PURPOSE AND OBJECTIVES OF THE COURSE

To form students' scientific base, theoretical and practical knowledge in the field of organization and implementation of processes of maintaining and restoring the airworthiness of aircraft according to service life criteria and fatigue operating life time of their structures.

Obtaining knowledge: on modern methods of determining the durability of aircraft; the provision and support of fatigue life, survivability and service life of aircraft (aircraft and helicopters). Acquaintance with the main keypoints of the FAR, JAR and Aircraft Regulations, certification of aviation equipment.

As a result of studying the discipline the student must

know

- basic concepts, terms and definitions of the discipline "Aircraft Operating Life and Durability";
- the content of the main processes, concepts and ideas about providing the operating life of aircraft structures;
- general requirements for the operating life and durability of aircraft structures in the expected operating conditions;
- the main factors of operating life conservation and durability of aircraft structures;
- power and other factors of the expected operating conditions of the aircraft;
- methods and techniques for provision of operating life and durability of the aircraft structures;
- main characteristics of the typical flight of aircraft and their characteristics;
- peculiarities of operation and maintenance of the airframe and functional systems of the aircraft from the point of view of ensuring the resource and durability of the aircraft structures.

be able:

- to assess the structural and technological features of the design and operation of the aircraft;
- to calculate the parameters of the operating life of aircraft structures;

- to provide the required levels of flight safety of the aircraft on the criterion of the operating life of their structures;
- to search and analyze the causes: the emergence of cells of probable destruction from tired elements of the aircraft design; violations of the rules of flight and technical operation of aircraft structures;
- to develop measures to prevent and eliminate the destruction of tired elements of the design of the aircraft.

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1 HISTORICAL REVIEW

Prevention of fatigue failure in structural parts has been an important concern in aircraft engineering for many years. Technological developments continually bring out new materials, new fabrication processes, improved design concepts, and additional information about service requirements. Hence, engineering procedures for prevention of fatigue need continual review.

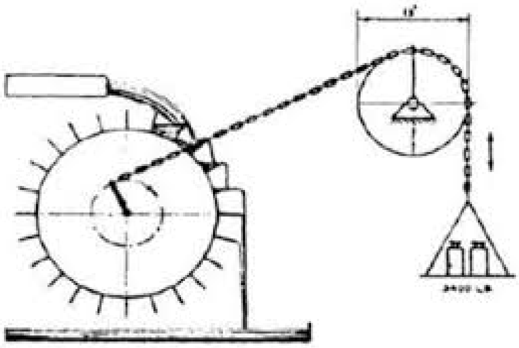
Fatigue failure – cracking of metal under repeated stressing – was discovered in the railroad industry. This industry presented some of the first situations where extensive repetition of mechanical loading of metal parts caused failures. As sources of vibration and of dynamic loading of materials have increased, fatigue failures have become increasingly important in engineering.

Fatigue is one of the major failure mechanisms in engineering structures. Time-varying cyclic loads result in failure of components at stress values below the yield or ultimate strength of the material. Fatigue failure of components takes place by the initiation and propagation of a crack until it becomes unstable and then propagates to sudden failure. The total fatigue life is the sum of crack initiation life and crack propagation life. Fatigue life prediction has become important because of the complex nature of fatigue as it is influenced by several factors, statistical nature of fatigue phenomena and time-consuming fatigue tests.

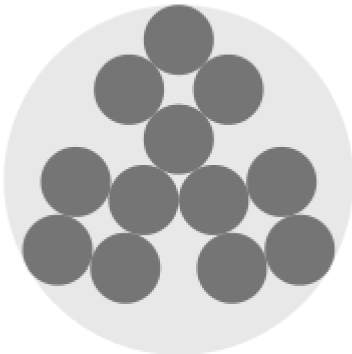
1.1 1837-1858. THE TIME BEFORE WOHLER

The history of fatigue begins with Wilhelm Albert, who was a Royal Hannoverian civil servant for mines. In 1837 he published in Clausthal the first fatigue-test results known. For this purpose he constructed a test machine for the conveyor chains which had failed in service in the mines. As early as that, he therefore tested actual components, not just the material! Since chains at the time could only be replaced by rope which had to be imported at great cost, Albert invented the wire rope - surely more important than those first fatigue tests.

Wilhelm Albert

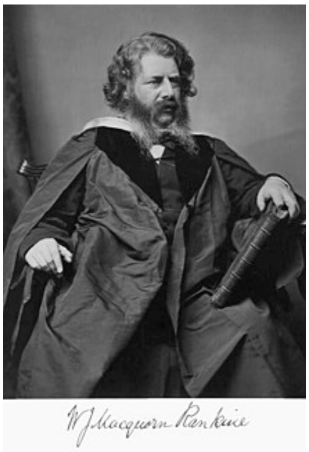


Albert Test Machine



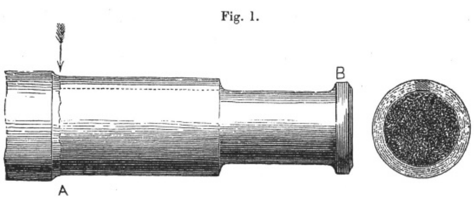
Wire Rope

In 1842, Rankine discussed the fatigue strength of railway axles. Rankine was one of the first engineers to recognize that fatigue failures of railway axles was caused by the initiation and growth of brittle cracks. In the early 1840s he examined many broken axles, especially after the Versailles train crash of 1842 when a locomotive axle suddenly fractured and led to the death of over 50 passengers. He showed that the axles had failed by progressive growth of a brittle crack from a shoulder or other stress concentration source on the shaft.



William John Macquorn Rankine

Versailles train crash



Drawing of a fatigue failure in an axle, 1843.

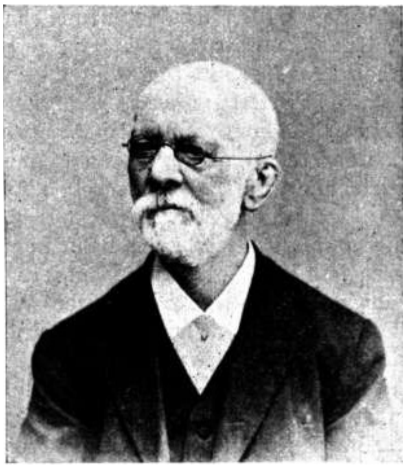
In 1853 the Frenchman Morin in his book Resistance of Materials discussed reports of two engineers responsible for horse-drawn mail coaches. The replacement of the axles of the coaches was prescribed after 60 000 km, an early example of the "safe life" design approach. The axles of other mail coaches were to be inspected thoroughly after 70 000 km, cracks to be repaired by "fire-welding". It was noted that those cracks mainly occurred at cross-section changes.

The term "fatigue" was mentioned for the first time by the Englishman Braithwaite in 1854. In his paper Braithwaite describes many service fatigue failures of brewery equipment, water pumps, propeller shafts, crankshafts, railway axles, levers, cranes, etc. Allowable stresses for fatigue-loaded components are also discussed.

In this period many disastrous railroad accidents due to fatigue occurred. In the history of the "Institution of Mechanical Engineers" in London of 1854 it is mentioned that a member had seen a collection of hundreds, if not thousands of failed railway axles. As late as 1887 English newspapers reported the "most serious railway accident of the week", and in many cases these were due to fatigue failures of axles, couplings and rails, and claimed many lives.

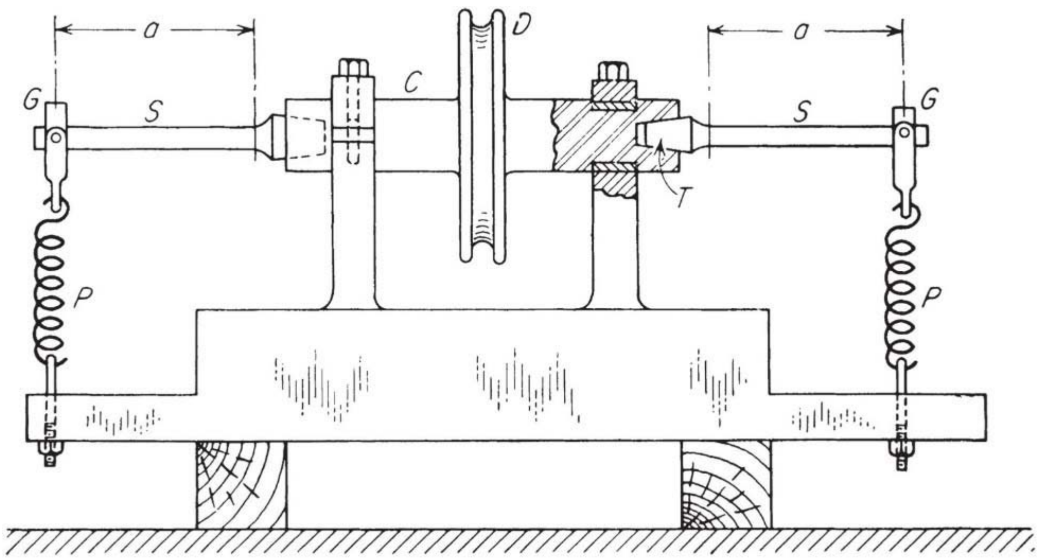
1.2 1858-1870: WOHLER

Wohler, Royal engineer of the Railways in Frankfurt, measured the service loads of railway axles with self-developed deflection gages.



August Wohler

Specifically, this was accomplished for a number of four-wheeled and six-wheeled freight and passenger cars on trips between Breslau and Berlin as well as Frankfurt and Berlin. The measurements were carried out for 22 000 km. The deflection of the axle was scratched on a zinc plate by a scriber. Only the largest deflection per trip was measured. According to Wohler: "In order to know the force necessary for a certain deflection, the axle was bent by a dynamometer, which was fastened to the rims of the wheels". This means in our words that Wohler even then calibrated the forces acting on the axles. Wohler then discusses the largest axle deflection per trip and the corresponding service load, and calculates the bending and torsional stresses of the axle. He then compares the measured bending forces with those caused by the static axle load and arrives at a factor of 1.33; that is, in our present-day terminology, he determined an impact factor of 1.33. Wohler then draws the following conclusions from his measurements: "The number of such cycles per trip is considerably smaller than the number of miles the axle travels during its life. Therefore, the safety requirements are met if the axles can withstand the maximum stresses measured as many times as its expected life in miles. If we estimate the durability of the axles to be 200 000 miles with respect to wear of the journal bearings, it is therefore only necessary that it withstands 200 000 bending cycles of the magnitude measured without failure". Thus Wohler implicitly suggested design for finite fatigue life, taking into consideration even the scatter of fatigue life, or in other words, the probability of failure. Since no fatigue-test data were available to him at that early date, he estimates them and arrives at an allowable axle load for 200 000 cycles of 6800 kg.



Wohler Test Machine

Beginning in 1860, Wohler published the results of fatigue tests with railway axles. Since the rotating-bending test machine he designed and built ran at a very low frequency, he designed new machines for carrying out axial-bending and torsion tests on different notched and unnotched specimens. In 1870 he presented a final report containing the following conclusions, often called "Wohler's laws": "**Material can be induced to fail by many repetitions of stresses, all of which are lower than the static strength. The stress amplitudes are decisive for the destruction of the cohesion of the material. The maximum stress is of influence only in so far as the higher it is, the lower are the stress amplitudes which lead to failure**". **Wohler therefore stated the stress amplitudes to be the most important parameter for fatigue life, but a tensile mean stress also to have a detrimental influence.**

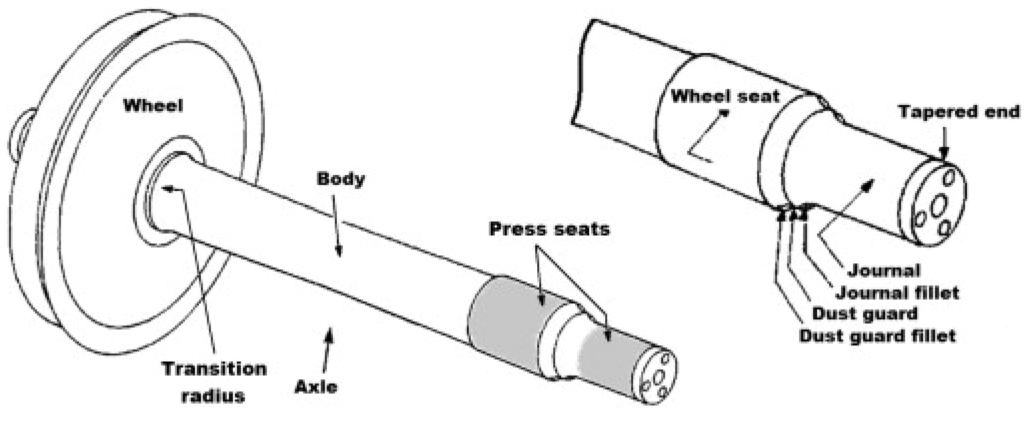
From his quantitative results he draws the following conclusions about this mean stress influence: "Components loaded in tension and compression like connecting rods, wheels, balances, etc. must be stronger by a factor of 9:5 than components loaded only in tension, like bridge members or roof beams. The springs of railway cars are loaded by small amplitudes, but high maximum stresses.

After a discussion of why a safety factor is necessary, Wohler comes back once more to finite life design: "It must be taken into consideration whether unlimited or limited life is required for the component. It follows that different components need different safety factors. In any case two such factors are necessary, one for the relation between the maximum stress in service and static strength, and the other for the allowable stress amplitude."

Wohler then suggests a safety factor of two for static strength and an additional one of two for fatigue strength. In his opinion this is adequate for all circumstances. These factors, however, are only valid for unnotched sections, because "the strength of joints in the form of riveted joints, keyed joints and such kind, and different shapes require special tests. The results of the tests with sharply notched specimens have proved the necessity of such special tests". Thus Wohler correctly does not present the additional safety factors for these joints, but requires special tests.

The safety factors given above are only valid for infinite design life, because Wohler continues: "For components with finite fatigue life other considerations apply: if, for example, it is known that the maximum bending stresses on a railway car axle occur when traveling over switches, and if the number of such switches during the life of the axles is known, it is in accord with the requirements of safety that the allowable stresses in the axle are those which lead to failure after many millions of cycles".

In another paper of 1870 Wohler describes the dimensioning, design and material selection for railway car axles. Wohler then describes the forces acting on the axle in service, for example the static load, lateral loads due to cornering, wind pressure, etc. He calculates the service stresses via the measured loads and the axle diameter. By comparing these stresses with the result of his fatigue tests he concludes that axles are completely safe. Furthermore he describes the allowable axle loads according to the "Technical Regulations of the German Railways", which depend on the material, diameter, etc., and which also contain rules about the size of the radii between the axle and journal diameter. The "metallurgical size effect" was already taken into account at that time, i.e. the allowable stresses for thinner axles were higher than those for thicker axles, "because it was assumed that smaller dimensions allow the material to be worked better and therefore would result in higher fatigue strength".

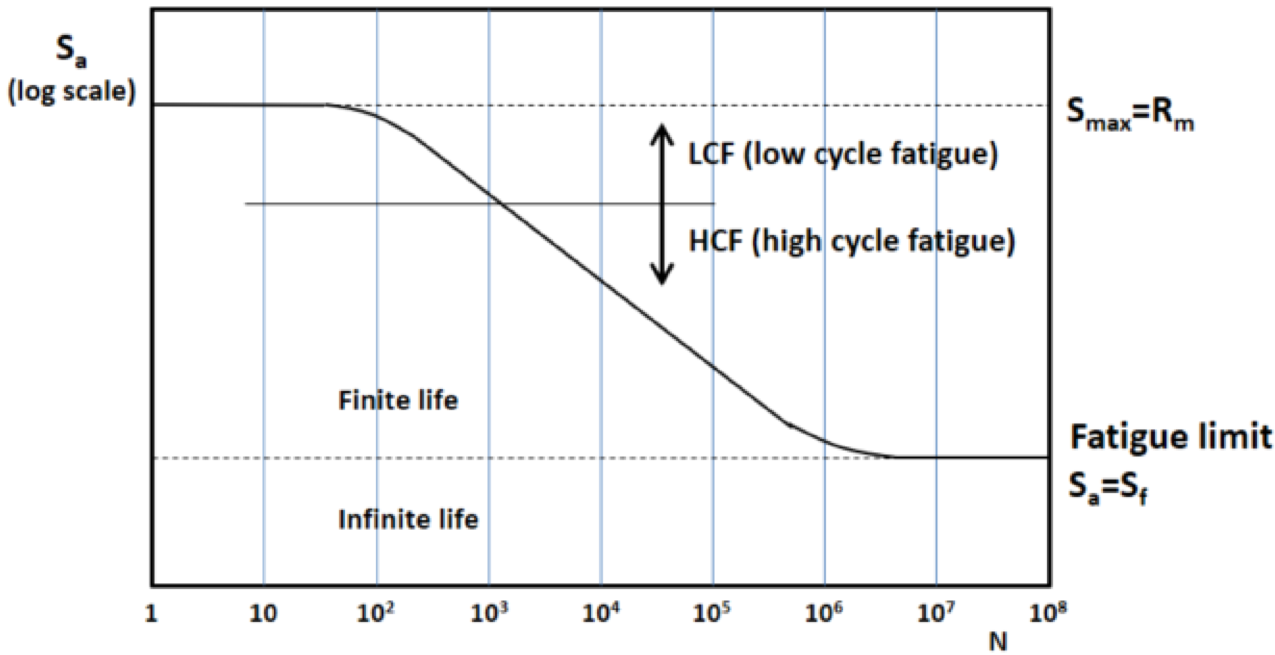


In summary the work of Wohler encompassing the measurement of service loads, the calculation of the corresponding service stresses, the design for finite life, observation of crack propagation and the quantitative suggestions for the decrease of the notch effect.

Wohler represented his test results in the form of tables. Only his successor Spangenberg plotted them as curves. The S-N curves were called "Wohler curves" since 1936.

Not until 1910 the American Basquin represent the finite life region of the "Wohler curve" in the form "log S_a, on the ordinate, log N on the abscissa" and describe it by the simple formula:

$$S_a = C \cdot N^n$$

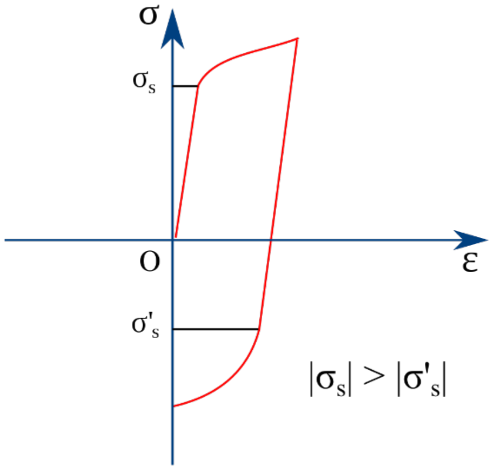


Wohler Curve

In a large table Basquin gives some numerical values for C and n, based for the most part on Wohler's tests.

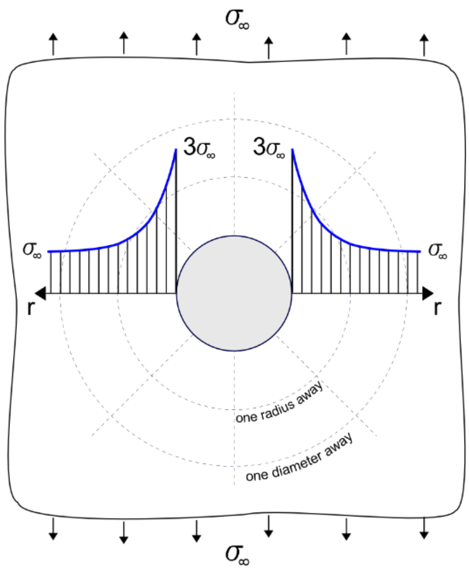
1.3 1870-1905

The next name to be mentioned would be Bauschinger, Professor of Mechanics at the Munich Polytechnical School, which now is the Technical University of Munich. The Bauschinger effect, in his words "the change of the elastic limit by often repeated stress cycles".

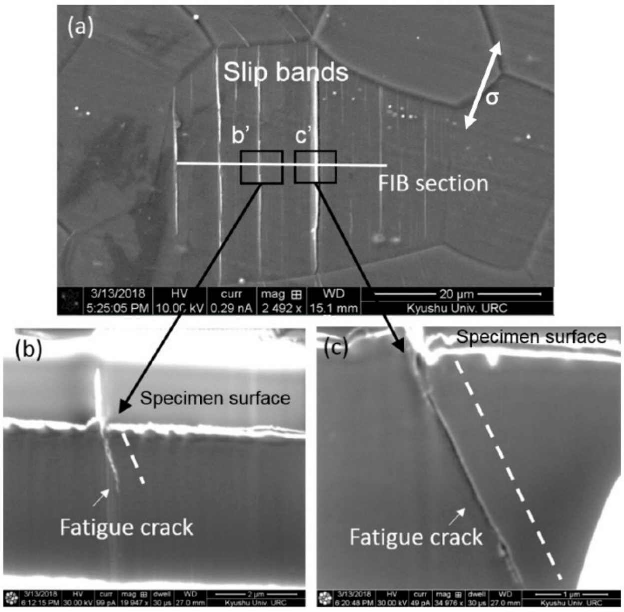


Bauschinger effect

Kirsch in 1898 was the first to calculate the stress concentration factor of 3.0 for a cylindrical hole in an infinite plate. The Englishmen Ewing and Humfrey in 1903 observed so-called slip bands on the surface of rotating-bending specimens. This probably was the first metallurgical description of the fatigue process.



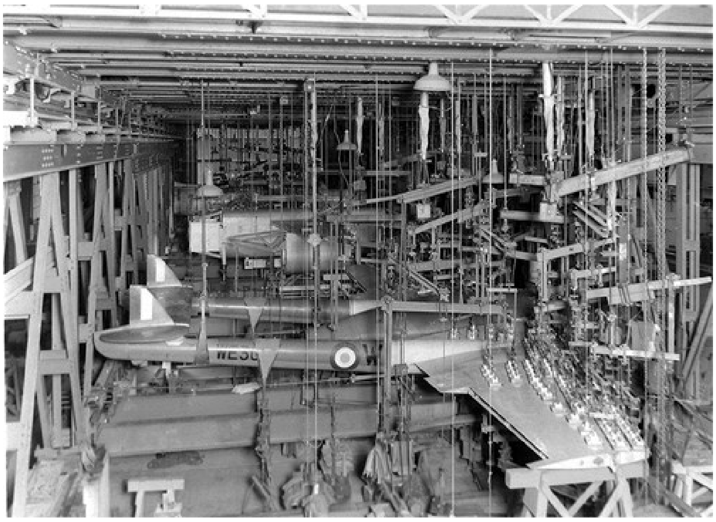
Concentration factor for a cylindrical hole in an infinite plate



Slip bands

1.4 1905 – 1925

The first full-scale fatigue test with a large aircraft component was carried out at the Royal Aircraft Establishment in the U.K. In the literature the notch effect on actual components - as apart from that on specimens - is quoted. The term "notch effect" was probably coined by the German Heyn in 1914, but implicitly it was already discussed by Rankine in 1842 and by all his successors including Wohler. The first experiments to improve the fatigue strength of components probably were carried out in the U.K. during the first World War.



Aircraft full-scale fatigue test

1.5 1920-1945

In this period of time the foundations were laid for almost all the fatigue knowledge we have today. The following topics originated or were investigated:

- the fatigue strength under variable amplitudes;
- the mechanical methods to improve fatigue strength by inducing compressive residual stresses, like cold-rolling, shot-peening and coining;
- the damage accumulation hypotheses for fatigue-life prediction under variable amplitudes;
- the first crack-propagation tests in 1936;
- the foundation of fracture mechanics.

In 1920 Griffith of the Royal Aircraft Establishment, U.K., developed the basis of fracture mechanics. Griffith later became chief engineer of Rolls Royce aircraft engines and also distinguished himself in the development of the gas turbine.

The 1924 book of Gough contains the first account of the influence of surface roughness on the fatigue limit and also the stress-concentration factors.

In 1937 the American Langer stated damage-accumulation hypothesis. Langer already separated the fatigue life into the crack initiation and crack propagation phases and suggested a damage sum of 1.0 for each phase. He also wrote that for the application of his hypothesis crack-propagation *S-N* curves were necessary.

In 1933 Teichmann and Michael stated: "In aircraft service, stress amplitudes are not of identical magnitude as in a laboratory test, but large and small amplitudes occur with different frequencies". In *1929* Batson and Bradley showed a load spectrum for an automobile spring. Kaul in 1938 wrote: "As a measure of the loading of the wing, the acceleration at the centre of gravity, the wing deflection or the strains of highly loaded wing components can be chosen". All three types of measurements were utilized, and Kaul mentioned dynamic overswing, suggested the level-crossing counting method as well as a standard load spectrum and also stated the basic idea of the variable-amplitude test.

Freise measure the strains in the wing spars of two aircraft types of Lufthansa for about 60 flying hrs. Kaul's measurements of 1938 contained the c.g. acceleration spectra for six other aircraft over about 700 hrs. In 1941 combat load spectra for 300 flying hrs were measured.

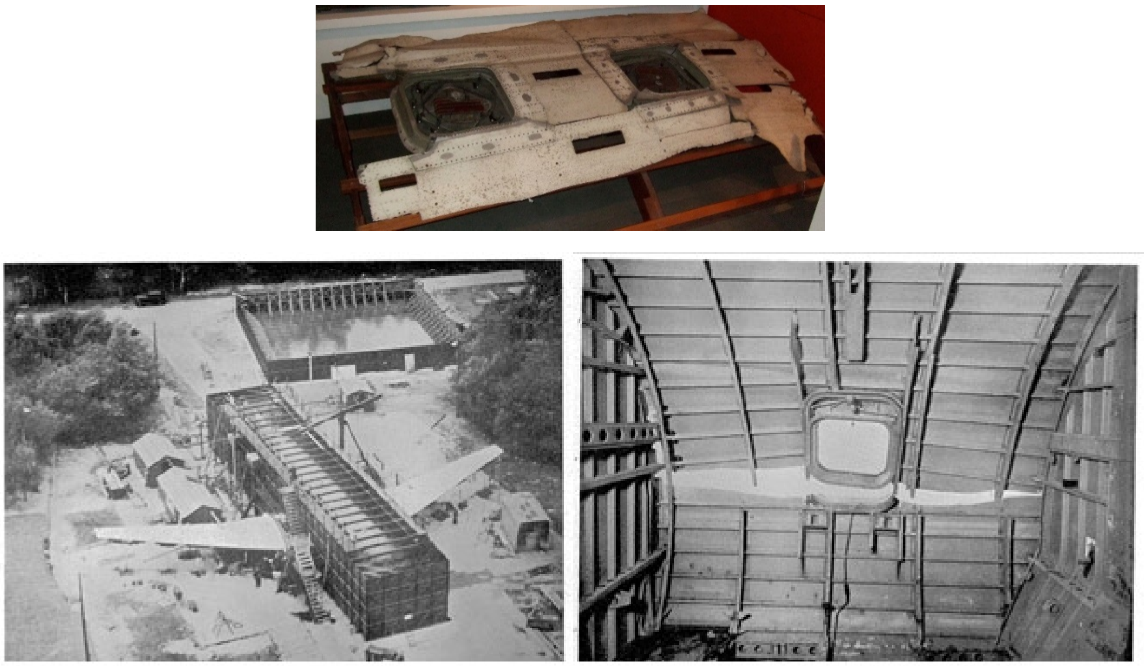
These spectra were the basis for the variable-amplitude fatigue tests of Gassner, who in 1939 described his fundamental ideas in the paper "Fatigue Tests on Aircraft Structures".

Gassner in his Ph.D. Thesis of 13 October 1941 describes his variable-amplitude fatigue test as follows: "The main idea is to apply stress cycles of various amplitudes in steps simulating the mixture of high and low loads in service". Gassner established the topic of operational fatigue strength which can be described as follows: dimensioning (sizing) of a component for finite, but sufficient fatigue life under variable loads. This is accomplished by:

- measuring the service stresses in the form of a stress spectrum employing the correct counting method, also counting the number of cycles per flying hr, km,;
- if at all possible, standardizing the shape of the spectrum, for example, specific spectra for civil aircraft, military aircraft and automobile components, respectively;
- simulating the service spectrum by a blocked variable-amplitude test (program test) and – after this is possible with suitable test machines – by a random fatigue test with the component.

1.6 THE PERIOD OF 1945-1960

The de Havilland "Comet", designed in about 1948, the first commercial jet aircraft of the Western world, had an operating altitude about twice that of contemporary propeller-driven aircraft. Therefore the pressurized fuselage had to support higher stresses. In 1954 two "Comets" crashed, one near Elba, one near Naples, by failure of the fuselage at a window cutout. In a large research and test program, the cause was clarified according to the level of knowledge of the day: the full-scale fatigue test had been carried out.



Comet full scale testing

Because of the "Comet" accidents, complex flight-by-flight tests with the complete aircraft structure, so-called full-scale fatigue tests, became the rule, the pressurized aircraft fuselage in a water tank (later air was used for cyclic pressurization), the wings loaded by servohydraulic cylinders with the ground-to-air cycle and 10-40 gusts of different magnitude per flight. Earlier aircraft had been tested in a much simpler way and often in parts, the wings for example only by the ground-to-air cycle and 10 gusts of equal magnitude per flight.

Beginning in about 1955 a discussion set in about "fail safe" and "safe life". Safe life means that the aircraft component in question has to be replaced on reaching the end of its previously determined life; fail safe means that the failure of a primary member by fatigue or otherwise must not endanger flight safety. Fail safety as a design requirement was, however, probably first employed with the Lockheed "Electra", and the first commercial jet aircraft B-707 and DC8. The large fail-safe test programme with the "Electra" fuselage, which withstood the sudden cutting of a fuselage frame at maximum differential pressure without failure, did not however prevent two fatal crashes of this aircraft due to fatigue fractures of engine mounts, since these were not fail safe. The required calculation procedures were also developed, still without the use of fracture mechanics.

1.7 1960 – PRESENT

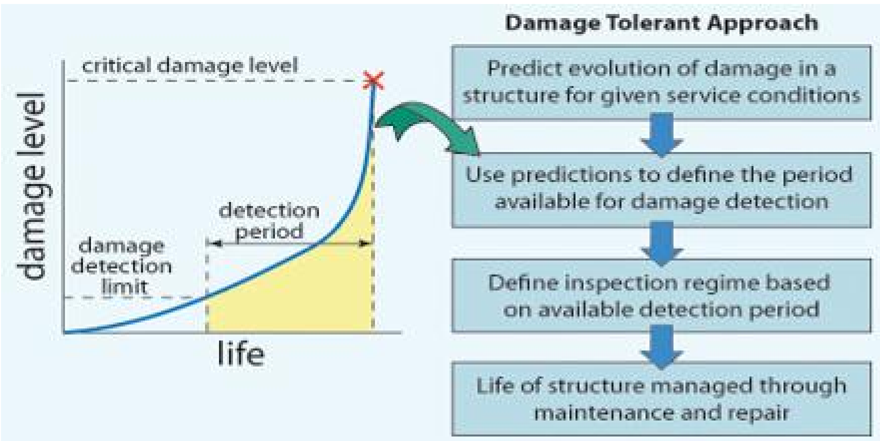
Branger from Switzerland also must be mentioned with regard to fatigue in aircraft structures. He succeeded in carrying out a very complex full-scale fatigue test on the Swiss Airforce de Havilland "Venom" in the early 1960s. Hundreds of different flights were applied to the structure. The result was that the safe fatigue life of this aircraft was five times longer than originally foreseen by the manufacturer. The cost of these complex full-scale fatigue tests of many millions of Swiss francs must surely have repaid itselfi This programme ran for over a decade and influenced full-scale fatigue tests on military aircraft all over the Western world, among them also the IABG tests on German military aircraft.

Paris of Lehigh University, in his Ph.D thesis of 1962 and in a previous paper, established that fatigue-crack propagation could be described by the following equation:

$$\frac{da}{dn} = C \cdot \Delta K^n .$$

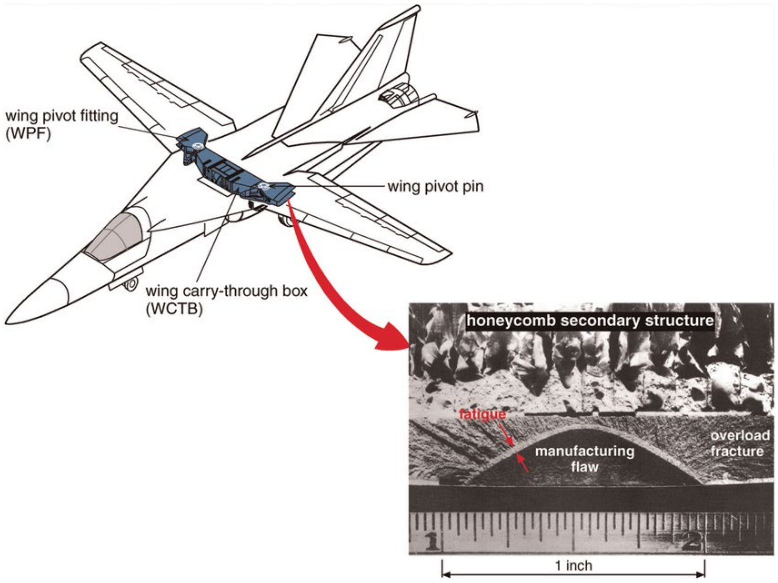
The fundamental contribution to an improved calculation of crack propagation under service-like variable amplitudes was supplied by the German Elber. In his Ph.D. Thesis at the University of New South Wales in 1968 he found out that after a high tensile load the crack closes before the load is reduced to zero. In contrast to many earlier hypotheses, which assumed a decrease of the mean stress after a high tensile load, Elber demonstrated experimentally that the amplitude decreased after such a high load; all promising crack-growth hypotheses since about 1975 are based on Elber's "crack closure".

In 1974 it introduced new structural specifications, the "Damage Tolerance Requirements", in which crack-like defects are assumed to be present from manufacture onwards in all critical points of the structure. These defects can be caused by machining processes during manufacture, or they can be caused by service loads. The aircraft manufacturer has to prove "by test and calculation" that in the cracked condition sufficient life (durability) and static strength ("damage tolerance") are available.



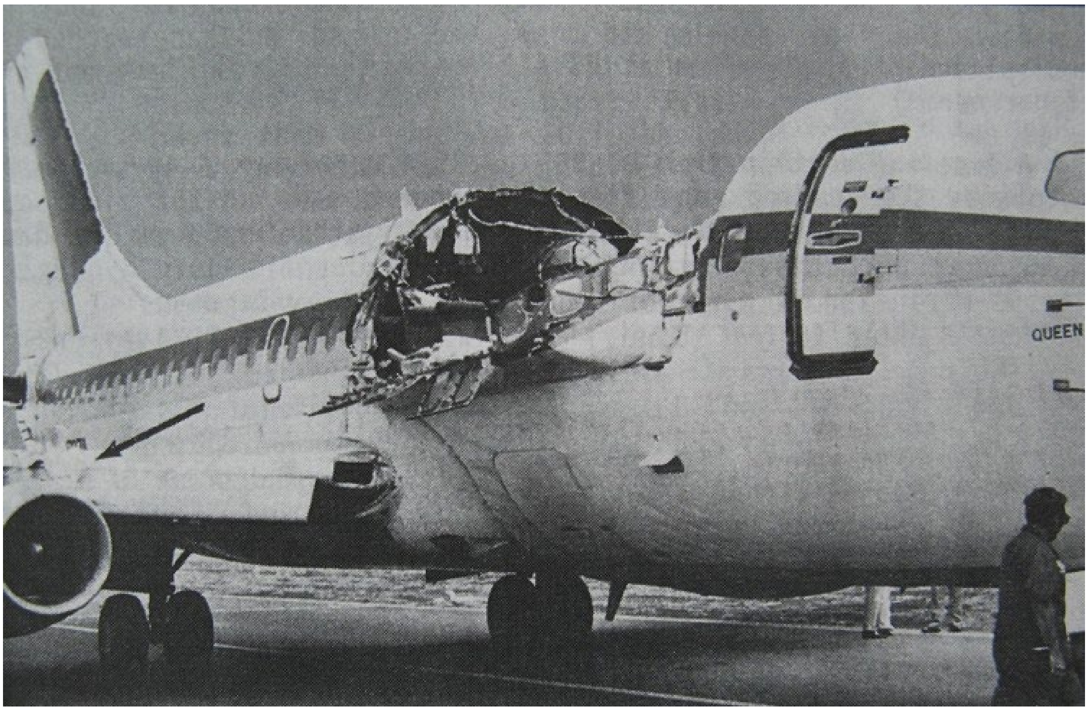
The cause and motivation for this change in the structural specifications was that the USAF even after 1960 did not succeed in obtaining a sufficient durability and structural integrity of its aircraft. Fatal fatigue accidents occurred all too often. The direct reason for the introduction of the new structural specifications was the crash of an

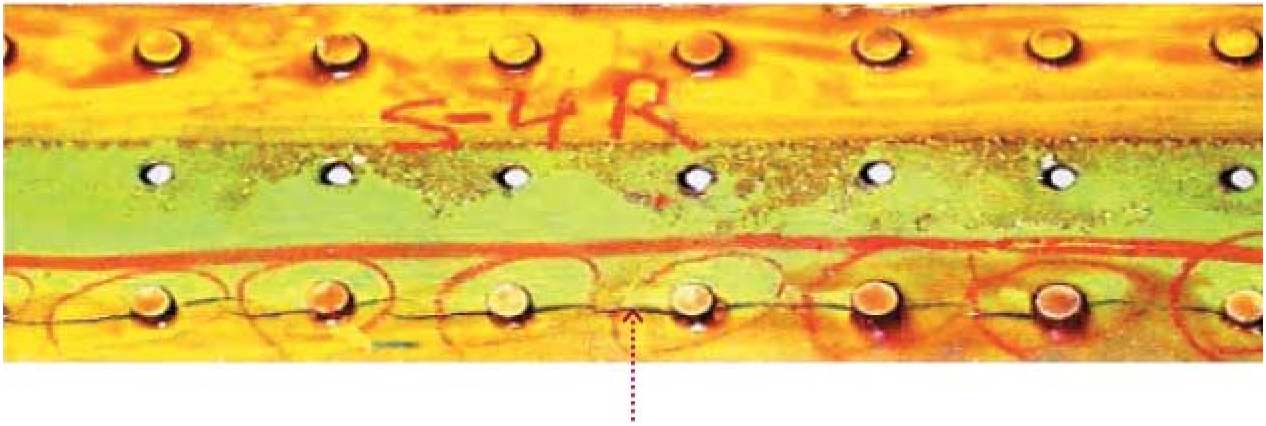
F-111 after only 100 flight hrs owing to a wing failure due to a crack-like defect, which had not been detected during the prescribed inspections. The failed wing box consisted of the ultra-high-strength steel D6AC. In consequence of this accident, a huge theoretical and experimental research programme was started in which almost all US fracture mechanics experts had a part. One finding, for example, was that the fracture toughness K of the D6AC steel was extremely sensitive to minute modifications of the heat treatment.



Crash of an F-111

The "multiple site damage" (MSD) – also called "widespread fatigue damage" (WFD) – in a structure is characterised by the simultaneous presence of fatigue cracks at multiple points that are of sufficient size and density that while individually they may be acceptable, link-up of the cracks could suddenly occur and the structure could fail. The authorities as well as the aircraft manufacturers and the airlines were alerted to MSD only after the nearly fatal accident to the Aloha Airlines Boeing 737 in 1988 [494]. The cause was corrosion and corrosion fatigue, to an unexpected extent, of the old (> 90 000 flights), badly maintained Aloha Airlines aircraft which in addition were employed in a very corrosive environment; also the cold-bonding of the titanium crack stoppers had failed.





Due to this accident, huge investigation efforts, as well as many repair and maintenance programs were undertaken, which for the Boeing 727 and 737 types alone cost more than a billion dollars. MSD also occurred in many other aircraft types, especially on longitudinal fuselage lap splices. Emmerson for example mentions the BAC-111, the DC9, the Airbus A-300, the Boeing 747, the Fokker F-28 and several military aircraft. It is still unclear why MSD did not occur in the full-scale fatigue tests on most of the above aircraft.

A significant feature from 1960 onwards was the introduction of the servohydraulic fatigue test machine, which for the first time permitted the application of arbitrary stress-time histories at sufficiently high frequencies. Strictly speaking, only from that point in time was it possible to check Miner's rule and similar hypotheses –

but also Gassner's blocked-program test. The servo hydraulic test machines at first proved to be extremely unreliable, mainly because of their punched-tape control systems. Only the introduction of digital computers in the 1970s [496] eliminated these deficiencies -- but even today a high-level quality assurance program is necessary to assure the user that the machine actually performs as it should.