7

COMPOSITE MATERIALS AND AEROSPACE CONSTRUCTION

Aeronautical constructors have been looking for light weight and robustness from composites since the earlier times. As a brief history:

- In 1938, the Morane 406 plane (FRA) utilized sandwich panels with wood core covered with light alloy skins.
- In 1943, composites made of hemp fiber and phenolic resin were used on the Spitfire (U.K.) airplane.
- Glass/resin has been used since 1950, with honeycombs. This allows the construction of the fairings with complex forms.
- Boron/epoxy was introduced around 1960, with moderate development since that time.
- Carbon/epoxy has been used since 1970.
- Kevlar/epoxy has been used since 1972.

Experiences have proved that the use of composites allows one to obtain weight reduction varying from 10% to 50%, with equal performance, together with a cost reduction of 10% to 20%, compared with making the same piece with conventional metallic materials.

7.1 AIRCRAFT

7.1.1 Composite Components in Aircraft

Currently a large variety of composite components are used in aircrafts. Following the more or less important role that composites play to assure the integrity of the aircraft, one can cite the following:

- **Primary structure components** (integrity of which is vital for the aircraft):

Wing box
Empennage box
Fuselage

- **The control components:**
  Ailerons
  Control components for direction and elevation
  High lift devices
  Spoilers
- **Exterior components:**
  Fairings
  "Karmans"
  Storage room doors
  Landing gear trap doors
  Radomes, front cauls
- **Interior components:**
  Floors
  Partitions, bulkheads
  Doors, etc.

Example: The vertical stabilizer of the Tristar transporter (Lockheed Company, USA)

- With classical construction, it consists of 175 elements assembled by 40,000 rivets.
- With composite construction, it consists only with 18 elements assembled by 5,000 rivets.

7.1.2 Characteristics of Composites

One can indicate the qualities and weak points of the principal composites used. These serve to justify their use in the corresponding components.

7.1.2.1 Glass/Epoxy, Kevlar/Epoxy

These are used in fairings, storage room doors, landing gear trap doors, karmans, radomes, front cauls, leading edges, floors, and passenger compartments.

- **Pluses:**
  High rupture strength[1]
  Very good fatigue resistance
- **Minuses:**
  High elastic elongation
  Maximum operating temperature around 80°C
  Nonconducting material

[1] See Section 3.3.3.

7.1.2.2 Carbon/Epoxy

This is used in wing box, horizontal stabilizers, fuselage, ailerons, wings, spoilers (air brakes) vertical stabilizers, traps, and struts.

- **Pluses:**
  High rupture resistance
  Very good fatigue strength
  Very good heat and electricity conductor
  High operating temperature (limited by the resin)
  No dilatation until 600°C
  Smaller specific mass than that of glass/epoxy
- **Minuses:**
  More delicate fabrication
  Impact resistance two or three times less than that of glass/epoxy
  Material susceptible to lightning

7.1.2.3 Boron/Epoxy

This is used for vertical stabilizer boxes and horizontal stabilizer boxes.

- **Pluses:**
  High rupture resistance
  High rigidity
  Very good compatibility with epoxy resins
  Good fatigue resistance
- **Minuses:**
  Higher density than previous composites[2]
  Delicate fabrication and forming
  High cost

7.1.2.4 Honeycombs

Honeycombs are used for forming the core of components made of sandwich structures.

- **Pluses:**
  Low specific mass
  Very high specific modulus and specific strength
  Very good fatigue resistance
- **Minuses:**
  Susceptible to corrosion
  Difficult to detect defects

[2] See Section 3.3.3.

7.1.3 A Few Remarks

The construction using only glass fibers is less and less favored in comparison with a combination of Kevlar fibers and carbon fibers for weight saving reasons:

- If one would like to have maximum strength, use Kevlar.
- If one would like to have maximum rigidity, use carbon.
- Kevlar fibers possess excellent vibration damping resistance.
- Due to bird impacts, freezing rain, impact from other particles (sand, dirt), one usually avoids the use of composites in the leading edges without metallic protection.[3]

Carbon/epoxy composite is a good electrical conductor and susceptible to lightning, with the following consequences:

- Damages at the point of impact: delamination, burning of resin
- Risk of lightning in attachments (bolts)
- The necessity to conduct to the mass for the electrical circuits situated under the composite element

Remedies consist of the following:

- Glass fabric in conjunction with a very thin sheet of aluminum (20 μm)
- The use of a protective aluminum film (aluminum flam spray)

Temperature is an important parameter that limits the usage of epoxy resins. A few experimental components have been made of bismaleimide resins (thermosets that soften[4] at temperatures higher than 350°C rather than 210°C for epoxies). One other remedy would be to use a thermoplastic resin with high temperature resistance such as poly-ether-ether-ketone "peek"[5] that softens at 380°C. Laminates made of carbon/peek are more expensive than products made of carbon/epoxy. However, they present good performance at higher operating temperatures (continuously at 130°C and periodically at 160°C) and have the following additional advantages:

- Superior impact resistance
- Negligible moisture absorption
- Very low smoke generation in case of fire

[3] The impacts can create internal damages that are invisible from the outside. This can also happen on the wing panels (for example, drop of tools on the panels during fabrication or during maintenance work).

[4] The mechanical properties of the thermoset resins diminish when the temperature reaches the "glass transition temperature."

[5] See Section 1.6 for the physical properties.

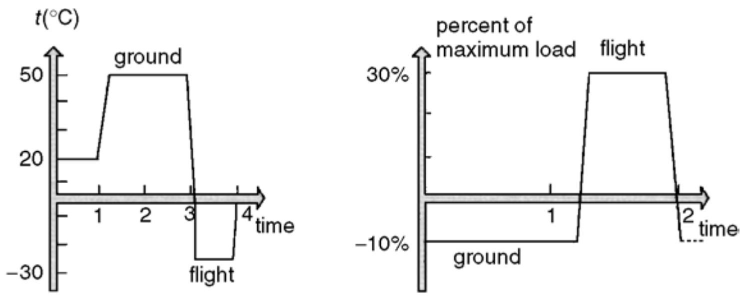

Figure 7.1 Temperature Cycle and Load Cycle for Components of an Aircraft

7.1.4 Specific Aspects of Structural Resistance

- One must apply to composite components the technique called *fail safe* in aerodynamics, which consists of foreseeing the mode of rupture (delamination, for example) and acting in such a manner that this does not lead to the destruction of the component during the period between inspections.
- Composite components are repairable. Methods of reparation are analogous to those for laminates made of unidirectionals or fabrics.[6]
- Considering the very important reduction of the number of rivets used as compared with the conventional construction, one obtains a smother surface, which can lead to better aerodynamic performance.
- One also considers that the attack of the environment and the cycles of fatigue over the years do not lead to significant deterioration of the composite pieces (shown in Figure 7.1 are two types of fatigue cycles for the components of aircraft structure).
- The failure aspect subject to a moderate impact is more problematic with the structures made of composite materials, because the energy absorbed by plastic deformation does not exist.
- For the cabins, one uses phenolic resins. These have good fire resistance, with low smoke emission. For the same reason, one prefers replacing Kevlar fibers with a combination of glass/carbon (lighter than glass alone and less expensive than carbon alone).
- It is possible to benefit from anisotropy of the laminates for the control of dynamic and aeroelastic behavior of the wing structures.[7]

7.1.5 Large Carriers

The following examples give an idea on the evolution of use of composites in aircrafts over two decades:

Example: Aerospatiale (FRA); Airbus Industry (EU) (Figure 7.2)
Example: Boeing (USA) (Figure 7.3)

[6] See Section 4.4.4.
[7] See Section 7.1.8.

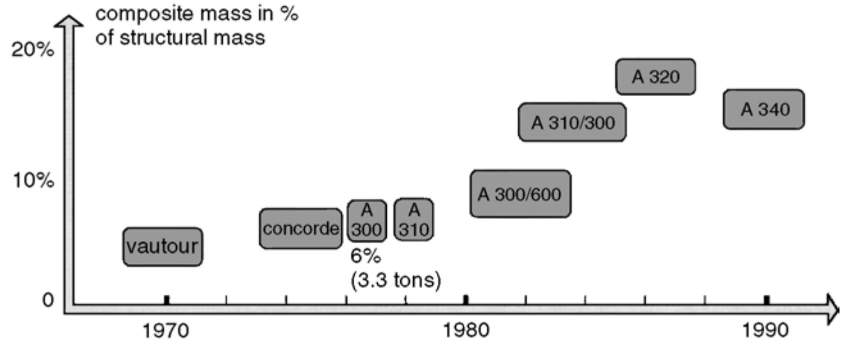

Figure 7.2 Evolution of Mass of Composites in Aircraft

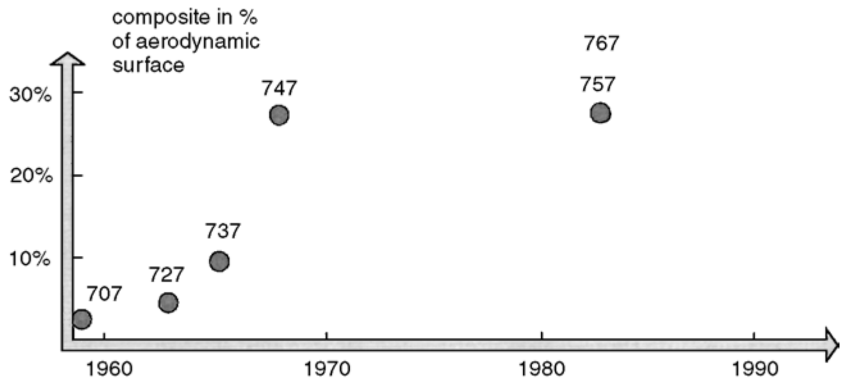

Figure 7.3 Use of Composite in Boeing Aircraft

How to evaluate the gains:

In theory: For example, a study was made by Lockheed Company (USA) for the design of a large carrier having the following principal characteristics: payload 68 tons, range 8300 km. This study gives the following significant results:

- for an aircraft made using conventional metallic construction:
  total mass at take-off: 363 tons
  mass of the structure: 175 tons
- for an aircraft made using "maximum" composite construction:
  total mass at take-off: 245 tons
  mass of the structure: 96 tons.

Such a difference can be explained by the cascading consequences that can be illustrated as in Figure 7.4.

In practice: In reality, introduction of composites in the aircrafts is limited to certain parts of the structures. It is done case by case and in a progressive manner during the life of the aircraft (re-evaluation operation). One is then led to consider the different notions:

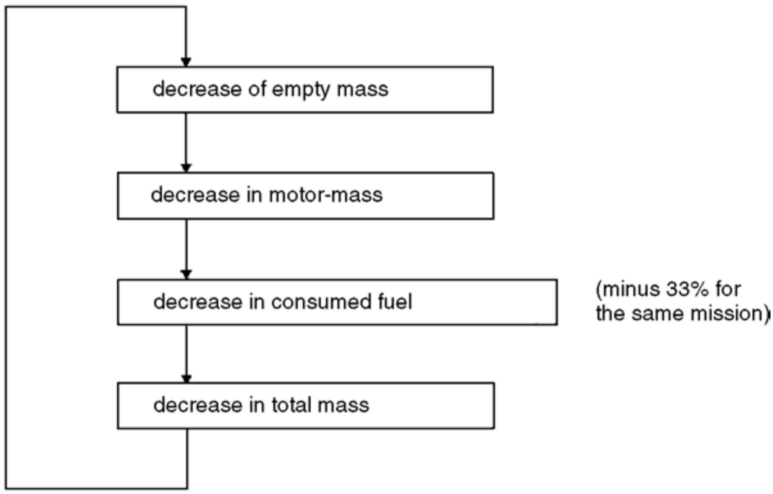

Figure 7.4 Cascading Effect in Mass Reduction

- Notion of the exchange rate is the cost for a kilogram saved when one substitutes a classical metallic piece with a piece made mainly with composite. For the substitution light alloy—carbon/epoxy—this cost is on the order of $160 (1984) per kilogram when the piece is calculated in terms of rigidity (similar deformation for the same load). It is amortized over a period of at least one year for the gain in "paying passenger."
- Notion of gain in paying passenger is the gain in terms of the number of passengers, of freight, or in fuel cost; for example, for a large carrier:
  - An aircraft of 150 tons, with 250 passengers consists of 60 tons of structure. A progressive introduction of 1600 kg of high performance composite materials leads to a gain of 16 more passengers along with their luggage.
  - A reduction of 1 kg mass leads to the reduction of fuel consumption of around 120 liters per year.

Why are the reductions of mass (average about 20%) not more spectacular? Consider the example of a vertical stabilizer. The distribution of mass of a composite vertical stabilizer can be presented as follows:

- Facings in carbon/epoxy: 30% of total mass
- Honeycombs, adhesives: 35% of total mass
- Attachments: 25% of total mass
- Connections between carbon/epoxy components and attachments: overlayers of carbon/epoxy
- Allowance for the aging of the carbon/epoxy: overdimensions of the facings (the stresses are magnified about 10% more for a subsonic aircraft and 13% for a supersonic aircraft)

In consequence, the global gain of mass in comparison with a classical metallic construction for the vertical stabilizer is not more than an order of about 15%.

Example: European aircraft Airbus A-310–300 (Figure 7.5).

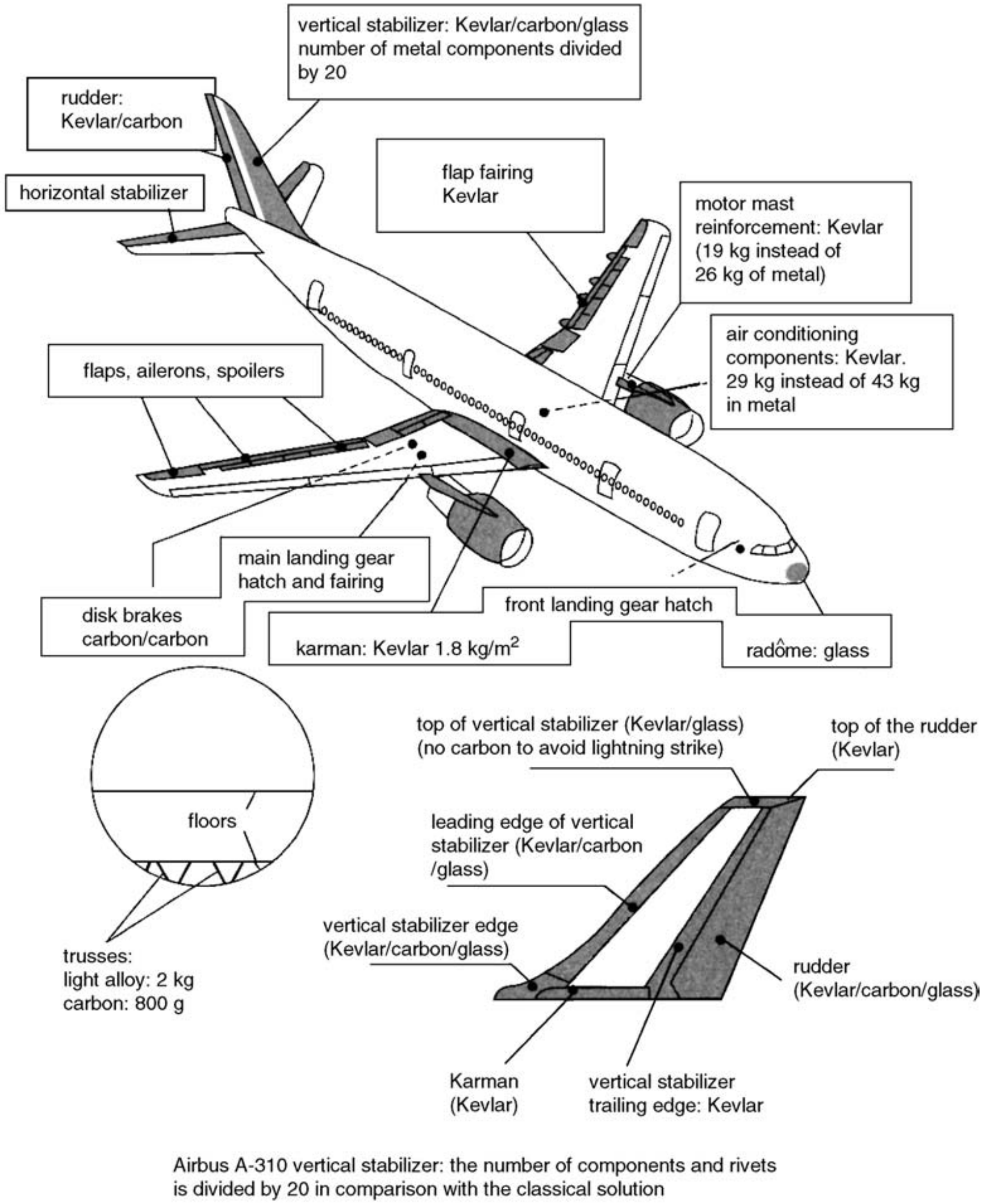

Figure 7.5 Composite Components in an Airbus A-310

- Total mass: 180 tons
- Mass of structure: 44.7 tons
- Mass of composites: 6.2 tons
- Mass of high performance composites: 1.1 tons
- Reduction of mass of structure: 1.4 tons
- Percentage of composites: 13.8% of mass of structure. A reduction of mass of the structure of 1 kg augments the range of the aircraft by 1 nautical mile.

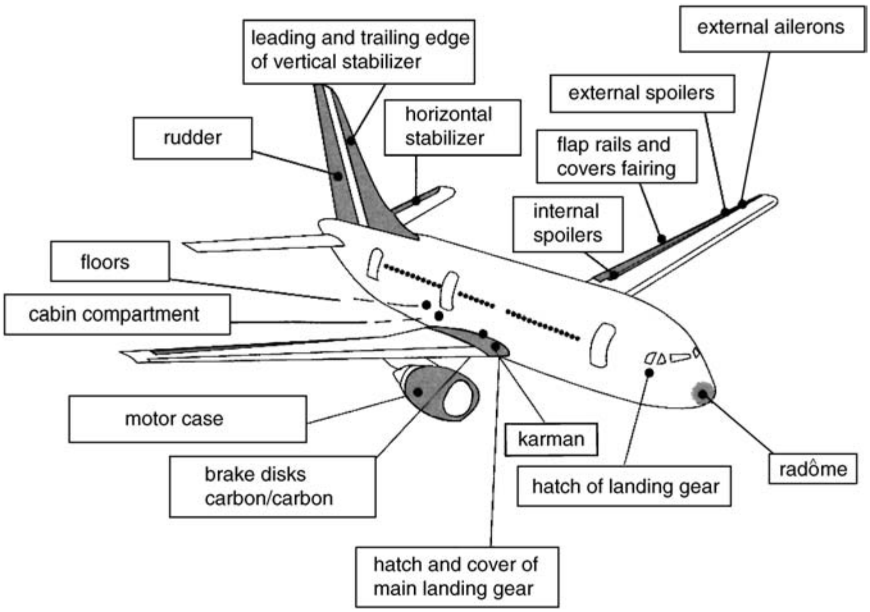

Figure 7.6 Composite Components in an Airbus A-320

Example: European aircraft Airbus A-320 (Figure 7.6).

- Total mass: 72 tons
- Empty mass: 40 tons
- Mass of structure: 21 tons
- Mass of composite materials: 4.5 tons, corresponding to a reduction of mass of the structure of 1.1 tons. The percent of composite mass is 21.5% of the mass of the structure.
- A few other characteristics: Length: 37.6 m; breadth: 34 m; 150 to 176 passengers transported from 3,500 to 5,500 km; maximum cruising speed: 868 km/h

Example: European aircraft Airbus A-340

- Total mass: 253.5 tons
- Mass of structure: 76 tons
- Mass of composites: 11 tons, corresponding to a reduction of structure mass of 3 tons
- Percentage of composites: 14.5% of the mass of the structure

Example: Future supersonic aircraft *ATSF* (Figure 7.7), *Aerospatiale (FRA)* and *British Aerospace* (UK). Principal characteristics defined at the stage before the project

- Transport of 200 passengers over a distance of 12,000 km
- Cruising speed between Mach 2 (2,200 km/hr) and Mach 2.4 (2,600 km/hr)

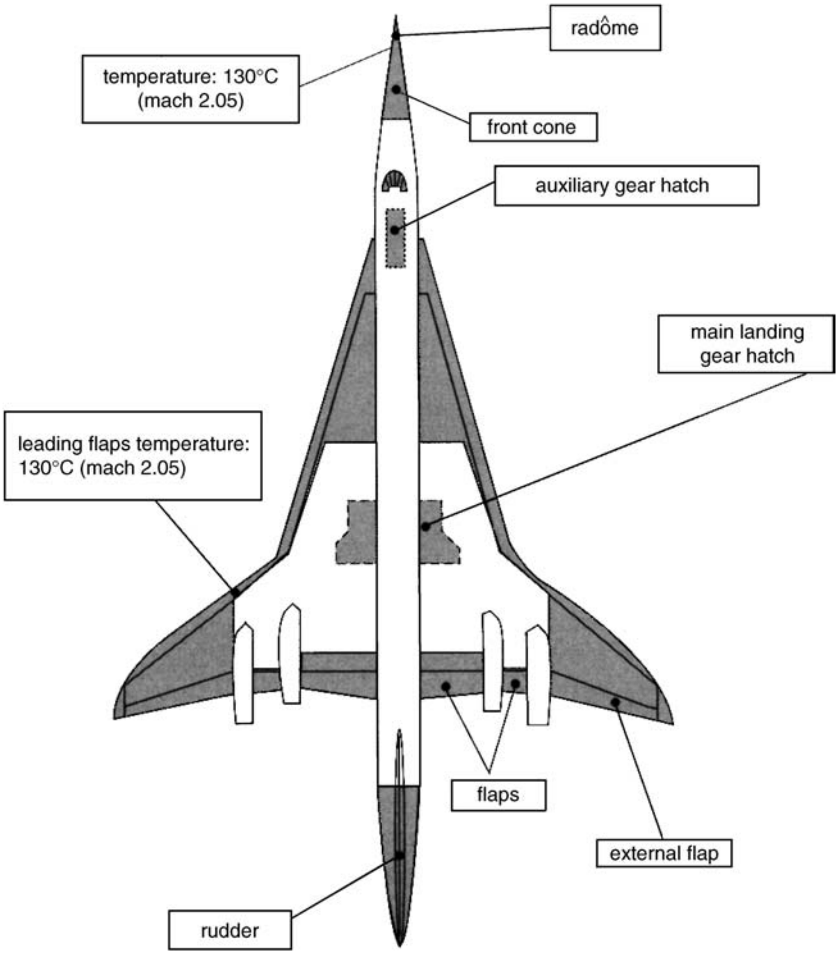

Figure 7.7 Composite Components in a Future Supersonic Aircraft

- Economically viable for a single type of aircraft on the market (enlarged international cooperation)

7.1.6 Regional Jets

Example: Regional transport aircraft ATR 72, ATR (FRA–ITA) (Figure 7.8):

- Total mass: 20 tons
- Percentage of composite materials more than 25% of the mass of the structure
- Transports 66 passengers over a distance of 2,600 kilometers
- Interior equipment: Facings of panels for portholes and ceiling, baggage compartment, bulkheads, toilets, storing armors in glass-carbon/phenolic resins/NOMEX honeycomb; decoration by a film of "TEDLAR"

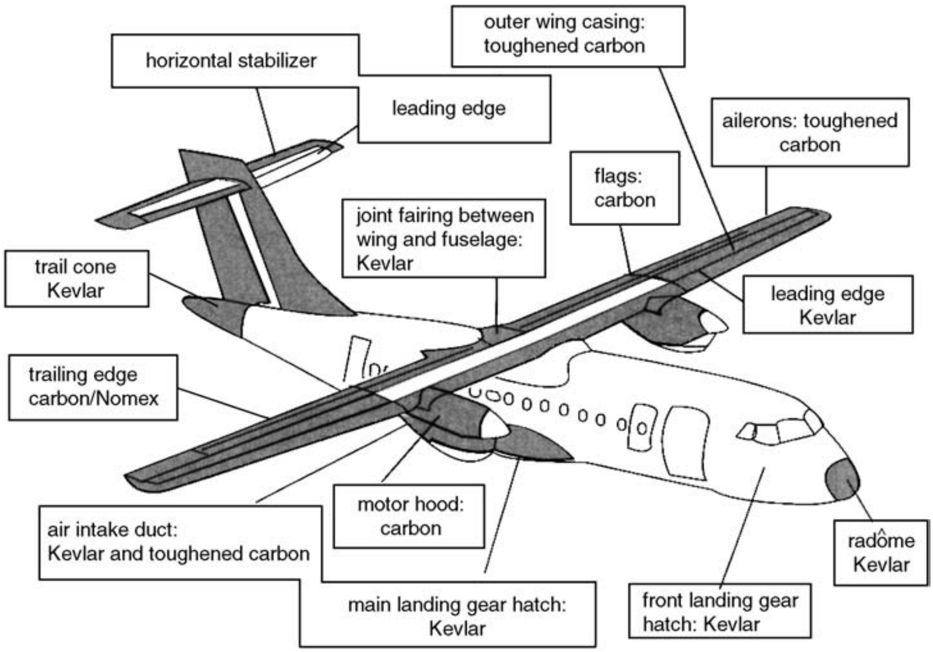

Figure 7.8 Composite Components in the Regional Transport Aircraft ATR 72

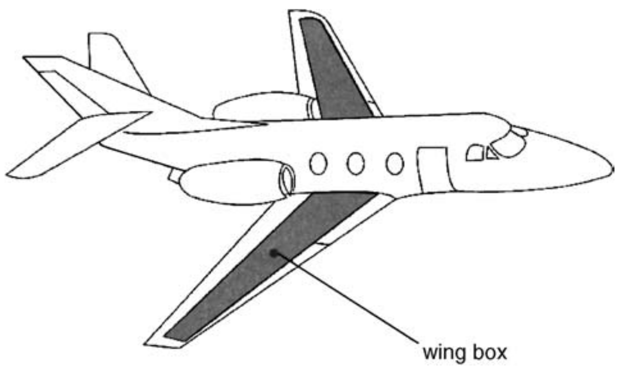

Figure 7.9 Business Aircraft Falcon 10

Example: Business aircraft Falcon 10 (Figure 7.9). Aircrafts (AMD–BA) (FRA).

- The principal wing box (primary structure) is constructed in ribbed panels of carbon/epoxy; it has been flying experimentally since 1985.
  Mass of wing box: 339 kg
  Reduction of mass in comparison with conventional metallic construction: 80 kg (20%)
- The connection between the wing and the fuselage and the attachment between the landing gears and the wing box are made using metallic pieces.

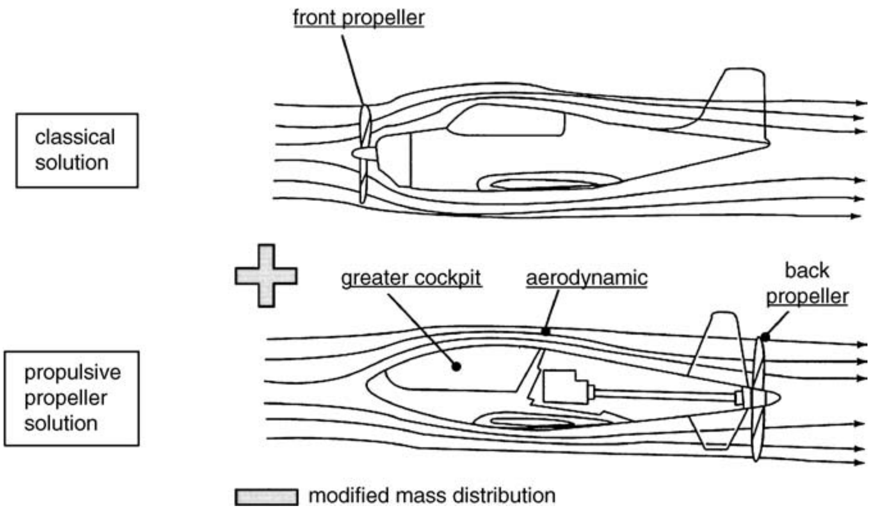

Figure 7.10 Propulsive Propeller Configuration

7.1.7 Light Aircraft

These are the aircrafts for tourism and for the gliders. The new generation of these aircrafts is characterized by

- A large utilization of composites
- A renewal in aerodynamic solutions

Remarks: In addition to the problems to be resolved by the manufacturers (small manufacturers for the most part), comes the preparation of the dossiers of certification including composite primary structures.

- The useful reduction of masses, the range of flight, and the cruising speed, due to the utilization of composites, are amplified more clearly in these types of aircrafts.

Example: Back propeller aircraft. The principle of this is illustrated in Figure 7.10, with the advantages and drawbacks. The modification of the mass distribution, due to the displacement of the motor, requires a propeller shaft (foreseen to be in carbon/epoxy) and a wing shifted to the back. One can propose the "all composite" solution as follows:

- The solution "long shaft." Sup'air airplane Centrair (FRA); Figure 7.11
- The solution of shifted wing and additional duck wing: Beech Starship aircraft (USA); Figure 7.12:
  Eight to ten passengers: 650 km/hr with low fuel consumption
  Structure in carbon/epoxy
  Mass of the wings: 800 kg (reduction of 35% in comparison with a metallic solution)
  Mass of fuselage (structure): 240 kg
  Mass of the composite: about 70% of the mass of the structure

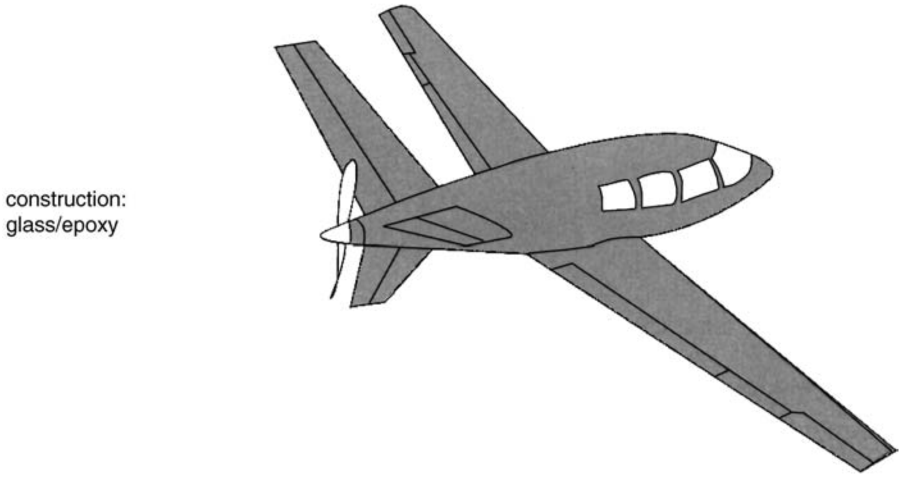

Figure 7.11 An All-composite Airplane

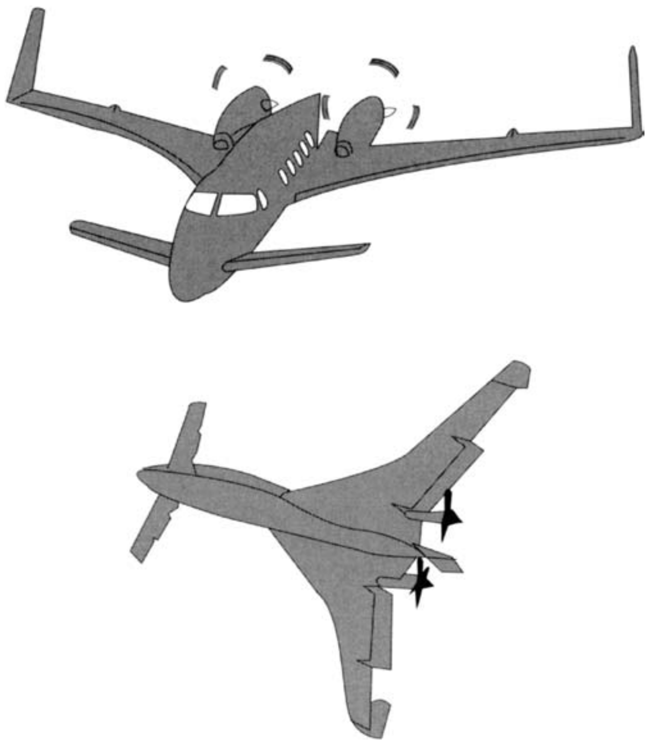

Figure 7.12 Beech Starship Aircraft

Example: The modern glider planes. These are made entirely of composites. Figure 7.13 shows a plane made of glass/epoxy:

- Two-seater glider plane: Marianne Centrair (FRA):
  Mass: 440 kg

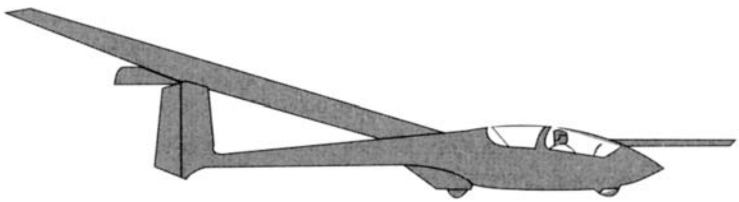

Figure 7.13 The Marianne Centrair Airplane

Wings: 2 parts bonded
Fuselage: 2 parts bonded

7.1.8 Fighter Aircraft

For this type of aircraft, there is a progressive replacement of metallic elements by composite elements. Beyond specific characteristics already mentioned previously for the large aircrafts, here the composite components have to assure the necessary rigidity for the wing box to conserve the ability of command in a domain of flight larger than for the case of large civil aircrafts.

- For the flight with electrical commands, the use of composites allows for an evolution of the aerodynamic design for better maneuverability.
- In the near future, 25 to 40% of the structure of the fighter aircrafts will be made of composite materials.

Example: European airplane Alphajet (Figure 7.14).

Example: Airplane Mirage 2000 A.M.D.–B.A. (FRA; Figure 7.15). Mass of composite materials: 65 kg (On this aircraft there are boron/epoxy composite components.)

- Characteristics of boron: The diameter of the fiber varies between 0.1 mm and 0.2 mm depending on the demand of the customer. The radius of curvature, in fact, cannot be less than 4 or 5 mm. One finds
  - for the sheets: width is 1 m, 80 filaments/cm, length: 3.5 m.
  - for the fabrics: patented process;[8] the warp direction consists of textile filaments, the fill direction consists of boron filaments.

Example: Airplane F-18 Hornet, M.D. Douglas/Northrop (USA; Figure 7.16).

Example: Airplane X-29 Grumman (USA; Figure 7.17).

Example: Airplane Rafale A.M.D.–B.A. (FRA; Figure 7.18). Note that on this airplane there is a very large usage of high performance composites (carbon/epoxy and Kevlar/epoxy). Mass of composite materials is 1,110 kg, leading to a 25% reduction in the mass of the structure.[9] Figure 7.18 shows the main components using composites.

[8] Patent Avions M. Dassault-Bréguet Aviation/Brochier.
[9] This is to compare with the number for Mirage 2000 airplane presented previously.

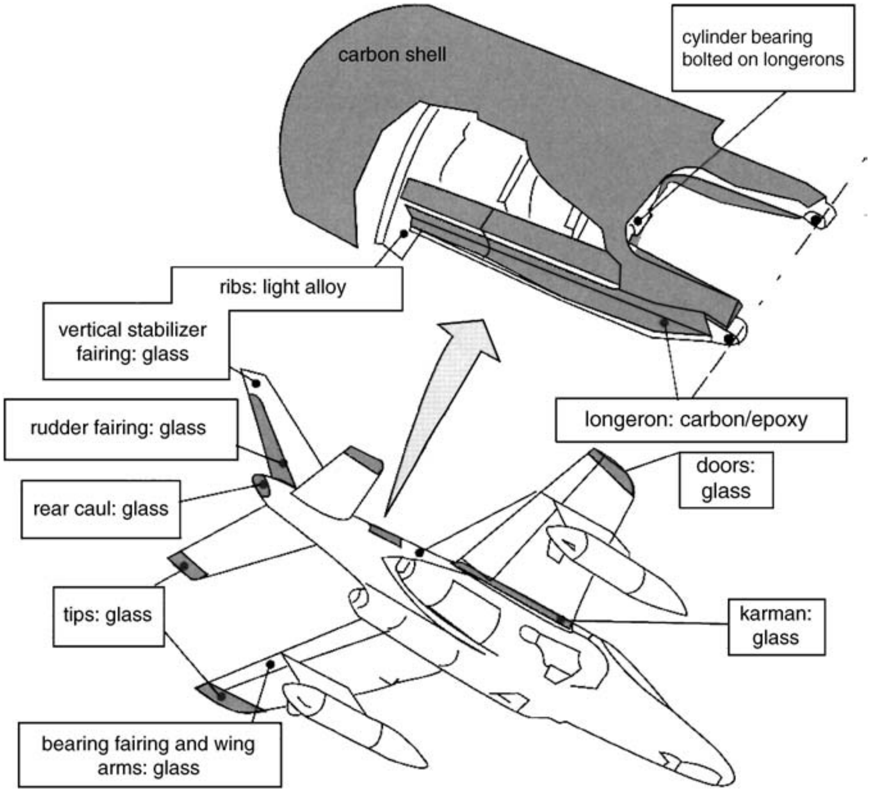

Figure 7.14 Alphajet Plane

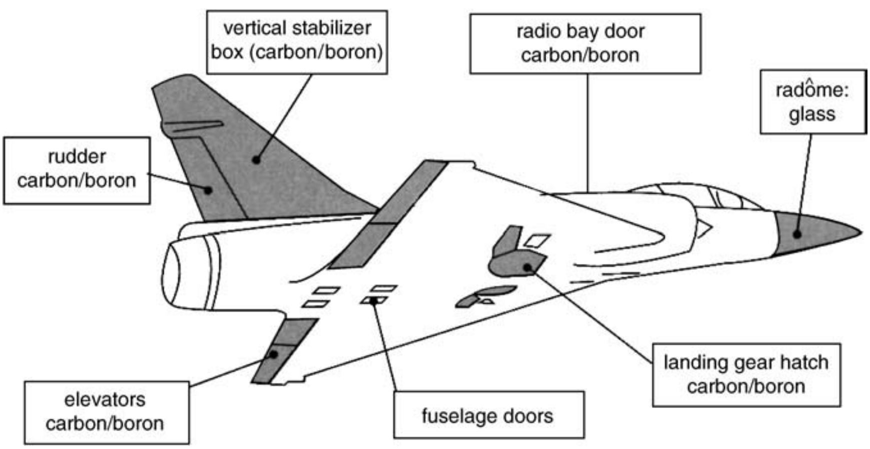

Figure 7.15 Mirage Airplane

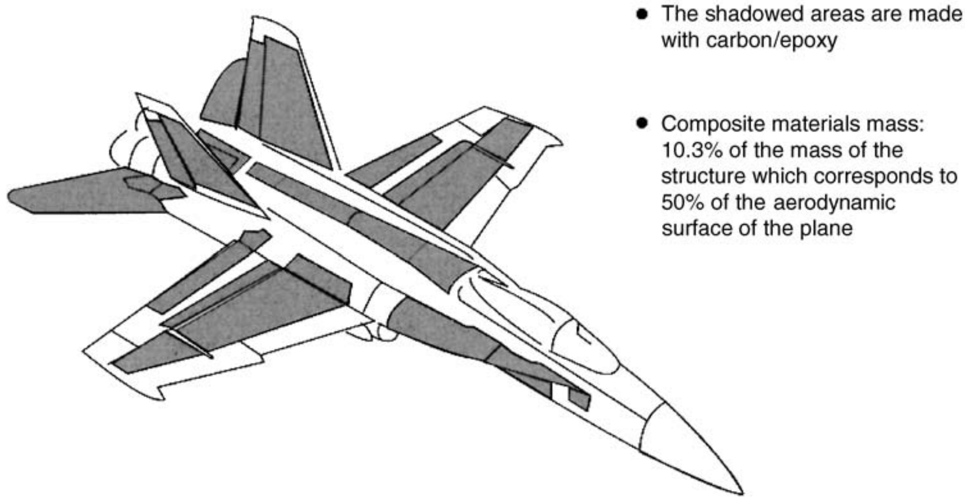

Figure 7.16 F-18 Hornet Airplane

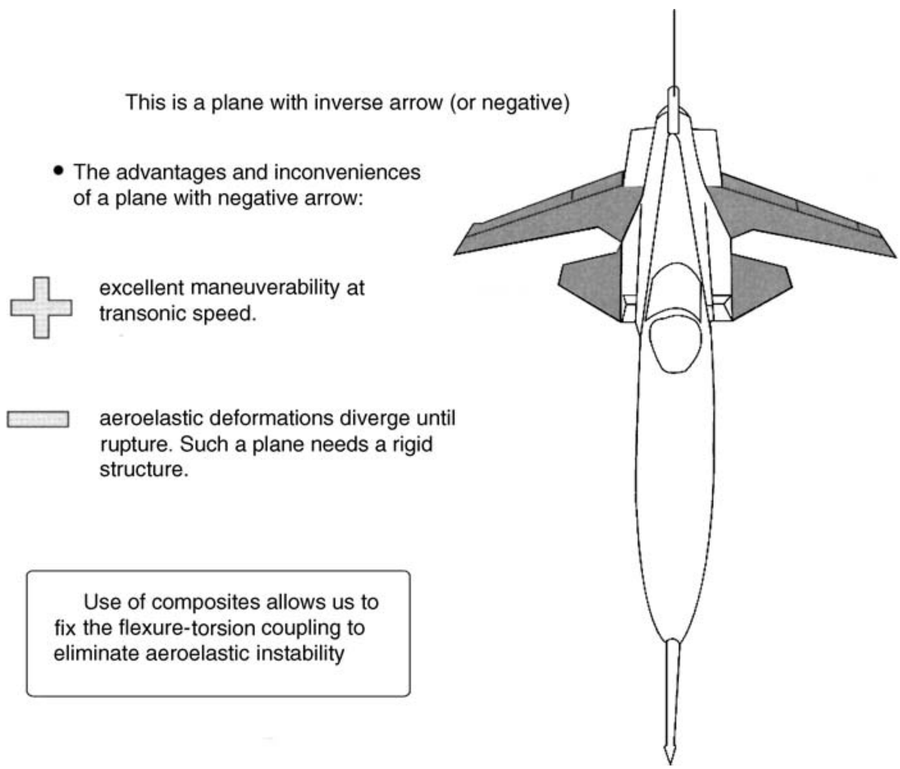

Figure 7.17 X-29 Grumman Airplane

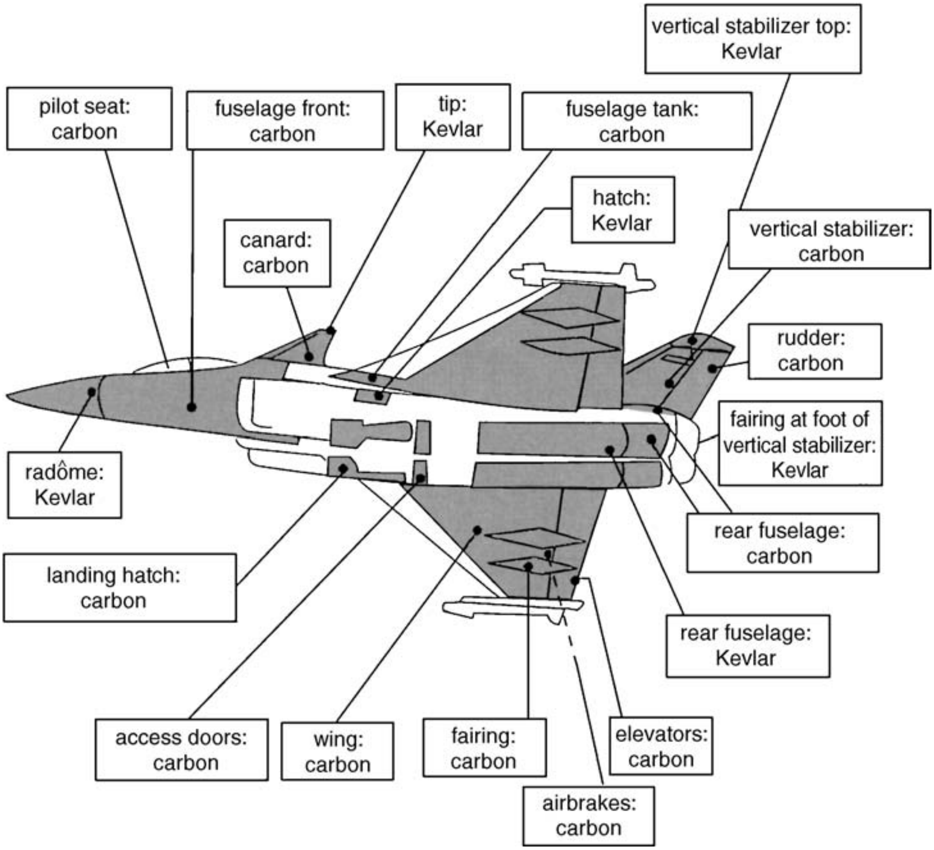

Figure 7.18 Rafale Airplane

7.1.9 Architecture of Composite Parts in Aircraft

7.1.9.1 Sandwich Design

Sandwich with transverse honeycomb: Following the nature of the component, one uses two methods of fabrication:

- **Multisteps** in which the facings of the sandwich piece are polymerized separately and then are placed on the core having an adhesive film. After that the assembly is polymerized following the method represented in Section 4.4.2, where eventually polymerization is done in an autoclave.[10]
- **Monostep** in which, after the honeycomb core is formed, the facings are placed directly on this core. The assembly is polymerized using the same method as for the multistep method.

Example: Wing box (Figure 7.19).

[10] See also Section 2.1.3.

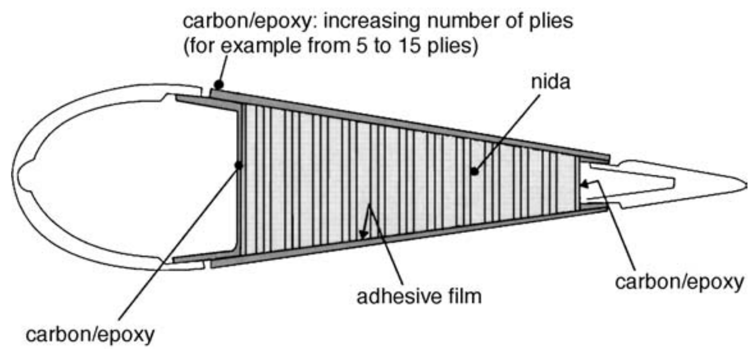

Figure 7.19 Wing Box

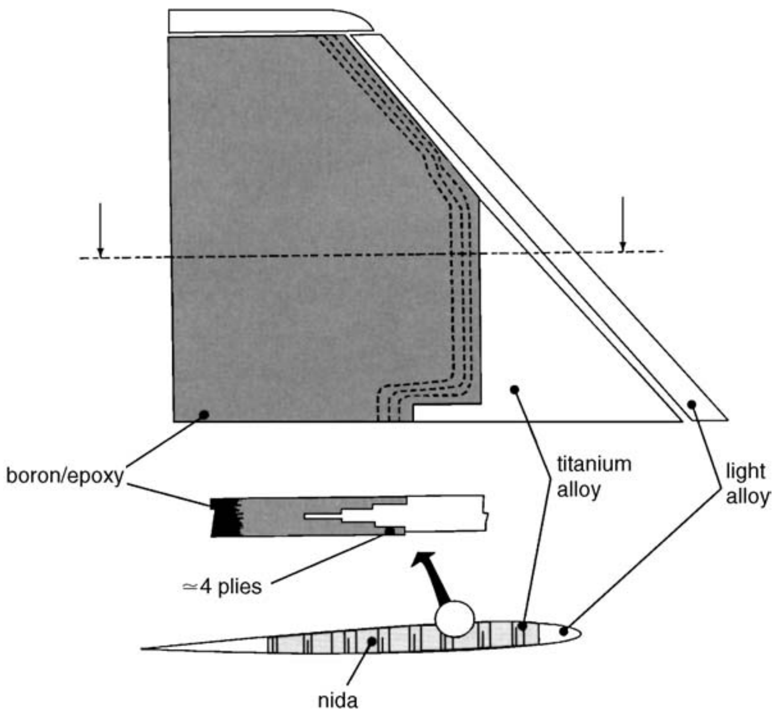

Figure 7.20 Horizontal Empennage of a Fighting Aircraft

The honeycomb core assures the rigidity of the component. However, the mass of the piece depends on the thickness of the core.

Example: Horizontal empennage of a fighting aircraft (Figure 7.20).

Remarks: One avoids drilling holes in boron/epoxy pieces as much as possible. This operation is onerous and requires ultrasonic technique with diamond tools.

There is a problem with corrosion of metallic honeycomb. The corrosion is due to the progressive condensation of water in the cavities. This is combined with the mechanical and thermal stresses (fatigue) in the structure.

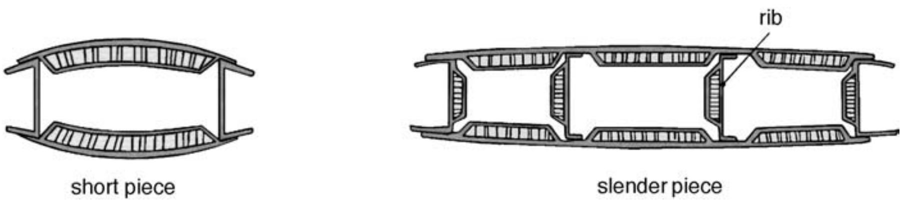

Figure 7.21 Sandwich Construction for Panels

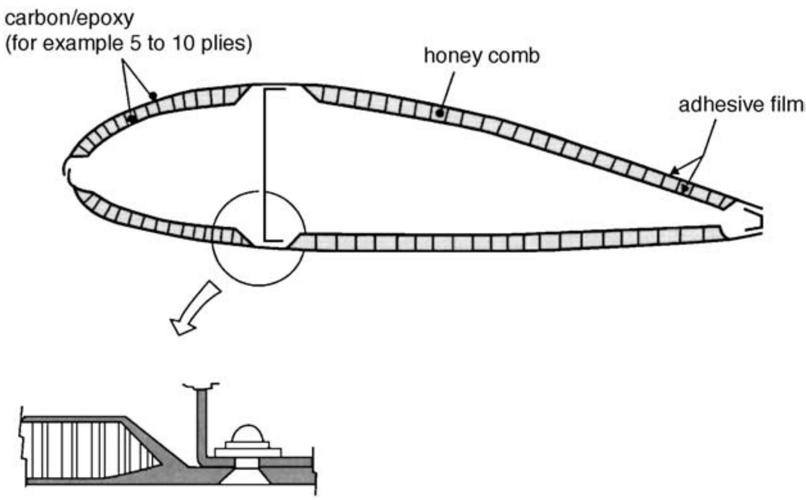

Figure 7.22 High Lift Devices Flap

Remedies include

- Covering the honeycomb core surface with a resin film
- Introducing an inorganic inhibitor at the potential points of attack to prevent the reaction with water

Sandwich construction for panels: When the thickness of the piece becomes large (on the order of 150 mm), the facings are stiffened separately by using a honeycomb core, following the arrangements shown in Figure 7.21. When the piece is of large size (long), the requirement of "nondeformation" can require the interposition of intermediate "ribs."

Each component (facings, ribs) is polymerized in the assembled state, following the technique of monostep described above.

Example: High lift devices flap (Figure 7.22)

Sandwich for the reinforcement of spars and ribs: One can increase the rigidity in flexure and in torsion by introducing honeycombs, as represented in Figure 7.23.

Stiffened panels: Currently one can find the ribbed panels in metallic construction. The ribs can be added, or monolithic, meaning that they are formed as part of the same piece when the panel is made. One observes in parallel here with the same technique in ribbed panels in composites.

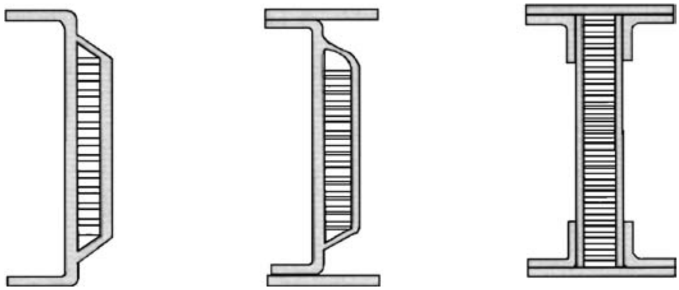

Figure 7.23 Sandwich for Spars and Ribs

Figure 7.24 Stiffeners Form

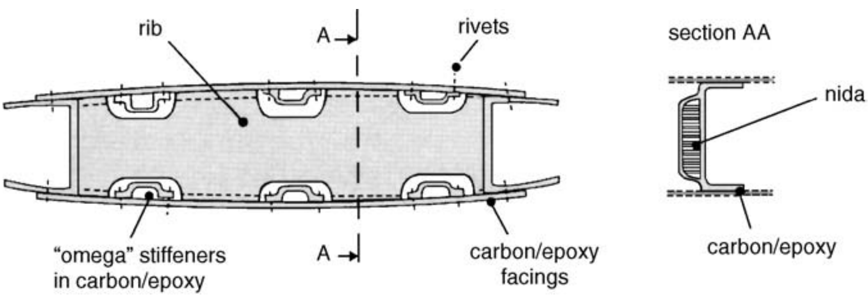

Figure 7.25 Wing Box

- **Added stiffeners:** The composite stiffeners can have the forms shown in Figure 7.24.

Example: Wing box (Figure 7.25).

- **Monolithic stiffeners:** These are cured at the same time with the facings. These can support higher loads than the previous case, but with higher cost. The mode of fabrication is shown schematically in Figure 7.26 for the so-called "omega" ribs. One uses cores, which are made partly by thermoexpandable silicone. One also uses hollow silicone cores stiffened by compressed air, or cores that melt at temperature on the order of 170°C, which is slightly higher than the polymerization temperature of the piece.

Example: Flanged plates (Figure 7.27)

Example: Stabilizer panel (European aircraft Airbus A-300; see Figure 7.28). The carbon/epoxy ribs are obtained by combining the autoclave pressure and the thermal dilatation of detachable metallic light alloy modules.[11] The steps of the process are shown schematically in Figure 7.28:

[11] See Section 1.6 for the coefficients of thermal expansion as compared between light alloy and carbon.

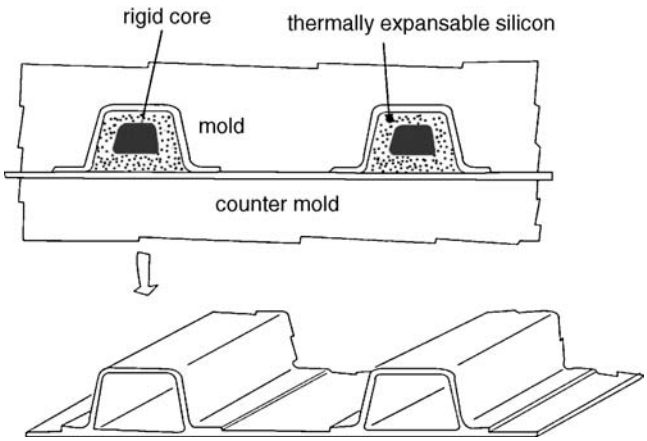

Figure 7.26 Monolithic Stiffeners

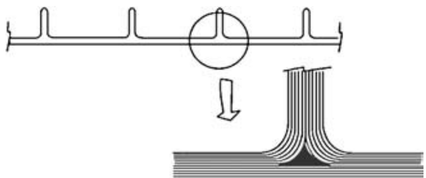

Figure 7.27 Flanged Plate

Example: Wing tip (Airplane ATR 72, ATR (FRA-ITA). This is a primary wing piece (its failure will bring about the failure of the airplane). It consists of two carbon/epoxy panels with monolithic ribs, two spars in carbon/epoxy, and 18 metallic flanges in light alloy folded sheets, as shown schematically in Figure 7.29.

- Mass of box: 260 kg (reduction of 65 kg as compared with a metallic solution).

Remarks: Lightning protection of such a structure requires specific precautions such as:

- Incorporation of a conducting fabric made of bronze wires on all external surfaces
- Installation of lightening conductors along the spars
- Protection of the connections

Example: Air brakes (European airplane Airbus A-320; Figure 7.30).

7.1.10 Elements of Braking

Different from the brakes for ground vehicles, the brakes for aircrafts are characterized by successively distinct phases of isolated operations over time. These repeat themselves in almost identical conditions from one landing to the next. These are

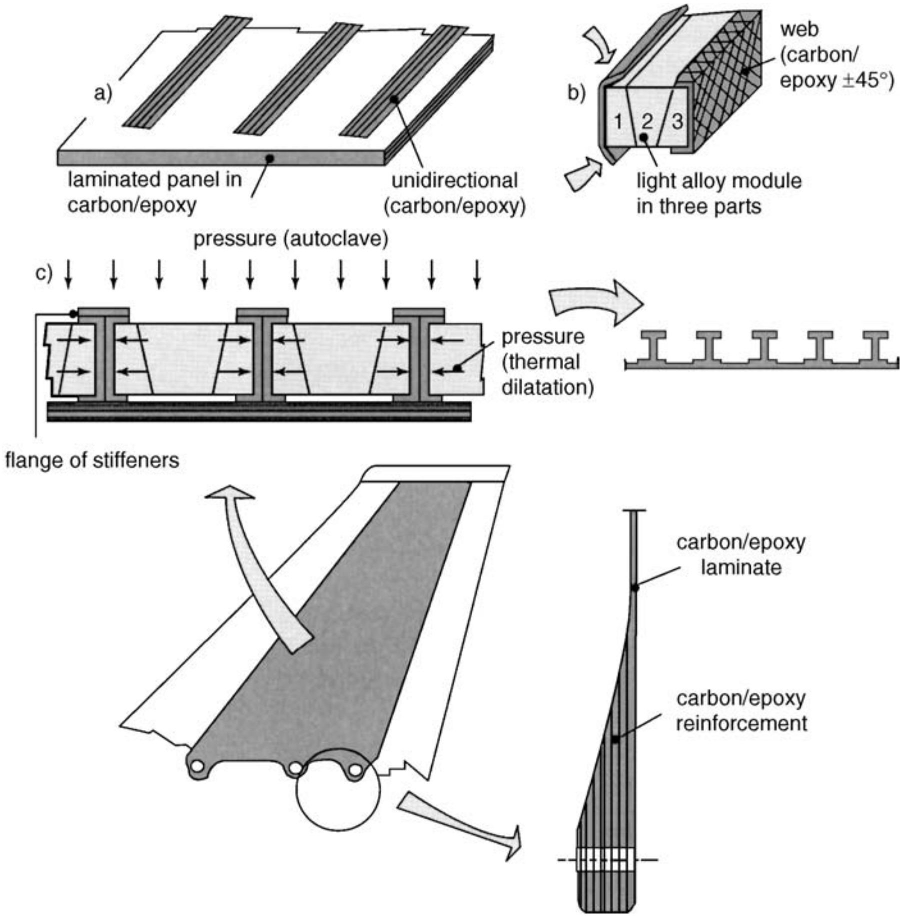

Figure 7.28 Stabilizer Panel

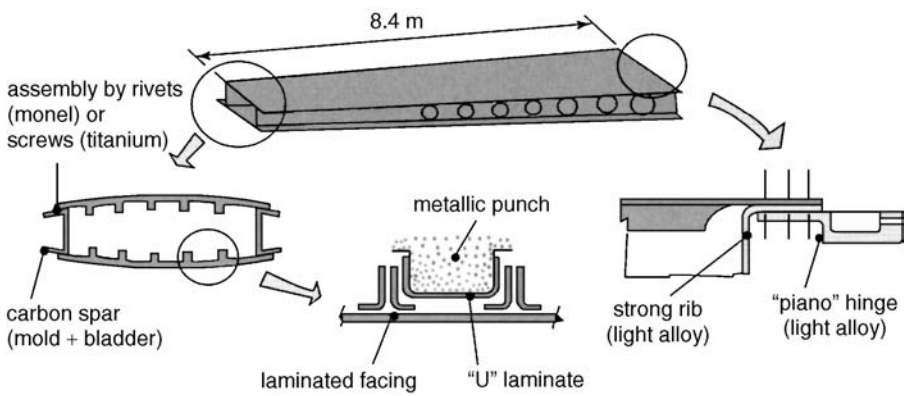

Figure 7.29 Wing Tip on ATR 72 Airplane

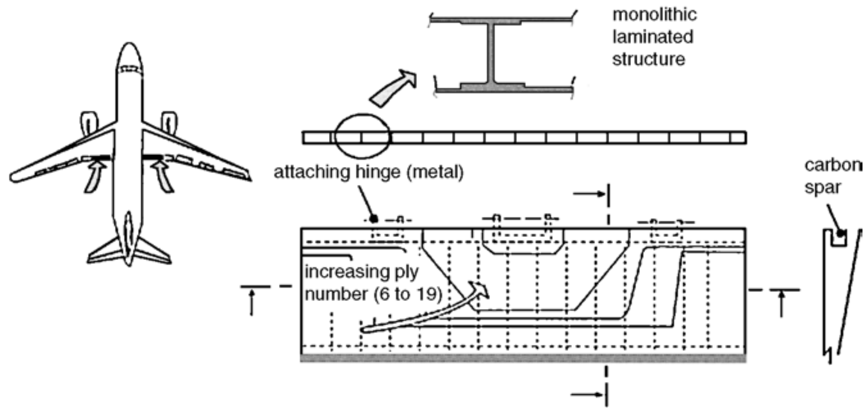

Figure 7.30 Air Brakes on Airbus A-320

"**heat absorption**" brakes, which are activated for only a few seconds (about 20 seconds). The subsequent cooling of these brakes happens progressively afterwards. The heat coming from the transformation of kinetic energy is stored in the components participating in the friction phenomenon, which serve as "**heat sinks**." These components must have the following characteristics:

- Being able to create a high braking moment which remains stable as the temperature increases
- Being able to support a very important "**thermal shock**," on the order of 10^6 joules per kg mass of the component
- Being refractory and retaining a good dimensional stability
- Being able to retain their mechanical properties at high temperature
- Having as low mass as possible

The corresponding brakes are of "disk" type. The materials that can be used to make these friction disks are compared in Figure 7.31. One can see the interest in using three-dimensional composite materials in carbon/carbon, which have the following characteristics:

- Their dynamic friction coefficient is stable with respect to the temperature, varying from 0.25 to 0.3.
- They resist thermal shock and are refractory until 1600°C.
- They retain their mechanical properties at high temperature.[12]
- They are light weight (specific mass of 1900 kg/m^3).

Example: Disk brakes in carbon/carbon (Figure 7.32) "Aerolor" (FRA).

Example: Supersonic transport aircraft Concorde (FRA-U.K.). The gain in paying passenger due to this type of brakes represents six passengers and their luggage, or 600 kg.

[12] See order of magnitude of the mechanical properties in Section 3.6.

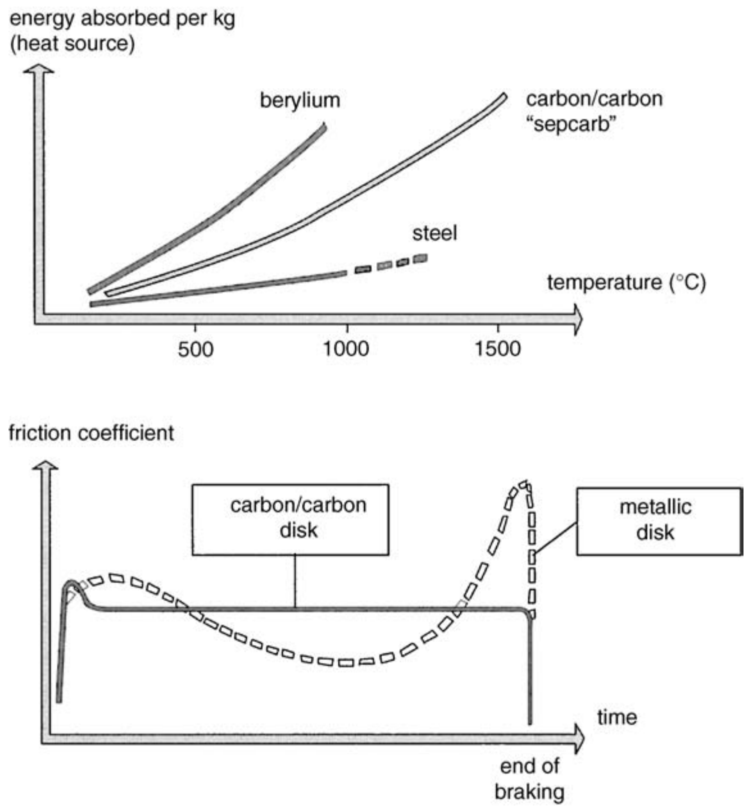

Figure 7.31 Airbrake Materials

Such types of brakes can also be developed for rapid trains, as well as for racing cars and motorcycles.

7.1.11 The Future

One can cite as the principal objectives for the airplane manufacturers:

- Obtain with composite materials a minimum mass reduction of 20% as compared with the metallic solution using the new light alloys **aluminum/lithium**. This implies the improvement in the performance of fibers and matrices.
- Improvement on the manufacturing process. The graph in Figure 7.33 shows that significant efforts remain to be done to reduce the labor cost in the manufacturing of high performance composite components.

Apart from improvement such as automatic draping or electron beam curing or by x-ray, other more classical techniques described in Chapter 2 have actually been adapted for the fabrication of aircrafts or their components. One can mention

- RTM process (see Section 2.3.1), for example, tail cone of airplane Airbus A-321.

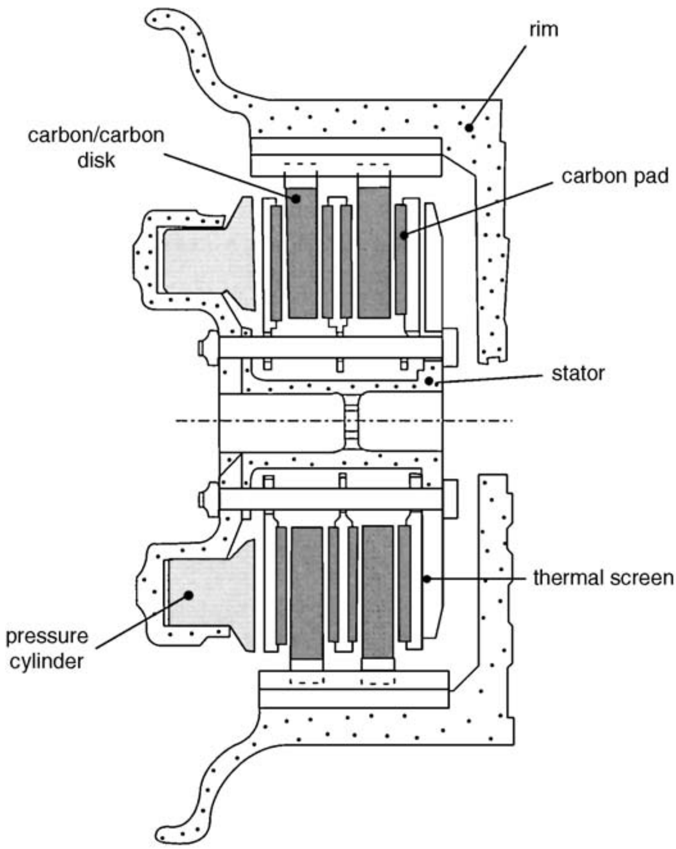

Figure 7.32 Disk Brakes in Carbon/carbon

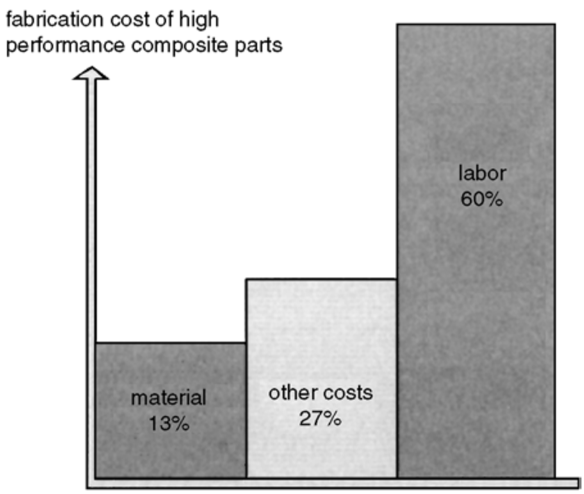

Figure 7.33 Different Costs in Composite Solution

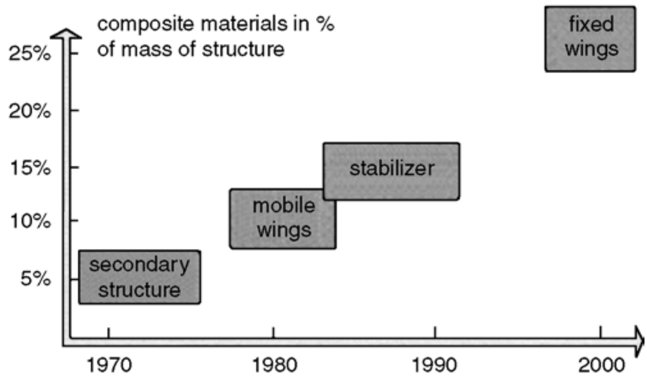

Figure 7.34 Evolution of Percent of Composite Materials in Aircraft Structure

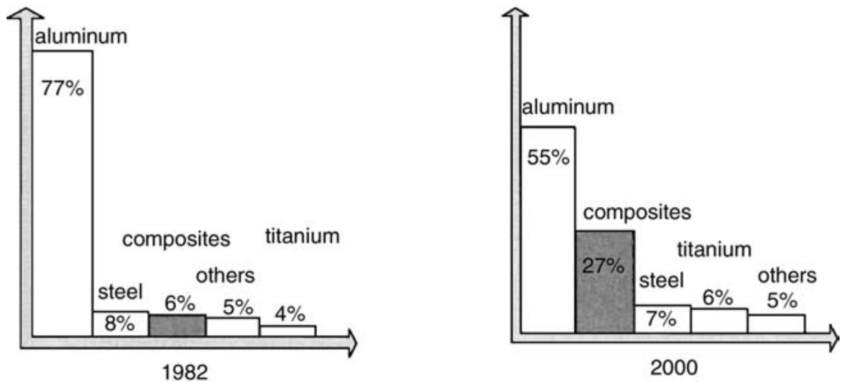

Figure 7.35 Relative Mass of Principal Materials Used in Aircraft Structures

- High pressure injection (see Section 2.1.5) with short fibers or with particles.
- Thermoforming (see Sections 2.3.1 and 2.2.3) for the small pieces.
- Compression molding (see Sections 2.3.1 and 2.1.2).

One can see in Figure 7.34 that about 20% of the mass of the structure of civil aircrafts should integrate composite materials. Figure 7.35 shows the evolution foreseen for the relative mass of the principal materials used for aircraft structures.

7.2 HELICOPTERS

7.2.1 The Situation

This category of aircraft is less advanced than the airplanes in terms of technological evolution towards "perfection" as shown in the graph in Figure 7.36.

In fact, taking into account the possibilities of specific mass reduction for this type of aircraft, one can see in the graph in Figure 7.37 the increasing trend in the strong integration of composites, with higher percentages as compared with the case of airplanes.

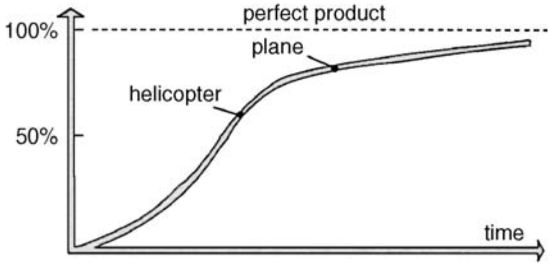

Figure 7.36 Degree of Technological Evolution

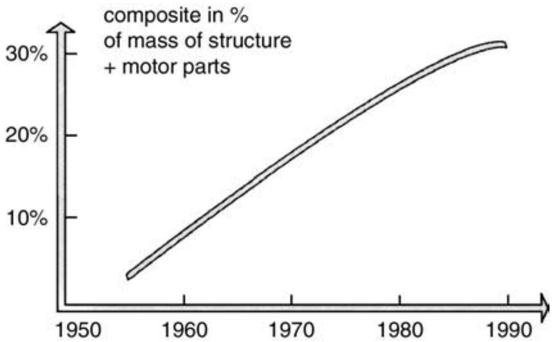

Figure 7.37 Evolution of Composites Mass on Helicopters

Example: Evolution of the mass of composite materials on the helicopters of Aerospatiale (FRA). In comparison with conventional metallic construction, one can mention the following mass reduction:\.

- 15% on the secondary structures
- Up to 50% in the working pieces, such as the elements of transmission of power and control

7.2.2 Composite Zones

Figure 7.38 shows the composite components in a helicopter.

7.2.3 Blades

The blades are the essential elements of the aircraft. They consist principally of the following:

- An envelope or a **box** that assures an aerodynamic profile and a stiffener for torsion (the blade does not twist under aerodynamic forces, at least for the actual generation of aircrafts).

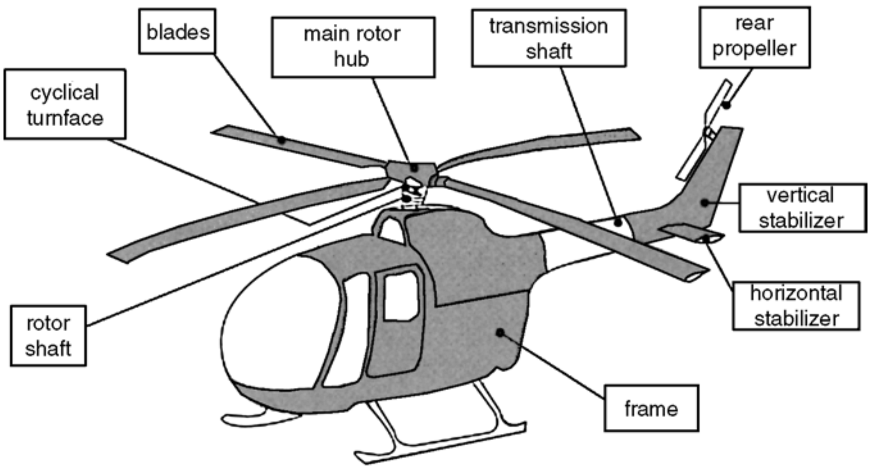

Figure 7.38 Composite Components in a Helicopter

- A spar which resists the centrifugal tension on the blade as well as the flexure caused by the lift and drag loads. It is made of glass/epoxy ("R" glass, more resistant and less sensitive to aging by humidity).
- A rear edge that stiffens the blade in flexure in the direction of the drag.
- A filler material (foam or honeycomb) that prevents the deformation of the profile.

Figure 7.39 shows the different parts of the blade.

7.2.3.1 Advantages

The list of advantages obtained with this type of design is impressive:

- The blade is molded (molding by assembly of two half shells under pressure). This solution allows one to obtain an **optimized profile** (variable chord and thickness, nonsymmetric profile, nonlinear twist).
- The stiffeners for fluttering and for torsion can be controlled thanks to judicious usage of composite materials.

7.2.3.2 Consequences

The payload is augmented. The mass reduction attains 400 kg for the aircraft Superpuma Aesrospatiale (FRA). The cruising speed is increased for the same power. The gain is 32 km/h at 1500 m altitude as compared with a previous helicopter.

- The cost of fabrication is reduced by **50%** in comparison with conventional metallic solution.
- The cost of operation is reduced.
- The life of the blade is practically **unlimited.** None of the load in the range of flight of the aircraft can lead to the fatigue damage. It is quasi-indestructible, even when testing the specimens.

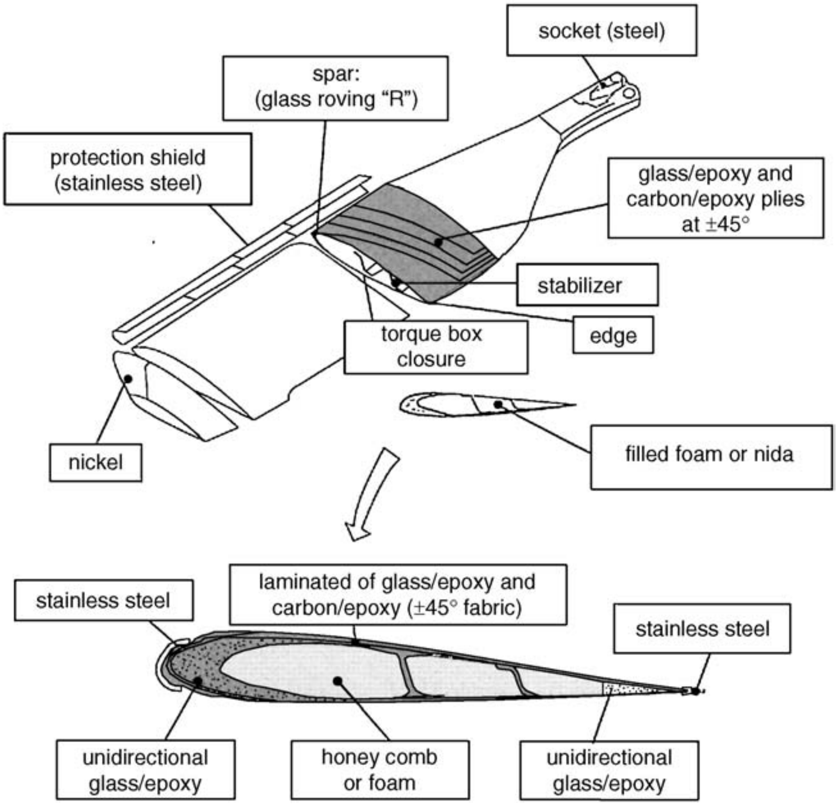

Figure 7.39 Helicopter Blade

- Increased security: the blade has the **fail safe** character.[13] An impact (projectile, collision) causes a local deterioration which does not lead to the fall of the aircraft.
- The blade is repairable with a relatively simple process.[14]
- The blade is not sensitive to corrosion.

Remarks: The blade as conceived can be ultralight. However, light weight cannot be below a value that assures a minimum inertia that is indispensable for the good operation of the rotor.

7.2.4 Yoke Rotor

This is the mechanical assembly that allows

- The rotation of the blades
- The small amplitude angular displacements of the blades during rotation

[13] See Section 7.1.4.
[14] See Section 4.4.4.

- Pitch control, that is, the control of the aerodynamic incidence of the profiles of the blades

To assure all these functions, the previous classical metallic rotors were very complex. They consisted of many pieces—in particular the ball bearings—and numerous points of lubrication. In fact, the maintenance was very costly.

The modern rotors—first developed by Aerospatiale (FRA)—substitute for these classical articulations the degrees of freedom starting from the elastic deformation:

- Composites made of metal/elastomer
- Laminates

Example: The yoke "Starflex" Aerospatiale (FRA). As its name indicates, this yoke has the form of a star with flexible arms (see Figure 7.40) obtained by draping a large amount of balanced glass/epoxy fabric and molding under heat and pressure.

The different degrees of freedom necessary for the operation as cited above are made possible by the capabilities as shown in Figure 7.41:

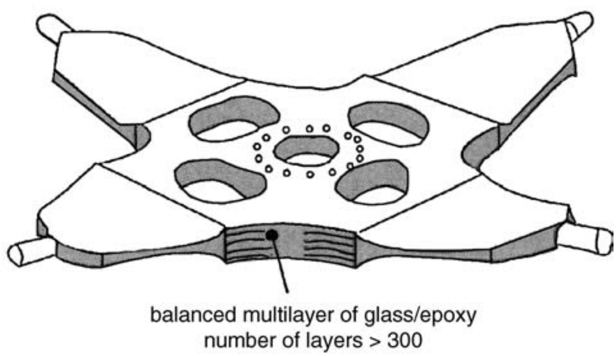

Figure 7.40 The Starflex Yoke

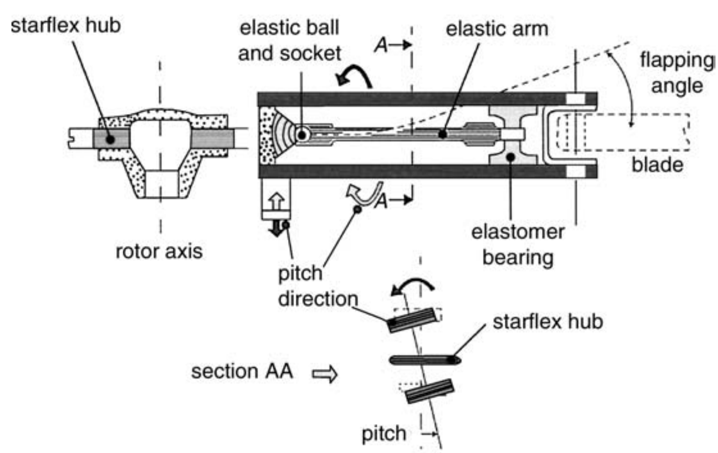

Figure 7.41 Details of the Starflex Yoke System

- The elastic arm assures angular displacement called “lift fluttering.”
- The elastic ball and socket allows for the rotation noted as pitch on the figure. This translates into a variation in the incidence of the profile.
- The elastomer bearing allows for fluttering of the blade in the plane of the figure, called “drag fluttering.”

Consequences include the following:

- A spectacular decrease in the number of components. (One goes from 377 pieces for a classical metallic solution with 30 bearings to 70 pieces for a composite solution without any bearings.)
- There is a corresponding mass reduction of 40 kg.
- There is a reduced cost of fabrication.
- The maintenance is reduced in considerable proportion, lowering significantly the hourly cost of the flight.
- There is increased security (more viability of the mechanical assembly).

7.2.4.1 Evolution of the Yoke Rotors

Example: The yoke “Triflex” Aerospatiale (FRA). The elastic deformation of the arms (see Figure 7.42) is sufficient to assure the displacements in lift, drag, and the variable incidence (pitch). The liaison arm/yoke and arm/joints of the blades are delicate works.

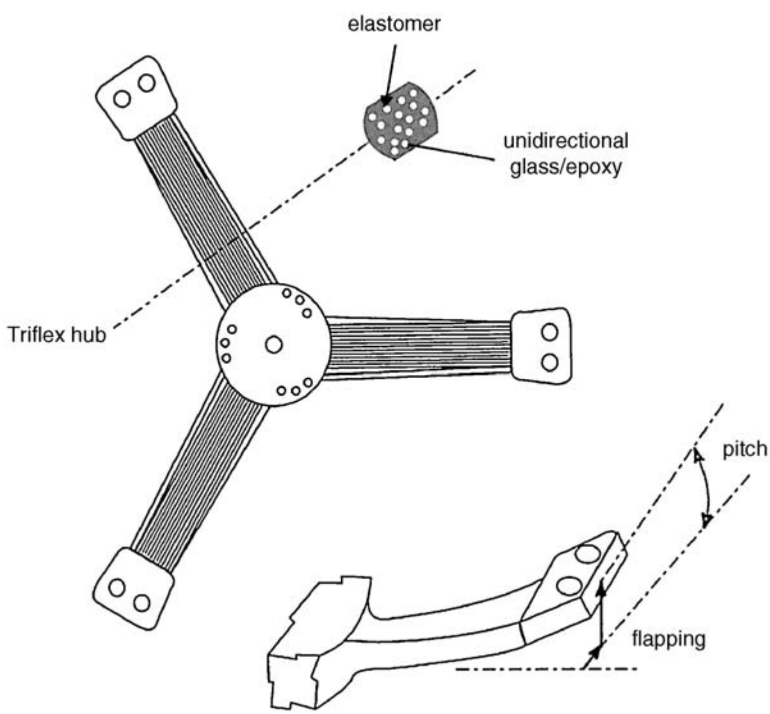

Figure 7.42 Triflex Yoke

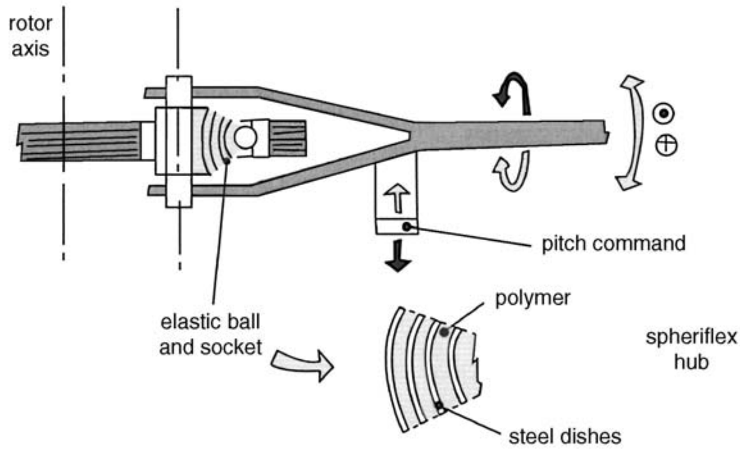

Figure 7.43 Spheriflex Yoke

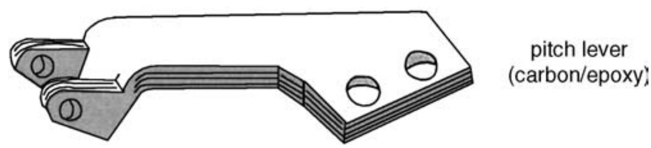

Figure 7.44 Pitch Lever

Example: The yoke "Spheriflex" Aerospatiale (FRA). This is so called because only the elastic ball-and-socket allows the various angular displacements: flapping and pitching. The foot of the blade is modified as a consequence (see Figure 7.43). The number of components becomes extremely reduced, with a minimum volume (less than the volume of the previous solutions).

7.2.5 Other Composite Working Components

Most of these are made of carbon/epoxy. The parts already in service or in development include

- The rotor mast
- The plate for the cyclical control of the pitch
- The struts for the control of the pitch
- The levers for the pitch (see Figure 7.44) where the composite design leads to a reduction of mass of 45% as compared with the metallic solution
- Lever winch gallows[15]
- The stabilizer

[15] See Section 1.5.

Example: Aircraft Dauphin Aerospatiale (FRA).

Stabilizer in light alloy	*Stabilizer in carbon/epoxy*
231 parts	88 parts
5900 rivets	0 rivets
Mass = 1	Mass = 0.78
Global cost = 1	Global cost = 0.66

In the case of the military helicopters:

- Utilization of composite materials reduces the "**radar signature**" of the helicopter.
- The damages by the projectiles on the blades, yokes, and command struts evolve more slowly in the composite parts and allow the aircraft to be able to return to its base (except for the case of a projectile shell break with a diameter larger than 20 mm).
- The "crash" resistance[16] is less for a composite structure as compared with conventional structure.

7.3 PROPELLER BLADES FOR AIRPLANES

The design using composites for the propeller blades for airplanes is analogous to that for the helicopter blades. They consist essentially of a torsion box of composite with a spar made of metal or composites.

Example: Propeller blade Hamilton Standard (USA) for the motor "14 SF" for the airplane ATR 42 (Figure 7.45).[17]

Example: Propeller blade Ratier-Figeac (FRA) for the motor of the plane TRANSALL (FRA–GER). The adoption of a spar in unidirectional glass and a torsion box in carbon leads to a particular weight reduction, when the diameters of the rotors become important, as indicated in Figure 7.46, which has the following characteristics:

- Diameter of the 4-bladed rotor: 5.5 m
- Mass of a composite blade: 51 kg
- Mass reduction as compared with a metallic blade: 53 kg (mass of a metallic blade: 104 kg)
- Total mass reduction (2 × 4 blades): 430 kg

The centrifugal inertia force at the foot of the blade decreases from 105,000 daN to 30,000 daN. This is taken up by the glass fibers in the spar which are bonded to a steel piece having the form of a tulip and addition of circumferential hoop winding of rovings to allow for the "fail safe" design. If there is bonding rupture, the blade is retained on its base by the hoop windings.

The construction of the Ratier-Figeac propeller blade is shown schematically in Figure 7.47.

[16] See Section 7.1.4.
[17] See Section 7.1.6.

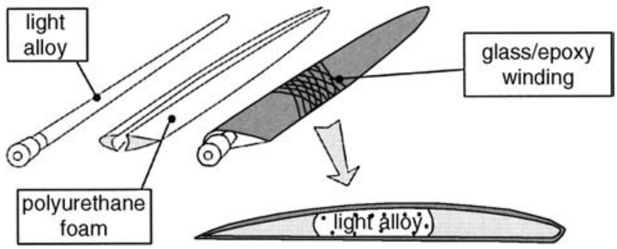

Figure 7.45 Propeller Blade, Hamilton Standard

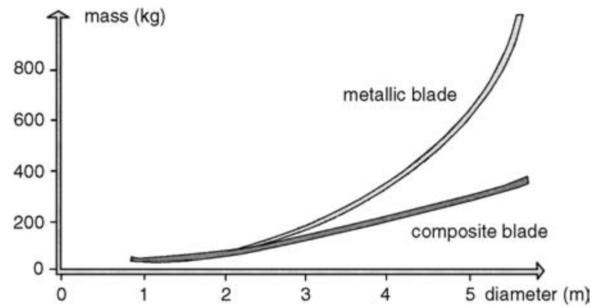

Figure 7.46 Mass Saving in Using Composites for Blades

Example: Airplane with rocking rotors XV-15 BELL (USA; Figure 7.48), propellers Dowty Rotol Ltd. (U.K.), which has the following characteristics:

- Rotor diameter: 7.6 m
- Chord at foot of blade: 0.5 m
- Mass of composites: 70% of the mass of the structure.
- Wing: stiffened panels in carbon/epoxy.

The new generation of the propellers (called "**rapid**" or "**transonic**") is destined to propel commercial airplanes with a speed close to that obtained with the jets (Mach 0.8 to 0.85, or more than 850 km/h). Interest in such propellers rests in a propulsion efficiency higher than that of modern jets (with double flux) at high speeds, as shown in Figure 7.49.

For good aerodynamic and acoustic behavior, the propellers are characterized by low thickness, a large "chord" and a strong curvature which gives them the form of an oriental saber. The complexity of the geometry combined with important speeds of rotation (more than 4000 revolutions per minute) requires the composite construction.

Example: Propeller "Propfan" Hamilton Standard (USA; Figure 7.50). Made of two rotors in "counter-rotation," this is designed to propel the middle range airplanes. The method of fabrication is the same as the more classical propellers mentioned above: a spar made with light metal alloy forged and machined. A filling foam is molded around the spar to give the form of the torsion box in glass/epoxy.

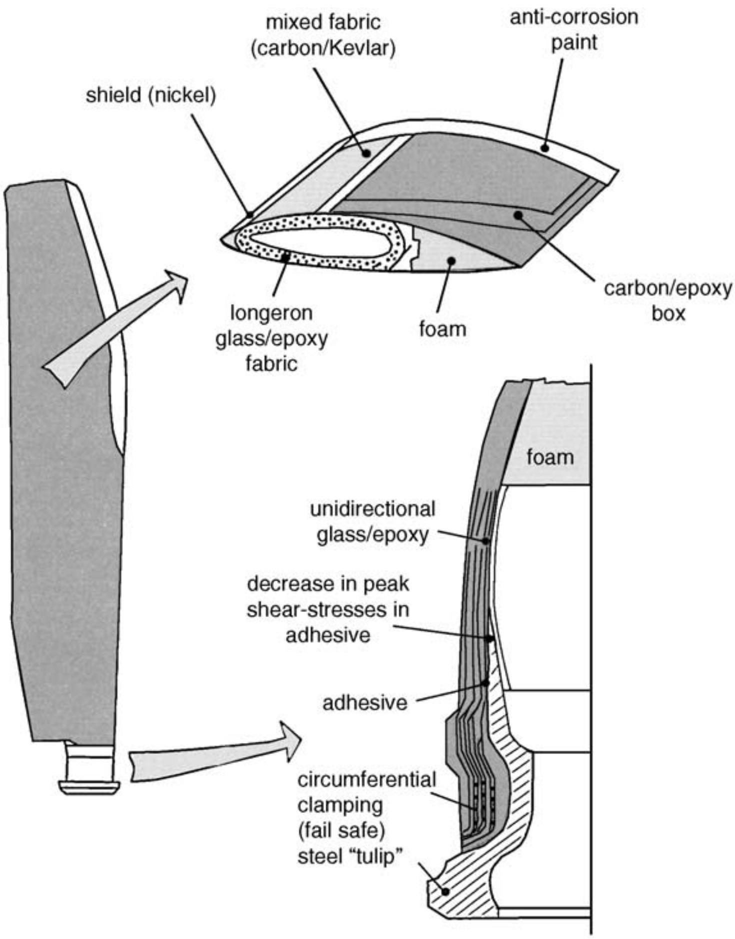

Figure 7.47 Ratier-Figeac Propeller Blade

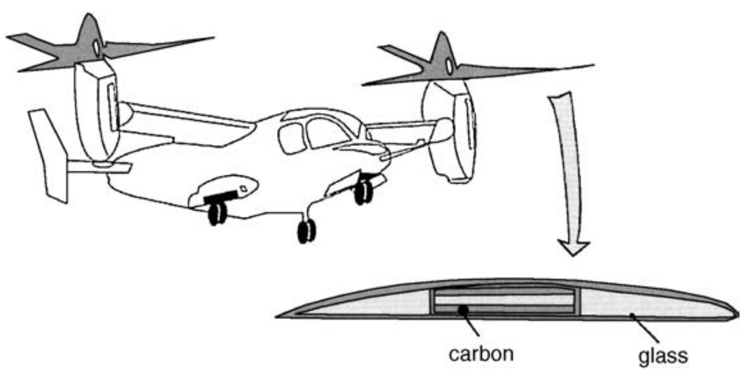

Figure 7.48 Rocking Rotor in Bell XV-15 Plane

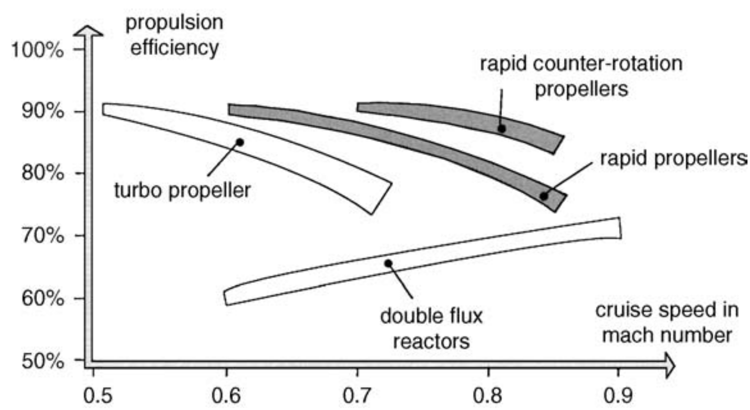

Figure 7.49 Propulsion Efficiency of Propellers

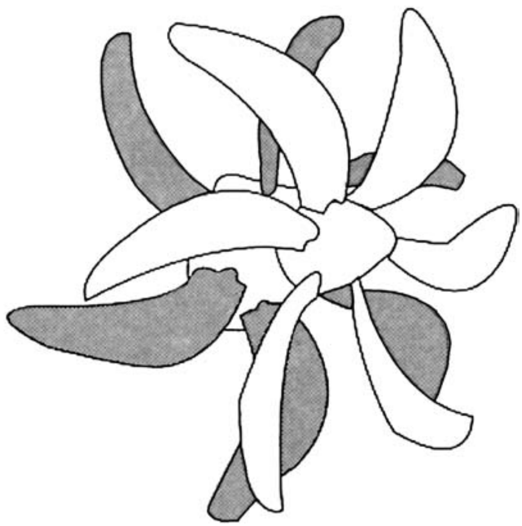

Figure 7.50 Profan Propeller

Example: Transonic propeller "Charme" ONERA (FRA; Figure 7.51). The number of blades is high (12) to reduce the load in each blade. The blades are made of carbon/epoxy bonded to the titanium foot of the blades.

7.4 TURBINE BLADES IN COMPOSITES

Research to increase the efficiency of aeronautical motors leads to the increase of

- Air compression ratios, which reach the values on the order of 45.
- Temperatures of the gases in the turbines. The fixed or mobile blades in the release stages have to operate with a gas temperature on the order of 1500°C.

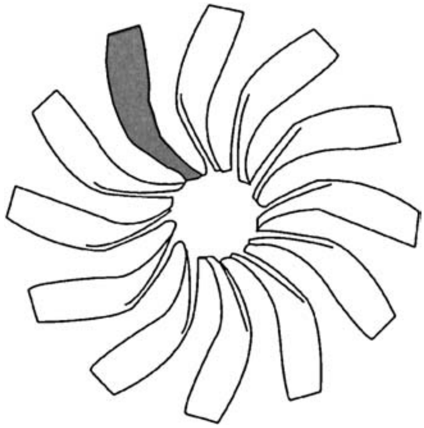

Figure 7.51 The Transonic Propeller "Charme"

Among the materials experimented with in view of increasing the operating temperature are the "oriented eutectics." These are composed of two distinct phases:

- A superalloy phase with nickel base
- A carbon phase

The solidification of this alloy is directed with a solidification front (interface between the liquid and the solid). The carbon phase is developed in the form of fibers with diameters on the order of microns and of infinite length, and parallel to the direction of displacement of the solidification front. One then obtains a unidirectional composite metal/metal.

The advantages and disadvantages of these types of materials can be summarized as follows:

- **Pluses:**
  It is possible to obtain directly, using solidification, pieces with the form of the turbine blades.
  There can be a gain of 30°C on the maximum operating temperature of actual blades.
- **Minuses:**
  The growing speed of the composite is low: 2 cm/hour.
  The proportion of fibers is low (5% to 10%) and cannot be controlled because it is constrained by the composition of the eutectic.
  The material is sensitive to thermal fatigue due to the run–stop operating cycles of the turbine.
  Fracture resistance at temperatures above 900°C is weaker than that for super alloys in actual service.

7.5 SPACE APPLICATIONS

There is no doubt that for launchers, space shuttles, and satellites the reduction of mass is most critical. Each kilogram reduction on the launcher for the European rocket Ariane E.S.A. (EU) gives a gain in payload of 30,000 US dollars.

7.5.1 Satellites

The structural part of the satellites is essentially constituted of an assembly of tubes and plates. Principally the structure has to

- Resist average and fluctuating accelerations of the launch, counted as number of times the acceleration of gravity ($g = 9.81$ m/sec^2), up to $5 \times g$ continuously and $5 \times g$ maximum amplitude in sinusoidal fluctuation, for frequencies up to 40 Hz. (In order to avoid resonance, the structure has to be very rigid. It is the **rigidity** that appears like the factor that controls the dimensions.)
- Be quasi-insensitive to temperature variations (such as in the case of precision optical instruments: telescope, high-resolution camera). Here, carbon is used for the tubular structure (very low coefficient of expansion, on the order of 10^{-7}).[18]

The primary structures of satellites can include sandwich plates, with the following characteristics:

- Light alloy honeycomb cores (not Nomex[19] because of gas emission in space).
- Facings (skins) made of laminates, without mirror symmetry for maximum lightness. The thickness of the skin is on the order of 0.1 mm. When demolding,[20] they are very deformed. These are then bonded onto the aluminum core. One then obtains a sandwich plate that is globally balanced.

Example: Camera V.H.R. (Visible high-resolution) SPOT (FRA), which is the upper part of the satellite shown in Figure 7.52.

In the case of the spatial structures, among the foreseen solutions for the construction of tubular space stations, one can experiment on tubes made of extruded carbon with junctions of half-shell made of carbon.

7.5.2 Pressure Vessels

The pressure vessels contain the combustibles, fuel or "powder," for the propulsion. These can be made by winding impregnated unidirectional ribbons over a mandrel with a particular form. The mandrel must be resistant to shrinkage after polymerization and should be designed to be extractable (see Figure 7.53).[21]

The **efficiency** of a filament-wound pressure vessel is defined as:

$$\underset{\text{(meters)}}{\text{efficiency ratio}} = \frac{p(\text{burst pressure})}{\rho g(\text{specific weight})}$$

and has the units of length, for example:

- Efficiency of glass/epoxy: 25 km.
- Efficiency of Kevlar/epoxy: 35 km.

which explains the predominant use of Kevlar/epoxy in these applications.

[18] See Section 1.6.
[19] See Section 1.6.
[20] See Section 5.2.3.
[21] See Section 2.1.7.

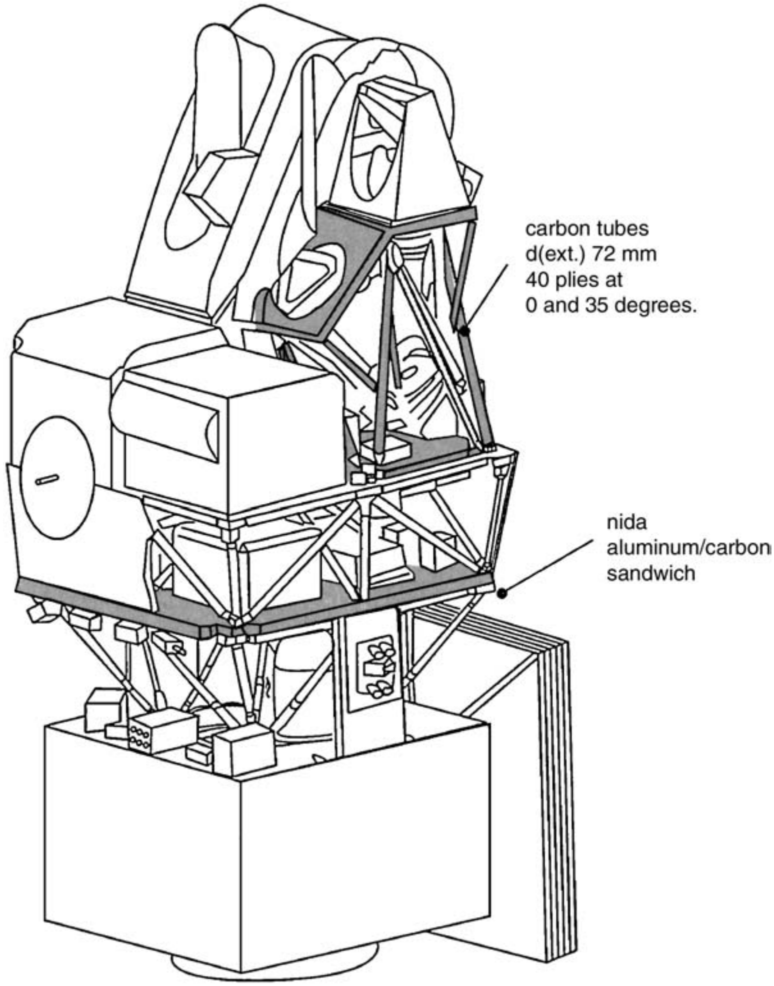

Figure 7.52 Camera V.H.R Spot

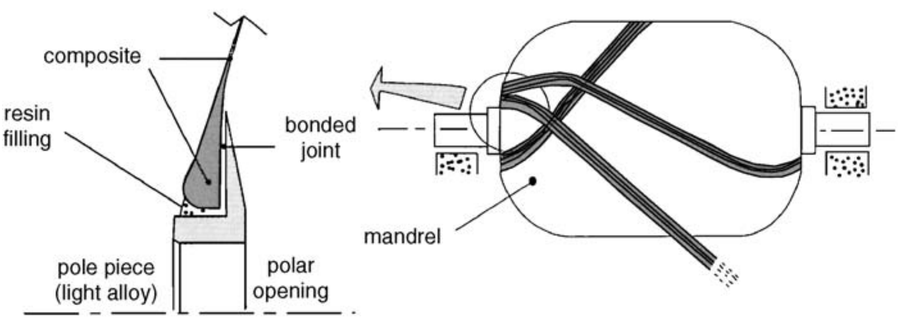

Figure 7.53 Filament-wound Pressure Vessel

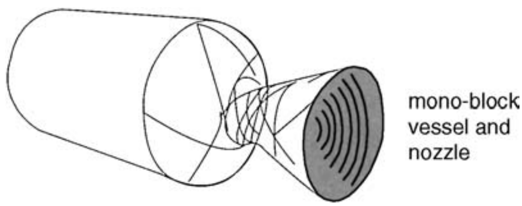

Figure 7.54 Filament Winding for Mono-block Part

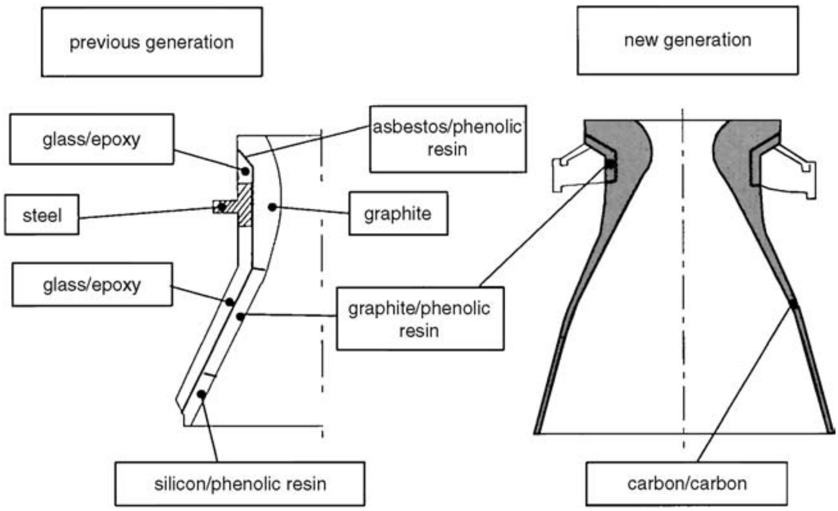

Figure 7.55 Evolution of the Structure of Nozzles

For some applications, the principle of filament winding allows one to obtain vessels and tubes at the same winding session (see Figure 7.54).

7.5.3 Nozzles

The propulsion nozzles of solid propergol (powder) have operating temperatures up to 3000°C during several dozens of seconds, with pressures varying between a few bars and several dozens of bars.[22] The material making up the internal liner disappears progressively by decomposition, melting, vaporization, and sublimation. This is the phenomenon of **ablation**.

The materials that can play such a role have to possess

- A strong resistance to ablation at a high operating temperature
- A low specific mass
- A strong resistance to mechanical and thermal shock

Figure 7.55 shows the evolution of the structure of these nozzles until the advent of the three-dimensional carbon/epoxy composite materials with the mechanical characteristics indicated in Section 3.6.

[22] 1 bar = 0.1 *MPa*.

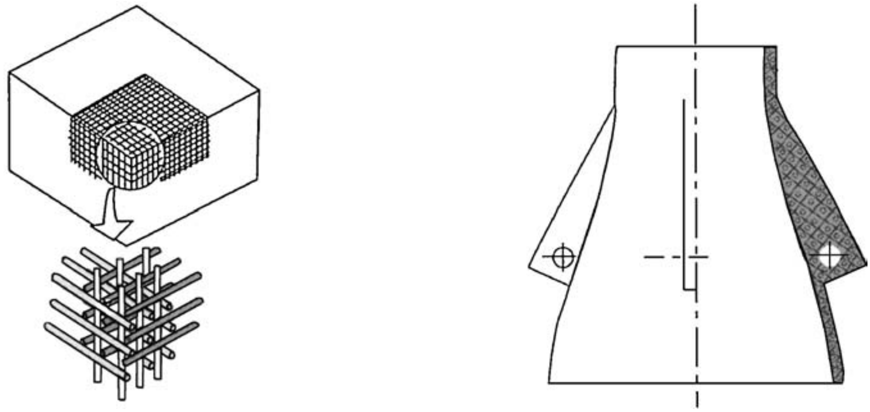

Figure 7.56 Sepcarb Material for Propulsion Nozzles

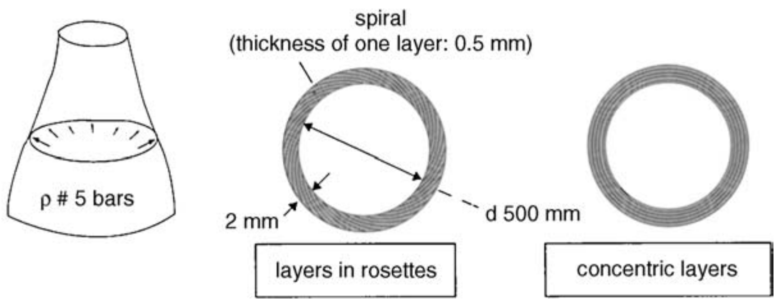

Figure 7.57 Nozzles in Rosette Form

Example: Material "Sepcarb" European company for propulsion (FRA; Figure 7.56).[23] The quantity of heat before ablation can reach 84×10^6 joules per kilogram of material. For example the motor for peak operation of the European launcher Ariane, with the divergent nozzle made of carbon/epoxy, has the following characteristics:

- A mass reduction of 50% in comparison with previous nozzle constructions
- A gain of the launch force of 10% thanks to higher elongation

Example: Divergent nozzle with "rosette" layering. Figure 7.57 shows the difference in constitution of this type of nozzle and a nozzle with classical concentric stratification, with a few orders of dimensional amplitude.

To compare with the concentric stratification, this design:

- allows more convenient machining (more precise work of the lathe tool).
- is more resistant to delamination.

[23] See Section 3.6.

7.5.4 Other Composite Components

7.5.4.1 For Thermal Protection

One can distinguish two modes on entrance into the atmosphere during the return of the space vehicles:

- Rapid entrance with strong incidence: This is the case of the ballistic missiles and manned capsules. The heat flux is very high (on the order of 10,000 kW/m^2) with relatively short time of entrance. One can use, depending on the particular case:
  - Heat sinks[24] in carbon/carbon or in beryllium (for case of the ballistic missiles).
  - Ablative materials (see above for the case of the nozzles) for the manned capsules.

- Slow entrance with weak incidence: This is the case of hypersonic planes or "space shuttles." The duration of the entrance is on the order of 2000 seconds. The heat fluxes are weaker but can attain hundreds of kilowatts per square meters of the structure at the beginning of the entrance (80 km altitude), for example:
  - 500 kW/m^2 at the leading edge
  - 100 to 200 kW/m^2 on the under part

The entrance temperatures reach 1700°C, or 2000°C at the nose of the shuttle. There are several types of thermal protection, depending on the zones of the equipment and the reutilization of the facing:

- Heat sinks[25] associated with insulation
- Reflective thermal barrier (lining of the vehicle reflects the heat flux it receives)
- Ablative facing (The transformation of the facing by fusion, vaporization, sublimation, chemical decomposition absorbs the heat, and the vaporized gases cool the remaining layer, decreasing also the convective thermal flux.)

The areal masses of these devices are related to the limiting admissible temperatures of the structure immediately below (see Figure 7.58).

Example: NASA space shuttle (USA), which has an empty mass of 70 tons.

Depending on the zones, one uses the linings made of composites of carbon/carbon or silicon/silicon and pieces of structure (horizontal members, cross members) in boron/aluminum. The useful temperature of the latter is 300°C for continuous use and up to 600°C for peak applications.

The under part is protected by composite "tiles" in silicon/silicon ceramic[26] that constitutes a reflective thermal barrier. The tiles are separated from the structure of light alloy or laminated boron/aluminum by a sandwich of felt and nonflammable

[24] See Section 7.1.10.
[25] See Section 3.7.
[26] See Sections 2.2.4 and 3.6.

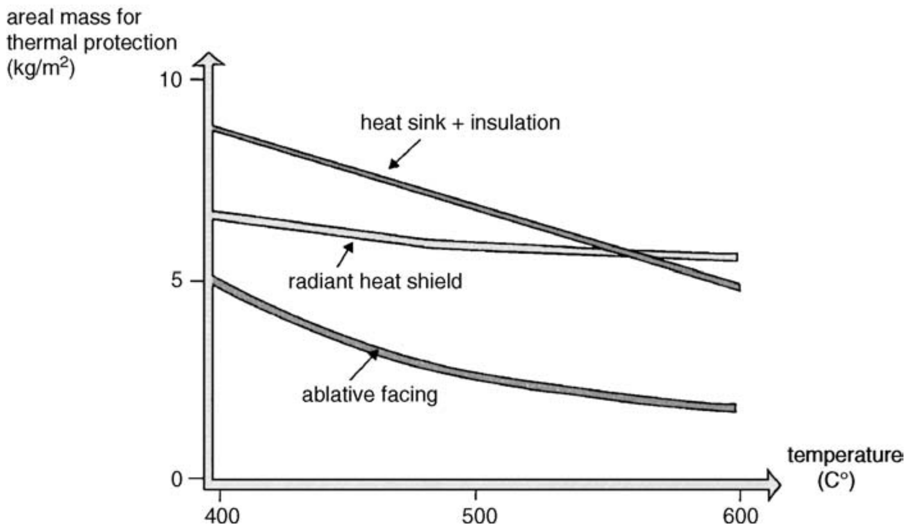

Figure 7.58 Areal Mass for Thermal Protection

nylon/silicon/"NOMEX" honeycomb. There are about 30,000 tiles. Their installation is shown in Figure 7.59.

Example: Space shuttle Hermes (EU), which has an empty mass of 8.5 tons. The tiles are replaced by thousands of pieces made of carbon/carbon, silicon/silicon (see Figure 7.60). The pieces have to be reused for thirty landings.

7.5.4.2 For Energy Storage

On board satellites and space stations, systems using the composite flywheels for the supply of electric power and for the control of attitude provide a mass reduction of 25% as compared with conventional storage methods using batteries and gyroscopic means (specific power on the order of 5 kW per kilogram of the device). In addition, in the Strategic Defense Initiative program (USA), the devices of flywheels can deliver high levels of specific powers on the order of 100 kW per kilogram of the device.

The peripheral speeds can attain 1400 m/sec (filament-wound flywheels in carbon), and the speeds of rotation from 40,000 to 60,000 rpm.

Example: Development of an energy storage module (USA; Figure 7.61).

- Total mass: 200 kg (occupied volume: 0.15 m^3)
- Specific energy: 230 kJ/kg (total energy # 46,000 kJ)
- Peripheric speed: 1100 m/sec

Figure 7.62 shows different solutions for the construction of carbon/epoxy flywheels.

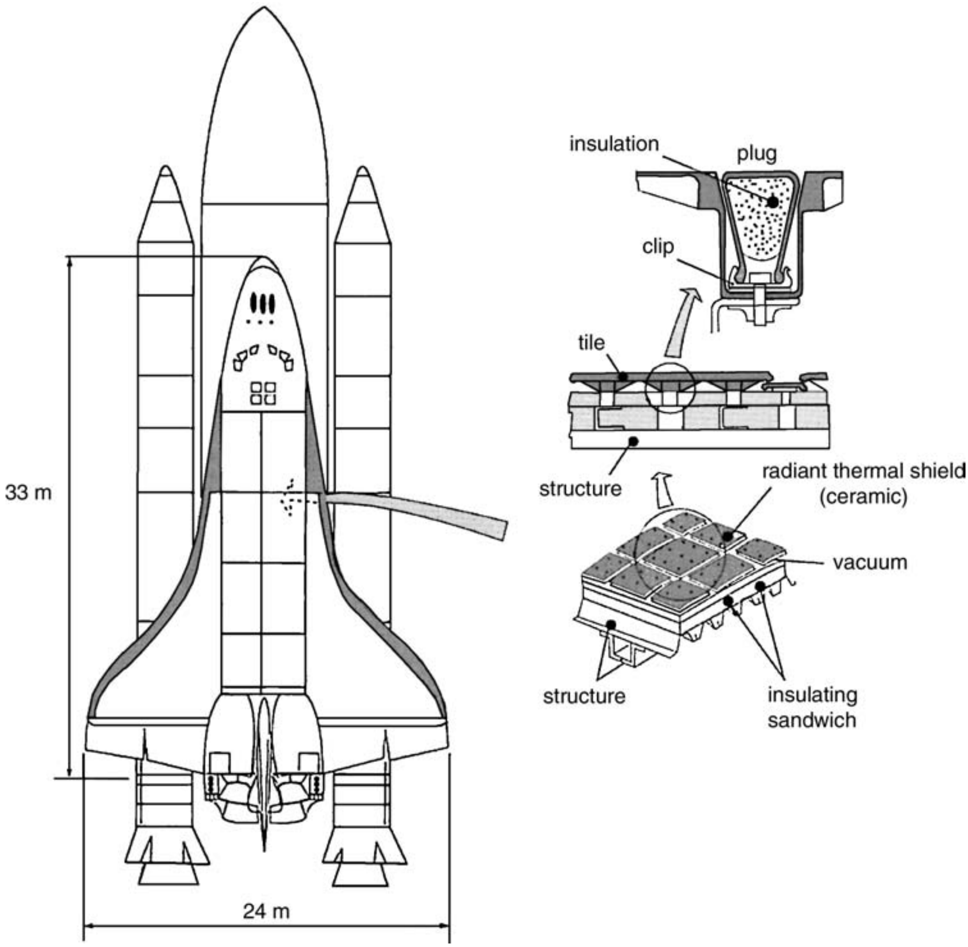

Figure 7.59 NASA Space Shuttle

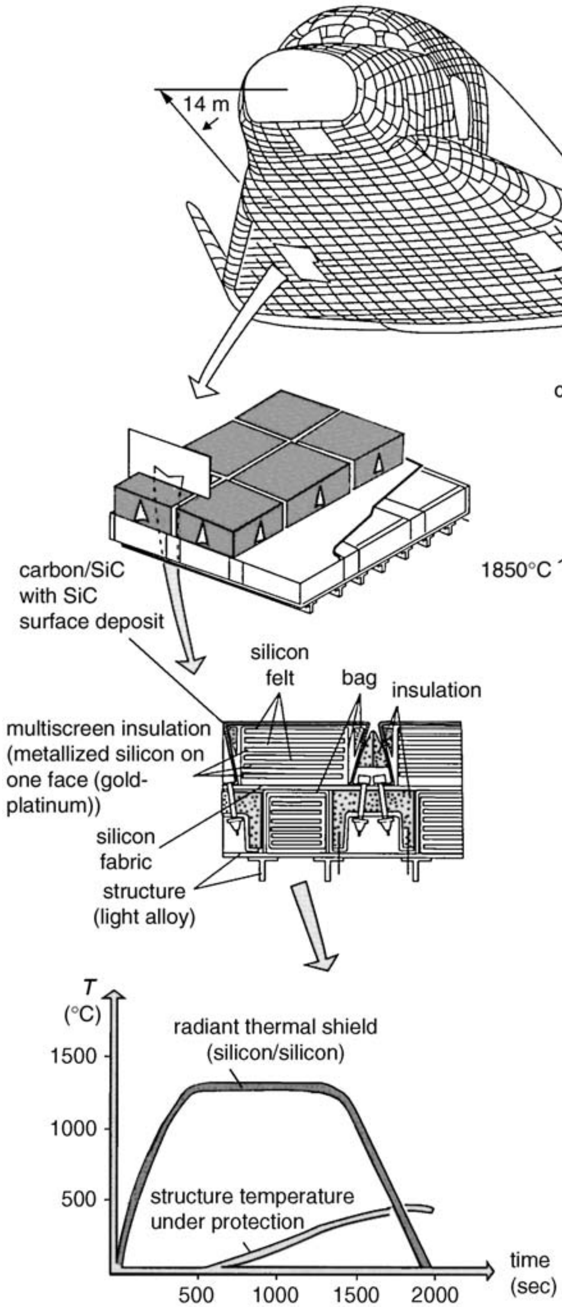

Figure 7.60 Space Shuttle Hermes

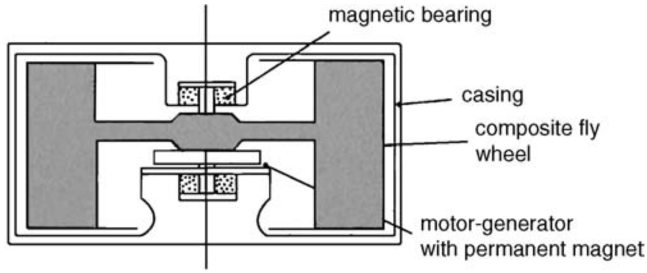

Figure 7.61 Flywheel Energy Storage

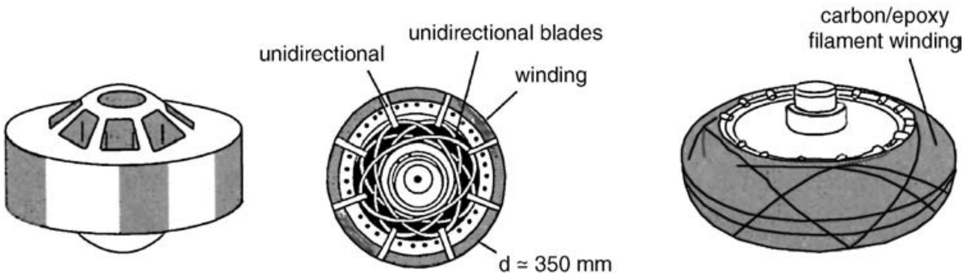

Figure 7.62 Different Flywheel Designs