Aerobasics – An Introduction to Aeronautics

13. The Airplane Structure

S P Govinda Raju

The structure of an airplane holds it together in flight without significant deformation due to flight loads. It contributes to about a quarter of the airplane take-off weight. Any reduction in structure weight results in an equal increase in disposable load (fuel or payload) and thus contributes significantly to improved performance or economy. Thus great pains are taken by the designers to make an airplane structure as light as possible consistent with strength and stiffness. This structure is primarily of semi-monocoque design. This implies that it is designed as a hollow stiffened shell in which the skin contributes a major share to its strength and stiffness. In this article, we describe the general principles of design of this type of structure. We indicate the nature of flight loads the structure has to resist and the design concepts which ensure that the structure is safe during the life of an airplane.

S P Govinda Raju retired as professor from the Department of Aerospace Engineering, Indian Institute of Science in 2003. He is currently active as a consultant in wind tunnel testing and teaches short term courses in aerodynamics and flight mechanics.

Previous parts:
Resonance, Vol.13: p.836, p.971, p.1009, p.1107; Vol.14: p.19, p.191. p.272, p.328, p.650, p.916, p.1071; Vol15: p.64.

Keywords
Semi-monocoque structure, structural materials, flight loads, gust loads, maneuver loads, structural safety, structural fatigue, strength calculations.

1. Introduction

The structure of an airplane defines its outside shape and holds it together in flight and on the ground without significant deformation. The structure is subjected to various loads due to a combination of aerodynamic, inertia and gravity forces as well as ground reaction when in contact with the ground. Thus, the parts of the structure must be strong enough to withstand these forces without failure over the life of the airplane which could be of the order of thirty years. To satisfy this requirement, light, strong and durable materials are necessary. In the early days of aeronautics, wood and fabric were used extensively. These materials are surprisingly light and strong and were the best available at that time. However, these materials deteriorate rapidly when exposed and are thus not preferred. Use was made of steel tubular structures for internal support of airplanes for some time until aluminum alloys of great strength and durability were developed. They continue to form the primary materials of airplane construction to this day. However their position is currently challenged by various composite materials like carbon fiber reinforced plastics (CFRP) which offer advantages of higher strength and stiffness, lower density and easier methods of fabrication. We shall first consider structures suitable for the aluminum alloys which can be easily rolled into large sheets. This type of structure is called semi-monocoque and is particularly well suited for airplanes.

2. The Semi-Monocoque Structure

The external surface of an airplane needs to be completely covered by the structure. An obvious way of doing this is by a thin sheet so that the structure is of the form of a thin shell. This shell structure must however be strong enough to resist without much deformation the forces that act on the airplane in flight and on the ground. An airplane in flight is subjected to various forces some of which act normal to the airplane surface. The shell considered above cannot resist them well and to solve this problem, a type of construction called the semi-monocoque is used. The logic of this type of construction using a thin sheet rolled into a tube (not necessarily circular or uniform in cross-section) is explained below.

Any sheet is strong in its own plane and resists well any planar forces – tension, compression or shear. However, forces acting on the sheet in its normal direction induce bending of the sheet and it cannot resist these well.

Figure 1 illustrates a uniform tube of rectangular section subjected to a transverse load. It is easily seen using elementary beam theory that the stresses in the walls of the tube are planar tension and compression as illustrated in the figure. While planar tensile stresses are well resisted by the sheet forming the walls of the tube, compressive stresses are not resisted well. This is due to structural instability (buckling) of a thin unsupported sheet in compression at a relatively small compressive stress as in *Figure* 2. This instability can be prevented by stiffening the tube walls by stiffeners as in *Figure* 3. The stiffeners which are typically of Z section are easily fabricated from sheets by cutting and bending and can be attached to the tube walls by rivets. Thus we arrive at the stiffened tube as a primary structural member of a light weight structure. The airplane fuselage, wings, horizontal and vertical stabilizers are basically stiffened tubes but with addition of ribs as explained below.

The way of applying forces at any section of the tube is important. A transverse force at any section of the tube as in *Figure* 1 cannot be directly applied on the tube as this will induce large local bending stresses. If the same force is applied by introducing a rib as in *Figure* 4, it is seen that the force is transferred to the tube as a distributed shear all around the periphery of the tube. Further, the transverse force is well restricted by the rib itself because the force is acting in its own plane. Thus a stiffened tube with ribs introduced forms a basic structural unit capable of resisting structural loads very effectively. A structure constructed using such units is said to be of semi-monocoque construction. Aircraft structures make extensive use of this concept. In fuselage construction, the rib as used in a wing is replaced by a frame or ring which serves a similar purpose. *Figure* 5 shows a panel of an airplane fuselage. The basic sheet which is stiffened by longitudinal stiffeners and transverse rings is clearly shown in the figure.

A tube stiffened by longitudinal stiffeners and provided with ribs for application of lateral loads is a key element of semi-monocoque type of construction.

An airplane is a large structure and can only be fabricated by assembling many parts. Joints weaken the structure and need to be carefully designed to reduce this effect. Riveting has been the traditional solution for this. In conventional construction, riveting has been

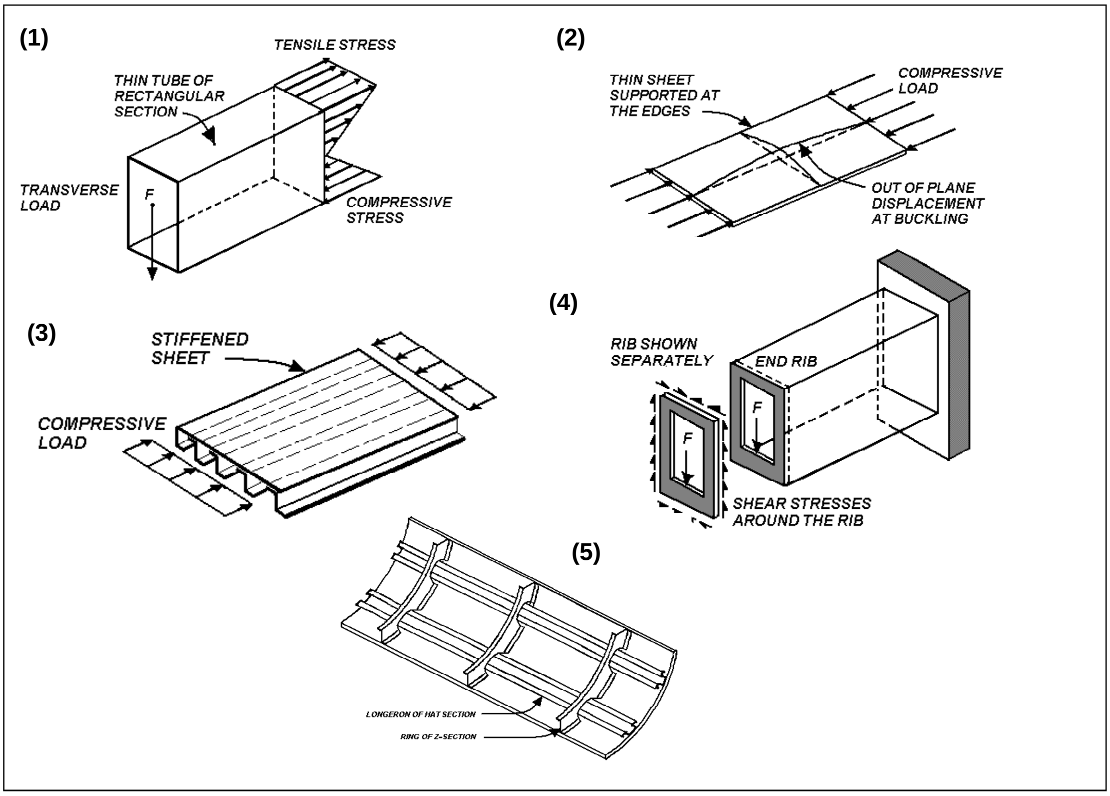

Figure 1. A tube with a transverse load: When a thin walled tube is subjected to a transverse load, it induces direct stresses in the walls as indicated. The top wall experiences a tensile stress in its own plane and the bottom wall experiences a similar compressive stress.

Figures 2 and 3. Buckling of a thin sheet: When a thin sheet constrained only at the edges is subjected to a compressive load, it develops a lateral displacement at a relatively small load. It cannot sustain the full load corresponding to the yield stress of the material of the sheet. Stiffening the sheet by longitudinal stiffeners prevents buckling and the full strength of the sheet in compression can be realized.

Figure 4. Application of a lateral load on a tube: Any lateral load directly applied on a tube will deform its cross-section and cause premature failure. Application of the lateral load using a rib ensures that the load is distributed as a shear around the tube. This shear is in the plane of the tube walls and also in the plane of the rib. Thus the tube and the rib both resist the stresses due to the lateral load well.

Figure 5. A part of an airplane fuselage: The fuselage of an airplane is typically a thin sheet stiffened in the longitudinal direction by stiffeners and supported internally by rings. The rings distribute the lateral loads while the stiffeners are helpful in preventing buckling.

used for connecting various structural elements like stiffeners and ribs to wing panels. Bonded joints have also been used for this purpose with some enhancement of structural efficiency. More recently, there is a tendency to reduce the number of joints by making structural panels with integral stiffeners. Extensive use is made of computer controlled machining for fabricating these parts. This permits the use of variable skin thickness over the structural elements matching the requirements of strength optimally and this helps in further reducing the structure weight.

3. Structural Materials

Desirable properties of materials suitable for airplane structures are those that ensure minimum structure weight consistent with strength and stiffness. These properties are adequately represented by the density d, the yield strength σ_{y}, the ultimate strength σ_{u}, the modulus of elasticity E (which is an indication of structural stiffness) and the elongation, e. *Table* 1 compares some structural materials based on these parameters. Other properties like fatigue strength, corrosion resistance, ease of fabrication and repair, etc., need to be considered in a full assessment of any material.

A study of the table indicates that among metallic materials, aluminum alloys with a relatively low density of 2.8 have a better strength-weight ratio compared to steel and titanium alloys. It is also seen that all metallic materials have practically the same ratio of modulus of elasticity to density, E/d and thus are about equal from the point of view of structural stiffness. Thus aluminum alloys are generally superior for the airplane structure. However, aluminum structures lose strength at temperatures above 100 °C and are not suitable for flight at Mach numbers above 2.2

Unlike general engineering structures which are designed to minimise cost, airframe structures are designed to minimise weight consistent with strength and stiffness.

A new class of structural materials based on thin fibers

Material	Density d (Mg/m^3)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)	Modulus of elasticity E (GPa)	E/d
Spruce wood	0.45		35–110		14	22
Aluminum alloy(2024-T3)	2.8	250	410	12	72	26
Steel (4140)	7.8	420	630	10	210	27
Titanium	4.5	500	800		110	24
Magnesium alloy	1.8	200	300		45	25
Glass fiber	2.5		2400–4400	3–5	70–80	30
GFRP sheet (UD)*	1.9		1190		39	20
Carbon fiber	1.8		2500–3500		250–350	160
CFRP sheet (UD)*	1.6		2040		130	80
Aramid fiber (Kevlar)	1.4		2750		80–120	70
Kevlar FRP sheet (UD)*	1.4		1400		75	55
Epoxy resin	1.15–1.25		50	1.25	3.7	3

* unidirectional reinforcement

Table 1. Typical properties of structural materials.

of glass, carbon or aramid polymer (better known by the trade name Kevlar) has emerged recently. Structures are fabricated using these fibers by embedding them in a polymer matrix (typically an epoxy resin). A typical structural element is prepared in these materials by laying the woven fibers (which resemble a cloth) coated with a liquid resin in moulds of suitable shape. The resin is allowed to set (polymerize) under some heat and pressure. After the setting of the resin, the finished structural element is removed from the mould. Complex shapes are easily fabricated by this process.

Structures made of a new class of materials called the fiber reinforced plastics (FRP) based on embedding strong, light weight fibers in a polymer matrix are being used on airplanes. They are significantly lighter than aluminium alloy structures they replace.

The strength properties of a composite material obtained as above are dependent on the properties of the fiber, the matrix and the orientation of the fibers relative to the direction of the load. The fibers can resist tension/compression only. Carbon fibers surpass steel by a large margin in their strength and stiffness while having a density only a small fraction (about 18%) of that of steel. Glass fibers have a lower stiffness and higher density but are very cheap. Kevlar is comparable to glass fiber in strength and stiffness but has about 56% of the density.

The fibers can only be used in structures in the form of composite materials. These are fiber reinforced composites (FRP) and are named based on the fiber used as CFRP, GRP and ARP. Typically, these consist of several layers of fiber reinforcement with fibers oriented in different directions held together by a matrix and resemble plywood. A typical matrix material is the epoxy resin whose properties are shown in *Table* 1. In general, the matrix materials have very low strength and stiffness and contribute little to the strength and stiffness of the composite while adding to their weight. All efforts are made in fabrication of composites to keep the quantity of the matrix as small as possible. However, the transfer of forces between fibers in a composite is critically dependent on the matrix. Failure of the matrix results in loss of strength of the composite material due to delamination of the layers in it. This has to be avoided by careful design.

Strength and stiffness properties of a composite material are strongly dependent on the orientation of fibers in the composite. The fibers can be woven into a cloth with different ratios of fibers along and at right angles to the run of the cloth. We shall only consider composites with unidirectional (UD) reinforcement using a cloth with fibers almost entirely in one direction. It is in these cases that FRP materials exhibit their best strength and stiffness properties. In this form, the composites resemble wood which is a natural composite with unidirectional reinforcement using cellulose fibers. *Table* 1 shows the structural properties of UD composites reinforced with glass, carbon, and Kevlar fibers.

This shows that CFRP sheet with UD reinforcement has strength and stiffness properties along the fiber direction exceeding steel while having a density less than a quarter of it. GFRP and ARP have stiffness properties comparable to that of aluminum alloys while their densities are lower. Glass fiber is relatively inexpensive and is widely available. FRP materials find general application in the manufacture of wind turbine blades, marine craft, musical instruments, sports equipment as well as airplanes. GFRP materials are transparent to microwaves and are suitable for use in radomes on aircraft and on the ground.

FRP materials can be used to maximum advantage in those applications where the loads are nearly unidirectional as in airplane propellers. Propellers of composite materials weigh about half as much as aluminum alloy propellers and are widely used. In other applications, the advantage is significant but is not spectacular. CFRP material appears to have shown a weight advantage of about 20% over aluminum alloys for a combat airplane wing. As cracks do not propagate easily in FRP materials, they have an advantage in structures that are subject to repeated loading. The latest civil airplane, Airbus A380, uses a material for the upper fuselage called GLARE (GLAss REinforcement) which is an FRP-aluminum sandwich with alternate layers of GFRP and aluminum alloy. Use of this material appears to result in a significant gain in durability of the structure (fatigue life) with some weight reduction.

4. Structural Loads

Stresses are induced in the components of an aircraft due to loads acting on the structure during the various phases of flight including ground roll, cruise, maneuvers and landing. Additionally, loads act on the structural components when an airplane flies through atmospheric disturbances like gusts. To design the structure optimally, loads acting on the various structural components during the above conditions need to be estimated accurately. Different types of aircraft perform different missions and critical loading conditions vary depending on aircraft type. Combat aircraft perform maneuvers during which large inertia loads which could be many times the weight of the aircraft are induced and these could be critical for the structure. The designer thus has to define the permissible maneuver loads and airplane has to be operated without exceeding these limits in flight. Civil aircraft also maneuver but within narrower limits. For these aircraft, loads due to atmospheric gusts could be more critical.

In order to evaluate the safety of the structure for these operating conditions, the flight envelope of an aircraft is defined at the design stage by using flight speed load factor (V–n) diagrams. These diagrams define the permissible operating region for an airplane as in *Figure* 6a and b. Load factor n indicates the factor by which the

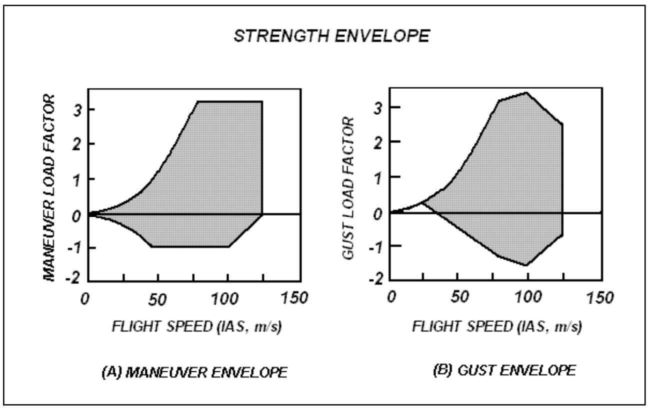

Figure 6. Maneuver and gust load factors for a civil airplane: Inertia loads are induced on an airplane due to maneuvers and gusts. Maneuvers are required for performing flight path adjustments in normal operation. Gust loads arise due to atmospheric disturbances. The airplane structure has to be strong enough to resist without failure the loads induced on its components due to gravity and inertia. The V–n diagrams are related to the magnitude of the total loads that will arise at various flight speeds. The actual loads on individual structural components can be calculated using the V–n diagrams and equilibrium considerations.

wing lift differs from the static weight of an aircraft. Thus the load factor is unity in steady level flight. It could reach values as high as six in a pull up from a dive. The load factor is minus one in inverted flight. Coordinated turns induce a load factor whose magnitude is equal to the secant of the bank angle. Combat aircraft structures are often designed for a maximum load factor of ten. At these high values of n, the pilot will become unconscious unless protected by special 'g' suits. Civil aircraft are limited to maneuver load factor of less than 3.8. *Figure* 6a shows a typical V–n diagram for maneuver loads applicable to a civil airplane. The V–n diagrams and equilibrium considerations are used in estimating the flight loads on various structural elements of an airplane under all permissible flight conditions.

V–n diagrams define the regions of operation of an airplane. The airplane structure must be designed so that the airplane is structurally safe everywhere in this region.

Gust loads arise due to atmospheric disturbances, primarily in the form of random vertical velocities in the atmosphere. A gust suddenly changes the wing incidence and induces a rapid change in lift. The magnitude of this change is proportional to the product of gust and flight velocities and could cause large excursions of the load factor. Civil aircraft often reduce flight speed when gusty air is anticipated so as to reduce the gust load factor. A typical V–n diagram for gust load factor is shown in *Figure* 6b. It is constructed following airworthiness codes which specify the magnitude of gusts at different flight speeds for any aircraft. The magnitude of the gust specified (up to about 55 feet/sec) in the airworthiness codes is based on experience. Certification of an airplane is subject to its structure being demonstrated to be safe within the regions defined in the V–n diagrams.

During landing an aircraft performs a controlled impact with the runway with a descent velocity of one or two feet/sec. During this process, the main wheels of the aircraft contact the ground first. Following this, the aircraft rotates about the main wheels bringing the nose wheel into contact. Thus both linear and angular accelerations are involved in landing and the inertia loads associated with these induce loads in the fuselage and landing gear structures which must be provided with adequate strength for meeting this situation.

Civil jet aircraft cruise at an altitude of about 11 km, where the atmospheric pressure is about a fourth of that at sea level. The passenger cabins are pressurized at this altitude to approximately three fourths of sea level atmospheric pressure. Thus the cabin is under excess internal pressure of about half atmosphere. The fuselage of a passenger jet is generally of circular or double bubble cross-section to efficiently resist this pressure difference. Many passenger aircraft make over 60,000 flights in their lifetime. Due to this reason, fatigue failure (failure due to repeated loading) of the fuselage structure needs to be considered carefully.

5. Structural Design for Safety

When a structural element is progressively loaded, its deformation remains relatively small and insignificant until the 'proof strength' of the structure is reached. If the load is removed at this point, the structure returns to its original shape without leaving any residual deformations. When loaded beyond this point, the deformation of the structure increases until the 'ultimate strength' of the structure is reached at which it fails to support the load and collapses. For aluminum structures commonly used on aircraft, the ultimate strength of any structure is approximately 1.5 times its proof strength. For an airplane to be safely flown, the proof strength defines the safe loading limit for all the major components. During the useful life, an airplane experiences a large number of applications of a variety of loads of varying magnitudes. This translates into a large number of load applications of varying magnitude on any component of the airframe. Safety of the airplane thus demands that the probability of the flight load exceeding the proof strength of any structural component during the life of the airplane is extremely remote (of the order of one in ten million flight or lower). This can be interpreted to mean that the proof strength of a structural element must be greater than the maximum flight load with an adequate margin for scatter in the estimates of loads. This load is called the 'design load' for the element.

It may be pointed out here that the concept of factor of safety as used in general engineering design is not directly applied in the design of airplanes. The factor of safety defines the factor by which the proof strength of a structural element is larger than the design load. This factor allows for a number of variables including errors in strength estimates due to simplifying procedures used in the analysis of strength, variations in material properties, variations due to manufacturing processes, corrosion and other deterioration in strength due to age and operating conditions. The concept leads to conservative designs but there is a weight penalty associated with it. In airplane design, this penalty is reduced by estimating the actual margins required for variability in the strength of materials used and other conditions based on a probabilistic analysis. The concept is illustrated in *Figure* 7 which shows the frequency distribution of the measured strength of specimens of a structural element. It is seen that the actual strength of nominally identical

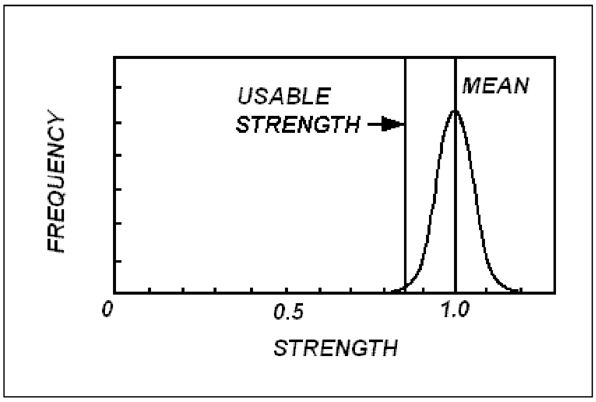

Figure 7. Variability of strength of structures: Nominally identical structural elements exhibit variations in strength. The figure shows a typical frequency distribution of strength of a structural element. The mean strength of the elements is significantly larger than the usable strength. Usable strength is defined such that the probability of the strength of any sample falling below it is extremely remote.

specimens is distributed around the mean. The usable strength for any level of reliability can be obtained from such a distribution. Metallic specimens produced using careful quality control in production exhibit very little scatter in strength and a margin of about 5% is often adequate to cover this. Specimens of composite materials often exhibit large variations in strength. Quantifying and providing for this is a major task. To minimize scatter, strict quality control is required and this is often very expensive. Use of composites which promise weight savings is often inhibited due to these factors.

Prior to the sixties, airplane structures were generally designed for adequate proof strength based on static loading (also called the static strength) as defined above. Some margin in static strength was included in the designs to allow for metal fatigue. Fatigue is a phenomenon due to which a structure subjected to repeated loads fails at a load smaller than its static strength. However several structural failures on civil jet airplanes at that time indicated that the margins included were inadequate. Since that time fatigue as a phenomenon has attracted much attention. The science and technology pertaining to design of structures for fatigue is still evolving.

Fatigue has been well known for over a century. The phenomenon was recognized early in the context of rotating machinery subjected to cyclic loading. However its clear recognition on structures subjected to repeated loads of varying magnitude as on airplane wings and passenger cabins is more recent. Fatigue failure is attributable to the development and growth of cracks over time. The cracks develop from microscopic defects present in materials or from regions of stress concentration like corners, rivet holes, etc. The phenomenon is illustrated in *Figure* 8. The figure shows the length of crack on a structural element as it develops over life measured in flight hours as installed on an airplane. The cracks, if any,

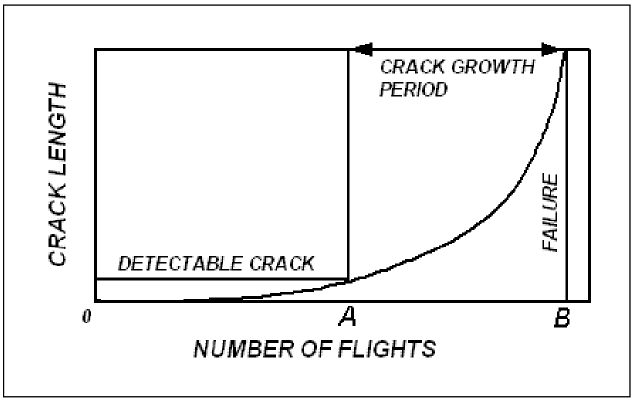

Figure 8. Structural failure due to crack growth: Any structural element has microscopic defects or points of stress concentration from which a crack can develop when subjected to repeated loads. The crack grows further with time and reduces the strength of the element sufficiently to cause failure. An element can be designed to be crack free during the life of the structure. But this results in excessive weight. It is better to design the element such that a crack is likely but develops slowly during the operational life of the structure. Any crack is detected by inspection before it can cause failure and the element is repaired or replaced. This is the concept of fail safe inspectable design.

are undetectable during early life. As the airplane gets older, a detectable crack develops due to the repeated applications of flight loads of varying magnitude. At a certain airplane life, A, the crack becomes detectable. If not attended to, further growth of the crack with flight hours results in sufficient weakening of the structure to result in failure at B. It may be noted here that the airplane life at A and B for any specific component can exhibit large variations among identical airplanes. This variability of life of identical components is basic to the fatigue phenomenon. *Figure* 9 shows the results of fatigue tests of machined metal specimens with polished surfaces. It is seen that metal specimens exhibiting little variation in static strength show a variation in fatigue life for any given stress level by a factor of ten or more.

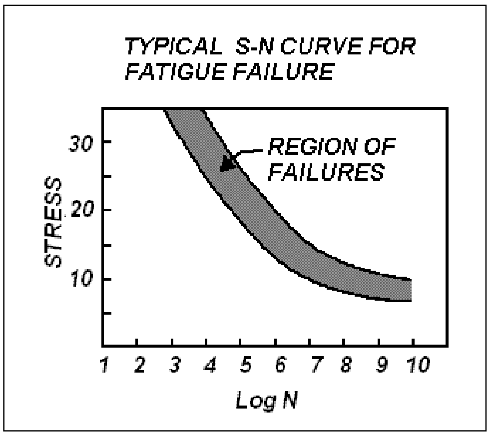

Figure.9. Nature of fatigue failure: When a structural element is subjected to repeated loads, it fails after the application of a number of load cycles, N. This fatigue life exhibits substantial scatter. The life of nominally identical components can differ by as much as a factor of ten at the same stress level.

The designer of a structural component of an airplane for safety over the life of an airplane has to recognize the above complex properties of the fatigue phenomenon. One may choose to adopt the principle of safe life and provide enough margins in the static strength of the components that visible cracks do not appear on the components during the life of the airplane. This principle is actually applied during the design of vital structural components which have no redundancy like the landing gears. In principle, such components need not be inspected for cracks during the life of the airplane. However use of this principle for designing other structural elements which have some inherent redundancy results in a large weight penalty and the principle of fail safe inspectable design is used instead.

The principle of a fail safe inspectable design [1] is suitable for structural elements which can be inspected for cracks at suitable intervals (typically around two years). In this case, cracks are likely to appear on the elements after some thousands of flight hours. It is ensured that the rate of growth of cracks is sufficiently small that they will not lead to failure before the next inspection (visually or by other means). To ensure a slow growth rate of cracks, several concepts like bonded doublers and crack stoppers are in use. One concept of a crack stopper is shown in *Figure* 10. In this, the fuselage skin is connected to a ring indirectly through a shear clip in the form of an angle. If the skin is directly connected to the ring of Z-section as at A, a crack originating on the skin will be able to cross over to the ring immediately and

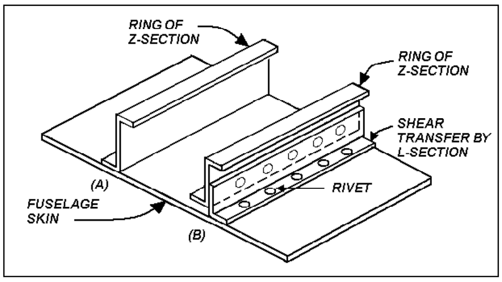

Figure 10. Design for extended fatigue life: When a ring is directly connected to the fuselage skin as at A, a crack from the skin can easily propagate into the ring. If a shear clip is introduced between them as at B, the crack will have to propagate and cross this clip before it propagates into the ring. This helps in extending the time available for inspection and is more suitable from fatigue point of view.

may lead to a failure of the ring. However, if a shear clip is introduced between the skin and the ring as at B, the crack will have go through the clip and this will take more time. During this time, the skin crack will be detected and repaired (by a patch) or the skin replaced.

In structures designed on the safe life inspectable principle, there is a possibility that cracks can occur in adjacent structural elements like skin panels on both sides of a fuselage ring. The interaction between cracks can lead to a premature failure. Such a possibility is anticipated by the civil airplane design codes. Airworthiness codes recognize such a possibility and provisions are made to consider and overcome such failures.

6. Strength Calculations

Design of any structural element for adequate static and fatigue strength is a complex task. Before the computer-based finite elements methods (FEM) became popular, analysis and design of any aircraft structural element was generally performed using the strength of materials approach. Peery [2] is an excellent introduction to this subject. In this approach a component is simplified and analyzed using equilibrium and elasticity considerations to obtain stresses in the element corresponding to a given load. The calculated stresses at critical locations are compared with permissible stresses established for the class of structures under consideration. The component is declared safe if the permissible stresses are greater than the calculated stresses. The concept of permissible stress is based on tests to destruction of components similar to the one under consideration. It is derived from extensive tests which are thus required for establishing the permissible stress levels for various classes of structures. The permissible stress is dependent on the material of construction in a complex manner and thus a change of material or type of construction is not easily accounted for in this approach. Thus this method is not easily applied to new types of construction or in new materials like composites. However it is relatively simple and well suited for the preliminary design of components in traditional aluminum alloys. This approach was refined over time and was the basis of airplane structural design till about the sixties. Reference [3] is a fine collection of the refined methods of strength analysis of airplane components using this approach. These methods are still valuable for use in general mechanical engineering.

The finite element method (FEM) of analysis is a computationally intensive method which can model and analyze complex structures easily. In this approach, the actual structure is treated as an assembly of finite elements with clearly defined elastic properties. The loads applied on the structure are related to the stresses in the various finite elements through computations involving equilibrium and compatibility of displacements of the elements. Failure is associated with maximum stress and is correlated with results from experiments conducted at a more basic level than in the strength of materials approach. This approach permits structural optimization. The structural material can be re-distributed iteratively based on analysis until an optimal configuration is reached. Complex materials like composites can be effectively modeled at the level of layers and even at the level of fibers. While FEM methods are very effective in analysis and refinement of structural components, the strength of materials approach is still valuable in understanding and interpreting structural behavior.

Suggested Reading

[1] **H J Schnidt, B Schmidt-Branddecker and G Tober, *Design of Modern Aircraft Structure and the role of NDI*, Seventh European Conference on NDT, Copenhagen, Denmark, 1998.**

[2] **David J Peery, *Aircraft Structures*, McGraw-Hill Book Company, Inc., 1950.**

[3] **D M A Leggett, M Langley (co-editors), *Structural Principles and Data*, The New Era Publishing Co., Ltd., 43, New Oxford Street, London, W.C.1., 1960.**

[4] **Henry Petroski, *To Engineer is Human – The Role of Failure in Successful Design*, Vintage Books, New York, 1992.**

Address for Correspondence
S P Govinda Raju
Department of Aerospace Engineering
Indian Institute of Science
Bangalore 560 012, India.
Email: spg@aero.iisc.ernet.in