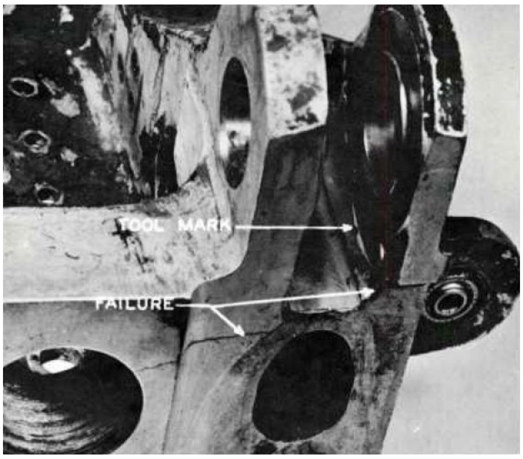
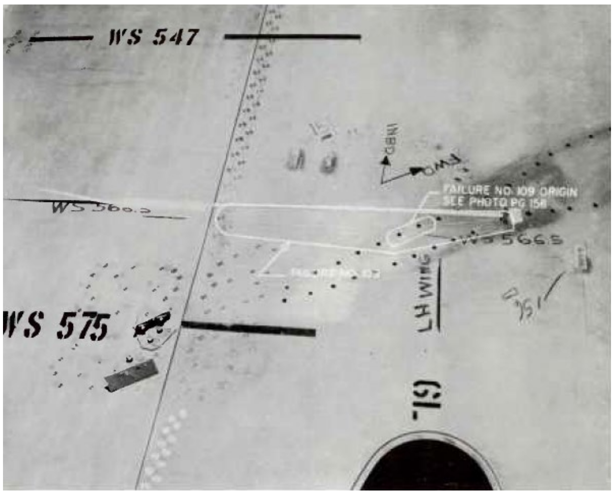
2 FATIGUE IN AVIATION. MAIN THERMS. AVIATION LEGISLATION FOR PROVISION OF AIRCRAFT SERVICE LIFE

2.1 FATIGUE IN AVIATION

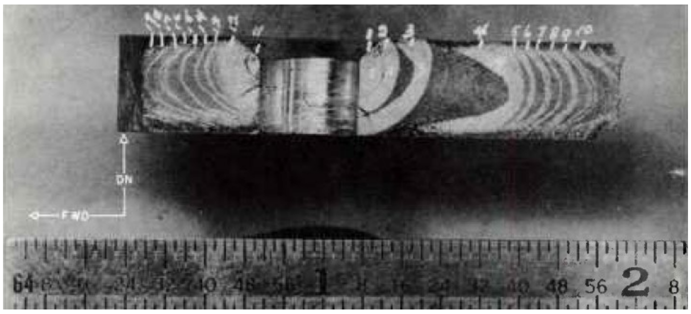
Perhaps nowhere is the prevention of failure by fatigue more important than in the aerospace industry. Here, sources of dynamic stressing are plentiful but design must avoid penalties of overweight.



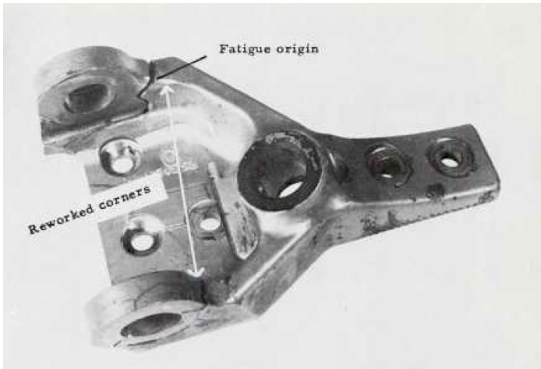
Fatigue failure of wing-fold fitting



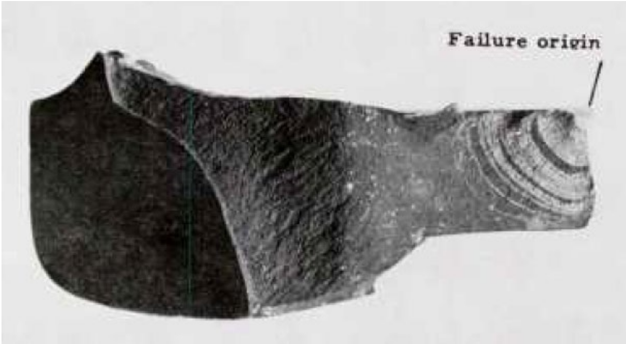
Fatigue failure in wing panel – crack through holes



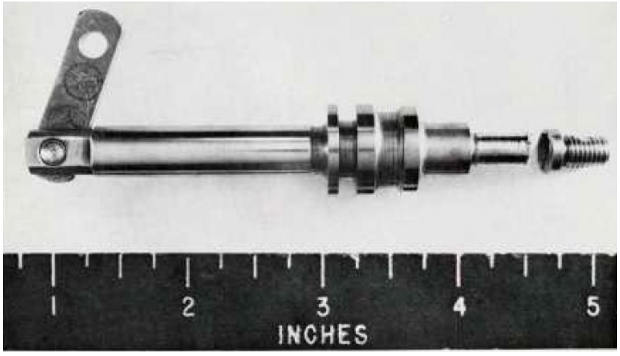
Fracture surface of fatigue failure of wing panel—clear lines of progression of crack at each side of hole.



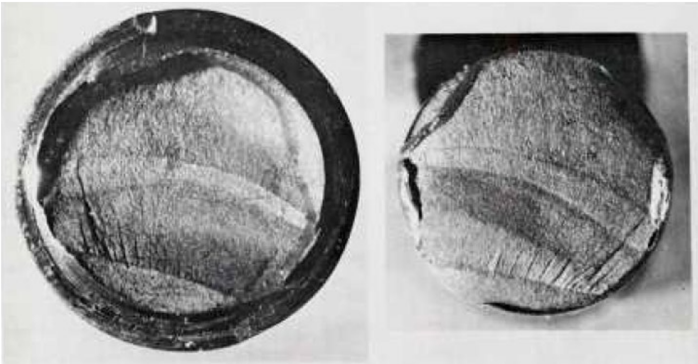
Cracked bracket



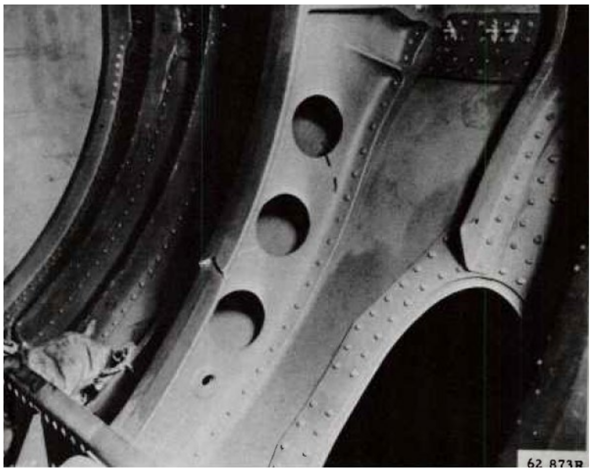
Failed door-cylinder bracket



Break at right

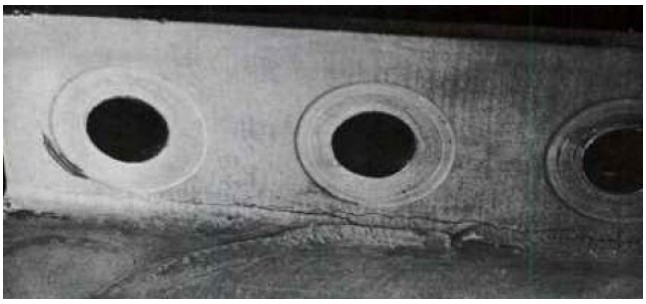


Fracture face – contour marks indicate progressive nature

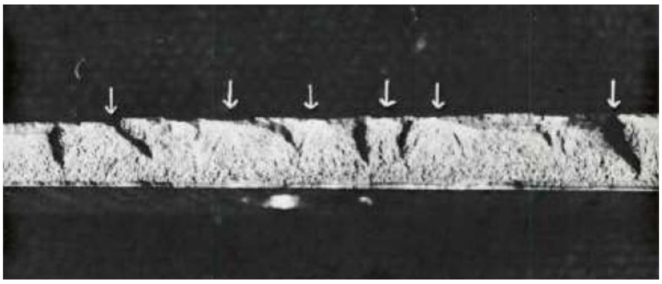


Fatigue failure in a fuselage ring – crack from large hole to stiff flange

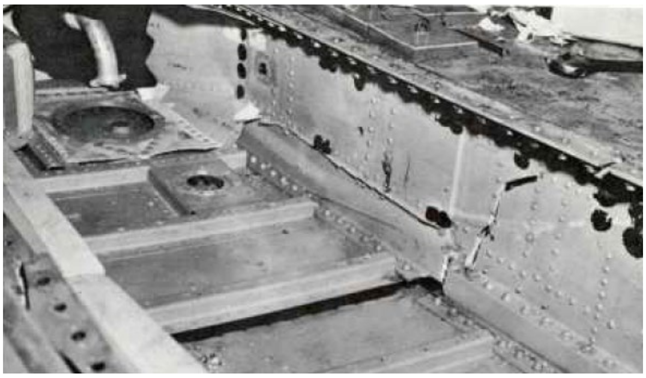
Failed door-cylinder bracket



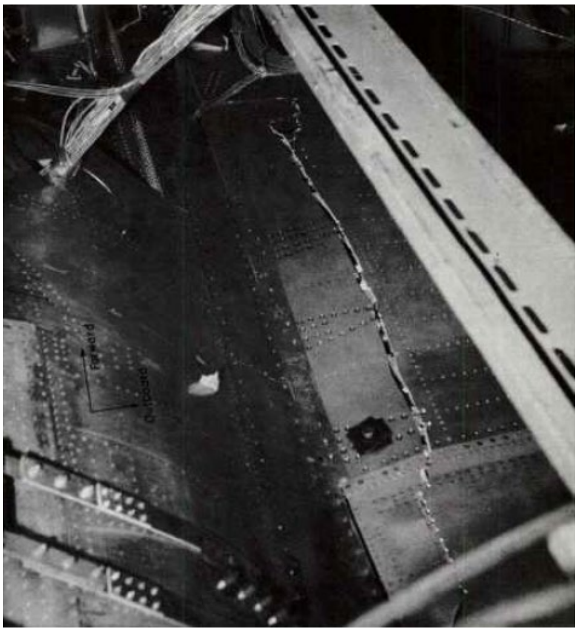
Crack at flange



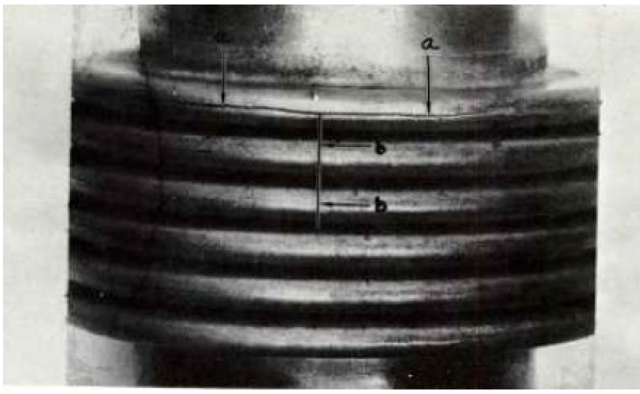
Fracture surface



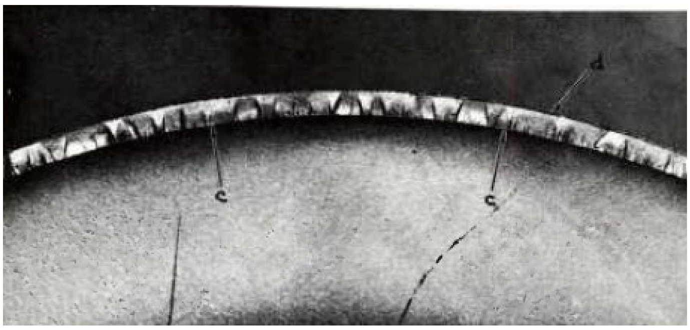
Fatigue failure of wing main spar – growth through areas of stress concentration



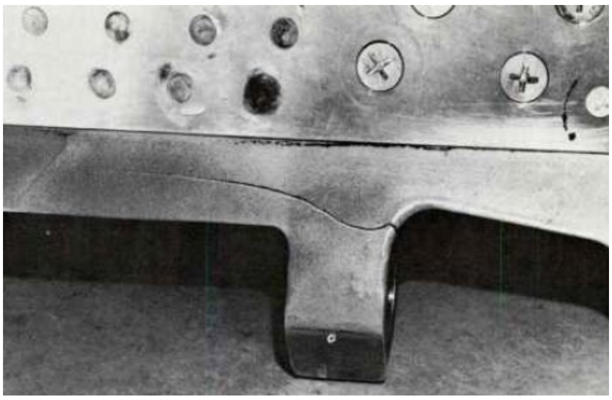
Fatigue failure of lower wing surface after spectrum loading



Crack caused by surface wrinkles and laps



Surface of crack along a-a



Fatigue crack in lug

Figures show examples illustrating a number of points:

1. Fatigue failures have occurred in many parts of aerospace structures.

2. These failures have involved different materials and diverse conditions of loading and of environment.

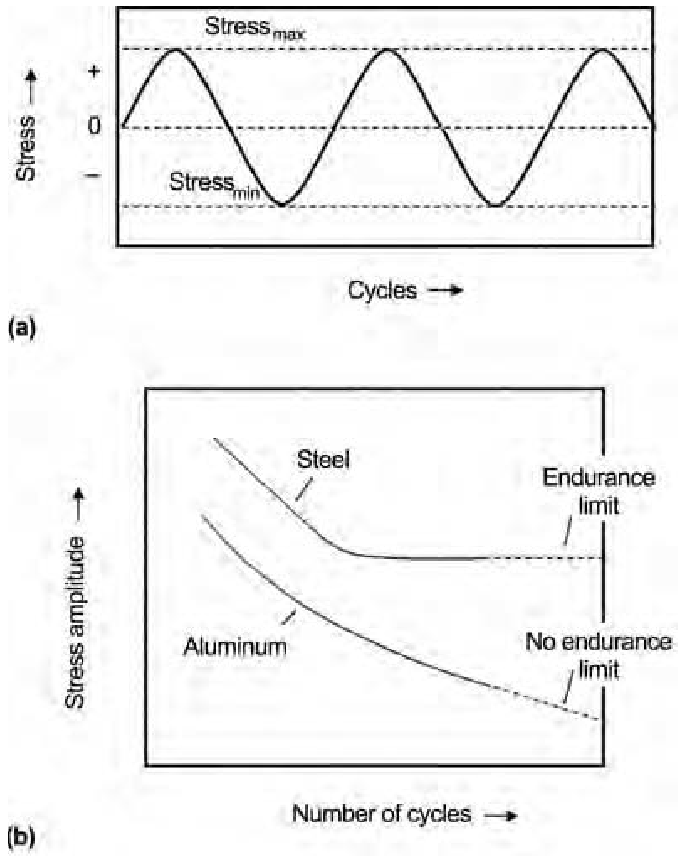
3. The failures usually start at some local stress raiser such as a bolt hole, a fillet, a flange, a rivet, or a tool mark.

4. Cracks tend not only to start at a stress raiser but also to propagate through others.

5. In some instances, fracture surfaces afford clear indications of fatigue crack progression; however, such evidence is not always clear.

The consequences and costs of fractured, cracked, corroded, and malfunctioned equipment are unwanted, dangerous, and expensive.

A simplistic view of the fatigue process is shown in Fig. In this example (Fig. a), the component is first loaded from a zero load (stress) to some maximum positive value, and then the load starts reversing, falling back through zero to a maximum negative value and finally back to zero to complete one cycle. After a number of such cycles, a small crack will initiate, usually on or near the surface at a discontinuity such as a scratch or gouge. As more cycles accumulate, the crack grows until finally the remaining uncracked portion can no longer carry the load, and the component fractures. The fatigue lives of typical steel and aluminum alloys are shown in Fig. (b). If the stress is low enough for this steel alloy, it can be theoretically cycled forever; that is, it has a definite endurance limit. On the other hand, aluminum alloys do not have an endurance limit; if enough cycles are applied at even very low loads, they will eventually fail in fatigue.



The process of fatigue. (a) Cyclic loading. (b) Fatigue life of steel with an endurance limit

Designing of modern aircrafts on the fail-safe concept is a complex scientific and technical challenge that is being addressed through the integration of scientific research of specialists representing the aviation industry and scientific centers.

Sevice life of aircraft is largely determined by the endurance strength of the structural members. In accordance with the standard requirements of the Aviation Rules secure service life is identified by the formula.

$$T = \frac{N}{\eta},$$

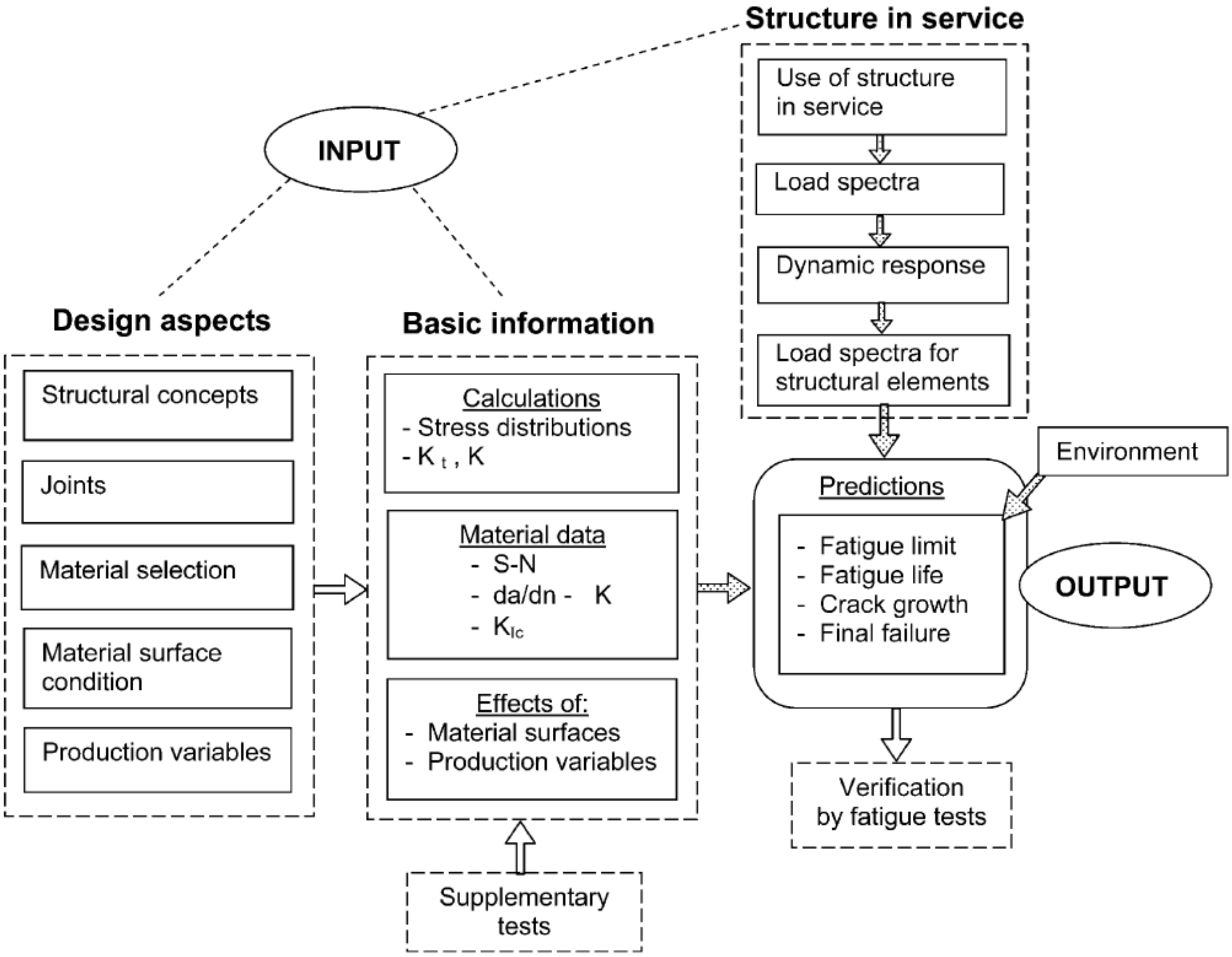
where N is the average durability; η – coefficient of reliability. The value η is selected so that the probability of fatigue failure is virtually zero within a safe (assigned) service life.

A structure should be designed and produced in such a way that undesirable fatigue failures do not occur during the design life of the structure. Apparently there is a challenge which will be referred to as “designing against fatigue”. It will be discussed later that various design options can be adopted to ensure satisfactory fatigue properties with respect to sufficient life, safety and economy. They are related to different structural concepts such as more careful detail design, less fatigue sensitive materials, improved material surface treatments, alternative types of joints, and lower design stress levels. Also, less obvious approaches can be considered, e.g. design for damage tolerance (fail safe), damage prevention (e.g. corrosion protection), alleviation of the dynamic loads in service. The spectrum of possibilities is extensive due to the large number of variables which can affect the fatigue behavior of a structure. Scenarios of designing against fatigue are also influenced by questions about the cost-effectivity of design efforts to improve the fatigue quality of a structure.

People working in the design office of an industry usually adopt standardized calculation procedures for predictions on fatigue strength, fatigue life, crack growth and residual strength. Standardized procedures can be useful, but it must be realized that such procedures may be unconservative or overconservative. Such calculation procedures start from some generalized conditions, which need not be similar to the conditions of the structure in service. It requires understanding, experience and engineering judgement to evaluate the significance of calculated results. The predictions may have a limited accuracy and reliability. In cases of doubt about calculated predictions, it is useful to perform supporting fatigue tests. Some people feel that an experiment is highly superior to theoretical calculations. Statements like “Experiments never lie” are well known. Unfortunately, an experiment gives results applicable to the conditions of the experiment. The question is, are the test conditions a realistic representation of the conditions in service. Also this question asks for understanding, experience and judgement. In other words, whether designing against fatigue is done by analysis, calculations or experiments, it requires a profound knowledge of the fatigue phenomenon in structures and materials and the large variety of conditions that can affect fatigue.

A summary of aspects of fatigue design procedures is given in Figure. The first column contains major topics of the design work. Various aspects of basic information are listed in the second column. This information should be used for selections of materials, material surface treatments and production variables, but also for detail design issues, noteworthy for joints. In order to arrive at an evaluation of the fatigue quality of a structure, predictions have to be made. It then is a prerequisite to have relevant information on the fatigue loads. This includes a number of steps listed in the third column, starting with considerations about how the structure is used in service. This should lead to load spectra and subsequently to stress spectra for the fatigue critical locations in the structure. As also indicated in Figure 1.2, it may be desirable to do supplementary tests on specific issues or verification tests to cover uncertainties of predictions.

A special issue is how to account for environmental effects. Experimental data used in the predictions are generally obtained under laboratory conditions and relatively high testing frequencies. However, in service corrosive environments may be present and the load frequency can be much lower. As an example, think of a welded structure for a drilling platform in the sea. The environment is salt water, and the loading rate of water waves is relatively low.



Survey of the various aspects of fatigue of structures, a multidisciplinary problem setting

2.2 Main Terms

Fatigue – the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point (or points) and that may culminate in cracks or complete fracture after a sufficient number of fluctuations.

Damage tolerance – the ability of aircraft structure to sustain anticipated loads in the presence of fatigue, corrosion or accidental damage until such damage is detected through inspections or malfunctions and repaired.

Safe life is a property of a construction and a way of ensuring its safety in terms of strength, which does not require special control in operation, by establishing the allowed operating time, calculated in the number of flights, landings, flight hours, operation cycles, in calendar duration (years), as well as in other units that can characterize the rate of reduction in strength due to degradation processes (fatigue, corrosion, etc.), during which the construction will not cause damage that reduces strength below an acceptable level.

Operational durability is a general term describing the properties of a construction and methods of ensuring its safety in terms of strength requirements, including damage tolerance and the safety of destruction (damage).

The assigned resource (service life) is the total operating time (the calendar operating time) of the aircraft, in terms of which the operation should be terminated irrespective of its condition. Uninterrupted operation is ensured by the timely extension of the next assigned resources (service lives) up to the decommissioning of the aircraft.

The primary load-carrying structure is a construction that takes up flight and ground loads and loads from overpressure.

The primary structural members are elements of the primary load-carrying structure that take up a significant part of the flight and ground loads and loads from excess pressure; its integrity is essential for maintaining the overall integrity of the aircraft structure.

Particularly crucial structural elements are the primary structural members of the construction that are in single-load condition, single failure (destruction, damage) of which leads to an emergency or catastrophic situation.

Critical points of construction – parts, elements, zones, local places of construction which operational durability determine the safety level in terms of the construction strength as a whole.

One-track loading is realized if the applied loads are ultimately transferred by a single element, the destruction of which leads to a loss of the construction ability to take up the applied loads.

Multi-track loading is realized in such a construction where after the destruction of separate element(-s), the applied loads are safely redistributed between the remaining elements of the structure.

Widespread fatigue damage (WFD) is a fatigue damage of a construction in one or more adjacent parts where numerous cracks of such dimensions and density are present that the residual strength of the structure cannot be maintained further at an acceptable level.

Multiple damage is the condition of the damaged structure leading to the extensive fatigue damage characterized by the simultaneous presence of fatigue cracks in the same structural element (i.e. fatigue cracks, which in case of combining, with or without other damage, will result in reducing the residual strength below the allowed level).

Multi-element damage is the condition of the damaged structure resulting in extensive fatigue damage, characterized by the simultaneous presence of fatigue cracks in adjacent structural elements.

LIMIT OF VALIDITY (LOV) – is the period of time (in flight cycles, flight hours, or both), up to which it has been demonstrated that WFD is unlikely to occur in an airplane's structure by virtue of its inherent design characteristics and any required maintenance actions.

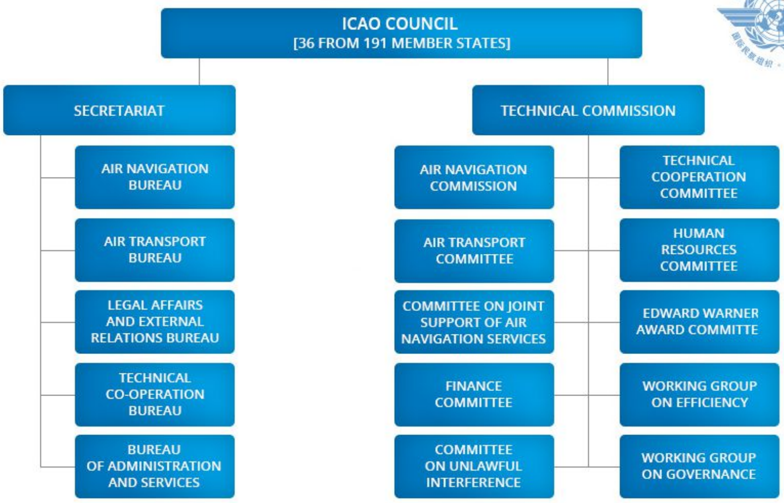
2.3 Aviation Legislation

Aviation is one of the most complex systems of interaction between human being and machines. Being everyday international transport communication it cannot function avoiding common rules and procedures.

Precision in procedures and systems is made possible by the existence of universally accepted standard and regulations.

The International Civil Aviation Organization (ICAO) is a United Nations specialized agency, created in 1944 in Chicago upon the signing of the Convention on International Civil Aviation (Chicago Convention).

International Civil Aviation Organization's sturcture



The Federal Aviation Administration (FAA) is a governmental body of the United States with powers to regulate all aspects of civil aviation in that nation as well as over its surrounding international waters. Its powers include the construction and operation of airports, air traffic management, the certification of personnel and aircraft, and the protection of U.S. assets during the launch or re-entry of commercial space vehicles. Powers over neighboring international waters were delegated to the FAA by authority of the International Civil Aviation Organization.

State regulatory system roles include:

a) aircraft type certification;

b) approval of modifications and repairs;

c) manufacture of aircraft and aviation products under a production approval;

d) registration of aircraft;

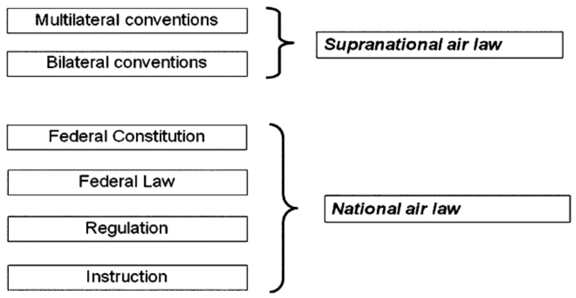
e) airworthiness certifications;

f) continuing airworthiness;

g) approval of aircraft maintenance organizations;

h) certification of operators; and

i) licensing of personnel.



Contracting State
Civil Aviation Authority

Type Certificate No. ____

Pursuant to Civil Aviation Regulations Number ________ of Contracting State, this Type Certificate is issued to:

- Name of Holder of Type Certificate -

- Complete Address of Holder of Type Certificate -

For the following Aeronautical product(s):

-Aircraft Model ___________ -

Details of this type design, basis of certification, operating limitations and other associated airworthiness requirements are specified in:

Civil Aviation Authority Type Certificate Data Sheet ______ or latest revision

Issuing Agency Seal or Logo

Authorized Person – Civil Aviation Authority

Date of Issue

2.4 FATIGUE STRENGTH OF TRANSPORT CATEGORY AIRPLANES IN ACCORDANCE WITH ICAO DOC 9760 – AIRWORTHINESS MANUAL

4.3.4.2 Damage-tolerance assessment

4.3.4.2.1 Damage tolerance characteristics should be based on the best information available, including analysis, test and operational experience and special inspections which can be related to the type. From this information, the site or sites of likely cracking within each structural part or component and the time or number of flights (cycles or hours) at which this might occur may be judged.

4.3.4.2.2 The growth characteristics of damage and the interactive effects on adjacent parts in promoting more rapid or extensive damage should be determined. This study should include those sites which may be subject to the possibility of crack initiation owing to fatigue, corrosion, stress corrosion, wear, disbonding, accidental damage, manufacturing defects or other discrepancies in those areas which service experience or design judgement has shown to be vulnerable.

4.3.4.2.3 The minimum size of damage that it is practical to detect and the proposed method of inspection should be determined together with the number of flights required for the crack to grow from detectable to the allowable final size of damage in such a way that the structure has a residual strength corresponding to the conditions stated for fail-safe qualification.

In determining the proposed method of inspection, consideration should be given to:

a) visual inspection;

b) non-destructive testing; and

c) analysis of data from built-in load and defect monitoring devices.

4.3.4.3 Safe-life structures

The basis for the determination of the safe-life of parts and components should be re-analysed using knowledge gained from service experience, including operational usage, loading assumptions and loading spectra and from any further tests that may have been conducted.

4.3.5 Inspection program

4.3.5.2 An allowable final size of damage should be determined for each site so that the structure has a residual strength for the load conditions, except where probabilistic methods can be used with acceptable confidence. The size of damage that it is practical to detect by the proposed method of inspection should be determined together with the number of flights required for the crack to grow from detectable to the allowable final size.

4.3.5.4 Inspection thresholds for supplemental inspections should be established. These inspections would be supplemental to the normal inspections, including the detailed internal inspections.

4.3.5.5 For structures with reported cracking, corrosion or wear, the threshold and recurrent inspection interval (i.e., initial inspection and periodicity for repeat inspections) should be determined by analysis of the service data and available test data for each individual case as appropriate.

4.3.5.6 For structures with no reported cracking or wear it may be acceptable, if sufficient fleet experience is available, to determine the inspection threshold on the basis of analysis of existing fleet data alone. The inspection threshold and intervals for modern structures are determined as part of a complex and extensive analysis and test verification program.

4.3.6.1 Supplemental inspections

4.3.6.1.1 A supplemental inspection programme should contain the recommendations for the inspection procedures and replacement or modification of parts or components necessary for the continued safe operation of the aeroplane.

4.3.6.1.2 The following points should be addressed in the inspection programme:

a) description of the part or component and any relevant adjacent structure (means of access to the part should also be given);

b) type of damage which is being considered (e.g. fatigue, wear, corrosion, accidental damage);

c) any service experience and service bulletins which may be relevant;

d) the likely site(s) of damage;

e) recommended inspection method and procedure and alternatives;

f) minimum size of damage considered detectable by the method(s) of inspection;

g) guidance to the operator on which inspection findings should be reported to the type design organization;

h) recommended initial inspection threshold;

i) recommended repeat inspection interval;

j) reference to any optional modification or replacement of part or component as terminating action to inspection;

4.3.7 Widespread fatigue damage

4.3.7.1 The likelihood of the occurrence of fatigue damage in an aeroplane's structure increases with aeroplane usage. The design process generally establishes a design service goal (DSG) in terms of flight cycles/hours for the airframe. It is expected that any cracking that occurs on an aeroplane operated up to the DSG will occur in isolation (i.e. local cracking), originating from a single source, such as a random manufacturing flaw (e.g. a mis-drilled fastener hole) or a localised design detail. The supplementary structural inspection programme derived inspections for damage, are intended to find this form of damage before it becomes critical. Therefore, if aircraft are not operated beyond the initial limit of validity of the maintenance programme, it may not be required to perform a widespread fatigue damage (WFD) assessment.

4.3.7.2 With extended usage, uniformly loaded structure may develop cracks in adjacent fastener holes, or in adjacent similar structural details. These cracks, while they may or may not interact, can have an adverse effect on the structural capability before the cracks become detectable. The development of cracks at multiple locations may also result in strong interactions that can affect subsequent crack growth, in which case the predictions for local cracking would no longer apply. An example of this situation may occur at any skin joint where load transfer occurs. Simultaneous cracking at many fasteners along a common rivet line may reduce the residual strength of the joint below required levels before the cracks are detectable under the routine maintenance programme established at time of certification.

4.3.7.3 The type design organization, in conjunction with operators, and in some cases the operators themselves, is expected to initiate development of a maintenance programme with the intent of predicting the onset of WFD and establishing an appropriate limit of validity (LoV) of the maintenance programme for the operation without multiple site damage or multiple element damage. Such programmes should be implemented before analysis, tests, and/or service experience indicates that widespread fatigue damage may develop in the fleet and substantially before LoV is reached on any aeroplane in service.

2.5 Evaluation of the fatigue strength of transport category airplanes in accordance with FAR AIRWORTHINESS STANDARDS. Part 25 (AIRWORTHINESS STANDARDS: TRANSPORT CATEGORY AIRPLANES)

Fatigue Evaluation

(a) ***General.*** An evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, corrosion, manufacturing defects, or accidental damage, will be avoided throughout the operational life of the airplane. This evaluation must be conducted for each part of the structure that could contribute to a catastrophic failure (such as wing, empennage, control surfaces and their systems, the fuselage, engine mounting, landing gear, and their related primary attachments). In addition, the following apply:

(1) Each evaluation required by this section must include

(i) The typical loading spectra, temperatures, and humidities expected in service;

(ii) The identification of principal structural elements and detail design points, the failure of which could cause catastrophic failure of the airplane;

(iii) An analysis, supported by test evidence, of the principal structural elements and detail design points.

(2) The service history of airplanes of similar structural design, taking due account of differences in operating conditions and procedures, may be used in the evaluations required by this section.

(3) Based on the evaluations required by this section, inspections or other procedures must be established, as necessary, to prevent catastrophic failure. The limit of validity of the engineering data that supports the structural maintenance program, stated as a number of total accumulated flight cycles or flight hours or both, established by this section must also be included in the Airworthiness Limitations. Inspection thresholds for the following types of structure must be established based on crack growth analyses and/or tests, assuming the structure contains an initial flaw of the maximum probable size that could exist as a result of manufacturing or service-induced damage:

(i) Single load path structure, and

(ii) Multiple load path “fail-safe” structure and crack arrest “fail-safe” structure, where it cannot be demonstrated that load path failure, partial failure, or crack arrest will be detected and repaired during normal maintenance, inspection, or operation of an airplane prior to failure of the remaining structure.

(b) ***Damage-tolerance evaluation.*** The evaluation must include a determination of the probable locations and modes of damage due to fatigue, corrosion, or accidental damage. Repeated load and static analyses supported by test evidence and (if available) service experience must also be incorporated in the evaluation. Special consideration for widespread fatigue damage must be included where the design is such that this type of damage could occur. An LOV must be established that corresponds to the period of time, stated as a number of total accumulated flight cycles or flight hours or both, during which it is demonstrated that widespread fatigue damage will not occur in the airplane structure. This demonstration must be by full-scale fatigue test evidence. The type certificate may be issued prior to completion of full-scale fatigue testing, provided the Administrator has approved a plan for completing the required tests. In that case, the Airworthiness Limitations section of the Instructions for Continued Airworthiness required by §25.1529 must specify that no airplane may be operated beyond a number of cycles equal to ½ the number of cycles accumulated on the fatigue test article, until such testing is completed. The extent of damage for residual strength evaluation at any time within the operational life of the airplane must be consistent with the initial detectability and subsequent growth under repeated loads. The residual strength evaluation must show that the remaining structure is able to withstand loads (considered as static ultimate loads) corresponding to the following conditions:

(c) ***Fatigue (safe-life) evaluation.*** Compliance with the damage-tolerance requirements of paragraph (b) of this section is not required if the applicant establishes that their application for particular structure is impractical. This structure must be shown by analysis, supported by test evidence, to be able to withstand the repeated loads of variable magnitude expected during its service life without detectable cracks. Appropriate safe-life scatter factors must be applied.

(d) ***Sonic fatigue strength***. It must be shown by analysis, supported by test evidence, or by the service history of airplanes of similar structural design and sonic excitation environment, that—

(1) Sonic fatigue cracks are not probable in any part of the flight structure subject to sonic excitation; or

(2) Catastrophic failure caused by sonic cracks is not probable assuming that the loads prescribed in paragraph (b) of this section are applied to all areas affected by those cracks.

(e) ***Damage-tolerance (discrete source) evaluation.*** The airplane must be capable of successfully completing a flight during which likely structural damage occurs as a result of –

(1) Impact with a 4-pound bird when the velocity of the airplane relative to the bird along the airplane's flight path is equal to V_c at sea level or $0.85V_c$ at 8,000 feet, whichever is more critical;

(2) Uncontained fan blade impact;

(3) Uncontained engine failure; or

(4) Uncontained high energy rotating machinery failure.

The damaged structure must be able to withstand the static loads (considered as ultimate loads) which are reasonably expected to occur on the flight. Dynamic effects on these static loads need not be considered. Corrective action to be taken by the pilot following the incident, such as limiting maneuvers, avoiding turbulence, and reducing speed, must be considered. If significant changes in structural stiffness or geometry, or both, follow from a structural failure or partial failure, the effect on damage tolerance must be further investigated.