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COMET ACCIDENT

Appendix to An impossible dream

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COMET

On May the 5th, 1952 the first jet liner - the deHavilland Comet 1 - went into service. The Comet flew at 490 mph (~800 km/h) much faster than any aircraft before and could fly above 30.000 ft (9144 m), that is above the worst weather and more fuel-efficient. Cutting some four hours of a trip to New York, five Comets could replace eight conventional airliners. The plane and was an instant commercial success. Already eight were sold before they were even built, which was extraordinary for those days - with the 787 and the A350 more than one thousand have been sold before first flight. With almost 30,000 passengers carried in the first year, over fifty Comets were ordered. Unfortunately some tragic accidents happened and already in 1954 all Comets were grounded at once and the certificate of airworthiness was withdrawn. A lengthy inquiry followed. The Comet would not fly again before 1958.

During the war the deHavilland Mosquito and Hornet excelled in a number of roles but at the end of the war the company had to recommence with civil aircraft. Having some years experience with jet fighters they were convinced that jet propulsion was the future and decided to go for it in 1946. Unfortunately right at the beginning management made a crucial mistake in that the initial deadline was moved forward from 1952 to 1949. That is, from about seven to an impossible three years - driven by the anticipated commercial success. This put enormous pressure on the engineers to deliver and indeed they did not deliver.

Introduction

The Comet was a monumental challenge. There was no point of reference - larger, faster, higher, and lighter - to carry further more payload. Ronald Bishop, the Chief engineer who had been responsible for the Mosquito fighter-bomber, realized that many very difficult problems had to be overcome. New aluminum alloys had to be developed as well as fully-powered hydraulics, adjusted fuel and refuelling equipment, a new atmospheric control system and metal to metal adhesives were used to attach the stringers to the skin of the wings and the fuselage - remind this were the early 1950's - to mention only a few of the innovations. A great deal of work had to be done in wind tunnel to reduce drag. A weak point in the design was the incorporation of the engines into the wings close to the fuselage. This has the advantage that the main mass is close to the aircraft's centre of gravity. But this makes the aircraft extremely vulnerable to engine fire. Economically the Comet exceeded expectations. Although 50% more expensive than contemporary aircraft and double on fuel consumption - crude oil at some $3 a barrel - operation cost were 20% down.

Design

Initially the idea was to build a delta shaped plane but by the summer of 1946 the Comet had grown a conventional tail with the swing sweep reduced from 400 to a more conventional 200. In order to provide an economically satisfactory payload and range at the high cruising speed which the turbo-jet engines offered, it was essential that cruising height should be upwards of 30,000 ft, about double that of the then current airliners and that the weight of the structure and equipment should be maintained as low as possible. Instead of the more powerful Rolls-Royce Avon, deHavilland decided for their own Ghost engines, but these were heavier and required further weight reduction. The cladding of the fuselage was rather thin. The deHavilland had developed special adhesives for the Mosquito and the Vampire and these were extensively used to further reduce weight - very thin glued laminar-flow aluminium cladding was applied for the wings. (Rumour has it, that to reduce weight early aircrafts were not painted).

The pressure differential between the cabin and the outside was at 8.25 psi about 50% greater than that in general use and there was in addition a much larger difference between the internal and external temperatures at these altitude –which were estimated at 60^0C to70^0C. Furthermore there were the problems of sudden and rapid depressurization, extreme vibration due to atmospheric turbulence at that high velocity and gusts. It was decided that all construction materials had to be thoroughly tested for these conditions and special attention was given to the structural integrity of the pressure cabin and the wings. But what can be done at such short notice. To resist *'the action of fatigue'* it was regarded adequate to double the current safety margins at the time. To test the cabin, high pressures were applied to the section of the front part of the cabin followed by a series of 2000 pressurizations in a specially build water tank. It was probably this combination that led eventually to the accidents, as will be discussed later. July 27th 1949, the Comet made its first test flight. A full test and development programme followed.

Warning signs

In 1952, with the Comet already in service, an investigation at the RAF found *'the likelihood that the fatigue resistance properties of a pressure cabin demands further precautions'* which led the Ministry of Supply to issue a draft requirement October 1952 that called for further static test to be performed at higher pressure together with repeated loadings to be applied 10,000 times also at higher pressure. deHavilland did not execute these tests. A first sign of a design flaw comes when a Comet brakes up mid air during a severe tropical storm near Calcutta, May 2nd 1953. The Air Registration Board published civil requirements that call again for the tests stipulated by the Ministry of Supply to be executed and proposes to increase the number of repeated loadings to 15,000. deHavilland's now reconsiders the position of the Comet's cabin and starts testing according to the new proposals. By September 1953, the specimen had withstood 18.000 applications of repeated loading in addition to some 30 earlier applications of static pressures before any damage occurred. It is important to note that the tests ended by a failure in fatigue originating from a small defect in the skin at the corner of a window. But the number of pressurization sustained was so large that, in conjunction with the numerous other test results, it was regarded as establishing the safety of the Comet's cabin with ample margin.

No proof whatsoever

The accident was a tragedy, but in the context of air-safety at the time, it did not diminish either public enthusiasm for the Comet nor operators' willingness to place orders. But this changed when, January 10th 1954, another Comet - G-ALYP *'Yoke Peter'* - crashed near Elba and the fleet was grounded. Autopsy of the bodies that were recovered showed a distinct pattern of injuries of fractured skulls and ruptured lungs. The latter was a sure indicator of sudden cabin depressurization. BOAC ignored these findings and desperately pushed to get Comet back in service, and two weeks later, March 23rd, they succeeded. Structural failure due to fatigue was discounted when deHavilland brought forward *'the 18,000 repeated loadings as removing any doubt about the fatigue life of the cabin'* and argued that *'the possibility of fatigue in the wing structure due to gusts was believed to be much more likely the cause than fatigue in the* *pressure cabin since this is subject to much less frequent chances of load'.* The Investigation the Board recognizes that *'no definite reason for the accident has been established'* but *'sees no reason why passenger services should not be resumed'* and *'recommends that Comet aircraft should return to normal operational use after all the current modifications have been incorporated and the aircraft had been flight tested'*. Amazingly, before a full investigation had taken place – the Royal Navy were still out fishing for evidence in the Mediterranean. With no proof whatsoever, fire was officially regarded to be the most likely cause of the accident - and after some modifications to protect the engines from damage that might lead to another fire, passenger service was resumed, March 23rd, ten weeks after the crash. BOAC's chairman defended his decisions to resume flights on television, *'we obviously wouldn't be flying the Comet with passengers if we weren't satisfied conditions were suitable.'* Comet crew were not so sure and raised doubts - an agreement to return to work was passed by just one vote. Within two weeks, April 8th, another Comet - G-ALYY *'Yoke-Yoke'* - crashed near Stromboli. The fleet was grounded again – now indefinitely. April 21st, the Royal Navy turned the engines from *'Yoke Peter'* were returned to deHavilland. Subsequent analysis proved that they had been working normally as the aircraft broke up - no fire. They should have waited.

Investigation

July 12th 1954, the then prime minister (yes the one with the cigar) called for an inquiry -'The cost of solving the Comet mystery must be reckoned neither in money nor in manpower'. It is therefore no surprise that after a lengthy investigation the court ruled that nobody was guilty to the accidents. The stakes were too high and indeed it is probably impossible to decide whether certain individuals were guilty or not guilty - but grove mistakes were made if not grove neglect.

Now it was decided to salvage the entire aircraft from scattered wreckage on the ocean floor near Stromboli. About 70% was recovered and it was possible to reconstruct large parts of the fuselage. Investigators concluded that *'Yoke Yoke'* broke up in-flight. Engineers suspected fatigue and a full-scale test on the whole cabin were carried out. An identical frame was subjected in a giant water tank to numerous cycles of pressurisation and depressurization. The particular frame had already made 1230 pressurized flights before the test and was now subjected to another 1830 pressurizations when the structure failed - after a total of 3060 pressurization cycles. Engineers discovered that the crack initiated near the front port-side escape hatch. Strain gauges were attached near the corner of the window and stresses were estimated to have reached 43.000 psi. This means that during the earlier test at double pressure local stresses must have reached 86.000 psi, which is some 30% above the ultimate strength of the material. By that time it was difficult for deHavilland engineers to understand that such high stresses could occur – they estimated 28,000 psi - but it was recognized that *'This apparent paradox can be explained by recognising that it neglects to take account of the effect of the ductility of the material in relieving 'stress concentrations'*, a consequence of the large window's square shape.

Although fatigue was now concluded to be the cause of the accidents, it appears that the dangers of cracks in the structure were still not fully recognized at the time of the investigation. The official investigation reads - amongst others - that *'....most aircraft experience cracks due to one or more of the causes mentioned above and that it would, indeed be hardly practicable to insist on a standard of design and construction which would preclude completely the possibility of any crack in the skin'* and that *'Cracks which occur during manufacture do not differ materially, in their significance, from those which may* *develop subsequently.....'* and '*Where frequent inspection shows that a particular crack is likely to spread, it is dealt with by a carefully considered repair scheme, either prepared by the designers or by the operators in collaboration with the designers. However if after such repair the crack continues to spread it is considered as a matter of major concern possibly requiring a radical modification to the design to reduce the stress which gave rise to it'* - a first sign of damage tolerance philosophy.

Causes of the accidents

Remains the question why the planes crashed after 1286 and 903 flights respectively whilst with earlier the deHavilland's tests before the accident, failure occurred after 16,000 cycles and with tests after the accident at the Royal Aircraft Establishment after 3,600 cycles. First of all fracture mechanics was poorly understood at the time – at least by the engineers involved – and consequently attention did not focus at the critical locations such as corners of the cabin windows, and no attention was paid to existing (micro)cracks. Another important contributing factor is that fluctuations in load, vibrations, temperature differences and so on were not simulated during testing. Instead it was assumed that the 'double' pressure applied during testing compensated for this influence. Then, deHavilland's tested only the nose section of the fuselage that was not fitted with the complete number of windows. Also, to make compression possible the section had to be fitted with bulkheads that imposed considerable constraint on the structure and made it probably stronger when compared with a complete fuselage. Furthermore, at deHavilland the pressurization tests were performed on a structure that had previously been subjected to static loading, well over the design load. Such preloading causes a permanent stretch or plastic yielding at critical locations where the stresses concentrate, resulting in pre-stressing that actually increases the strength at these critical locations and hence the pressurization resistance of the structure as a whole. The general nature of this process was understood at the time but the investigator remains somewhat reluctant with regard to this subject, *'there are obvious difficulties, not to say dangers, in applying it. Nevertheless, the subject should undoubtedly receive more study'.* Finally, pressurization tests were not performed in a decompression chamber but in a water tank. This to avoid that bits would be blown in an uncontrolled explosion at the moment of failure. The water acted as a damper, "freezing" the damage, so engineers could find the cause. However, such pressure testing is about ultimate strength and leak resistance, not fatigue.

Visions of a thousand Comets

As is so often the case with such development, the envelope was pushed too far. Engineers easily become over confident. Around 1950, managers had become probably even more overconfident by early commercial success with visions of a thousand Comets. deHavilland was clearly in the lead in the civil yet market, but competition was looming from Boeing. Driven by fear, mangers pushed delivery times forward, putting unrealistic pressure on the engineers. But the biggest blunder, no doubt, is the decision by the Investigation Board to let the planes fly again after the Elba accident - probably influenced by deHavilland's management.

Cause of the accident

Essentially it is the rectangular shape of the windows that caused the accident. Concerns had been raised about this shape within the aviation community. The problem was exacerbated by the punch rivet construction technique that was employed. The windows had been engineered to be glued and riveted, but this proved to be so difficult that it was decided only to punch the rivets. Unlike drill riveting, the imperfect nature of the hole created by punch riveting is likely to initiate fatigue cracks around the rivet. The very thin nature of the aircraft's skin around the windows contributed to the problem.

Fatigue

Another question that remains is whether the engineers could have known about dangers of fatigue. It was certainly a hot topic within the engineering community. The famous paper of Griffith on this subject *'The phenomena of rupture and flow in solids'* was published in 1921 and Irwin published his now also classic sequence *'Fracturing of metals'* in 1948. So, fatigue was definitely not an unknown phenomenon at the time – with brittle fracture suspected to be at the root of many structural problems and major accidents those days. Also in aviation, when a Martin 2-0-2 operated by Northwest Orient Airlines heading from Chicago to Minneapolis crashed in a thunderstorm, August 29th 1948 - with official cause *'The loss of the outer panel of the left wing which separated from the aircraft as a result of a fatigue crack in the left front outer panel attachment fitting which had been induced by a faulty design of that fitting, the fatigue crack having been aggravated by severe turbulence encountered in the thunderstorm.'* Also a report in Time on the Comet accident, November 1st, 1954, described metal fatigue *'Failure of a metal after repeated straining. Small cracks, which sometimes start at tool marks, sharp indentations or other 'stress raisers', spread through metal until it breaks. Sufficient strength, correct design and careful fabrication can prevent such failures.'* Nowhere in the official investigation report can such precise definition be found.

Last but not least – and this is always referred to when the Comet is discussed

– in those days everybody involved must have seen the 1951 movie *'No Highway in the Sky'* starring Jimmy Stewart and Marlene Dietrich. The movie was based on Nevil Shute's novel *'No Highway'* from 1948 that portrays a fictional professor who has come up with a novel theory on metal fatigue and calculates that a particular aircraft - *the Reindeer* - will fail within a certain number of takeoffs and landings and that a particular aircraft is about to exceed that number. He tries to warn officials but no one takes him seriously. Nevil Shute was a former Vickers aeronautical engineer and wrote his novel as a cautionary tale due to his concern that British aviation officials were not taking the problem seriously enough. He proved to be right, but that is poor comfort for those who died. He published numerous other novels, among them *'On the Beach'* that became a classic and was also adapted as a film.

Whatever may be 'the truth', it is important that the investigation provides most important lessons and did put the focus on fracture mechanics. After some time, scientist learned how fatigue and brittle failure can be explained by fracture mechanics - even much more important how fracture mechanics can be applied to avoid failure through fatigue. The critical length where the crack becomes self propagating can now easily calculate - based on formulas derived from the work of Griffith. The Comet had a fuselage of clad aluminium that had a critical strain energy release rate of 300 in-psi. Taking the hoop stress due to relative pressurization at 20,000 psi, this means that the critical length where a crack becomes self-propagating can be calculated to be some 2.62 inch. A crack of this length can be possibly detected in time, but in case of the Comet the cracks were propagating from the rivet holes near the radio directing finding aerial window. When the crack reaches the window, it grew into it which size adds to the crack length, effectively creating a very large catastrophic crack.

These insights paved the way to more responsible design, manufacturing and maintenance where fracture is controlled. It is now possible to design certain components, like turbine blades, such that stresses remain well below the fatigue strengths of the material in a way fatigue cracks 'never develop' to critical length during their design lifetime. Unfortunately with aircraft this cannot be achieved with aluminium alloys. Their high strength to weight ratio makes them attractive for aircraft structures, but these alloys are also characterized by relatively low fatigue strengths. A design below the fatigue limit would make the plane too heavy for economical flight. Composites have better fatigue strength but poses other problems, as will be discussed later. Aircraft have therefore to be designed above their fatigue strength and the designer must consider the possibility that fatigue cracks may appear within the lifetime of the aircraft. Critical locations can be designed more strongly and extra protected for such influences as corrosion and impact, and have to be inspected and possibly tested more frequently and replaced at specified intervals. Moreover, the structure can be designed in such a way that there remains sufficient structural redundancy in the structure when a particular member fails. But with composites this poses a problem, because of its poor impact response.

Seven Oh Seven

It took deHavilland four years of hard work to bring the completely redesigned Comet-4 into service – now with a strengthened fuselage and round windows to alleviate the metal fatigue problem and equipped with Rolls-Royce Avon engines that had twice the thrust of the Comet 1's deHavillands' Ghosts. September 30th 1958 the Comet-4 became the first jet airliner to enter transatlantic service flying from London to New York - the plane could carry about 80 passengers. Panam began service on the same route three weeks *later - October 28th - inaugurating the Boeing 707. A larger Comet 5 was proposed, but never built.*

It is probably true that Boeing's success is due largely to Comet's misfortune. When deHavilland developed their Comet, Boeing was in a comfortable second position. Representatives from Boeing had the chance to see the Comet at the Farnborough air show in 1950 and they realized, like de Havilland, that the future of commercial airliners lay in jets. With the B47 bomber they were the only American manufacturer with vast experience about large jet aircraft. May be a bit of a gamble at that time, but they provided ample time for development - valuable lessons learned from deHavilland. Boeing decided to go for a much larger jet liner, at least doubling the 44 passengers of the Comet - actually it became more than 150. The Pratt and Whitney engine had three times more thrust than the Ghost. Like the B-47 the engines were pod mounted below the wing which is much safer position and easier to maintain. The fuselage wall was taken four and a half times as thick and additionally strengthened at intervals with titanium strips (and contained round windows). Already in 1954 a prototype rolled out for the military and it took another four years to bring the 707 into civil service.

The 707 was a huge success. When production stopped in 1991, over one thousand had been sold – as pointed out before, deHavilland envisaged once to sell such number of the original Comet but in the end only 79 Comet-4's were build. The 707 paved the way ultimately for the 747, the world's most successful plane so far. For Boeing development of the 747 involved essentially 'only' scaling of proven technology – the real innovation was the turbofan engine developed by General Electric that delivered double the trust of earlier turbojets while consuming a third less fuel. Design started in 1965 with Joseph Sutter as Principal engineer. Boeing agreed to deliver the first 747 to Pan Am by the end of 1969. The delivery date left 28 months to design the aircraft, which was two-thirds the normal time. September 30th 1968, the first 747 rolled out at Everett, exactly according schedule with first flight, February 9th 1969. Production passed the 1,000 mark in 1993. As of January 2009, more than 1440 747's have been delivered in different variants with more than 100 on order. The 707 was replaced by the 777 of which more than a thousand have been sold and the plane has not been involved with any tragic accident - but recently a 777 crashed when the plane lost suddenly power just before landing, fortunately without casualties. Now Boeing has decided to widen the horizon once again going for an all-composite aircraft pushing technology again to the limit, if not beyond. But now Boeing is frontrunner with Airbus in comfortable second position.