Failure Analysis Case Studies II
D.R.H. Jones (Editor)

FATIGUE FAILURE OF THE DE HAVILLAND COMET I

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Abstract—The de Havilland Comet I entered service in 1952, and became the first commercial airliner to be powered by jet engines. It was introduced as the flagship aircraft on the routes of the British Overseas Airways Corporation, and was hailed as a triumph of British engineering. However there were a number of accidents involving this aircraft, culminating, in 1954, in the loss of two aircraft in similar circumstances. These were Comet G-ALYP near Elba, and Comet G-ALYY near Naples. A Court of Inquiry was convened, and the task of discovering the cause of these accidents was given to the Royal Aircraft Establishment at Farnborough. The investigation explored a number of avenues, and finally gave structural failure of the pressure cabin brought about by fatigue as the cause of the accidents. The use of fracture mechanics methods not used in 1954 has enabled the analysis of these fatigue cracks to be made, and the initial defect size has been estimated to be approximately 100 μm in the case of G-ALYP. This is not incompatible with the manufacturing techniques of the time, and information regarding cracks in the cabin identified during manufacture. © 1997 Elsevier Science Ltd.

1. HISTORICAL BACKGROUND

In the 1930s and 1940s, there were a number of technological advances in the sphere of military aviation, which took aircraft design from propeller-driven biplanes to jet-powered monoplanes. However, by the end of the 1940s, the world of civil aviation was still dominated by large propeller-driven aircraft.

On 2 May 1952, the de Havilland Comet (Fig. 1) entered service as the first commercial jet

Fig. 1. The de Havilland Comet I. © British Aerospace plc (reproduced with permission).

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airliner, and propelled civil aviation into a new era. The de Havilland DH106 had been conceived in 1943 by Sir Geoffrey de Havilland, and design work had begun in September 1946. The prototype first flew on 27 July 1949, by which time agreements to supply 14 aircraft to the British Overseas Airways Corporation (BOAC) and two to the Ministry of Supply had been signed. On entering service, the aircraft could carry 36 passengers at a cruising speed of 450 mph (200 m s^{-1}), with a range of 2500 miles (4000 km).

To enable the payload to be sufficiently large for commercial viability, the weight of the aircraft and fuel had to be kept to a minimum. The construction techniques used were a mix of old and new, rivets being used in certain areas as well as a method of glueing the aircraft skin and stringers, called "Redux". This new technique had been pioneered by de Havilland, in the Hornet and Dove aircraft, to reduce the weight of the structure whilst maintaining the strength. The power for the aircraft was delivered by four Ghost turbofan engines built by the de Havilland Engine Company Limited. To enable these engines to run as efficiently as was practicable, this aircraft was expected to fly at 40,000 ft (10.7 km), or double the cruising altitude of the then commercial airline fleet. At this cruising altitude, the passengers and crew require an artificial oxygen supply, and it was decided to pressurize the cabin at the equivalent to a comfortable 8000 ft (2.4 km), which gave a pressure differential across the aircraft skin of 8.25 psi (56 kPa) at cruising altitude. This was double that which had been previously employed, and de Havilland conducted many tests to ensure the integrity of the cabin.

As well as the four turbofan engines, there were a number of other new features, including high-pressure refuelling, the hydraulic actuation of the control surfaces, and an air-conditioned cabin, which altogether made this a completely new aircraft.

The Comet I was seen as the new hope of the British aircraft industry, but a number of crashes tarnished the image of this graceful airliner. There were a number involving take-off, which culminated, on 3 March 1953, in the death of the crew delivering Comet CF-CUN to Canadian Pacific Airlines. These were ascribed to the unfamiliarity of the pilots with the new aircraft. The mid-air break-up of Comet G-ALYV 50 km north-west of Calcutta, exactly 1 year after the inaugural flight, was found to be due to excessive stresses in the airframe due to a tropical storm in the area.

However, there then followed two accidents under similar conditions in the space of 3 months, which could not be so easily explained. The first of these was on 8 January 1954, and involved Comet G-ALYP (Yoke Peter) approximately half an hour after take-off from Ciampino airport in Rome bound for London on the last leg of a journey from Singapore. Yoke Peter was climbing to 27,000 ft (8.27 km) in good weather conditions when it was seen to crash into the sea near Elba in a number of pieces, some of which were in flames. The Comet fleet was grounded, and the possible causes examined, a process which was not assisted by the inspection of the wreckage, as most of this was on the seabed at the time. A number of recommendations were made, resulting in improvements to the Comet I, and the fleet re-entered service on 23 March 1953.

On 8 April 1954, Comet G-ALYY (Yoke Yoke) took off from Ciampino airport bound for Cairo. After approximately 30 min, when Yoke Yoke would have been reaching the top of its climb to 35,000 ft (10.6 km), all contact was lost, and wreckage was later found in the sea near Naples. The operator of the Comets (BOAC) again withdrew all Comets from service, and on 12 April the Ministry of Transport and Civil Aviation removed the Certificate of Airworthiness from the Comet.

2. THE INVESTIGATION

Following these accidents, the Secretary of State for Civil Aviation requested a full investigation into their causes by the Royal Aircraft Establishment (RAE) at Farnborough, and a Court of Inquiry was established [1]. This investigation encompassed a number of lines of approach, but two aspects of particular interest are the reconstruction work on G-ALYP (Yoke Peter), and the accelerated simulated flight testing of Comet G-ALYU (Yoke Uncle).

Comet Yoke Uncle had been obtained from BOAC after flying for 3539 h and undergoing 1221 cabin pressurizations [2]. The accelerated simulated flight testing took the form of cabin pressurization using water, and wing loading using hydraulic rams (Fig. 2). Water was chosen to pressurize the cabin as it is reasonably incompressible, and any failure would not result in the complete loss of the pressure cabin due to the stored energy. If air had been used, any failure of the

Fig. 2. Aerial view of Comet G-ALYU in testing tank. Crown Copyright. Reproduced with the permission of the Controller of HMSO.

skin would have been equivalent to the explosion of a 500 lb (220 kg) bomb in the cabin [1]. To remove the effects of the weight of the water inside the cabin, Yoke Uncle was placed inside a water tank with the wings protruding through seals in the walls of the tank.

This arrangement enabled the loads associated with a flight to be applied in 5 min. This accelerated testing showed a severe weakness to fatigue crack growth in the aircraft skin around cut-outs such as windows and escape hatches. The skin of Yoke Uncle had undergone 3057 flight cycles [1] (1221 actual and 1836 simulated) before a fatigue crack grew to failure from a rivet hole near the forward port escape hatch (Fig. 3). The crack length before final failure was less than 2 mm in this accelerated test [2]. This failure was then repaired, and the simulated flight testing continued. Cracks were observed around a number of other windows and in the wings, and their growth monitored. This programme of tests was only stopped after 5546 pressurizations, when a fatigue crack grew to failure from the port number 7 window, and removed a 4.5 m section of cabin wall. It was concluded [2] that Comet Yoke Uncle, had it continued to fly, would have suffered cabin failure at around 9000 h. In addition to the cabin pressurization simulation, there were also proving tests conducted every 1000 flights to a pressure of 11 psi (76 kPa) to simulate those conducted by the operators or designers from time to time [2] to test the structural integrity of the cabin.

The reconstruction of Yoke Peter at Farnborough continued until September 1954 as pieces were recovered from the seabed by the Royal Navy. This process used underwater television cameras for the first time, and was assisted by the break-up of scale models of the Comet at Farnborough to ascertain the pattern of the falling pieces. Eventually, about 70% of the aircraft was recovered, and this allowed a scenario for the last moments of the aircraft to be constructed.

Yoke Peter was the first jet aircraft to enter commercial service and, at the time of the accident,

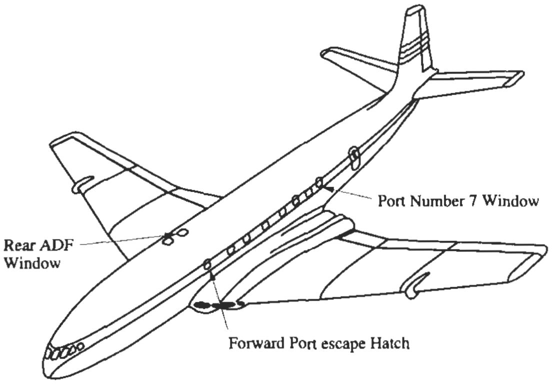

Fig. 3. The main failure sites on Comets G-ALYP and G-ALYU.

was undertaking its 1286th pressurized flight in addition to 255 flights without cabin pressurization. The Court of Inquiry [1] concurred with the findings of the RAE investigation [2] that the cause of the accident was sudden cabin failure due to fatigue crack growth followed by the break-up of the aircraft. The accident which occurred to G-ALYY was attributed to the same cause, as the flight circumstances were similar, although insufficient wreckage was ever recovered to prove the case.

The root of this rapid failure due to metal fatigue was shown to be high stresses around cut-outs, such as windows, in the aircraft skin. The aircraft manufacturer, de Havilland, had made estimates of these stresses averaged over a large area, and ascertained the fatigue life of the aircraft by testing sections of the cabin and the 22 gauge (0.71 mm) pressure cabin skin was thickened to 20 gauge (0.91 mm) around the windows. However, the Court of Inquiry reported that the nature of the sections used meant that they were not representative of a whole aircraft, as bulkheads fitted to these sections to enable pressurization may have affected the stresses around the cut-outs in the locality. This enabled the forward cabin section tested by de Havilland to withstand 18,000 cycles before fatigue failure from a defect in the skin near the corner of a window. In addition, this section was proof tested to 16.5 psi (114 kPa), or twice the operating pressure, before the fatigue testing began, and this may have caused local plastic deformation in the regions of high stress of interest here [1]. Proof testing of the pressure cabin was undertaken on all Comets during manufacture, before acceptance by BOAC, and at predetermined times during service, to 11 psi (76 kPa), but never to 16.5 psi (114 kPa), and a safety valve to prevent overpressurization of the cabin during service was set to 8.5 psi (59 kPa).

Cracks were known to be present in the aircraft upon manufacture, and there was an approved technique for identifying such defects and "locating" them by drilling the end of the crack with a $\frac{1}{16}$ in. (1.6 mm) drill [1]. In most cases, the crack was seen not to extend beyond the location hole, and this was assumed to be adequate security against further crack growth. In fact, there was a "located" crack near the forward port corner of the rear ADF (automatic direction finding) window (Fig. 3) on Yoke Peter, which did not grow beyond the locating hole until the final failure of the cabin.

The failure of Yoke Peter was deduced to be a fatigue crack near the starboard rear corner of the rear ADF window (Fig. 4). This crack emanated from a 10 mm diameter bolthole, and propagated to failure after unexpectedly few pressure cycles of the cabin. This bolthole in such a highly stressed

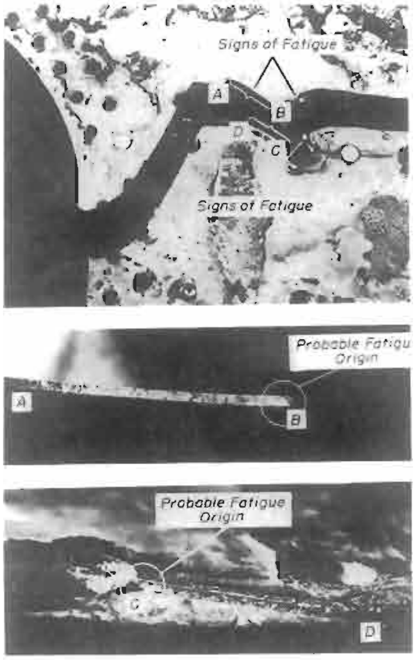

Fig. 4. Close-up views of the failure in the skin of Comet G-ALYP. Crown Copyright. Reproduced with the permission of the Controller of HMSO.

area was recognized as a prime site for fatigue failure initiation, and de Havilland subsequently redesigned the windows and increased the thickness of the skin in these areas to prevent this occurring on later Comet aircraft. The stress around a cut-out was shown to be over 3 times the remote stress due to cabin pressurization both experimentally [2] and theoretically [3]. Using the *S–N* data available at the time, it was possible to explain the shortened fatigue life.

3. ANALYSIS OF THE FAILURE

It is of interest to use fracture mechanics analyses (not used in 1954) to give an insight into the relative importance of the factors which combined to produce the catastrophic failure.

The bolthole which was the origin of the failure in Yoke Peter was over 50 mm from the ADF window (Fig. 4), and the stress in this area was significantly below the maximum stress at the ADF window itself. In fact, as part of the RAE investigation, strain gauges were placed around areas such as the ADF windows on Yoke Uncle to examine the stresses in this area. The stress in the vicinity of the bolthole was calculated to be around 70 MPa, compared to 315 MPa around the edge of the windows. This stress is reasonably close to that expected as a general level for a pressurized cylinder of 1.6 m radius, and a thickness of 1.42 mm. This thickness is derived from the 0.71 mm (22 gauge) skin and 0.71 mm thick doubler plate around the ADF window. Although the crack grew principally towards the ADF window, the stresses in this area were shown, using strain gauges, not to vary much, and the crack was only 25 mm long when failure occurred [2].

If it is assumed that linear elastic fracture mechanics can be applied, use may be made of the Paris law

$$\frac{da}{dN} = A\Delta K^m. \tag{1}$$

However, to begin such an analysis it is necessary to obtain fatigue crack growth data for this particular alloy. The alloy in question is DTD 546B, an aluminium-coated high tensile strength aluminium alloy for sheet use containing between 3.5 and 4.5% copper [4]. This alloy was developed before fatigue crack growth plots were taken for materials, but data can be obtained from the actual fatigue of Comet I G-ALYR (Yoke Robert) in a water tank at the RAE [5].

A number of cracks were monitored on Yoke Robert propagating from the rivets near corners of the cabin windows, and the data given as plots of number of cycles against crack length.

Yoke Robert underwent 11,313 cycles, and cracks were prevented from further growth at a length of 165 mm, as this was felt to be the length at which cracks would propagate to failure within a few more cycles. This gives a fracture toughness of around 35 MPa m$^{1/2}$. Using the strain gauge measurements made on the same fuselage, it is possible to construct a plot of da/dN against ΔK for the Comet I skin (Fig. 5).

This plot gives a value for A of 9.6×10^{-7} for da/dN measured in mm/cycle, and a Paris exponent,

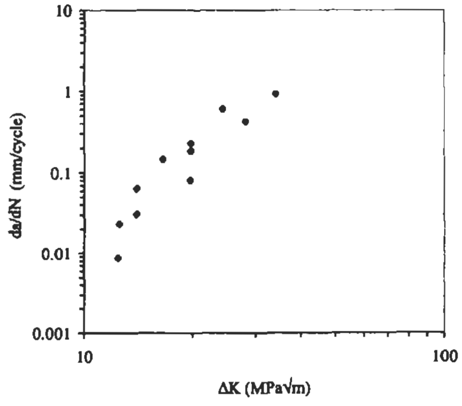

Fig. 5. Fatigue crack growth of the Comet I fuselage.

m, of 4.0. The crack growth rate is much faster than for subsequent aluminium alloys, but it is unclear whether this is due to the alloy itself, the application, or the water environment of the test. The consequences of the water environment of the tank test were addressed by Atkinson *et al.* [5] at the time of the tests, and it was felt that a cabin skin would be cycled through wet and dry periods during service (outside due to the weather and inside due to condensation), and this cycling may be more damaging than the environment of a tank test. The degraded environmental performance in aluminium alloys in aerospace applications has also been noted by Barter *et al.* [6].

The relation between ΔK, the applied stress range, $\Delta\sigma$, and the crack length, a, can be written as

$$\Delta K = F(a)\,\Delta\sigma\sqrt{\pi a}, \tag{2}$$

where $F(a)$ is a term (weight function) modifying the stress field in the presence of the bolthole, and is a function of the crack length. The relationship in Eqn (2) can be substituted into Eqn (1) to obtain

$$\frac{\mathrm{d}a}{[F(a)\sqrt{a}]^m} = A(\Delta\sigma\sqrt{\pi})^m\,\mathrm{d}N. \tag{3}$$

The number of cycles to failure for particular initial and final crack sizes can be calculated by integrating the above equation. The weight function for a crack emanating from a hole is a function of the crack length, and hence makes the analytical evaluation of the integral more difficult. However, there are tabular and graphical forms of these weight functions [7] which can be incorporated into the calculations. It may be assumed that there was only one crack emanating from the bolthole. There was a second fatigue crack at the opposite side of the hole, but it had not grown to any great extent before failure occurred. The value of $\Delta\sigma$ to be placed into Eqn (3) can be assumed to be the maximum value of the stress for the appropriate crack length, as one pressure cycle of the aircraft cabin always began at and returned to a pressure difference of zero, and hence the stresses in the skin approached zero. The weight function used here is the case for a uniaxial tensile stress perpendicular to the crack growth direction. This may not have been the case for the Comet skin, and a biaxial tensilc stress field may be closer to reality: however, the effect on the calculation of initial crack sizes is small, and serves to increase the initial defect size required to cause failure after 1286 pressurization cycles.

Such a calculation gives an estimated initial defect size of around 100 μm, corresponding to the total life of 1286 flights for Yoke Peter. As cracks many millimetres in length were seen during construction, and located using a $\frac{1}{16}$ in. (1.6 mm) drill, it is not surprising that a crack of the order of 100 μm in size was not spotted during manufacture and subsequent inspections. It can also be shown that, due to the accelerating nature of fatigue crack growth, the crack would have been visible emanating from under the bolthead for very few flights. A compressive stress around the bolthole, introduced during formation of the hole, would have reduced the fatigue crack growth rate in the vicinity of the hole [8], and would thus require a larger initial defect size to cause failure after 1286 pressurized flights than has been calculated above.

Using similar calculations for G-ALYU (the accelerated flight simulation Comet), which had only 1.7 mm of fatigue crack growth before failure after 3057 "flights", the size of the initial defect would be predicted to be smaller, at less than 10 μm.

At the time of the Court of Inquiry, much was made of the difference in the lives of Yoke Peter (1286 pressurizations), Yoke Yoke (903 pressurizations), and Yoke Uncle (3057 pressurizations). The explanation at the time was that the expected spread in fatigue results from shortest to longest was a ratio of 1:9, and the largest ratio here was 1:3.4. These results are not a surprise as the weakest aircraft would always fail earlier than average, and Yoke Uncle, chosen at random from the Comet fleet, was always statistically likely to have a longer fatigue life than those which had failed.

The difficulty in observing cracks during manufacture and subsequent inspection was highlighted by the number of cracks monitored during the fatigue testing of Yoke Robert [5]. In this case, cracks were first observed when they were around 6 mm in length, even though the probable locations of the cracks were known. Using the crack growth data, the approximate initial defect size was less than 10 μm. This is much less than the 100 μm estimate for Yoke Peter, and no cracks were observed in Yoke Robert around the ADF windows, even when the doubler plate had been removed for inspection. It is probable that there was a larger than average production crack near the starboard rear corner of the rear ADF window on Yoke Peter, and that this grew to failure after only 1286 flights.

It has been reported that Mr Ronald Bishop, the Chief Designer at de Havilland during this period, felt that the mistake made was to allow rivets and bolts to be used to assemble the windows and reinforcements onto the aircraft skin. Other parts of the aircraft were glued using "Redux", but the tooling required was thought to be too difficult to achieve, and too expensive for these cut-out areas. Other riveted areas, some wing skin sections for example, were known to be susceptible to fatigue crack growth from the rivet holes, and the use of riveting to fix such thin-section aluminium sheet in the vicinity of cut-outs was probably more damaging than the shape of the windows. In fact, none of the cracks in the body or wings of the test Comet emanated from the cut-outs directly, but came from rivet or boltholes near cut-outs, and the initial failure site on Yoke Peter was from a bolthole rather than the edge of the ADF window.

4. CONCLUSIONS

The de Havilland Comet was a truly novel aircraft. It had a number of new features which are now accepted as part of modern aircraft design, but at the time set a completely new trend. A number of technical advances had to be made to enable the aircraft to fly, and these stretched the scientific knowledge of the time to the limit. However, as with all pioneers, the first to enter a new field are the first to encounter the problems, and this is especially so in commercial aviation, where failure can be spectacular and high-profile.

The failure of the pressure cabin was due to fatigue crack growth from defects which were probably present from the construction of the aircraft and had not been a problem in earlier designs of aircraft, as the required cabin pressure had been lower. That this problem was not detected by the rigorous testing undertaken by de Havilland was probably due to an unfortunate set of circumstances with regard to the order in which the tests were performed, and could not easily be foreseen at the time. The knowledge gained from these unfortunate accidents enabled scientific knowledge to advance, and testing procedures to be instigated which ensured the increased safety of future civil aircraft.

All the observed cracks in the pressure cabin [1, 2] emanated from bolt or rivet holes near the cut-out areas. It was probably not the shape of the cut-outs that was so damaging to the fatigue life of the cabin, rather the method of fixing the windows and doubler plates onto the pressure cabin. Had the windows not been square then the "Redux" glueing method might have been applied to these areas, and the failure avoided.

After the problems of the Comet I, de Havilland produced the Comet IV, which was larger, carried 80 passengers, and had a greater range. This aircraft entered history as the first commercial jet aircraft to cross the Atlantic on 4 October 1958, and inaugurated a route which has carried many millions of passengers since. However, 3 weeks later, a Pan American Boeing 707 flew the same route carrying 120 passengers, and indicated the supremacy of the American airline industry. The Comet continued to be built until 1962, by which time 113 had been made, showing the quality of a design commenced in September 1946, and has entered history as the first commercial jet airliner and the first to operate a scheduled service across the Atlantic.

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