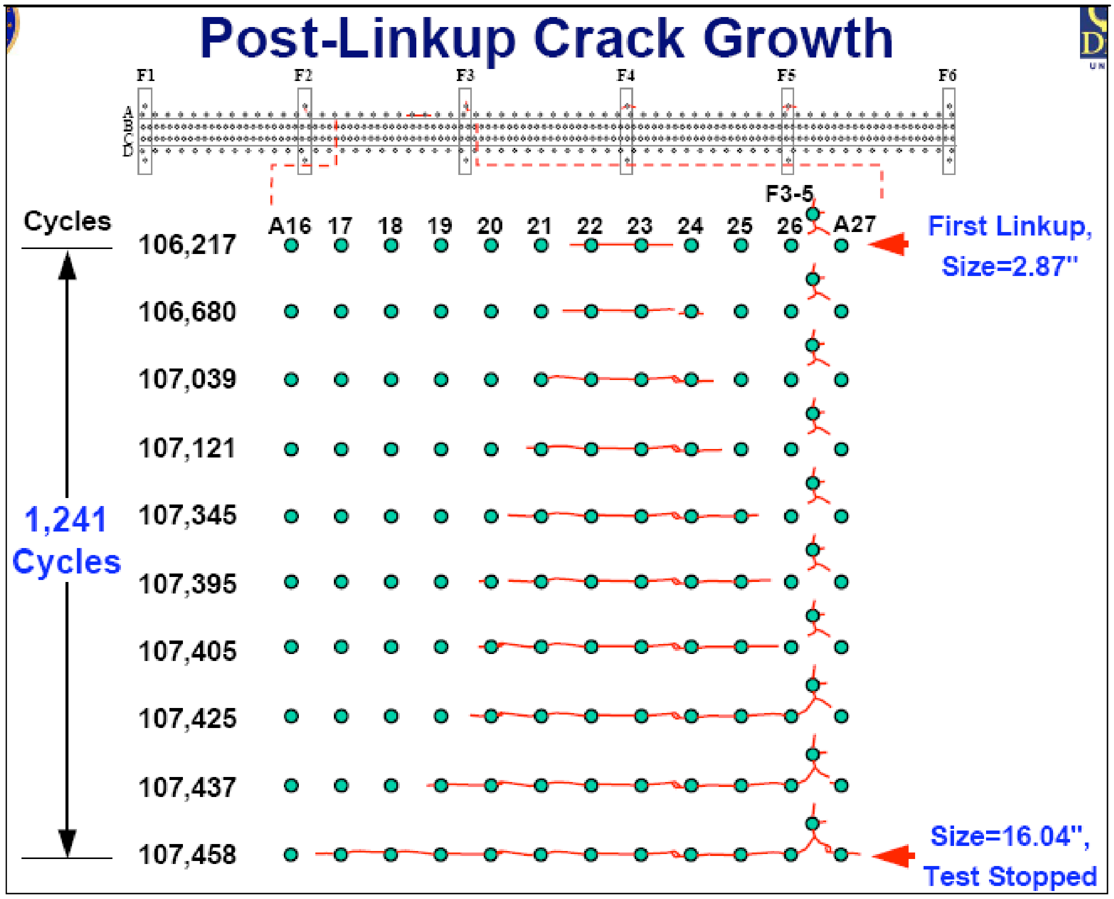


Figure B12. Crack grouth

Fractographical examinations revealed damage along the faying surface of the outer skin. As a result, subsurface cracks initiated at multiple origins and grew mainly along the faying surface before becoming through-the-thickness cracks.

The life from first linkup to failure is less than 5 % of total fatigue life.

Linköping 2007-02-19

KMT Sven-Åke Karlsson

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The George W Woodruff School of Mechanical engineering

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APPENDIX 7

FRACTURE SURFACE ANALYSES

Fracture characteristics – general

Fatigue cracks can form in a structural element that is subjected to changing mechanical loads which are usually below the material yield strength. Fatigue cracks are characterised by lacking signs of plastic deformation, unlike instantaneous overload fractures, which have a ductile character.

The striation patterns on fracture and crack surfaces can provide information about the type and direction of the forces that have been applied to the part along with the size and variation of those forces, and thereby contribute to an understanding of the causes of a fatigue failure. This pattern can also provide general information about the time period from the initiation of a crack to the final fracture.

On the surface of fatigue cracks there are often macroscopically visible striation patterns of beach lines in many metal alloys, including those based on aluminium. These beach lines are formed when large changes in the load spectrum occur, such as when machinery starts or stops.

Between the beach lines there are, e.g. in aluminium alloys, striations, which are built up due to load changes during the growth of a fatigue crack. This applies when the load changes (variations in the size of loads) are high enough to contribute to crack growth. The striations build up a thinner concentric beach line pattern with their centres at the start point of the crack. The pattern is so dense that an electron microscope must be used to be able to study it.

Each striation thus represents one load cycle that is sufficiently great as to result in a microscopic amount of crack growth. The total number of cycles in a fatigue sequence is usually much greater than the number of visible striations. By determining the number of striations and the distance between them, it is possible to gain information about the crack sequence in respect of spread speed at different crack depths.

Fracture characteristics – the accident aircraft

On the accident aircraft two types of striation could be seen in the wing fatigue crack surfaces:

A. With a small crack depth, less than half the skin sheet thickness, there is a very regular striation pattern within the same visible field, with an internal distance of between 0.04-0.09 µm.

B. With a large crack depth, > 0.5 mm, the surface has a different appearance, more irregular and with a large striation distance, with secondary cracks in a plane at right angles to the direction of the main cracks.

Examples of both types are shown below:

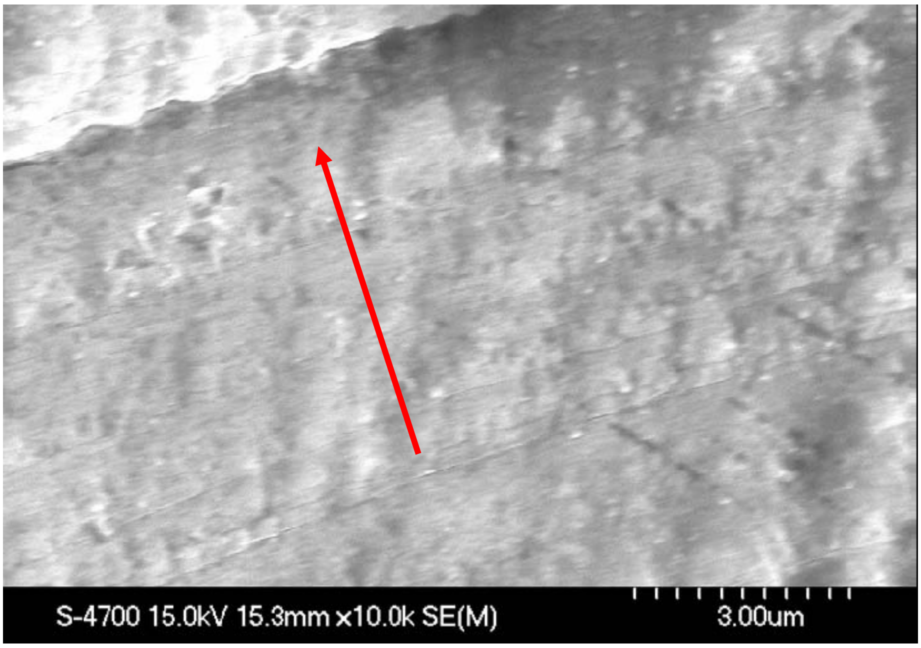

Figure B13. Sweep electron microscope image of the type A crack surface

The image shows the type A crack surface; the striation separation distance is short, about 0.05 µm, which is representative of the initial stage of crack development, i.e. a crack depth of less than half the thickness of the wing skin. The arrow shows the direction of growth.

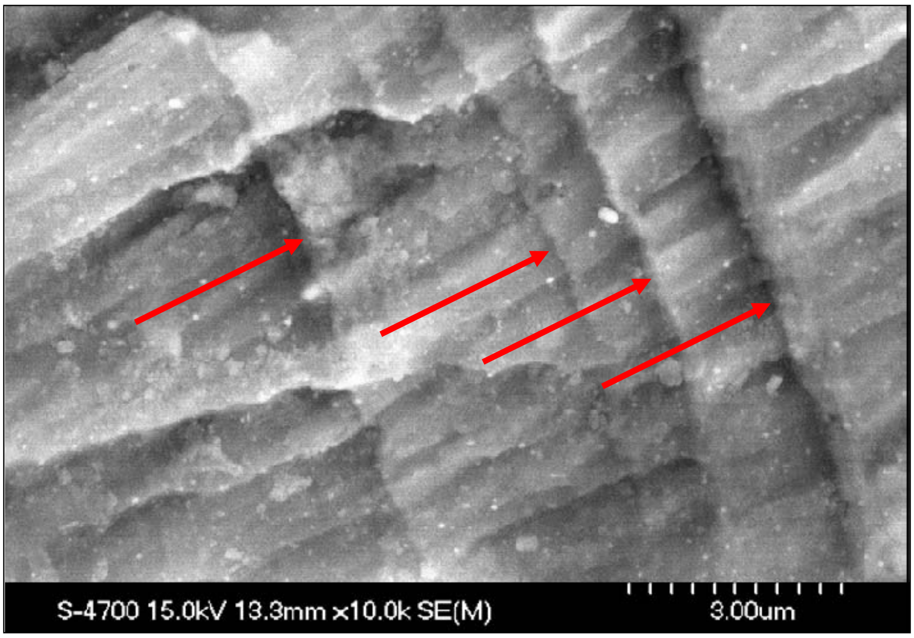

Figure B14. Sweep electron microscope image of the type B crack surface

The image shows the type B crack surface; the striation separation distance is large and varies between 1 and 5 µm. The arrows mark the secondary cracks, at right angles to the direction of spread. This type of coarse striations is found at the deepest crack depth and the spread has taken place in jumps due to high loads.

Quantitative measurements of the inter-striation distances at known crack depths permits the calculation of stress levels during the fatigue sequence.

Stress level calculations

Comprehensive examinations of the fracture and crack surfaces in the left and right wings on the accident aircraft have been carried out by Bodycote Materials Testing (BMT) and by the manufacturer CASA's materials laboratory. The quantitative results of the measurements of the inter-striation distances at different crack depths are reported in the AIRBUS/CASA technical report NT-2-ID-06015. The value pairs were used to calculate the stress levels at different stages of the fatigue sequence with the aid of linear fracture mechanics.

The inter-striation distance at small crack depths is very small, 0.04 – 0.4 µm. This means for example that a 1 mm deep crack requires 1000/0.04 = 25,000 cycles from the start of the crack until it becomes 1 mm deep. This calculation is based on the fact that the inter-striation distance is constant over the whole of this crack depth.

In the case of fatigue cracks the initiation phase to a crack starting is 75-80 % of the fatigue sequence, so that the creation of a 1 mm deep crack probably requires more than 100,000 cycles. The longest individual cracks in the crack system are of 10-15 mm. Not all the cracks had been started and grown at the same time, which means that there were a very large number of cycles before the wing fracture occurred.

Fracture toughness is a material parameter within linear fracture mechanics and expresses the ability of the material to resist initiation of crack growth.

The basis for the definition of the fracture toughness of a material is the stress intensity factor K, to which a defect (such as a crack) gives rise.

K is defined as:

$$K = \sigma\sqrt{\alpha \ \pi \ C}$$

Where σ = the nominal stress, i.e. the applied stress
α = a constant, depending on the sample's and crack's geometry
C = distance to initiation point

K is related to the striation growth per cycle. As can be seen by the formula, K depends on both σ and α, and that a change in σ has a greater effect than a change in crack length (beneath the square root sign).

Fracture mechanics is used to calculate the stable growth of a crack during cyclic loading, and the initiation of unstable growth. Fracture mechanics is thus a tool for determining to some extent the damage resistance characteristics of a structure.

If one knows the striation distance at a certain crack depth it is possible to calculate backwards to find the size of the stress that caused the crack to grow to that depth.

In such a calculation the term fracture toughness is used, K_{Ic} , which is characteristic of the material, determined by some kind of strength test. When the value of the stress intensity factor $K = K_{Ic}$ a fracture occurs.

In the fracture mechanics calculations presented in the Bodycote Technical report TEK07-0059, measurement results from the AIRBUS/CASA report were used, along with material data and form factors from established manuals.

The results show that a stress of 115 MN/m^2 at 1 mm crack length is equivalent to about 1/3 of the yield strength of the material, which indicates that the stress in the wing skin was not initially extremely high.

With an inter-striation distance of 5.0 µm the alloy fracture toughness was exceeded, which meant there was a momentary break in the material. This corresponds with the crack surface appearance at a large crack depth, in accordance with type B striations as described above.

CASA has performed similar fracture mechanics calculations, based on the measurement results from AIRBUS/CASA's report. The calculations are presented in CASA MEMO MM-2 ADF-07002 A.

CASA used somewhat different values than BMT in terms of material characteristics, etc., but the results are almost the same.

Types of crack

There are in principle two types of fatigue crack in the wings of the CASA C-212 aircraft S/N 346.

- Cracks that follow rivet row #1 on both the left and right sides.
- Cracks at the bottom of grinding scratches.

The latter type of cracks are located outside rivet row #1 and are in the approximately 50 µm thick sheet metal layer of pure aluminium, which has lower fatigue strength than the "core material" of alloy AA 2024 T3.

All these cracks are related to bending forces on the underside of the skin sheet. In the case of bending forces the stress level is greatest at the surface layer and reduces at increasing depths below the surface.

With the mild notching that the grinding scratches caused, the stress levels have nevertheless been sufficient to initiate cracks in the soft skin sheet surface, but in most cases the crack generation was not propagated due to the reduced stress level and higher fatigue strength of the alloy.

The stress level in the riveted joint itself was clearly higher, as the rivet holes formed a strong notch, further reinforced by processing scratches, sharp corners and fretting.

The cracks that run along rivet row #1 often started at the hole edges, or near to the holes themselves (≤ 1 mm), or from fretting between the holes. As a result of the high static and dynamic stress levels, there has been enough impetus for multiple crack initiation and crack propagation to the final fracture.

Interpretation of the character of the fracture surface is summarised as follows:

- The number of partial cracks in the wing fracture is very large, in the order of hundreds. Not all these cracks were initiated at the same time, since oxidation and fretting show internal age differences. Some cracks could possibly have started as late as during the accident flight.
- A large number of small cracks have grown together and formed cracks of great combined length along a row of rivets.
- During growth, cracks have "jumped" from one fatigue crack to another.

- The characteristics of the fatigue cracks in the left and right wings are similar.
- In all there are a very large number of striations, indicating in the order of millions of load changes for the entire crack sequence.
- In an initial stage of the fatigue sequence, i.e. with little crack depth, the stress level in the load spectrum was low and with similar internal size. This seems to indicate an oscillatory phenomenon rather than random flexure, attributable to turbulence or manoeuvring loads. These have however contributed to continued crack spreading.
- At deeper crack depths, in a developed stage of the fatigue sequence, the load spectrum is different, with high peaks, often with varying amplitudes. Here the crack propagation has often taken place in jumps and partial cracks have successively linked up to become a connected main crack that grew to the final fracture.
- There are four types of notch that have contributed to localisation of the starting points of cracks:
  - The corner between a rivet hole and the underside of the wing skin.
  - Fretting between the skin and doubler.
  - Mechanical damage in rivet holes.
  - Scratches in the skin cladding, arising during manufacture when surface finishing with a rotating tool.
- None of these notches were assessed as being so great as to be considered as the only reasons for fatigue crack generation, but they have contributed to localised crack start points.
- The notches were assessed as being common in aircraft from that time.
- The fatigue cracking status of the accident aircraft shows very strong similarities to a commonly occurring fatigue phenomenon in older aircraft; Multiple Site Damage, MSD.

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APPENDIX 8

SUMMARY OF CASA REPORT NT-2-ADF-08002

Note: This summary, including the results and conclusions, is based entirely on CASA report NT-2-ADF-08002 and is without any factual evaluation from the SHK expert group.

The manufacturer's purpose of the tests that have been carried out was to examine whether the crack formation along rivet row # 1 in the accident aircraft could have been caused by:

- a possible overload,
- abnormal vibration for a certain time, and

to investigate the stress conditions including local bending in the wing lower skin in the area along rivet row # 1.

The examination took place in three parts.

A Fatigue testing of samples
B Fatigue testing of segments of the wing lower skin
C Flight testing

Summary of the implementation and conclusions

A. Fatigue testing of samples

The purpose of the test was:

- to gain increased knowledge of the fatigue tolerance along rivet row #1,
- to evaluate how the use of sealing compound affects the fatigue tolerance in riveted joints, and
- to estimate the fatigue tolerance of 3.2 mm and 4.0 mm diameter rivets.

Implementation
Almost 100 tests were carried out on samples in accordance with the accepted methods for fatigue testing. Such tests involve securing the test sample in a special fixture and applying various types of static and oscillating loads. These apply stress to the material that is normally much lower that the yield strength of the material, but remains for a long time. The test usually continues until a fatigue crack appears, and that successively leads to a fracture. In this way the individual structural part's K_t-value[2] and fatigue life can be calculated and verified.

[2] K_t-value – A measure of the fatigue tolerance in a structural element. *Actually the notch factor: e.g. how a hole of a certain diameter affects the fatigue strength. An open hole normally gives K_t = 3.*

Figure B15. Fatigue test in one load direction

Figure B16. Test with added side load

Conclusions

- In order for a fatigue fracture in a 3.2 mm rivet to occur after about 8,000 cycles a fatigue load of 1000 N[3] (approx. 100 kPa) is required.
- Irregularities on the sheet surface, equivalent to the actual finishing marks, have no decisive effect on the fatigue life of the joint.
- The use of sealing compound in the joint has a favourable effect on the fatigue life.
- The fatigue life for test samples that are subjected to compression loads can in some cases be reduced by 20 %. There are large variations in the measured results.
- The test results have shown that the actual Kt value is lower than that which was used during the original fatigue analyses.

B. Fatigue testing of segments of the wing lower skin

The purpose of the test was:

- to gain increased knowledge of the fatigue tolerance in the wing lower skin along rivet row #1, and
- to gain increased knowledge of the fatigue mechanism, morphology and crack growth in respect of fatigue loads that can arise in connection with coastguard flight operations.

Implementation and conclusions

The tests have not been completed and there are as yet no conclusions.

C. Flight tests

The purpose of the flight tests was:

- To compare the actual material stresses in the wing lower skin with the theoretical calculations.
- To verify how certain parts of the vertical loads are taken up by the fairings.

[3] N (Newton) – Measuring unit of force: 1.0 N = 0.10 kp

- To collect information concerning the presence of high local material stresses in the critical area of the wing lower skin.
- To examine the influence of propeller imbalance on the wing.

Implementation
An aircraft was prepared with special measuring equipment to measure the local material tensile stress in the wing structure during flight. With knowledge of the tensile stress the local material stress could be calculated.

In all there were 15 strain gauges attached to the inside of the wing lower skin in the area around the critical row of rivets and on the outside of the skin.

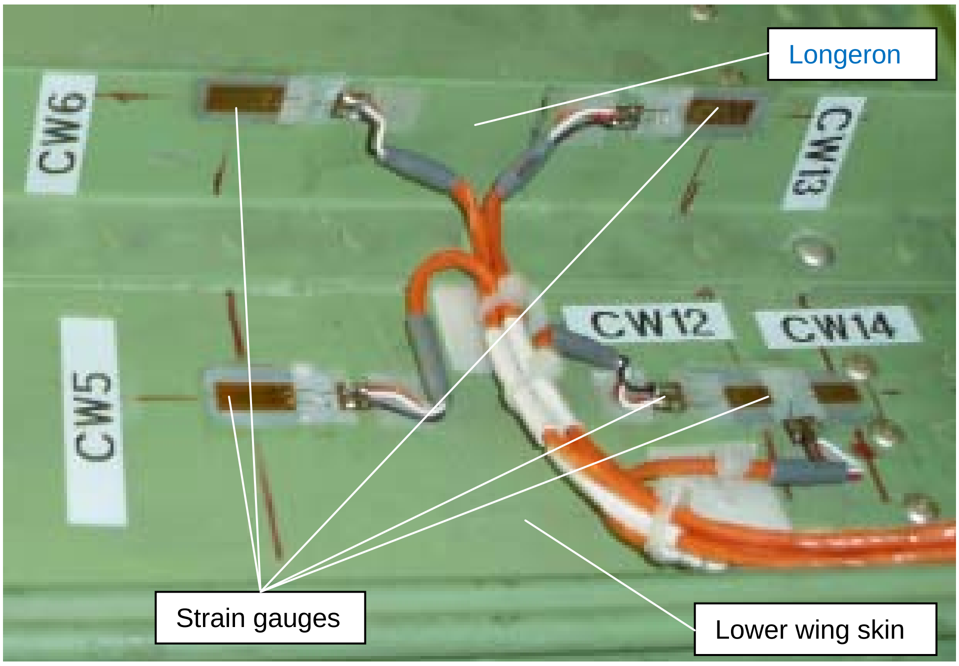

Figure B17. Strain gauges inside the wing

The flight tests were carried out during normal flying in a straight line and in turns during which the G-loads varied from -0.50 G till +2.17 G. During the flights the aircraft was loaded to 90 % of the maximum permitted take off/landing mass. Several landings were performed during the flights.

The following diagram shows the stress in the wing skin at one of the measuring points during different phases of the flight, and covers the whole flight from taxiing before take off to the final landing.

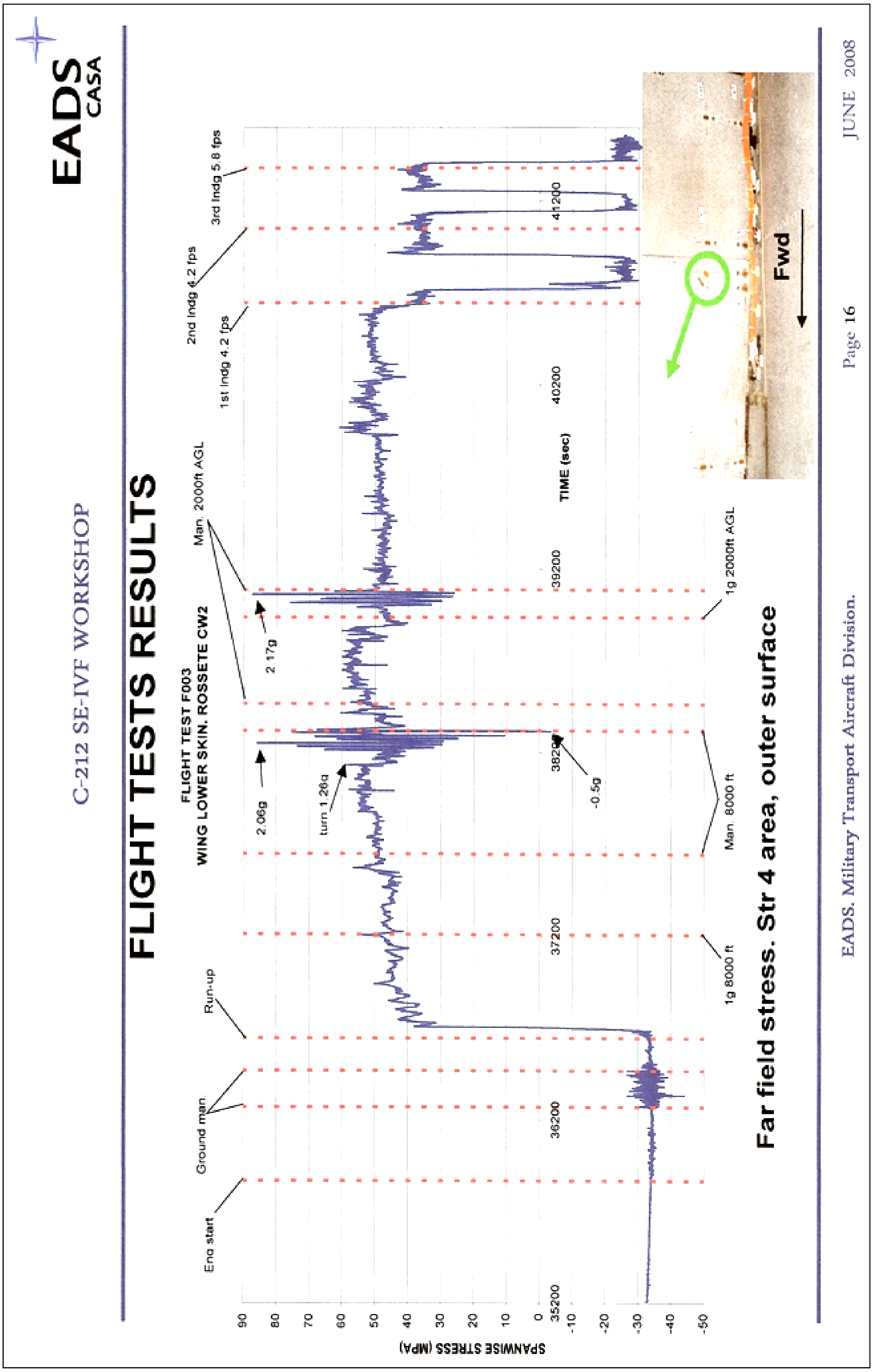

Figure B18. Material stress during one flight

From the diagram it can, among other things, be seen that the material stress during this flight peaked at about 88 MPa, which is about 33 % of the material yield strength. (It can be worth noting that the stress level at an early stage of the crack sequence was calculated by BMT by means of fracture mechanics to be about 1/3 of the yield strength.)

The following diagram shows the material tensile stress at various measuring points, at the wing lower skin, along the span of the wing and in the area close to the critical row of rivets. On the measuring occasion the vertical load was +2.06 G.

From the diagram it can be seen, among other things, that the measured tensile stress is at a maximum just outside the critical row of rivets and that the tensile stress does not exceed that which was theoretically calculated.

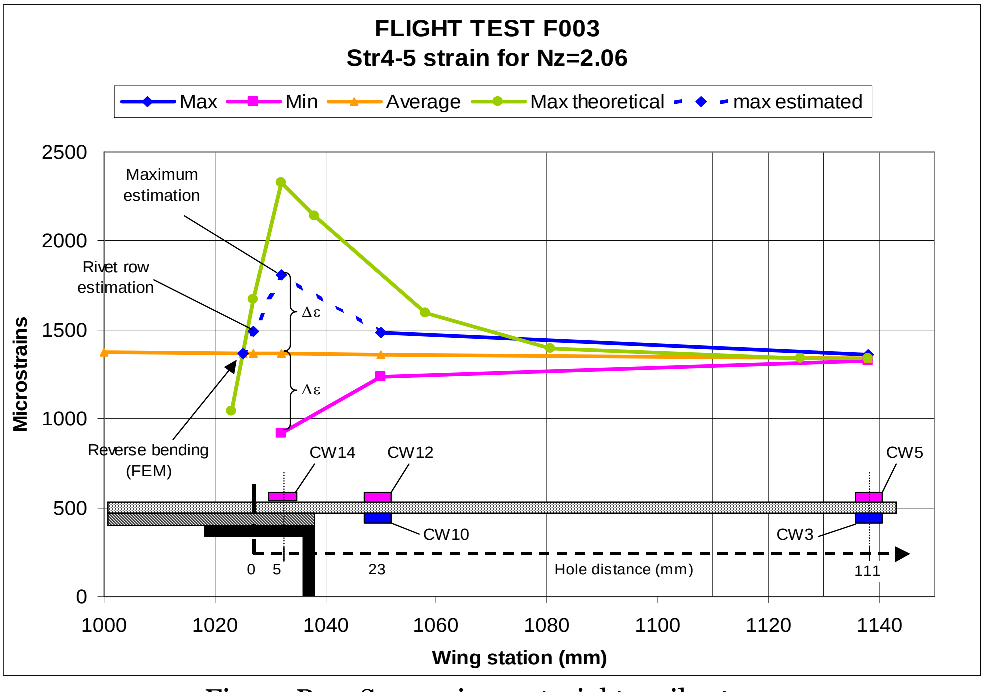

Figure B19. Span-wise material tensile stress

Equivalent measurements were also taken with induced vibration loads from the engines in the form of propeller imbalance at various frequencies and amplitudes.

Conclusions

Load levels:

- There was good correlation between the actual and calculated stress levels. The calculated predictions were conservative ("on the safe side").
- The tests showed that the fairings do take up a certain amount of the vertical loads. Local increases of material stress also take place as a result of secondary bending. The secondary bending is caused by stress concentration ("the hard point effect") that arises at the fairing attachment to the wing doubler.
- Analysis of the test results shows that the material stress along rivet row # 1 is up to 12 % higher, and just outside the rivet row 35 % higher, than in other areas of the wing lower skin.
- During ground testing (taxiing with full wing tanks) the material stress just outside rivet row #1 is up to 56 % higher than in other areas of the wing lower skin. After removal of the fairings this value reduced to 42 %. The fairings were therefore assessed as increasing the material stress in the critical area by about 10%.

Fatigue analysis:

- The calculated fatigue life of rivet row #1, calculated as being 23,000 flights, is conservative. Based on the test results the fatigue life can be calculated as 42,000 flights.

- In order to explain a fatigue life of 3,500 flights, it is necessary for Kt = 4.78. The Kt value for the actual structure does not exceed 2.0.
- The area with grinding scratches has a higher fatigue tolerance than the area outside rivet row # 1.
- The calculated stress level of the affected rivets is so low that fatigue fractures cannot be expected.
- Statistical analysis of the measured values shows that the risk that fatigue cracks will be initiated after 3,500 flights is 1 in 1.0E+8 (one in a hundred million).

Imbalance:

- The first order propeller frequency is about 26.5 Hz.
- Vibration peaks arise at frequencies of 9.4 and 26.5 Hz. The amplitudes at 26.5 Hz are not significant.
- A propeller imbalance of 0.3 IPS can reduce the fatigue life by 10 %. (The maximum permitted imbalance is 0.2 IPS.)
- Propeller imbalance up to 1.01 IPS had no significant effect on the measured results in relation to normal imbalance.

Summarised conclusions of Report NT-2-ADF-08002

The performed tests and analyses of the test results have not on their own been able to explain the early initiation of fatigue cracks in the accident aircraft, which is assessed to have taken place after about 3,500 flights. Taking into account the loads applied, the use of the aircraft, its design and production standards, etc. it is considered that the calculated fatigue life of the wing had been adequate.

Some further factor must have been applied to explain the early crack initiation. A possible theory is therefore that the wing, at some time long ago, could have been subjected to a very high compression load which caused plastic deformation in the wing lower skin (along rivet row #1), resulting in a residual local internal stress. This would also explain the presence of micro-cracks along the rivet row which caused the start of crack formation that resulted in the wing fracture.

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