

occurrence of fatigue failure in ductile solids, it is now recognized that mechanical fatigue effects in nonmetallic materials can arise in some cases from the kinematic irreversibility of microscopic deformation under cyclic loads even in the absence of cyclic dislocation motion. Mechanisms which impart kinematic irreversibility of deformation during fatigue can be as diverse as microcracking, stress-induced phase transformations, dislocation plasticity, creep, interfacial sliding or 'craze' formation. An extension of existing knowledge on the fatigue of metallic systems to these advanced materials and the identification of new mechanistic phenomena associated with the fatigue of nonmetals and metal-nonmetal composites form the basis for many ongoing research efforts. Chapters 3, 5, 6, 11, and 12 in this book provide a detailed description of the fatigue characteristics of a wide variety of brittle and noncrystalline materials, including many nonmetallic composites and layered solids.

1.1.1 Case Study: Fatigue and the Comet airplane

The dramatic effect of subcritical crack growth by fatigue on the mechanical integrity of aircraft structures was clearly brought to light by the series of crashes involving the first commercial jet aircraft, the Comet. This airplane was manufactured by the de Havilland Aircraft Company, England, and was designed to capture the rapidly growing long-distance air travel business, spurred by the economic recovery of Great Britain and Continental Europe after World War II. The fatigue failures of the Comet cabin structures, which led to several accidents in the 1950s, also obstructed the prominent role played by the British in the commercial jet aircraft industry. It is widely believed that the fatigue problem of the Comet may have served as a catalyst in the eventual emergence of the rival Boeing Aircraft Company in the United States as a world leader in commercial aviation.

The use of the jet engine, pioneered by Sir Frank Whittle in Great Britain, for propelling the commercial jet aircraft was still an untested proposition at the time of design of the Comet. The fuel consumption rate of a jet engine was more than twice that of a piston engine. In order to limit the fuel consumption rate of a jet aircraft to a level no higher than that of one propelled by a piston engine, the plane had to travel twice as fast.[†] This meant flying in the rarefied atmosphere of high altitude, typically around 12 000 m (or 40 000 ft), which was more than double the altitude at which the World War II vintage aircraft flew. The speed of sound is approximately 1200 km/h (or 760 miles per hour) at sea level; at an altitude of 12 000 m, it drops to about 1060 km/h. At this high altitude, termed the lower stratosphere, the coldest air with a temperature of approximately -56°C exists, and clouds

[†] There are several basic requirements for the optimum performance of a passenger jet aircraft. Firstly, it must travel as fast as possible for optimizing such factors as fuel efficiency, number of flights per unit time period, and return on capital expenses. Secondly, it must fly below the speed of sound in order to avoid a precipitous rise in the specific energy consumption, which is related to the ratio of thrust to weight or to the ratio of drag to lift. Thirdly, the colder the air through which the aircraft flies, the greater the efficiency of the jet engine. Fourthly, an aircraft should not fly at an altitude higher than what is necessary because flying through rarefied atmosphere requires oversized wings. For passenger jet aircraft, the first two requirements suggest a maximum cruising speed typically in the neighborhood of 90% of the speed of sound or Mach 0.9, and the last two requirements suggest an optimum altitude of 10 000–12 000 m (Tennekes, 1996).

and thunderstorms are rare so that meteorological conditions do not impede flight schedules during cruising. The colder outside air at such altitudes also enhances the efficiency of the jet engines as the difference between the intake temperature and the combustion temperature is raised.

A particularly important issue for high altitude flights was the design of the cabin wherein the temperature and pressure had to be at near-ground levels for the comfort of the passengers and the crew. The aircraft fuselage would have to be repeatedly stressed from no pressure differential between the inside and the outside whilst on the ground to a large pressure difference between the inside passenger cabin and the rarefied atmosphere outside during cruising. The fuselage, therefore, had to be capable of withstanding high stresses arising from cabin pressurization during such high altitude flights in thin air. It would turn out that the fatigue stress cycles induced on the metal skin of the fuselage by the repeated pressurization and depressurization of the cabin during each flight contributed to the catastrophic fracture in several Comet airplanes (e.g., Dempster, 1959; Petroski, 1996).

On the first anniversary of commercial jet aircraft operation, May 2, 1953, a de Havilland Comet airplane disintegrated in mid-air soon after take-off from the airport in Calcutta, India. The crash occurred during a heavy tropical thunderstorm. The official organization investigating the crash concluded that the accident was the result of some form of structural fracture, possibly arising from higher forces imposed on the airframe by the stormy weather, or from the overcompensation by the cockpit crew in trying to control the plane in response to such forces. Consequently, the design of the aircraft structure was not viewed as a cause for concern.

On January 10, 1954, another Comet aircraft exploded at an altitude of 8230 m (27 000 ft) in the vicinity of Elba Island in the Mediterranean Sea, after taking off from Rome in good weather. Once again, no flaws in design were identified, and the aircraft was placed back in service only weeks after this second crash.

The third accident took place soon afterwards on April 8, 1954, when a Comet exploded in mid-air upon departure from Rome, after a brief stopover during a flight between London and Cairo. The wreckage from the crash fell in deep sea water and could not be recovered. This led investigators from the Royal Aircraft Establishment (RAE), Farnborough, England, to renew efforts to recover pieces from the second crash over Elba. Evidence began to emerge indicating that the tail section was intact from the Elba crash, and that the pressurized cabin section had torn apart before fire broke out.

In order to probe into the origin of cabin explosion, RAE engineers retired a Comet airplane from service and subjected its cabin to alternate pressurization and depressurization, to about 57 kPa (8.25 psi) over atmospheric pressure, by repeatedly pumping water into it and then removing it. During such simulated cabin pressurization, the wings of the aircraft were also stressed by hydraulic jacks to mimic wing loading during typical flight conditions. After about 3000 pressurization cycles, a fatigue crack originating in a corner of a cabin window advanced until the metal skin was pierced through. Figure 1.1 schematically shows the location of cracks in a failed Comet airplane.

The Comet, being the first commercial jetliner, was designed and built at a time when the role of fatigue in deteriorating the mechanical integrity of airframe components was not appreciated, and when subcritical fatigue crack growth had not evolved into a topic

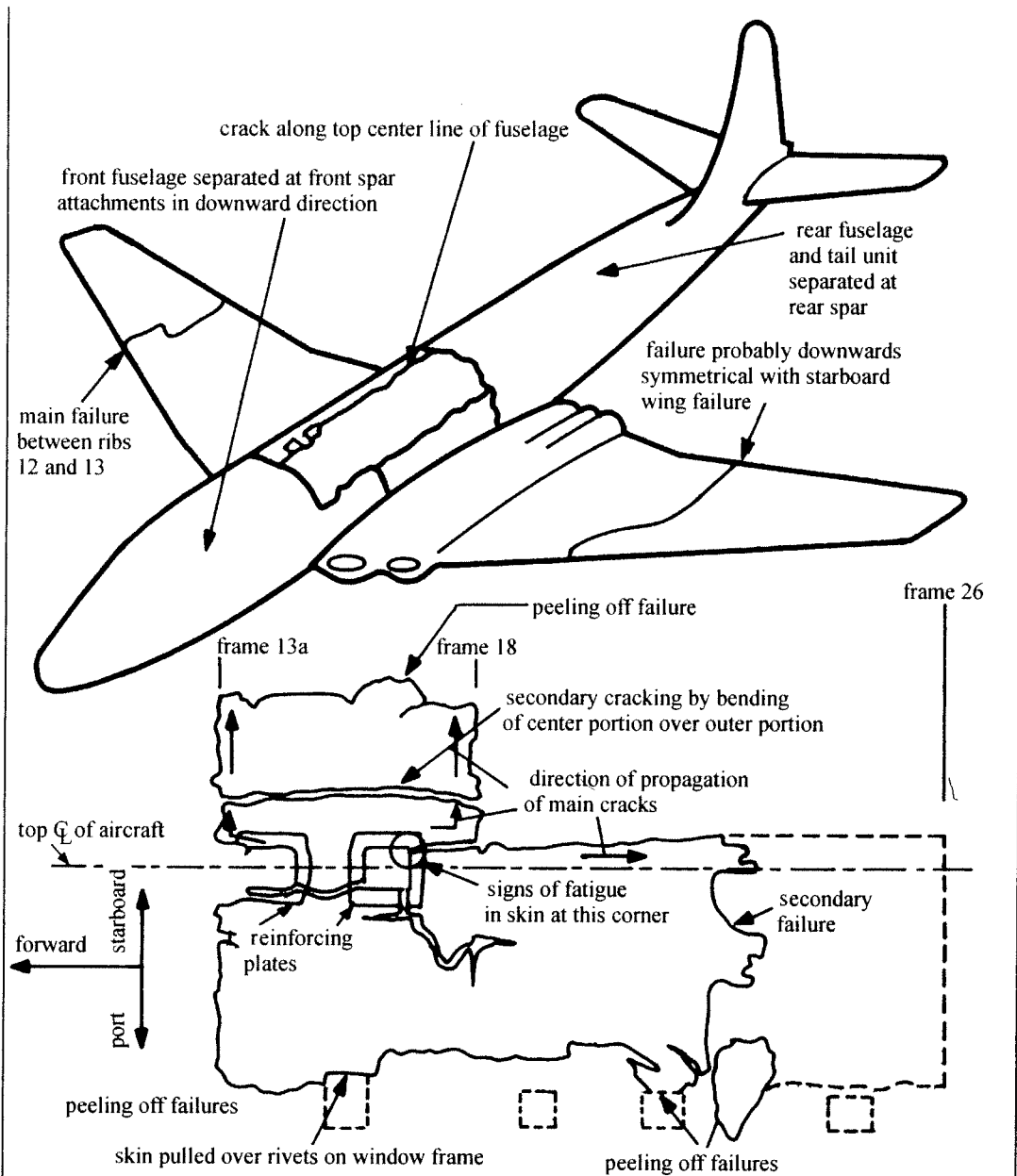


Fig. 1.1. Schematic diagram illustrating the location of fatigue cracks in a failed Comet airplane. (After Petroski, 1996.)

of extensive research. It was assumed that the possibility of one fatigue cycle per flight, due to cabin pressurization upon take-off and depressurization during landing, would not be significant enough to advance any flaws in the fuselage to catastrophic proportions. The cabin walls were designed to contain a pressure of 138 kPa (20 psi), two and a half times the service requirements. As an added demonstration of safety, the passenger cabin of each Comet was pressurized once to 114 kPa (16.5 psi) in a proof test, before the plane was placed in service. The investigative report of the Court of Inquiry into the Comet failures noted that the de Havilland designers believed '... that a cabin (which) would

survive undamaged a test to double its working pressure ... would not fail in service under the action of fatigue...'. This notion was proven erroneous, at a significant cost to de Havilland and to the British commercial aircraft industry.

The RAE tests revealed that the cabin failures in the first three Comet accidents were due to fatigue cracking which was aided by stress elevation at the rivet holes located near the window openings of the passenger cabin. In subsequent designs of the new Comet 4 models, which facilitated trans-Atlantic commercial jet travel for the first time, the window sections were replaced with a new reinforced panel which had much greater resistance to fatigue failure.

No aircraft has contributed more to safety in the jet age than the Comet. The lessons it taught the world of aeronautics live in every jet airliner flying today.

D.D. Dempster, 1959, in *The Tale of the Comet*

1.2 Different approaches to fatigue

There are different stages of fatigue damage in an engineering component where defects may nucleate in an initially undamaged section and propagate in a stable manner until catastrophic fracture ensues. For this most general situation, the progression of fatigue damage can be broadly classified into the following stages:

- (1) Substructural and microstructural changes which cause nucleation of permanent damage.
- (2) The creation of microscopic cracks.
- (3) The growth and coalescence of microscopic flaws to form 'dominant' cracks, which may eventually lead to catastrophic failure. (From a practical standpoint, this stage of fatigue generally constitutes the demarkation between crack initiation and propagation.)
- (4) Stable propagation of the dominant macrocrack.
- (5) Structural instability or complete fracture.

The conditions for the nucleation of microdefects and the rate of advance of the dominant fatigue crack are strongly influenced by a wide range of mechanical, microstructural and environmental factors. The principal differences among different design philosophies often rest on how the crack initiation and the crack propagation stages of fatigue are quantitatively treated.

It is important to note here that a major obstacle to the development of life prediction models for fatigue lies in the choice of a definition for crack initiation. Materials scientists concerned with the microscopic mechanisms of fatigue are likely to regard the nucleation of micrometer-size flaws along slip bands and grain boundaries, and the roughening of fatigued surfaces as the crack inception stage of fatigue failure. A practicing engineer, on the other hand, tends to relate