



Australian Government
Australian Transport Safety Bureau

In-flight break-up involving modified PZL Mielec M18A Dromader, VH-TZJ

37 km west of Ulladulla, New South Wales | 24 October 2013



Investigation

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Addendum

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Safety summary

What happened

On 24 October 2013, the pilot of a modified PZL Mielec M18A Dromader, registered VH-TZJ, was conducting a firebombing mission about 37 km west of Ulladulla, New South Wales. On approach to the target point, the left wing separated. The aircraft immediately rolled left and descended, impacting terrain. The aircraft was destroyed and the pilot was fatally injured.

VH-TZJ on 22 October 2013



Source: Witness

What the ATSB found

The ATSB found that the left wing separated because it had been weakened by a fatigue crack in the left wing lower attachment fitting. The fatigue crack originated at small corrosion pits in the attachment fitting. These pits formed stress concentrations that accelerated the initiation of fatigue cracks.

The ATSB also found that, although required to be removed by the aircraft manufacturer's instructions, the corrosion pits were not completely removed during previous maintenance. During that maintenance, the wing fittings were inspected using an eddy current inspection method. This inspection method was not approved for that particular inspection and may not have been effective at detecting the crack.

Data from a series of previous flights indicated that the manner in which the aircraft was flown during its life probably accelerated the initiation and growth of the fatigue crack.

Finally, the ATSB also found a number of other factors which, although they did not contribute to the accident, had potential to reduce the safety of operation of PZL M18 and other aircraft. These included the incorrect calculation of the flight time of M18 aircraft and a lack of robust procedures for the approval of non-destructive inspection procedures.

What's been done as a result

The Civil Aviation Safety Authority (CASA) revised the airworthiness directive for inspection of the wing attachment fittings to ensure that they were inspected using the magnetic particle inspection method. CASA also made, or plans to make, a number of changes to their systems and procedures to address issues identified in this report.

Separately, the ATSB reminded operators of M18 aircraft of the importance of the correct application of service life factors when operating at weights above the original maximum take-off weight. In addition, PZL Mielec plans to release additional maintenance documentation clarifying the need for removal of the wings for proper inspection of the wing attachment fittings. Finally, at the request of the owner, the supplemental type certificate for operation of the modified M18 Dromader at take-off weights up to 6,600 kg has been suspended by CASA.

Safety message

This accident shows that even when flying within operational limits, the 'harder' and faster an aircraft is flown the more rapidly the structure will fatigue.

To help ensure that maintenance objectives are consistently met, the ATSB reminds aircraft maintenance personnel of the importance of only using properly-approved maintenance instructions. This accident confirms the importance of referring directly to those maintenance instructions when conducting maintenance.

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The occurrence

On 24 October 2013, at about 0922 Eastern Daylight-saving Time,¹ the pilot of a modified PZL Mielec M18A Dromader, registered VH-TZJ (TZJ) took off from Nowra Airport, New South Wales. The flight was to dispose of water stored in the aircraft's hopper overnight, before returning to Nowra to take on a load of fire retardant for a firefighting mission. The aircraft landed at 0928, and records indicated that the retardant was loaded at 0934.

The aircraft took off again at about 0940 to conduct a firebombing mission about 62 km to the south-west of Nowra in the Budawang National Park, New South Wales (Figure 1).² Another firebombing aeroplane with one pilot and a support helicopter with two crew and one observer were also involved in the mission.

Figure 1: Accident site location and flight path overview



Source: Google earth, modified by the ATSB

When the aircraft arrived in the operations area, the crew of the support helicopter identified a firebombing target near the north end of a ridgeline, and marked its location to the pilots of the firebombing aeroplanes by hovering overhead. The pilot of TZJ acknowledged the target location and advised the intended flight path. The crew of the helicopter then stationed nearby to observe the drop.

The three crew aboard the helicopter later reported that TZJ made a broad, descending left turn onto an approximate north-westerly heading, flying along or slightly across the ridgeline at about 100 ft above the trees and directly towards the target (Figure 2).³ The aircraft rolled level and, at about the same time or immediately afterwards, the aircraft's left wing folded up and separated. The aircraft immediately rolled left and descended, impacting trees and terrain.

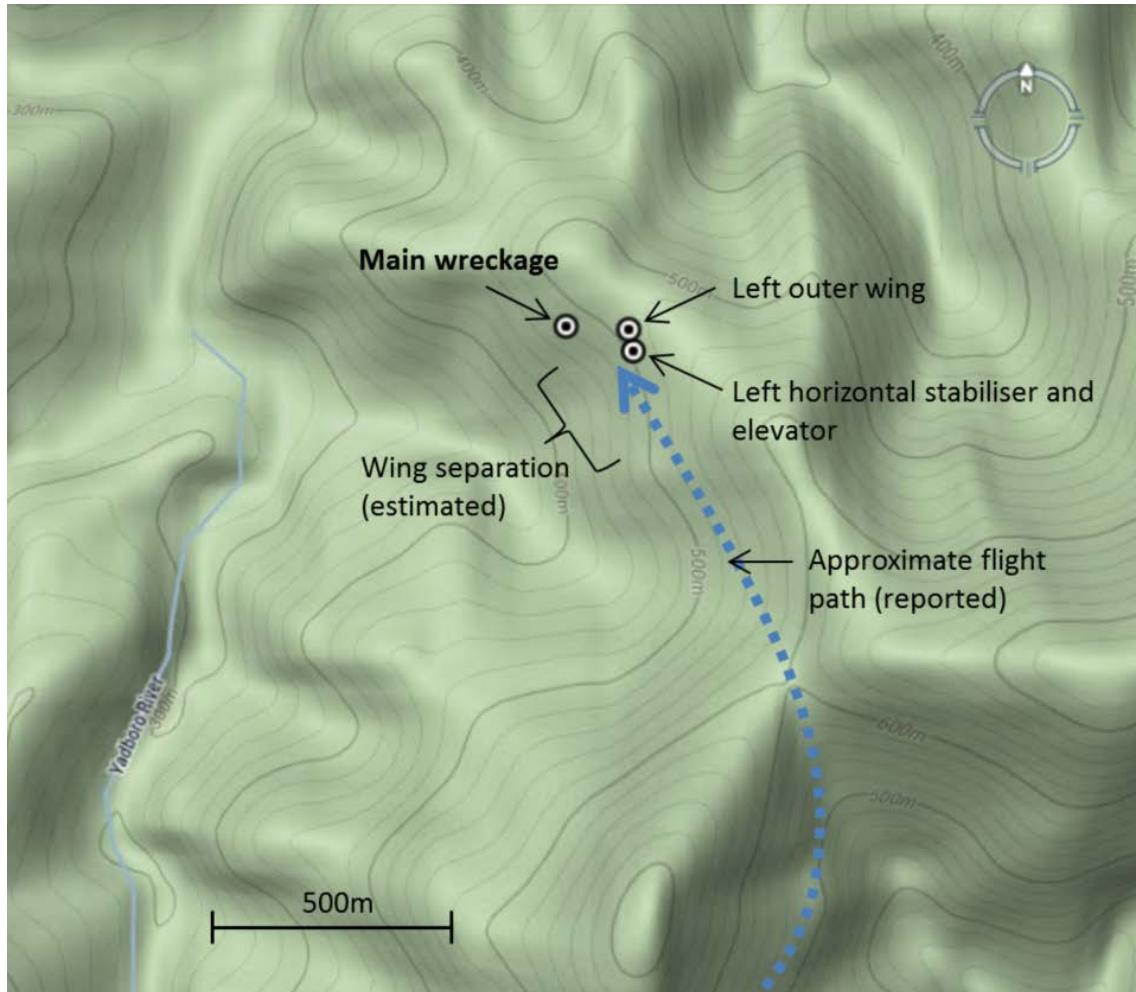
¹ Eastern Daylight-saving Time was Coordinated Universal Time (UTC) + 11 hours.

² The aircraft was fitted with a TracPlus unit, which transmitted aircraft position, altitude, ground track and speed data to a ground station about every 2 minutes. The last recorded data point was at 1002, with the aircraft heading south at 3,455 ft and 105 kt, about 3 km north of the accident location.

³ The pilot of the other firebombing aircraft did not see the accident.

The accident occurred at about 1004. The aircraft was destroyed by impact forces and some parts of the wreckage were additionally damaged by small post-impact fires. The pilot was fatally injured.

Figure 2: Accident site overview, showing TZJ's north-westerly track along or slightly across the ridgeline and the location of a number of items of wreckage



Source: Google Maps, modified by the ATSB

Context

Operator information

The original operator was established in 1982 to provide aerial application services to the agricultural industry.

In 2009, the operator was issued with a Supplemental Type Certificate (STC), numbered SVA521, that permitted an increase in the maximum take-off weight for the M18A aircraft. Further information on these operations is contained in the section *Operation of the M18 at increased take-off weights*.

In October 2011, ownership of the company changed and, in May 2012, the chief pilot changed. Ownership of the STC also transferred to the new owner at this time as part of the purchase of the company.

At the time of the accident, the operator had a fleet of 14 aircraft that included six PZL M18A Dromader aircraft (including VH-TZJ).

Pilot information

The pilot held an Air Transport Pilot (Aeroplane) Licence that was issued in 2003. The pilot's logbook recorded a total of 9,501.6 hours, including 228.0 hours firebombing and 8,223.8 hours agricultural flying. The pilot was a co-owner of the aircraft operator business, and its Chief Pilot since May 2012.

Records showed that the pilot was endorsed to fly the Honeywell TPE331 turbine-engined M18, with relevant experience including 183.4 hours on that version and 65.4 hours on the piston version. Since 1 August 2013 the pilot accrued 54.5 hours flying time including 34.0 hours on the turbine M18.

The pilot held a valid Class 1 Medical Certificate with the restriction that reading correction must be available when exercising the privileges of the licence. A pair of reading glasses was recovered from the aircraft wreckage.

The pilot flew TZJ from the operator's base in Trangie, New South Wales to Nowra on 21 October 2013. The pilot conducted three firebombing missions from the Nowra base on 21 October and six on 22 October. Because of poor weather on 23 October, the pilot conducted only one operational flight that day. The total recorded flying time from 21–23 October was 10.2 hours.

A post-mortem examination and toxicological screening did not identify any physiological conditions that may have contributed to the accident.

Meteorological information

A post-accident Bureau of Meteorology report prepared for the ATSB stated that:

Moderate turbulence below 18,500 feet (AMSL^[4]) was [...] forecast on the lee of the ranges, which covered the incident location.

A SIGMET^[5] for severe turbulence below 10,000 feet (AMSL) was also current for part of Area 21^[6] at the time of the incident but was not applicable to the incident location.

⁴ Above mean sea level.

⁵ A weather advisory service issued to warn of potentially hazardous (significant) or extreme meteorological conditions that are dangerous to most aircraft, such as thunderstorms or extreme turbulence.

⁶ Australia is subdivided into a number of forecast areas. The flight was carried out in Area 21.

Examination of meteorological observations and analyses indicates that moderate turbulence below 5,000 feet (AMSL) was very likely to have been present near the incident location.

The relevant forecasts were consistent with the likely weather conditions in the area of the incident.

A pilot who was flying nearby described the weather at the time of the accident as 'okay' with moderate wind and little turbulence. Another pilot who flew to the site shortly after the accident reported that the wind was gusting to 20 or 25 kt, and that the smoke situation around the accident site was fine with clear skies.

Aircraft information

General information

The PZL Mielec M18 Dromader is a low-wing, single- or two-seat agricultural aircraft designed and manufactured in Poland. There are three main aircraft variants, the M18, M18A and M18B. The aircraft was originally fitted with a 2,500 L hopper. However, the hopper had a contents weight limitation of 1,500 kg.

The aircraft type was originally fitted with a supercharged nine-cylinder radial piston-engine, driving a four-blade propeller. The engine was rated as producing up to 967 horsepower for continuous operation, depending on the variant.

Aircraft history

VH-TZJ (TZJ), an M18A variant, was manufactured in 1984 (Figure 3). Its history from manufacture to 2004 was unclear, but at some point during that time it was exported from Poland to the United States (US). In 2004, with a total time in service of 3,031.4 hours, the aircraft was imported into Australia in a disassembled condition.⁷

Figure 3: VH-TZJ on 22 October 2013



Source: Witness

⁷ For convenience, a timeline of major events is provided in appendix A.

Before being issued with an Australian Certificate of Airworthiness, the aircraft was modified as follows:

- replacing the piston engine with a 1,000 horsepower rated Honeywell TPE331-11U-612G turboprop engine and a five-blade propeller,
- fitment of geared servo tabs⁸ to the flight controls (a co-requisite of the turboprop engine installation)
- increasing the capacity of the hopper to 3,028 L⁹
- installation of vortex generators on the wings
- elevators modified to match M18B elevators.

All of these modifications were carried out in accordance with US Federal Aviation Administration (FAA)-approved Supplemental Type Certificates (STC)¹⁰ and/or Australian Civil Aviation Regulation (CAR) 35-approved engineering orders.

The aircraft's logbook indicated that at that time, all upper and lower wing attachment fittings were replaced in accordance with PZL service bulletin SB E/02.170/2000.¹¹ It also recorded that serviceable wings from another M18, VH-TGH (TGH), were fitted and repairs carried out as required. The Chief Engineer for the maintenance organisation reported that the attachment fittings on those wings were replaced. However, the logbook did not clearly state that this had occurred and the replacement could not be confirmed.

According to the US logbook for TGH,¹² the wings had a total time in service of 3,021 hours, or about 10 hours different to those in TZJ at that time. The logbook also noted that the US operator had removed the aircraft from service because of a landing accident that damaged the aircraft's wings, centre section and landing gear. The ATSB could not determine from the documentation the extent of the damage or the reported repairs carried out to the wings before their installation on TZJ.

Observation:

It was reported that the centre-to-outboard wing attachment fittings were replaced on TZJ in 2004. Although it was likely that they were changed at that time, ambiguity in the aircraft's maintenance documentation, and the absence of unique wing fitting serial numbers, meant the ATSB was not able to positively confirm whether the attachment fittings on the outboard wings were replaced in 2004.

TZJ was issued with an Australian Restricted Category Certificate of Airworthiness on 28 October 2004. Since then, it was generally used for agricultural (such as crop spraying) and firefighting operations.

Maintenance information

The aircraft's logbook stated that it was maintained in accordance with a Civil Aviation Safety Authority (CASA)-approved system of maintenance. A valid maintenance release was found in the wreckage with no outstanding defects noted. The aircraft's last scheduled maintenance was a

⁸ A tab in a primary flight control surface that moves in a direction opposite to the primary surface, generating aerodynamic loads that reduce the force required to manipulate the controls.

⁹ On its own, the hopper modification did not change the maximum weight that could be carried. The benefit was in being able to carry a greater volume of low-density material (such as granules).

¹⁰ A form of airworthiness approval issued by a National Airworthiness Authority that permits modification of an aircraft, engine or propeller operating under an approved type certificate.

¹¹ It was reported that the fittings were replaced as a matter of convenience and not as the result of a problem with the existing fittings.

¹² The wings were removed from VH-TGH before it was operated in Australia and the last applicable data for the airframe was contained in the US logbook.

300-hourly inspection that was carried out on 17 October 2013. Other maintenance carried out at that time included replacing engine fuel components and elevator servo tab bolts.

The centre-to-outboard wing attachment fittings were last inspected on 8 August 2013 when the aircraft had accumulated 6,887.3 flight hours. No defects were reported on the documentation relating to that inspection. The ATSB calculated that, at the time of the accident, the aircraft had accumulated 126.3 flight hours since that inspection. Further detail on the inspections and inspection requirements is presented in the section titled *Wing attachment fitting inspections*.

An aircraft logbook entry indicated that the aircraft struck a wire in 2012. No damage to the airframe as a result was reported.

The aircraft's time in service was different to its flight time as the result of the application of service life factors (further information is provided in the section titled *Application of service life factors to VH-TZJ*). Using the most recent maintenance release and estimates of the duration of the aircraft's last two flights, the ATSB determined that the aircraft had accrued 7,013.6 flight hours. The most recent maintenance release listed the total time in service as 8,815.4 hours.

Weight and balance

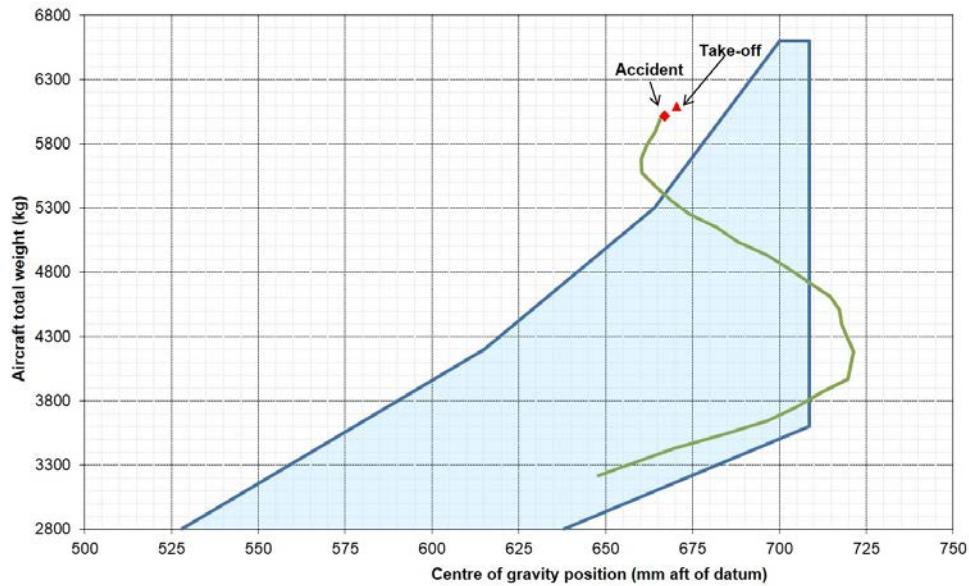
Witness reports and fuel records indicated that the aircraft was fully fuelled after the last landing on 23 October.

A load sheet carried in the aircraft recorded the take-off weights as determined or estimated by the pilot for each flight from 18 to 23 October 2013. The records of all 10 firebombing flights from 21 to 23 October showed a take-off weight of 6,100 kg.

Assuming that the pilot's estimate of weight was correct,¹³ the ATSB estimated that the aircraft's centre of gravity (c.g.) would have been about 15 mm forward of the forward c.g. limit at take-off, and similarly forward of the limit at the time of the accident (as shown by the red marks in Figure 4). The green line shows the projected c.g. shift if a retardant dump had been made at that point.

¹³ The specific gravity of the fire retardant was 1.076. The mixer/loader and one firebombing pilot later reported that they thought the specific gravity of the retardant was 1.25. This would result in the aircraft being loaded with about 14 per cent less weight of product if it was loaded by volume using the incorrect specific gravity. It was not possible to determine whether the pilot established the weight using a specific gravity of 1.00 (commonly used as a convenient estimate which equates weight in kilograms to volume in litres), 1.076 (the actual specific gravity of the retardant), 1.25 (the specific gravity of the retardant as reported by the mixer/loader), or another value.

Figure 4: Estimated aircraft centre of gravity, showing that it was outside of the limits at take-off (red triangle) and at the time of the accident (red diamond)



Source: ATSB

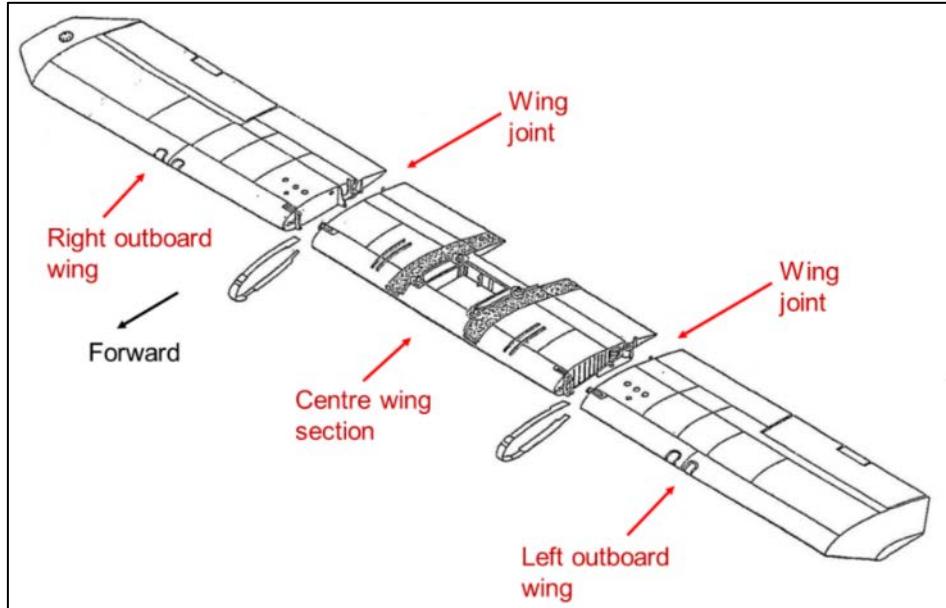
Observation:

In late 2011, as part of an investigation into another M18 accident, the ATSB identified a safety issue that the c.g. of some Australian M18s varied significantly with hopper load and could exceed the forward and aft limits at different times during flight.¹⁴

Wing structure

M18 aircraft have a cantilever wing consisting of three sections: the centre wing section and the left and right outboard wing sections (Figure 5).

Figure 5: Overview of the M18 wing structure

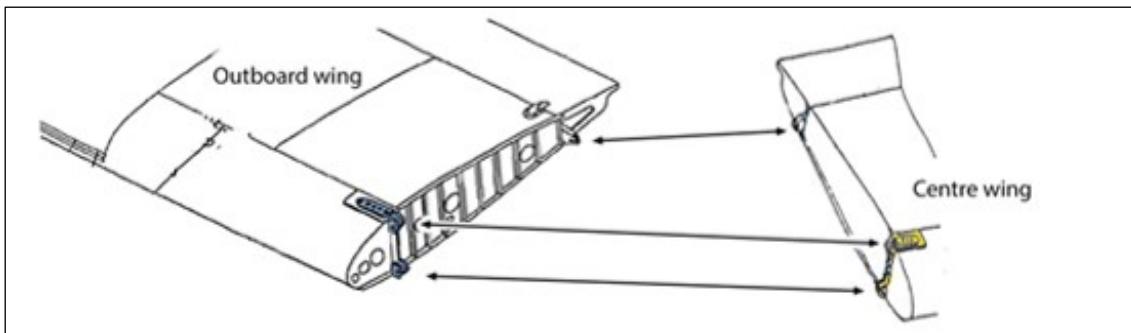


Source: PZL Mielec, modified by the ATSB

¹⁴ ATSB safety issue AO-2011-082-SI-01, available at www.atsb.gov.au.

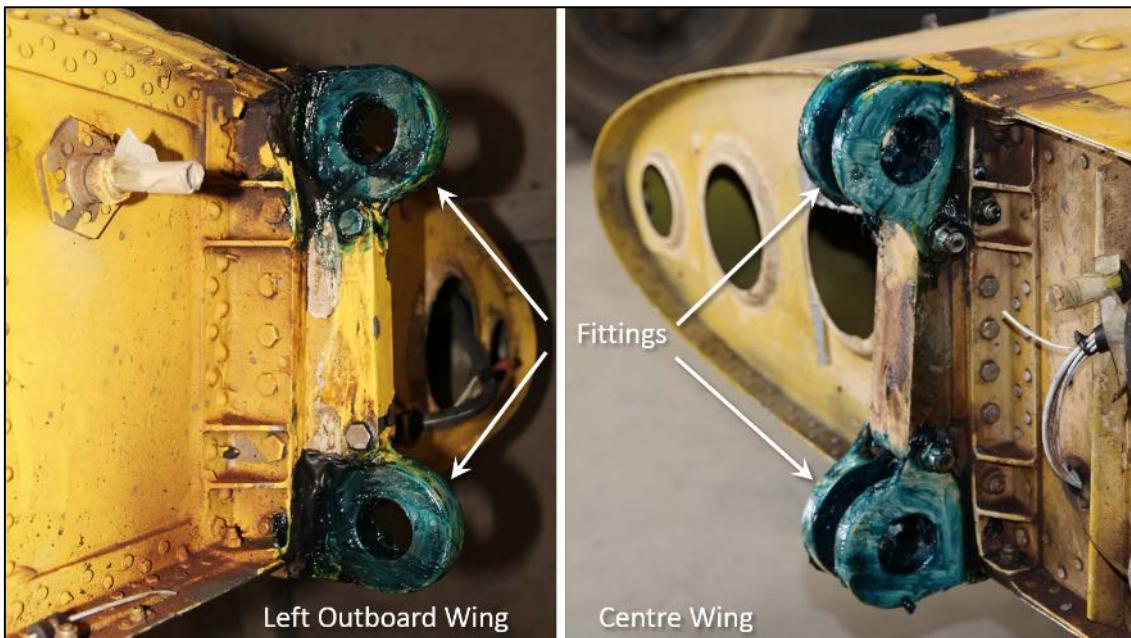
The outboard wings are attached to the centre section at three points. Two attachment points, an upper and a lower, are on the wing's main spar,¹⁵ and a third is on the rear spar (Figure 6). The upper and lower attachment points on the main spar consist of an inboard fitting, attached to the wing centre section, and an outboard fitting, attached to the outboard wing section (Figure 7).

Figure 6: Centre-to-outboard wing attachment joint. The right wing is shown with the wing sections separated. The arrows indicate the three corresponding attachment points



Source: PZL Mielec, modified by ATSB

Figure 7: Exemplar upper and lower attachment fittings (view looking forward with wing sections separated). The outboard wing attachment fittings (left) contain a single lug and the centre wing attachment fittings contain a double lug



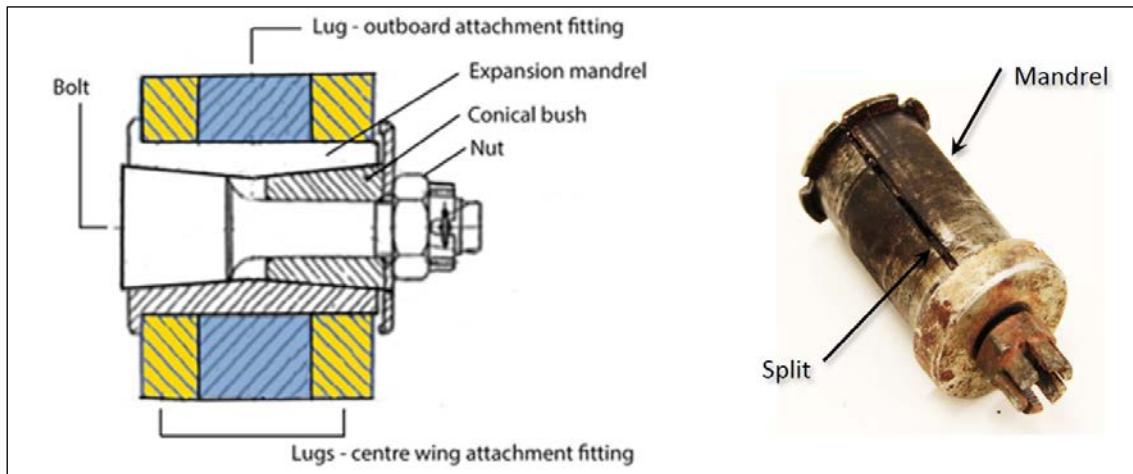
Note: The green coating on the fittings is a grease that was applied for protection during storage.

Source: ATSB

A single lug on the outboard fitting is secured between the two lugs on the centre wing fitting using an expanding mandrel (Figure 8). The mandrel is a specialised pin assembly that is inserted into the bore of the assembled fittings to transfer loads from the outer wing fitting into the centre wing fitting. The mandrel contains a 'split' designed such that, when the bolt through the mandrel is tightened, the mandrel expands to fill the bore of the fittings and prevent movement within the joint.

¹⁵ The spar is the main structural member of the wing. It consists of a beam structure running along the span of the wing and carries the primary flight loads.

Figure 8: Assembled main spar wing attachment fittings showing the single lug of the outboard wing fitting (in blue) secured between the two lugs of the centre wing fitting (in yellow) with the expansion mandrel in situ (left). Expansion mandrel showing the split (right)



Source: PZL Mielec, modified by the ATSB (left) and ATSB (right)

Observation:

The primary flight loads are transferred from the outboard wing sections to the centre wing section through the attachment fittings on the main spar. Because there are no secondary load paths, failure of an attachment fitting will result in a loss of structural integrity.

The upper and lower attachment fittings are manufactured from alloy steel and the bores are reamed during manufacture to 36 mm.

Wreckage and site information

Site description

The main wreckage was located on the south-western slope of a heavily wooded ridge (Figure 9). The wreckage distribution and impact marks were consistent with witness descriptions of the left wing separating from the aircraft at low level.

Figure 9: Site overview. Area containing the main wreckage site indicated by dashed yellow ellipse



Source: ATSB

The main wreckage was contained within a small area and included all major components, except for the left-outboard wing and a section of the left stabiliser/elevator. Those components were located about 130 m and 150 m respectively back along the aircraft's flight path as reported by the crew of the support helicopter (Figure 2). The left stabiliser and wing showed impact marks consistent with the left wing striking the stabiliser during the break-up. The aircraft was significantly damaged from contact with the trees and the impact with the terrain (Figure 10). Some parts of the wreckage sustained additional damage as a result of the bushfire passing through the accident site.

Figure 10: Main wreckage



Source: ATSB

Based on the evidence available,¹⁶ there was no indication of any pre-existing damage or defects other than as discussed in the following sections. Propeller damage indicated that it was being driven at the time of impact with terrain. The accident was not considered to have been survivable.

The following components were removed from the accident site for further examination:

- the left wing lower attachment fittings
- the left wing upper attachment fittings
- part of the left wing rear attachment fitting
- the right wing lower attachment fittings.

Left wing examination

The outboard left wing had separated at the centre-to-outboard wing attachment joint and was found in the wreckage trail as a single piece containing the outboard section of flap and the left aileron (Figure 11). Fire had damaged the inboard end and there were numerous indentations that were consistent with post-separation impact with the left stabiliser and terrain (Figures 11 and 12). Examination of the left centre-to-outboard wing attachment fittings indicated that the outboard wing lower attachment lug had fractured (Figure 12).

Figure 11: Left outboard wing, looking from the wingtip inboard and showing the lower surface of the wing



Source: ATSB

¹⁶ Detailed examination of the main wreckage was hampered by fire and impact damage, the risk of tree collapse and wreckage instability.

Figure 12: Left outboard wing from the inboard end showing fire damage and the fractured lower attachment lug



Source: ATSB

Detailed inspection of the left wing attachment fittings

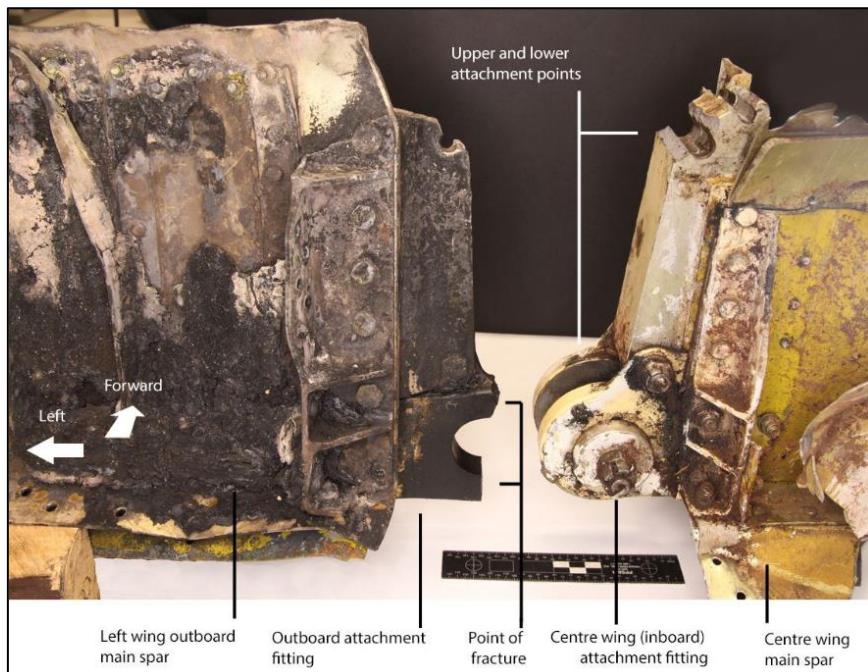
General examination

The recovered sections of the main spar from the centre and outboard wing are shown in Figure 13. The upper and lower ligaments¹⁷ of the fractured outboard lower wing fitting lug contained two distinctly different fractures:

- the upper ligament had a rough, three dimensional form with gross deformation of the material
- the lower ligament had a flat, planar fracture with no obvious deformation.

¹⁷ Sections of lug material above and below the hole in the lug.

Figure 13: Left wing main spar at the centre-to-outboard attachment point (the upper attachment fitting separated from the assembly during the accident and is not shown)

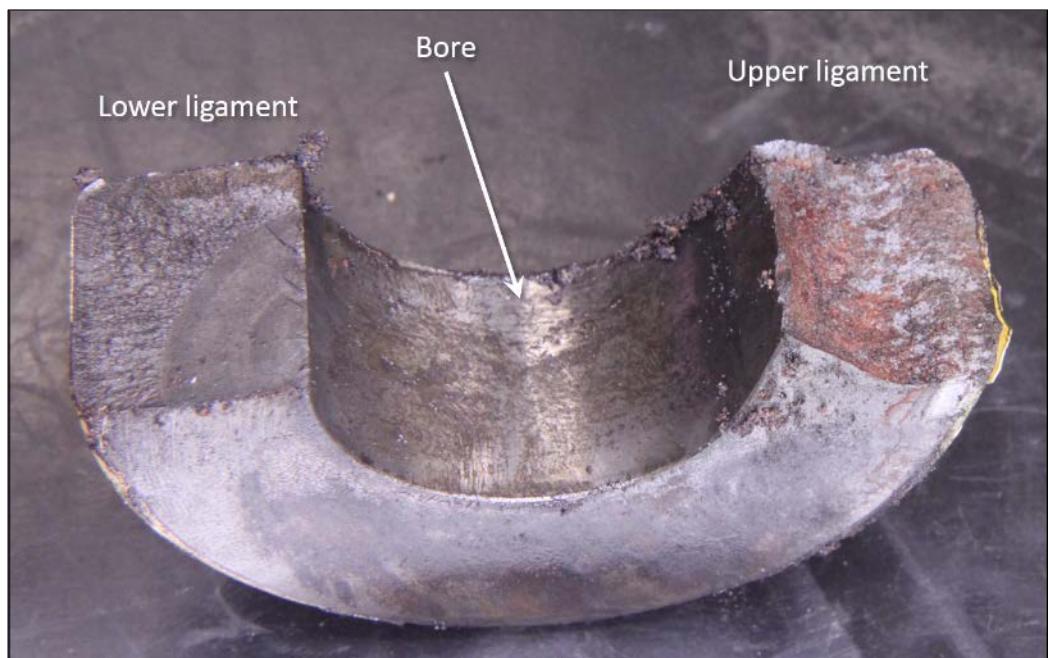


Source: ATSB

The detached portion of the outboard wing attachment fitting lug was retained by the centre wing lower attachment fitting. The fracture surfaces on the detached portion corresponded to those on the outboard section of the fitting.

A post-impact fire damaged the portion of the lug that remained in place on the outboard wing section. However, the detached portion of the lug that was retained in the centre wing lower attachment fitting contained no post-failure damage (Figure 14).

Figure 14: Detached portion of the left outboard wing lower attachment lug that was recovered from the centre wing lower attachment fitting (prior to cleaning and detailed examination)



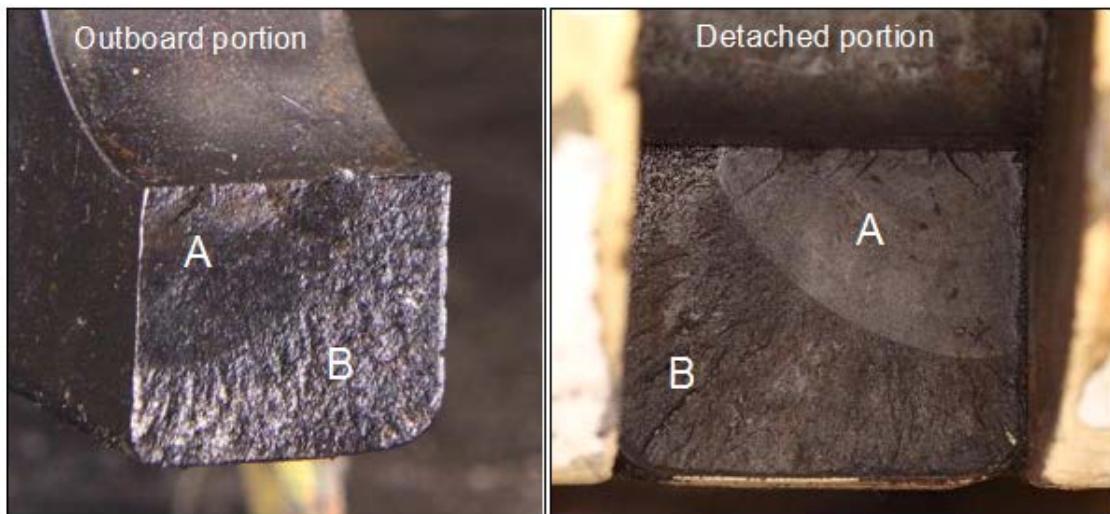
Source: ATSB

The fracture surface of the lower ligament exhibited two distinct regions (Figure 15):

- a smooth area of progressive crack growth that originated at the inner bore of the lug (region A)
- a rough area of rapid fracture that corresponded to the final failure of the fitting material (region B).

The associated mandrel was found in the centre wing section lower attachment fitting. The split was located at about the 12 o'clock position (upwards) in accordance with the manufacturer's instructions.

Figure 15: Left lower attachment lug showing the two different fracture regions on the lower ligament. Region A is a smooth area of progressive crack growth and Region B is an area of rapid fracture (the detached portion was retained in the centre attachment fitting when image taken)



Source: ATSB.

A greasy compound, which had a copper colour, covered the detached portion of the lug and the associated mandrel. Examination of a sample of that grease identified that it contained microscopic flakes of a copper-coloured substance.

The bore of the wing attachment fittings, through which the mandrel passed, were also covered in a thin greasy film. The surface of the bore of the detached portion of the outboard fitting lug presented a generally bright appearance with a distribution of darker regions (Figure 16). Microscopic examination found that these darker regions consisted of corrosion pitting.

Figure 16: Surface condition of the wing attachment fitting bore with dark staining (corrosion damage)



Source: ATSB

Measurement of a number of the corrosion pits found that they varied in depth. Most were less than 0.03 mm deep, but the deepest observed was 0.16 mm. It was also noted that the surface of the bore:

- was bright due to the absence of corrosion product
- included a number of fine circumferential marks.

Observation:

The corrosion process normally results in the formation of a corrosion product. In steel this corrosion product is commonly a brittle dark red/orange-to-black material that is distinctly different from the steel and often referred to as 'rust'. In a bolted system such as this, corrosion product would be expected to be covering the site of any corrosion, unless it was previously removed.

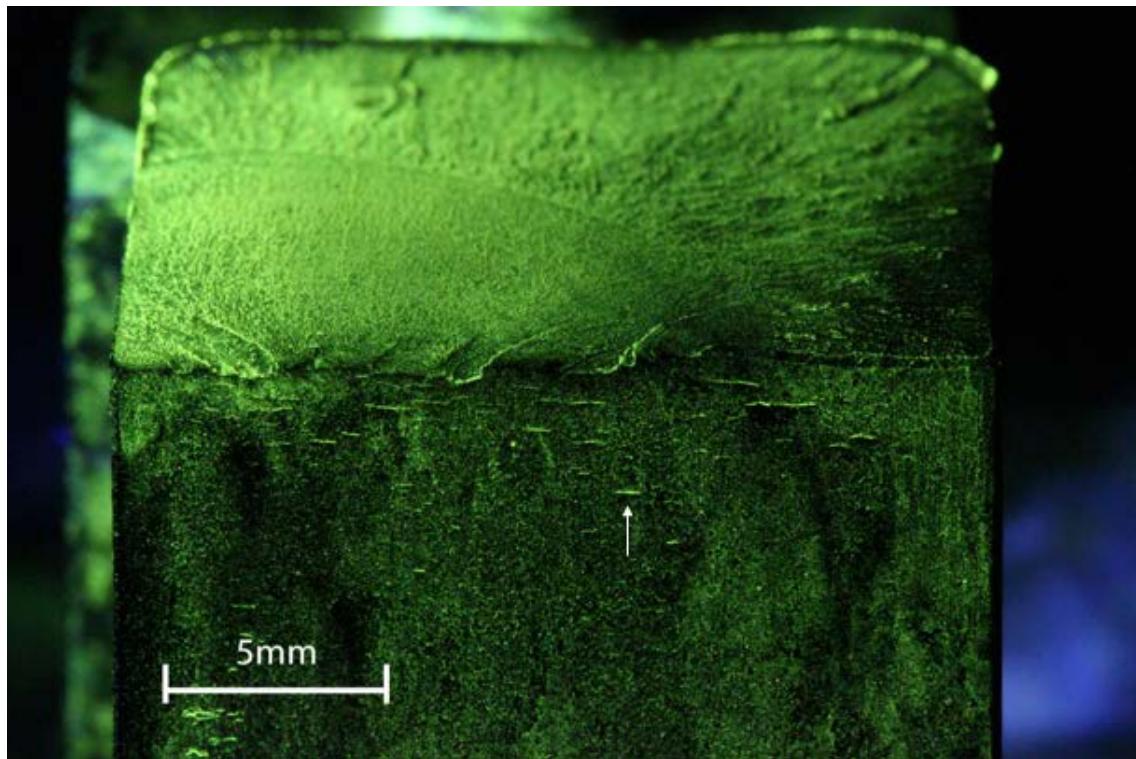
The greasy film identified in the bore of the outboard wing attachment fitting would have protected the surface from corrosion. This would suggest that the corrosion occurred, and that the corrosion product was removed, at some time prior to examination by the ATSB.

The fine circumferential marks identified in the bore of the outboard fitting are consistent with the application of an abrasive.

The lower section of the outboard wing attachment fitting lug bore contained numerous microscopic cracks (micro-cracks) that were co-located with corrosion pits. Examination using a

fluorescent magnetic particle inspection (MPI) technique¹⁸ found that some, but not all of the micro-cracks were detectable using that method (Figure 17).¹⁹

Figure 17: Fluorescent magnetic particle inspection of the detached portion of the left outboard wing lower attachment fitting lug. The micro-cracks present as short horizontal bright lines (an example micro-crack is identified by a white arrow)



Source: ATSB

Examination of the fracture surface

The progressive crack growth area identified as region A in Figure 15, contained markings that were consistent with a fatigue fracture mechanism.²⁰ The fracture surface markings indicated that the crack had multiple origins located at the bore of the lug (Figure 18). Each of the fatigue origins corresponded to a corrosion pit in the bore of the lug.

Observation:

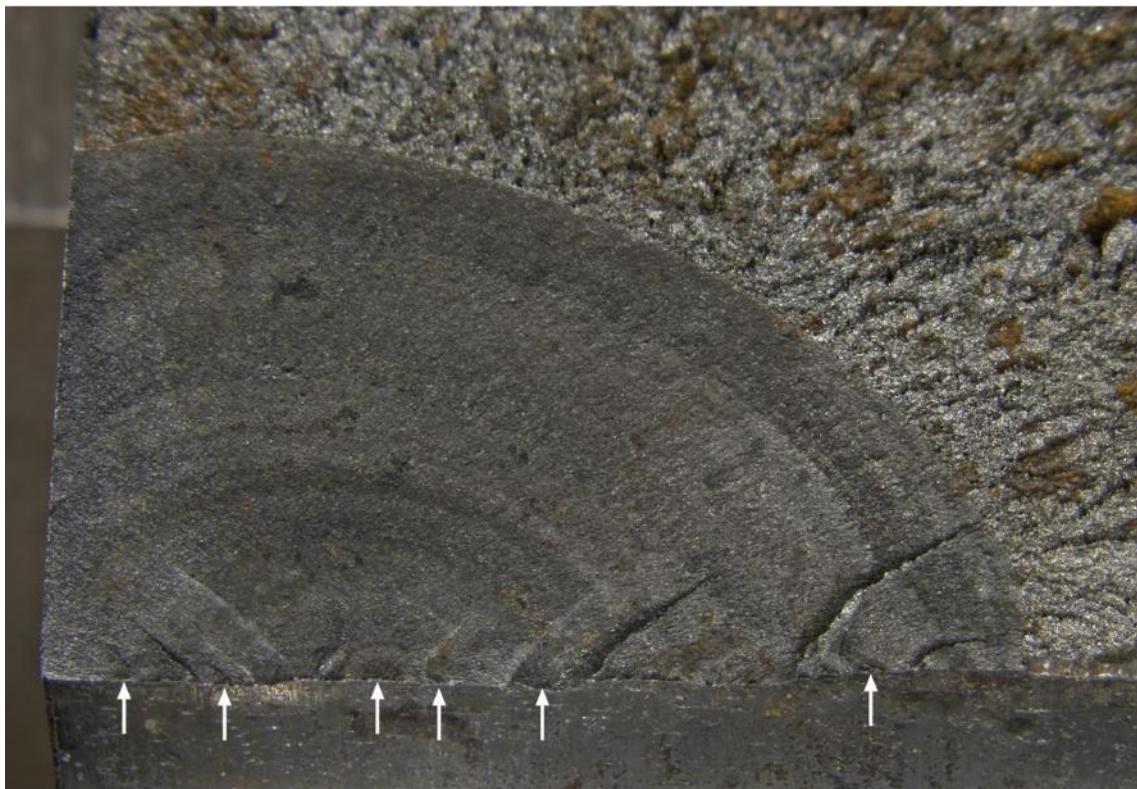
A number of fatigue cracks formed at the sites of localised pitting in the bore of the lug on the outboard wing attachment fitting. A number of these cracks joined to form a single fatigue crack, which continued to grow until the fitting fractured on the accident flight.

¹⁸ A form of non-destructive testing (NDT) where a magnetic field is passed through the object being inspected. A solution containing ferromagnetic particles is applied to the object and cracks are highlighted by an accumulation of those particles as a result changes in the magnetic field. In this case, the particles fluoresce under ultraviolet light to assist in the detection of cracks.

¹⁹ Note, this was in laboratory conditions with ready visual access to the bore surface and knowledge that the cracks were present. Factors such as technique, equipment, lighting, access and expectation can affect the results of the same inspection method when used in the field.

²⁰ Fatigue cracking is a progressive cracking mode when the material is subjected to repeated varying stresses. Each time a tensile stress is applied, the crack grows larger on a microscopic scale. When the crack reaches a critical size, the remaining material is unable to withstand the applied stress and the remaining material rapidly fractures.

Figure 18: Portion of the lower ligament fracture surface showing the fatigue crack. White arrows indicate the location of some of the fatigue origins



Source: ATSB

Microscopic examination of the fatigued section of the crack surface identified flakes of copper and carbon pressed into the surface. These flakes were consistent with those identified in the content of the grease found on the fitting.

Further details of the technical examination of the wing attachment fittings are provided in appendix B.

On-board recorded flight data

The aircraft was fitted with a Perkins Technologies Data Acquisition Alarm Monitor (DAAM) system to monitor and record a number of aircraft operating parameters.

The ATSB was unable to locate the aircraft's DAAM system during the on-site period. However, the aircraft maintenance organisation located the DAAM during its removal of the wreckage from the site and forwarded it to the ATSB.

On receipt, the unit was sent to its manufacturer for data download. Inspection by the manufacturer revealed that the DAAM was subjected to heat, most likely from the bushfire after the accident. The heat damaged the circuitry, which disconnected the memory chip from the unit's internal battery, resulting in the loss of recorded data from the chip.

The aircraft was also fitted with a Farmscan Can-link 3000 dispersion control system, which was capable of recording certain operating parameters. An associated external memory card, which may have been fitted at the time of the flight, was not found.

Aircraft fatigue management

Fatigue

Aircraft are designed so that the stresses in their structures from the expected flight loads do not exceed the strength of the materials from which they are constructed. However, the materials

used to construct aircraft can be damaged by fluctuations in those stresses, even if they are below the static strength of the material.²¹ The damage from each stress fluctuation is small, but the accumulation of a large number of them over time can result in significant damage. The accumulated damage from these fluctuating stresses is referred to as 'fatigue damage'.

Fatigue damage leads to the formation of cracks in the aircraft's structure. Cracks reduce the load-carrying capability of the structure, which if not managed, could ultimately lead to a structural failure during flight.

Management approaches

There are currently three basic design approaches for managing fatigue in aircraft structures: safe-life, fail-safe and damage tolerance. FAA Advisory Circular AC 23-13A²² defines these approaches as follows:

The **safe-life** of a structure is that number of events, such as flights, landings or flight hours, during which there is a low probability that the strength will degrade below its design ultimate value due to fatigue cracking.

Fail-safe is the attribute of the structure that permits it to retain its required residual strength for a period of unrepaired use after the failure or partial failure of a principal structural element.

Damage tolerance is the attribute of the structure that permits it to retain its required residual strength for a period of use after the structure has sustained a given level of fatigue, corrosion, accidental, or discrete source damage.

Put more simply:

- Safe-life design is intended to have the structure retired before there is a likelihood of fatigue cracks affecting its strength.
- Fail-safe means that redundant structure will cope with the failure of major structure until it is discovered during an inspection program.
- Damage tolerance relies on detection of cracks through a specifically designed inspection program to ensure that cracks from fatigue, corrosion or accidental damage are identified before they become large enough to sufficiently degrade the remaining strength.

As is typical for an aircraft of the type, the manufacturer of the M18 used the safe-life approach to manage fatigue. Thus, the manufacturer determined a 'service life' during which cracking from fatigue was unlikely to affect the aircraft's strength.

A more detailed description of the fatigue management approaches and management of fatigue in the M18 is provided in appendix C.

M18 service life limitations

An aircraft's service life limitation is the maximum time in service that the aircraft structure is permitted operate. When the service life limitation is reached, the aircraft is required to be retired from service.

Section 3 of the M18 Structural Repair Manual listed the service life limits for the airframe and specified components. The service life limit for the airframe was 6,000 flight hours. However, the application of various aircraft manufacturer service bulletins (SB)²³ allowed this life limit to be extended to a maximum of 10,000 hours. Those SBs required modifications and additional

²¹ The static strength of the material is the maximum strength the material can sustain if the load is applied slowly then held constant.

²² Federal Aviation Administration 2005. *Fatigue, fail-safe, and damage tolerance evaluation of metallic structure for normal, utility, acrobatic, and commuter category airplanes*. Advisory Circular 23-13A.

²³ An advisory notice issued by a manufacturer to alert operators of service issues and/or modifications for a particular aircraft type.

inspections to obtain the life extensions. While the airframe was subject to life limits, no specific life limits applied to the centre-to-outboard wing attachment fittings.

Flight load spectra

Regardless of the fatigue management approach used, designers need to understand how the in-flight stresses vary within the structure over the life of the aircraft. This will depend on a large range of factors, from the weight for each flight, the environment in which the aircraft is operated, to the manner in which the aircraft is operated. The designer will not know all of these factors in advance for each aircraft, so they typically use an assumed load spectrum that will represent that design.

Flight load spectra for fatigue analysis purposes are typically presented as the distribution of the number of times that a flight load factor²⁴ would be exceeded for a range of flight load factors within the normal flight envelope. For example, flight load factors around 1g would be expected to occur often, whereas loads near the limit load factor would be expected to occur rarely.

Because flight events such as gusts and manoeuvres typically occur relative to geographical locations, the spectra are often provided as flight load exceedances per distance travelled, for example nautical miles. However, aircraft service lives are normally based on flight hours. To determine the expected life of an aircraft, in flight hours, from the flight load spectra, the designers must assume an average expected airspeed.

A number of spectra have been developed over the years, but at the time that the M18 was designed, there were no spectra generally available for agricultural operations and the aircraft manufacturer developed its own. The manufacturer provided the manoeuvre flight load spectrum for the M18 to the ATSB and reported that they used an assumed average speed of 180 km/h (97 kt).

Since the design of the M18, the US FAA has developed and released its own flight load spectrum for agricultural aircraft.²⁵ This spectrum is contained, along with other operational spectra, in FAA AC 23-13A.

Operation of the M18 at increased take-off weights

Instruments permitting operations at increased weights

The M18 aircraft had a maximum take-off weight (MTOW) of 4,200 kg when operated in the normal category.²⁶ However, because the aircraft was typically operated in the restricted category,²⁷ there were several ways in which an operator could choose to operate at take-off weights above the normal MTOW. These included aircraft flight manual (AFM) supplements from the aircraft manufacturer, and Supplemental Type Certificates (STC) (Table 1). Associated with the weight increases were changes in the operational airspeed limitations.

²⁴ The vertical (with reference to the aircraft) acceleration relative to gravity, often referred to in terms of 'g'. For example a load factor of 3, or 3g, is three times the acceleration due to gravity.

²⁵ Referred to as 'aerial application' by the FAA.

²⁶ Aircraft are type certified in different categories depending on their intended use and operating limitations. The normal category is for light aircraft intended for a range of roles, including the carriage of passengers over populated areas.

²⁷ The restricted category is for those aircraft conducting special purpose operations where some of the requirements of other categories, such as normal or transport categories, are inappropriate for the special purpose. Special purpose operations include the conduct of agricultural operations (for example, spraying, dusting and seeding) and firefighting.

Table 1: Operations at increased take-off weight

Condition	Basic AFM	AFM Supplement No.1	AFM Supplement No. 16	US STC SA01276AT	Australian STC SVA521
MTOW (kg)	4,200	4,700	5,300	5,300	6,600
Never exceed speed (kt)	148	121	121	121	135
Maximum cruise speed (kt)	121	104	104	104	115
Minimum operating speed (kt)	None provided	None provided	89	92	100

In addition, several CASA exemptions from 2002 to 2011 related to the operation of restricted or agricultural category aircraft at weights in excess of the MTOW stated in the relevant AFM. In November 2008, while flight tests and approval for STC SVA521 were pending, CASA issued an exemption specifically applying to eight Australian-registered M18s. It permitted operations up to 6,600 kg as 'an interim measure to allow the aircraft to be used for firefighting and agricultural operations during the fire season' and ceased having effect on 1 April 2009.

The AFM from TZJ did not include any of the aircraft manufacturer's issued supplements. Since being imported into Australia, TZJ had been operated under a combination of CASA exemptions and the above-listed STCs. Between November 2008 and the issue of STC SVA521, TZJ was operated under the M18-specific CASA exemption. For a period prior to this, TZJ was authorised to operate overweight under an experimental Certificate of Airworthiness as part of the certification program for STC SVA521.

The operator reported that due to the size of the fuel tanks on VH-TZJ, the highest take-off weight attainable was 6,400 kg.

Service life factoring

Increasing an aircraft's take-off weight increases the stresses in the airframe. This in turn increases the fatigue damage to the aircraft structure, effectively aging the aircraft quicker.

To account for the higher rate of fatigue damage, a 'service life factor' is applied to the flight time. Multiplying the actual flight time by the service life factor results in a 'factored flight time'. The factored flight time is then used to determine the aircraft's time in service for retirement and maintenance scheduling purposes.

Aircraft manufacturer service life factoring requirements

The aircraft manufacturer originally determined the service life limitation for the M18 based on a MTOW of 4,700 kg. As such, no service life factors were listed in AFM Supplement No. 1. At take-off weights above 4,700 kg, AFM supplement No. 16 required the application of a service life factor as follows:

The recorded flown hours of the aircraft with weight ranged from 10340 Lbs (4700 kg) to 11700 Lbs (5300 kg) shall be multiplied by 1.35 coefficient and the obtained result used for counting the service life.

A similar requirement was included in the *M18 Aircraft Repair Manual*.

The aircraft manufacturer previously provided clarification that the factor was to be applied for the entire flight time when the take-off weight was between 4,700 kg and 5,300 kg, not just the time that it was above 4,700 kg.

The manufacturer advised the ATSB that the fatigue life and factoring was:

...applicable only for M18 and M18A firefighting airplanes with piston ASz62 engine, with empty weight about 2825-2870 kg and with MTOW more than 4700 and less than 5300 kg. This coefficient does not apply to turboprop M18-s with MTOW higher [than] 5300 kg.^[28]

US STC service life factoring requirements

The AFM supplement provided as part of US STC SA01276AT, for take-off weights up to 5,300 kg, did not include a specific requirement for the application of a service life factor.

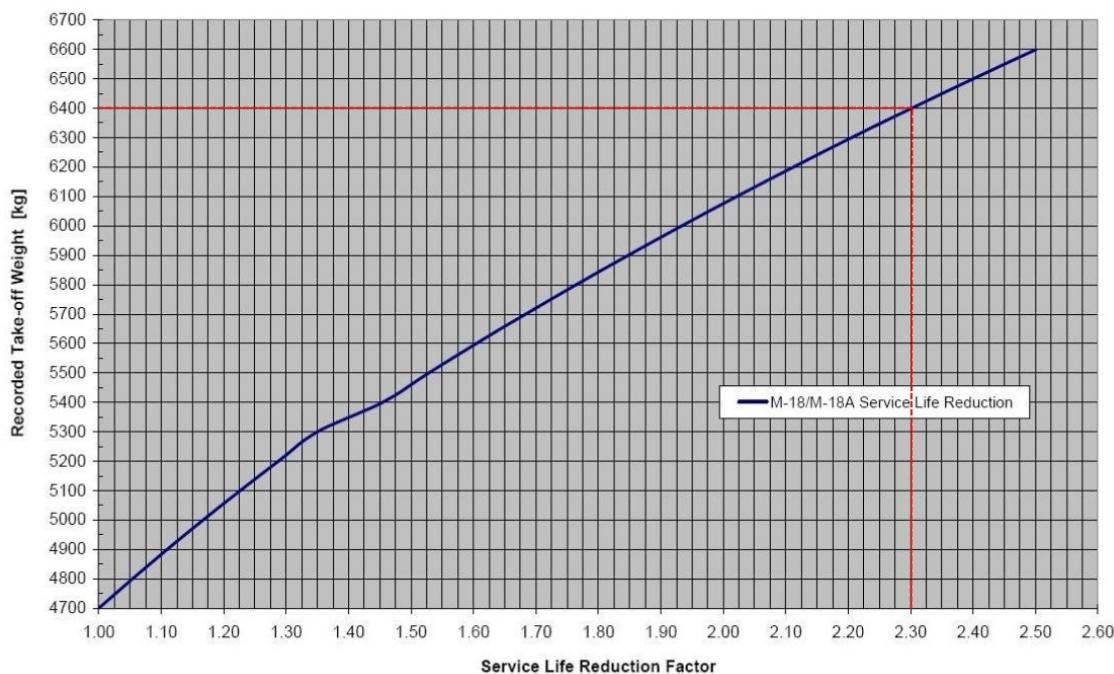
Observation:

Although there was no requirement in the AFM supplement for the STC, the *Aircraft Repair Manual* required factoring of the flight time when the take-off weight was above 4,700 kg.

Australian STC service life factoring requirements

For operations up to 6,600 kg, Australian STC SVA521 required the application of a service life factor. Unlike the single service life factor provided by the aircraft manufacturer, the associated Maintenance Manual Supplement for STC SVA521 provided a factor that was weight-dependent. It varied from 1.35 for a take-off weight of 5,300 kg to 2.50 at 6,600 kg. The variation in the factor with take-off weight was not linear and was provided in both tabular and graphical form (Figure 19).

Figure 19: Service life factor chart from the STC SVA521 Maintenance Manual Supplement. The example (red lines) shows that, for a take-off weight of 6,400 kg, the applicable service life factor²⁹ is 2.3



Source: STC SVA521 Maintenance Manual Supplement

The associated AFM supplement stated that (original emphasis) 'it is the corrected service life which is to be used as the basis for scheduling and completing all of the required aircraft maintenance and inspection tasks.'

²⁸ This does not mean that a service life factor did not apply to the turboprop version of the aircraft. It means that the manufacturer could not quantify the effect of the turboprop modification on the airframe's fatigue life. As such, the manufacturer cannot be assured that its service life factor will properly manage the fatigue on a modified (turboprop) aircraft.

²⁹ Referred to as 'service life reduction factor' in the chart.

The method used to determine the service life factors was based on an extrapolation of the factor for operation up to 5,300 kg as supplied by the manufacturer in their flight manual supplements and aircraft repair manual. This was based purely on the increase in stresses due to the increase in weight. The fatigue justification report contained no reference to the possible effect that any other operational factors could have on the fatigue.

Observation:

An ATSB review of the weight-dependent factoring method did not identify any flaws in the logic as a comparative justification for a weight increase. Comparison with a hypothetical service life factor curve provided by the aircraft manufacturer³⁰ indicated that the STC design methodology resulted in a service life factor that was similar to the manufacturer's data at 6,600 kg.

In the case of TZJ, the aircraft was fitted with the smaller of two possible fuel tank configurations. This configuration resulted in a maximum practical take-off weight of 6,400 kg. Thus, the maximum applicable service life factor that could be applied to TZJ was 2.3 (see Figure 19).

Application of service life factors to VH-TZJ

Historic application of service life factors

There were no records available to determine whether the aircraft was operated at weights above 4,700 kg prior to being imported into Australia and, if it had, whether service life factors had been correctly applied.

There were some aircraft flight and weight information records from 2004 to the time of the accident, but no evidence that any factoring had been calculated or incorporated into the aircraft's maintenance records prior to August 2013.

A 2008 letter written by the original holder of STC SVA521³¹ was included in the engineering justification package for certification of that STC. That letter stated that three operators had flown nine M18 aircraft, including TZJ,³² 'at all-up weights of 6,400 kg to 6,633 kg for more than 90 per cent of the time' in the period 1999–2008.

It was reported that, prior to about 2011, pilots had been instructed for factoring purposes to record only that part of a flight when the aircraft was above 4,700 kg (that is, the take-off weight above which factoring was required). The recorded flight times and weights were indicative of this method being used. For example, over a 2-month period in 2010, the aircraft accrued 112.7 flight hours, of which 19.0 hours were recorded as requiring factoring with an equivalent, average adjustment factor of 2.01. This approach and associated difference amounted to about 94 factored hours that were not accounted for over this period.

In August 2013, as the result of a CASA direction, service life factoring was retrospectively applied to TZJ (and other aircraft in the operator's fleet) for the period 2009–2013³³ using a factor of 1.85.³⁴ The refactoring did not account for operations in Australia at higher weights from 2004–2009 (up to about 2,500 flight hours) nor any flights that might have occurred at higher weights overseas from 1984–2004 (up to about 3,000 flight hours).

³⁰ The manufacturer's analysis was based on a piston-engined M18, where only the maximum weight was changed. All other factors were in accordance with the manufacturer's operational limitations.

³¹ Ownership of the company that held STC SVA521 changed in October 2011. Responsibility for the STC changed to the new company owners at that time. The same company also owned and operated TZJ and several other M18s.

³² Incorrectly stated as VH-PZJ in the letter. The aircraft registered as VH-PZJ at the time was a Piper PA-18.

³³ STC SVA521 was approved in March 2009.

³⁴ The aircraft's system of maintenance called for inspections at 75-, 150-, 300- and 450-hour intervals. A 450-hourly inspection, which called for additional structural inspections compared with the others, became overdue as a result of the recalculation but no record of one was made in the aircraft's maintenance records. Those inspections were unrelated to the wing fittings.

Pilot reports and aircraft records showed that, around this time, the operator implemented a new system that required pilots to calculate factoring and record the adjusted hours on the aircraft's maintenance releases. A comparison between the maintenance release and a load sheet found in the records indicated that, apart from minor errors,³⁵ the flight times had subsequently been appropriately adjusted.

ATSB estimate of service life

Due to the absence of complete records and lack of consistent and accurate service life factoring, it was not possible to determine the aircraft's time in service (TIS) had the factors been correctly applied throughout its life. However, to obtain an indication of what the corrected service life could have been, the ATSB made an estimate using the assumptions that:

- no factors were applicable prior to the fitment of the larger hopper in 2004, at which time the aircraft had accrued 3,031.4 hours and new wing fittings were installed
- a constant service life factor was applied from 2004.

For the purposes of this calculation, the constant service life factor of 1.85, which the operator determined was representative from 2009 to 2013, was applied from 2004, onwards.

Alternatively, if it is assumed that the aircraft carried its maximum weight for every flight from 2004 to 2013, an upper limit to the airframe life can be established. Both estimates are provided in Table 2 along with the unfactored flight hours for comparison.

Table 2: Service life estimates

Estimate scenario	Scenario service life adjustment factor(s)	Scenario-adjusted airframe hours at the time of the accident	Scenario-adjusted wing fitting hours at the time of the accident
No factoring (lower limit)	1.00 (1984-2013)	7,014	3,982
Sample-based	1.00 (1984-2004) 1.85 (2004–2013)	10,398	7,367
Maximum factor (upper limit)	1.00 (1984-2004) 2.30 (2004–2013)	12,190	9,159

Observation:

At various times in the aircraft's history in Australia, its time in service was either not factored correctly or not at all. Based on the ATSB's calculations there is a possibility that, had the service life factors been applied to the aircraft in accordance with its maintenance documentation for all of the time it was operated in excess of 4,700 kg, the aircraft may have exceeded its service life limitation of 10,000 hours.

Application of service life factors to other M18 aircraft

In the interim report for this accident, the ATSB noted:

As of 16 December 2013, there were 29 M18s registered in Australia. Of those, six were listed on the aircraft register as being turbine-powered. However, the ATSB has determined that at least four other M18s in Australia are turbine-powered, three of which have the TPE331 engine.

³⁵ A factor of 1.0 was applied to several consecutive flights throughout October 2013 at weights where a higher factor should have been used. The error amounted to a shortfall of 8 hours TIS over that period. On several other occasions, load sheets were not completed or hours were incorrectly totalled.

Based on a CASA review, other M18s in Australia have accrued between 3,100 and 9,200 hours. It is unknown whether service life factoring has been correctly applied over the life of those aircraft; however, it is possible that some or all have been flown at weights above 4,700 kg without the associated factoring having been correctly applied.

As at 18 August 2015, there were still 29 M18 aircraft on the CASA register, five of which are listed at turboprop versions. The ATSB remains aware that there are others with turboprop installations that are not listed as such in the register. Of the nine aircraft listed in the 2008 letter from the original holder of STC SVA521, three remain on the register.

On 18 February 2015, CASA advised that the majority of turboprop-equipped M18 aircraft operating under STC SVA521 were not being used by their operator. The operator of TZJ had also previously informed the ATSB that they were not using their M18 aircraft.

CASA also confirmed that a number of the M18 aircraft operated under STC SVA521 did not have their service lives correctly calculated.

In July 2013, CASA wrote to all operators of M18 aircraft operating under STC SVA521 directing them to adjust their aircraft's time in service to account for operations above 4,700 kg. The direction only required operators to account for time since 6 March 2009, when the STC was approved by CASA. However, prior to that time, many of the aircraft had been operating under various exemptions from CASA. Also, the 2008 letter from the original holder of STC SVA521 stated that a number of them had operated at weights up to 6,633 kg since 1999.

Historical recorded data and flight load spectrum

Although the ATSB was unable to obtain any data from the on-board DAAM system following the accident, a number of DAAM data files were obtained from the operator that contained recorded flight data from some of TZJ's previous operations. The files contained data from:

- forty flights (totalling about 49 flight hours) carried out between June 2007 and August 2008
- thirty-one flights (totalling about 29 flight hours) between February and August 2013.

Data from the 2007–08 period had previously been used as part of an engineering justification provided to CASA for the approval of STC SVA521. That data was collected for the purpose of showing that the reduced flight load factor limits would not be exceeded in normal operations at the increased take-off weights. The data was not used, nor was there an intention to use the data, for the determination of a flight load spectrum for fatigue purposes.

Data for other flights, including some within the periods listed, was not available to the ATSB.

Flight load spectrum for TZJ derived from the recorded DAAM data

Among other parameters, the recorded data included indicated airspeed and g-load (flight load factor). Analysis of the DAAM data from the recorded flights enabled the ATSB to calculate a manoeuvre load spectrum for those flights, and compare it with the aircraft's design spectrum and the current FAA spectrum in AC 23-13A (see appendix C). The resulting spectrum is plotted in Figure 20, along with the FAA spectrum and the spectrum used by the aircraft manufacturer in its fatigue safe-life justification. A description of the method used to determine the load spectrum for TZJ is presented in appendix D.

The recorded data contained the raw vertical flight loads. This included both gust and manoeuvring loads. Only the manoeuvre load spectrum was developed because it was a fatigue inducing factor that could be affected by the manner of operation. The gust load spectrum cannot be controlled by the operator and, as such, was unlikely to significantly vary from the design spectrum.

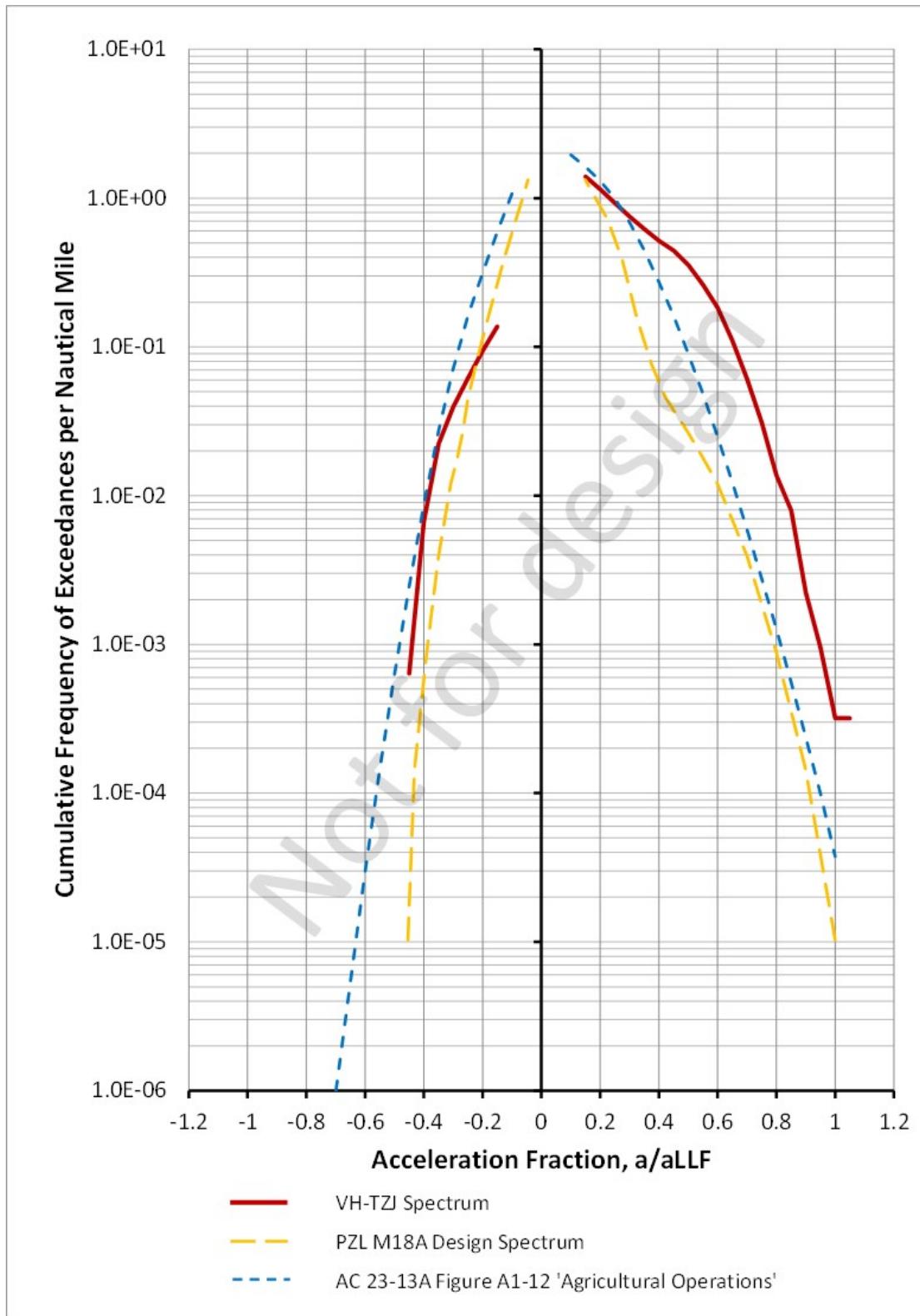
The data used to develop the TZJ spectrum was obtained from about 25 hours of operation, covering a distance of 3,010 NM (5,578 km). Although the data represented only a small portion of the aircraft's operating life, the pilot who flew about 70 per cent of those flights reported that those

flights were typical of normal operation. The type of operation and the operator did not change for the majority of the aircraft's life. Thus, for the purposes of examining the circumstances surrounding the failure of the wing attachment fitting, the data was considered to be acceptably representative of the aircraft's normal operation.

The data files also included simulated firefighting missions that were carried out as part of the justification of STC SVA521. The nature of the firefighting operation was such that the hopper contents were released in 2 to 3 seconds, during which the aircraft weight changed significantly. The recorded data did not include a parameter for the release of the hopper contents and, as such, the time at which the aircraft weight started to change was unknown. Because of this, the aircraft weight, and hence load factor limitation, at any particular time during the firefighting flights could not be reliably ascertained.

In addition, firefighting operations made up only a small fraction of the aircraft's total operating time. Thus, the effect on the aircraft's fatigue life from firefighting operations was likely to be small compared to agricultural operations.

Figure 20: Comparison of TZJ's manoeuvre load spectrum as derived from recorded DAAM data (in red), the PZL M18A design spectrum (in yellow) and US FAA AC23-13A Figure A-12 *Agricultural Operations* (in blue)



Source: ATSB

The following observations were made regarding the available DAAM data recorded between 2008 and 2013:

- the aircraft's limit load factor was exceeded on at least one occasion during those flights³⁶
- the negative acceleration fraction spectrum correlated well with the other reference spectra, falling between the FAA and aircraft manufacturer's spectra
- other than at low acceleration fractions, the positive acceleration fraction spectrum was significantly greater than both the FAA and aircraft manufacturer's spectra
- during the period 2007 to 2008 the average airspeed³⁷ was 118 kt and in the 2013 data it was 111 kt
- the maximum airspeed in the period 2007 to 2008 was 145 kt and in the 2013 data the maximum airspeed was 137 kt.

Manufacturer's assessment of the derived flight load spectrum

The manufacturer reported that its original design analysis for the M18 was based on:

- a take-off weight of 4,700 kg
- an assumed flight time of 10 minutes
- an average speed of 180 km/h (97 kt).

However, a random sample of the aircraft's operation indicated that a typical flight time was about 30 minutes and the average operating speed was about 115 kt.³⁸ The ATSB sought assistance from the manufacturer to determine the potential effect of these operational differences on the fatigue life of the aircraft.

The aircraft manufacturer compared the effect that the derived spectrum, flight time and operating speed would have with that from the original design spectrum and assumed conditions. A take-off weight of 4,700 kg was used throughout the analysis. The results of that analysis are shown in Table 3.

Table 3: Comparison of the fatigue life reduction estimates from the aircraft manufacturer based on differences in the flight load spectrum, flight time and operating speed for a take-off weight of 4,700 kg

Airspeed km/h (kt)	flight duration (minutes)	fatigue life reduction factor for VH-TZJ load spectrum
180 (97.2)	10	4.56
180 (97.2)	30	3.58
213 (115)	10	4.88
213 (115)	30	3.85

³⁶ On one occasion during flight tests in 2008, the aircraft's load peaked at 3.59 g, which is above the highest limit load of 3.4 g. As the aircraft's limit load changed with aircraft weight, and complete weight records were not available for all of the recorded flights, the ATSB could not determine whether the limit was exceeded on other occasions.

³⁷ Although the ATSB did not locate a calibration certificate for the airspeed recorded by the DAAM, CASA's files for the STC contained a statement that the installed DAAM system had been calibrated. In the context of the calibration statement, the correspondence referred to the flight test schedule, which required calibration of the airspeed system.

³⁸ This was based upon an average of the average speeds before and after approval of STC SVA521. It was assumed that the reduction in average speed between 2008 and 2013 was a result of a decrease in the maximum normal operating speed from STC SVA521. Given that the STC was approved in 2009, it was assumed that for 5 of the 9 years of operation (2004 to 2009) the average speed was 118 kt and, for the remaining 4 (2009 to 2013), the average speed was 111 kt. This resulted in an estimated average speed over the 9-year period of 114.9 kt.

Observation:

Recorded data indicates that, though the aircraft was generally operated within its limitations, it experienced a flight load spectrum generally higher than that assumed by the manufacturer. TZJ's average operating speed and average flight time were also greater than the design assumptions for the original service life determination. As a result, TZJ could have effectively reached its service life limit 3.85 times faster than anticipated if continually operated in this manner.

The manufacturer's analysis was done at 4,700 kg, where there are no weight-based service factors applicable. Operating at weights above this would require the application of a service life factor, reducing the time taken to reach the service life limit even further.

Relevant maintenance regulations

Approved maintenance data

Civil Aviation Regulation (CAR) 42V required that a person carrying out maintenance on an Australian aircraft must ensure that it is done in accordance with the applicable provisions of the aircraft's approved maintenance data. CAR 2A definitions of approved maintenance data included such things as:

- directions made under an airworthiness directive
- instructions issued by the manufacturers of an aircraft that specify how maintenance on the aircraft is to be carried out
- instructions issued by the designers of modifications of aircraft that specify how maintenance on the aircraft is to be carried out
- any other instruction approved by CASA under CAR 2A(4) relating to how maintenance on the aircraft is to be carried out.

CASA reported that an approval under CAR 2A(4) does not necessarily mean that the procedures were assessed as suitable for a particular task. In some cases, the approval may only indicate that performing the inspection in accordance with the procedure is unlikely to cause aircraft damage or otherwise degrade airworthiness.

Airworthiness directives

According to Civil Aviation Safety Regulation (CASR) 39.001, CASA may issue an airworthiness directive (AD) for a type of aircraft where an unsafe condition exists in an aircraft of that type, and if the condition exists, or is likely to exist, or could develop in other aircraft of that type.

An AD specifies the actions required, in the opinion of CASA, which are necessary to correct the unsafe condition. These actions are required to be taken at the time, or in the circumstances specified in the AD.

A person must not operate an Australian registered aircraft affected by an AD while any requirement of the AD has not been complied with. However, a person may apply for permission to use an alternative means of compliance (AMOC) with an applicable AD. According to CASR 39.004³⁹, an AMOC allows an unsafe condition to be addressed in an approved, alternative way (such as using different methods or equipment) to that prescribed by the AD. An approval under CAR 2A(4) by itself was not sufficient to address an AD by an alternative means.

CASA may also approve an 'exclusion' from the requirements of an AD because the unsafe condition does not exist due to a modification or repair.

³⁹ Previously referred to as 39.4 in early amendments of the CASRs.

CASA Advisory Circular AC 39.1(1)⁴⁰ contained guidance on matters relating to compliance with ADs. Section 14 of the AC dealt with exclusions from ADs and stated:

14.1 Most ADs specify a means of compliance. It cannot however be assumed that only one specific repair, modification, or inspection method is acceptable to correct an unsafe condition. Therefore, development of alternative methods of correcting an unsafe condition is not precluded. An equivalent means of compliance satisfying CASR 39.4 must be substantiated and approved by the Authority.

14.2 Depending on the circumstances, the alternative method could be; by inspection, modification, repair, replacement, or a combination of these methods. It is the applicant's responsibility to prove that the aircraft can be operated to the same level of safety as stipulated by the requirements of the AD.

14.3 To enable approval of an alternative method of compliance, the applicant will need to supply engineering justification as to how the proposed alternative means will establish an equivalent level of safety to that required by the AD.

Defect reporting

The Civil Aviation Regulations 1988, Part 4B contained requirements for the mandatory reporting of certain defects to CASA. The type of reportable defects are primarily broken down into major defects (CAR 51A) and defects discovered in complying with a direction, including ADs (CAR 51B). Major defects include, among other things, any defect that has caused, or that could cause, a primary structural failure in an aircraft.

Wing attachment fitting inspections

Requirements for inspection

Background

The aircraft manufacturer, US FAA, and CASA developed a series of inspection requirements in response to two wing separation accidents involving M18 aircraft in 1999 and 2000.⁴¹ Investigation of those accidents by the US National Transportation Safety Board found that 'heavy' pitting corrosion had formed in the lower bore of the lower centre-to-outboard wing attachment fitting corresponding to the location of the split in the mandrel. The stress-raising effects of the corrosion pitting led to the formation of fatigue cracks that grew undetected until the fitting fractured and the wing separated in flight.

On 20 January 2000, following the first accident, the FAA released Special Airworthiness Information Bulletin (SAIB) CE-00-13 to provide safety information on the inspection and maintenance of M18 aircraft. The FAA encouraged operators to examine the fittings in accordance with the existing M18 service information.

On 11 July 2000, following the second accident, the FAA released SAIB CE-00-27 to alert operators of M18 aircraft of possible cracks and corrosion in the centre-to-outboard wing attachment fittings. In the SAIB, the FAA noted that the failed fittings were inspected using a dye penetrant inspection method and that no cracks were detected. The first wing separation occurred about 530 hours after the wing was inspected and the second about 1,000 hours after the inspection. The FAA recommended that the fittings be inspected using a magnetic particle method, or equivalent, after the first 3,000 hours TIS and every 500 hours thereafter.

Manufacturer service bulletin

On 3 August 2000, the aircraft manufacturer issued service bulletin E/02.170/2000. This bulletin provided procedures for dealing with corrosion when reaming, or replacing, the centre-to-outboard wing attachment fittings. Its main focus was the repair of the attachment fittings, rather than their

⁴⁰ Effective June 2000.

⁴¹ Refer to the section on US accidents in appendix E. A third related accident occurred shortly before the FAA AD became effective.

inspection for corrosion and cracking. A later revision of the aircraft's service manual required the service bulletin to be carried out every 500 hours.

The service bulletin specified repairs for minor (surface) corrosion, pitting corrosion and ovalisation.⁴² All of the repairs required that attachment fittings found to be corrosion-affected must be inspected for possible cracks prior to the removal of any corrosion. The service bulletin also noted that the only acceptable inspection method was 'magnetic crack detection [original emphasis]'. It was confirmed with the aircraft manufacturer that this meant a magnetic particle inspection (MPI) method. If any cracks were detected, the replacement of the fitting was mandatory.

The inspection instructions in the service bulletin noted that there was 'no need for outboard wing removal upon expansion mandrels removal', but did not provide detail on how this was to be accomplished.

The process in the service bulletin for treating minor (surface) corrosion was:

3. Minor (surface) corrosion: If only minor (surface) corrosion is found on the insides of a dia. 36 mm hole (expansion mandrel holes), proceed as follows:

- Inspect the hole by magnetic crack detection method – no cracks are allowable;
- Using fine-grain sand-paper, polish to remove traces of corrosion (no corrosion pits to show afterwards);
- Visually inspect external surfaces of the mandrel and wing holes: no cross scratches or notches are allowable;
- Install the mandrels, preserving with DINITROL AV-30 along the mandrel's upward cutting line, as detailed in Sec. VI, para. 5+9. Follow with preservation of the adjoining area with AV-30 (Use nominal-diameter expansion mandrels $\phi 36.0$).

The repair of pitting corrosion was similar except that instead of using abrasion to treat corrosion, it required the fitting to be reamed out to 36.3 mm in diameter (a radius increase of 0.15 mm) and an oversized mandrel fitted. It noted that if, after reaming, the fitting surface exhibited an uneven surface (that is, including remaining pitting), then the fitting was to be replaced.

After repair, the fitting was to be treated by the application of Dinitrol AV 30, an anti-corrosion compound, to preserve the fitting.

The service bulletin also contained procedures for the replacement of attachment fittings. This included the fitment of mandrels with the split side up to help prevent corrosion on the critical lower side of the lug bore.

The service bulletin execution procedures noted:

- Surfaces of the dia. 36 mm holes can be inspected by magnetic cracks detection method with no need for outboard wing removal upon expansion mandrels removal (make sure to properly support the wing for operation). When checking the lower holes, upper expansion mandrels remain installed, and the other way round;

⁴² A condition where the bore is worn or distorted into an oval shape, rather than the required circular shape.

Following the accident, the ATSB asked the aircraft manufacturer whether the mating faces of each lug need to be visually inspected as well as the bores, and how this may be accomplished without removing the outer wings. In response, the aircraft manufacturer stated that:

[The maintenance manual] orders the inspection of the center wing-to-outboard wing attachment joints, which means inspection of everything.

and that:

We agree that the method of conducting a magnetic inspection of fittings without separating the outer wing from center wing is troublesome and difficult. The Bulletin does not recommend this method but it only states that in this way the inspection can also be conducted (if somebody is able to do it and will successfully conduct such inspection).

United States FAA airworthiness directive

On 5 September 2000, the FAA issued airworthiness directive AD 2000-13-12, which became effective on 27 September 2000, to address corrosion and cracking in the centre-to-outboard wing attachment fittings. The AD required that upon reaching 3,000 hours TIS, and at 500-hourly intervals thereafter, the fittings be inspected and repaired, as necessary, in accordance with the manufacturer's service bulletin No. E/02.170/2000. The AD specifically stated that magnetic particle methods must be used to accomplish the inspection.

The FAA advised that it had worked with the aircraft manufacturer to determine the method to be used for the inspection of the centre-to-outboard wing attachment fittings for cracking. It also advised that it continued to work with the manufacturer after the release of the AD to ensure that the inspection interval assured that any cracks could be detected within the 500-hour interval. Further information on the work carried out by the manufacturer is contained in the section *Manufacturer's examination of crack growth*.

Australian airworthiness directive

On 19 October 2000, CASA issued airworthiness directive AD/PZL/5, which became effective on 25 October 2000. It required operators to inspect the centre-to-outboard wing attachment fittings in accordance with the manufacturer's service bulletin.

Like the FAA AD, CASA required that the repetitive inspections occurred at 500-hourly intervals.⁴³ However, the CASA AD reduced the inspection threshold from the FAA's 3,000 hours to 2,500 hours TIS. This was because a crack had been detected in a wing fitting in Australia with 2,776 hours TIS in September 2000.⁴⁴

The CASA file for PZL M18 airworthiness directives did not contain any technical background information on the development of AD/PZL/5 and consisted only of drafts of the final AD. The ATSB found the background technical information in a separate file for the M18 structural fatigue and fail-safe characteristics. That file dated back to the introduction of the M18 in Australia, when the then-Civil Aviation Authority⁴⁵ required the manufacturer to justify the fatigue characteristics of the aircraft for certification in Australia.

During the development of the AD, CASA received a proposal from the inspector who identified the crack in the Australian aircraft to consider using an eddy current inspection method. The inspector considered this method to be more sensitive and easier to use than MPI, improving the chances of an inexperienced operator detecting a crack.⁴⁶ Correspondence in the CASA file

⁴³ Or 12 calendar months, whichever came first.

⁴⁴ It is understood that this crack was identified by an Australian operator when it proactively inspected its aircraft after reading the FAA Special Airworthiness Information Bulletins.

⁴⁵ The Civil Aviation Authority was the predecessor of CASA and was the name of the regulator at the time the file was started.

⁴⁶ A non-destructive testing method where a probe induces eddy (swirling) currents in a material and detects changes in the eddy currents that result from discontinuities (such as cracks) in the material.

showed that CASA queried the FAA as to why it specified magnetic particle methods. The FAA referred CASA to the aircraft manufacturer who had advised that magnetic particle was the only acceptable method. The aircraft manufacturer responded to CASA's subsequent enquiries stating:

Basing on experience and consultations with our specialists crack research laboratory we found that:

- both methods (magnetic particle and eddy-current) are good and eddy-current method is even better if you deal with elements without corrosion and galvanic coatings.
- in our case, we deal with steel elements mostly having corrosion pitting and outside surfaces (fitting lugs inclusive) cadmium plated. In such cases eddy-current method can appear to be ineffective. That is why we have chosen the application of magnetic particle method.

Based on this advice, CASA specifically required that magnetic particle methods be used to accomplish the inspections when the AD was issued.

Manufacturer's examination of crack growth

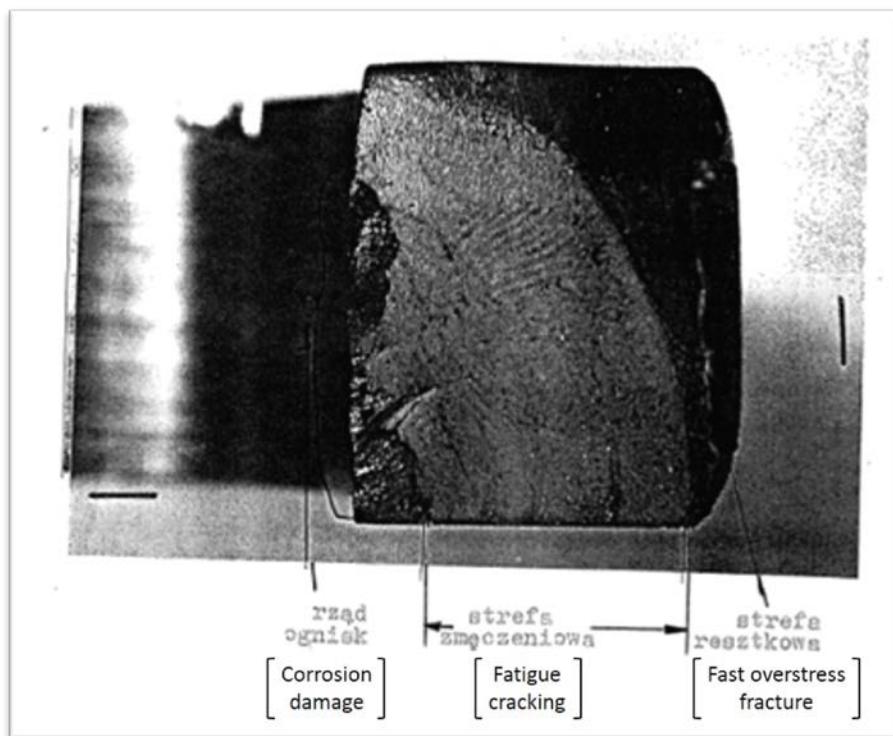
The aircraft manufacturer reported that:

After issuing of the FAA directive ordering the inspection of wing fittings with the determined method there were diagnosed 9 cases of airplanes with cracked fittings. All fittings were sent to PZL with the descriptions: airplane number, number of flight hours, time period of airplane operation. The size of cracks was determined at PZL. All fittings were subject to tests in order to determine the growth rate of the crack and the permissible, safe period of operation. On the basis of these tests there was determined the safe time interval of airplane operation between the inspections.

The manufacturer supplied an image of a sample of one of the fittings that it tested and examined (Figure 21). Three distinct regions are present on the fracture surface:

- corrosion damage (the dark irregular region to the left)
- an area of fatigue cracking (the light region covering most of the surface)
- a region of fast overstress fracture (the dark band to the upper right).

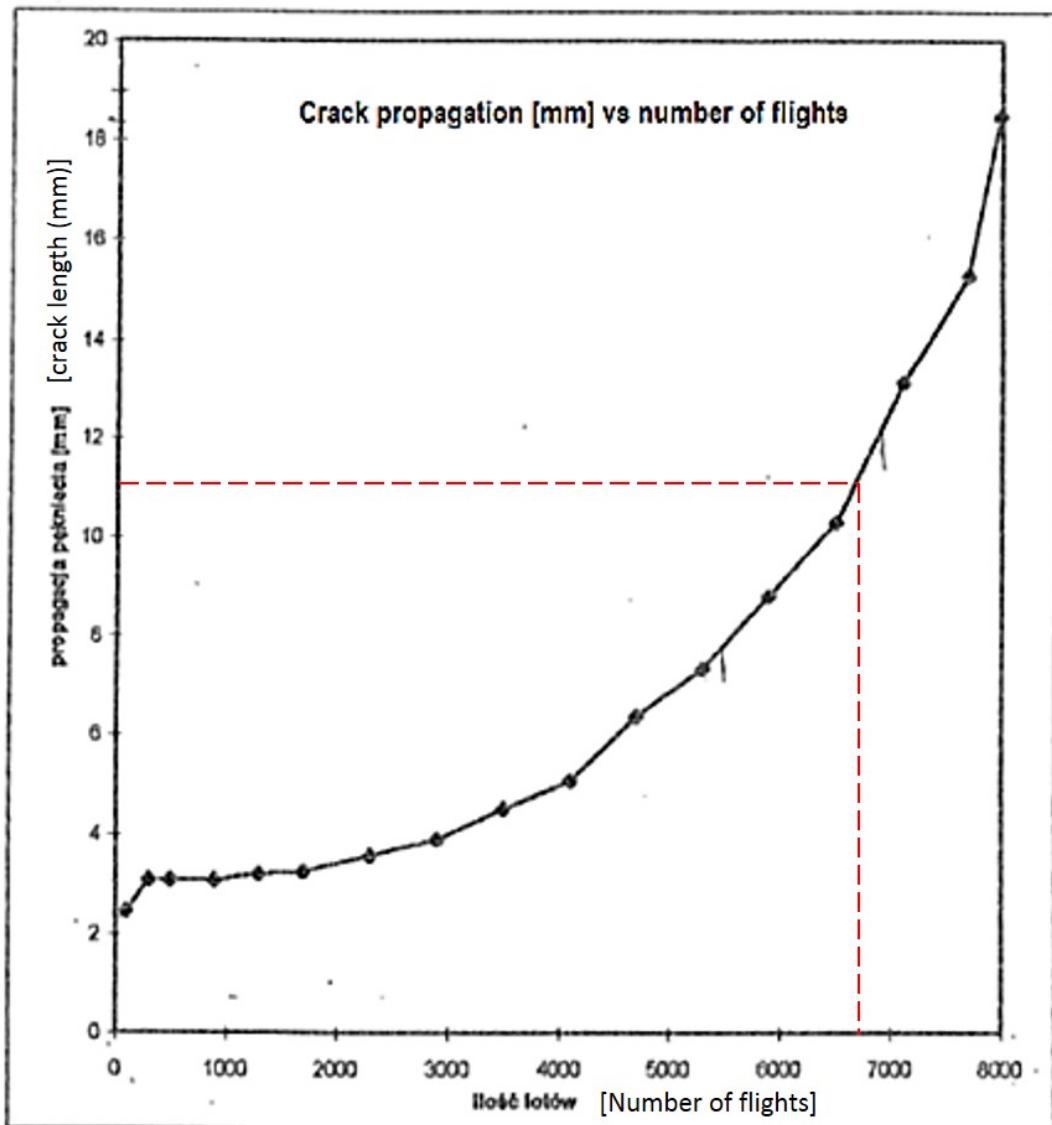
Figure 21: Sample fitting examined by the aircraft manufacturer showing areas of corrosion damage, fatigue cracking and fast overstress fracture



Source: PZL Mielec, modified by the ATSB

From its testing and analysis, the manufacturer determined a crack growth rate from the initial damage as shown in Figure 22. This data was determined for the base aircraft with the original piston engine and operated in accordance with the manufacturer's aircraft flight manual and associated supplements. It may not be valid for modified aircraft or any aircraft operated under different parameters.

Figure 22: Basic M18 crack growth rate as determined by the manufacturer, with the size of the crack in the centre-to-outboard wing attachment fitting in TZJ applied to the manufacturer's data (dashed red lines) to estimate the number of flights before failure



Source: PZL Mielec. Modified by the ATSB

Observation:

The corrosion pitting damage in the image provided by the manufacturer is significantly greater than that observed in the bore of TZJ's failed centre-to-outboard wing attachment fitting. Based on information provided by the manufacturer, and in the absence of other factors that affect the rate of crack growth, the ATSB estimated that it would take between 6,000 and 7,000 flights for a crack to grow to the 11 mm before failure as observed in TZJ (dashed line in Figure 22). Based on recorded data, for which the average flight was about 30 minutes, the ATSB estimated this equated to between 3,000 and 3,500 flight hours.

Inspections of the centre-to-outboard wing attachment fittings on TZJ

Inspection history

A review of the maintenance records for TZJ found that inspections for AD/PZL/5 were conducted on 10 occasions (Table 4). The test reports recorded that the equipment used each time was a rotating probe and eddy current instrument.

Table 4: History of centre-to-outboard wing attachment fitting inspections for AD/PZL/5⁴⁷ on TZJ

Date	Recorded airframe flight hours	Flight hours since previous inspection	Flight hours prior to accident
31 Aug 2004	3,031.4 (new fittings)	Not applicable	3,982.2
23 Apr 2008	4,255.8	1,224.4	2,757.8
28 Apr 2009	4,636.3	380.5	2,377.3
27 Apr 2010	5,123.2	486.9	1,890.4
9 Nov 2010	5,554.7	431.5	1,458.9
1 Jun 2011	5,943.5	388.8	1,070.1
27 Jul 2011 ⁴⁸	5,943.5	0.0	1,070.1
23 Feb 2012	6,216.7	273.5	796.9
18 Oct 2012	6,619.7	403.0	393.9
8 Aug 2013 ⁴⁹	6,887.3	267.2	126.3
24 Oct 2013 (accident)	7,013.6	126.3	0.0

There was no reference to any cracks being identified, or repairs being carried out as a result of those inspections.

Conduct of AD/PZL/5 by the maintenance organisation

The following description of the conduct of the work carried out for compliance with AD/PZL/5 are based on interviews with the Licensed Aircraft Maintenance Engineers (LAMEs) and NDT technicians involved.

The wing fittings were prepared for inspection by the LAME by gaining access to the wing attachment fitting being inspected and removing the mandrel. The wings were supported during this operation and there was no need to remove the wings. The LAME would then clean the fitting. This would include cleaning the bore of the fitting and mandrel by lightly rubbing with

⁴⁷ The seven most recent test reports incorrectly referenced a procedure numbered QP.00.30 (E). The NDT organisation reported that:

- there was no such procedure in its system
- it was likely a typographic error
- the correct procedure number was QP.00.36 (E)
- QP.00.30 (MP) was a procedure for the magnetic particle inspection of a radial engine.

Note: The letters in the brackets do not form part of the procedure number and were included by the NDT organisation for quick identification of the inspection method.

⁴⁸ The 27 July 2011 inspection was recorded only as an NDT inspection report and not in the aircraft's maintenance records. It was reported to have been performed as a matter of convenience rather than to formally meet maintenance requirements.

⁴⁹ TZJ was one of eight M18s inspected on 8 August 2013. This inspection report listed the registration as VH-TZT. At the time, VH-TZT was not recorded on the Australian register as a PZL M18 and was not owned by the operator. This was likely a typographical error by the test report writer.

Scotch-Brite.⁵⁰ The LAME would conduct a 'quick' visual examination of the fitting and mandrel for damage.

The NDT technician would have a brief inspection of the fitting to see if it was clean enough for them to perform the NDT inspection. If it was not clean enough, they would inform the LAME, who would further clean the fitting. Once cleaning was satisfactory, the NDT technician would perform the inspection using their eddy current inspection equipment. The NDT technician might require additional cleaning of the fitting if the equipment could not get a clear result.

If no defects were reported by the NDT technician, the LAME would refit the mandrel before preparing the next fitting for inspection. The LAME reported that when refitting the mandrel, they would apply a coating of Dinitrol AV 30, a corrosion inhibiting compound, to the fitting and mandrel, before coating with grease. The maintenance organisation reported that they used a copper based anti-seize grease for this purpose.^{51,52}

The LAME who carried out the work on TZJ reported that they had completed the work for the AD on numerous occasions. They reported that the first few times that they carried out the work they directly referenced the service bulletin required by the AD. However, since then they had not directly referenced the service bulletin because it had not changed and felt that they understood the requirements contained within it.

The LAME was aware that the NDT inspection was looking for anomalies such as cracks and that responsibility for inspecting for corrosion lay with them. When corrosion was identified in the fitting, the LAME would make a subjective assessment to determine if it was severe enough to remove. The LAME reported that they had never had to ream a fitting.

The maintenance documents for TZJ recorded that the eddy current inspection method was used to comply with AD/PZL/5 on all occasions. However, it was reported that use of the eddy current inspection method was not limited to TZJ and was used on most Australian M18 aircraft.

Wing attachment fitting inspections of other M18 aircraft

There was no requirement for operators to inform the aircraft manufacturer of wing attachment fittings that did not pass inspections. However, the manufacturer reported that it had received and examined nine such fittings following the release of the FAA AD. In addition, the manufacturer was also able to infer additional failed fittings when new fittings were ordered.

The ATSB identified one other occasion when a crack was found in the wing attachment fitting of an Australian-registered M18. There were also two other occasions where crack-like indications were found but later confirmed to be false. A summary of these occasions follows:

- In September 2000, a crack was found in a fitting with 2,776 hours time in service.⁵³ The aircraft operator was the same as for TZJ. CASA correspondence at the time indicates that the fitting was destructively tested by the owner to determine the depth of the crack, which was

⁵⁰ A brand name covering a range of commercial abrasive products by 3M. In this case the LAME was referring to a mild abrasive product, which according to the manufacturer is '...for general purpose cleaning ... without damaging the workpiece'

⁵¹ In September 2015, the maintenance organisation informed the ATSB that Dinitrol AV 30 would not typically be applied to the internal bore of the fittings or the mandrel, which would be coated with a copper-based anti-seize grease. Dinitrol AV 30 would only be applied externally after the reassembly of the fitting. The ATSB did not identify any physical evidence to confirm whether or not AV 30 had been applied to the mandrel and internal bore of the fitting during the last inspection.

⁵² The Chief Engineer for the maintenance organisation reported that originally, they did not apply the Dinitrol AV 30, instead using a lubricating grease as a corrosion inhibitor in the fitting. Due to some indications of damage in the fittings, they had changed to using AV 30 a 'few years' prior to the accident.

⁵³ The ATSB was unable to determine whether the time in service was required to be, or had been factored for that aircraft.

0.020 inches (0.508 mm). The fitting could not be located by the ATSB and further details of the crack or fitting bore were not available.

- In October 2012, a defect indication was found in a lower-left centre section wing attachment fitting. It was inspected by the same NDT organisation and technician that inspected the TZJ fittings, and the aircraft operator was the same as for TZJ. The test report stated: 'Crack indication detected in LH LWR [left hand lower] centre section wing fitting.' The report did not identify the location of the defect within the fitting. The ATSB obtained the subject wing attachment fitting and conducted a detailed visual examination under magnification, and via MPI. There was some slight mechanical damage (scoring) in the bore but no cracking or corrosion was identified.
- In August 2013, the report of a dye penetrant inspection of another M18's wing attachment fittings stated: 'cracking & corrosion noted on Fore & Aft Attachment Lugs, items do not comply with inspection criteria.' In 2015 all sets of fittings (upper and lower, inner and outer, left and right) from that aircraft were inspected by an NDT specialist under the supervision of the ATSB, using the same equipment (eddy current device, probe, and reference standard) and equipment settings as were used to inspect TZJ's wing fittings.⁵⁴ Minor surface marks were detected and there were crack-like indications on several lugs. Some of these indications were at a level greater than the threshold used for TZJ's wing attachment fittings and some were lower. Later detailed visual (under magnification) and MPI did not identify any cracks and the ATSB concluded that all of the indications were most likely due to surface irregularities including scoring and corrosion.

All of the above occasions involved turbine-engine aircraft and each inspection was carried out by different NDT organisations.

A search of the CASA service difficulty report database found no record of either the 2012 or 2013 defects discussed above.

On 1 November 2013, CASA directed all Australian M18 operators to conduct additional wing attachment fitting inspections using MPI. All operational aircraft were inspected and there were no reports of cracked fittings.

Eddy current inspection procedure

Development and approval of the eddy current inspection procedure

In September 2000, the NDT organisation applied to CASA for approval of an eddy current inspection procedure as an alternative to the magnetic particle procedure in service bulletin E/02.170/2000. That procedure, number QP.00.36 (EC), marked as issue 2 and dated 8 September 2000, was approved by CASA on 11 September 2000 under CAR 2A(4).

The NDT organisation reported that the procedure was developed because inspecting the wing attachment fittings using MPI could be considered unworkable with the wings in place. This was due to the size and shape of the MPI yoke⁵⁵ and the geometry of the inspection areas. The eddy current method allowed inspections with the wings in place as the required equipment was much smaller.

A copy of the procedure and letter of approval was obtained from CASA. The procedure made reference to service bulletin E/02.170/2000 and detailed an eddy current inspection that used a hand-rotated probe. The header on the procedure identified the NDT organisation that applied for the approval and was listed in the letter of approval from CASA.

⁵⁴ The fittings had been stored for over a year in an outdoor scrap yard and most of the bores were severely corroded when retrieved.

⁵⁵ A hand-held device for magnetising test pieces.

Review of the CASA file that contained the eddy current inspection procedure approval found that the procedure was reviewed by a CASA NDT specialist. A number of minor comments about the initial issue that was supplied for approval (issue 1) were made by the CASA NDT specialist, and the NDT organisation revised the procedure. The revised procedure (issue 2) was accepted by CASA's NDT specialist on the basis of their judgement that 'it will offer an equivalent, or superior, level of safety to the magnetic particle inspection.' Based on the NDT specialist's recommendation, the procedure was approved under CAR 2A(4) in regard to how maintenance is carried out on an aircraft, its components or material.

The available CASA files contained no evidence of correspondence with the aircraft manufacturer, by either the NDT organisation or CASA, for advice on the suitability of the proposed procedure. Other than some general comments regarding the merits of eddy current inspection over MPI, there was no detailed engineering justification to show that the proposed procedure would provide equivalent, or superior safety to the service bulletin procedure.

Correspondence in a CASA file indicated that in October 2000, during the development of CASA AD/PZL/5, the CASA NDT specialist was copied in on correspondence with the aircraft manufacturer. The correspondence made the NDT specialist aware that the aircraft manufacturer considered that the eddy current method could be ineffective for inspecting the wing attachment fittings.

Observations:

Thirty-eight days elapsed between CASA approving the eddy current inspection procedure under CAR 2A(4) and the release of AD/PZL/5. However, there was nothing identified in any CASA file that showed CASA made the NDT organisation aware that the eddy current method could be ineffective.

Once AD/PZL/5 was issued by CASA, the CAR 2A(4) approval was not sufficient in itself for the NDT organisation to use procedure QP.00.36 (EC) for wing attachment fitting inspections. To use the procedure for compliance with the AD, approval of an alternate means of compliance (AMOC) was required. There was no record in the CASA files of an application from the NDT organisation for an AMOC.

Procedure versions

The ATSB obtained copies of inspection procedure QP.00.36 (EC) issue 2, dated 8 September 2000, from both CASA and the NDT organisation. Although the procedure number, issue number and date were the same,⁵⁶ there were significant differences between the documents. Some of these differences are shown in Table 5.

⁵⁶ The cover page for the procedure listed the procedure as QP.00.36(E), but all other pages identified the procedure as QP.00.36(EC).

Table 5: Comparison of the eddy current procedures supplied by CASA and the NDT organisation

	Version on the CASA file	Version supplied by the NDT organisation
Applicability	PZL Service Bulletin E/02-170/2000	CASA Service Bulletin [sic] AD/PZL/5
Equipment	Manual probe with adjustable collar	Motorised rotating probe
Probe frequency⁵⁷	100 kHz	300 kHz
Reference standard	Text describes a 0.1 mm x 2 mm deep slot and refers to a figure that does not exist	Text describes 1 mm slot; however, there are two illustrations, one detailing a 2.0 mm x 2.0 mm corner slot in the reference standard and another that describes a 1 mm x 0.5 mm slot
Acceptance criterion	Less than 10% full-scale deflection	Less than 40% full-scale deflection

In addition to these differences, the NDT organisation changed identity in 2007 when it was purchased by the current owner. The version of the procedure supplied to the ATSB by the NDT organisation identified the new company name and business registration number in the document header. This company name was different to that listed in the version on the CASA file and specified in the approval letter.

The NDT organisation's copy of the CASA approval letter was the same as the one held in the CASA files (that is, referring to procedure QP.00.36 (EC) and dated 11 September 2000).

Observation:

The reference in the NDT organisation-supplied version of the eddy current procedure to AD/PZL/5 indicates that the procedure was developed after its original approval by CASA. The different company names identified on the documents indicates that it was produced in 2007, or later.

The version of the eddy current procedure supplied by the NDT organisation could not be located in CASA records and there was no record of approval being sought for any related procedure after 11 September 2000.

Eddy current reference standard

The reference standard reportedly used by the NDT organisation to calibrate the equipment for each inspection was constructed from a retired M18 wing attachment fitting (Figure 23). The reference standard contained a corner notch that was 2.4 mm long, 2.4 mm deep (maximum) and about 0.18 mm wide at the edge of the bore. An apparent identifying mark (engraving) had been made on the reference standard but, when examined in December 2013, the mark was very worn and unreadable.

⁵⁷ Higher frequencies have less depth penetration. At 300 kHz, penetration depth will be about 58 per cent of that at 100 kHz. In general, an anomaly (such as a crack) that is shallower than the penetration depth will provide a stronger response at higher frequencies, because a higher proportion of the eddy currents are disrupted. However, other factors can reduce the effectiveness at higher frequencies.

Figure 23: Eddy current reference standard used by the NDT organisation for its M18 wing attachment fitting inspections (inset showing the corner notch)



Source: ATSB

Eddy current procedure technical assessments

ATSB assessment of the eddy current procedure

The ATSB reviewed both versions of eddy current inspection procedure QP.00.36 (EC) issue 2 for their technical content and identified a number of issues.

The procedures included information regarding the preparation of the aircraft without direct reference to the appropriate instructions in the aircraft maintenance manual. In addition, the quality of both versions of the procedure was not to a standard that would permit reliable and repeatable inspections, and there were many errors and inconsistencies in both. Issues with the procedures included:

- ambiguous instructions
- ambiguous reference standard specification
- non-specific probe specification
- incomplete specification of test settings (such as filters).

In addition, the procedures did not state that only part of the manufacturer's service bulletin or CASA AD/PZL/5 would be addressed.

CASA assessment of the eddy current inspection method following the accident

An internal CASA report on a visit⁵⁸ to the NDT organisation following the accident was obtained by the ATSB. That report identified the following technical issues with the procedure:

It would appear that this NDT procedure is an amended generic manual bolt hole inspection procedure, and was not fully corrected and detailed for the specifics of the PZL-M-18 wing attach lug inspection. Accordingly, there are anomalous instructions throughout, which result in it being confusing and impractical to follow... The corrections required to make this procedure acceptable as a coherent work instruction would constitute a complete rewrite, including corrected figures and drawings, inclusion of [instrument filter] settings, clarification of the accept/reject criteria and clarification that it only replaces the magnetic particle inspection method part of AD/PZL/5 compliance, other aspects of the AD remain with the LAME.

⁵⁸ The visiting group included an independent NDT specialist as advisor to CASA.

CASA processes for NDT procedure approval

CASA reported that they do not have a defined process for the assessment of industry-proposed NDT inspection procedures. Prior to about 2009, CASA assessed the adequacy of any industry-proposed alternative procedure internally using a Level 3 NDT-qualified CASA official. At the time of writing, CASA reported that it now contracts the National Aerospace Non Destructive Testing Board (NANDTB)⁵⁹ for this purpose. The NANDTB evaluates the proposals from industry and provides technical input in the form of a recommendation to CASA, upon which a CASA delegate can make an approval. CASA advised that there is an emphasis on the applicant to provide any supporting information and justification required to make a decision.

When it came to an application for an AMOC with an AD, section 14 of AC 39.1(1) stated (emphasis added):

An equivalent means of compliance satisfying CASR 39.4^[60] must be substantiated and approved by the Authority... It is the applicant's responsibility to prove that the aircraft can be operated to the same level of safety as stipulated by the requirements of the AD. To enable approval of an alternative method of compliance, **the applicant will need to supply engineering justification as to how the proposed alternative means will establish an equivalent level of safety to that required by the AD.**

In addition, CASA's Airworthiness Directive Procedures Manual stated that 'Any Exclusion approved must be to an acceptable level of safety based on thorough engineering assessment.'⁶¹

A review of the CASA files containing approved NDT procedures found that the files typically only contained a:

- copy of the proposed procedure
- referral to the CASA delegate for approval
- statement indicating that CASA's NDT specialist had assessed the procedure and recommended it for approval
- letter to the applicant stating that the procedure was approved under CAR 2A(4).

There were no detailed records of engineering justifications, made either by an applicant or by CASA, within the files.

A request for approval of a magnetic particle inspection procedure to inspect M18 centre-to-outboard wing fittings was submitted to CASA following the accident involving TZJ. ATSB review of that approval found that, although the assessment appeared to be more thorough, there was no indication of a systematic approach to show that the proposed procedure had the appropriate sensitivity and repeatability to ensure equivalent, or better, safety than the original procedure.

Applications for AMOCs to CASA AD/PZL/5

Records in CASA's files showed that the operator of TZJ applied for exclusions to the AD. These exclusions were assessed and approved by CASA and were effectively AMOCs.

In May 2004, exclusions were granted to allow the operator to extend the inspection interval for the upper wing attachment fittings on three of its M18 aircraft. These exclusions did not include TZJ and permitted an extension in the inspection interval for the affected aircraft from 500 hours to 800 hours. To support the application, the operator sought advice from the aircraft manufacturer,

⁵⁹ The NANDTB is an organisation comprised of industry NDT specialists. CASA funds the NANDTB board under a deed of agreement to provide such input among other matters relating to NDT.

⁶⁰ CASR 39.4 was later renumbered 39.004.

⁶¹ Airworthiness Directives Procedures Manual, version 2.0, August 2004. In this context, an exclusion may be provided for a 'different method of inspection to that specified'. That is, an alternate means of compliance.

who had no objection to the interval extension. That advice was supplied to CASA with the application. The application was assessed by an engineering officer in CASA's Airworthiness Standards Branch.

In 2009, an exclusion was approved by CASA that allowed use of the eddy current inspection procedure in place of the magnetic particle procedure. To support the application, the operator supplied a copy of the NDT organisation's September 2000 CAR 2A(4) approval letter for the eddy current inspection. However, the approval was only for one of the operator's M18s, VH-JTJ. The application was assessed and approved by one of CASA's regional offices. There was no evidence that either CASA, or the operator contacted the aircraft manufacturer for advice during this approval process.

Other than the approval for VH-JTJ, there was no record of the eddy current inspection procedure being approved for use to comply with AD/PZL/5 or any applications for such approval.

In contrast, the FAA reported that they had not permitted any AMOCs to their AD. In fact, they had declined a request to use an eddy current method in 2011. This decision was made by the FAA after consultation with the aircraft manufacturer.

Management of firebombing operations

In November 2013, anecdotal reports emerged claiming that the pilot of TZJ was under operational pressure to fly in adverse weather conditions in the days prior to the accident. The ATSB interviewed some of the involved individuals and obtained correspondence between the pilot and the NSW Rural Fire Service (RFS). The sequence of events derived from that correspondence is discussed in the remainder of this section.

On 22 October 2013, the RFS sent a notice to all flight operations managers and chief pilots, stating that 'safety remains paramount' and emphasising the need to 'maintain safe operations at all times.'

On 23 October 2013, the pilot (in the capacity of chief pilot) voluntarily and temporarily grounded four of the operator's aircraft due to adverse weather conditions. Subsequently, a local airbase manager asked two of the operator's other pilots to fly, which was refused. According to reports, the airbase manager made a disparaging remark, criticising their decision.

The pilot of TZJ later raised the issue with RFS officials, objecting to the remark. The RFS supported that position and reiterated its support of pilots having ultimate control over whether to fly. The airbase manager who made the remark was reprimanded by the RFS and transferred to a different role.

The event was unlikely to have had an adverse impact on the operation of TZJ. The pilot flew three times on the afternoon of 21 October, six times on 22 October and only once when the weather was worse on 23 October. This indicates that weather was likely to have been taken into consideration by the pilot on that day. Also, the pilot's family reported that a telephone conversation prior to the 24 October flight did not indicate that the pilot had any concerns at the time. Furthermore, the witness reports indicated that the aircraft was being operated normally at the time of the accident.

While explicit and implicit pressure to continue operations at times of increased risk to persons and property should be avoided, there was little potential for any pressure that might have been felt by the pilot of TZJ to have contributed to the accident. In addition, the evidence available gave no indication that organisational pressure was a systemic problem within the RFS.

Safety analysis

Wing failure and fatigue cracking

Eyewitness reports and the wreckage distribution are consistent with VH-TZJ's (TZJ) left wing separating in flight. Examination of the wreckage indicated that pre-existing fatigue cracking in the lug of the left outboard wing lower attachment fitting had weakened the fitting.

Descriptions of the final moments of the flight did not indicate that TZJ was carrying out any extreme manoeuvres, or encountering any extreme meteorological conditions, when the left wing separated. This indicates that the weakened attachment fitting was probably not subjected to abnormally high loads at the time of the accident.

At some stage in TZJ's history, corrosion pits formed in the bore of the fitting. These pits created local stress concentrations that significantly increased the likelihood of the formation of fatigue cracks. Over time, micro-cracks developed at a number of the pits located in the lower ligament of the fitting. The micro-cracks grew under repeated flight loads and a number that had been roughly aligned with each other merged to form one crack. The crack continued to grow until the strength of the fitting reduced to the point that it was incapable of withstanding the flight loads, and it failed.

TZJ's wing fittings were last inspected in August 2013, 11 calendar weeks and 126.3 flight hours prior to the accident flight. This inspection used visual and eddy current inspection techniques, and no cracks or other anomalies were reported. This would indicate that either there was a crack present but not detected at the time of inspection, that the crack initiated and grew much faster than expected, or both.

Opportunities to detect corrosion and cracking in the bore of the left outboard wing lower attachment fitting

Overview

Pitting corrosion and resultant fatigue cracking in the bore of the wing attachment fittings was a known issue in the PZL M18 since 2000 and was the subject of airworthiness directives (ADs) issued by the United States (US) Federal Aviation Administration (FAA) and the Australian Civil Aviation Safety Authority (CASA). Those ADs mandated inspections and repair to be carried out in accordance with a service bulletin from the manufacturer. This service bulletin clearly stated that all corrosion was to be removed and, if any cracking was present, then the fitting was to be replaced.

Corrosion

The ATSB was not able to determine with a reasonable degree of certainty when the corrosion pitting in TZJ's lug commenced. However, evidence in the bore of the fitting indicated that the pitting was present, but not removed, during previous maintenance.

The release of the aircraft back into service with the corrosion pitting present was probably a result of the maintenance organisation's practices when carrying out the work for CASA AD/PZL/5. Because those practices did not make direct reference to the manufacturer's service bulletin while carrying out the work, the Licensed Aircraft Maintenance Engineer (LAME) who undertook the work was likely not aware of the manufacturer's strict requirements on corrosion removal. Instead, the LAME either did not detect the corrosion, or applied their own subjective assessment on what level of pitting was acceptable and did not take the appropriate actions to remove the pitting.

The continuing presence of corrosion pits increased the likelihood of the initiation of fatigue cracks in the wing attachment fittings.

Cracking

The ATSB was unable to quantitatively determine the period over which the fatigue cracking in TZJ's lug developed. This was because of the variable and irregular nature of the wing loading spectrum, the corroded bore surfaces and the somewhat oxidised and poorly defined microscopic fracture features. However, the fracture surface features were consistent with the cracking initiating and developing over an extended period. On that basis, the ATSB concluded that it was likely the cracking initiated and had been developing for a period significantly longer than the 126.3 hours of time in service and 11 calendar weeks since the last maintenance inspection.

The non-destructive inspections that were carried out as part of CASA AD/PZL/5 used a method that the manufacturer previously advised CASA to be ineffective for detecting cracks in M18 wing attachment fittings. CASA were aware of this in 2000 and the AD specifically stated that a magnetic particle inspection method was to be used.

The eddy current procedure was approved by CASA for use as approved maintenance data under CAR 2A(4) prior to AD/PZL/5. However, it was not subsequently approved by CASA as an alternate means of compliance (AMOC) with the AD for TZJ. Nonetheless, a number of maintenance personnel had certified for the inspection of TZJ and other M18 aircraft in accordance with AD/PZL/5 using eddy current-based procedure QP.00.36 (EC). This inspection procedure was used by these personnel as an alternative to the stipulated magnetic particle procedure without evidence of, or reference to, any approved exemption/variation. Instead, all of the maintenance records related to wing attachment fitting inspections were referenced against AD/PZL/5. This indicated that the LAME and the non-destructive test (NDT) technicians involved considered the eddy current inspections acceptable to meet the requirements of AD/PZL/5.

Other issues regarding the eddy current inspection procedure were also identified by the ATSB. These issues are discussed further in the section titled *Eddy current inspection procedure*.

Factors affecting the wing attachment fitting fatigue age and crack growth

Overview

Many factors contribute to the accumulation of fatigue damage. The US FAA Advisory Circular AC 23-13A stated that:

...changes to the operational characteristics that may be important for fatigue include higher design airspeeds or higher average speed. They also include changes to the maximum allowable weight and centre of gravity envelope, changes to the average weight and centre of gravity location, and engine or propeller changes.

In the case of TZJ, several modifications and operational factors would have resulted in changes to the rate of fatigue damage accumulation, as discussed in this section.

The aircraft had accrued 7,013.6 unfactored flight hours at the time of the accident. This time was used as the basis for subsequent estimates of the aircraft's effective fatigue age.

The ATSB identified a number of factors that probably contributed to the left outboard wing lower attachment fitting sustaining greater fatigue damage than the recorded flight hours would indicate – that is, that the cracks would have initiated more rapidly.

Incorrect application of service life factors

The aircraft's flight and repair manuals required the operator to apply a service life factor to the flight time whenever the aircraft was operated at take-off weights above 4,700 kg. The factor's numerical value depended on the take-off weight and applied to the entire flight time. The resultant 'factored' time was to be used for determining the aircraft's age (time in service) and for scheduling maintenance. As factored, time operating overweight increased the aircraft's age and effectively reduced the required time between scheduled maintenance actions.

The ATSB found that the operator did not correctly apply the appropriate service life factors. In August 2013, M18 operators were directed by CASA to account for the operation of their aircraft under Australian Supplemental Type Certificate (STC) SVA521 for overweight operations.

However, CASA only required this data from when the STC was approved in 2009. In the case of TZJ, the aircraft was operated at weights in excess of 4,700 kg for some time prior to 2009, potentially since its importation into Australia.

The operator had not recorded, or retained the take-off weights for each flight for the entirety of the aircraft's operational life. Therefore, it was not possible to precisely determine the full effect of the lack of factoring. However, by extending the factor used by the operator to recalculate the aircraft service life in August 2013 back to the aircraft's introduction in 2004, the effect of the overweight operations since 2004 could be estimated. This increased the aircraft's total time in service to about 10,398 hours and the wing fitting's to about 7,367 hours. However, the aircraft's time in service could have been as high as about 12,190 hours, and the fitting about 9,159 hours if all operations were at the maximum possible weight.

A letter from the then operator to CASA as part of the STC justification package indicated that a number of other M18's were also operated at weights in excess of 4,700 kg prior to the approval of the STC. Additionally, the ATSB had previously identified a safety issue relating to an incorrect method used to apply service life adjustments when operating at higher weights.⁶²

Higher operating speeds

The recorded data indicated that TZJ was operated at average speeds higher than assumed by the manufacturer in their fatigue analysis. Aircraft flight load spectra are based on the number of flight load exceedances per nautical mile travelled. An increase in an aircraft's average operating speed results in the aircraft travelling further for the same flight time. A proportional increase in the rate of accumulation of fatigue-inducing flight load cycles follows. This is supported by the fact that an aircraft will generally conduct more turns and encounter more turbulence cycles over a period of time if it is travelling faster.

TZJ's average recorded airspeed in 2007 and 2008 was about 22 per cent above the average operating speed of 97 kt that was assumed by the manufacturer for the purposes of fatigue calculations. It was also 13 per cent above that speed in data from the 2013 flights. The 2007-08 flights occurred before STC SVA521 lowered the maximum operating speed from 121 kt to 115 kt, which may explain the reduction in the average operating speeds.

The data set available was relatively small and varied significantly between each flight, so it was not possible to positively determine the aircraft's overall average speed throughout its operating life. However, an estimate was made by assuming that the aircraft was operated at the recorded average speeds before and after the approval of the STC in March 2009. This estimate resulted in an estimated average operating speed of 115 kt. This would increase the rate at which the aircraft encountered fatigue-inducing flight loads by about 18 per cent.

Flight load spectrum

The recorded data from the flights in 2007 and 2008 also indicated that the actual flight load spectrum experienced by the airframe in that period was much more severe than that used by the manufacturer to determine the fatigue life of the aircraft. According to the aircraft manufacturer, the effect of this increased flight load spectrum alone on the effective fatigue age of the aircraft was as high as a factor of about 4.6. However, when the higher airspeed and the average flight time for TZJ was included in the analysis, the reduction in the fatigue life was a factor of about 3.85.

⁶² Refer to appendix E and ATSB safety issues investigation AI-2011-150, available from the ATSB website at www.atsb.gov.au.

Although the effect of the flight load spectrum on the effective age of the aircraft is significant, the operator would not be expected to know that the manufacturer's assumed spectrum was being exceeded or that additional damage was being accumulated. This is normal for the operation of aircraft in which the management of aircraft structural fatigue is based on the safe-life approach. In the absence of corrosion pitting, the effect of the actual flight spectrum in TZJ may have been within the conservative margins applied to the determination of the fatigue life. However, in the case of TZJ, the pitting probably resulted in an acceleration in the formation of the fatigue cracks.

Although the operator generally operated the aircraft within the approved flight envelope, the recorded data indicated that the limit load was exceeded on at least one occasion. The effect of this exceedance on the aircraft's fatigue life could not be determined. However, an exceedance of this nature can result in discrete damage to the structure and requires a series of special inspections to check for such damage. No special inspections were identified in the aircraft's maintenance records.

Modifications to the aircraft

The aircraft had a number of approved modifications that potentially affected the fatigue of the wing attachment fittings. Those modifications included:

- replacing the piston engine and 4-blade propeller with a turboprop engine and 5-blade propeller
- installation of servo tabs on the flight controls
- the installation of vortex generators on the wings
- modification of the hopper.

The ATSB could not determine whether any of these individual or combined modifications had an effect on fatigue. There was no indication of an effect in the documentation associated with the modifications, though the respective designers might have considered any effect negligible in isolation. However, the potential that the combined effect of the multiple modifications was other than negligible could not be discounted.

Overall effect of aging factors on the aircraft and wing attachment fitting

Assuming that the combined effect of aging factors was additive, the overall fatigue age of the aircraft could be estimated by multiplying the time in service (TIS) by each of the factors as follows:

$$\begin{aligned}
 \text{Estimated airframe fatigue age} &= \text{TIS prior to 2004} + (\text{TIS from 2004} \times \text{weight factor} \times \text{flight load spectrum factor}) \\
 &= 3,031.4 + (3,982.2 \times 1.85 \times 3.85) \\
 &= 31,395 \text{ hours}
 \end{aligned}$$

It follows that the effective age of the wing fittings on TZJ was probably around 28,364 hours, as they were likely replaced at 3,031 airframe hours. If they had not been replaced in 2004, then the estimated effective age of the wing fittings would be similar to the airframe age.

These fatigue ages are much higher than the permitted airframe service life of 10,000 hours. This indicates that the likely level of fatigue damage on TZJ's airframe and, in particular, the wing attachment fittings would have been much higher than the maximum permitted by the aircraft's safe-life justification. This would result in a significantly higher likelihood of fatigue cracks forming and a more rapid rate of fatigue crack growth.

The damaging effect of this accelerated aging was further amplified by the presence of pitting corrosion in the left wing attachment fitting. By comparison, the right hand outboard wing attachment fitting was subjected to the same loadings and conditions, yet had no crack indications. This was probably due to the absence of pitting corrosion in the critical stress region of that fitting.

Overall effect of aging factors on crack growth

The aircraft manufacturer estimated that, on a base M18 aircraft, it would take between 6,000 and 7,000 flights for a crack to grow to the size observed in TZJ. The ATSB estimated this number of flights to equate to about 3,000 to 3,500 flight hours. However, the factors that affected the age of the aircraft would also have had an effect on the rate of crack growth.

Although related, the factors affecting an aircraft's fatigue age cannot be applied in the same way to crack growth as they were to determine the effective fatigue age. Due to a number of unknown variables, such as certain material properties relating to crack growth, the ATSB was not able to quantify the extent to which they contributed to the crack growth rate in this case.

Effect of aging factors on wing fitting inspection intervals

The aircraft's maintenance documentation required the scheduling of maintenance to be based on the factored flight hours.

For example, at the AD/PZL/5 inspections carried out on 18 October 2012, the aircraft had logged 403 flight hours since the previous inspection. Assuming the same weight factor for overweight operations used in the above calculations was applied during that period, the factored hours between inspections was 746 hours (1.85×403 hours). However, this could potentially be as high as 927 hours (2.3×403 hours), if all operations in that period had been at the maximum take-off weight permitted by the STC. At the time, the operator probably thought that they were inspecting the aircraft more regularly than required. However, the fatigue damage being accumulated in that 403 hours was likely significantly more than the 500 hours accounted for by the AD.

Following the direction from CASA in July 2013, the operator was properly accounting for the take-off weight in the records for the aircraft. However, because there had been no requirement for the hours-based inspections since that time, the ATSB could not verify that the future scheduling would have been based on the factored hours.

The effect on the aircraft's service life due to increased take-off weight was available to the operator. However, the effect of the higher operating speeds and flight load spectrum, which would also contribute to the effective 'fatigue age' of the aircraft, was not information that was available to the operator. Accounting for this in the 18 October 2012 estimated airframe fatigue example above, TZJ could have effectively accumulated a fatigue equivalent of about 2,872 hours (3.85×746 hours) in that 403 hours of actual flight. Assuming all flight in that period was at the maximum weight, this could be as high as about 3,569 hours (3.85×927 hours).

The shortest interval between inspections of 267.2 hours occurred on 8 August 2013. Using the same factoring as above, the equivalent fatigue damage in this inspection interval could have been in the order of 1,900 to 2,370 hours.

Even though it may have appeared that the operator was inspecting the fittings more regularly than required, the aircraft, and hence the wing attachment fittings, were likely accumulating significantly more fatigue damage. That equivalent amount of fatigue damage far exceeded that accounted for in the AD's 500-hourly inspection interval. Thus, the inspections were not providing the level of safety that was intended by the AD.

Similarly, the first inspections of the replacement wing attachment fittings occurred when they had accrued 1,224.4 flight hours. If this is multiplied by all of the above factors, the effective fatigue age of the fittings at the time could have been in the order of 8,720 to 10,840 hours. This is more than twice the initial inspection threshold of 2,500 hours in the CASA AD.

Eddy current inspection procedure

Control of inspection procedure versions

The CAR 2A(4) version of eddy current procedure QP.00.36 (EC) held on file by CASA was significantly different to that supplied to the ATSB by the non-destructive test (NDT) organisation, even though they had the same procedure number, date and issue number.

The NDT organisation reported that the version of QP.00.36 (EC) that it supplied was used on all the M18 wing attachment fittings it had inspected. The NDT organisation's version of the procedure referenced AD/PZL/5 and was on the letterhead of a company whose name was not in use until 2007. Therefore, the NDT organisation's version of the procedure must have been produced after the release of AD/PZL/5, and also after 2007, thus after the date of the original approval letter.

There was no evidence that the NDT organisation applied to have its revised version of the procedure approved by CASA. This approval process, if applied, would have provided an opportunity for CASA to advise the organisation of the limitations of the method identified by the aircraft manufacturer and to ensure compliance with the AD.

The use of the unapproved procedure indicated that the NDT organisation did not ensure revisions to procedures were appropriately managed. The effective control of approved maintenance documentation is vital to the safe operation of aircraft and the use of unapproved procedures diminishes that level of safety.

Technical suitability

The differences in the two versions of the eddy current procedure included different equipment, presentation of defects, system settings and reference standards that would likely have resulted in different crack detection sensitivities.

ATSB and CASA reviews of the procedures in response to this accident found that the quality of both versions was not to a standard that would permit reliable and repeatable inspections. There were many errors and inconsistencies in both versions. This included:

- ambiguous instructions
- an ambiguous test piece specification
- a non-specific probe specification
- an incomplete specification of test settings.

In addition, the reference standard used by the NDT organisation had inadequate identifying markings and contained a notch that did not match any of the procedural specifications.

The effect of these problems could not be quantified but probably affected the consistency and sensitivity of the NDT inspections.

Finally, the eddy current procedure did not specifically state what parts of the manufacturer's service bulletin it replaced. As a result, there was a risk that maintainers could think that completion of the eddy current procedure alone was sufficient to address all of the requirements of AD/PZL/5 or the service bulletin.

CASA processes and records

Information contained on airworthiness directive file

The effectiveness of the CASA file pertaining to AD/PZL/5 was significantly reduced by the absence of relevant information. This included the technical information considered during the development of the AD and on the approval of an exclusion against the AD.

In many cases, the background and technical information contained in an AD may be sufficient in itself to make an acceptable assessment. In this case, however, there was information regarding

the importance of the specified inspection methodology contained in another file. To another CASA officer making a decision regarding the AD, unless cross-referenced, that file may not have been obviously related. There were neither copies of the relevant information, nor cross-references to its availability, in the AD file.

This would likely make it difficult for another CASA officer to discover the important information and make appropriately-informed decisions regarding the AD, such as when assessing the suitability of AMOC applications.

CASA procedures for the assessment of alternative non-destructive inspection procedures

Assessment of the M18 eddy current inspection procedure

In its considerations for the CAR 2A(4) approval of QP.00.36 (EC), CASA noted several general characteristic benefits of eddy current inspection. However, there were no records of the method being considered in the M18 wing attachment fitting context, such as inspection in the presence of corrosion. Neither was there evidence that engineering rigour was applied to the theoretical or practical effectiveness of the reference standard notch size, either:

- absolute (with regard to the material strength and crack growth characteristics of the wing fittings)
- relative (by comparison with the originally-specified magnetic particle inspection method).

Assessment of alternate inspection procedures

Regardless of whether a proposed alternate inspection procedure applies to an AD or normal maintenance instructions, the alternate method must not reduce the safety of the aircraft. To this end, it would be expected that justification would have been provided, or an assessment been made, that the proposed alternate method was as sensitive at detecting the required defects as the process proposed for replacement. This should not be limited to the technical capabilities of the methodology, but should include assessment of other items effecting the reliability of detection such as the test equipment, human factors, testing environment, and the access to and condition of the part being tested.

There was no evidence in CASA's approved NDT procedures file of any engineering justification, by either the applicant or CASA, for the proposed alternative non-destructive inspection methods. Most of the recommendations for approval of the alternative procedures appeared to be based on the engineering judgement of the person assessing the application, rather than on a robust, systematic approach.

Although the change to CASA's use of an external NDT board, rather than an internal NDT specialist, means that it is more likely that the assessment of proposed procedures receives a broader review base, the process still appears to rely on the engineering judgement of the reviewer. CASA does not have a defined process that provides a robust, systematic approach to the technical assessment of proposed alternative NDT inspection procedures and does not assure an equivalent, or better, level of safety than the original procedure.

Importantly, this accident highlights the value of consultation with aircraft manufacturers when making decisions regarding variations to their maintenance processes. In this case, the manufacturer had specified an inspection method in their service bulletin for a particular reason. However, CASA approved an alternative inspection method without consulting the manufacturer, missing the opportunity to draw on their expert knowledge during their assessment.

Manufacturer's service bulletin

Aircraft manufacturer service bulletin E/02.170/2000 on the inspection and repair of centre-to-outboard wing attachment fittings stated that the wings do not need to be removed for inspection of the wing fittings. That statement was emphasised in the bulletin by being underlined,

which may suggest to a reader that the preferred method was to leave the wings in place. However, the ATSB noted that due to limited physical access to the attachment fitting lugs with the wings in place, it would be difficult or impossible to conduct a magnetic particle inspection (particularly in the case of the outboard wing attachment fitting). In addition, the mating faces of the fitting lugs are not accessible without removing the wing. As a result, any corrosion or cracking in those areas would likely not be observable, and the likelihood of flaw detection would likely be lower.

When there are two ways to carry out a safety-critical task, and each has different risks, there needs to be sufficient information in the instruction to help the maintainer select the most appropriate method.

In the case of TZJ, non-removal of the wings was not likely to have significantly affected the performance of the eddy current testing on the fitting bores. However, it would have made visual inspection of the bores for corrosion/pitting damage more difficult. Also, it is possible that a large crack, if present, might have been visible from the side of the lug.

Australian Supplemental Type Certificate for overweight operations

Australian Supplemental Type Certificate (STC) SVA521 permitted increased-weight operations and accounted for the effect that the increased weight had on the fatigue life. It also had a minimum operating speed of 100 kt. This was faster than the average speed assumed by the manufacturer in their determination of the fatigue life for the M18 of 97 kt.

In practice, the aircraft's normal operating speeds would be greater than the minimum operating speed. This observation is consistent with the average speeds in the available recorded data for TZJ of 111 to 118 kt.

The effect of the increased average operating speed was not accounted for during development of the STC. Detailed analysis would be required to determine how significant the effect may be, however it may result in the service life factor underestimating the equivalent amount of fatigue damage.

The operating speed on which the manufacturer based the M18 fatigue life was not a published figure. Without knowledge of this speed, the STC holder could not have accounted for the detrimental effect of the STC's changed operating speed limitations on the aircraft's fatigue life.

Application of service life factors to other M18 aircraft

CASA had directed the operators of M18 aircraft that had, or were operating to the requirements of STC SVA521, to recalculate the service lives of those aircraft to account for operations above 4,700 kg. However, they were only required to do so back to 2009. This resulted in a substantial amount of time where the weight of the operators' aircraft likely exceeded 4,700 kg, but the associated service life factors were not accounted for, and hence the respective aircraft's service life was not correctly calculated.

Service life factoring is not only applicable to turboprop-powered M18 aircraft. The operation of piston-engined M18 aircraft above 4,700 kg also requires the application of a service life factor as per the M18 Repair Manual. The effect on these aircraft's service life is less due to a smaller potential service life factor. However, it is still important that the service life of such aircraft be correctly calculated to ensure that life limitations and maintenance intervals are not exceeded.

Under-reporting of defects

Any cracks and/or corrosion detected in the M18s wing attachment fittings would be considered a major defect and, as such, should have been reported to CASA. In addition, any defect detected when complying with the AD should have been reported to CASA. However, the ATSB found no

record of the 2012 or 2013 defects identified in M18 wing fittings in CASA records. This indicated that they were probably not reported to CASA.

In each case, no crack was identified by more detailed ATSB inspection of those 2012 and 2013 wing fittings as part of this investigation. However, if the indications had been genuine flaws, CASA needed to be made aware in order to monitor the effectiveness of the current AD, or to determine if there was a wider problem with the fittings.

The reporting of defects is an important process that allows regulatory agencies and manufacturers to identify and manage potential fleet safety and ongoing airworthiness issues related to a specific aircraft type or component. Defects identified in one aircraft potentially affect all other aircraft of that type and by not reporting any defects identified, the safety of those other aircraft may be reduced.

Findings

From the evidence available, the following findings are made with respect to the in-flight break-up involving modified PZL Mielec M18A Dromader aircraft, registered VH-TZJ, which occurred 37 km west of Ulladulla, New South Wales on 24 October 2013. It should not be read as apportioning blame or liability to any particular organisation or individual.

Safety issues, or system problems, are highlighted in bold to emphasise their importance.

A safety issue is an event or condition that increases safety risk and (a) can reasonably be regarded as having the potential to adversely affect the safety of future operations, and (b) is a characteristic of an organisation or a system, rather than a characteristic of a specific individual, or characteristic of an operating environment at a specific point in time.

Contributing factors

Occurrence events

- The aircraft's left outboard wing lower attachment lug fractured through an area of pre-existing fatigue cracking in the lug lower ligament, leading to in-flight separation of the wing, loss of control and impact with terrain.
- Corrosion pits in the bore of the aircraft's left outboard wing lower attachment fitting produced stress concentrations in the fitting that influenced the formation of numerous fatigue cracks.

Wing attachment fitting inspections

- Contrary to the requirements of Civil Aviation Safety Authority airworthiness directive AD/PZL/5 and the associated aircraft manufacturer's service bulletin, corrosion pits in the left outboard wing lower attachment fitting were not completely removed during maintenance.
- Numerous micro-cracks, which were probably present in the bore of the left outboard wing lower attachment fitting at the last inspection for Civil Aviation Safety Authority airworthiness directive AD/PZL/5, were not detected by the non-destructive inspection.

Aircraft operation

- The aircraft had been operated at higher speeds and subjected to a more severe flight load spectrum than assumed by the manufacturer when it determined the aircraft's service life limitation. This likely increased the rate of fatigue damage, increasing the rate of formation and growth of the micro-cracks in the left outboard wing lower attachment fittings.

Other factors that increased risk

Incorrect application of service life factors

- Although VH-TZJ's recorded time in service was within the aircraft's life limitations, the service life factoring required for overweight operations had not been appropriately applied for all overweight operations, leading to the calculation of an artificially low time in service.
- **Operators of some Australian M18 Dromaders, particularly those fitted with turbine engines and enlarged hoppers and those operating under Australian supplemental type certificate (STC) SVA521, have probably conducted flights at weights for which airframe life factoring was required but not applied. The result is that some of these aircraft could be close to or have exceeded their prescribed airframe life, increasing the risk of an in-flight failure of the aircraft's structure. [Safety issue]**

Aircraft operation

- Operation of M18 aircraft with a more severe flight load spectrum results in greater fatigue damage than anticipated by the manufacturer when determining the service life of the M18. If not properly accounted for, the existing service life limit, and particular inspection intervals, may not provide the intended level of safety. [Safety issue]

Eddy current inspections

- The eddy current inspection used on VH-TZJ, and other M18 aircraft, had not been approved by the Civil Aviation Safety Authority as an alternate means of compliance to airworthiness directive AD/PZL/5. This exposed those aircraft to an inspection method that was potentially ineffective at detecting cracks in the wing attachment fittings. [Safety issue]
- Although it was identified by the same procedure number, issue number and date, the procedure used by the non-destructive testing organisation for inspection of M18 wing attachment fittings contained significant differences from the approved procedure held on the Civil Aviation Safety Authority file.
- The documented procedure for eddy current inspection of M18 wing attachment fittings did not assure repeatable, reliable inspections. [Safety issue]

Civil Aviation Safety Authority records and processes

- Important information relating to Civil Aviation Safety Authority (CASA) airworthiness directive AD/PZL/5 was not contained in CASA's airworthiness directive file, but on other CASA files with no cross-referencing between those files. This impacted CASA's future ability to reliably discover that information and make appropriately-informed decisions regarding the airworthiness directive. [Safety issue]
- The Civil Aviation Safety Authority did not have a defined process for a robust, systematic approach to the assessment and approval of alternative non-destructive inspection procedures to ensure that the proposed method provided an equivalent, or better, level of safety than the original procedure. [Safety issue]

Inspection without removal of the wings

- Although wing removal was necessary to provide adequate access for effective visual and magnetic particle inspections of M18 wing attachment fittings, the aircraft manufacturer's service bulletin E/02.170/2000 allowed the wings to remain attached during these inspections. [Safety issue]

Australian supplemental type certificate SVA521

- The engineering justification package supporting Australian supplemental type certificate SVA521 did not contain consideration of the effect an increase in the average operating speed could have on the rate of fatigue damage accumulation. [Safety issue]

Under reporting of defects

- On at least two occasions involving different maintenance organisations, defect indications discovered in M18 wing attachment fittings were not reported to the Civil Aviation Safety Authority. Under-reporting of defects reduces the effectiveness of a system designed to provide regulators and manufacturers with timely information on potential in-service issues.

Other findings

- The combination of several modifications to VH-TZJ may have affected the rate of fatigue damage accumulation, although the extent of any effect could not be determined.
- The recorded data showed that there was at least one occasion in 2008 when the aircraft exceeded the flight load limit. However, there was no record in the maintenance documentation indicating that the operator carried out the inspections required following a flight load limit exceedance. The effect of this exceedance on the aircraft's fatigue life could not be determined.

Safety issues and actions

The safety issues identified to date during this investigation are listed in the Findings and Safety issues and actions sections of this report. The ATSB expects that all safety issues identified by the investigation should be addressed by the relevant organisation(s). In addressing those issues, the ATSB prefers to encourage relevant organisation(s) to proactively initiate safety action, rather than to issue formal safety recommendations or safety advisory notices.

All of the directly involved parties were provided with a draft report and invited to provide submissions. As part of that process, each organisation was asked to communicate what safety actions, if any, they had carried out or were planning to carry out in relation to each safety issue relevant to their organisation.

The initial public version of these safety issues and actions are repeated separately on the ATSB website to facilitate monitoring by interested parties. Where relevant the safety issues and actions will be updated on the ATSB website as information comes to hand.

M18 Dromader airframe life factoring

Number:	AO-2013-187-SI-01
Issue owner:	Civil Aviation Safety Authority
Operation affected:	Aviation: General aviation
Who it affects:	Operators of PZL M18 aircraft

Safety issue description:

Operators of some Australian M18 Dromaders, particularly those fitted with turbine engines and enlarged hoppers and those operating under Australian supplemental type certificate (STC) SVA521, have probably conducted flights at weights for which airframe life factoring was required but not applied. The result is that some of these aircraft could be close to or have exceeded their prescribed airframe life, increasing the risk of an in-flight failure of the aircraft's structure.

ATSB safety action

Action number: AO-2013-187-SAN-005

Action status: Released

As part of its interim report released on 23 December 2013, the ATSB issued the following Safety Advisory Notice to operators of M18 aircraft:

The Australian Transport Safety Bureau cautions M18 operators of the risks associated with not reliably applying service life factoring to any overweight operations in this aircraft type. It is suggested that operators review the extent to which their aircraft may have been operated above 4,700 kg, and whether the correct service life factoring has been applied to such operations throughout its full operational life.

Proactive safety action taken by the Civil Aviation Safety Authority

Action number: AO-2013-187-NSA-047

Action status: Closed

In July 2013, prior to the accident involving VH-TZJ, the Civil Aviation Safety Authority (CASA) issued directives to operators of M18 aircraft modified by STC SVA521. The directives required operators to adjust the recorded flight times to account for the applicable factors under the STC.

After receiving notification from the ATSB of the safety issue in December 2013, on 28 October 2014, CASA released Airworthiness Bulletin (AWB) 02-050 to:

highlight to agricultural aircraft operators the importance of ensuring the fatigue lives of any lifed aeronautical product or the aircraft is correctly calculated and recorded.

The AWB recommended that:

...operators who have operated their single engine agricultural aircraft above the certificated maximum take-off weight via any of the CASA exemptions have the airframe life and/or lifed aeronautical products fatigue lives reassessed for those times the aircraft was operated at those higher operating weights.

On 18 February 2015 CASA advised that it had reviewed the records of four Australian M18 aircraft. Of those, three were reportedly not in operation and the fourth was 'low on hours in relation to the STC and [CASA] concluded there was not a risk of overrun.'

ATSB comment in response

CASA's safety action taken in July 2013 ensured that M18 aircraft operators using STC SVA521 had accounted for operations since the STC was approved. However, this action did not capture operations under exemptions issued by CASA.

Release of AWB 02-050 has now alerted all operators of agricultural aircraft that conduct overweight operations, including operators of M18 aircraft, of the requirement to correctly calculate and record all flight times that attract service life factors.

Current status of the safety issue

Issue status: Adequately addressed

Justification: The ATSB considers that CASA has taken all reasonable steps to alert operators of M18 aircraft of the requirement to correctly calculate and record all flight times that have service life factors applicable to them.

Removal of wings to complete service bulletin actions

Number:	AO-2013-187-SI-02
Issue owner:	PZL Mielec
Operation affected:	Aviation: General aviation
Who it affects:	Maintainers of M18 aircraft completing CASA AD/PZL/5 and PZL Mielec service bulletin E/02.170/2000

Safety issue description:

Although wing removal was necessary to provide adequate access for effective visual and magnetic particle inspections of M18 wing attachment fittings, the aircraft manufacturer's service bulletin E/02.170/2000 allowed the wings to remain attached during these inspections.

Response to safety issue by PZL Mielec

Action number: AO-2013-187-NSA-048

Action status: Monitor

On 16 September 2015, PZL Mielec reported to the ATSB that:

PZL Mielec will issue a Service Letter ... in which it will be stated that if during executing the Service Bulletin no. E/02.170/2000 its executor is not sure that a bore in the PZL M18 wing attachment fitting is correctly inspected for the lack of cracks, he should disassemble the outer wing.

ATSB comment in response

Inspection of the wing attachment fittings with the current inspection processes does not appear to ensure an adequate inspection without removal of the wings. However, the ATSB accepts that a suitable non-destructive inspection procedure that can adequately examine the wing attachment fittings without removing the wings may be developed in the future.

The ATSB has assessed the proposed safety action and considers that it should adequately address the identified safety issue. However, the ATSB will reconsider this assessment when the proposed safety action has taken place to determine if it remains adequate.

Current status of the safety issue

Issue status: Safety action pending

Justification: Although the proposed safety action appears adequate, until it has been implemented and the detail deemed to be adequate, the ATSB will monitor the action by PZL Mielec.

Spectrum of flight loads

Number:	AO-2013-187-SI-04
Issue owner:	Operators of M18 aircraft
Operation affected:	Aviation: General aviation
Who it affects:	All operators of M18 aircraft

Safety issue description:

Operation of M18 aircraft with a more severe flight load spectrum results in greater fatigue damage than anticipated by the manufacturer when determining the service life of the M18. If not properly accounted for, the existing service life limit, and particular inspection intervals, may not provide the intended level of safety.

ATSB action

Action number: AO-2013-187-NSA-049

Action status: Closed

At the time of publishing this report, there were 12 registered operators of PZL M18 aircraft on the Australian Civil Register. The ATSB has sent a copy of this report to each of those operators to alert them of this safety issue.

Current status of the safety issue

Issue status: Adequately addressed

Justification: The safety action adequately addresses the safety issue.

Use of eddy current inspection for airworthiness directive AD/PZL/5

Number:	AO-2013-187-SI-03
Issue owner:	Aviation NDT Services Pty Ltd
Operation affected:	Aviation: General aviation
Who it affects:	All operators of M18 aircraft that have had their M18s inspected using the eddy current procedure QP.00.36 (EC)

Safety issue description:

The eddy current inspection used on VH-TZJ, and other M18 aircraft, had not been approved by the Civil Aviation Safety Authority as an alternate means of compliance to airworthiness directive AD/PZL/5. This exposed those aircraft to an inspection method that was potentially ineffective at detecting cracks in the wing attachment fittings.

Response to safety issue by the Civil Aviation Safety Authority

Action number: AO-2013-187-NSA-050

Action status: Closed

On 15 November 2013, the Civil Aviation Safety Authority (CASA) issued an amendment to airworthiness directive AD/PZL/5, revoking the approval for the eddy current procedure to be used for M18 wing joint inspections. It also added a 100-hourly visual inspection, and additional wing-off inspections in M18 aircraft every 2,500 hours. CASA also issued a direction to all registered operators of M18 aircraft in Australia that the aircraft could be flown after compliance with the amended AD.

On 22 November 2013, CASA issued AD/PZL/5 Amendment 2, to additionally require:

- completion of magnetic particle inspections on M18 aircraft with less than 2,500 hours' time in service
- allow the use of CASA-approved alternative magnetic particle inspection methods
- reduce the complexity of the AD
- make corrections to reference documents.

Current status of the safety issue

Issue status: Adequately addressed

Justification: The ATSB is satisfied that the actions taken by CASA address the safety risk associated with this issue.

Adequacy of the eddy current inspection procedure

Number:	AO-2013-187-SI-06
Issue owner:	Aviation NDT Services Pty Ltd
Operation affected:	Aviation: General aviation
Who it affects:	All operators of M18 aircraft that have had their M18s inspected using eddy current procedure QP.00.36 (EC)

Safety issue description:

The documented procedure for eddy current inspection of M18 wing attachment fittings did not assure repeatable, reliable inspections.

Current status of the safety issue

Issue status: Adequately addressed

Justification: As a result of the actions taken by CASA in response to AO-2013-187-SI-03, the eddy current inspection procedure is explicitly prohibited from use. This action has minimised the safety risk associated with this safety issue.

Civil Aviation Safety Authority records

Number:	AO-2013-187-SI-07
Issue owner:	Civil Aviation Safety Authority
Operation affected:	All aviation operations
Who it affects:	All aircraft operators in Australia

Safety issue description:

Important information relating to Civil Aviation Safety Authority (CASA) airworthiness directive AD/PZL/5 was not contained in CASA's airworthiness directive file, but on other CASA files with no cross-referencing between those files. This impacted CASA's future ability to reliably discover that information and make appropriately-informed decisions regarding the airworthiness directive.

Response to safety issue by the Civil Aviation Safety Authority

Action number: AO-2013-187-NSA-051

Action status: Closed

On 7 October 2015, the CASA advised the ATSB that,

...historically CASA Airworthiness Directive (AD) files were used to manage the administrative side of AD publication and the technical assessment aspects were stored separately. Since 2009 CASA has used an electronic filing system and the AD procedures manual mandates an individual file for each AD. This allows CASA to include all the background information and any further correspondence on the same file. Any alternate means of compliance and exclusions to the AD are also stored in the electronic file, and the files are electronically linked in accordance with the AD procedures manual.

ATSB comment in response

The ATSB accepts that the changes already made by CASA have adequately addressed the safety issue for those files started after 2009.

The safety issue may still remain for those airworthiness directives issued prior to 2009. However, the ATSB acknowledges the practicalities in attempting to identify AD-related material in a large number of files and consolidate the applicable information into a single AD file.

Current status of the safety issue

Issue status: Adequately addressed

Justification: A search of the ATSB occurrence database identified no occurrences where separate, non-referenced AD files were found to have contributed to the occurrence. The ATSB considers that although some risk remains, it is as low as reasonably practicable.

Assessment of NDT procedures

Number:	AO-2013-187-SI-08
Issue owner:	Civil Aviation Safety Authority
Operation affected:	All aviation operations
Who it affects:	All aircraft operators in Australia

Safety issue description:

The Civil Aviation Safety Authority did not have a defined process for a robust, systematic approach to the assessment and approval of alternative non-destructive inspection procedures to ensure that the proposed method provided an equivalent, or better, level of safety than the original procedure.

Response to safety issue by the Civil Aviation safety Authority

Action number: AO-2013-187-NSA-052

Action status: Monitor

On 7 October 2015, the Civil Aviation Safety Authority (CASA) advised the ATSB that,

CASA has considered the issue raised and is in the process of developing a policy and/or supporting procedure to address this. The procedure will give recognition to the relationship between the consensus standard for non-destructive inspection (NDI) AS3669 and reg. 2A of the Civil Aviation Regulations 1988, ensuring a minimum equivalent level of safety for alternate NDI procedures and approved maintenance data.

ATSB comment in response

The ATSB has assessed the proposed safety action by CASA and considers that it should adequately address the identified safety issue. However, the ATSB will reconsider this assessment when the proposed safety action has taken place to determine if it remains adequate.

Current status of the safety issue

Issue status: Safety action pending

Justification: Although it appears that the proposed safety action will address the safety issue, until it has been implemented and the detail deemed to be adequate, the ATSB will monitor the action by CASA.

Australian supplemental type certificate SVA521

Number:	AO-2013-187-SI-09
Issue owner:	Rebel Ag Pty Ltd
Operation affected:	Aviation: General aviation
Who it affects:	All aircraft operators of the M18 aircraft in Australia operating under STC SVA521

Safety issue description:

The engineering justification supporting Australian supplemental type certificate SVA521 did not contain consideration of the effect an increase in the average operating speed could have on the rate of fatigue damage accumulation.

Response to safety issue by: Rebel Ag Pty Ltd – Holder of supplemental type certificate SVA521

Action number: AO-2013-187-NSA-053

Action status: Monitor

On 9 December 2015, the holder of supplemental type certificate SVA521, Rebel Ag Pty Ltd, advised the ATSB that, at their request, the Civil Aviation Safety Authority (CASA) had suspended the certificate. The suspension came into effect on 20 August 2015. The notice of suspension specifies that the suspension ceases on release of the ATSB's investigation report into this accident.

Current status of the safety issue

Issue status: Safety action pending

Justification: Until the release of the ATSB's investigation report into this accident, the outcome of the action by Rebel Ag Pty Ltd to seek suspension of supplemental type certificate (STC) SVA521 prevents its operational use, thereby addressing the safety issue. However, release of

the ATSB's investigation report rescinds the suspension of STC SVA521. The ATSB will monitor the status of the STC approval following the release of this investigation report.

Additional safety action

Whether or not the ATSB identifies safety issues in the course of an investigation, relevant organisations may proactively initiate safety action in order to reduce their safety risk. The ATSB has been advised of the following proactive safety action in response to this accident.

Maintenance organisation that conducted the most recent inspections on VH-TZJ's wing fittings

On 25 October 2013 the maintenance organisation that conducted the most recent inspections on TZJ's wing fittings, having information that TZJ's wing had detached in-flight, grounded all of the other M18 aircraft that it had inspected pending further investigation.

Civil Aviation Safety Authority

On 25 October 2013, the Civil Aviation Safety Authority (CASA) issued directions to the registered operators of eight M18 (Dromader) aircraft, stating that the aircraft must not be flown until further notice. On the same day, CASA sent a letter to all M18 operators with information on:

... some issues that operators of these aircraft need to understand so that the aircraft is operated and maintained within the prescribed limitations for the approved configurations. These issues relate to the service life calculation and centre of gravity movement during flight.

Shortly after, on 1 November 2013, CASA issued directions to all registered operators of the 29 M18 aircraft in Australia that the aircraft must not be flown until further notice. In addition, it directed that operators of M18 aircraft provide information relating to the fulfilment of airworthiness directive (AD) AD/PZL/5 (including maintenance certification and non-destructive test reports), as well as information about each aircraft's operating weights.

On 7 October 2015, after reviewing a draft of this investigation report, CASA advised the ATSB of their observation of potential weaknesses in the supplemental type certificate approval process. As a result, CASA advised that:

...whilst the requirements for an STC application are found (in part) in the compliance matrix/checklist listed in the Type certification procedure manual section 2.8.1. CASA is considering the necessary amendments to the associated procedure and guidance in relation to the application of the procedure, to ensure appropriate engineering justification in relation to such design changes is provided to avoid any doubt on the need to comply that already exists. These amendments will be incorporated in the procedures manual at the next available amendment opportunity.

Maintainer of VH-TZJ

On 30 September 2015, the ATSB was advised that the organisation that maintained VH-TZJ had:

...changed its procedures by now providing an NDT contractor with a current copy of any relevant SB or AD documents and we assist them in carrying out their inspection and ask questions to ensure it is as per the documents. Also we have moved to a computer based maintenance program which has the ability to link to procedures and documents and once fully set up there is a tick box to ensure all maintenance staff have read this information for certain tasks.

General details

Occurrence details

Date and time:	24 October 2013 – 1004 EST	
Occurrence category:	Accident	
Primary occurrence type:	In-flight break-up	
Location:	37 km west of Ulladulla, New South Wales	
	Latitude: 35° 20.62' S	Longitude: 150° 04.78' E

Aircraft details

Manufacturer and model:	PZL Mielec	
Registration:	VH-TZJ	
Serial number:	1Z013-32	
Type of operation:	Aerial work	
Persons on board:	Crew – 1	Passengers – 0
Injuries:	Crew – 1 (fatal)	Passengers – 0
Damage:	Destroyed	

Sources and submissions

Sources of information

The sources of information during the investigation included the:

- Bureau of Meteorology
- Civil Aviation Safety Authority (CASA)
- Defence Science and Technology Group
- New South Wales Rural Fire Service
- United States Federal Aviation Administration
- United States National Transportation Safety Board
- aircraft maintainer
- aircraft records
- aircraft manufacturer
- non-destructive test organisation, records, and technicians
- operator and operator records
- pilot's medical records and logbook.

References

Eastin B and Swift S, 2005. *Rough diamond*. 22nd International Committee on Aeronautical Fatigue Symposium. Vol. 6.

Federal Aviation Administration, 1993. *Damage Tolerance Assessment Handbook*, Volume I. Report DOT/FAA/CT-93/69.I. p1 27.

Submissions

Under Part 4, Division 2 (Investigation Reports), Section 26 of the *Transport Safety Investigation Act 2003* (the Act), the ATSB may provide a draft report, on a confidential basis, to any person whom the ATSB considers appropriate. Section 26 (1) (a) of the Act allows a person receiving a draft report to make submissions to the ATSB about the draft report.

A draft of this report was provided to the Defence Science and Technology Group, New South Wales Rural Fire Service, United States Federal Aviation Administration, United States National Transportation Safety Board, aircraft maintainer, State Commission of Aircraft Accident Investigation (Poland), aircraft manufacturer, aircraft operator/holder of supplemental type certificate (STC) SVA521, developer of STC SVA521, the non-destructive test organisation and CASA.

Submissions were received from the aircraft maintainer, State Commission of Aircraft Accident Investigation (Poland), aircraft manufacturer, aircraft operator/holder of supplemental type certificate SVA521, developer of the supplemental type certificate, non-destructive test organisation and CASA. The submissions were reviewed and where considered appropriate, the text of the report was amended accordingly.

Appendices

Appendix A – Timeline of major events

18 Jul 1999	First United States (US) accident
20 Jan 2000	First US Federal Aviation Administration (FAA) special airworthiness information bulletin (SAIB)
22 May 2000	Second US accident
6 June 2000 – 19 Oct 2000	Civil Aviation Safety Authority (CASA) correspondence in respect of a proposed airworthiness directive (AD)
11 Jul 2000	Second FAA SAIB
3 Aug 2000	Aircraft manufacturer service bulletin (SB) issued
5 Sep 2000	FAA AD issued
8 Sep 2000	Date of eddy current procedure QP.00.36 (EC) , issue 2
11 Sep 2000	Eddy current procedure QP.00.36 (EC) approved under Civil Aviation Regulation 2A(4)
21 Sep 2000	Third US accident
25 Sep 2000	CASA advised of M18 wing fitting with crack at 2,776 hours
27 Sep 2000	FAA AD effective
17 Oct 2000	Aircraft manufacturer advised CASA that 'in our case... eddy current method can appear to be ineffective'
19 Oct 2000	CASA AD issued
25 Oct 2000	CASA AD effective
26 Mar 2004	Aircraft imported into Australia and registered as VH-TZJ (TZJ)
5 Mar 2009	Exclusion for another M18 approved
14 Jun 2011	CASA requested that the operator of TZJ show how times were being factored for overweight operations
26 Jul 2013	CASA directed the operator to factor time in service for TZJ in accordance with the supplemental type certificate SVA521 maintenance manual supplement for all operations above 4,700 kg since 6 March 2009
8 Aug 2013	Last wing fitting inspection carried out on TZJ
19 Aug 2013	TZJ time in service retrospectively factored to comply with CASA direction
24 Oct 2013	TZJ accident

Appendix B – Detailed examination of the fractured wing attachment fitting

The occurrence

On the morning of 24 October 2013 the pilot of a modified PZL Mielec M18A Dromader, aircraft serial number 1Z013-32, registered VH-TZJ, was conducting firebombing operations in the Budawang National Park, about 37 km west of Ulladulla, New South Wales. The left wing separated from the aircraft during low-level flight, at the point of interconnection to the centre wing. The aircraft impacted terrain shortly afterwards and the pilot was fatally injured as a result. The separated left wing and some parts of the wreckage were significantly damaged by post-impact fire.

ATSB investigators recovered the majority of the aircraft's left wing connection structure, including the upper and lower front spar interconnections of both wings. The recovered wing and fuselage structures were transported to the ATSB's engineering facilities for detailed technical analysis.

Scope of the examination

The purpose of this examination was to analyse the recovered left wing spar structure to determine the mechanism of wing separation, including the identification and characterisation of any pre-existing material or structural anomalies.

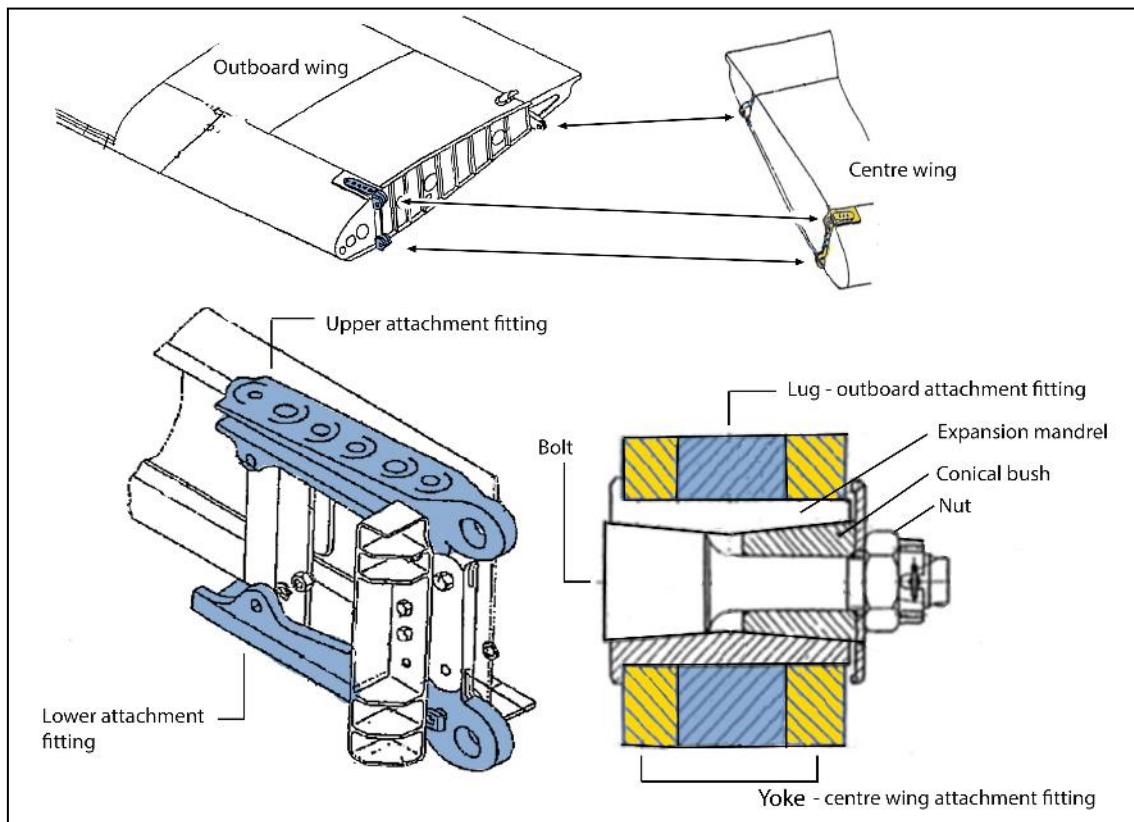
Wing structure general

The PZL Mielec M18A Dromader aircraft was designed and manufactured in Poland and is used for agricultural and firefighting operations. The aircraft used a low-wing cantilever design that consisted of three sections: a centre wing, left outboard and right outboard section. The wing section structures consisted of a main and rear spar that were joined by ribs and covered with aluminium alloy skin. The outboard wing sections were attached to the centre wing section at three points: two on the front main spar and one on the rear spar.

Wing attachments

The centre and outboard wing sections were principally connected at the main spar using forged steel fittings that were bolted together using a yoke and lug arrangement. The lugs of the upper and lower fittings on the main spar were joined using a split mandrel, expansion bolt and conical bush. When the bolt was tightened, the mandrel was forced to expand into the bore of each lug which then locked the fittings together (Figure B1).

Primary flight loads were transferred from the outboard wing sections to the centre wing section and then to the fuselage by the lugged attachments on the front main spar. A smaller lugged connection located at the rear spar was primarily designed to balance the wing drag loads. Separation of the outboard section of the left wing from VH-TZJ in the accident sequence was associated with structural fracture at, or adjacent to each of those primary interwing connection points.

Figure B1: Outboard wing to centre wing attachment detail

Source: PZL Mielec, modified by the ATSB

Attachment fitting manufacturing detail

The technical documentation supplied by the aircraft manufacturer showed that the lower wing attachment fittings were forged from a Polish-grade low-alloy high-strength steel, 30 HGSA, and heat treated to an ultimate strength of 120 ± 10 kg/mm² (1,200 MPa). The fittings were supplied from the aircraft manufacturer with a 34 mm diameter hole. Prior to fitment to the aircraft the hole was reamed to a diameter of 36 mm with a H8 tolerance⁶³ to accommodate the split mandrel, conical bush and expansion bolt. All surfaces of the attachment fitting, except for the main holes, were specified to be shot-peened and then cadmium plated.

Aircraft history

Aircraft modifications

A review of the maintenance documentation for the aircraft stated that in October 2004 a number of extensive modifications had been completed that included: replacement of the original radial piston engine with a turbine-propeller engine, and modification of the hopper to increase the capacity. Those modifications would change the performance of the aircraft and allowed an increase in maximum take-off weight from 4,700 kg up to 6,300 kg.

New upper and lower main spar wing attachment fittings were installed on the aircraft at that time. Following the modifications, the records indicated that the aircraft had operated for around

⁶³ H8 describes an engineering design tolerance to ensure a clearance exists between the hole and the expansion bolt during assembly. The lower limit size of the hole within the fitting is greater or at least equal to the upper limit diameter of the bolt.

3,982 hours of time in service up until the in-flight separation of the wing. The retirement life of the fitting was 10,000 hours (the retirement life of the airframe as a whole).

Aircraft inspection

Records showed that the bore of the wing fittings from VH-TZJ had been non-destructively inspected for cracking using an eddy current technique 126.3 hours prior to the accident. The inspection was conducted in August 2013, around 11 calendar weeks prior to the accident. No defects were recorded during that inspection. Further discussion on the development of the wing fitting inspection and how it was applied to VH-TZJ is contained in the main investigation report.

Recovered structure

Once received at the ATSB engineering facilities in Canberra, all recovered sections of wing structure were documented, photographed and then disassembled to allow a more detailed examination of the parts to be conducted in the presence of directly involved parties.

Figures 2-8 illustrate the left wing structural sections that were recovered from the accident site. Of the aircraft wing sections, the structural interconnection (attachment fittings) between the outboard section of the separated left wing and the centre wing section main spar were of primary importance to the investigation.

General observations - wing attachments

Left wing main spar upper attachment fitting

The left upper outboard-to-centre wing attachment assembly was found separated from the aircraft within the debris field at the accident site. The attachment fittings remained connected via the bolt and mandrel assembly (Figure B2 and Figure B3). A length of heavily deformed spar cap remained attached to both fittings. The presence of wood fibres indicated that it had contacted a tree during the wing break-up sequence. The upper attachment fittings had detached from the wing where they had been bolted to a main spar web stiffener.

The fracture surfaces at the point of spar separation presented features typical of ductile overstress, with tearing through the web structure from a single high load event. There was no evidence of any pre-existing anomalies that might have resulted in premature failure of the upper fitting.

The upper fitting was disassembled and the inner bores of both the outboard and centre-wing attachment fittings examined optically and then non-destructively using fluorescent magnetic particle techniques. An assessment of the general condition of the bore showed the bore surface to be scored from contact with the expansion mandrel during service. No cracking or corrosion damage was found within the lugs from either section.

Left wing main spar lower attachment fitting

The outboard section of the left wing main spar displayed evidence of heat damage from the post-accident fire. The fracture surfaces and bore of the fitting were heavily deposited with melted material and combustion by-product (Figure B4 to Figure B6). Of critical note, the lug from the main spar lower attachment fitting had fractured and was contained within the yoke of the inboard attachment on the centre wing section. That separated lug displayed no accident-related damage to the fracture surfaces (Figure B7 and Figure B8).

During disassembly of the parts, it was observed that the attachment fitting had been assembled with a copper-containing grease. Remnants of the grease remained on the external surfaces of the fitting, on part of the expansion mandrel and within the bore of the fractured fitting which indicated that it had been used in the last reassembly. The expansion mandrel was oriented in the fitting such that the split-line was located at about the 12 o'clock position (upwards).

After degreasing and cleaning, the general surface condition of the lug bore appeared bright and lightly polished around the circumference. Corrosion damage was also noted, with regions of dark staining from the effects of corrosion pitting of the steel surface visible in the bore.

Left wing rear spar connection

The left wing, rear spar attachment exhibited necking and deformation around the lug section fracture that was consistent with an overstress failure. There were no features identified to indicate that fracture of the rear spar interconnection had been an initiating factor in the left wing failure.

Right wing main spar lower attachment fitting

The right wing, lower attachment fitting did not separate from the main spar during the wing break-up sequence. The fitting was identified at the accident site and destructively sectioned from the primary wing structure to facilitate recovery. Upon disassembly of the joint, remnants of copper-containing grease were found in the bore of the fitting and on the mandrel surfaces. A visual assessment of the general condition of the bore showed the surfaces to be scored from contact with the mandrel during service. Non-destructive inspection (fluorescent magnetic particle) showed that no cracking had developed in the attachment lugs.

Figure B2: Left wing main spar upper fitting and spar cap – as recovered from the accident site



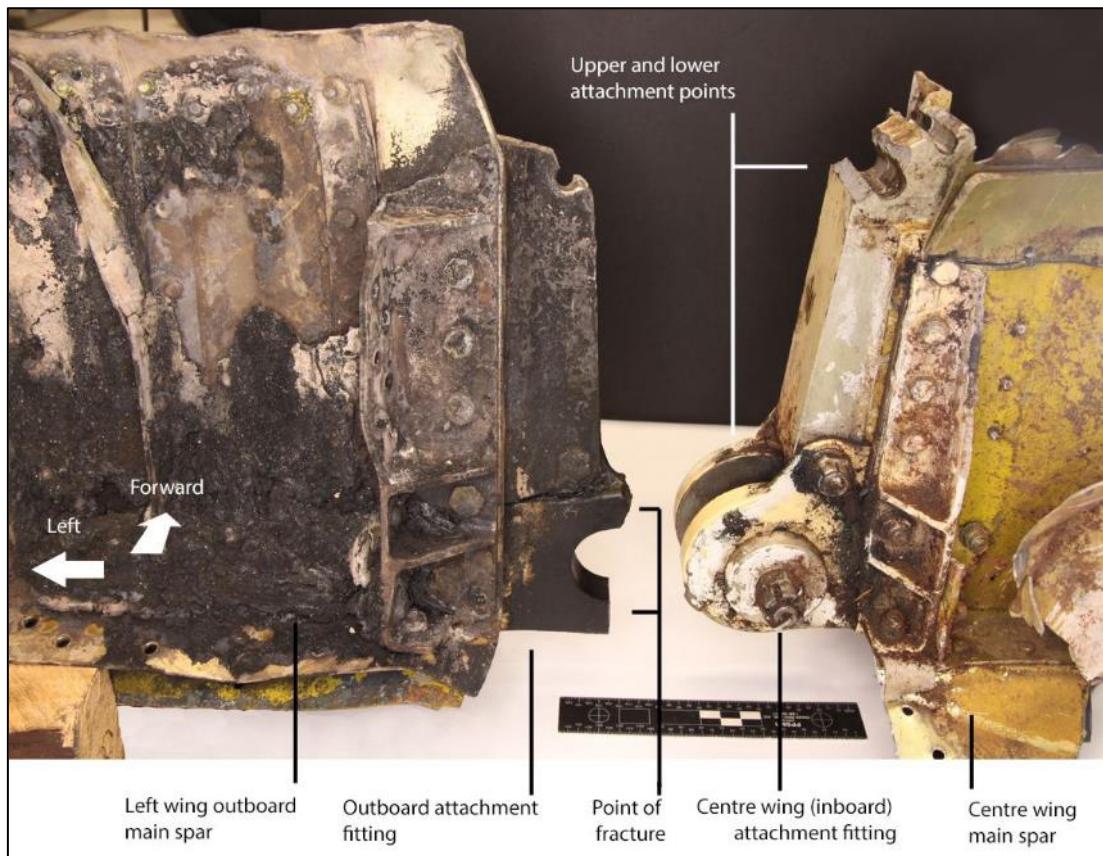
Source: ATSB

Figure B3: Left wing main spar upper attachment



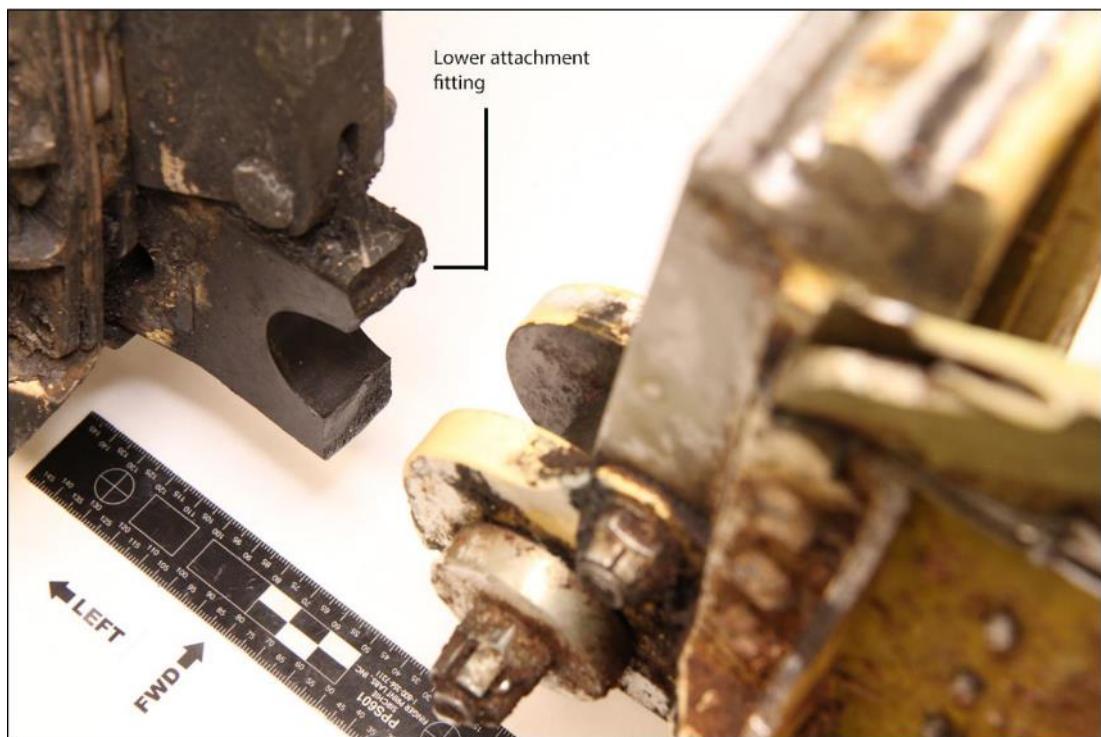
Source: ATSB

Figure B4: Left wing main spar outboard to centre wing structure, as recovered from the accident site



Source: ATSB

Figure B5: Outboard view of the fractured lower attachment fitting at the left wing to centre wing main spar interconnection



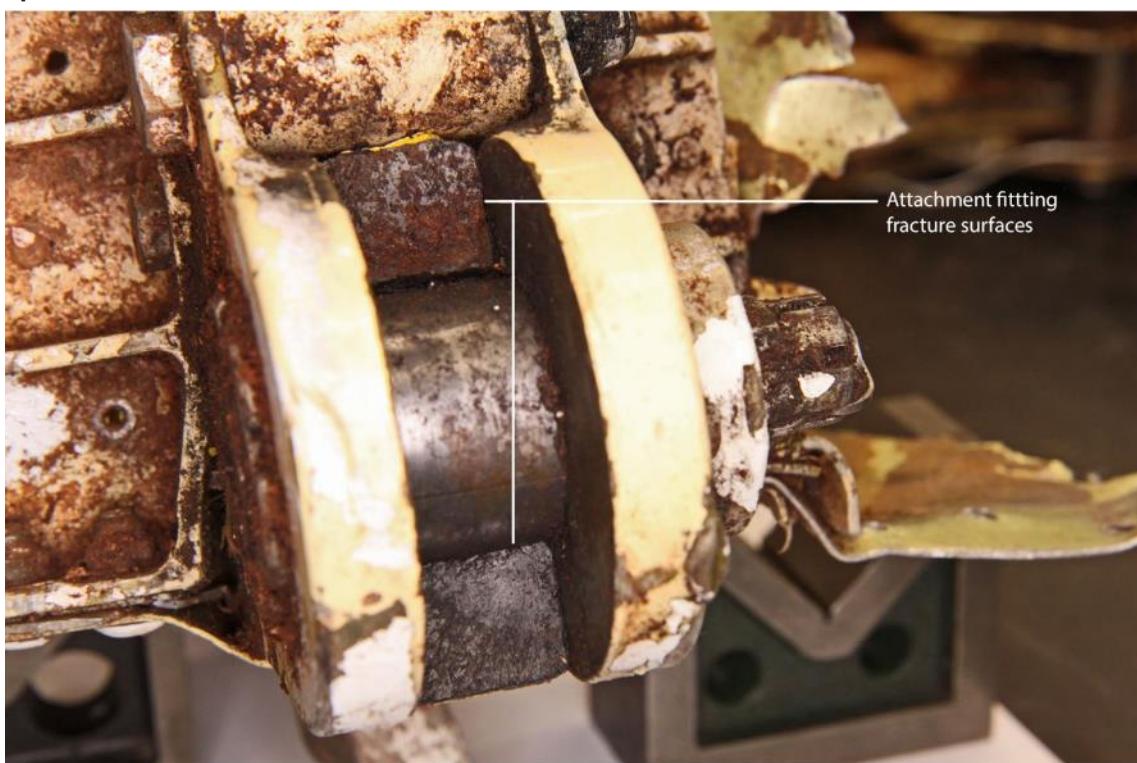
Source: ATSB

Figure B6: Outboard view of the fractured lower attachment fitting at the left wing main spar interconnection



Source: ATSB

Figure B7: Inboard view of the fractured lower attachment fitting at the left wing main spar interconnection



Note: the fitting is shown as received, with much of the surfaces covered in red fire retardant, dirt, wood fibres and other substances from the accident site.

Figure B8: Comparison of the left and right main spar lower outboard attachment fittings from VH-TZJ (post disassembly)



Source: ATSB

Left wing main spar outboard lower attachment fitting

Visual examination of the fracture surfaces

The separated lug section from the main spar outboard attachment fitting was examined at varying magnifications using a binocular microscope (Figure B9 and Figure B10). The cross section adjacent to the upper lug fracture surface displayed plastic deformation and elongation (necking) from the bore. The upper fracture surfaces were heavily corroded (post fracture), but otherwise presented uniform features entirely consistent with a ductile overstress failure.

The lower section of the lug contained two separate regions of crack growth on the fracture surface (Figure B11 and Figure B12). Most obvious was a region of flat fracture containing a series of concentric beach marks associated with fatigue crack progression. The remaining region presented a dull fibrous appearance consistent with final fracture of the section by a ductile overstress. No plastic deformation could be observed around the lower lug fracture and it was apparent that the region of overstress had been created from a single loading event.

The concentric radiating features present on the fracture showed that fatigue cracking had initiated at the lowermost (6-o'clock) position within the bore of the fitting. A series of steps and ridges (ratchet marks) across the fracture plane at the intersection with the bore surface indicated that fatigue cracking had initiated from numerous discrete origins. Further inspection revealed that each of the crack origins were associated with the presence of corrosion pits that had penetrated and damaged the bore of the fitting (Figure B13).

It was also noted that the region of fatigue cracking on the fracture surface displayed crack progression bands and was discoloured by oxidation. Such features indicated that each band was associated with an extended period of crack growth from cyclic loading of the wing structure during service. The visual examination could not identify any evidence of finer fatigue striations that might have been associated with an individual load cycle, or a discrete event such as a ground-air-ground cycle (that is, take-off and landing). No markers could be identified on the

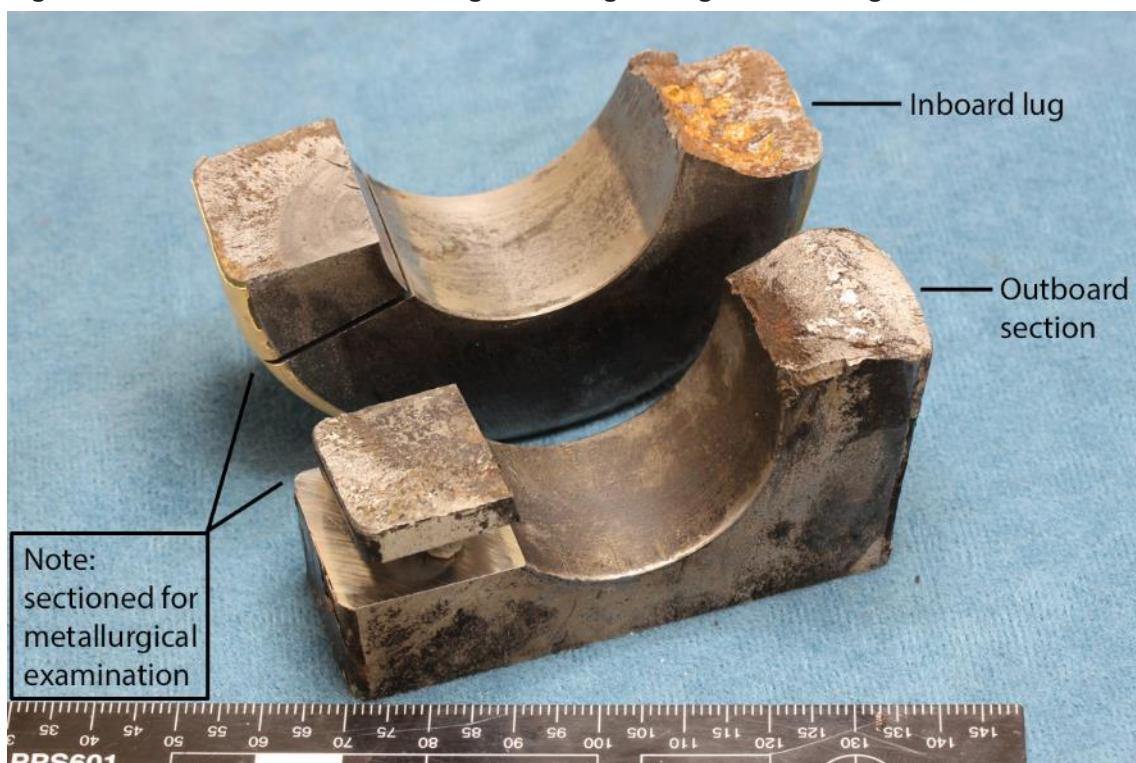
fracture surface to indicate a defined period in the service history of the attachment fitting that might have been otherwise used to calculate the rate of crack growth.

Figure B9: The fractured lug section from the left wing main spar outboard lower attachment fitting. The lug is shown uncleared as disassembled



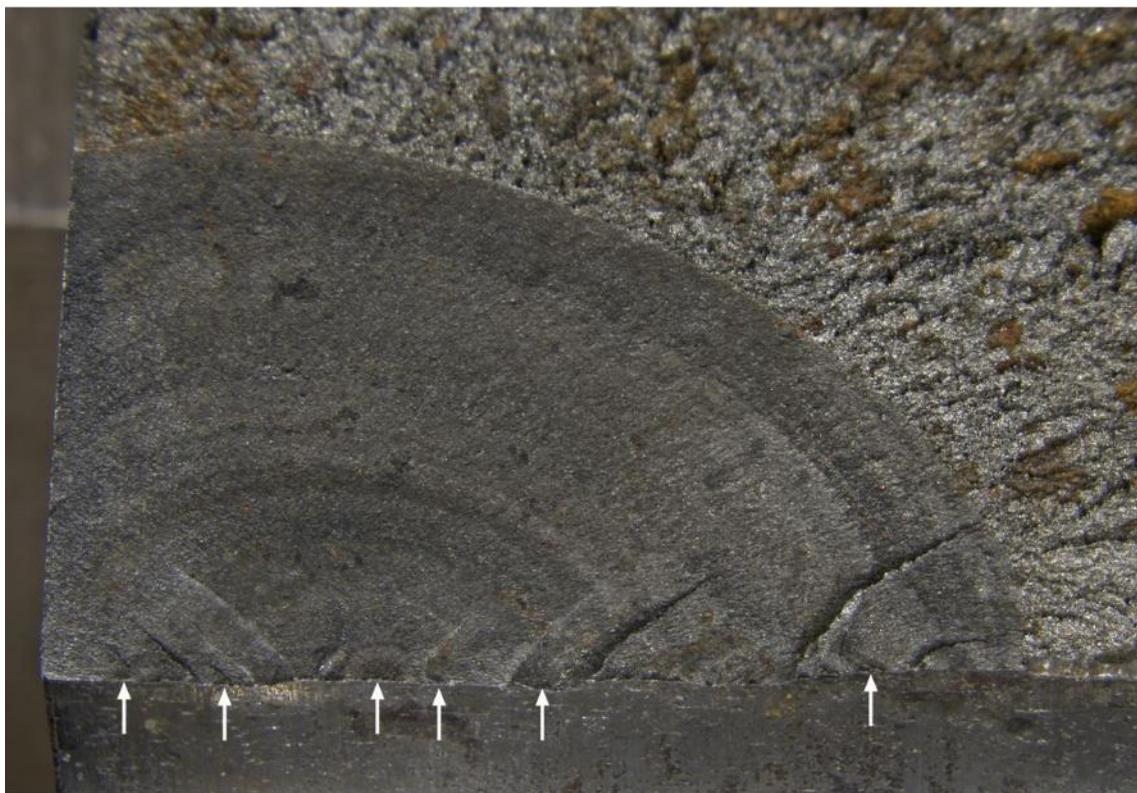
Source: ATSB

Figure B10: Inboard and outboard lugs after degreasing and cleaning



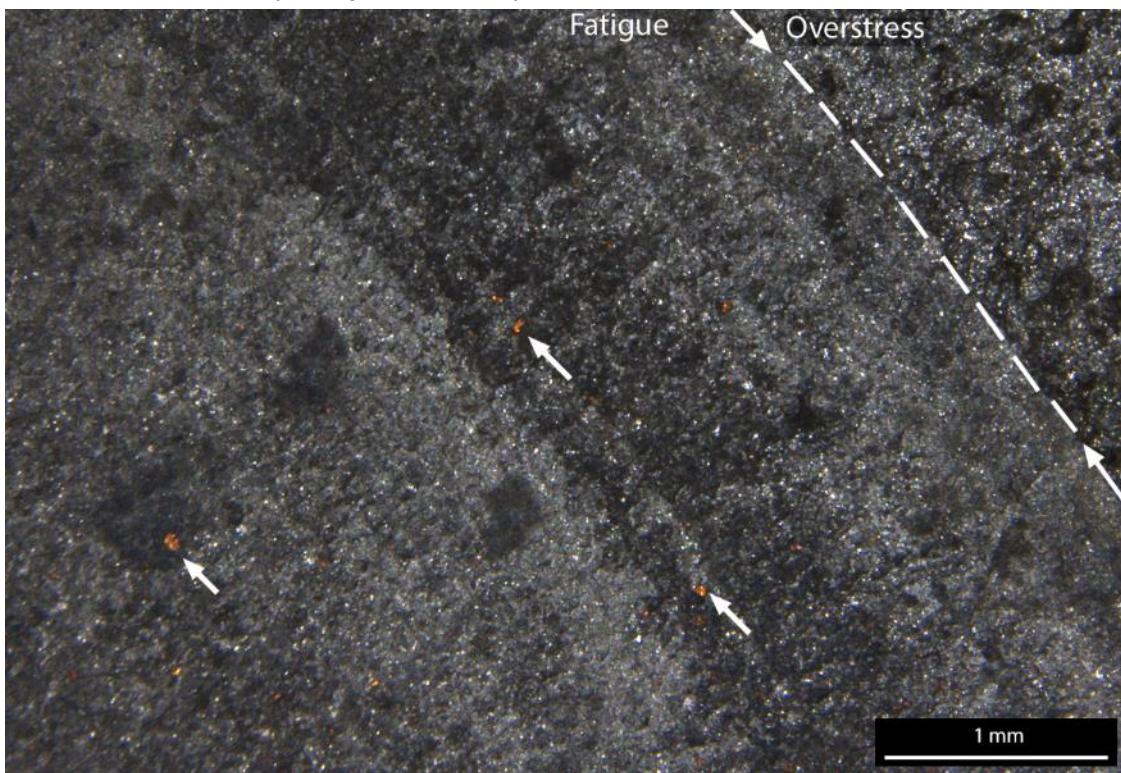
Source: ATSB

Figure B11: The fatigue crack with some of the fatigue origins arrowed



Source: ATSB

Figure B12: High magnification optical view of the fracture surface. Bands of crack progression (beach marks) show the advance of the fatigue crack front as it propagated through the lug to the point of overstress. Note also the small copper-coloured particles on the crack surface (examples arrowed)



Source: ATSB

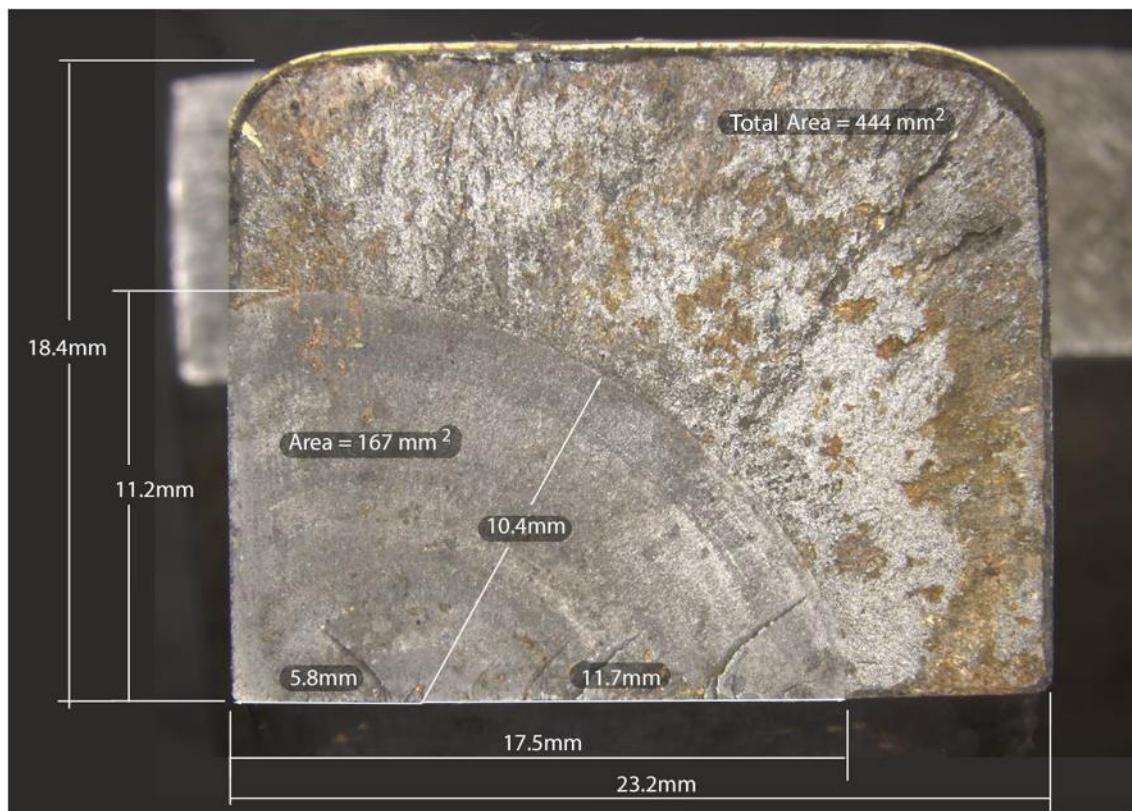
Figure B13: One of the fatigue crack origins (labelled) initiated from a corrosion pit within the bore of the fitting



Source: ATSB

Crack measurements

Measurements were taken of the significant features from the fractured lug, as shown in Figure B14. The fatigue cracking had extended from the 6-o'clock (lower) portion within the bore before reaching a critical length of 10.4 mm. The crack origins extended approximately three-quarters across the bore surface. The extent of fatigue cracking represented close to 38 per cent of the overall cross-sectional area of the lower lug ligament.

Figure B14: Critical measurements of the fracture detail

Source: ATSB

Characterisation of the wing fitting bore

Corrosion damage

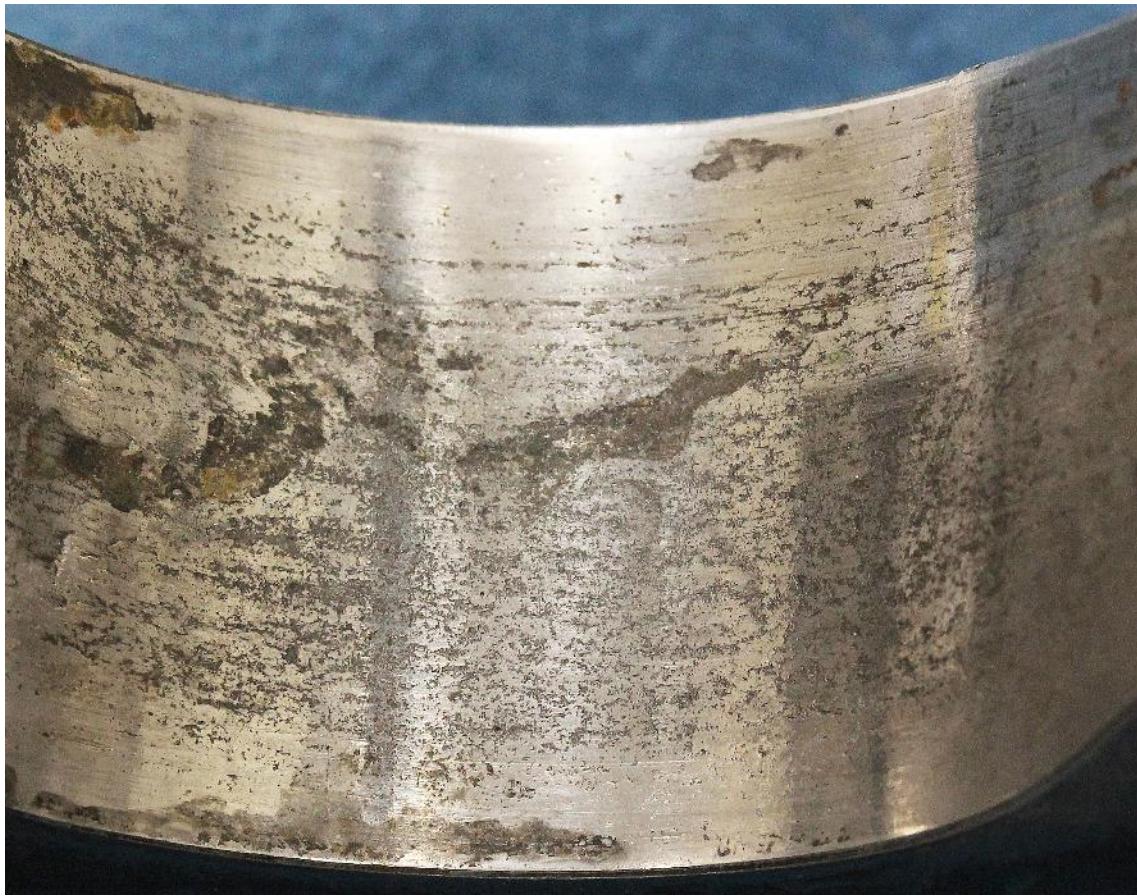
To the unaided eye, the surface condition of the bore of the fractured fitting was in good condition. There were no obvious corrosion products (ferrous oxides), nor any significant scoring or gouging present. Very fine circumferential marks were noted around the bore surface, which was consistent with the application of a fine abrasive material.

Under a binocular microscope, it was evident that the fitting had sustained corrosion damage during its service life, prior to the failure (Figure B15 and Figure B16). That corrosion had led to the development of an array of micro-pits in the bore surface. Without adequate corrosion protection, pitting of that nature is not unusual for an alloy steel of the type used in the manufacture of the fitting. The bore surface was discoloured where the pitting corrosion had developed. There was no loose corrosion product surrounding the pitted regions.

Corrosion damage quantification

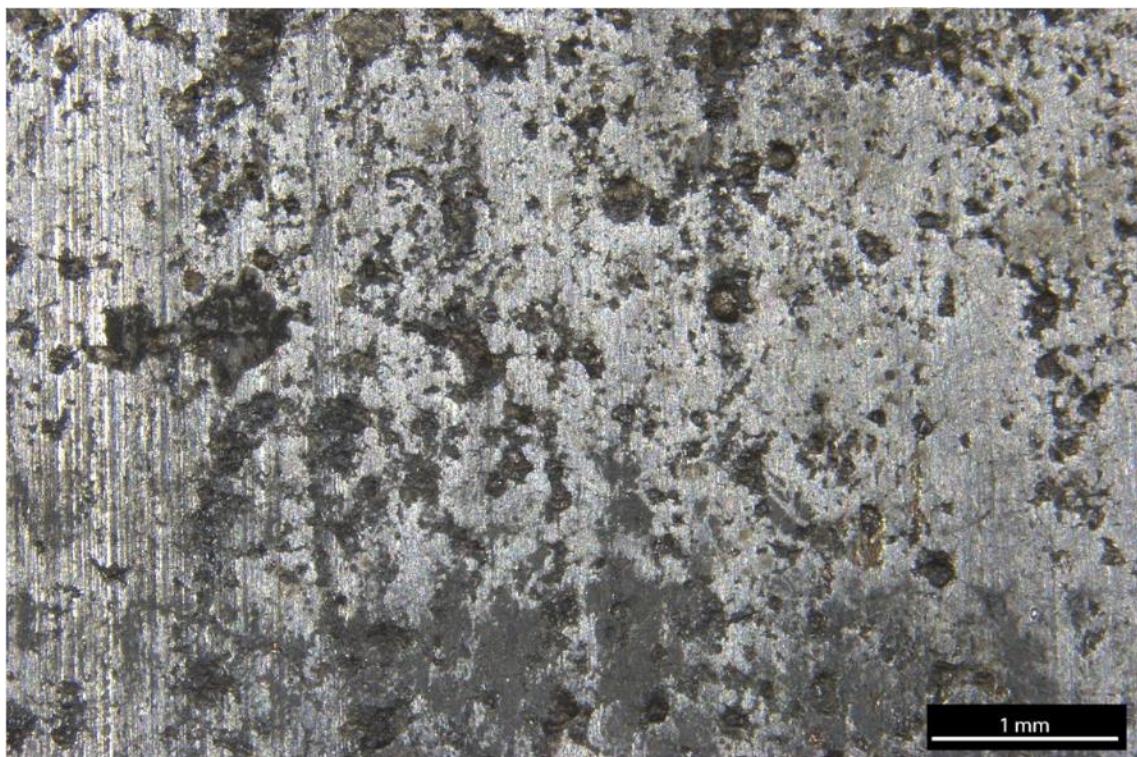
In order to assess the extent of pitting corrosion damage within the bore, the fractured lug section was sent to the Defence Science and Technology (DST) Group for quantification. The DST Group used an automated optical profiler to scan the bore surface in a 4 mm swathe across the full width of the fitting, adjacent to the fracture plane. Hundreds of very fine pits were identified. The measurement results are presented in Figure B17 and Figure B18. The deepest pit measured approximately 0.16 mm.

Figure B15: Fractured lug bore exhibiting extensive corrosion pitting



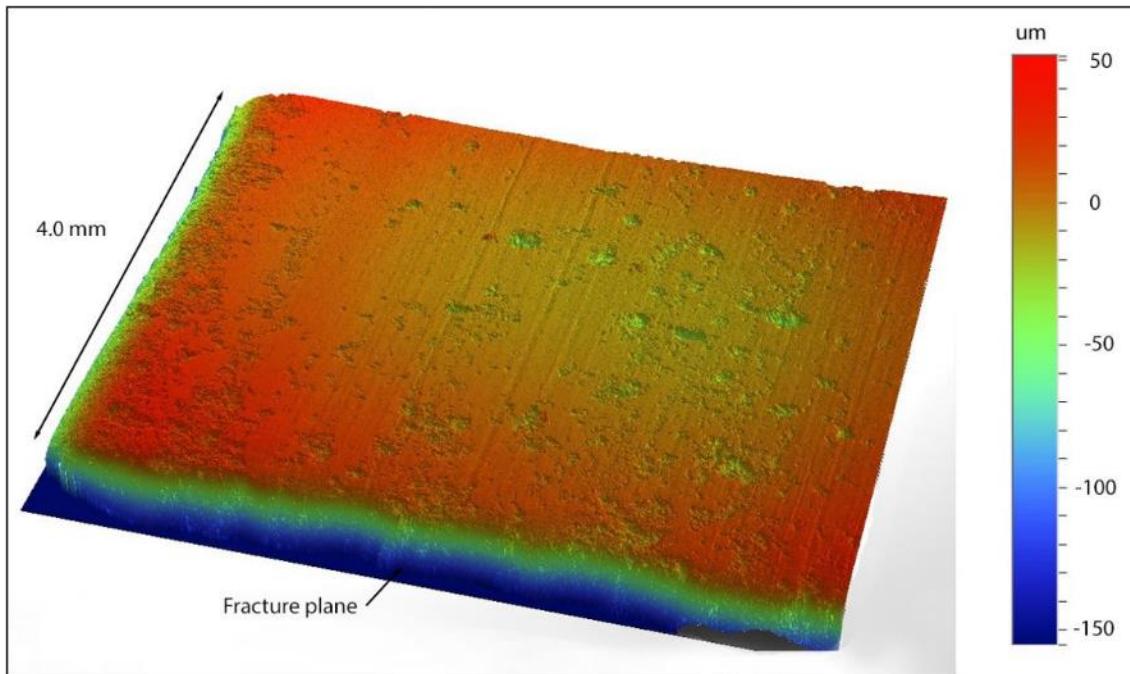
Source: ATSB

Figure B16: High magnification view of characteristic pitting damage within the bore of the fitting. Fine circumferential scoring can be seen (aligned vertically in this image).



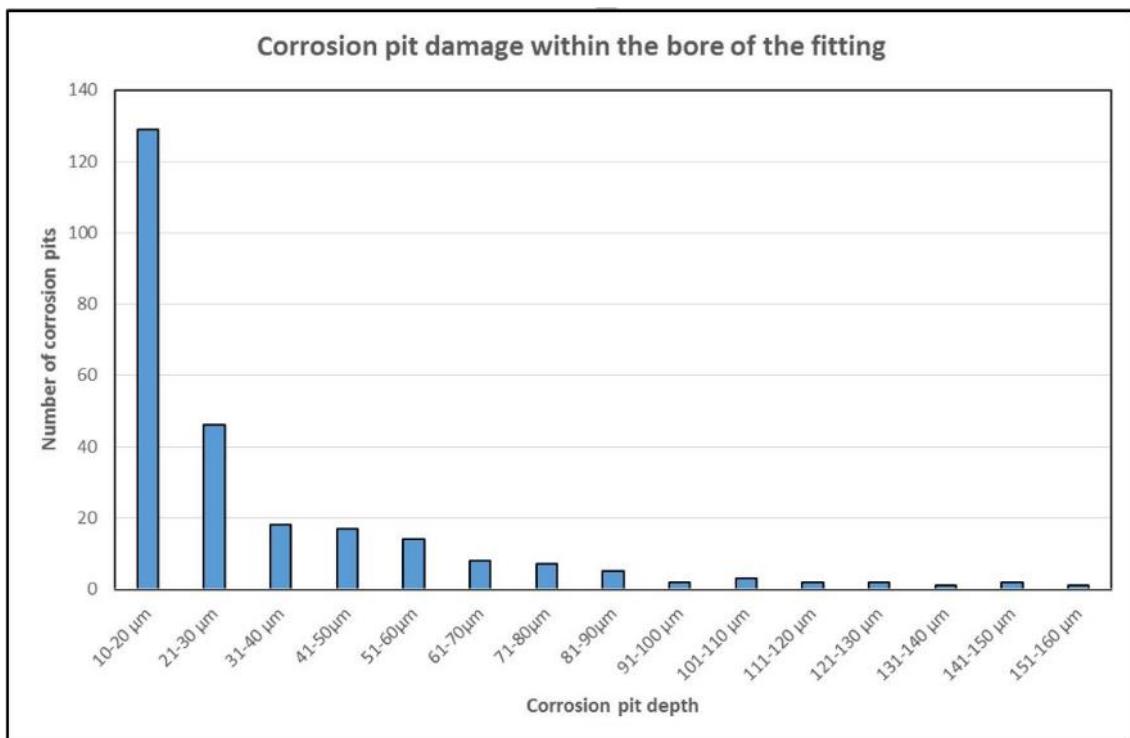
Source: ATSB

Figure B17: Representation of the pitting corrosion damage within the bore of the separated lug in a 4 mm band across its section



Source: Defence Science and Technology Group

Figure B18: Histogram of pit depths within the bore of the separated lug in a 4 mm band across its section



Source: ATSB

Secondary micro-cracking

Visual examination of the separated lug section identified at least 32 secondary micro-cracks in the bore surface. Micro-cracks were also identified in the adjoining bore of the fractured attachment fitting. That section had remained with the detached left wing, however much of the

surface was obscured through oxidation and melted deposits from exposure to the post-accident fire.

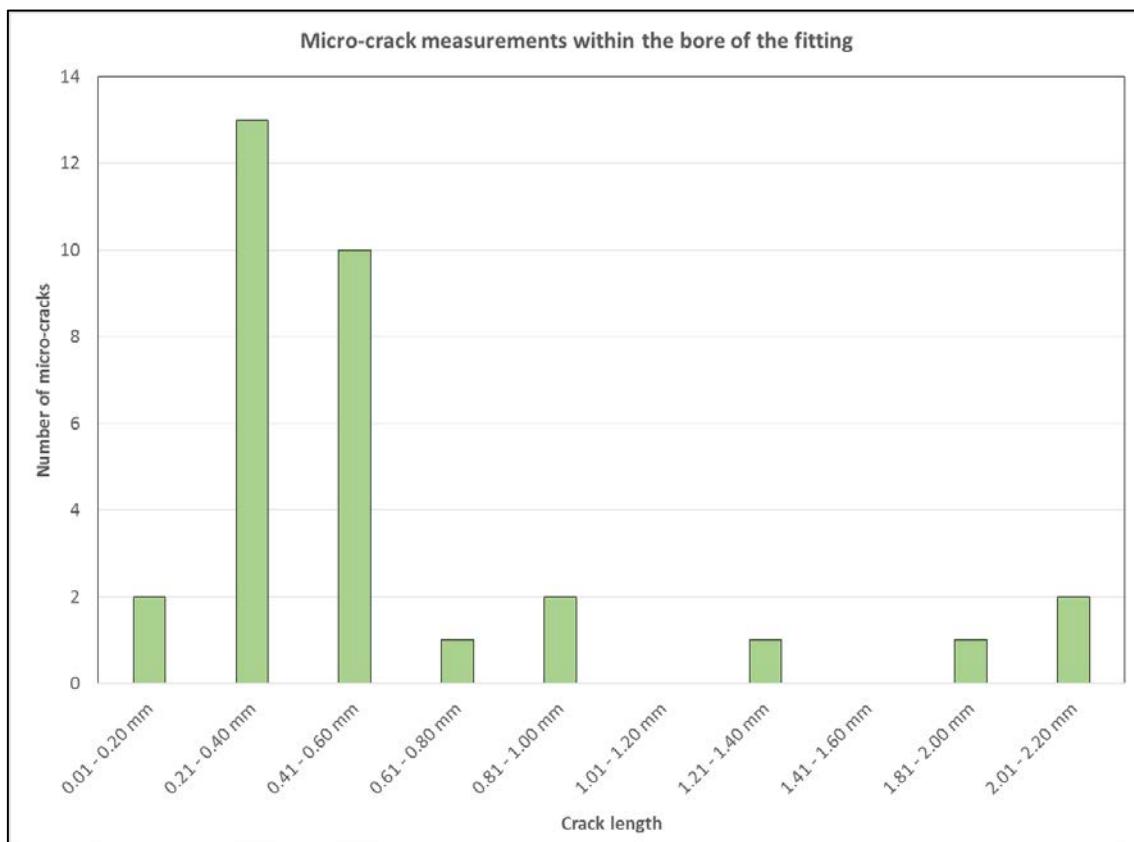
Each of the identified micro-cracks were located adjacent to, and had a similar orientation to the primary fatigue crack as shown in Figure B19. The micro-cracks varied in length up to a maximum surface length of 2.1 mm (Figure B20). It was noted that each of the micro-cracks were associated with an area of localised pitting damage. Examination of the detached portion of the fitting lug using a fluorescent magnetic particle inspection technique found that some, but not all of the micro-cracks were readily detectable (Figure B21). The surface length of the micro-cracks alone could be measured (and not their depth), however assuming a semicircular morphology, the largest micro-crack probably extended about 1 mm deep.

Figure B19: Secondary micro-cracking adjacent the primary fracture plane



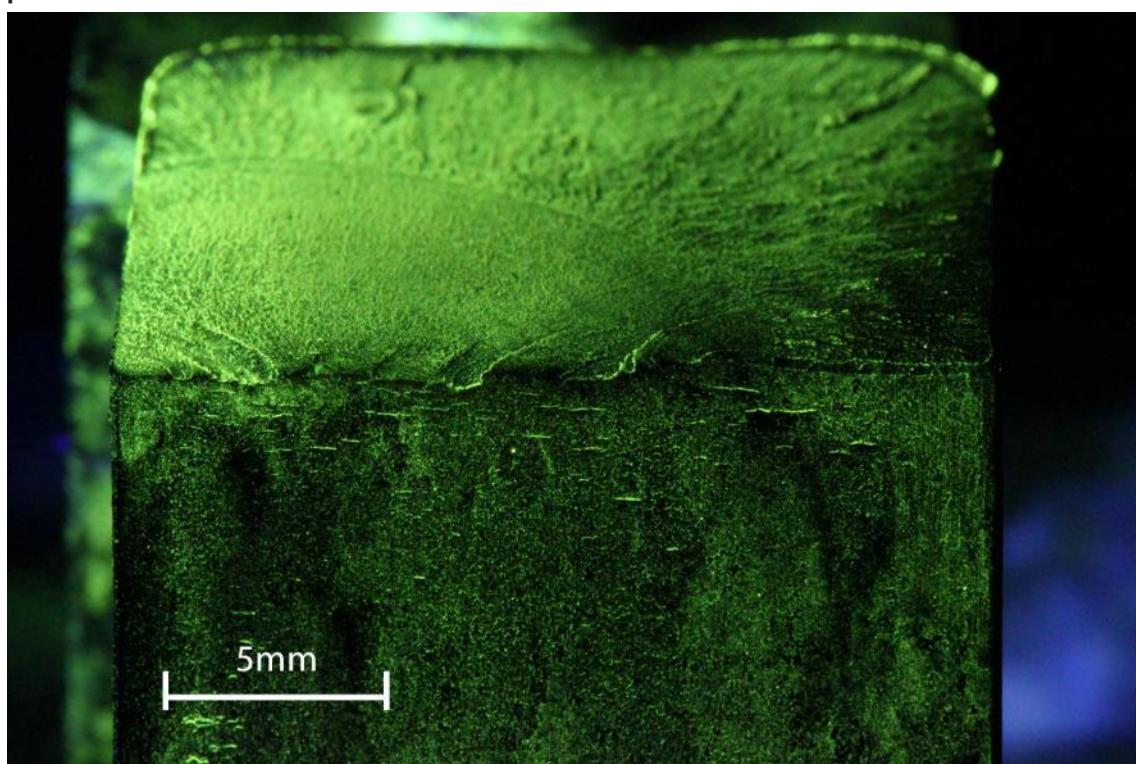
Source: ATSB

Figure B20: Histogram of secondary cracks within the bore of the fitting



Source: ATSB

Figure B21: Fluorescent magnetic particle inspection of the fractured fitting. Many small secondary micro-cracks can be seen within the bore adjacent the primary fatigue fracture plane



Source: ATSB

Scanning electron microscopy

Scanning electron microscopy (SEM) techniques were used to closely examine and characterise the surfaces of the fractured lower fitting and was conducted to further support the visual assessment. Energy dispersive x-ray spectroscopy (EDS) was also used to assist in the identification of material on the fracture surfaces.

Lower lug section from the fractured fitting

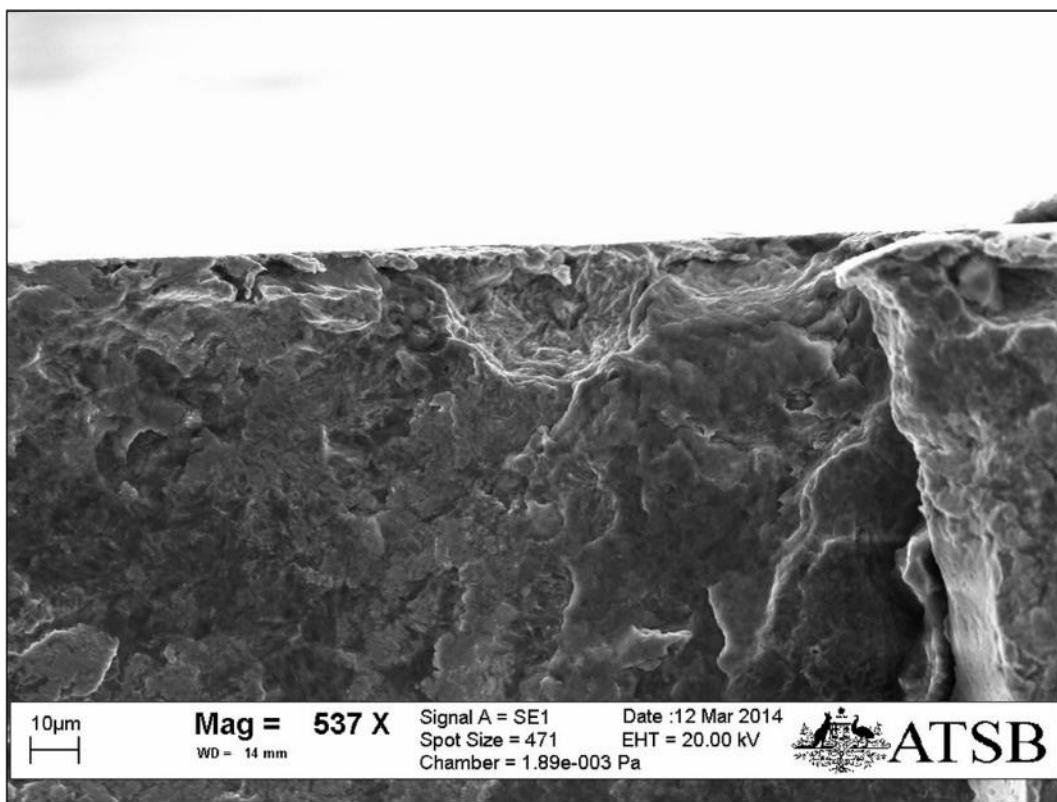
The two very distinct fracture morphologies (fatigue and overstress) from the lower section of the detached lug were examined in the scanning electron microscope.

The fatigue crack progression was entirely transgranular, with no evidence of ductile tearing – even toward the transition from fatigue cracking to overstress where it would be expected that the stress intensity factor (and hence crack growth rate) would be increasing. The numerous crack origins were identified as initiating from corrosion pits varying in depth from 50- to 100-micron (Figure B22).

Only a very small number of fatigue striations were able to be identified. The thin layer of surface oxidation over the fatigue portion of the fracture rendered the fine spacing between individual fatigue striations almost entirely unresolvable with the SEM. The few striations that were identified were less than 1-micron in spacing towards the overstress boundary (Figure B23). The fineness of the striation spacing, in combination with the lack of any tensile tearing in proximity to the fatigue-overstress boundary, indicated that the fatigue crack progression had occurred over a considerable period of aircraft operation.

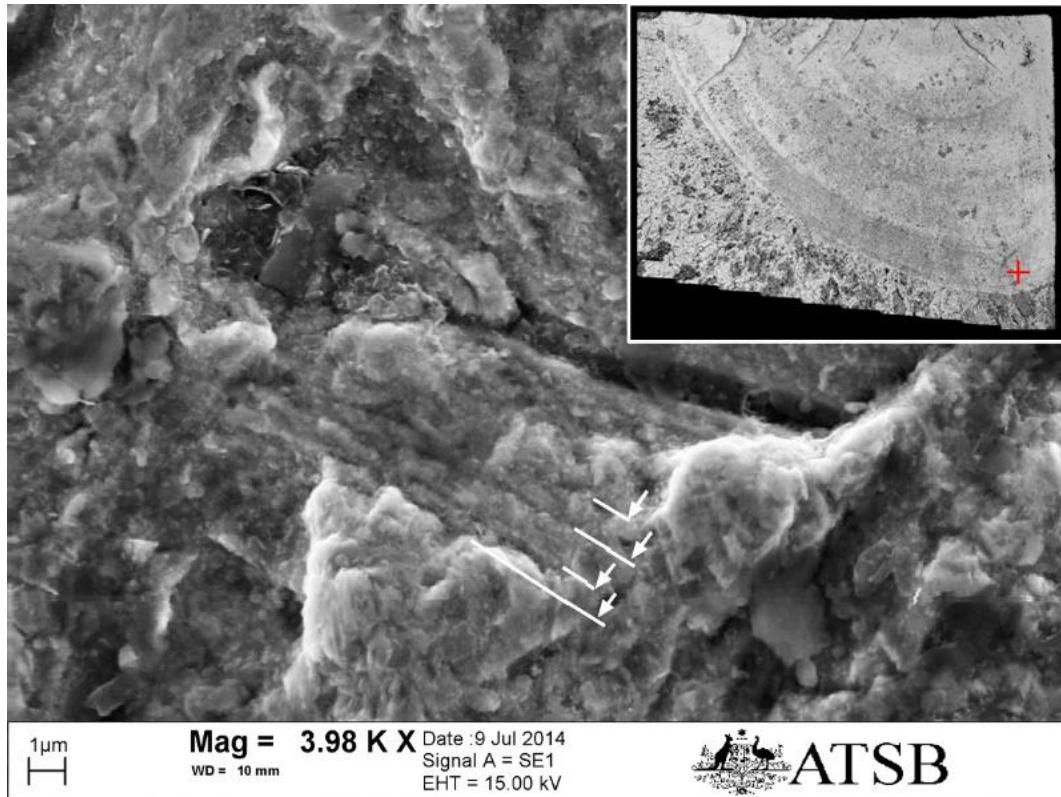
The region of overstress on the lower lug section was dominated by quasi-cleavage facets and pockets of micro-void coalescence (ductile tearing). Such fracture features are typically generated with high strength steels that have been exposed to extremely high rates of loading.

Figure B22: SEM micrograph of a corrosion pit at a site of fatigue crack initiation



Source: ATSB

Figure B23: Composite SEM micrograph - very high magnification view of the only fatigue striations (arrowed) was identified on the fracture toward the overstress boundary (inset)



Source: ATSB

Chemical analysis of fracture surface contaminants

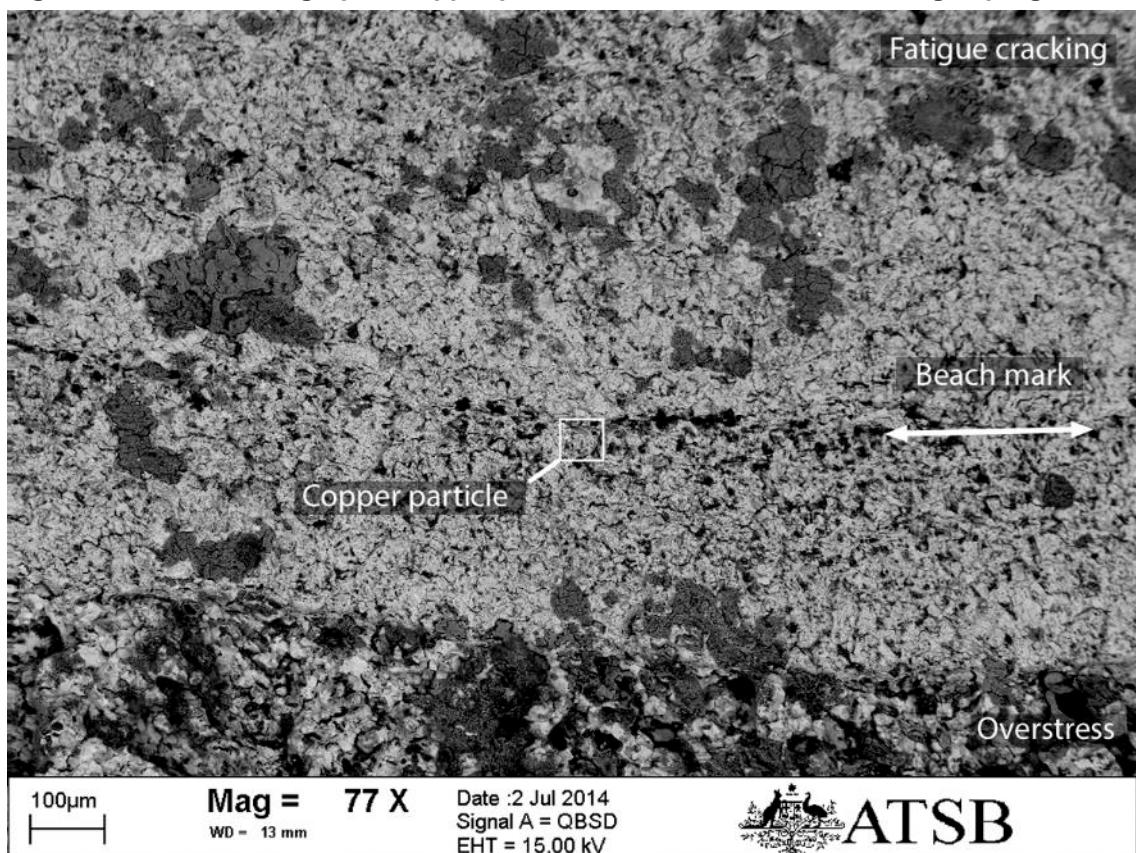
During the visual examination, numerous dark particles, as well as bright orange metallic flecks, were observed adhered to the fatigue portion of the fracture surface. Elemental analysis of those particles was conducted using the EDS.

The darker particles were shown to be comprised primarily of carbon, aluminium, silicon and trace amounts of cadmium. The origin of those particles could not be positively determined, though it is probable they are associated with an external contaminant.

A large amount of bright orange metallic particles were identified on the fatigue portion of the fracture (Figure B12), aligned to some extent with the crack front beach marks. EDS analysis confirmed that the particles were copper metal. Copper-containing grease was found on all parts of the attachment fitting during the component disassembly which indicated that it had been used in the last reassembly. It was likely that the copper-containing grease entered the crack during operation and migrated toward the advancing crack tip. The copper particles were embedded up until the final beach mark (Figure B24 and Figure B25).

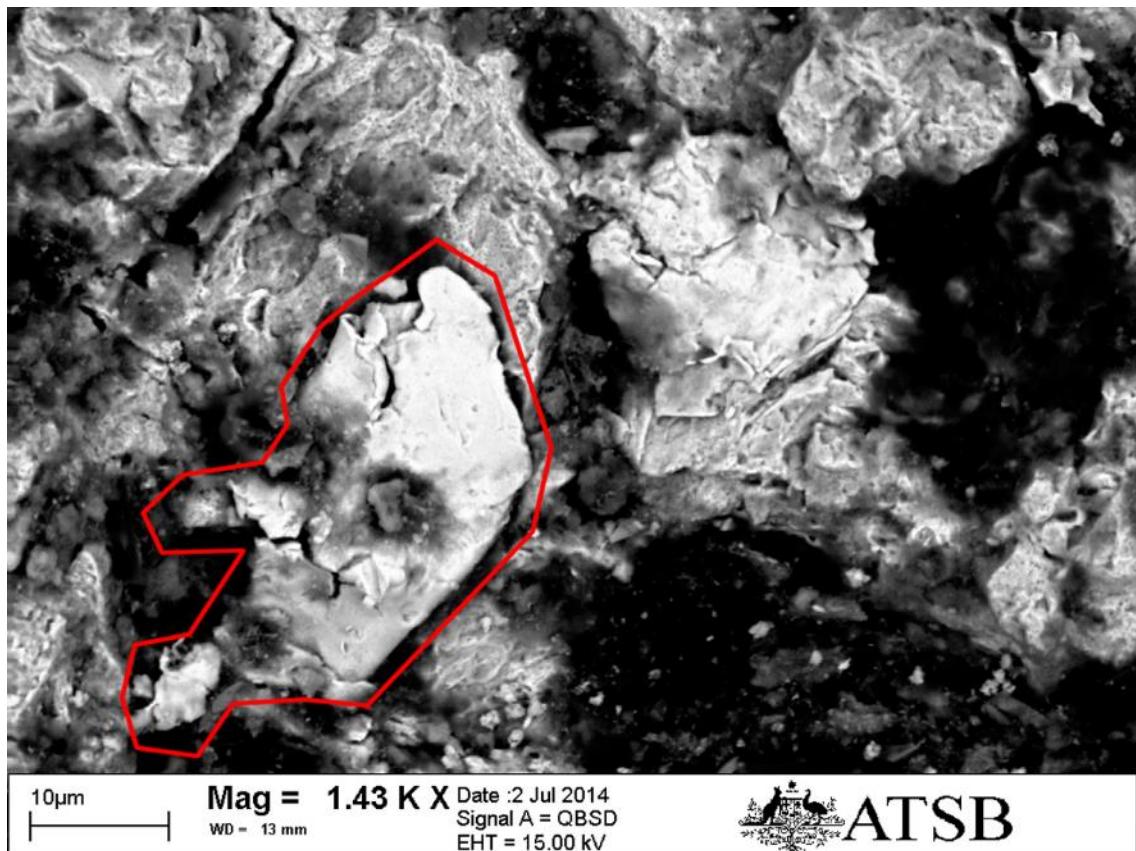
Analysis of the outer surface of the fitting confirmed that it had been cadmium plated, as specified.

Figure B24: SEM micrograph – copper particle shown at final band of fatigue progression



Source: ATSB

Figure B25: SEM micrograph showing copper particles from the grease that were pressed onto the fracture



Source: ATSB

Metallurgical characterisation

Hardness

Vickers micro-hardness measurements were conducted on suitably prepared sections through the fatigue-fractured (left) fitting. For comparison, hardness measurements were also conducted on the lower fitting from the right wing of VH-TZJ. The hardness results were then converted⁶⁴ to approximate tensile strength values (Table B1). As measured, the hardness results for both left and right lower fittings were consistent with the prescribed value from the aircraft manufacturer for 30HGSA high-strength low-alloy steel. The results indicate that the fittings had been heat-treated to within the correct strength range.

⁶⁴ ASTM E140, Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, Scleroscope Hardness, and Leeb Hardness

Table B1: Attachment fitting hardness measurements

Aircraft and fitting	Vickers Hardness (HV0.5)	Tensile strength (MPa)
VH-TZJ – Left lower fitting (fractured)	381	1,229
VH-TZJ – Right lower fitting (intact)	366	1,204
30HGSA – Specified material	--	1,200

Material chemistry

Quantitative chemical analyses of samples taken from the left (fractured) and right (intact) lower main spar outboard attachment fitting was conducted using an optical emission spectrometer.⁶⁵ The results of the material testing are contained in Table B2 and are displayed as elemental weight percentage. Both attachment fitting materials conformed to the chemical composition of the specified 30HGSA alloy.

Table B2: Chemical composition of attachment fitting materials (weight %)

	Fe	C	Mn	Si	S	P	Ni	Cr	Cu	Mo	V
Left fitting (fractured)	~Bal	0.29	0.99	1.10	0.01	0.02	0.30	1.04	0.14	0.08	0.01
Right fitting (intact)	~Bal	0.30	0.89	1.09	0.01	0.02	0.05	0.87	0.06	0.04	0.01
30HGSA (specified material)	~Bal	0.28 - 0.34	0.80 - 1.10	0.90 - 1.20	0.025 Max	0.025 Max	0.30 Max	0.80 - 1.10	0.30 Max	-- --	-- --

History of Dromader wing attachment fitting failures

The investigation findings from three in-flight wing separation accidents, conducted by the United States (US) National Transportation Safety Board (NTSB), found that severe pitting corrosion in the bore of the fittings led to the development of undetected fatigue cracking and eventual fracture of the attachment fitting. Fatigue cracking had propagated through about 90 per cent of the outboard attachment fitting lug in two of the accidents and about 60 per cent of one of the centre wing attachment fitting lugs in the other.

Safety analysis**Wing separation**

The in-flight separation of the left wing from VH-TZJ was associated with the ductile overstress fracture of the lower lug from the outboard attachment fitting at an area of pre-existing fatigue cracking. The attachments represented a critical part to the wing structure between the outboard and centre wing sections. Flight loads were transmitted from the outer wing to the centre wing and to the fuselage structure via the attachment fittings. The loss in structural integrity through the lower fitting fracture, in combination with the continued application of lift loads, resulted in immediate overstress failures of the remaining left wing attachment points and separation of the wing.

Location of the fatigue crack initiation points and direction of crack progression indicated that the lug had cracked and subsequently failed at the expected point of maximum tensile stress, resulting from upwards bending of the wing (aerodynamic lift loads). The remaining left wing attachments contained no pre-existing defects and had fractured as a result of overstress.

⁶⁵ Chemical analysis was conducted by Spectrometer Services Pty Ltd, test report 58357

Corrosion damage

Corrosion damage was evident throughout the bore of the fractured lower attachment fitting, with multiple fatigue micro-cracks initiating at areas of corrosion pitting. The pitting had created localised stress raisers, effectively reducing the fatigue endurance of the wing fitting and allowing the micro-cracks to initiate.

High strength steels such as the steel used in the manufacture of the Dromader attachment fitting are susceptible to pitting corrosion. Following the recovery and degreasing of the attachment fitting, the general appearance of the bore was bright and shiny and lightly abraded, punctuated by a distribution of corrosion pits and some surface staining. This is consistent with the reported use of a mildly abrasive cleaning process during the last maintenance inspection, 11 weeks prior to the accident.

Corrosion of the attachment fitting bore is a known issue with the M18A Dromader and was found to be a precursor to three fatigue failure and in-flight wing separation accidents in the US between 1999 and 2000. The corrosion damage within the bore of those fittings was described as 'severe pitting'. The history of failures shows that the fittings are sensitive to the development of fatigue cracking in the presence of pitting corrosion, irrespective of whether that pitting damage is assessed as severe, or relatively minor as in the case of VH-TZJ.

Attachment fatigue cracking

The series of adjacent micro-cracks that had initiated in the bore of the attachment fitting grew and linked to form the large single fatigue crack that progressed until failure of the lug. The area of fatigue cracking had progressed through approximately one third (38 per cent) of the ligament before final overstress fracture. In contrast, the US-investigated wing fitting failures exhibited fatigue cracks that had propagated through about 90 per cent of the same lug section. The stresses in the fittings are variable and are affected by factors such as aircraft weight, its speed and the type and severity of operations being flown. Gust and manoeuvre loads of varying magnitudes are the typical loads a wing structure might experience during operation to affect its fatigue life. The significant difference in the critical fatigue crack size between the US aircraft and VH-TZJ showed that the VH-TZJ fitting had been exposed to a considerably higher operational load at the time of the wing failure.

Because of factors such as the variable and irregular nature of the wing loading spectrum, the corroded bore surfaces, and the somewhat oxidised and poorly defined microscopic fracture features, the examination was unable to quantitatively determine the period over which the fatigue cracking had developed. However, the following features were consistent with the cracking initiating and developing over an extended period:

- the distribution of oxidation across the full extent of the fatigue surface
- the relatively poorly defined and finely spaced fatigue striations
- the absence of any identifiable areas of ductile tearing across the fatigue fracture surface or adjacent to the fatigue-overstress boundary.

On that basis, the ATSB concluded that it was likely that the cracking had initiated and had been developing for a period significantly longer than that accrued since the last maintenance inspection, 126.3 hours of time in service and 11 calendar weeks prior to the accident.

Appendix C – Fatigue management

General information

Fatigue, in a materials failure context, has been defined in a number of ways, including.⁶⁶

The process of progressive localised permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points, which may result in cracks or complete fracture after a sufficient number of fluctuations.

For many engineered systems, the stresses in the materials may be low, or the type of loading may not result in fatiguing stresses (for example, compressive or static loads) and fatigue is not a consideration within the expected operational life of the product. However, because of the need to optimise the aircraft structures to reduce weight, the stresses within the materials are relatively high and the airframe is subjected to a variety of loads during operation. Hence, fatigue is a prime concern for the design and continued airworthiness of an aircraft. Along with accidental damage and corrosion, fatigue is one of the primary causes of damage to an aircraft.

Fatigue leads to the formation of cracks in the structure that grow in size over time. These cracks significantly reduce the strength of the airframe and the usable ‘life’ of an aircraft is typically determined by how quickly the cracks form and grow.

United States Federal Aviation Administration guidance for the management of fatigue in new aircraft

To support United States (US) Federal Aviation Regulations (FAR),⁶⁷ the US Federal Aviation Administration (FAA) provided guidance on how to show compliance with the regulations for fatigue justification in a number of publications as follows:

- In 1973, the FAA released report AFS-120-73-2 *Fatigue evaluation of wing and associated structure on small airplanes*, which provided a method for evaluating fatigue in the entire structure.
- AFS-120-73-2 was superseded in 1993 by the release of advisory circular (AC) 23-13 *Fatigue and Fail-Safe Evaluation of Flight Structure and Pressurized Cabin for Part 23 Airplanes*.
- An updated version of AC 23-13, AC 23-13A *Fatigue, fail-safe, and damage tolerance evaluation of metallic structure for normal, utility, acrobatic and commuter category airplanes*, was released in 2005.

The information in the following sections is based on these and related publications, particularly the FAA Damage Tolerance Handbook.⁶⁸

Design approaches

Overview

At the time of writing, there were three basic design approaches for managing fatigue in aircraft structures. These were safe-life, fail-safe and damage tolerance. AC 23-13A defined these approaches as follows:

The **safe-life** of a structure is that number of events, such as flights, landings or flight hours, during which there is a low probability that the strength will degrade below its design ultimate value due to fatigue cracking.

⁶⁶ Federal Aviation Administration Advisory Circular AC 23-13A.

⁶⁷ Namely, FAR part 23 §§23.571, 23.572, 23.573, 23.574 and 23.627.

⁶⁸ Federal Aviation Administration, 1993. *Damage Tolerance Assessment Handbook*, Volume I. Report DOT/FAA/CT-93/69.I. pp. 1–27.

Fail-safe is the attribute of the structure that permits it to retain its required residual strength for a period of unrepaired use after the failure or partial failure of a principal structural element.

Damage tolerance is the attribute of the structure that permits it to retain its required residual strength for a period of use after the structure has sustained a given level of fatigue, corrosion, accidental, or discrete source damage.

Put more simply:

- Safe-life design is intended to have the structure retired before there is a likelihood of fatigue cracks affecting its strength.
- Fail-safe means that redundant structure will cope with the failure of major structure until it is discovered during an inspection program.
- Damage tolerance relies on detection of cracks through a specifically-designed inspection program to ensure that cracks from fatigue, corrosion or accidental damage are identified before they become large enough to sufficiently degrade the remaining strength.

Safe-life design

The FAA's Damage Tolerance Handbook sums up the safe-life approach quite succinctly:

For safe-life, the design objective was to make the time needed to form a crack longer than the operational life of the structure.

According to AC 23-13A section 2-2:

Since a safe-life evaluation usually does not include demonstration of crack growth rates or residual strength capability, we assume [using the safe-life design approach] that the development of a detectable crack may result in catastrophic failure of the structure.

The safe-life of a structure is typically determined using a combination of analysis, component testing, and full-scale testing. According to FAA AC 23-13A, the essential elements of a safe-life evaluation are:

- Estimate or measure the expected loading spectra for the structure.
- Conduct a structural analysis to determine gross stresses and stress concentration factors for all the principal structural elements.
- Conduct a fatigue test to determine the response of the structure to typical in-service loading spectra. Full-scale testing is the most reliable method for determining the response of the structure to expected loadings.
- Determine reliable replacement times by interpreting the loading history, variable load analysis, fatigue test data, service experience, and fatigue analysis. The reliability of the replacement times is usually achieved by the use of scatter factors.
- Provide data for inspection and maintenance instructions and guidance information to operators.

The methodology for safe-life prediction in FAA report AFS-120-73-2 and AC 23-13A uses Miner's Linear Cumulative Damage Theory. The concept behind Miner's Theory is that the fatigue damage from a given stress level is proportional to the number of cycles applied at that stress level divided by the total number of cycles to failure at the same stress level. These are referred to as cycle ratios. The total damage is the sum of the damage from all the applied cycle ratios. Failure is predicted to occur when the sum of cycle ratios is equal to 1.

The range, or spectrum, of loads that the aircraft is subjected to over its life needs to be determined. The principal types of loads are:

- flight loads – manoeuvring and gust
- taxi loads
- landing impact loads
- ground-air-ground.

These methodologies have their limitations and are aimed at being conservative in their application as they examine the major load types only. There are a number of other load types that could produce fatigue-inducing loads, including the load variations as a result of control inputs and vibrations from powerplants.

The spectra of loads within these types are a function of the type of aircraft (for example, single- or twin-engine, pressurised or unpressurised) and its use (for example, low-level survey, long-distance cruise). Given that the exact spectra to which a particular aircraft will be subjected cannot be known before it enters service, a spectrum for a typical aircraft and operation is used in the analysis and testing. These conservative spectra are empirically based on data collected during operational use and experimentation.

Both FAA report AFS-120-73-2 and AC 23-13A contain examples of spectra for a range of general aircraft types and operations. However, the spectra presented in AFS-120-73-2 notes that 'aerial application to be added at a later date'. That does not appear to have occurred until AC 23-13. However, in correspondence with the Civil Aviation Safety Authority (CASA), PZL Mielec indicated that their specified service lives were based on a spectrum recorded during 992 hours of agricultural operations involving the M18.

An important aspect of the load spectra in the referenced literature is that they present the cumulative frequency per nautical mile. However, aircraft lives are determined in flight hours. This means that the operating speed will affect how quickly loading cycles, and hence fatigue damage, is accumulated. Hence, if an aircraft's average operating speed is increased, fatigue damage will accumulate at a greater rate. FAA report AFS-120-73-2 specified that the aircraft velocity used for determining the gust and manoeuvre spectra shall not be less than 100 kt or 90 per cent of the maximum manoeuvring speed, whichever is less, for 'special usage' aircraft (such as those used in agricultural and firefighting operations).

The stresses from flight, taxi and landing loads are quite obvious and most people are aware of these, but an important factor in this fatigue analysis is the ground-air-ground cycle. The ground-air-ground cycle is a once per flight cycle and is the cycle from the minimum (largest negative or smallest positive) stress to the maximum stress experienced on a flight. AC 23-13A notes that for typical aircraft certified in the 'normal' category, two thirds to three quarters of the total fatigue damage on the wing may be caused by the ground-air-ground cycle.

Experimentation has shown that the number of cycles to failure for a particular material decreases with increasing stress level, but it is not linear and there is a large degree of variation, or 'scatter', in the results for a given stress level. To accommodate this uncertainty in the material's response to the stresses, and also to account for some of the limitations of the methodology, variation in operation and service issues, scatter factors are applied to the calculated mean fatigue life to determine the safe-life. FAA report AFS-120-73-2 specifies scatter factors of 4 for a safe-life based on full-scale testing through to 8 for a safe-life based on analysis alone. Intermediate scatter factors can be used if some component testing is also included. AC 23-13A also specifies the use of scatter factors, but the methodology is more complex and takes a more statistical approach.

FAA report AFS-120-73-2 notes that the scatter factor associated with full-scale testing may be reduced from 4 to 3 if 'equivalent safety is provided by determining crack location and growth rate and prescribing an inspection program based on this information that will assure that catastrophic failure will not result from initiation and growth of fatigue cracks.' AC 23-13A however, notes that 'Today, we do not allow a type certificate (TC), amended type certificate, or supplemental type certificate (STC) program to rely on inspections alone, without demonstrated residual strength, as a means of maintaining continued airworthiness.' Other than these, there is no guidance provided on inspection of fatigue susceptible structure.

AC 23-13A has a section that deals with alterations, modifications or changes in design. Along with changes in construction and materials, it notes:

You should also evaluate the effect of any change to the airplane's operational characteristics that invalidate the assumptions used in the original fatigue substantiation. Changes to the operational characteristics that may be important for fatigue include higher design airspeeds or higher average speed. They also include changes to the maximum allowable weight and centre of gravity envelope, changes to the average weight and centre of gravity location, and engine or propeller changes.

Damage-tolerant design

Damage tolerance was not introduced into US Code of Federal Regulation (CFR) Part 23 until 9 July 1993 at amendment 23-45, and remains an optional method for showing compliance for metallic structures. At the time of certification, the applicable regulation was CFR §23.572, at amendment 23-14, and required either a safe-life determination or fail-safe structure. Therefore, the damage tolerance design approach was not applicable to the PZL M18A. However, the following information is provided as background for later discussion.

Chapter 4 of AC 23-13A notes that the FAA had not developed guidance for part 23 damage tolerance evaluations and that the guidance provided in AC 25.571C may be used. AC 25.571C *Damage Tolerance and Fatigue Evaluation of Structure* was superseded by AC 25.571-1D on 13 January 2011. AC 25.571-1D is used in this report.

Contrary to what the name might suggest, damage tolerance is not a property of the design. It does not necessarily mean that the structure can tolerate discrete sources of damage, such as the fuselage being punctured by a propeller blade. Neither is it simply a method for working out the life of a structure. It is a holistic approach to develop a maintenance programme to manage the airworthiness of an aircraft. Damage tolerance includes the management of fatigue through a range of design methodologies and a structured maintenance programme that accounts for a number of critical aspects.

In a 2005 paper, CASA and FAA authors highlighted five facets of a damage tolerance assessment:⁶⁹

- **Site.** Where could cracks start?
- **Scenario.** How will cracks grow? Will there be one, or more? Will a crack in one part initiate cracks in another?
- **Detectable.** As a crack grows, what is the length at which it becomes readily detectable?
- **Dangerous.** What is the maximum size of the crack that ensures that the structure retains the required strength?
- **Duration.** How long will a crack take to grow from detectable to dangerous?

Once the probable sites and scenarios for cracking have been identified through a combination of structural analysis and experience, the behaviour of the crack is modelled using 'fracture mechanics' to determine the rates of crack growth.

According to the FAA Damage Tolerance Handbook:

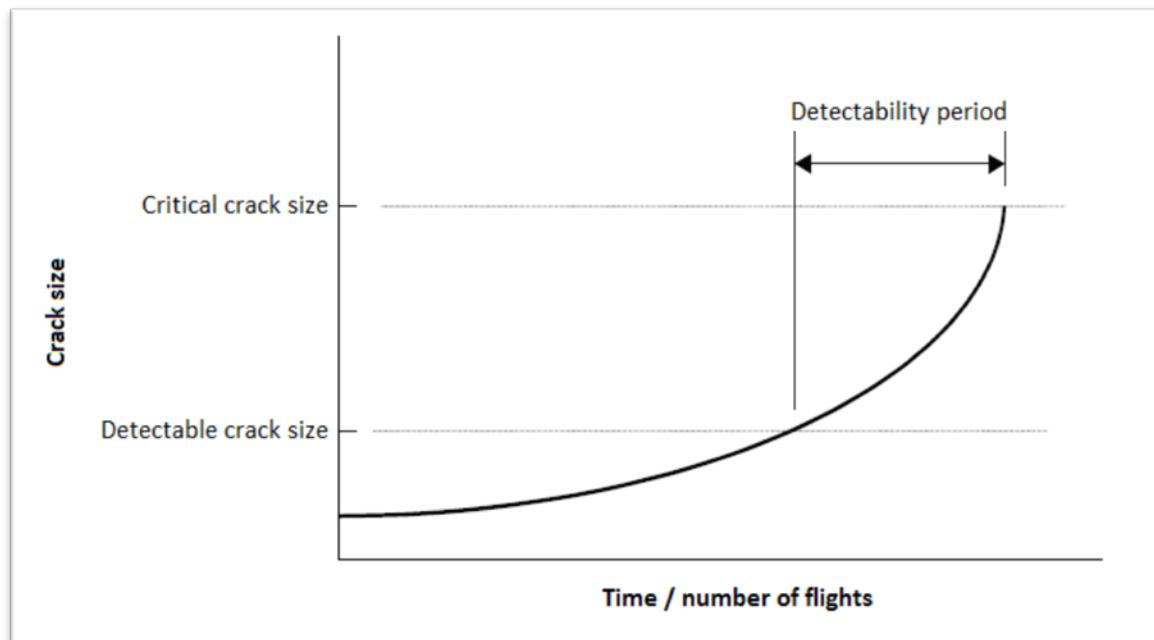
The purpose of damage tolerance analysis is to ensure that crack growth life is greater than any accumulation of service loads that could drive a crack to a dangerous size. This objective can be achieved with an inspection program that detects cracking initiated by fatigue, accident, or corrosion before propagation to failure.

The time that a crack becomes detectable is heavily dependent upon the method of inspection.

⁶⁹ Eastin B and Swift S, 2005. *Rough diamond*. 22nd International Committee on Aeronautical Fatigue Symposium. Vol. 6.

Unlike the empirical methods used in a safe-life analysis, fracture mechanics is based on the physics of crack growth, which shows that cracks grow at an exponential rate. For a long period, there is very little, or no, growth of the crack but, over time, a crack forms and will grow at an increasing rate (Figure C1). As shown, there will be a period of time between when a crack reaches a detectable size and when it grows to a critical (dangerous) size. It becomes critical when the material does not have the residual strength to resist the applied forces without failure. This period is shown in Figure C1.

Figure C1: Crack growth showing the period in which the crack is detectable before becoming dangerous (the critical crack size)



Source: FAA AC 91-82A *Fatigue Management Programs for In-Service Issues*, modified by the ATSB

As mentioned above, the damage tolerance approach uses a structured inspection program to detect any cracks before they reach a dangerous size. Based on the damage tolerance analysis, the inspection program will typically specify a threshold number of cycles, or time, at which inspections start and a follow-on inspection period. The threshold is based on when a crack will become detectable.

The detectability limit is the crack size at which a crack can be reliably detected by an inspector using the prescribed inspection method. This reliably detectable crack size is dependent on a number of factors including the inspection method, accessibility of the crack and the NDT technician.

The inspection interval will be set to give a sufficient number of opportunities to detect a crack before it becomes dangerous. The actual inspection interval is dependent on the results of the damage tolerance assessment and the probability of detecting a crack using the chosen inspection method. For example, according to FAA AC 91-82A, for a single load path, the inspection interval should ensure that there are at least two opportunities to find a crack between the time it reaches a detectable size and grows to a critical dangerous size.

Flight load spectra

Regardless of the fatigue management approach used, designers need to understand how the stresses vary within the structure over the life of the aircraft. The stresses will depend on a large range of factors, from the aircraft's weight for each flight, the environment in which it is operated,

to the manner in which it is operated. The designer will not know these in advance for each aircraft, so they typically use an assumed load spectrum that will represent the aircraft design.

A number of spectra have been developed over the years, but the most commonly used spectra for small aircraft have been provided by the FAA in report AFS-120-73-2 and AC 23-13A. The FAA identified that different categories of aircraft and types of operation result in different flight load spectra and as such present spectra for the different types. In this context, 'load' does not refer to the amount of weight an aircraft carries but rather the acceleration applied to the airframe.

To represent each aspect of a safe-life fatigue analysis, each aircraft category and type of operation have a number of their own spectra representing gust, manoeuvre, landing and taxi. The only aspect not covered is the ground-air-ground spectrum, because this is a once per flight loading case that represents the variation between the largest and smallest, or largest negative, loads sustained during the flight.

The important spectrum for this investigation is the manoeuvre load spectrum, which plots the cumulative frequency of exceedances per nautical mile against the acceleration fraction. Relevant definitions include:

- The **cumulative frequency of exceedances** is the number of times that the load factor of interest has been exceeded. The cumulative factor includes all load factor exceedances below the one of interest. For example a 2g load factor exceedance would also be counted as exceeding 1.9g, 1.8g and so on.
- The **acceleration fraction** is the load factor mapped to a scale between 0 and 1, where 0 is level unaccelerated flight and 1 is the limit load. For example an acceleration fraction of 0.8 represents 80 per cent of the limit load.

The flight load spectra provided in FAA report AFS-120-73-2 and AC 23-13A were developed by the FAA from flight load data recorded from a range of aircraft and types of operation over a number of years. There are a number of methods for recording an aircraft's normal load factor history. These can include using a fatigue meter, where a g-level exceedance is recorded on a dial representing that g-level each time that the event occurs, or a time-based recording that records a trace of the g-level along a time axis.

It is unknown what method was used to develop the spectra in FAA report AFS-120-73-2, but the development of the spectra provided in AC 23-13A was described in FAA report *DOT/FAA/CT-91/20 General Aviation Aircraft – Normal Acceleration Data Analysis and Collection Project*. The study described in that report used a time-based method that recorded traces of the test aircraft's airspeed, altitude and normal acceleration (g-loading) on a photographic tape. The spectra was developed from manual readings of the films collected, where the difference between a manoeuvre load and a gust load was subjectively assessed by analysts.

PZL M18 fatigue management approach

The PZL M18 aircraft was designed and its fatigue life justified in the 1980s thru early 1990s, pre-dating the release of ACs 23-13 and 23-13A. Thus, FAA report AFS-120-73-2 was the current FAA guidance at the time of fatigue justification. According to the aircraft manufacturer, it used AFS-120-73-2 as the basis for determining the service life factor for operations between 4,700 kg and 5,300 kg.

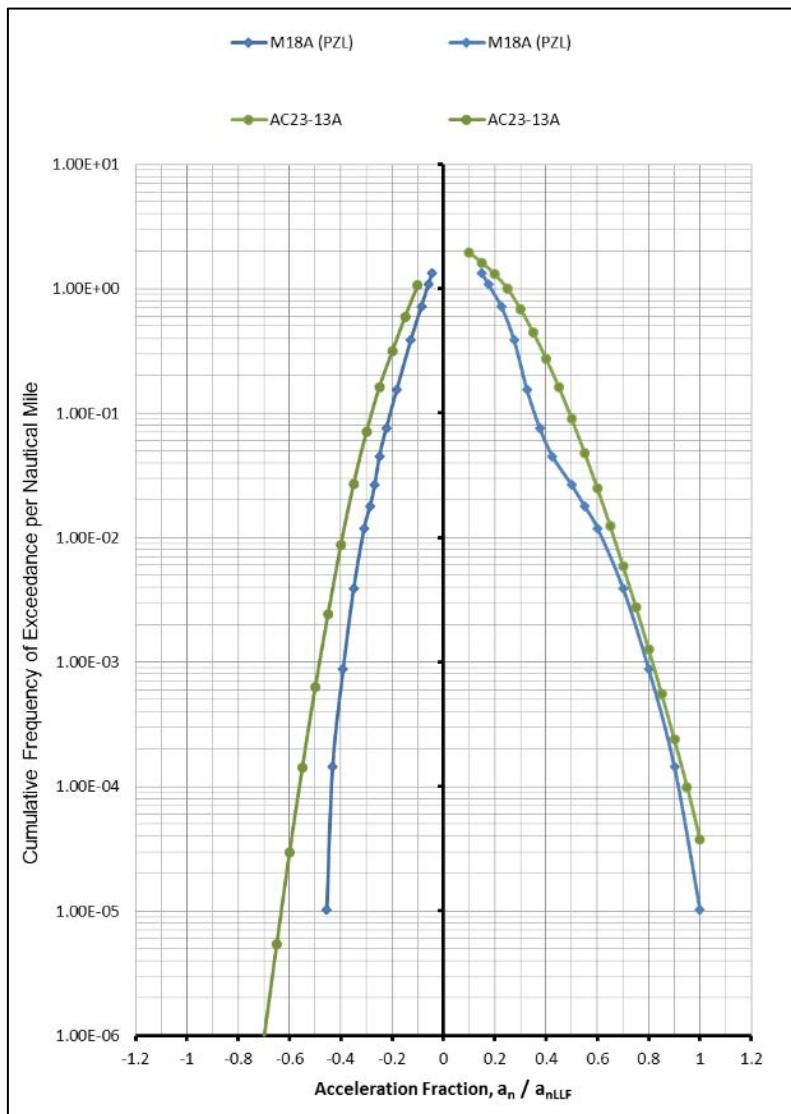
The M18 was designed on the safe-life basis. CASA files show that the aircraft initially had a 1,000-hour fatigue life limitation, but that this was an interim measure while full-scale fatigue testing was carried out.

At the time the M18 was certified, the FAA did not provide a manoeuvre load spectrum for agricultural operations, so the aircraft manufacturer determined their own spectrum based on 992 hours of operation of their early production aircraft in Europe. A copy of the manufacturer's manoeuvre load spectrum, along with a comparison to the AC 23-13A spectrum, is provided in

Figure C2. This indicates that the spectrum for the M18A was a little less severe than the later produced AC 23-13A spectrum. That is, exceedances of the same g-loading were encountered less often in the aircraft manufacturer's spectrum.

The aircraft manufacturer advised that the airspeed used in its safe-life analysis of the M18A was 180 km/h (97.2 kt).

Figure C2: Aircraft manufacturer's fatigue design flight load spectrum for the M18A compared to that provided in FAA AC23-13A



Source: PZL Mielec, modified by the ATSB

Manufacturer's airframe life limits

While the full-scale testing of the aircraft was being conducted in Poland, the fatigue life limit was incrementally extended by the release of a number of manufacturer service bulletins (SB) as follows:

- SB E/02.109/86 increased the life to 3,000 hours (from 1987)
- SB E/02.123/88 increased the life to 5,000 hours (from 1988)
- SB E/02.142/91 and E/02.152/94 increased the life to 6,000 hours (from 1994)
- SB E/02.172/2001 increased the life to 10,000 hours (from 2001).

These fatigue life limits were mandated in Australia through airworthiness directive AD/PZL/1. This AD was cancelled on 12 February 2009 because the SBs were otherwise mandated through the aircraft's repair manual.

US FAA guidance for the management of fatigue in ageing aircraft

AC 91-60 The Continued Airworthiness of Older Airplanes

In June 1983, the FAA issued AC 91-60, which provided broad information and recommendations to aircraft manufacturers, owners and operators on the development of maintenance programs to assure the continued airworthiness of older aircraft. The AC included a list of areas requiring special attention, including wing spars and attachment points, and advice on communication between manufacturers, owners and operators.

FAA AC 91-82 Fatigue Management Programs for Airplanes with Demonstrated Risk of Catastrophic Failure Due to Fatigue

In April 2008, the FAA superseded AC 91-60 with AC 91-82, which was significantly more comprehensive than AC 91-60 and had provided guidance on developing and implementing a fatigue management program (FMP). It also provided guidance for actions once the FAA determined that an AD was necessary to address an unsafe condition associated with a demonstrated risk of catastrophic failure due to fatigue.

The AC's definition of 'a demonstrated risk of catastrophic failure due to fatigue' included when:

An airplane has experienced a catastrophic failure due to fatigue and the same scenario is likely to occur on other airplanes in the fleet

It also defined a fatigue critical structure as:

A structure that is susceptible to fatigue cracking that could lead to catastrophic failure of an airplane. This would typically include airframe primary load carrying elements subjected to repeated tension dominant loading. Examples include ... Joints or splices of tension dominant load path, e.g. lower spar caps, skins, stringers, fittings, bolts, etc ...

The applicability of AC 91-82 included small aircraft certificated to part 23 and those certificated in the 'restricted' category. Both of these apply to the PZL M18 Dromader.

AC 91-82 provided two options for a fatigue management plan for the structural elements directly related to the unsafe condition:

- a replacement/modification program, or
- a damage tolerance-based inspection program.

The AC presented the following method for the determination of demonstrated risk of catastrophic failure due to fatigue:

If the investigation finds that fatigue cracking contributed to the accident, incident, or in-service finding, and that it is likely to exist or develop in other airplanes of the same type design, the FAA may determine that a demonstrated risk exists. In these cases, the FAA would consider issuing an AD requiring mandatory actions to maintain the continued operational safety of the affected fleet. These actions would be included in an FMP to mitigate the demonstrated risk and proactively address the broader risk posed by other fatigue critical structure.

In some instances, the FAA will issue an AD mandating initial, short-term actions to provide short-term mitigation of the demonstrated risk and allow the fleet to return to service. These short-term actions often include operating limitations or immediate and short-interval inspections. The FAA often issues these short-term actions as emergency ADs or Immediately Adopted Rule (IAR) ADs. Information learned from these short-term actions, including inspection results, will help the FAA and the applicant to determine a long-term or permanent solution to mitigate the demonstrated risk.

FAA AC 91-82A Fatigue Management Programs for In-Service Issues

The FAA released revision A of AC 91-82 in August of 2011. The change notification included with the revision indicated that there were no substantive technical changes.

Appendix D – VH-TZJ manoeuvre g-load spectrum

Introduction

As part of its investigation, the ATSB obtained electronic copies of data recorded by the Perkins Technologies Digital Acquisition Alarm Monitor (DAAM) data recording system on VH-TZJ. The operator had downloaded the data from VH-TZJ prior to the accident.

The DAAM recorded a number of parameters regarding the operation of the aircraft at a rate of 10 samples per second (Table D1).

Table D1: Recorded parameters

Date	Outside air temperature
Time	Engine torque
Propeller RPM	Fuselage g-force
Starter button (on/off)	Turbine temperature
Fuel flow rate	Indicated airspeed
Supply voltage	Air pressure/altitude ⁷⁰
Engine oil pressure	

The downloaded data could not be directly analysed because it was in a binary format. The ATSB converted the binary files to comma-separated value (CSV) files using a proprietary program supplied by the manufacturer of the DAAM system.

The total data set included a number of flights from 2007 through to 2013, but not the entire flight history over that time. However, the ATSB identified that the flights between 15 June 2007 and 2 April 2008 were recorded as part of a program to justify aspects of supplemental type certificate (STC) SVA 521. An engineering report associated with those data gathering flights contained flight data cards for each flight.⁷¹

The sample for analysis consisted of 45 individual flights and 25.2 hours of flight.

Methodology

Calculation of aircraft weight

For the data-gathering flights, the pilot recorded the fuel quantity and hopper load on the flight data card at the start of each flight.

The take-off weight was calculated as the sum of the:

- aircraft's empty weight
- weight of the pilot
- recorded fuel load at the start of the flight
- recorded hopper load at the start of the flight.

The empty weight listed in the Flight Manual for VH-TZJ was 2,658.1 kg.

The weights of the pilots involved were unknown, so an estimate of 80 kg was used for all cases. A variation of plus or minus 20 kg in a pilot's weight would have a less than 1 per cent effect on the take-off weight and was assumed to be negligible.

⁷⁰ Earlier recordings presented air pressure data, whereas later recordings presented altitude data.

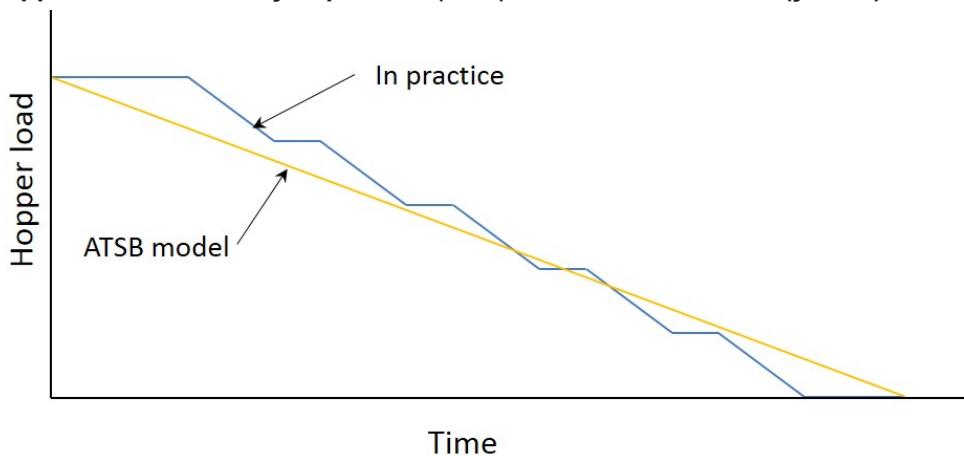
⁷¹ The report was obtained as part of an earlier ATSB investigation into another M18 accident. This investigation, AO-2008-084, is available from the ATSB website at www.atsb.gov.au.

The fuel was recorded in litres, so it was converted to weight using an assumed specific fuel density of 0.81 kg/L for Jet A1 fuel.

As the flight progressed, the weight of the aircraft reduced as the fuel was burnt and the hopper contents dispensed. The weight of the aircraft was estimated at any time in the flight by subtracting the weight of the used fuel and the amount of load dispensed. The weight of fuel burnt at any particular time was calculated by a step-wise integration of the fuel flow rate up to that time.

In practice, the hopper contents were dispensed only during a spray run, not while the aircraft positioned to the spray area and manoeuvred between spray runs. Because the DAAM data did not include a parameter for spray equipment operation, the ATSB assumed that the hopper load was evenly dispensed over the entire flight (Figure D1).

Figure D1: Hopper load variation models showing the differences between the how the hopper load would vary in practice (blue) and the ATSB model (yellow)



Source: ATSB

For the analysis, it was assumed that the aircraft was airborne when the airspeed was above 60 kt.

Method to determine acceleration fraction

To develop a spectrum that was in the same format as those provided by the Federal Aviation Administration (FAA)⁷² and the manufacturer, the load factor (g-load) measurements were converted to an acceleration fraction.

FAA report AFS-120-73-2 defined *acceleration fraction* as:

The ratio of the incremental load factor at the operating weight to the incremental design limit load factor at maximum gross weight.

The incremental load factor is the deviation of the load factor from the 1g steady-state value. By this definition, steady level flight is an acceleration fraction of zero and limit load is an acceleration fraction of 1. Negative acceleration fractions are those below the 1g steady-state value.

When the take-off weight was above the original maximum take-off weight (MTOW) of 4,200 kg, the limit load factor decreased (Table D2). At any particular time, the calculation of the acceleration fraction accounted for this by using the limit load factor applicable to the current weight.

⁷² The FAA spectra are presented in FAA report AFS-120-73-2 and FAA advisory circular (AC) 23-13A.

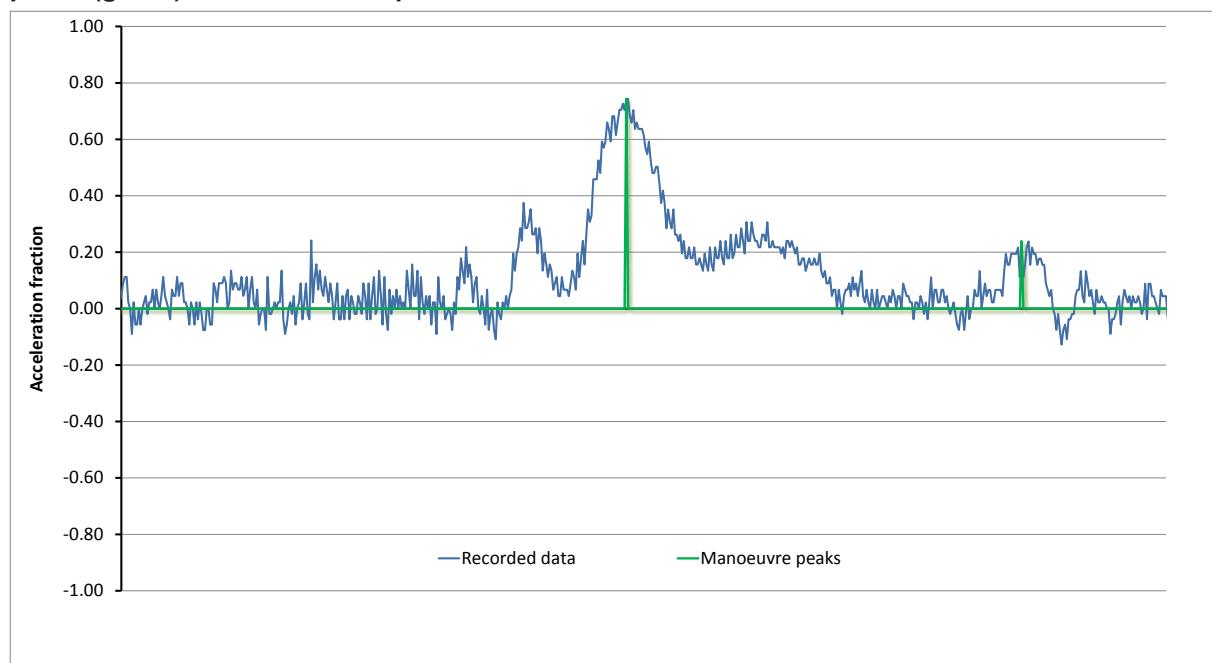
Table D2: Limit load factors⁷³

Weight (kg)	N_{LLF} (g)
4,200	3.4
4,700	3.0
5,300	2.8
6,600	2.5

Separation of gust and manoeuvre loads and identification of load exceedances

The data recovered from the DAAM system contained raw load factor measurements. The data did not identify the source of the load, and included a combination of manoeuvres and gusts. A load duration criteria was applied to the data to differentiate between manoeuvre and gust loads. Based on the manoeuvre-gust separation method described by the FAA,⁷⁴ any load cycle with a duration of less than 2 seconds was considered to be a gust. Conversely, any load duration of 2 seconds or greater was considered to be a manoeuvre.

The data showed that during a manoeuvre, the load factor was variable and could contain a number of local peaks before returning to steady, level flight. However, the manoeuvre loads presented in the FAA spectra represented only the largest load experienced during a manoeuvre.⁷⁵ The ATSB used the same principle to identify manoeuvre loads within the recorded data. An example of the raw data (blue lines), with peak manoeuvre loads identified (green lines) is presented in Figure D2.

Figure D2: Sample data showing the recorded data (blue) and identified manoeuvre peaks (green) over a 1-minute period

Source: ATSB

⁷³ Limit load factors sourced from the flight manual supplement for STC SVA521.

⁷⁴ FAA report DOT/FAA/AR-99/14, *An Evaluation of Methods to Separate Maneuver and Gust Load Factors From Measured Acceleration Time Histories*, April 1999.

⁷⁵ The rules used by the FAA in reading the flight data used to develop their spectra are presented in appendix F of FAA report DOT/FAA/CT-91/20 *General Aviation Aircraft – Normal Acceleration Data Analysis and Collection Project*, February 1993.

Compilation of the resulting manoeuvre load spectrum

The number of acceleration fraction exceedances, in the range 0.15 to 1.0 at intervals of 0.05, were counted for each flight. The results from each flight were then summed to get the total cumulative number of exceedances⁷⁶ for each acceleration fraction. The cumulative frequency per nautical mile was derived by dividing the sum for each acceleration fraction by the total distance travelled.

The distance travelled for each flight was calculated from a simple step-wise integration of the instantaneous airspeed recorded by the DAAM. The DAAM recorded indicated airspeed, which was not suitable for calculating the distance travelled. Calculation of the distance travelled required knowledge of the true airspeed. Fortunately, the data also included the air pressure and outside air temperature, which permitted conversion of the indicated airspeed to true airspeed.

The analysis determined that the total distance travelled in the 45 flights was about 3,140 NM (5,815 km).

Manoeuvre load spectrum

The manoeuvre load spectrum derived from the recorded DAAM data is presented in Table D3.

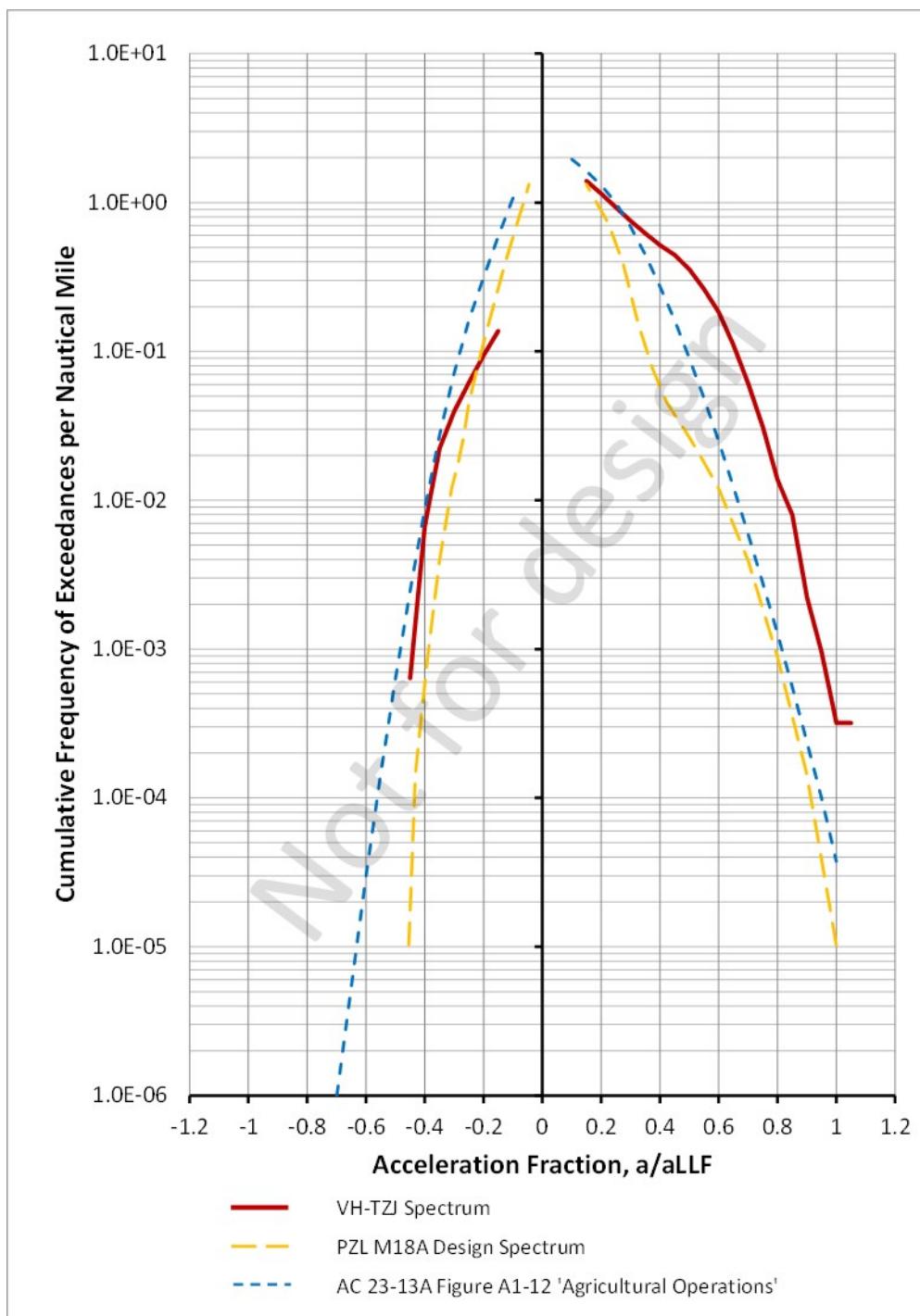
Table D3: VH-TZJ manoeuvre spectrum as derived from the recorded DAAM data

Acceleration fraction, a_N/a_{NLLF}	Cumulative Frequency of exceedances per nautical mile	Acceleration fraction, a_N/a_{NLLF}	Cumulative Frequency of exceedances per nautical mile
0.15	1.39687E+00	-0.15	1.37204E-01
0.20	1.14920E+00	-0.20	9.42282E-02
0.25	9.27002E-01	-0.25	6.14393E-02
0.30	7.52552E-01	-0.30	3.94740E-02
0.35	6.22352E-01	-0.35	2.22837E-02
0.40	5.17937E-01	-0.40	6.68511E-03
0.45	4.44082E-01	-0.45	6.36677E-04
0.50	3.54311E-01	-0.50	0
0.55	2.61993E-01	-0.55	0
0.60	1.84000E-01	-0.60	0
0.65	1.10145E-01	-0.65	0
0.70	6.11210E-02	-0.70	0
0.75	3.08788E-02	-0.75	0
0.80	1.36886E-02	-0.80	0
0.85	7.95846E-03	-0.85	0
0.90	2.22837E-03	-0.90	0
0.95	9.55016E-04	-0.95	0
1.00	3.18339E-04	-1.00	0

⁷⁶ A manoeuvre load exceedance at a particular level includes exceedance of all levels below them. For example, exceedance of an acceleration fraction of 0.6, includes exceedance of 0.55, 0.5, 0.45, and so forth. Because, the count of acceleration fractions at any particular level is an accumulation of those below it, they are referred to as the cumulative number of exceedances.

The resulting load spectrum is shown graphically in Figure D3.⁷⁷ For comparison, the spectrum from Table A1-12 and Figure A1-12 of AC 23-13A and the spectrum supplied by the aircraft manufacturer are included in the plot.

Figure D3: VH-TZJ manoeuvre spectrum (in red) as derived from the recorded DAAM data with FAA AC-23-13A (in blue) and aircraft manufacturer (in yellow) data for comparison



Source: Graphic developed by the ATSB based on data sourced from the FAA, aircraft manufacturer and the DAAM

⁷⁷ The vertical axis is plotted with a logarithmic scale. This method of presentation is consistent with that used by the FAA.

Limitations and assumptions

Exceedance counting method

The spectra provided in both FAA report AFS-120-73-2 and AC 23-13A were derived from data that was recorded on analogue devices and manually interpreted by analysts. Being a computational analysis, the ATSB method of analysis was not prone to human variation and may have resulted in identification of a different number of exceedances. It is difficult to quantify how much this would have affected the number of counts. However, in commenting on its methodology, the FAA report indicated that the accuracy of the acceleration counts could be within 30 per cent. The ATSB methodology is likely to be within this range.

Effect of weight modelling

Due to the model used, the hopper load, and hence aircraft weight, would likely have been less than the actual weight for the first half of each flight. Similarly, the modelled aircraft weight in the latter half of each flight would likely be greater than the actual weight.

Because the limit load factor was lower at weights above 4,200 kg, underestimating the aircraft weight would result in a limit load factor that was higher than it should otherwise have been at those weights. This in turn would result in an effectively lower acceleration fraction. In the latter half of each flight, when the weights were probably below 4,200 kg, the limit load factor did not vary with weight and the approximation had no effect on the resulting acceleration fraction.

Given that at the higher weights the hopper load model would effectively lower the exceedance count for each acceleration fraction, the load spectrum was likely to have been underestimated by this method.

Calibration of the g-sensor

The report associated with the STC data gathering included a calibration certificate for the sensor used to measure the g-load factor. That certificate indicated that the sensor slightly under-read. That is, the sensor reported a load factor that was less than the actual load factor. In the absence of other factors this would result in an underestimated load spectrum.

The location of the sensor in VH-TZJ was unknown by the ATSB. Ideally, the sensor would be located at, or near, the centre of gravity to remove the artificial effect of pitch rate when manoeuvring. The resultant data was considered acceptable by the Civil Aviation Safety Authority for the purposes of the STC. As such, the effects of the location of the sensor on the results were likely to have been insignificant.

Sample size

The aircraft manufacturer used 992 hours of flight time to develop its spectrum. The sample used in the ATSB analysis represents only 2.5 per cent of that flight time and less than 1 per cent of the total flight time of VH-TZJ.

Although in terms of flight time the ATSB's sample was relatively small, the nature of agricultural operations meant that the data captured a considerable number of manoeuvres. Additionally, the data was collected over a 10-month period and was carried out by two of the operator's senior pilots. The pilot that carried out around 70 per cent of the flights used in this analysis reported to the ATSB that the flights were typical of normal operations. Because of the relatively large time span, it is unlikely that aircraft handling was affected by ongoing pilot awareness of their operating under observed conditions.

Appendix E – Related accidents and other investigations

United States accidents

Investigations by the United States (US) National Transportation Safety Board (NTSB) into three US M18 accidents in which the wings separated in-flight in 1999 and 2000 discovered severe corrosion and cracking in the wing lower attachment fittings, which led to fatigue cracking and failure of the fittings.

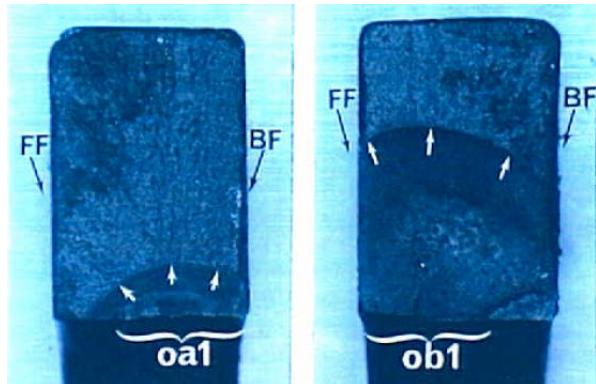
The relevant investigation reports are available at <https://www.ntsb.gov/>.

NTSB investigation FTW99LA170

On 18 June 1999, a PZL Mielec M18A with about 4,700 hours time in service (TIS) was substantially damaged when its right wing separated in flight while manoeuvring in Louisiana, US. The pilot received minor injuries. Examination of the aircraft revealed that both lugs of the right wing main spar lower centre attachment fitting had failed due to fatigue cracking. The larger crack developed to about 60 per cent of the lug area (Figure E1). There was also a crack in the left wing inboard attachment fitting's forward lug. Severe pitting corrosion was noted in the bores and on the faces of the lugs, as well as on the other wing fittings. The fittings were found to contain insufficient lubricating grease.

The NTSB found that although the aircraft records showed that all required inspections had been completed, including a fluorescent dye penetrant inspection of the wing attachment fittings, 'metallurgical examination disclosed no trace of dye penetrant residue on any of the examined components.'

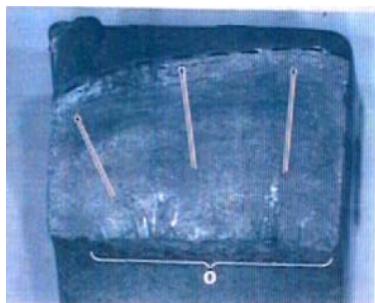
Figure E1: M18 wing fitting, NTSB investigation FTW99LA170



Source: NTSB

NTSB investigation FTW00LA149

On 22 May 2000, a PZL Mielec M18A with about 5,000 hours TIS was destroyed when its right wing separated in flight while manoeuvring in Louisiana, US. The pilot received serious injuries. Examinations showed that the right wing main spar lower outer attachment fitting had failed due to fatigue cracking through about 90 per cent of the lug area (Figure E2). The wing attachment fittings displayed a line of heavy corrosion pitting on the inside circumference. The fatigue cracking in the lug initiated at multiple origins located in the bore of the lug, corresponding with areas of severe pitting corrosion.

Figure E2: M18 wing fitting, NTSB investigation FTW00LA149

Source: NTSB

NTSB investigation FTW00LA267

On 21 September 2000, a PZL Mielec M18A with about 5,000 hours TIS was destroyed when its right wing separated in flight while manoeuvring in Arkansas, US. The pilot received minor injuries. The NTSB found that the right wing main spar lower outer attachment fitting lug had failed due to fatigue cracking through about 90 per cent of the lug area (Figure E3). There was a line of deep corrosion pits on the inner circumference of the lug near the fracture line. Each of the wing attachment fitting lugs displayed a line of heavy corrosion pitting on their inner circumference. The fittings were found to contain no lubricating grease. The NTSB found no evidence that the required 3,000-hour wing attachment fitting inspection had been conducted, and that the right lower mandrel and bolt had no grease or anticorrosive agents.

Figure E3: M18 wing fitting, NTSB investigation FTW00LA267

Source: NTSB

Australian accidents

Since 2006, the ATSB has investigated three other fatal accidents involving M18s, including one in-flight break-up (investigation AO-2008-084: *In-flight breakup -PZL M18A Dromader, VH-IGT, 58 km south-west of Nyngan, New South Wales, 29 December 2008.*). That in-flight break-up involved a separation of the outboard 1.8 m of the right wing. The failure mechanism did not involve fatigue cracking. The other two accidents involved an in-flight loss of control as follows:

- Investigation 200600851: *Aircraft loss of control -20 km SSW of Cootamundra, New South Wales – 16 February 2006 VH-FVF, PZL M-18A Dromader.*
- AO-2011-082: *Collision with terrain - PZL-Mielec M18A Turbine Dromader, VH-FOZ, 23 km WSW of Dirranbandi, Queensland, 19 July 2011.*

In April 2013, the ATSB published safety issues investigation report AI-2011-150: *Operation of the PZL-Mielec M18 Turbine Dromader at take-off weights above 4,200 kg*. Among other findings, this investigation established a number of issues regarding the potential for pilots and operators to apply incorrect operating limitations for flights at some weights under supplemental type certificate (STC) SVA521, and the method used to apply service life adjustments required at higher weights.

All of these investigation reports are available on the ATSB website at <http://www.atsb.gov.au>. A summary of the relevant findings and safety actions resulting from those investigations is provided below.

AO-2008-084: *In-flight break-up of M18A, registered VH-IGT, 29 December 2008*

On 29 December 2008, a PZL Mielec M18A Dromader (TPE331) aircraft impacted terrain while conducting spraying operations on a property near Nyngan, New South Wales. The pilot, who was the sole occupant, was fatally injured. The operator of the aircraft was the same as for TZJ.⁷⁸

The ATSB found that the outboard 1.8 m of the right wing separated from the aircraft resulting in a loss of control and subsequent impact with the terrain. The separation of the right wing section could not be conclusively attributed to any particular factor, and there was no observed fatigue cracking in the wing structure.

The ATSB identified the following safety issue:

A number of operators of the PZL M18 Dromader aircraft had not applied the appropriate service life factors to the aircraft's time in service for operations conducted with take-off weights greater than 4,700 kg, as required by the aircraft's service documentation. Hence the operators could not be assured that their aircraft were within their safe service life.

The ATSB also found that:

Operation of the M-18A in accordance with Civil Aviation Safety Authority exemptions^[79] EX56/07 and EX09/07 at weights in excess of the basic aircraft flight manual maximum take-off weight (MTOW), and up to the MTOW listed on the Type Certificate Data Sheet, may not provide the same level of safety intended by the manufacturer when including that weight on the Type Certificate.

As a result of the accident, the following safety action was taken or proposed:

- The aircraft operator reported that it undertook a retrospective process of applying the service life factors to its aircraft fleet during operations that had involved take-off weights above 4,700 kg and planned to apply them to all relevant future flights.
- The Civil Aviation Safety Authority (CASA) directed some operators to ensure that service life factors had been correctly applied. In July 2013, it directed the operator of TZJ to recalculate airframe hours for its four M18 aircraft, dating from when STC SVA521 was incorporated in 2009.
- CASA advised that it had contacted Certificate of Registration holders of M18 Dromader aircraft to verify that they had procedures for recording and factoring aircraft hours that included overweight operations. Further verification would also occur as part of CASA's routine surveillance program.
- CASA released a revised exemption that clarified the operation of aircraft at weights in excess of the basic aircraft flight manual maximum take-off weight. That exemption cancelled the previous exemptions.
- In addition, CASA advised that it would provide education to operators on the intention of the increased-weight exemptions.

⁷⁸ Under the previous ownership.

⁷⁹ Exemptions EX56/07 and EX09/07, which were valid from 2007 to 2009, exempted a pilot from compliance with the aircraft's published or otherwise approved MTOW.

AO-2011-082: Collision with terrain of M18A, registered VH-FOZ, 19 July 2011

On 19 July 2011, a PZL Mielec M18A Turbine Dromader aircraft, registered VH-FOZ, impacted terrain on a cotton station about 23 km west-south-west of Dirranbandi, Queensland while conducting a spraying flight. The pilot was fatally injured and the aircraft was destroyed by impact forces.

The ATSB found that, for reasons that could not be determined with certainty, the aircraft departed from controlled flight during a turn at low altitude and the pilot was unable to recover before impacting the ground.

The ATSB identified a significant safety issue affecting the safety of spraying operations in turbine Dromader aircraft. This issue related to the potential for the aircraft's centre of gravity (c.g.) to vary significantly depending on the weight in the aircraft's hopper and exceed the forward and aft limits during a flight. The issue was not found to have contributed to the VH-FOZ accident.

Moreover, although also not found to have contributed to the accident, there was an increased risk to the flight from the aircraft's operation, at times, in excess of its published airspeed and angle of bank limitations.

As a result of this accident, on 22 December 2011, CASA distributed a letter to operators of the M18, M18A, and M18B Dromader advising of the potential unusual movement of the aircraft's c.g. as the payload in the hopper is dumped or dispensed. The letter also advised operators to:

- assess the weight and balance of their aircraft
- develop new loading systems if necessary
- ensure that all pilots are familiar with the aircraft loading systems and the potential for c.g. variation.

On 12 January 2012, the owner/developer of STC SVA521 advised that the design would be reviewed to assess and address any excessive c.g. variation that may occur as the result of hopper payload and fuel usage during a flight. In addition, they planned to advise all operators using the STC of the potential for excessive c.g. variation.

The ATSB reported that, at the time of the report's publication, it was 'satisfied that the actions taken and proposed by CASA and owner/developer of the STC will, when complete, adequately address the safety issue.'

ATSB safety issue investigation AI-2011-150

Among other findings, as a result of this investigation, the ATSB established a number of issues regarding the potential for pilots and operators to apply incorrect operating limitations for flights at some weights under STC SVA521, and the method used to apply service life adjustments required at higher weights.

In response, the owner and developer of STC SVA521 reported that they were in the process of amending the STC and were developing a proposal for CASA consideration and approval. This proposal would address the maximum bank angle limitation and required aircraft modifications, as well as clarify the applicability of the flight manual limitations and airframe service life adjustment method. At the time of the accident involving TZJ, the STC had not been revised to address these issues.

Australian Transport Safety Bureau

The ATSB is an independent Commonwealth Government statutory agency. The ATSB is governed by a Commission and is entirely separate from transport regulators, policy makers and service providers. The ATSB's function is to improve safety and public confidence in the aviation, marine and rail modes of transport through excellence in: independent investigation of transport accidents and other safety occurrences; safety data recording, analysis and research; fostering safety awareness, knowledge and action.

The ATSB is responsible for investigating accidents and other transport safety matters involving civil aviation, marine and rail operations in Australia that fall within Commonwealth jurisdiction, as well as participating in overseas investigations involving Australian registered aircraft and ships. A primary concern is the safety of commercial transport, with particular regard to fare-paying passenger operations.

The ATSB performs its functions in accordance with the provisions of the *Transport Safety Investigation Act 2003* and Regulations and, where applicable, relevant international agreements.

Purpose of safety investigations

The object of a safety investigation is to identify and reduce safety-related risk. ATSB investigations determine and communicate the factors related to the transport safety matter being investigated.

It is not a function of the ATSB to apportion blame or determine liability. At the same time, an investigation report must include factual material of sufficient weight to support the analysis and findings. At all times the ATSB endeavours to balance the use of material that could imply adverse comment with the need to properly explain what happened, and why, in a fair and unbiased manner.

Developing safety action

Central to the ATSB's investigation of transport safety matters is the early identification of safety issues in the transport environment. The ATSB prefers to encourage the relevant organisation(s) to initiate proactive safety action that addresses safety issues. Nevertheless, the ATSB may use its power to make a formal safety recommendation either during or at the end of an investigation, depending on the level of risk associated with a safety issue and the extent of corrective action undertaken by the relevant organisation.

When safety recommendations are issued, they focus on clearly describing the safety issue of concern, rather than providing instructions or opinions on a preferred method of corrective action. As with equivalent overseas organisations, the ATSB has no power to enforce the implementation of its recommendations. It is a matter for the body to which an ATSB recommendation is directed to assess the costs and benefits of any particular means of addressing a safety issue.

When the ATSB issues a safety recommendation to a person, organisation or agency, they must provide a written response within 90 days. That response must indicate whether they accept the recommendation, any reasons for not accepting part or all of the recommendation, and details of any proposed safety action to give effect to the recommendation.

The ATSB can also issue safety advisory notices suggesting that an organisation or an industry sector consider a safety issue and take action where it believes it appropriate. There is no requirement for a formal response to an advisory notice, although the ATSB will publish any response it receives.

Investigation

ATSB Transport Safety Report

Aviation Occurrence Investigation

In-flight break-up involving modified PZL Mielec M18A
Dromader, VH-TZJ, 37 km west of Ulladulla, New South Wales
24 October 2013

AO-2013-187
Final – 15 February 2016

Australian Transport Safety Bureau

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