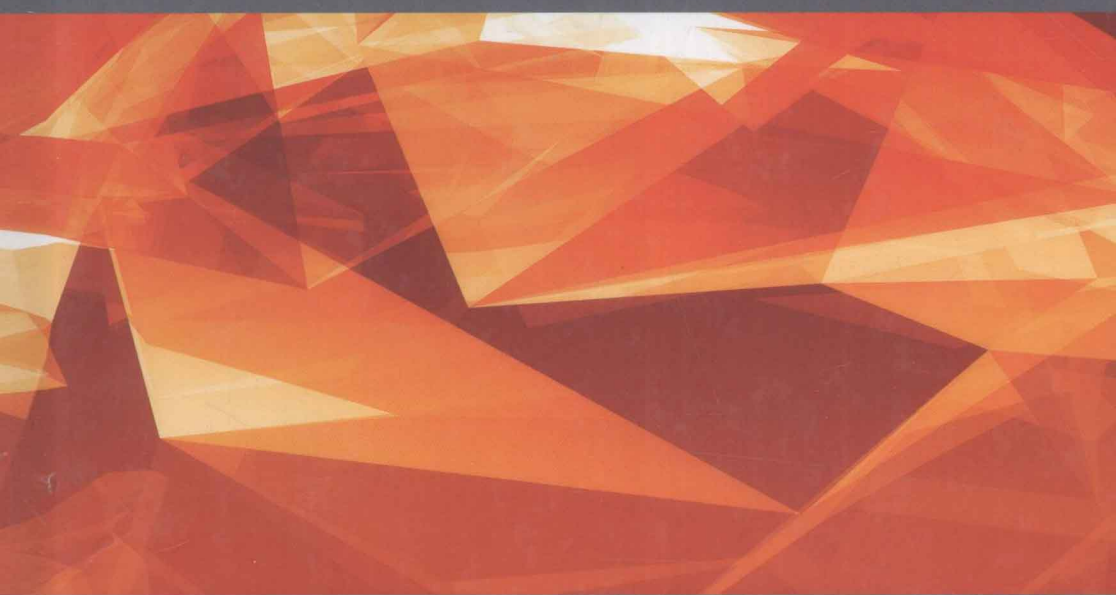
Fatigue of Materials and Structures

Fundamentals

Edited by
Claude Bathias and André Pineau



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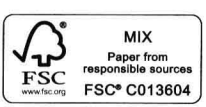

Fatigue of Materials and Structures

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Chapter 1

Introduction to Fatigue: Fundamentals and Methodology

1.1. Introduction to the fatigue of materials

1.1.1. *Brief history of fatigue: its technical and scientific importance*

Experience shows that fracture of structures or machine parts during regular operating conditions are most often due to fatigue. Structural integrity has always been an obstacle to industrial development. Its consequences could be seen during the development of mechanical industry in the 19th century. The industrial revolution, particularly the development of rail transportation, was affected from the start by a certain number of serious accidents, such as the one in Versailles, 1842, where the rupture of an axle caused the death of 60 people [SMI 90]. This death toll is close to that of the two Comet plane crashes that occurred in 1954.

It is known that fatigue damage costs several percent of the gross domestic product of the engineering industry. For this reason, we can understand the fact that articles and papers about this type of damage are ever increasing. Toth [TOT 01], who recently checked the COMPENDEX data base, found about 10,000 articles on this topic between 1988 and 1993, which comes to 2,000 articles a year.

According to Schütz [SCH 96], Braithwaite [BRA 1854] introduced the term "metal fatigue" in 1854. Despite this, Lemaitre [LEM 01] reckons that Poncelet

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Chapter written by André PINEAU and Claude BATHIAS.

mentioned this term during an engineering lecture in Metz as early as 1839, and that Rankine used it in 1843. To gain a better understanding of the work carried by Poncelet and Rankine in this field, we can refer to Timoshenko's work dealing with the history of the strength of materials [TIM 53]. As a matter of fact, this term has probably been in use for a long time. For instance, Stendhal used it in one of his pieces "Memoirs of a tourist" published in 1838 [STE 1838]. On his way to Civitavecchia, in Italy (where he had been appointed Consul), while crossing the Loire river in La Charité one of the axles of his carriage broke. What he wrote is as follows:

"La Charité – April 13. I was riding through the small town of La Charité, when, as a reminder of the long thoughts I had in the morning about iron diseases, the axle of my carriage suddenly broke down. I have to be blamed: I swore that if I ever had my own carriage, I would get a nice Fourvoirie axle, with six mild steel rods, forged under my own eyes… I checked the iron grain of my axle; it was larger as it has apparently been used for a long time… ."

We should remember that in those times, and for many years during the 19th century, people thought that iron "crystallized" due to mechanical vibrations. The fact that Stendhal, who lived at the same time as Poncelet, already knew what fatigue was, at least in this form, is not surprising. They both campaigned for Napoleon in Russia in 1812 and we can assume that they would have discussed this subject.

Excellent reviews on the history of fatigue have been written, some of them very recently. We can for instance refer to the work of Schutz [SCH 96] which lists more than 550 references, such as Toth [TOT 01], or Schijve [SCH 03].

It is worth noting that some works on this subject have recently been published:

– Bathias and Baïlon [BAT 97];

– Bathias and Paris [BAT 05];

– Henaff and Morel [HEN 05];

– Murakami [MUR 02, MUR 03];

– Polak [POL 91];

– Reifsnider [REI 91];

– Schijve [SCH 01];

– Shaniavski [SHA 07]; and

– Suresh [SUR 98].

Here we should mention two regularly published journals that explicitly refer to the fatigue phenomenon: *Fatigue and Fracture of Engineering Materials and Structures* and the *International Journal of Fatigue*. In addition to this, in other countries scientific societies organize lectures and conferences on this subject, such as the ASTM (American Society for Testing and Materials) in the USA and the SF2M (French Society of Metallurgy and Materials) in France.

Year	Event
1842	Meudon railway accident
1858	First publication by Wohler
1860-70	Wohler experiments on smooth and notched axles. Bending and torsion tests – Investigation on the effect mean stress
- 1881	Study by Bauschinger which initiated low-cycle fatigue
1910	Basquin law
1913	Stress distribution within notches (Inglis)
1920	Energy balance regarding the propagation of a crack (Griffith)
1930	Stress concentration factor and endurance limit (Peterson)
1937	Neuber concept applied to notches
1939	Statistical approach Weibull law
1945	Miner concept for fatigue damage accumulation
1953-54	Low cycle fatigue. Manson – Coffin law
1954	Comet aircrafts accidents
1956	Introduction of strain energy released rate (Irwin)
1960	Servohydraulic machines
1961	Paris law
1968	Introdcution of effective stress intensity factor (Elber)
1988	Aloha B737 accident
1989	DC 10 Sioux City accident
1996	Pensacola accident
1998	ICE. Eschede railway accident
2006	Los Angeles B767 accident

Table 1.1. *A few stages and main events regarding the history of the fatigue phenomenon*

Some memorable stages and events that have marked the history of fatigue are highlighted in Table 1.1. As mentioned earlier, this type of damage has clearly been of great importance during the development of rail transportation. The various ruptures that Wöhler observed in Germany led him to undertake a systematic study of this type of damage.

Along with trains and many other mechanical structures, aircraft were also readily affected by the fatigue phenomenon. The first serious accidents that occurred are those involving two Comet aircraft in 1954. A more recent example was the Aloha accident in 1988, which involved a Boeing 737. The damage was really serious, as we can see in Figure 1.1. This accident was caused by the formation of cracks due to fatigue and corrosion in the assembly rivets area within the fuselage. As a result, numerous studies have been carried out regarding the issue of multiple site damage.

Figure 1.1. *The Aloha Airlines Boeing 737at Honolulu international airport, Hawaii, following the accident on April 28, 1988*

Another example concerns the MacDonald Douglas DC 10 crash, which occurred in Sioux City in Iowa in 1989 (see Figure 1.2). The explosion of one of the engines led to this tragic accident. Even more recent was the Pensacola crash, when one of the engines broke apart due to cracking initiation caused by a drilling defect within a fan disk (see Figure 1.3).

These three examples from the aeronautical industry should not lead people to think that aircrafts as a means of transportation are dangerous and the only means affected by fatigue phenomenon. If we calculate the distance to passenger ratio, flying remains the safest means of transport. Nevertheless, due to its rapid development and despite the work being done on its design, manufacturing and maintenance, we can predict that in about 10 years' time a major aircraft accident is likely to occur every week (see Figure 1.4). Let us keep in mind that human error is the main cause of accidents involving aircraft. Accidents caused by defects in the materials are still occurring in spite of improved manufacturing processes.

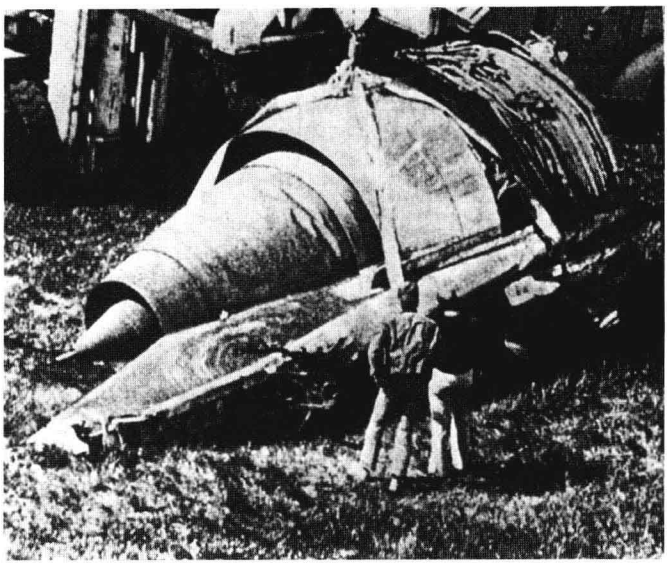

Figure 1.2. *DC 10 aircraft crash. Part of a detached engine. Sioux City Airport, July 19, 1989*

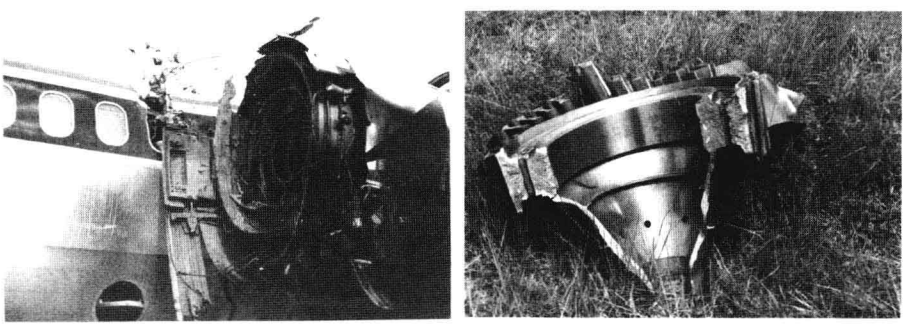

Figure 1.3. *Pensacola Crash (Florida, USA), July 6, 1996, was due to a failure during thetake off of a Delta Airlines MD-88 aircraft*

Fatigue also affects many other fields of transport, as shown in Figure 1.5 where cylinder heads of diesel engines subjected to increasing thermo-mechanical loading can break due to thermal and mechanical fatigue cracking if their design is wrong [SAL 07].

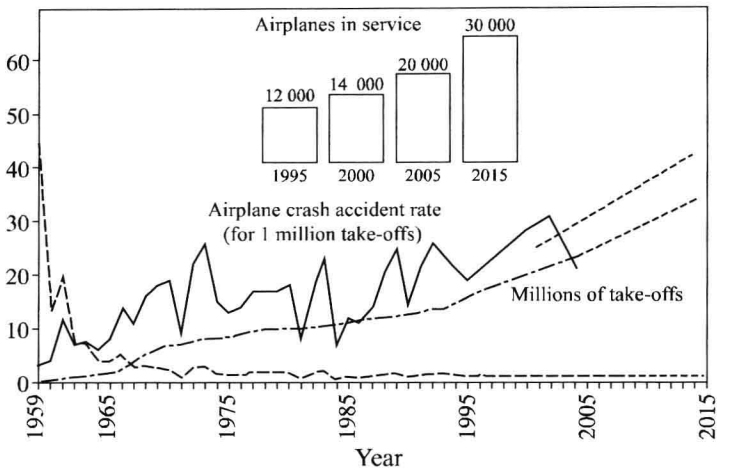

Figure 1.4. *Statistical study of the evolution of air traffic and of the number of crashes (MANHIRP, 2001, see also 1001crash.com)*

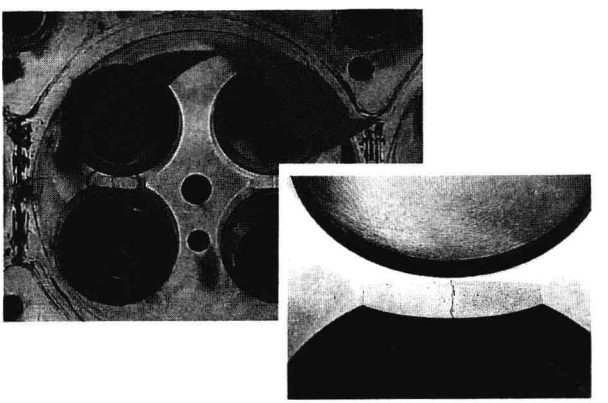

Figure 1.5. *Cracking within the cylinder head of a diesel engine [SAL 07]*

1.1.2. *Definitions*

Fatigue or *fatigue damage* refers to the modification of the properties of materials due to the application of stress cycles whose repetition can lead to fracture.

Uniaxial loading is defined as *the amplitude of the maximum stress* during a cycle σ_{max}. The *stress ratio* R is the ratio between the *minimum stress* σ_{min} and the