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Aircraft Materials and Analysis

Tariq Siddiqui
tariq836@erau.edu

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Tariq Siddiqui

Mc Graw Hill Education

Chapter

1

Aircraft Design

The commercial aviation industry is unlike any other transportation mode. In aviation, we cannot pull off the road and wait for a tow truck whenever we a have problem. We are required by Federal Aviation Administration (FAA) regulations to meet the certification of the aircraft by ensuring that commercial and general aviation aircraft meet the highest safety standards, from their initial design to retirement. This is often not the case with other commercial transport modes. In aviation we have a relationship with gravity that differs considerably from that of any other transportation. We have problems with extremes of temperature (e.g., very hot engines and very cold air at high altitude).

In aviation we have an interactive group of people determined to make aviation a safe, efficient, and pleasurable activity. Aircraft manufacturers, makers of onboard equipment and systems, airline operators, industry trade associations, regulatory authorities, flight crews, and maintenance personnel all work together to ensure aviation safety from the design of the aircraft and its systems, through the development of maintenance programs and modifications, and continuing throughout the lifetime of the aircraft. By working together and providing feedback at all levels and in all directions between and among these factions, the aviation industry is able to provide continually improved systems and services to the public.

The Federal Aviation Administration (FAA) normally provides guidance on the commercial aircraft design approval, supplement-type certificate, and airworthiness certificate. Depending on the aircraft design, both commercial and military, the aircraft manufacturer follow strict guidelines and design approval from FAA. The aircraft manufacturer follow some other guidelines known as Military Standards (Mil-Std), which are discussed later because of their complexity of design, pay loads, and structural integrity.

In the design of an aircraft, there are few things to consider. What is the purpose of this aircraft? What is the aircraft going to do? Is it a commercial transport, military lift, high-wing, center fuselage wing-type aircraft, fighter jet, or an amphibious-type aircraft, aerodynamic of the aircraft, loads, flutter, vibration, and stress? These factors must be considered before an aircraft is designed. Because of recent regulation changes in the environment regarding emissions, noise factors must be considered. Also the safety aspects reflected in the operating limits, aircraft crashworthiness, and stresses placed on the aircraft, and many other safety items, have to be addressed during design and/or the production process.

Military Standard (Mil-Std-1530C) Aircraft Structural Integrity Program

Two documents define the policies, procedures, and responsibilities that ensure the safe operation of the aircraft: Military Standard Mil-Std-1530C, Standard Impalements, Air Force Policy Directive (AFPD) 63-10, Aircraft Structural Integrity, Air Force Instructions (AFI) 63-1001, and Aircraft Structural Integrity Program. They provide direction to government personnel and contractors engaged in the development, production, modification, acquisition, and/or sustainment of military aircraft and rotorcraft.

The standard also describes the Aircraft Structural Integrity Program (ASIP) of the U.S. Air Force (USAF) which defines the requirements to achieve structural integrity of the aircraft by managing cost and schedule risks through a series of disciplined, time-phased tasks. Every aircraft program must address all sections of this standard, including all tasks and elements within each task. The ASIP master plan is required for all programs. Tailoring is only permitted when all the following conditions exist:

1. The overall aircraft reliability (probability of failure) is established and approved by the appropriate Risk Approval Authority as defined in Mil-Std-882, Standard Practice for System Safety.
2. The aircraft structure reliability is defined and supports the overall aircraft reliability requirement.
3. The effect of each tailored ASIP task and/or element and its associated impact on aircraft structure are determined.
4. The combined impact of all tailored ASIP tasks and/or elements on aircraft structural reliability is determined and achieves the allocated overall aircraft reliability requirement.
5. The tailored ASIP tasks and/or elements and the impact of this tailoring on aircraft structural reliability are documented in the ASIP master plan and approved in accordance with AFPD 63-10 and AFI 63-1001.

Military Standard – Mil-Std-1530C (3.1) provides definitions on various baselines, i.e., aircraft structure, certification, service life of the aircraft, corrosion, design service life, design load/environment spectrum, durability, economic life, fail-safe structure, and supportability.

Military Standard – Mil-Std-1530C (4.1) refers to ASIP goals and objectives and defines the effectiveness of military force and its dependability regarding the operational readiness of aircraft and their weapon systems. One major aspect of an aircraft system that affects the operational condition of the aircraft structure—its capacities, condition, and operational limitations—is the need to maintain operational readiness. Potential structural or material problems must be identified early in the life cycle to minimize their impact while the aircraft is in the operational phase. In addition, a preventive maintenance program must be developed and implemented to provide effective and orderly scheduling of inspections as well as replacement or repair of life-limited elements of the aircraft structure.

Military Standard – Mil-Std-1530C (5.1.4.2) refers to criteria that should be established to select aircraft structural critical parts or processes and the control for these critical processes. The impact on flight safety, mission completion, and production and maintenance costs shall be considered in the selection of the critical parts or processes. Figure 1-1 represents critical part/process selection and control.

Military Standard – Mil-Std-1530C (5.2.3) refers to design service loads spectra. The distribution, frequency, and sequence of loading of that aircraft structure will expire based on the design service life and usage.

Military Standard – In Mil-Std-1530C (5.2.14), the design development test is conducted to establish the materials, processes, and joints allowable to verify

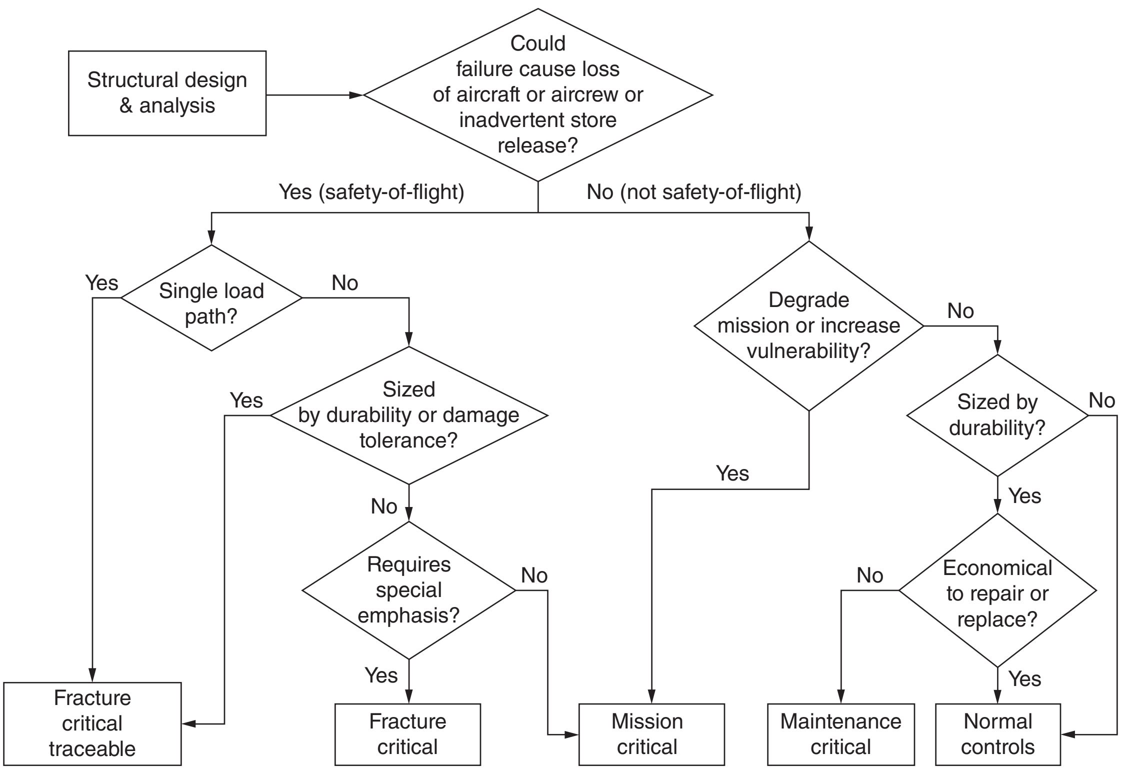

Figure 1-1 Critical part selection flowchart.

analysis methods and procedures; to gather information; and to evaluate allowable stress levels, material selections, the fastener system, and the effect of the design on chemical and thermal environmental spectra. This establishes the design development test of small elements, splices and joints, panels, fittings, control system components, the structural operating mechanism, and major components such as wings, wing pivots, tail, and other assemblies.

Military Standard – (Mil-Std-882E) Standard Practice for System Safety

The Mil-Std-882E standard practice for system safety is an approved standard for use by all military departments and defense agencies with the Department of Defense (DoD). This standard practice of system safety is the key element of system engineering that provides a standard, generic method for identification, classification, and mitigation of hazards. This system safety specified the DoD approach to identifying hazards and assessing and mitigating associated risks encountered in the development, test, production use, and disposal of the defense system's risk acceptance authorities.

This system safety standard practice identifies the DoD approach for identifying hazards and assessing mitigating associated risks encountered in development, test, and production use. This standard's approach for safety standards is to eliminate hazards, where possible, and minimize risks where those hazards cannot be eliminated. Mil-Std-882E clearly addresses mandatory definitions that apply when using this standard. Below is an example of the addressed definitions. Further information can be found on Mil-Std-882E.

Event Risk (3.2.8): The risk associated with a hazard as it applies to a specified hardware/software configuration during an event. Typical events include developmental testing/operational testing (DT/OT), demonstrations, fielding, and postfielding tests.

Hazard (3.2.14): A real or potential condition that could lead to an unplanned event or series of events (i.e., mishap) resulting in death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment.

Life-Cycle (3.2.19): All phases of the system's life including design, research, development, test and evaluation, production, deployment (inventory), operations and support, and disposal.

Military Standard – (Mil-Std-8861B) Airplane Strength and Rigidity Flight Loads

Mil-Std-8861B refers to the requirements for the strength and rigidity for the flight loading conditions applicable to the airplane. The environmental conditions must be considered in the structural design of the aircraft required to operate at low levels and the development of improved gust load criteria for the aircraft.

Gross Weight (3.1.1): The design gross weight for the flight loads and the loading conditions specified in Mil-Std (AS) are all gross weight from the minimum flying gross weight to the maximum design gross weight. The strength shall be provided for all conditions for the parameters specified for the basic flight design gross weight.

Mission symbols for the class of airplane follow:

- A – Attack
- F – Fighter
- O – Observation
- P – Patrol
- R – Reconnaissance
- S – Antisubmarine
- T – Trainer
- U – Utility
- W – Weather

Aerodynamic Configurations (3.1.3): For the flight load conditions of the specifications, all devices such as flaps, slats, slots, cockpit enclosures, landing gears, speed limit devices, and bomb bay doors shall be in their closed, retracted positions.

a. Speed limit devices, including landing gears if used as a speed limitation device, and the bomb bay doors shall be in full open or extended positions as limited by available actuating (operating or holding) force or power, and alternately in all critical intermediate positions.

b. Aerodynamic devices used for maneuvering in flight other than takeoff and landing, such as variable-position aerodynamic surfaces that provide for changes in altitude, attitude, translational motion, roll, or camber, shall be in the maximum open or extended position.

c. For airplanes having variable-geometry surfaces, such as wing sweeping, variable-camber, or variable-position thrust devices, and thrust-directed controls or engine nozzles, these surfaces or devices shall be in all position limits of their scheduled program of travel.

Mil-Std-8861B is a very useful document, and aircraft manufacturers are required to conduct different categories of test while the aircraft is on the ground and in flight to accurately engage in meeting the expected aircraft specification and structural integrity and structural limit loads as described in the Military Standard. The data collected here shall be the deciding factor in what's acceptable for the aircraft's structural design envelope.

The civilian aircraft flight loads are described in CFR Title 14 Part 23, CFR Title 14 Part 25, CFR Title 14 Part 27, and CFR Title 14 Part 29 as described in §23.301, §25.301, §27.301, and §29.301.

a. Strength requirements are specified in terms of limit loads (the maximum loads to be expected in service) and ultimate loads (limit loads multiplied by prescribed factors of safety). Unless otherwise provided, prescribed loads are limit loads.
b. Unless otherwise provided, the specified air, ground, and water loads must be placed in equilibrium with inertia forces, considering each item of mass in the airplane. These loads must be distributed to conservatively approximate or closely represent actual conditions. Methods used to determine load intensities and distribution must be validated by flight load measurement unless the methods used for determining those loading conditions are shown to be reliable.
c. If deflections under load would significantly change the distribution of external or internal loads, this redistribution must be taken into account.

Military Standard – (MIL-A-8870C) Airplane Strength and Rigidity, Vibration, Flutter, and Divergence

Mil-Std-A-8870C addresses the requirement for the airplane rigidity, vibration, flutter, and divergence. The general requirement is described in section 3.1: flutter, buzz, divergence, aeroservoelastic instability, aerothermoelastic instability, or other related static or dynamic aeroelastic instabilities, including sustained limit amplitude instabilities, shall not occur.

Also, the airframe fatigue failures resulting from structural dynamic responses induced by aeroacoustic, mechanical, structural, or other oscillatory loading shall not occur.

Rigidity

Rigidity is a behavior of material under load. It is a resistance of material to deflection that is known as *stiffness*. It also refers to an ensemble of a rigid object connected by any type of hinge or actuator. Rigidity is normally associated with control surfaces and tabs to prevent any aeroelastic instability. To eliminate rigidity, the following criteria must be applied:

a. The adequacy of the control surface or tab bending, torsional, and rotational rigidity about the hinge line and the frequency for both normal and failure operating conditions of the actuating system shall be established together with the maximum allowable changes in inertia properties (from nominal) of the control surface or tab.
b. The maximum allowable inertia properties (such as weight, center-of-gravity location, static unbalance about hinge line, and mass moments of inertia

during service conditions) shall be established and include the effects of changes, structural repair, and painting.

c. The bending, torsional, and rotational rigidity shall include the rigidity of all actuating elements, the rigidity of the structure to which these elements are attached, and the rigidity of the control surface or tab.

d. The actuators shall be located as close as practicable to the control surface or tab and to a hinge to minimize the flexibility caused by connecting elements.

Vibration

Vibration is an aircraft's natural movement during a flight. Vibration is also created by flutter that occurs in two adjacent and connected parts, any uncommanded lifting of flight control, ambient temperatures, the opening of any panel during flight, or the delamination of panel. Vibration is also caused by aircraft propellers if they are not synchronized.

These are some factors that may result in vibration:

a. Propeller noise, including blade passage loads

b. Jet exhaust turbulence noise

c. Thrust reversers

d. Oscillating shocks

e. Fuel slosh

The aircraft actuating system for control surfaces and tabs has preloaded springs that are used to dampen the vibration. The aircraft goes through rigorous vibration testing via structural dynamic flight testing which consists of the following:

1. Aeroelastic stability of flight test
2. Vibration ground and flight test
3. Aeroacoustic ground and flight test

The vibration test flights are performed to demonstrate that the airframe structure and structural components do not experience severe vibration. The flight test data are also used to:

- Verify, and revise if required, the predicted design vibration environment levels.
- Validate analytical design data. Also use analytical, laboratory, and ground test data to substantiate that fatigue failures of the airframe structure and structural components will not occur for the service life of the airplane.

Flutter

Flutter is an aeroservoelastic phenomenon in which unsteady aerodynamic forces combine with structural vibrations to produce a self-feeding oscillation that usually leads to airplane damage. Flutter analysis is done to ensure that the aircraft is safe and free from flutter at all points in the flight envelope. All aircraft must be shown to be free from flutter for flight safety and per civil and military airworthiness requirements.

Mil-Std-A-8870C focuses on flutter for design criteria for the prediction and prevention of panel fluttering. The aerodynamic structural damping coefficient should not be less than 3% for any critical flutter mode for all altitudes and flight speeds. This also focuses on control surfaces and tabs due to sufficient bending, torsional, and rotational rigidity or a combination of these means to prevent flutter of all critical modes under all flight conditions. That may require balance weight in control surfaces and tabs that are to be located so that flutter safety for both the tab and control surface and the main surface is ensured.

Hydraulic dampeners

Hydraulic dampeners are used when mass balance or rigidity criteria are impracticable. Normally two parallel hydraulic dampeners are used for flutter prevention of a control surface, tab, or any other movable component that is exposed to the airstream.

Divergence

Divergence is a static aeroelastic instability of lifting surface that occurs when the structural moment of the surface is exceeded by the applied aerodynamic moment. The elastic rearward flexing of the aircraft airfoil, such as wings or stabilizers, is due to an increase in air pressure on their forward surface. As the wing pushes through the air, it flexes rearward. This effect increases as the air pressure and airspeed are increased. This increased load deflects the structure further, which brings the structure to the limit loads and to failure. The most common type of divergence is the wing torsional divergence.

Divergence analyses are normally performed for the wings, stabilizers, fins, flap leading edges, all movable control surfaces and their actuating systems, and the leading edges of surfaces.

Aircraft structure

An aircraft is a device that is used, or intended to be used, for flight, according to the current Title 14 of the Code of Federal Regulations (14 CFR). The Part 1 definitions and abbreviations categories of aircraft for certification of airmen include the airplane, rotorcraft, glider, lighter-than-air, powered-lift, powered parachute, and weight-shift control. Also14 CFR Part 1 defines an airplane as an engine-driven, fixed-wing aircraft that is supported in flight by the dynamic reaction of air against its wings.

The airplanes are designed for a variety of purposes. Most have the same major components, but the overall characteristics are largely determined by the original design. The aircraft structure normally includes the fuselage, wing, empennage, landing gear, and power plant.

Fuselage

The fuselage is the central body of an airplane and is designed to accommodate the crew, passengers, and cargo. It also provides the structural connection for the wings and tail assembly. The aircraft fuselage normally consists of frames, stringers, splices (frame, stringers, and longitudinal). The fuselage is normally divided into three categories: forward, center, and aft/rear. The older types of aircraft design utilized an open truss structure constructed of wood, steel, or aluminum tubing. The most popular types of fuselage structures used in today's aircraft are the monocoque (French for "single shell") and semimonocoque.

Monocoque. Monocoque construction uses stressed skin to support almost all loads much as an aluminum beverage can does. Although very strong, monocoque construction is not highly tolerant to deformation of the surface. For example, an aluminum beverage can supports considerable forces at the ends of the can, but if the side of the can is deformed slightly while supporting a load, it collapses easily.

Because most twisting and bending stresses are carried by the external skin rather than by an open framework, the need for internal bracing was eliminated or reduced, saving weight and maximizing space. One of the notable and innovative methods for using monocoque construction was employed by Jack Northrop. In 1918, he devised a new way to construct a monocoque fuselage used for the Lockheed S-1 Racer. The technique utilized two molded plywood half-shells that were glued together around wooden hoops or stringers. To construct the half-shells, rather than gluing many strips of plywood over a form, three large sets of spruce strips were soaked with glue and laid in a semicircular concrete mold that looked like a bathtub. Then, under a tightly clamped lid, a rubber balloon was inflated in the cavity to press the plywood against the mold. Some 24 h later, the smooth half-shell was ready to be joined to another to create the fuselage. The two halves were each less than 0.25 in thick. Although employed in the early aviation period, monocoque construction would not reemerge for several decades because of the complexities involved. Every day examples of monocoque construction can be found in automobile manufacturing where the unibody is considered standard.

Semimonocoque. Semimonocoque construction, partial or one-half, uses a substructure to which the airplane's skin is attached. The substructure, which consists of bulkheads and/or formers of various sizes and stringers, reinforces the stressed skin by taking some of the bending stress from the fuselage. The main section of the fuselage also includes wing attachment points and a firewall. On single-engine airplanes, the engine is usually attached to the front of the fuselage. There is a fireproof partition between the rear of the engine and the flight deck or cabin to protect the pilot and passengers from accidental engine fires. This partition is called a firewall and is usually made of heat-resistant material such as stainless steel. However, a new emerging process of construction uses the integration of composites or aircraft made entirely of composites.

Wings

The wings are airfoils attached to each side of the fuselage and are the main lifting surfaces that support the airplane in flight. There are numerous wing designs, sizes, and shapes used by the various manufacturers. Each fulfills a certain need with respect to the expected performance for the particular airplane. Wings may be attached at the top, middle, or lower portion of the fuselage. These designs are referred to as high-, mid-, and low-wing, respectively. The number of wings can also vary. Airplanes with a single set of wings are referred to as monoplanes, while those with two sets are called biplanes.

Many high-wing airplanes have external braces, or wing struts, which transmit the flight and landing loads through the struts to the main fuselage structure. Since the wing struts are usually attached approximately halfway out on the wing, this type of wing structure is called semicantilever. A few high-wing and most low-wing airplanes have a full cantilever wing designed to carry the loads without external struts. The principal structural parts of the wing are the spars, ribs, and stringers. The aircraft wing structures are divided into different sections to better understand the construction and maintenance issues. These divisions are center wing, left wing, and right wing.

The center wing of the aircraft is located below the fuselage for the midwing type of aircraft and also refers to as wing box where the left and right wing extend. The left and right wings also have other associated structures that are part of the aircraft such as engine pylons, spoilers, ailerons, flaps, slats, and main landing gears. The newer types of aircraft have wing tips that are bolted to wings for aircraft flight performance and fuel efficiency.

Empennage

The empennage includes the entire tail group and consists of fixed surfaces such as the vertical stabilizer and the horizontal stabilizer. The movable surfaces include the rudder, the elevator, and one or more trim tabs. The rudder is attached to the back of the vertical stabilizer. During flight, it is used to move the airplane's nose left and right. The elevator, which is attached to the back of the horizontal stabilizer, is used to move the nose of the airplane up and down during flight. Trim tabs are small, movable portions of the trailing edge of the control surface. These movable trim tabs, which are controlled from the flight deck, reduce control pressures. Trim tabs may be installed on the ailerons, the rudder, and/or the elevator.

A second type of empennage design does not require an elevator. Instead, it incorporates a one-piece horizontal stabilizer that pivots from a central hinge point. This type of design is called a *stabilator*, and it is moved using the control wheel, just as the elevator is moved. For example, when a pilot pulls back on the control wheel, the stabilator pivots so the trailing edge moves up. This increases the aerodynamic tail load and causes the nose of the airplane to move up. Stabilators have an antiservo tab extending across their trailing edge. The antiservo tab moves in the same direction as the trailing edge of the stabilator and helps make the stabilator less sensitive. The antiservo tab also functions as a trim tab to relieve control pressures and helps maintain the stabilator in the desired position.

Landing gear

The landing gear is the principal support of the airplane when parked, taxiing, taking off, or landing. The most common type of landing gear consists of wheels, but airplanes can also be equipped with floats for water operations or skis for landing on snow.

The landing gear consists of three wheels—two main wheels and a third wheel positioned at either the front or rear of the airplane. Landing gear with a rear-mounted wheel is called conventional landing gear. Airplanes with conventional landing gear are sometimes referred to as tail wheel airplanes. When the third wheel is located on the nose, it is called a nosewheel, and the design is referred to as a tricycle gear. A steerable nosewheel or tail wheel permits the airplane to be controlled throughout all operations while on the ground. Most aircraft are steered by moving the rudder pedals, whether nosewheel or tail wheel.

Power plant

An aircraft engine, or power plant, produces thrust to propel an aircraft. Reciprocating engines and turboprop engines work in combination with a propeller to produce thrust. Turbojet and turbofan engines produce thrust by increasing the velocity of air flowing through the engine. All these power plants also drive the various systems that support the operation of an aircraft. They also generate electric power, provide a vacuum source for some flight instruments, and in most single-engine airplanes provide a source of heat for the pilot and passengers.

Reciprocating engine. Reciprocating engines operate on the basic principle of converting chemical energy (fuel) into mechanical energy. This conversion occurs within the cylinders of the engine through the process of combustion. The two primary reciprocating-engine designs are the spark ignition and the compression ignition. The spark ignition reciprocating engine has served as the power plant of choice for many years. Most small aircraft are designed with reciprocating engines. The name is derived from the back-and-forth, or reciprocating, movement of the pistons which produces the mechanical energy necessary to accomplish work.

Propeller. The propeller is a rotating airfoil, subject to induced drag, stalls, and other aerodynamic principles that apply to any airfoil. It provides the necessary thrust to pull, or in some cases push, the aircraft through the air. The engine power is used to rotate the propeller, which in turn generates thrust very similar to the manner in which a wing produces lift. The amount of thrust produced depends on the shape of the airfoil, the angle of attack of the propeller blade, and the revolutions per minute (rpm) of the engine. The propeller itself is twisted so the blade angle changes from hub to tip. The greatest angle of incidence, or the highest pitch, is at the hub while the smallest angle of incidence, or smallest pitch, is at the tip.

Turbine engines. An aircraft turbine engine consists of an air inlet, compressor, combustion chambers, a turbine section, and exhaust. Thrust is produced by increasing the velocity of the air flowing through the engine. Turbine engines are a highly desirable aircraft power plant. They are characterized by smooth operation and a high power-to-weight ratio, and they use readily available jet fuel. Prior to recent advances in material, engine design, and manufacturing processes, the use of turbine engines in small and light production aircraft was cost-prohibitive.

Types of turbine engines. Turbine engines are classified according to the type of compressors they use. There are three types of compressors: centrifugal flow, axial flow, and centrifugal-axial flow. Compression of inlet air is achieved in a centrifugal flow engine by accelerating air outward perpendicular to the longitudinal axis of the machine. The axial flow engine compresses air by a series of rotating and stationary airfoils moving the air parallel to the longitudinal axis. The centrifugal-axial flow design uses both kinds of compressors to achieve the desired compression. There are four types of aircraft turbine engines: turbojet, turboprop, turbofan, and turboshaft.

Structural integrity

The importance of structural integrity to commercial aircraft safety is obvious. The real challenge to commercial aircraft is that they experience much higher flight hours at lower stress level. One hour of low-level flight is equivalent to 80 h at cruise. These lessons learned were shared with all, and manufacturers have been benefiting from the improvements in aircraft safety.

The introduction of the material's fracture-mechanics properties changed the designing of aircraft; bridges, buildings, and pipelines are designed to have adequate strength after sustaining fatigue, corrosion, and damage to an inspectable level. Attention was focused on the rate at which cracks grow, the strength of cracked structures, and the variation of these factors in different materials. It was found that crack growth was a function of loading, and that provided an understanding of the loading cycles that commercial aircraft would normally see in their service time.

The design concepts supported by testing have been achieved through diligent attention to the details of design, manufacturing, and maintenance and through the work to ensure that the fleet of commercial aircraft is flying safely. This system has three major participants for the structural integrity program.

- The manufacturer that designs, builds, and supports the airplane in service
- The airlines that operate, inspect, and maintain the airplanes
- The airworthiness authorities who establish rules and regulations, approve the design, and promote airline maintenance performance

Aircraft Systems

The aircraft systems are very complex and are divided into relationships of the functional/physical groups of the system together with scope and outstanding features. The aircraft systems are normally explained with their subsystem, which normally covers the primary system found on most aircraft. Some of these systems include:

- Engine (power plant)
- Ignition
- Fuel
- Flight controls
- Fire protection
- Electrical
- Pneumatics
- Environmental (air-conditioning)
- Oxygen
- Ice protection (deicing and anti-icing)

Service life of the aircraft

The service life of the aircraft is normally determined by the following:

- Total flight hours (TAT)
- Number of landings, known as cycles (CYC)

The total flight hours are the hours an aircraft has actually flown. Some of the aircraft maintenance work such as replacement of rotatable parts is tied to the hours they must fly and must be removed for overhaul. TAT is also used for the aircraft A-type checks or phase checks. TAT is also used to sign off logbook discrepancies.

The number in landing is calculated as following. Each takeoff and landing count as one cycle. Some of the major components such are aircraft landing gears, engines, and other components are also monitored via aircraft cycles for their intended timely usage.

The actual service life of the aircraft, which determines when an aircraft must be parked and retired from service so that it no longer takes a flight, cannot be measured. That is a generalization. Older aircraft such as the B-52, DC-3, and many others have been flying for decades and are still in service. It all depends on the upkeep and maintenance of the aircraft. When the aircraft is old, the maintenance frequency increases due to life extension which may require a very thorough inspection of the structure and all the components.

The commercial airline operator tends to stay away from keeping older aircraft in the fleet because of upkeep and constant maintenance spending. The older aircraft also consume more fuel and are not as environmentally friendly as the current trend. Also constant maintenance requires spending of money and the aircraft being on the ground. An aircraft on the ground for an airline does not generate any revenue. The commercial aircraft in an airline normally fly 15 to 18 h each day, and because of the pressurization and depressurization the airframe expanding the aircraft fuselage is subject to develop stress and fatigue. The fatigue in an aircraft metal normally generates cracks that will require maintenance and very thorough inspection in case other cracks may have been overlooked.

The airline management must address the decision for upgrading its fleet, due to high fuel prices, aircraft route flying capability, and the aircraft in their fleet showing signs of aging. However, the older aircraft are still in airworthiness condition, and most of the time aircraft is sold to cargo-carrying companies that will purchase these older aircraft and retrofit them with their cargo operation requirements. That allows an extension to the aircraft useful life.

Mil-Std-1530C subsection 3.1 refers to aircraft structure, for the service life of the aircraft, and subsection 3.3 refers to baseline service life. The baseline service life is the period of time (e.g., years, flight cycles, hours, landings) established subsequent to design during which the structure is expected to maintain its structural integrity when flown to the baseline loads/environment spectrum. Subchapters 3.10 and 3.11 also refer to the design service life of the aircraft and the durability of the aircraft. The durability is the ability of the aircraft structure to resist cracking, corrosion, thermal degradation, delamination, wear, and the effects of foreign object damage for a prescribed period of time.

Review Problems

1. Air Force Policy Directive (AFPD) 63-10 and Air Force Instructions (AFI) 63-1001 define the structural integrity program. True False
2. Q2 – Military Standard MILMil-Std-1530A (11) establishes the
   a. Aircraft safety and material program
   b. Aircraft structural integrity program
   c. Aircraft aerodynamic and loads program
3. Critical part selection flowchart is part of
   a. Mil-Std-1530C
   b. Mil-Std-882E
   c. 88Mil-Std-61B
4. The Department of Defense (DoD) approach for identifying hazards and associated risks in development, test, and production are defined in Mil-Std-882E. True False
5. Write these three mission symbols for class of aircraft:
   A = O = W =

6. Rigidity is a behavior of material under load. It is a resistance of material to deflection known as stiffness. True False
7. When two adjacent and connected parts are lifted during flight, it is known as
   a. Vibration
   b. Flutter
   c. Divergence
8. What is the purpose of using hydraulic dampeners?

Endnotes

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Chapter

10

Dynamic Stress, Temperature Stress, and Experimental Methods

Dynamic Loadings; General Conditions

Dynamic loading, as mentioned previously, is defined as any loading during which the parts of the body cannot be considered to be in static equilibrium. It was further pointed out that two kinds of dynamic loading can be distinguished: (1) that in which the body has imposed upon it a particular kind of motion involving known accelerations and (2) impact loading, of which sudden loading may be considered a special case.

Impact and sudden loading

When a force is suddenly applied to an elastic body (such as by a blow), a wave of stress is propagated, which travels through the body with a velocity

$$v = \sqrt{\frac{gE}{\delta}}$$

where E is the modulus of elasticity of the material and δ is the weight of the material per unit volume.

Bursting speed. The stress in rotating disks presupposes elastic conditions; when the elastic limit is exceeded, plastic yielding tends to equalize the stress intensity along a diametral plane. Because of this, the average stress on such a plane is perhaps a better criterion of the margin of safety against bursting than is the maximum stress computed for elastic conditions.

Numerous tests that have been conducted show the material's rupture, which occurs in both solid and pierced disks, computed for the original dimensions, becomes equal to the ultimate tensile strength of the material as determined by a conventional test. On the other hand, some materials fail at values as low as 61.5% of the ultimate strength, and the lowest values have been observed in tests of solid disks. The ratio of failure to the ultimate strength does not appear to be related in any consistent way to the ductility of the material; it seems probable that it depends on the form of the stress-strain diagram. In none of the tests reported did the weakening effect of a central hole prove to be nearly as great as the formulas for elastic stress would seem to indicate.

Bar with free ends. When one end of an unsupported uniform elastic bar is subjected to longitudinal impact from a rigid body moving with velocity v, a wave of compressive stress of intensity is propagated

$$\sigma = \frac{\upsilon}{V} E = \upsilon\sqrt{\frac{\delta E}{g}}$$

The intensity of stress is seen to be independent of the mass of the moving body, but the length of the stressed zone, or volume of material simultaneously subjected to this stress, does depend on the mass of the moving body. If this mass is infinite (or very large compared with that of the bar), the wave of compression is reflected back from the free end of the bar as a wave of tension and returns to the struck end after a period $t_1 = 2L/V$ s, where L is the length of the bar and the period t_1 is the duration of contact between the bar and body. If the impinging body is very large compared with the bar (so that its mass may be considered infinite), the bar, after breaking contact, moves with a velocity $2v$ in the direction of the impact and is free of stress.

Bar with one end fixed. If one end of a bar is fixed, the wave of compressive stress resulting from impact on the free end is reflected back unchanged from the fixed end and combines with advancing waves to produce a maximum stress very nearly equal to

$$\sigma_{\max} = \frac{\upsilon}{V} E\left(1 + \sqrt{\mu + \frac{2}{3}}\right)$$

where, as before, μ denotes the ratio of the mass of the moving body to the mass of the bar. The total time of contact is approximately

$$t_1 = \frac{L}{V}\left[\pi\sqrt{\mu + \frac{1}{2}} - \frac{1}{2}\right] \text{s}$$

Sudden loading. If a dead load is suddenly transferred to the free end of a bar, the other end being fixed, the resulting state of stress is characterized by waves, as in the case of impact. The space-average value of the pull exerted by the bar on the load is not one-half the maximum tension, as is usually assumed, but is somewhat greater than that. Therefore the maximum stress that results from sudden loading is somewhat less than twice that which results from static loading.

Vibration. Vibration is a periodic or oscillatory motion of a mechanical system. Depending on the existence of the external load, vibration of a mechanical system can be free vibration or forced vibration, where in either case the system can be considered damped and undamped.

A very important type of dynamic loading occurs when an elastic body vibrates under the influence of a periodic impulse. This occurs whenever a rotating or reciprocating mass is unbalanced and also under certain conditions of fluid flow. The most serious situation arises when the impulse synchronizes (or nearly synchronizes) with the natural period of vibration, and it is of the utmost importance to guard against this condition of resonance (or near resonance). There is always some resistance to vibration, whether natural or introduced; this is called *damping* and tends to prevent vibrations of excessive amplitude. In the absence of effective damping, the amplitude of near-resonance vibration will greatly exceed the deflection that would be produced by the same force under the static conditions. Obviously, it is necessary to know at least approximately the natural period of vibration of a member in order to guard against resonance.

Remarks on Stress due to Impact

It is improbable that, in any actual case of impact, the stresses can be calculated accurately by any of the methods or formulas. For instance, it is supposedly very nearly precise if the conditions assumed are realized, but those conditions—perfect elasticity of the bar, rigidity of the moving body, and simultaneous contact of the moving body with all points on the end of the rod—are obviously unattainable. On one hand, the damping of the initial stress wave by elastic hysteresis in the bar and the diminution of the intensity of that stress wave by the cushioning effect of the actually nonrigid moving body would serve to make the actual maximum stress less than the theoretical value. On the other hand, uneven contact between the moving body and the bar would tend to make the stress conditions nonuniform across the section and would probably increase the maximum stress.

Temperature Stresses

Whenever the expansion or contraction that would normally result from the heating or cooling of a body is prevented, stresses are developed that are called thermal, or temperature, stresses. It is convenient to distinguish two different sets of circumstances under which thermal stresses occur:

1. The form of the body and the temperature conditions are such that there would be no stresses except for the constraint of external forces; in any such case, the stresses may be found by determining the shape and dimensions

the body would assume if unconstrained and then calculating the stresses produced by forcing it back to its original shape and dimensions.

2. The form of the body and the temperature conditions are such that stresses are produced in the absence of external constraint solely because of the incompatibility of the natural expansions or contractions of the different parts of the body.

Temperature stress in aircraft

The aircraft structural stress and aerodynamic heating have always been a great concern of the aircraft airframe engineers and designers due to increase of the temperature during flight and material expansion. For these purpose high ~~temprature~~ material is used for the airframe construction, so that structure can withstand different ~~temprature~~ and pressure during flight. Also any significance stress associated with the combination of external loading, will present the challenge of inelastic behavior and buckling load. The aircraft leading edges normally constructed from high temperature material since they endure the increased heat loads during flight.

The structural loading conditions of the aircraft require analysis to be performed for the airframe temperature heating and aerodynamic heating. This also includes the heating incidental operation of the power plants and other heat sources of the aircraft within the consistent operational limits. The environmental exposure, conditions, and temperature exposure range of the material used should include the full range of temperature stress and heat sources anticipated during the life span of the aircraft. This establishes the temperature stress, loading condition, and structural load.

Stress due to pressure between elastic bodies

The stresses caused by the pressure between elastic bodies are important in connection with the design or investigation of ball and roller bearings, gears, trunnions, expansion rollers, track stresses, etc., developed the mathematical theory for the surface stresses and deformations produced by pressure between curved bodies, and the results of this analysis are supported by experiment. Formulas based on this theory give the maximum compressive stresses, which occur at the center of the surfaces of contact, but not the maximum shear stresses, which occur in the interiors of the compressed parts, nor the maximum tensile stress, which occurs at the boundary of the contact area and is normal thereto.

Experimental Methods

A structural member may be of such a form or may be loaded in such a way that the direct use of formulas for the calculation of stresses and strain produced in it is ineffective. One then must resort either to numerical techniques such as the finite element method or to experimental methods. Experimental methods can be applied to the actual member in some cases, or to a model thereof. Which choice is made depends upon the results desired, the accuracy needed, the practicality of size, and the cost associated with the experimental method. There has been a tremendous increase in the use of numerical methods over the years, but the use of experimental methods is still very effective. Many investigations make use of both numerical and experimental results to cross-feed information from one to the other for increased accuracy and cost-effectiveness.

Measurement techniques

The determinations of stresses produced under a given loading of a structural system by means of experimental techniques are based on the measurement of deflections. Since strain is directly related to (the rate of change of) deflection, it is common practice to say that the measurements made are those of strain. Stresses are then determined implicitly using the stress-strain relations. Deflections in a structural system can be measured through changes in resistance, capacitance, or inductance of electrical elements; optical effects of interference, diffraction, or refraction; or thermal emissions. Measurement is comparatively easy when the stress is fairly uniform over a considerable length of the part in question, but becomes more difficult when the stress is localized or varies greatly with position. Short gauge lengths and great precision require stable gauge elements and stable electronic amplification if used. If dynamic strains are to be measured, a suitable high-frequency response is also necessary.

On a free surface under a general state of plane stress, three measured normal strains in different directions will allow the determination of the stresses in directions at that position. At a free edge in a member that is thin perpendicular to the free edge, the state of stress is uniaxial and, as stated earlier, can be determined from one normal strain tangent to the edge.

Mechanical measurement

A direct measurement of strain can be made with an Invar tape over a gauge length of several meters or with a pair of dividers over a reasonable fraction of a meter. For shorter gauge lengths, mechanical amplification can be used, but friction is a problem and vibration can make them difficult to mount and to read. Optical magnification using mirrors still requires mechanical levers or rollers and is an improvement but still not satisfactory for most applications.

A scratch gauge uses scratches on a polished target to determine strain amplitudes, and while the scratches are in general not strictly related to time, they are usually related to events in such a way as to be extremely useful in measuring some dynamic events. The scratched target is viewed with a microscope to obtain peak-to-peak strains per event, and a zero strain line can also be scratched on the target if desired

Brittle coatings

Surface coatings formulated to crack at strain levels well within the elastic limit of most structural materials provide a means of locating points of maximum strain and the directions of principal strains. Under well-controlled environmental conditions and with suitable calibration, such coatings can yield quantitative results. However, it is not universally applicable, since the coatings may not be readily available due to environmental problems with the coating materials.

Electrical strain and displacement gauges

The evolution of electrical gauges has led to a variety of configurations where changes in resistance, capacitance, or inductance can be related to strain and displacement with proper instrumentation.

Resistance strain gauge For the electrical resistance strain gauges, the gauge lengths vary from less than 0.01 in to several inches. The gauge grid material can be metallic or a semiconductor. The gauges can be obtained in alloys that are designed to provide minimum output due to temperature strains alone and comparatively large outputs due to stress-induced strains.

Capacitance strain gauge Capacitance strain gauges are larger and more massive than bonded electric resistance strain gauges and are more widely used for applications beyond the upper temperature limits of the bonded resistance strain gauges.

Inductance strain gauges The change in air gap in a magnetic circuit can create a large change in inductance depending upon the design of the rest of the magnetic circuit. The large change in inductance is accompanied by a large change in force across the gap, and so the very sensitive inductance strain gauges can be used only on more massive structures. They have been used as overload indicators on presses with no electronic amplification necessary. The linear relationship between core motion and output voltage of a linear differential transformer makes possible accurate measurement of displacements over a wide range of gauge lengths and under a wide variety of conditions.

X-ray diffraction

X-ray diffraction makes possible the determination of changes in interatomic distance and thus the measurement of elastic strain. The method has the particular advantages that it can be used at points of high stress concentration and to determine residual stresses without cutting the object of investigation.

Stress Pattern Analysis by Thermal Emission

This technique uses computer enhancement of infrared detection of very small temperature changes to produce digital output related to stress at a point on the surface of a structure, a stress graph along a line on the surface, or a full-field isopach stress map of the surface. Under cyclic loading, at a frequency high enough to ensure that any heat transfer due to stress gradients is insignificant, the thermoelastic effect produces a temperature change proportional to the change in the sum of the principal stresses. Although calibration corrections must be made for use at widely differing ambient temperatures, the technique works over a wide range of temperatures and on a variety of structural materials including metals, wood, concrete, and plain and reinforced plastics.

Review Problems

1. When a force is suddenly applied to an elastic body (such as by a blow), a wave of stress is propagated, known as impact and sudden loading. True False
2. Bursting speed is the stress in rotating disks that presupposes elastic conditions. True False
3. Vibration is a periodic or oscillatory motion of a mechanical system? True False
4. Temperature stresses result from the heating or cooling of a body. True False
5. This has always been a great concern of the aircraft airframe engineers and designers.
   a. Temperature stress in aircraft
   b. Buckling of aircraft metals
   c. Pressurization of aircraft

Endnotes

Budynas, Richard G., *Advanced Strength and Applied Stress Analysis,* 2d ed., McGraw-Hill, New York, 1999.

Young, Warren C., Richard G. Budynas, and Ali Sadegh, *Roark's Formulas for Stress and Strain,* 8th ed., McGraw-Hill, New York, 1999.