FATIGUE OF MATERIALS & STRUCTURES

G. Hénaff

Outline

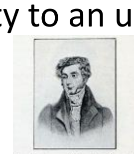
- Introduction
- Cyclic deformation & Low-Cycle Fatigue
- High-Cycle Fatigue
- Fatigue from Notches
- Fatigue Crack Propagation

INTRODUCTION TO FATIGUE

Definition

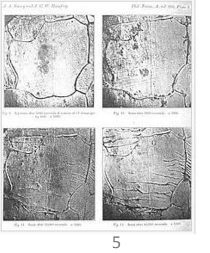
- « Progressive damage process developping as cracks under reversed loads, even of very small amplitude, without any concomitant change in the macroscopic behaviour but leading to failure »

- The origin of the wording « Fatigue » is controversial: Jean-Victor Poncelet, in 1839, described metals as “fatigued” after many load reversals. The word “fatigue” would have been first introduced by John Braithwaite in 1854 but he attributed the paternity to an unknown *Mr Field*.



Timeline of early research history

- **1837**: Wilhem Albert publishes the **first paper** on fatigue. He devised a test machine for conveyor chains in the Claustahl Mines.
- **1839**: Jean-Victor Poncelet describes metals as being *tired* in his lectures in military school in Metz.
- **1842**: William John Macquorn Rankine recognises the importance of stress concentrators in his investigation of railroad axle failures. The Versailles train crash is caused by axle fatigue.
- **1854:** Braithwaite reports on common service fatigue failure and coins the term *fatigue*.
- **1870**: August Wohler summarises his work on railroad axles. He concludes that cyclic stress range is more important than peak stress and introduces the concept of endurance limit.
- **1903**: Sir James Alfred Ewing demonstrates the origin of fatigue failure as microscopic cracks



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Timeline of early research history

- **1910**: O. H. Basquin proposes a log-log relationship for S-N curves using Wohler's data.
- **1945**: A. M. Miner popularises A. Palgrem's linear damage rule (1924) as a practical design tool.
- **1954**: L. F. Coffin and S. S. Manson explain fatigue crack growth in terms of cyclic plastic strain at the crack tip. A series of crash occurs on teh Comet I civil transport aircraft.
- **1961**: P. C. Paris proposes methods for predicting the fatigue crack growth rate in the face of initila septicism and popular defence of Miner's rule.
- **1968**: Tatsuo Endo and M. Matsuishi devise the rainflow counting algorithm and enable the reliable application of Miner's rule to random loading
- **1970**: W. Elber elucidates the mechanisms and importance of crack closure in slowing the growth of a fatigue crack due to the wedging effect of the plastic wake left behind the crack tip.

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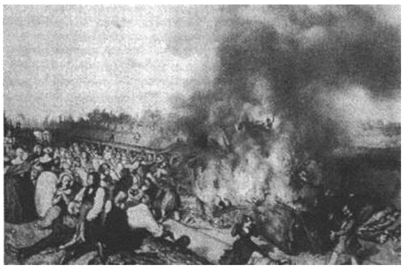
The crash of the Versailles train



The Meudon railway disaster is the first railway disaster in France and one of the first in the world. On May 8, 1842, a train from Versailles to Paris derailed in the Bellevue trench at Meudon. This derailment is followed by an overlap of leading cars followed by a fire. The accident caused 55 deaths including the sailor and explorer Jules Dumont d'Urville and his family.

Historic Timeline

In the early 1840s, Scottish engineer William Rankine (1820-1872) began to examine broken axle fracture surfaces and showed that the mode of rupture was not related to any "Brittleness" of the material used, but to a mode of failure now known as fatigue mode. At that time, there was indeed a lot of confusion about the problem. His theory will be contested for several years by advocates of an opposite and erroneous theory around the myth, somehow strange, of a hypothetical "re-crystallization", weakening the material when applying a field of constraint.

Historic Timeline

Given the severity of accidents due to failures in service (for example, the Paris-Versailles train in the 1840s), the author asks "if it would not be prudent to prescribe a limit in the distance traveled, beyond which all the axles of the railway equipment should be repaired or visited carefully. "
The author asks this question to two engineers, Mr. Marcoux, director of the material of the service of the mail coaches, and Mr. Arnoux, administrator of the general messengers. Mr Marcoux, on axles used in prolonged service, does not recognize "any appreciable change in the texture of the grain with what it was at the time of manufacture of the axles. "
Does Mr. Marcoux deny the fatigue of the axles? No !
The latter "thinks, on the contrary, that the vibrations which the axles experience in the high-speed steps deteriorate the iron, without however the grain texture experiences any appreciable change", and that "the axles are less resistant after a long period Service ". Accordingly, the latter "prescribes, in the specifications of the maintenance of the coaches, that the axles of these coaches will be renewed after having provided a course of 60 thousand kilometers".

Arthur
Morin
1862


RÉSISTANCE

DES MATÉRIAUX

PAR

ARTHUR MORIN

Troisième édition

TOME SECOND

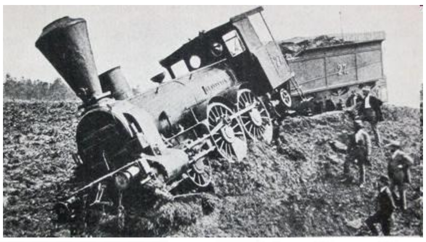
PARIS
LIBRAIRIE DE L. HACHETTE ET Cie

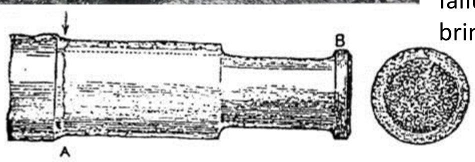
1862

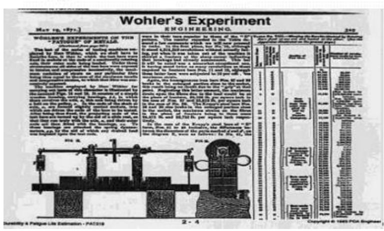
Historic Timeline

- Mr. Marcoux then remarks that "well-made axles, with good quality irons, fail after having provided a course of 60 to 80 thousand kilometers, because small cracks are formed below the flange of the spindles, It is difficult to recognize without heating the iron of the spindles: if these cracks, which have a small depth when they are formed, remain undetected, the axles fail at this point when they penetrate from 10 to 15 millimeters in the section of the spindle. ".
- He then gives his explanation of the phenomenon: "I think that these cracks are formed after a long use, that they are occasioned by the vibrations of the axles, and that this effect occurs in a manner analogous to what happens when one breaks a wire by bending it several times in opposite directions. If a wire is subjected only to very slight inflections over a great length, it cannot be broken: it is the effect which vibrations must produce on the body of the axle. But if the wire is tightened in a vice and subjected to several inflections in opposite directions, the iron extends on one side, discharges from the other, and the wire breaks close to the vice, as the axles break at the flange of the spindles. "

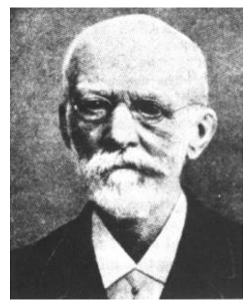
Historic Timeline







On October 19, 1875, the Amstetten locomotive serving the line Salzburg-Linz derailed: the cause of the accident was the fatigue ruin of a running gear. It was unknown at that time that the cyclic failure load of a material is less than its static failure load: it was up to August Wöhler to bring this fact to light.



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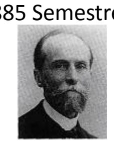
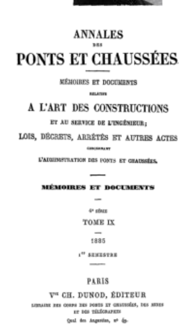
Historic Timeline

Armand Considère in « Annales des Ponts et Chaussées 1885 Semestre 1 ».





ANNALES
DES
PONTS ET CHAUSSÉES
MÉMOIRES ET DOCUMENTS
RELATIFS
A L'ART DES CONSTRUCTIONS
ET AU SERVICE DE L'INGÉNIEUR;
LOIS, DÉCRETS, ARRÊTÉS ET AUTRES ACTES
CONCERNANT
L'ADMINISTRATION DES PONTS ET CHAUSSÉES.
MÉMOIRES ET DOCUMENTS
TOME IX
1885
1er SEMESTRE
PARIS
Vve CH. DUNOD, ÉDITEUR

73. *Valeur des lois de M. Woehler.* — Bien que nous ayons fait plusieurs réserves importantes au sujet des expériences de M. Woehler, nous pensons qu'elles ont néanmoins une grande valeur; car on doit remarquer que l'erreur commise dans le calcul des tensions de flexion a eu pour résultat d'exagérer les valeurs des limites dangereuses. L'extrême brièveté de l'action des efforts, qui rend leur effet incomplet et moins destructeur, concourt au même résultat que l'erreur en question; comme elle, elle conduit à assigner aux limites dangereuses des valeurs trop élevées.

Par conséquent, le danger spécial résultant de la répétition des efforts, que M. Woehler a découvert et mis hors de doute est plus pressant encore qu'il ne l'a pensé, et des expériences comparatives, plus précises, ne pourront que faire apparaître plus étroites encore les limites dans lesquelles doivent être renfermés les efforts répétés, pour ne pas altérer le fer et l'acier.

Si donc, il est fort désirable que des expériences nouvelles

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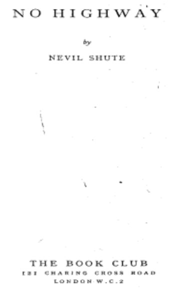
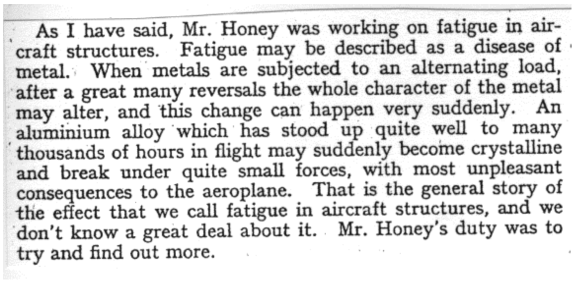
Historic Timeline : « No Highway»


NO HIGHWAY

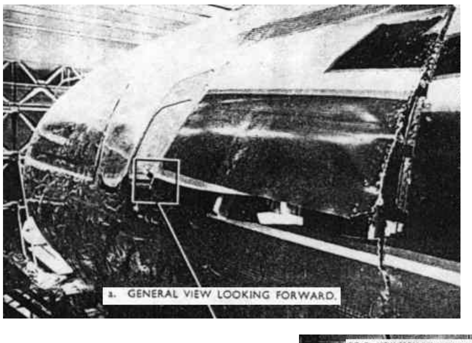
by

NEVIL SHUTE

THE BOOK CLUB
121 CHARING CROSS ROAD
LONDON W.C.2

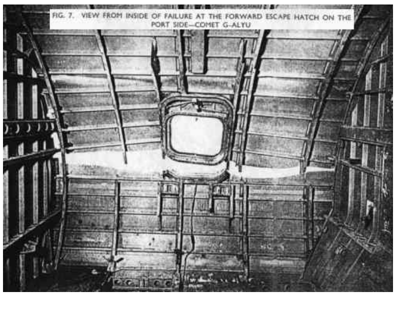

As I have said, Mr. Honey was working on fatigue in aircraft structures. Fatigue may be described as a disease of metal. When metals are subjected to an alternating load, after a great many reversals the whole character of the metal may alter, and this change can happen very suddenly. An aluminium alloy which has stood up quite well to many thousands of hours in flight may suddenly become crystalline and break under quite small forces, with most unpleasant consequences to the aeroplane. That is the general story of the effect that we call fatigue in aircraft structures, and we don't know a great deal about it. Mr. Honey's duty was to try and find out more.

Comet crashes



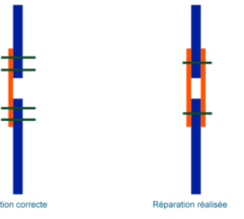
1954 : series of crashes on Comet I aircrafts de crash sur les appareils Comet I.

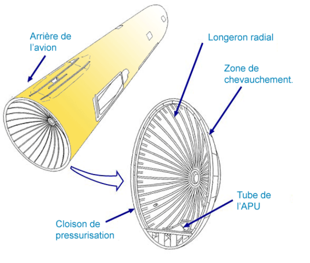
2 cases → failure due to metal fatigue



Japan Airlines 123, Boeing 747 (520 fatalities, 4 wound persons)

- Incident (Tailstrike) in 1978: the rear pressure bulkhead was damaged .
- Repair by Boeing : a technician used two plates instead of one but the assembly was idfficult to fix, so he decided to use only 1 rivet line instead of two.
- This poor repair holds for many years, but quite a long time before the crash it gives signs of weakness characterised by a whistling at the rear of the aircraft during the flight. The crack is however too small at this stage to hamper the pressurization of the main cabin.
- The fateful day, when the plane arrived at 24'000 feet, a typical altitude for decompression accidents, the pressure bulkhead tears explosively. The cabin air is propelled inside the tail unit and pulls out the rudder, the vertical stabilizer, half of the elevator and its stabilizer as well as the APU.
- The JAL is pointed at the finger and in the press spread the shortcomings and errors that led to the drama. Several senior officials commit suicide. The technician who made the famous repair will also end his days.





Japan Airlines 123, Boeing 747 (520 fatalities, 4 wound persons)

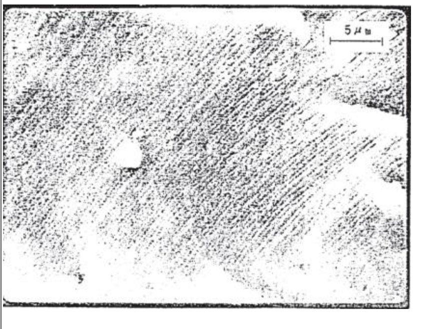
AIRCRAFT ACCIDENT INVESTIGATION REPORT

Japan Air Lines Co., Ltd.
Boeing 747 SR-100, JA8119
Gunma Prefecture, Japan
August 12, 1985

Aircraft Accident Investigation Commission
Ministry of Transport

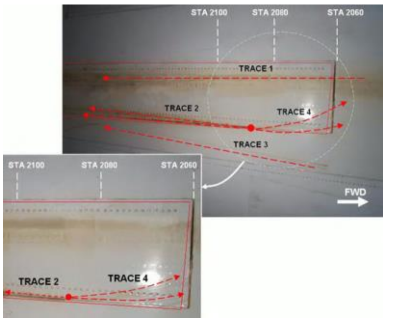
June 19, 1987

(Tentative Translation from Original in Japanese)



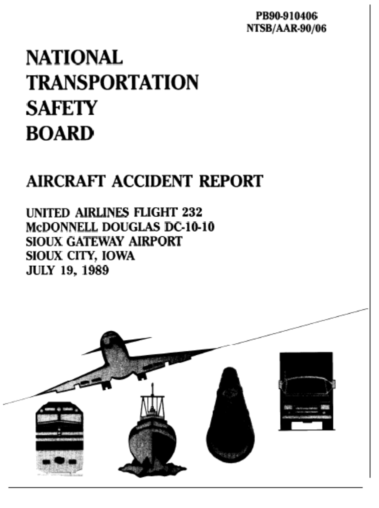
China Airlines 611, 2002 (225 fatalities)

The investigation showed that the accident was caused by the fatigue of the structure of the aircraft, combined with a poor repair after an incident (Tailstrike): on February 7, 1980, the aircraft tail had hit the runway on landing in Hong Kong.
This repair was not made according to the SRM (Structural Maintenance Manual) requirements: the damaged part of the aircraft (section 46) was not removed and the reinforcement affixed was not wide enough to cover the entire damaged area.
During the many subsequent flights (depressurization and pressurization cycles), the badly repaired part gradually cracked. It finally failed 22 years later, during a flight. The decompression that followed completely disintegrated the aircraft.



Nicotine stains are tell-tail signs of fatigue crack growth in pressure hull skin
2.3m crack growth in 20,000 flights

United Airlines 232 , Sioux City, DC-10, 1989

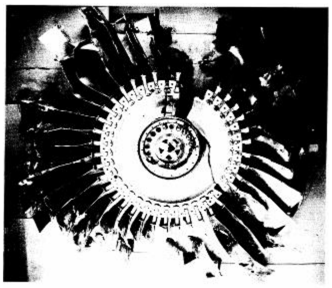

PB90-910406
NTSB/AAR-90/06

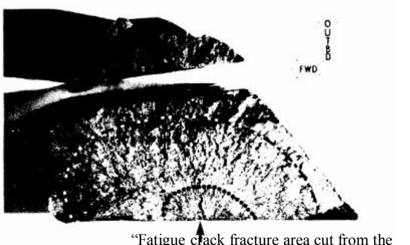
NATIONAL
TRANSPORTATION
SAFETY
BOARD

AIRCRAFT ACCIDENT REPORT

UNITED AIRLINES FLIGHT 232
McDONNELL DOUGLAS DC-10-10
SIOUX GATEWAY AIRPORT
SIOUX CITY, IOWA
JULY 19, 1989

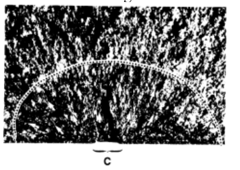
United Airlines 232 , Sioux City, DC-10





"Fatigue crack fracture area cut from the bore of the smaller piece of the separated stage 1 fan disk.cavity (arrowThe fatigue crack extends from the"C") to the dashed line position. The discolored portion ofthe fatigue crack is between the cavity and the dotted line. Magnification:2.26X."

"Some areas of fatigue striations were found just outboard of the stabilized-alpha portion of the inclusion at the fatigue origin. However, between the cavity bottom and a radial distance of 0.025 inch outboard of the bore surface, areas with brittle fracture features and a lack of fatigue striations were found intermixed among more ductile-appearing bands with fatigue striations.
The zone with a mixture of brittle features and fatigue striation areas correlated with the enriched alpha microstructure surrounding the stabilized-alpha core of the inclusion.
The fatigue striation spacing generally increased as distance from the origin area increased. However, starting at a distance of about 0.145 inch outboard of the bore surface, areas with much more closely spaced striations were also found. The more closely spaced striations were referred to as minor striations, and the striations with wider spacings were referred to as major striations."



American Airlines N330AA, LAX (June, 2nd 2006)

American Airlines N330AA, LAX (June, 2nd 2006)

American Airlines N330AA, LAX (June, 2nd 2006)

Qantas QF 32, 2010 (0 victim)

- Off Singapore, Nov 2010, 21
- 2 year old A380 superjumbo, Trent 900 engine
- Main cause: “defect of manufacture of high pressure and intermediate pressure turbines, where the circuit distributes the oil for the bearings of the shafts"
- Repairs 139 million Australian dollars (All four engines have been replaced, the wing has been repaired and six kilometers of wiring have been changed, overweight: 94 kg)

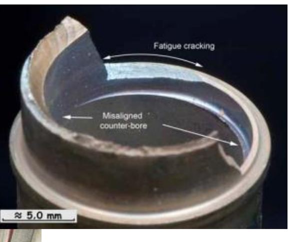


Image source: Courtesy of the 'Posmetro' newspaper, Indonesia.

Qantas QF 32, 2010 (0 victim)

Uncontained failure of a GE CF6-80C2B6 engine occurred on a Boeing 767-300 (Oct. 28, 2016)

Recovered stage 2 HPT disk pieces

Fatigue crack location on a disk fracture surface

Airport Overview with Disk Fragment Locations

10,984 cycles / life limit of 15,000 cycles

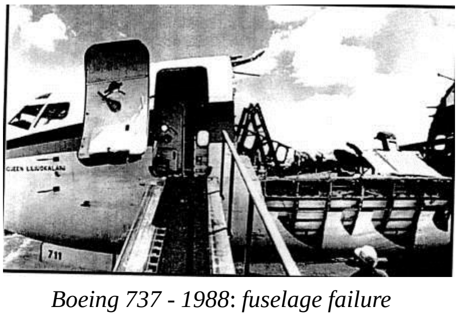
http://www.ntsb.gov/news/press-releases/Pages/pr20161104.aspx

ICE Eschede 1998

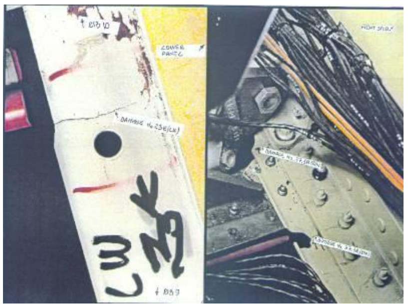
ICE Eschede 1998

Fatigue : still an issue

- Today: less disasters;
- Nevertheless, this problem is always present and must always be taken into account in the design and maintenance of structures (transport, energy production, mechanical industry, etc.) and in the development of new alloys.



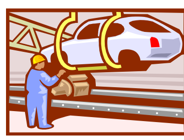
Boeing 737 - 1988: fuselage failure

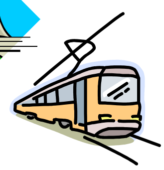
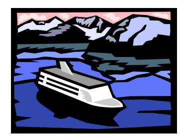


Longerons ATR : présence de fissures de fatigue

Fatigue in practice

- 80% of failures in service are due to the fatigue phenomenon (1982 estimated cost of about 4% of GDP in the USA);
- Among these failures, about 80% are due to a poor understanding of this phenomenon in the design (bad design, inadequate criterion, ...)

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Fatigue in practice

- Fatigue affects many fields of activity. Examples:
  - Automotive
  - Agricultural machineries
  - Aéircrafts
  - Pressure vessels
  - Pipings
  - Implants (valves, prostheses, ...)
  - Microelectronics
  - ….

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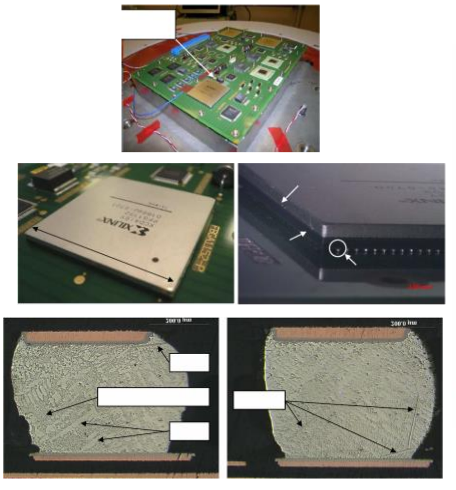
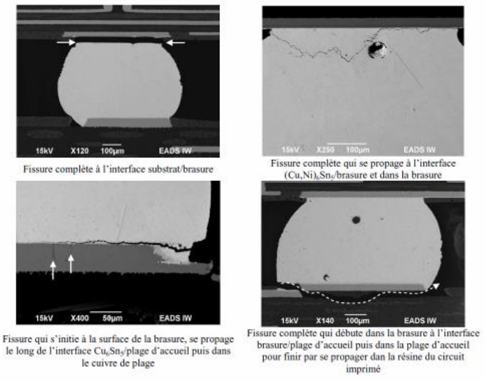
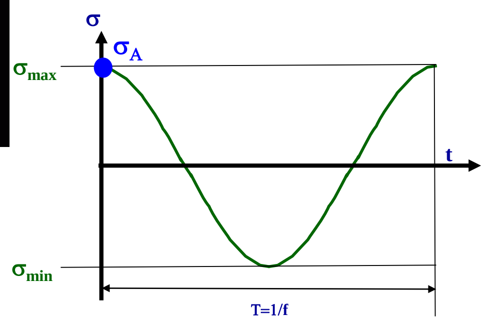
Microelectonics



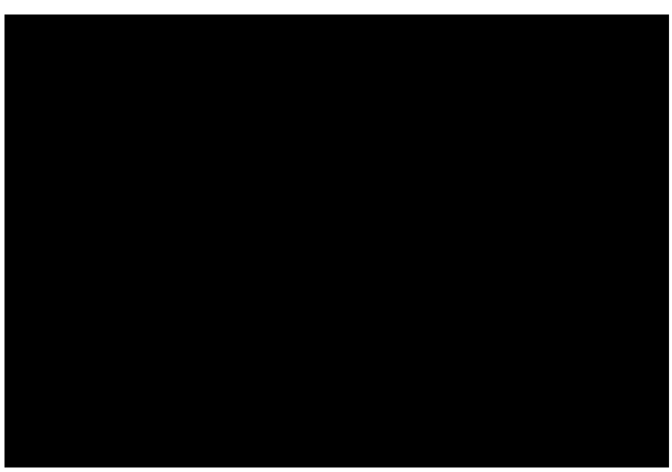


Examples of Fatigue Failure

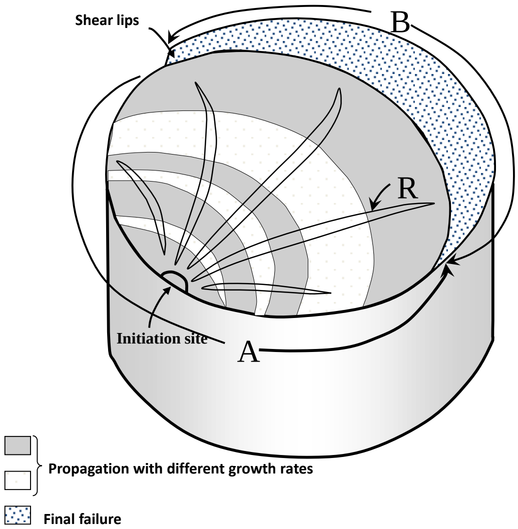
Fatigue Damage

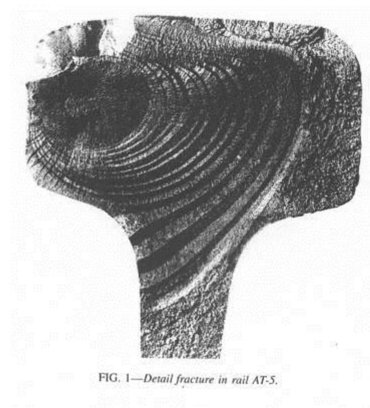


Morphology of a Fatigue Fracture Surface

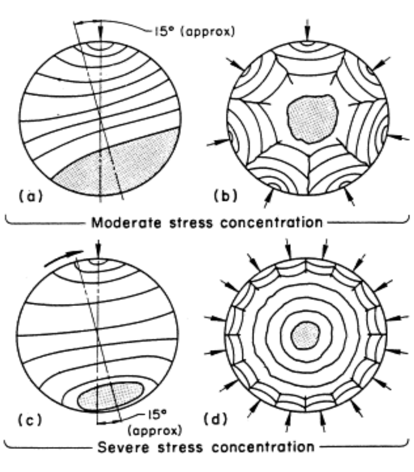


Morphology of a Fatigue Fracture Surface

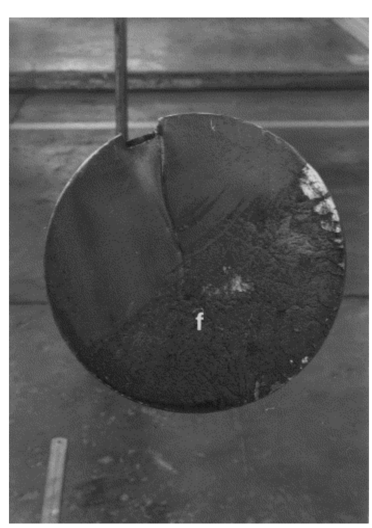




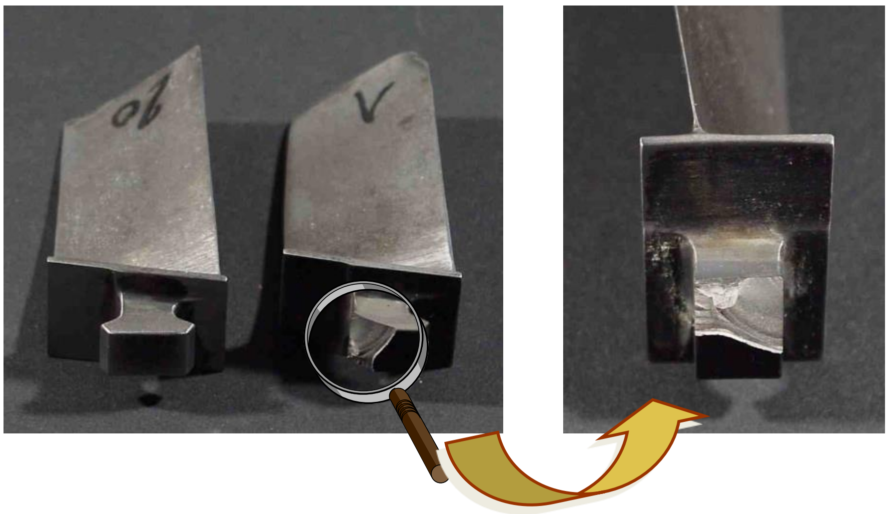
Pump shaft failure



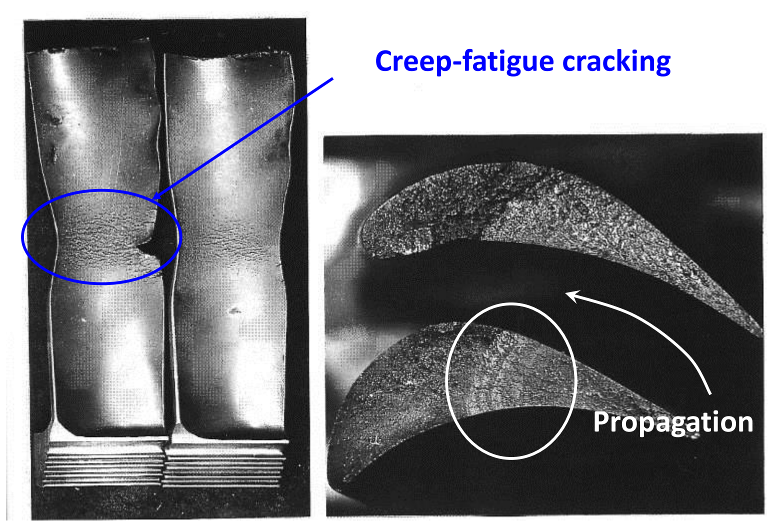
Morphologie des Ruptures



Failure of a titanium alloy turbine blade

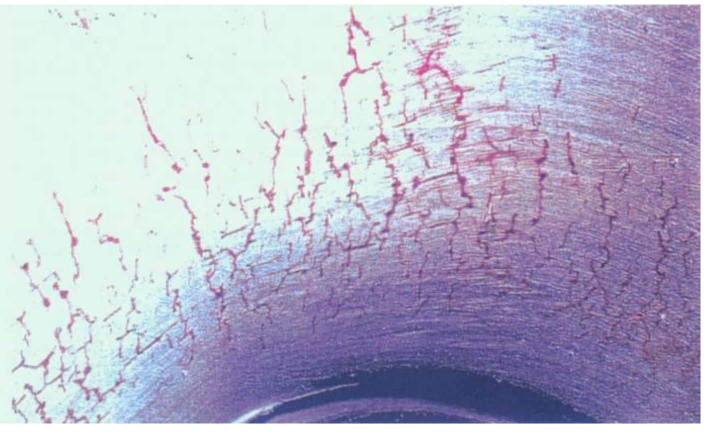


High temperature failure blade



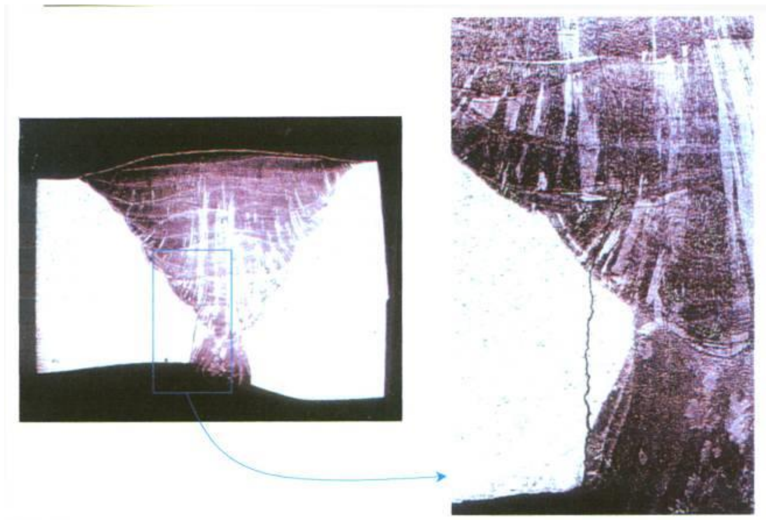
Failure of a land turbine

Thermal fatigue



Faïençage thermique dans un coude de tuyauterie

Thermal Fatigue: Failure at a weld joint



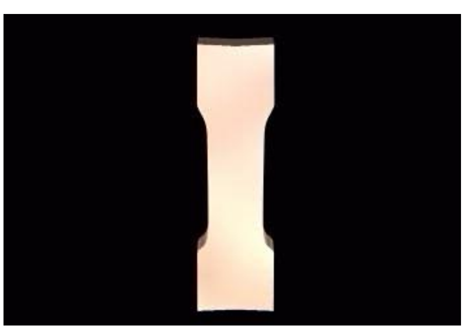
Fatigue Mechanisms

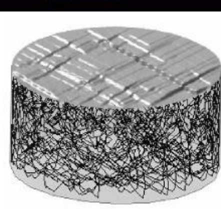
Fatigue Failure

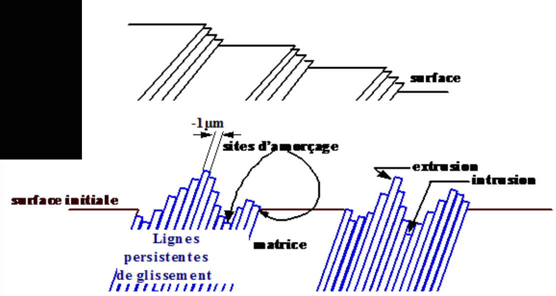
3 stages:
- **Initiation of one of several microcracks**
- **Propagation of a main crack**
- **Final failure**

Fatigue Life

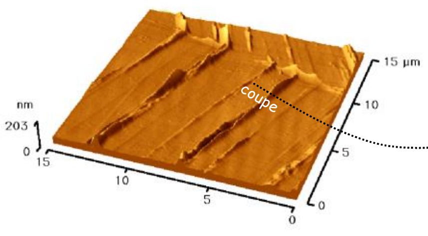
Cyclic Deformation and Initiation

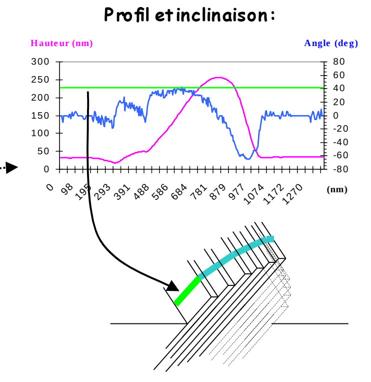






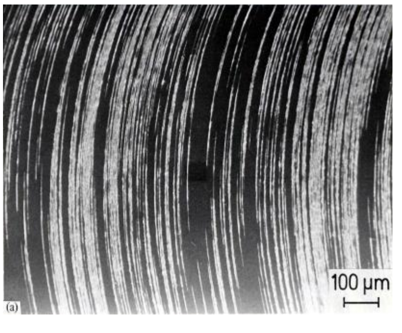
AFM observation of extrusions

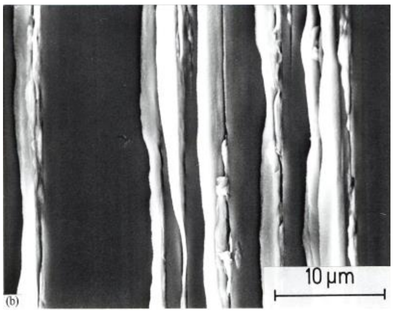




316L, traction-compression, 20°C,
vide
$\Delta\varepsilon_p/2 = 2.10^{-3}$, 5000 cycles

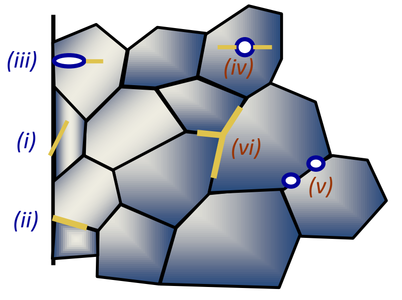
Surface deformation





Intrusion/extrusion at the surface of a fatigued copper single crystal

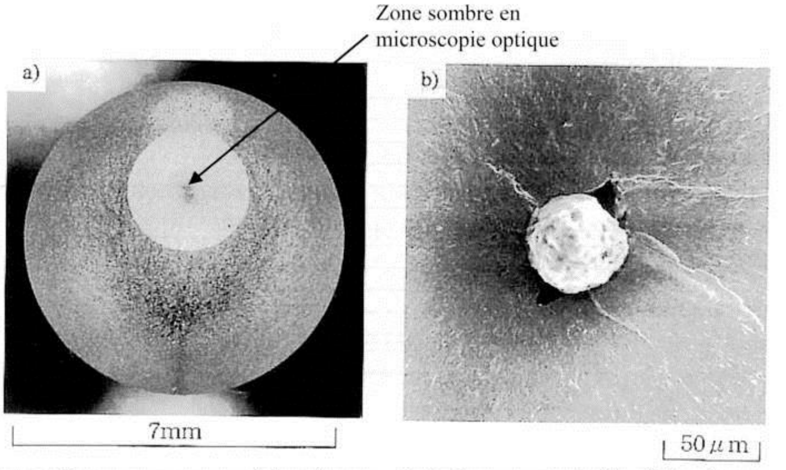
Crack initiation sites



Surface
- *(i)* Transgranular (persistent slip band)
- *(ii)* Intergranlular (along a grain boundary)
- *(iii)* On a defect (porosity, shrinkage, inclusion)

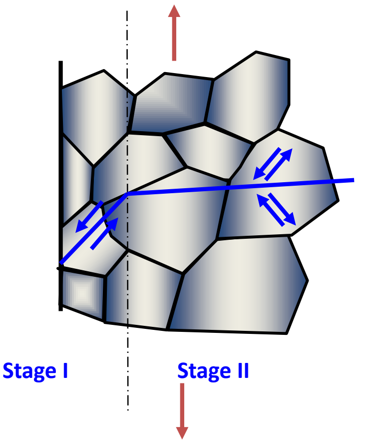
Internal
- *(iv)* On a defect (porosity, shrinkage, inclusion)
- *(v)* Along a grain boundary
- *(vi)* On a triple junction

Example of internal initiation: « Fish-eye » failure



Aspect d'un amorçage en « œil de poisson » Inclusion au centre de l'« œil de poisson »

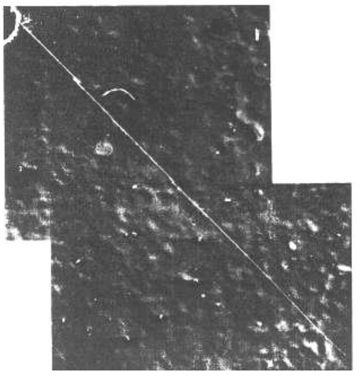
Propagation stages



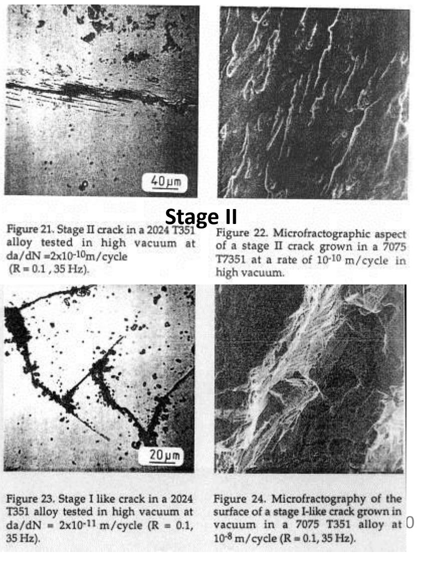
Stage I : crystallographic cracking mode

Stage II : propagation macroscopically perpendicular to the mode I loading axis

Propagation stages



Stage I propagation in an Aluminium single crystal



Stage II

Figure 21. Stage II crack in a 2024 T351 alloy tested in high vacuum at da/dN =2x10^{-10}m/cycle (R = 0.1 , 35 Hz).

Figure 22. Microfractographic aspect of a stage II crack grown in a 7075 T7351 at a rate of 10^{-10} m/cycle in high vacuum.

Figure 23. Stage I like crack in a 2024 T351 alloy tested in high vacuum at da/dN = 2x10^{-11} m/cycle (R = 0.1, 35 Hz).

Figure 24. Microfractography of the surface of a stage I-like crack grown in vacuum in a 7075 T351 alloy at 10^{-8} m/cycle (R = 0.1, 35 Hz).

Design Methodologies

Industrial approach

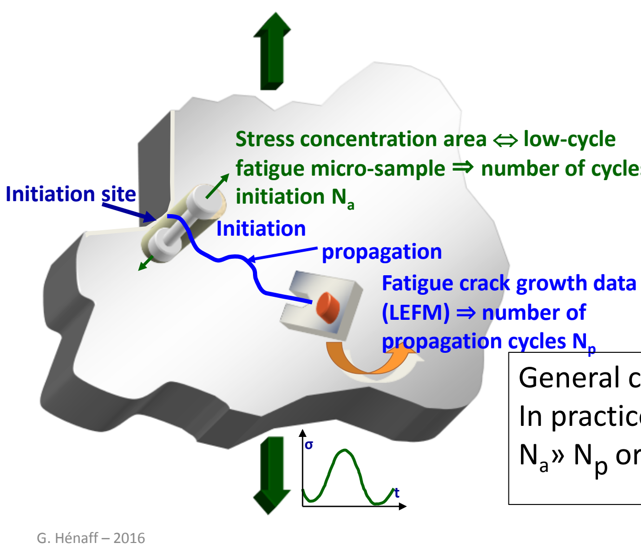
- Need to have both an experimental approach and a "calculation" approach
- The closer the calculation and the experimentation to the real service conditions, the higher the level of confidence in the results
- Different approaches exist, more or less costly and / or complex;
- It is necessary to properly evaluate the cost over the operating life of the structure;

Industrial approach

- Safety factors are commonly used. A too high value leads to an over conservatism, therefore to a non-competitive product; Too low a value may lead to failures before the end of the lifetime.

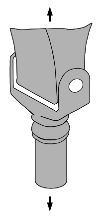
- The use of safety factors does not exonerate from a suitable design approach.

Different approaches to predict fatigue life of a component

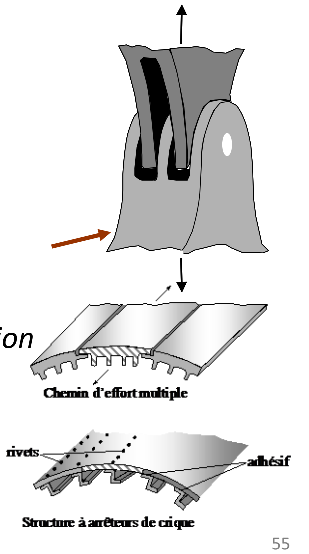


General case: $N_f = N_a + N_p$
In practice:
$N_a \gg N_p$ or $N_a \ll N_p$

Design Philosophies



➢ **Safe Life** (« *Durée de vie sûre* »).
➢ **Fail safe** (*Multiple load paths; crack arresters*).
➢ **Damage tolerance** (*controlled propagation of an initial crack-like flaw*)



Certification A380

- Accelerated test simulating 47 500 flights, i. e. 25 years of commercial service, in 26 months
- 184 computer-controlled hydraulic rods

Certification A380

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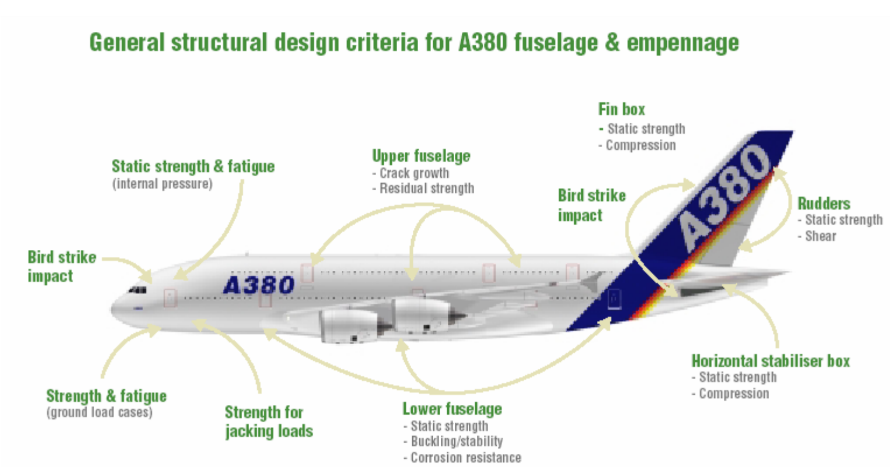
Design criteria for the A380 fuselage



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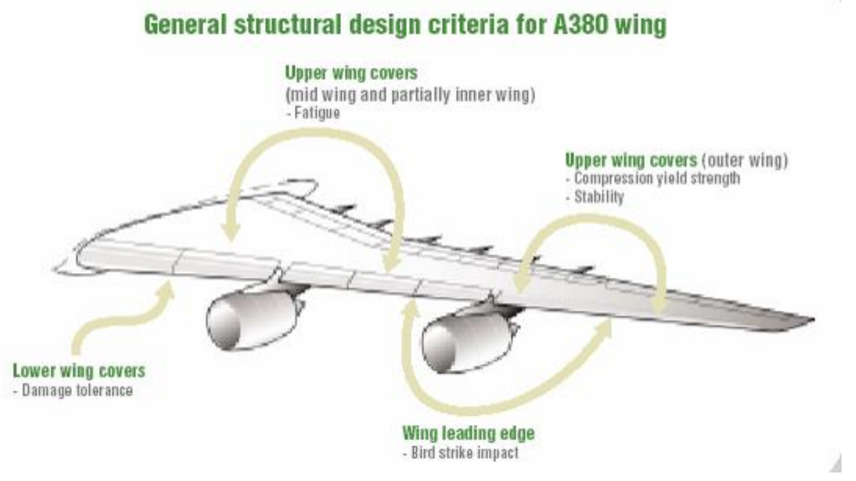
Design criteria for the A380 wing



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