Chapter 14
Carbon Fibre Polymer Matrix Structural Composites

R.J.H. Wanhill

Abstract This chapter concisely surveys the applications and properties of polymer matrix structural composites (PMCs), concentrating on carbon fibre reinforced composites. These are the most widely used composite materials, notably in aerospace, and are commonly called carbon fibre reinforced plastics (CFRP). A major source for this chapter is Baker et al. (Composite materials for aerospace structures. American Institute of Aeronautics and Astronautics, Inc., Reston, Virginia, USA, 2nd edn, 2004).

Keywords Polymer matrix composites · CFRP · Processing · Properties · Damage Tolerance · Applications

14.1 Introduction

Aircraft structural materials must have outstanding combinations of engineering properties and also enable the manufacturing of lightweight and durable structures (i.e. the airframe). Aluminium alloys have predominated in aircraft manufacturing since introduction of the Boeing 247 (1933) and Douglas DC-2 (1934), but composites (mainly carbon fibre reinforced plastics, CFRP) increasingly provide competition, Fig. 14.1.

There are two more points to note with reference to Fig. 14.1:

1. Tactical aircraft tend to use higher percentages of composites than transport aircraft.
2. Military aircraft with special qualities (VTOL, stealth) have higher percentages of composites than their more conventional contemporaries. (The Northrop Grumman B2 has a high-cost composite airframe mainly because of the radar-absorbing properties.)

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N. Eswara Prasad and R.J.H. Wanhill (eds.), *Aerospace Materials and Material Technologies*, Indian Institute of Metals Series,
DOI 10.1007/978-981-10-2134-3_14

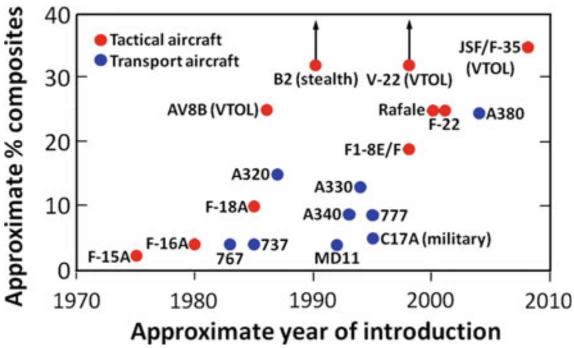


Fig. 14.1 Increasing use of CFRP composites in aircraft: main source Ref. [1]

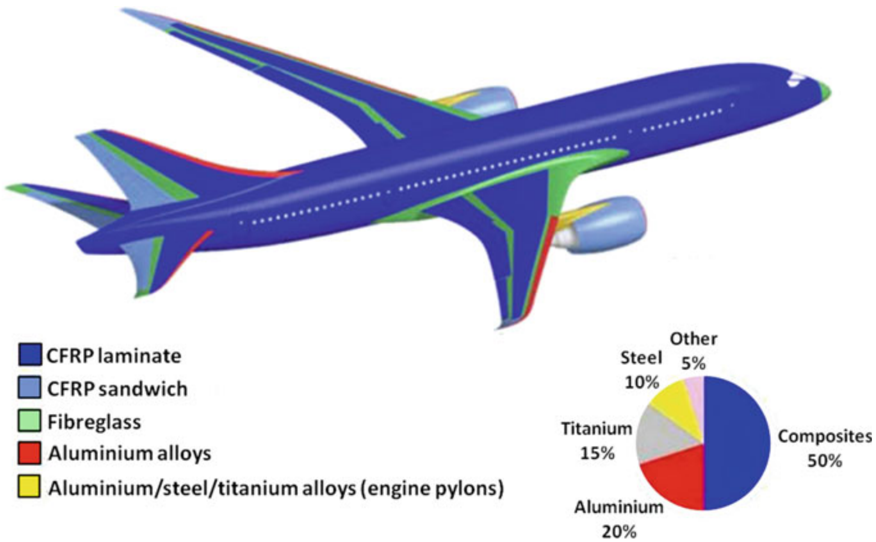


Fig. 14.2 Airframe materials distributions and percentages for the Boeing 787: The Boeing Company

For civil transport aircraft the introduction of the Boeing 787 (2011) and Airbus A350 (2015) represents a potential 'game changer'. The airframes are about 50 and 52 % composites, respectively, e.g. Figure 14.2. However, some authorities doubt whether future aircraft in the Boeing 737 and Airbus A320 size category will have such high percentages of composite structures, since they are more expensive than comparable aluminium alloy structures. There are also other disadvantages, as well as advantages, in using composites, as will be discussed in Sect. 14.4.

What is more evident is an increasing trend to design and build hybrid airframe structures for both civil and military aircraft. An illustration of this trend is provided by Fig. 14.3, which points out the various types of materials in major structural locations of the Airbus A380. The amount of composite structure in the A380 is about 22–24 %, which is significantly higher than in previous transport aircraft, see Fig. 14.1.

N.B: Information on conventional aluminium alloys and aluminium-lithium (Al–Li) alloys is given in Chaps. 2 and 3 of this Volume of the Source Books. Al–Li alloys are also the subject of a recent book [2]: they can provide structural efficiencies that rival those of composites. GLARE (GLAss REinforced aluminium laminates) is discussed in Chap. 13 of this Volume.

14.2 Types of Composites

Composites are materials composed of two or more physically distinct components whose combination results in enhanced properties. The primary component is a continuous matrix. The secondary (but no less important) component is the filler material or materials. Composites may be classified into several categories, based on the materials used and also the fabrication methods. An overview concentrating on carbon fibre polymer matrix composites (PMCs) is given in Fig. 14.4.

Fig. 14.3 Airframe materials distributions for the Airbus A380 [2]: AA 2XXX, 6XXX and 7XXX = conventional aluminium alloys; *Al–Li* aluminium–lithium alloys; *LBW* Laser Beam Welding [3]

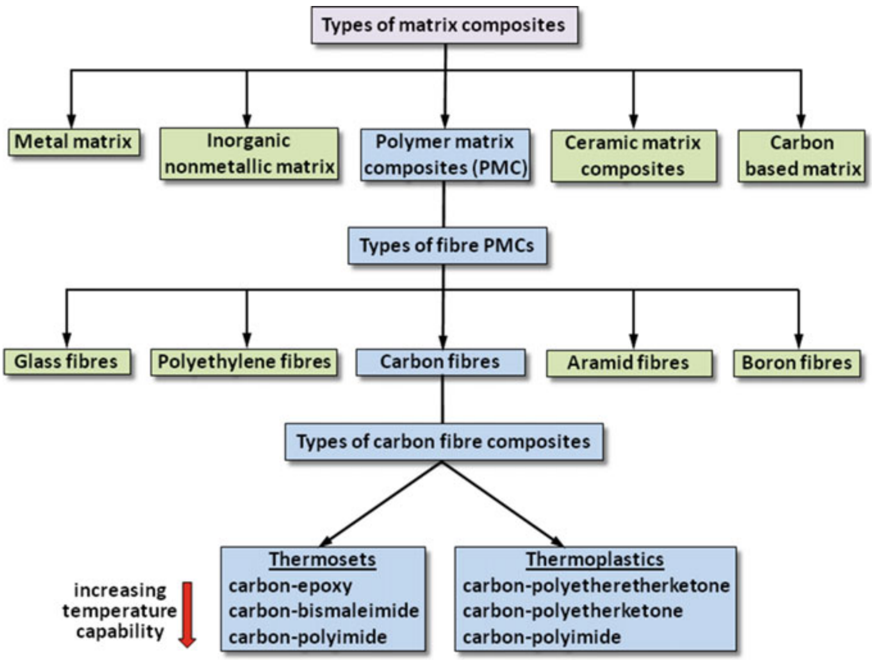


Fig. 14.4 Composites progressively classified according to the types of (i) matrix, (ii) fibre PMCs, (iii) carbon fibre—PMC (CFRP) thermosets and thermoplastics: main source Ref. [1]

14.3 CFRP Composites

14.3.1 CFRP Composite Matrices

As Fig. 14.4 shows, there are two categories of CFRPs, thermosets and thermoplastics, depending on the type of matrix:

Thermosets: The most widely used thermosets for aircraft structures are epoxy resins, since they are readily processed and have good chemical and mechanical properties. They also undergo a low-viscosity stage during cure, thereby enabling liquid resin-forming techniques like resin transfer moulding (RTM) [1], see Sect. 14.3.3.

Bismaleimide resins (BMIs) have similar processability and mechanical properties compared to epoxies. However, the higher resin costs limit their use to operating temperatures (up to about 180 °C) that are beyond those of epoxies (100–130 °C).

For higher operating temperatures polyimides could be used. These allow operating temperatures up to 300 °C, but they are more expensive than BMIs and much more difficult to process [1].

Thermoplastics: The matrices for thermoplastic CFRPs include polyetheretherketone (PEEK), used up to 120 °C; polyetherketone (PEK), up to 145 °C; and thermoplastic-type polyimide, up to 270 °C [1]. These three matrix types are the most suitable for aerospace applications.

Thermoplastics are fully polymerised before they are used to make composites. Hence they are unsuitable for RTM. Fabrication by resin-film infusion (RFI) or hot pressing of pre-coated fibres (prepregs) is more suitable [1].

Comparisons of the properties of thermosets and thermoplastics are presented in Table 14.1. Important points in comparing and considering thermosets and thermoplastics are:

1. Thermosets have relatively low fracture strains and fracture toughness, which result in poor fracture resistance in CFRPs. Thermosets also absorb moisture, which reduces the matrix-dominated properties like elevated temperature shear and compressive strengths [1].
2. Thermoplastics are generally more expensive and require high processing temperatures and pressures, which increase the cost differentials.
3. Overall, thermoset CFRPs are more extensively used, with thermoplastic CFRPs favoured when the need for high resistance to impacts and edge damage justifies the higher costs [1].

Table 14.1 Properties and comparisons for thermosets and thermoplastics [1]

Thermosets	Thermoplastics
Main characteristics	
• Undergo chemical change when cured • Low strain to failure • Low fracture energy • Irreversible processing • Very low-viscosity possible • Absorbs moisture • Highly resistant to solvents	• Non-reacting, no cure required • High strain to failure • High fracture energy • Very high viscosity • Processing is reversible • Absorbs little moisture • Limited resistance to organic solvents, in some cases
Advantages	
• Relatively low processing temperature • Good fibre wetting • Formable into complex shapes • Liquid-resin manufacturing feasible • Resistant to creep	• Short processing times possible • Reusable scrap • Post-formable: can be reprocessed • Unlimited shelf life without refrigeration • High delamination resistance
Disadvantages	
• Long processing time • Long cure (~1–2 h) • Restricted storage life (requires refrigeration)	• Lower resistance to solvents • Requires high temperature (300–400°C) and pressure • Can be prone to creep • Very poor drapability[a] and tack[b]

[a]Ability of a fabric to form pleating folds when deformed under pressure
[b]Adhesive quality

14.3.2 CFRP Composite Fibres

There are three categories of carbon fibres used in aerospace CFRPs. These are high modulus (HM, Type I), high strength (HS, Type II) and intermediate modulus (IM, Type III). Examples of their properties are given in Table 14.2, which shows the considerably different mechanical properties of the three types of fibres. Although the strength properties of HM and HS fibres overlap somewhat, it is evident that there is a trade-off between modulus and strength: high modulus (HM) is traded for high strength (HS).

N.B: Fibre manufacturers present a bewilderingly wide range of tensile moduli and strength values within the three fibre categories. Furthermore, there are two other categories, referred to as ‘standard’ and ‘ultrahigh modulus’ (UHM). The trade-off for the UHM category is fracture resistance: the higher the modulus, the more brittle the fibres.

Carbon fibre production: The fibres are made from organic precursors by carbonisation. Most are made from polyacrylonitrile (PAN) fibres, which give the best carbon fibre properties. However, they can also be made from pitch. Details of the PAN and pitch-based fibre carbonising process are given by Baker et al. [1]. The final properties of the fibres depend on the processing details and also whether the fibres undergo a final graphitisation heat treatment.

Carbon fibre filaments: The finished PAN fibres have diameters between 5 and 10 μm. Examples are shown in Fig. 14.5. The surface finish is reminiscent of tree bark. Additional processing can strip off the ‘bark’, leaving smoother and smaller diameter fibres that can be packed into smaller spaces in the matrix, and hence provide higher stiffness per cross-sectional area. However, these fibres are more expensive owing to the additional processing.

Dry carbon fibre products: The PAN fibre process is set up to produce continuous fibre bundles called tows, which are used for weaving into fabrics with various weave patterns. These undergo subsequent processing into PMCs using pre-impregnation (prepreg), resin films or liquid resin injection.

Table 14.2 Typical properties of commercial carbon fibres [1]

Property	HM type I	HS type II	IM type III
Density (g/cm^3)	1.9	1.8	1.8
Tensile modulus (GPa)	276–380	228–241	296
Tensile strength (MPa)	2415–2555	2105–4555	4800
Ultimate strain (%)	0.6–0.7	1.3–1.8	2.0
Thermal expansion (X10^{-6} mm^{-1} K^{-1})	−0.7	−0.5	N/A
Thermal conductivity (Wm^{-1} K^{-1})	64–70	8.1–9.3	N/A
Resistivity (μΩ m)	9–10	15–18	N/A

Prepreg products: These are made by infusing fibre tows and fabrics with epoxy resin. The prepregs are subsequently processed into PMCs. Most prepregs are unidirectional tapes and are made by spreading and collimating many fibre tows into a sheet of parallel fibres that is then prepregged.

14.3.3 CFRP Aerospace Components Production

The manufacturing of aerospace components and structures from CFRPs is discussed in detail in Chap. 5 of Ref. [1]. An overview is given here.

The main method of making CFRP aerospace components is (i) the lamination of woven fabrics or aligned-fibre sheets and tapes. The other methods are (ii) resin transfer moulding (RTM); (iii) filament winding and (iv) braiding onto rotating mandrels; (v) tow placement; and (vi) pultrusion [1]. Table 14.3 lists typical CFRP aerospace composite forms that can be made by these techniques.

However, there is much more to manufacturing CFRPs than the choice of forming technique: Fig. 14.6 is an example of the several steps involved from producing carbon fibres to obtaining a finished component. In this schematic the 'Intermediates' represent some of the above-mentioned forming techniques, notably laminating (lay-ups) and filament winding.

Figure 14.6 also helps to explain an important point mentioned in Sect. 14.1: composite structures are more expensive to manufacture than comparable aluminium alloy structures.

Laminating procedures: Aircraft manufacturers prefer epoxy prepreg as the starting material for laminates [1]. As mentioned in subsection 14.3.2, the prepregs can be tows and fabrics, and most are unidirectional, notably tapes. The lay-up of large laminated components (wing and empennage covers, fuselage shells) uses

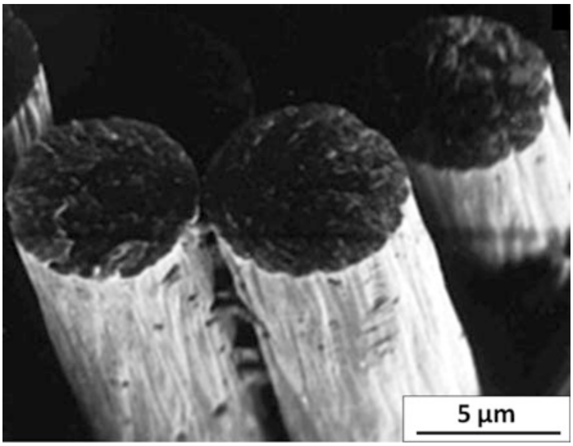


Fig. 14.5 Carbon fibres viewed in the scanning electron microscope (SEM). The fibre ends are fracture surfaces

Table 14.3 Typical CFRP aerospace components formed by several techniques [1]

Techniques	Types of structures	Applications
Laminating	• Sheets, thick monolithic	• Wing skins
	• Sheets, integrally stiffened	• Empennage skins
	• Sandwich panels	• Control surfaces; floor sections
	• Shells	• Fuselage sections
	• Beams	• Spars; ribs
	• Complex forms	• Aerofoils
RTM	• Small complex forms	• Doors; door pillars; flaps; spoilers
Filament winding	• Closed shells	• Pressure vessels
	• Open shells	• Radomes; rocket motors
	• Tubes	• Drive shafts
	• Secondary formed tubes	• Helicopter blades
Braiding	• Tubes	• Drive shafts
	• Complex tubes	• Curved pipes; truss joints; ducts
	• Closed shells	• Pressure vessels
	• Secondary formed	• Fuselage frames; propellers; helicopter blades
Tow placement	• See laminating	• See laminating
	• Complex wraps	• Grips; shafts; ducts
Pultrusion	• Beams	• Floor beams; stringers; spars; ribs; longerons

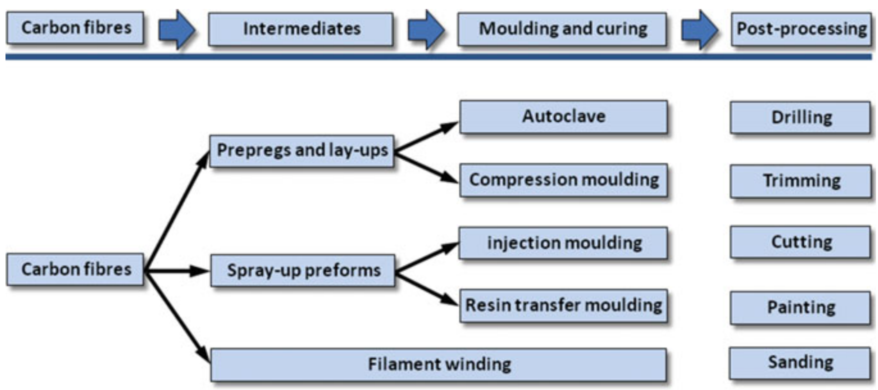


Fig. 14.6 Some methods for manufacturing CFRP components: Lux Research, Inc., Boston, USA

automated tape layer (ATL) and automated tow placement (ATP) equipment, for example Fig. 14.7.

An ATL tape laying head is multi-functional. Thus it (i) removes backing paper from the prepreg tape, (ii) delivers the tape to the lay-up tool with application of

Fig. 14.7 Automated tape laying: CFRP tape layers being placed on the lay-up tool for an Airbus A350 upper shell fuselage skin section: Premium AEROTEC, Nordenham, Germany

pressure, (iii) lays the tape in a programmed path (course), (iv) cuts the material at the precise location and angle, (v) lifts away from the tool, (vi) retracts to the start position, and (vii) begins laying the next course [4].

The tape laying head also has an optical flaw detection system that signals to stop laying tape when a flaw is detected, and a heating system that heats the prepreg to increase tack for tape-to-tape adhesion [4].

Resin transfer Moulding (RTM): This technique uses the epoxy thermoset characteristic of a low-viscosity stage during cure in an autoclave. Dry fabric preforms are put into matched-cavity moulds, preheated in the autoclave, and then filled with preheated injected resin under pressure: a vacuum is usually applied at an exit port in the preform/mould assembly to remove air and moisture before injection. After injection the mould temperature is increased to cure the component under autoclave pressure.

A variant, referred to as vacuum-assisted RTM (VARTM) involves placing a permeable membrane on top of the preform, vacuum bagging the mould/preform assembly, preheating it in an oven, and then applying a vacuum at the assembly exit port to enable the resin to infuse the preform via the permeable membrane. The advantage is lower costs, using an oven instead of an autoclave. However, the absence of autoclave pressure, relying on vacuum-compaction only, results in fibre volume-fractions about 5 % less than from RTM [1].

Resin-film infusion (***RFI***): In this process a film of resin is placed onto a mould either beneath or above the dry fabric preform. The assembly is then vacuum bagged and loaded into an autoclave. The temperature is raised to the resin's low-viscosity stage and a low-level pressure forces the resin into the preform. When infusion is complete the temperature and pressure are increased to compact and cure the component [1].

Filament winding: This involves laying down resin-impregnated continuous fibres on a stationary or rotating mandrel. The mandrel is removed *after* cure. This technique is best suited to components with simple surfaces of revolution, e.g. shells and tubes, see Table 14.3.

The fibres may be (i) wet wound, whereby dry fibres are impregnated with a low-viscosity resin during winding, (ii) dry wound and subsequently impregnated with resin under pressure or (iii) prepregged before winding. Thermoset resins are most commonly used, requiring curing after winding. Thermoplastics can be used in prepregs that are consolidated during winding [1]. This is more or less implied by the extended 'Filament winding' box in Fig. 14.6, although thermoplastics are not consolidated by curing, i.e. chemical conversion, see Table 14.1.

Pultrusion: This is an automated process for manufacturing constant cross-sectional profiles [1]. Continuous unidirectional fibre tows are impregnated with a thermosetting epoxy resin and pulled through a heated die to shape and cure the composite product. However, full cure is not normally achieved before the component exits the die, so post-curing needs to be considered.

Although pultrusion can be used for several types of aerospace components, see Table 14.3 and Fig. 14.10 in Sect. 14.4.1, the limited production runs are usually too short for pultrusion to be economically viable. There may also be quality issues compared with other manufacturing techniques unless special resins are used that enable relatively high fibre volume-fractions [1].

14.3.4 Reference Guidelines for CFRP Materials and Processing

Aerospace manufacturers have in-house and therefore proprietary guidelines and specifications for the characterisation and processing of CFRPs. In particular, the determination and evaluation of fibre and matrix properties are essential to selecting optimum combinations for particular applications.

However, Besides Ref. [1], open-source *guidelines* are available from the U.S. Department of Defence Composite Materials Handbook, Volumes 1–3 [5–7], which may be downloaded from the Internet.

14.4 CFRP Properties

The main incentive for developing CFRPs has been to obtain high structural efficiency owing to a combination of their relatively low densities, $\rho = 1.52$–$1.63\ g/cm^3$ [7] and high strength and stiffness.

In particular, the specific stiffnesses are basic design parameters for aircraft:

1. The specific stiffness E/ρ is important for lower wing surfaces, upper tailplane surfaces and spars, ribs and frames.
2. The specific buckling resistance $E^{1/3}/\rho$ is important for upper wing surfaces, lower tailplane surfaces and the fuselage.

However, as mentioned in Sect. 14.1, CFRP components and structures are more expensive than comparable aluminium alloy ones. Other properties and factors are of course important: see Table 14.4, which lists the advantages and disadvantages of CFRPs with respect to aluminium alloys.

Sections 14.4.1–14.4.3 focus on the following major topics: (i) specific mechanical properties and weight savings and costs, (ii) impact damage and inspections, and (iii) structural repairs.

14.4.1 Specific Mechanical Properties and Practical Weight Savings and Costs

The mechanical properties of CFRPs depend on the fibre volume-fractions, the orientations of the fibres with respect to the applied loads and—*most importantly*—on the component lay-ups and geometries. The fibres carry almost all the loads and are therefore responsible for the strengths and stiffnesses of CFRP components and structures.

Figures 14.8 and 14.9 present some data for the specific strengths and stiffnesses of CFRPs compared to those for aluminium alloys:

Specific strengths: Figure 14.8 shows that 100 % aligned-fibre CFRP laminates have intrinsically very high specific strengths, well beyond the capabilities of aluminium alloys. However, reduction factors accounting for property variabilities and environmental and notch effects greatly decrease the CFRP 'allowables', especially in compression: also see the remark about compression failures in Table 14.4.

Furthermore, when the dependence of CFRP strengths on the degree of fibre alignment is considered, Fig. 14.8 shows that the reduction factors can eliminate the CFRP-specific strength advantages compared to aluminium alloys.

Table 14.4 Relative advantages and disadvantages of CFRPs compared to aluminium alloys: information from various sources, including Refs. [3, 8–11]

Advantages	Disadvantages
• Higher and much higher specific stiffnesses, depending on percentages of aligned fibres • Greater flexibility in designing structurally efficient components: tailored directional properties • 10–20 % weight savings in actual components[a] • Dimensional stability • (Greatly) reduced part count owing to largely integral assemblies with limited mechanical fastening • High fatigue strength • Corrosion resistant: reduced maintenance costs • Radar-absorbing properties (stealth) • Vibration damping (sometimes) • Possible self-healing (under development)	• High material, labour and manufacturing costs • Possible delaminations and other flaws during fabrication, e.g. from drilling fastener holes • Intrinsically anisotropic: complex components difficult to analyse, sometimes resulting in poor predictions; complex failure modes and processes in compression make it difficult to develop failure criteria for compression loading • Higher notch sensitivity under static loading (e.g. fastener holes) • Conservative design and safety factors owing to – high susceptibility to impact damage – damage growth difficult to control and predict – difficult validation and certification of repairs – susceptibility to moisture pick-up (thermosets) and fuel absorption • Non-destructive inspection (NDI) difficulties • Low electrical conductivity requiring metal (copper) mesh in external surface layers to protect against lightning strikes • Flammable and non-recyclable

[a]See Sect. 14.4.1 for discussion of this very important point

These examples may be thought of as extreme cases, but they illustrate the points that (i) CFRP mechanical properties are much more complex to assess than those of aluminium alloys or, indeed, other metallic materials; and (ii) it is by no means a foregone conclusion that CFRPs will provide large specific strength benefits in actual structures.

Specific stiffnesses: Figure 14.9 compares the specific stiffnesses of conventional aerospace aluminium alloys and third generation Al–Li alloys with some examples for high-fibre-density CFRPs *without reduction factors*.

The overall advantages of CFRPs are much less than in the case of specific strengths. Even so, the aluminium alloys match only the 25 % aligned-fibre composites in terms of specific stiffness E/ρ.

Practical weight savings: Actual CFRP components are assembled from layers with different fibre orientations. Also, most aircraft structures are subjected to multidirectional loads, and this means that mechanical property isotropy will often be important. **N.B**: This is discussed further, and in detail, after Figs. 14.8 and 14.9.

For CFRP components a requirement of mechanical isotropy means that the amount of fibres aligned in the principal loading direction will be about 25 % [8], which is the *lowest* value in Fig. 14.9.

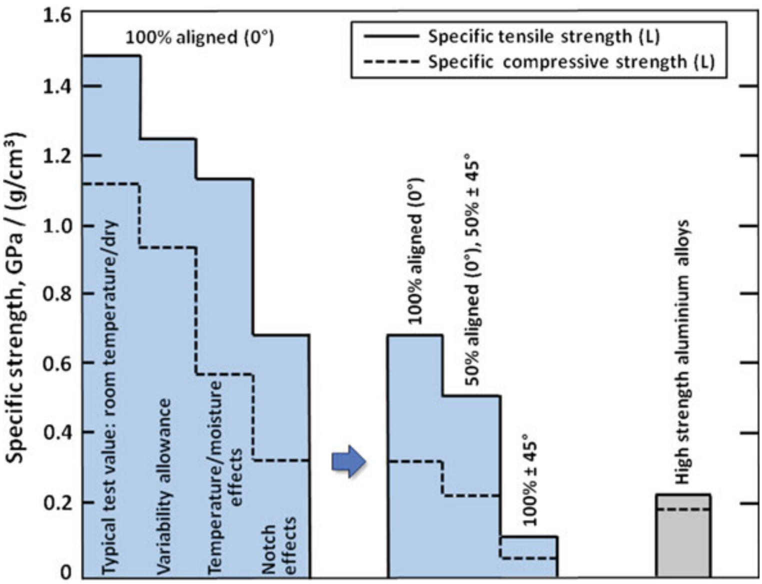


Fig. 14.8 Reduction factor effects on CFRP specific strengths, and comparison with high strength aluminium alloy specific strengths. The CFRP properties are for intermediate modulus fibres and a toughened resin system [12]

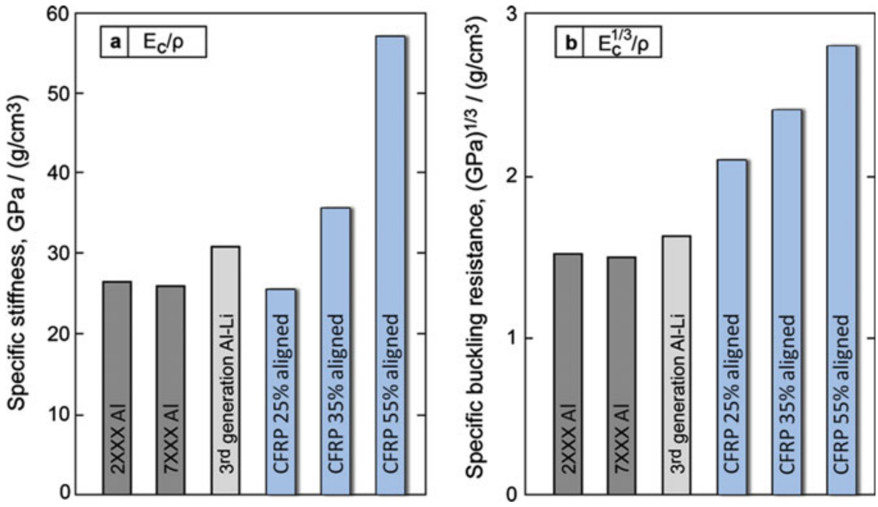


Fig. 14.9 Specific stiffnesses (average values) for high-fibre-density (60 % volume) CFRP composites tested in the aligned-fibre direction [10], conventional aerospace aluminium alloys and third generation Al–Li alloys [3]

On the other hand, if property isotropy is not necessary, the CFRP layers of a component can be ‘tailored’ to preferentially align some or most of the fibres in the principal loading direction, thereby increasing the structural efficiency: see Table 14.4.

The foregoing discussion is most important. It shows that although CFRPs with high percentages of aligned fibres have (very) high specific strengths and stiffnesses compared to aluminium alloys, a direct translation to high weight savings in actual components is not possible. This is the case even in the absence of reduction factors.

Mouritz [8] suggests 10–20 % weight savings from using CFRPs instead of aluminium alloys. This weight savings range is only slightly higher than the 8–15 % achievable by substituting third generation Al–Li alloys for conventional aluminium alloys [3]. Thus despite the increasing use of CFRPs in aircraft structures, Fig. 14.1, there is still potential competition from aluminium alloys. And, as also mentioned, there is an increasing trend to design and build hybrid structures.

Trade-off between stiffness, weight savings and costs: An instructive example of a trade-off between specific stiffness, weight savings and costs is given in Fig. 14.10. This shows different material choices, CFRP pultrusions [13] and Al–Li AA2196-T8511 alloy extrusions [14], for nominally identical applications in the Airbus A380.

The reasons for these differing choices are:

1. To maximise usable space the upper deck floor must span the entire fuselage without the intermediate supports commonly used for lower/main deck flooring.

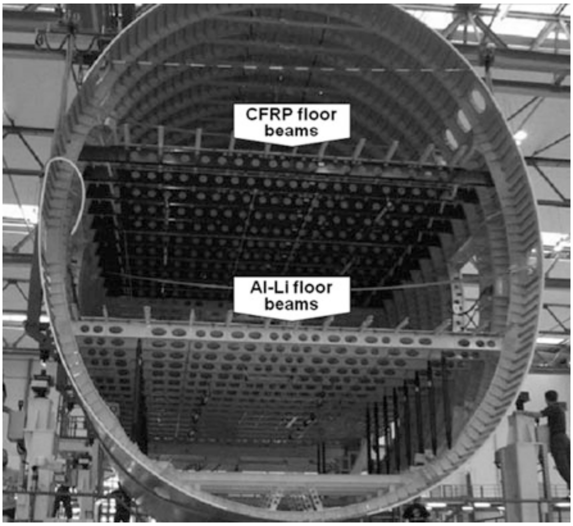


Fig. 14.10 A380 CFRP and Al–Li alloy floor beams [3]: see Fig. 14.3 also

This puts great demands on the floor beam stiffness, favouring the use of CFRPs, see Fig. 14.9.

2. On the other hand, the main/lower deck beams can be supported, as seen in Fig. 14.10. This enabled the Al–Li alloy extrusions to successfully compete for the beams, in a trade-off between the engineering properties, the resulting component weights, and the manufacturing costs.

14.4.2 Impact Damage and Inspections

Table 14.4 indicates that CFRPs have high fatigue strengths compared to aluminium alloys. However, CFRPs are highly susceptible to impact damage, which can grow during service, but not necessarily *or at all* by fatigue [1: p. 371].

In fact, CFRPs have the least impact resistance of any composites [1]. As an example, Fig. 14.11 compares a *thermoplastic* CFRP (i.e. a CFRP with better fracture resistance than thermoset CFRPs) with a standard damage tolerant aerospace aluminium alloy, AA2024-T3, and a damage tolerant version of GLARE. Note the especially high impact resistances of GLARE: this has led to its use as

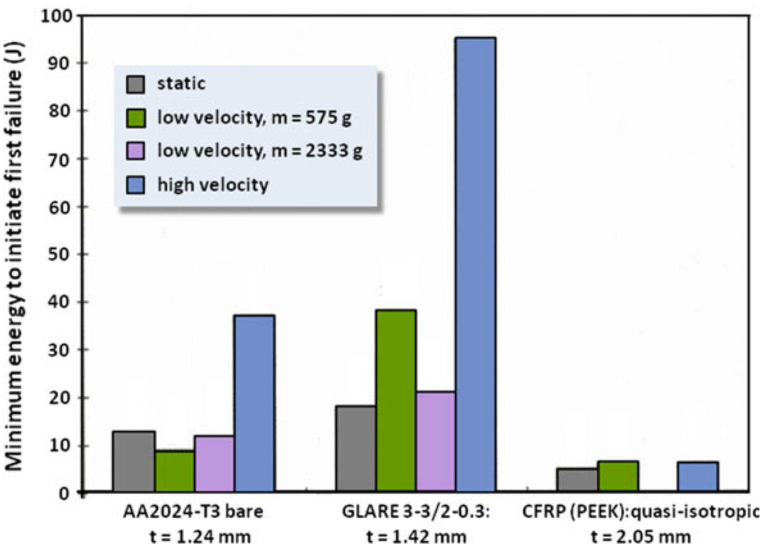


Fig. 14.11 Impact properties for a quasi-isotropic thermoplastic (PEEK) CFRP, aluminium alloy AA2024-T3, and a GLARE laminate [15]: *m* the mass of the impactor (unspecified for the high velocity impacts)

leading edge protection for the CFRP empennage on the Airbus A380: see Fig. 13.2 in Chap. 13 of this Volume.

Types of impact damage: These are various and varied, including hailstones (in-flight and on the ground), bird and lightning strikes, runway debris, tyre rupture, incidental contact with ground vehicles and installations, tool drop during maintenance, and engine blade loss or even rotor burst. The damage can be classified as shown in Table 14.5.

Several types of damage are obvious. However, there is a very important category of damage that is defined by the assumption that most in-service inspections are visual [19]. This damage is called ‘barely visible impact damage’ (BVID).

The importance of BVID lies in its threat to the structural integrity. BVID is difficult to detect by in-service inspections, and it could lead to visually undetectable damage growth (by whatever mechanisms) within the composite, followed by sudden failure at loads below the design allowables for nominally undamaged structures.

The reason why BVID can be so damaging is that impact effects are not confined to the composite surface [20]. A particularly severe example is shown in Fig. 14.12. The dominant type of damage is extensive delamination between the fibre layers; and in general it is delamination growth during service that is of most concern.

There are strength (and inspection) requirements to deal with all types of impact damage, including BVID, see Sect. 14.5, specifically 14.5.4.

N.B: Besides impact damage there are many types of manufacturing damage, including delaminations, voids, disbonded areas in skin/stringer interfaces, inclusions, scratches and fibre and matrix damage at drilled-hole locations [1]. These are accounted for by quality control inspections during manufacturing, see below, and a ‘Building Block’ (BB) test and analysis approach of validating composite structures for service [7, 18, 22–25]. This approach is also discussed in Section 14.5.

Table 14.5 Classification of specific types of impact damage [16–18]

Impact type	Self-evident	Impact location
Hail	Yes	Yes
Bird strike	Yes	Yes
Runway debris	Sometimes	Usually
Tyre rupture	Yes	Sometimes
Panels lost in-flight	Yes	Sometimes
Contact on ground	Sometimes	Yes
Tool drop	Sometimes	Yes
Engine blade/rotor	Yes	Yes
Lightning strike	–	–

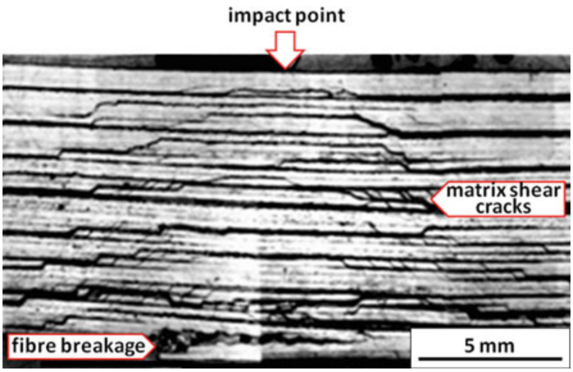


Fig. 14.12 BVID 'hidden' damage in a CFRP laminate cross-section: modified photomontage from [21]

Inspections: NDI methods for BVID and quality control of production processes can be summarised as follows:

1. BVID may be assessed visually at two levels, namely general and detailed visual inspections [22]. General visual inspection (GVI) includes service-induced impact damage and screening of impact test results. Detailed visual inspection is more appropriate to test results.
   The impact dent depth is widely used as a BVID criterion [22]. For GVI a typical detectable dent depth is about 0.25–0.5 mm [18]. For service components and structures the BVID dent depth is taken to be the minimum that can be reliably detected by scheduled inspections.

2. The majority of CFRP production defects are internal, so visual inspections, though necessary, are not sufficient. NDI techniques that establish internal defect acceptance and rejection limits are required [7].
   The most used NDI techniques are ultrasonics [7, 26], usually through-transmission C-scan inspections [7] and sometimes pulse-echo A-scans. X-ray inspection is often used to check the bonding of inserts in laminate panels and honeycomb/facesheet bonds in sandwich panels [7].
   The extent of this production-oriented NDI depends on whether the components are for (i) primary (safety-of-flight) structures, (ii) secondary structures, whose failure would affect aircraft operation but not the safety, and (iii) tertiary structures, whose failure would not significantly affect aircraft operation.

More information on CFRP NDI techniques may be obtained from Ref. [7] and specialist publications. As noted in Table 14.4, this is a difficult topic. The reasons are the variety of possible manufacturing defects and the ways in which CFRP structures can be built up. Another important point is that this subject area is continually evolving as the technique capabilities improve and new methods are developed.

14.4.3 Repairs of CFRP Structures

The previous topic, ***Inspections***, is directly related to repairs. And like inspections, repairs of CFRP structures have difficult aspects, particularly validation, which is discussed in Sect. 14.5.5.

Repair options depend on several factors [1]:

- Types of damage
- Component and/or structural build-up and requirements
- Field or depot level repair possibilities
- Criticality with respect to flight safety and operation.

Figure 14.13 classifies repairs into non-patching techniques for minor damage (surface and potting repairs), and patching for more serious damage that affects the load-carrying capability.

A detailed discussion of the types of repairs, with supporting literature, is given by Baker et al. [1]. Similar and additional information is present in the U.S. Department of Defence Composite Materials Handbook, Volume 3 (MIL-HDBK-17-3F) [7], which, as stated earlier, may be downloaded from the Internet.

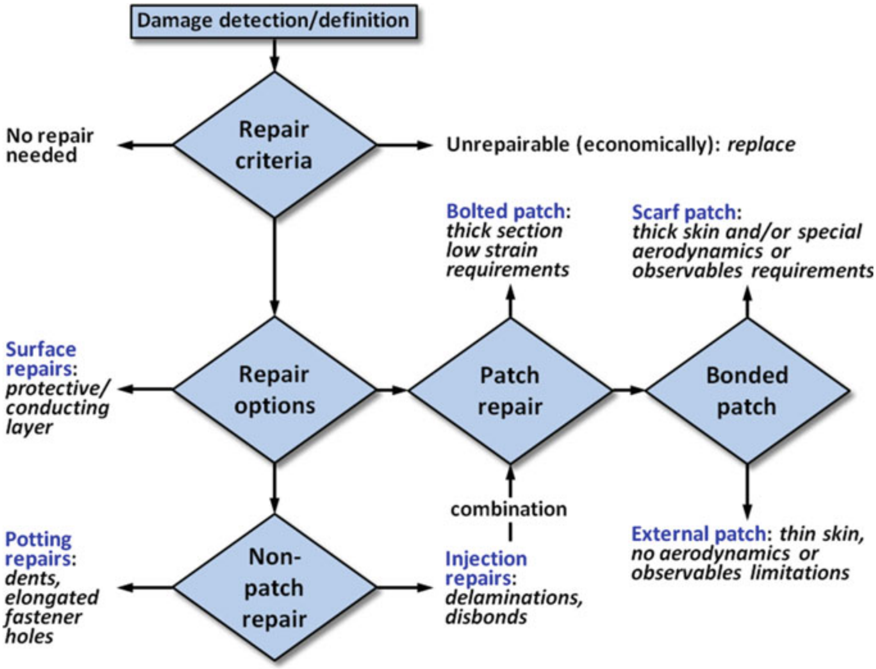


Fig. 14.13 Classification of CFRP repairs into non-patching and patching techniques: after [1]

Also, the Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) sponsor CFRP composite research in several key areas, including structural substantiation; damage tolerance; maintenance and repair practices; materials control and standardisation; and advanced material forms and processes [16–19, 21–24, 27]. These activities, in which major companies (Airbus, Boeing) participate, provide continuing updates to the guidelines [7] and requirements for composite structures [25].

14.5 Safety and Damage Tolerance of CFRP Components and Structures

This Section summarises the Damage Tolerance (DT) and fatigue requirements for CFRP composite aircraft structures. A full discussion is beyond the scope of this Source Book Volume, and could also be misleading, since the subject area is continually evolving as part of the activities mentioned at the end of Sect. 14.4.3.

14.5.1 Strength and Safety Definitions

There are two essential basic strength requirements for ensuring aircraft safety. These are the airframe structural limit load (LL) and ultimate load (UL) definitions:

Limit Load (***LL***): Maximum load to be expected in service.
Ultimate Load (***UL***): Limit Load multiplied by a historically-based safety factor, LL × 1.5 [28].

The limit load (LL) and ultimate load (UL) definitions apply to all possible types of external flight and ground loads on the airframe structure. The 1.5 safety factor on LL covers inadvertent service flight and ground loads greater than LL, structural deflections above LL that could compromise structural integrity, and as-built part thicknesses within tolerance but less than those assumed in the stress analyses. However, the safety factor *does not* cover:

- analysis or modelling errors
- poor design practice
- material property variations
- process escapes (e.g. different materials used than those specified, improperly drilled holes, etc.).
- damage and repairs
- environmental effects on composite properties.

14.5.2 Reduction Factors on Allowables

From Fig. 14.8 it was already pointed out that reduction factors greatly decrease the CFRP 'allowables' from those theoretically possible. A more general illustration is given in Fig. 14.14. This shows how manufacturing anomalies, service-induced damage, environmental effects and the 1.5 safety factor must be taken into account when designing CFRP structures. The reduction on allowable strain can be as much as two-thirds [29].

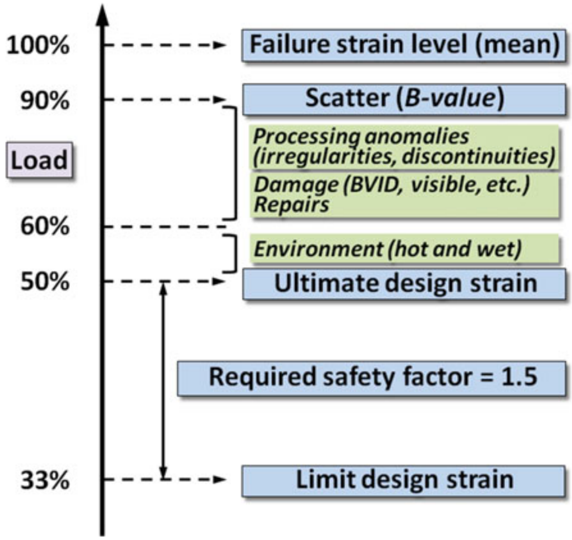
14.5.3 Testing to Determine Allowables

Accurate and reliable estimates of the design allowables for CFRP aircraft structures present many challenges, since together with the design details, all the factors shown in Fig. 14.14 must be considered. The general consensus is that a so-called 'Building Block' (BB) test and analysis approach should be used, see Fig. 14.15.

The BB approach may be viewed as a pyramid consisting of four levels of testing and analysis: (i) specimens, (ii) components, (iii) structural units, and (iv) full-scale units. Each level of the pyramid is the foundation for the next, and the complexity and costs increase with each upward level.

The overall purpose of the tests, and the supporting analyses, is to validate the structures for service. The final phase, leading to certification of the aircraft, is ground and flight testing.

Fig. 14.14 Reduction of strain allowables for CFRP structures: after [18, 29]



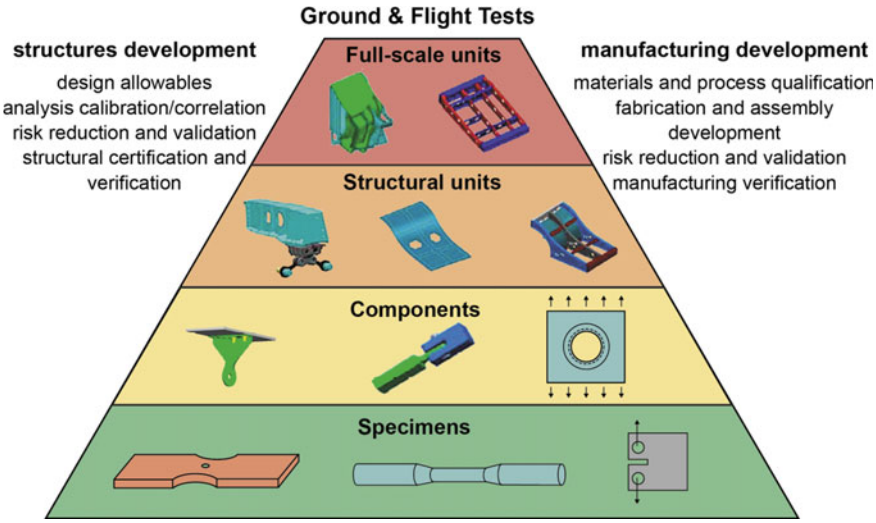


Fig. 14.15 'Building block' test approach for materials, components and structures: after [30]

Important

Levels **(*i*)–(*iii*)**: Up to the level of full-scale testing the BB approach for composite structures is broadly analogous to the BB approach for metallic airframe structures, see Chap. 16 in Volume 2 of these Source Books. However, there are major differences. Metallic airframe materials have better defined and consistent material and mechanical properties; considerably fewer types of manufacturing anomalies (especially in built-up structures); much less susceptibility to impact damage; and mechanical properties insensitive to environmental effects. (Another difference, this time an advantage of CFRPs, is that they are not susceptible to corrosion, unlike, for example, most aerospace aluminium alloys.)

Level **(*iv*)**: There are also major differences at the full-scale test level. For CFRP composite structures there is *emphasis* on static proof tests and separate fatigue tests on impact- and discontinuity-damaged structures to demonstrate 'no-growth' damage behaviour [7, 25]. On the other hand, metallic aircraft structures are subjected to full-scale fatigue testing to demonstrate (a) adequate fatigue life and crack growth characteristics, and (b) adequate residual static strength after fatigue testing.

The word '*emphasis*' in the previous paragraph is used because the MIL-HDBK-17-3F [7] and FAA AC-20-107B [25] guidelines do not exclude full-scale fatigue testing of CFRP aircraft structures, whereby the objective is to account for limited growth of impact (BVID) damage and/or manufacturing discontinuities during service.

For more, and more detailed, information on the testing of CFRP composite structures the reader should consult both of these guidelines, which have been developed with joint consultation, but differ in scope and extent. For example, the MIL-HDBK-17-3F guidelines have been developed for military aircraft (although there is much information relevant to civil aircraft), while the FAA AC-20-107B guidelines are primarily concerned with civil transport aircraft.

N.B: The MIL-HDBK-17-3F and FAA AC-20-107B guidelines are continually evolving, and they are updated at appropriate intervals.

14.5.4 Damage Tolerance (DT) Allowables

MIL-HDBK-17-3F [7] and FAA AC-20-107B [25] provide extensive information on assessing the effects of various types of impact damage (see Table 14.5) and other damage on the integrity of CFRP airframe structures.

An outline of the FAA AC-20-107B guidelines for DT evaluation of damage is given in Table 14.6. This outline is derived from the guidelines for *all* types of damage, i.e. including manufacturing anomalies as well as service-induced damage.

Again following FAA AC-20-107B, completion of the first step in Table 14.6 allows the various types of damage to be classified into five categories, as shown in Fig. 14.16. In more detail these are:

Category 1: Allowable damage that may go undetected (BVID) in service and also allowable manufacturing defects. Structural substantiation includes a reliable service life while maintaining UL capability.

Category 2: Damage reliably detectable by field inspections. Structural substantiation includes demonstration of reliable inspection and the retention of LL capability. Examples of category 2 include visible impact damage (VID), deep

Table 14.6 Outline of guidelines for DT evaluation of damage in CFRP composite aircraft structures

1.	Identification of structure whose failure would reduce the structural integrity, and a damage threat assessment to determine possible locations, types and sizes of damage that may occur during manufacture, operation or maintenance
2.	Realistic testing (i.e. including service loads and environmental simulations) according to the BB approach to define the sensitivity of the structure to damage growth
3.	Establish the extent of initially detectable damage consistent with the inspection techniques used during manufacturing and service
4.	Establish the extent of damage for residual strength assessments, including considerations about the probability of detection using field inspection techniques
5.	Develop an in-service inspection programme for inclusion in a maintenance plan. Establish inspection intervals for reliable detection of damage between the time it initially becomes detectable and the time at which the extent of damage reaches the limits for the required residual strength
6.	For continued airworthiness the maintenance and repair should meet all the appropriate considerations covered in FAA AC-20-107B

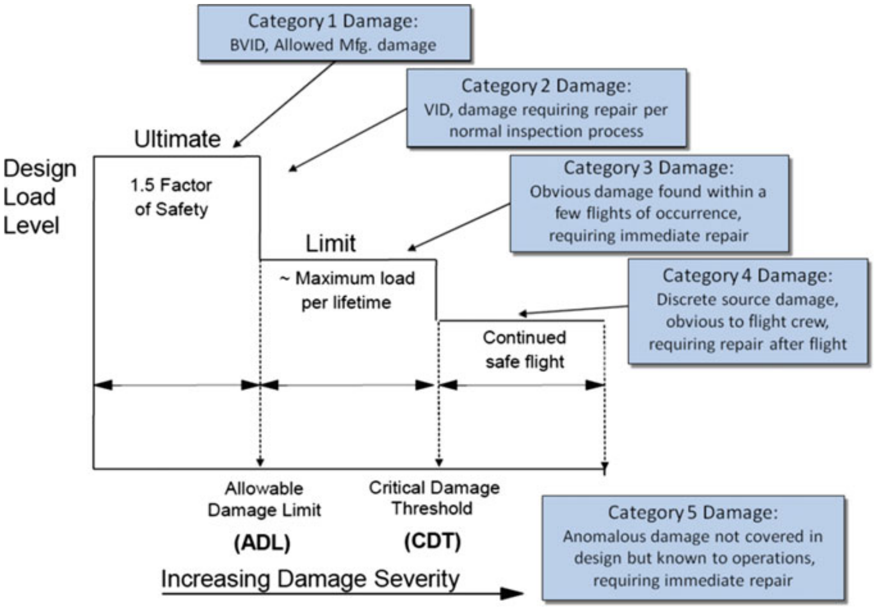


Fig. 14.16 Schematic diagram of design load levels versus categories of damage severity [25]

gouges or scratches, detectable delamination or disbonding, and local major heat or environmental degradation.

Category 3: Damage reliably detected within a few flights of occurrence by operations or maintenance personnel with no special skills. Structural substantiation includes demonstration of reliable quick detection and the retention of LL or near-LL capability. An example of Category 3 is large VID.

Category 4: Discrete source damage from a known incident such that flight manoeuvres are limited. Structural substantiation includes a demonstration of residual strength. Examples of Category 4 include severe in-flight hail, bird strikes, and tyre and rotor bursts.

Category 5: Severe damage from anomalous ground or flight events, and not covered by design criteria or structural substantiation procedures. This category is included in FAA AC-20-107B to make all concerned (design engineers, operations and maintenance personnel) aware of possible damage from Category 5 events, which need immediate reporting. Examples of Category 5 include severe collisions with ground vehicles, anomalous flight load conditions, abnormally hard landings, and loss of parts in flight with possible subsequent high-energy impacts on adjacent structures.

14.5.5 Repair Issues: Validation

Validation of repairs relies on strict attention to repair design and analysis, appropriate design values supported by tests, damage removal and site preparation, appropriate choice of the repair materials and fabrication processes, and inspection (quality control) [7, 25]. Some damage types may need special instructions for field repair and the associated quality control [25]. In addition, the service inspectability and durability of the repairs must be verified: this is a difficult task.

Thus although the schematic in Fig. 14.13 appears straightforward, the actual repair procedures can be complex. For example, bonded repairs require more in-process quality control than bolted repairs [7]:

Bonded repairs: The composite materials and adhesives must be compatible with the original structure, and so must the repair process, which involves patch and parent surface preparation, adhesive application, bagging (enclosing the repair for curing) and the cure thermal cycle [1, 7]. Each of these activities may be different for the type of bonded repair and the component being repaired.

Bolted repairs: These are simpler, since a pre-processed patch is mechanically fastened to the damaged structure. Even so, drilling and reaming holes in both the patch and parent material require much care to avoid damaging the hole vicinities and prevent splitting of parent skin material.

14.6 Developments Old and New

The title of this Section may seem unusual, but it reflects the fact that development and introduction of aerospace materials is a long-term process, often taking 10 years or more. For example, although high-modulus carbon fibres were developed in the mid-1960s [31], the first CFRP applications were in tactical aircraft in the mid-1970s, see Fig. 14.1. Transport aircraft applications followed in the 1980s.

More recent developments, though not deserving the designation 'new', are so-called smart structures, three-dimensional (3D) fibre reinforcements, and self-healing matrices.

Smart structure technology uses the layered configuration of composite laminates to insert interlayer optical fibres and sensors for structural health monitoring (SHM). SHM is the subject of Chap. 22 of Volume 2 of these Source Books, and is also discussed specifically for CFRPs in Ref. [1]. Hence smart structures will not be considered here.

The incentive to develop 3D and self-healing CFRPs stems from trying to improve the damage resistance of conventional CFRP composite structures. These topics, 3D and self-healing CFRPs, are briefly discussed in Sects. 14.6.1 and 14.6.2.

14.6.1 3D CFRP Components and Structures

Laminated two-dimensionally (2D) reinforced CFRP composites have poor impact resistance, see Sects. 14.4 and 14.5 and also low through-thickness strength. It was realised more than 25 years ago [32] that these properties could be improved by fabricating 3D composites. This is partly why NASA set up an Advanced Composites Technology (ACT) programme in 1989, followed by the first ACT conference in 1990 [33]. Thus the development of 3D CFRPs already has a respectably long history.

In 3D reinforcement some of the fibres are oriented in the through-thickness (z) direction. This can be obtained from 3D weaving or braiding, or by stitching-in fibres in the z-direction [1]. This z-stitching is much simpler than weaving, but it does not provide all the benefits of fully 3D fibre configurations [1].

Whichever type of reinforcement is used, a dry preform is made and then converted into a composite part using one of the liquid resin moulding techniques (RTM or RFI, see Sect. 14.3.3). Besides enabling 3D configurations, the RTM and RFI techniques have the additional advantage of relatively low cost compared with conventional laminating procedures [1].

The ACT programme initially concentrated on developing large composite wing structures for commercial aircraft. Several types of composite fabrics were evaluated, and it was found that stitching combined with RFI showed the greatest potential for overcoming the cost and damage tolerance restrictions [34].

The stitched/RFI CFRP wing manufacturing process used three textile processes, knitting, braiding and stitching, as follows [34]:

1. The wing covers were made from knitted tow preforms stacked in layers as few as two stacks in low-stress areas and up to twenty stacks in high-stress areas. Then the stacks were stitched to make solid wing cover preforms.
2. The stiffeners and rib clips were made from braided tubes, which were collapsed and stitched to make blade-shaped profiles. The braiding process made it easier for the components to conform to the wing contours.
3. The stiffening elements were stitched to the wing cover preforms, ready for the RFI process.

This manufacturing process required a very large Advanced Stitching Machine (ASM), which is also discussed in Ref. [34].

More recently, NASA and Boeing set up a demonstrator programme for a large CFRP multi-bay pressure box [35–38], whose configuration is derived from a Blended Wing Body design concept [39]. The box consists of stitched/RFI sub-assemblies that form the exterior shell and floor members and 4 interior sandwich rib panels. The stitched/RFI sub-assemblies were designed, manufactured and evaluated using the Building Block (BB) approach, whereby the stitching is intended to suppress interlaminar failures, arrest damage and turn cracks [37].

An illustration of the sub-assemblies, the sandwich panels and the box is given in Fig. 14.17. The box itself was assembled at Boeing's C-17 assembly site in Long Beach, California, by mechanically fastening the sub-assemblies [38]. After final assembly the box was transferred to the NASA Langley Research Center, to be statically tested under combined pressure and bending loads, firstly in the pristine condition and subsequently with interior and exterior BVID [38].

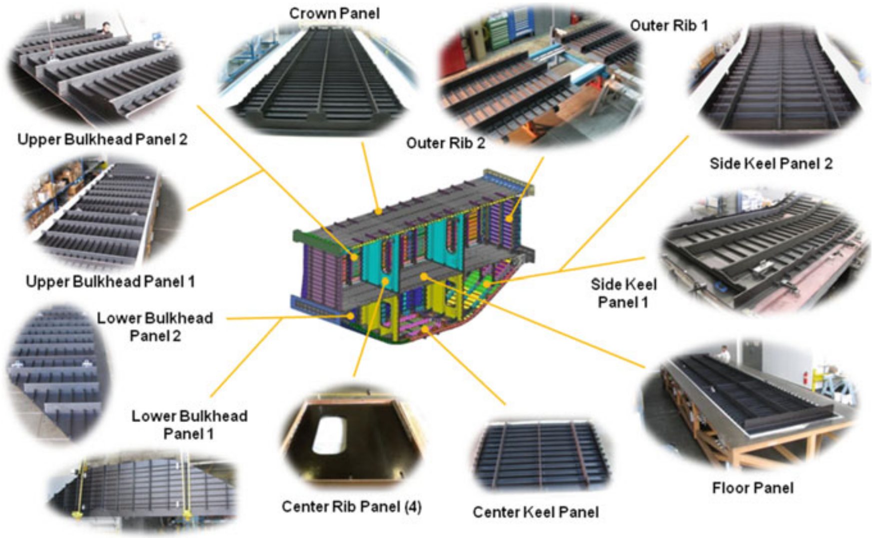


Fig. 14.17 CFRP Stitched/RFI sub-assemblies, sandwich panels and a schematic of the large multi-bay pressure box [38]: reproduced by permission from NASA/Boeing

This demonstrator programme has already been extensively reported in the open literature [35–38], and there will undoubtedly be much more follow-on information in the next few years.

14.6.2 Self-healing CFRPs

Over the past 20 years, and especially in the last decade, there has been much interest in developing self-healing polymer resins and, by extension, self-healing PMCs. Two recent and extensive reviews [40, 41] are available via the Internet.

The basic self-healing idea is shown in Fig. 14.18, progressing from (a) to (c). A growing crack breaks microcapsules that contain either a liquid resin (healing agent) or a catalyst (cure agent). The contents of these capsules react to polymerise the resin within the crack and heal it. Another possibility is to use hollow glass fibres as the encapsulating vessels [41].

Recovery of more than 90 % of the pristine resin fracture toughness properties is possible for capsule-based healing of epoxy resins [40, 41]. However, limited data show that CFRP fracture toughness recovery does not exceed 80 %, and can be much less [41]. This adverse result, which appears to be generally true for PMCs, has been attributed to insufficient amounts of self-healing resin to close cracks and delaminations, and thermal loss of the healing reaction to the fibres [41].

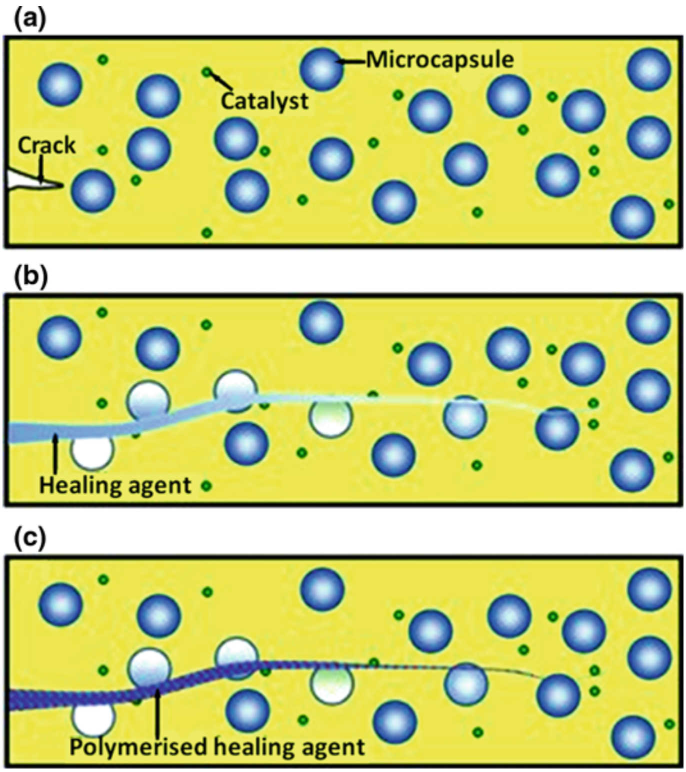


Fig. 14.18 Schematic of microcapsule self-healing of a resin

Disadvantages of incorporating microcapsules in PMCs were demonstrated for C-glass/epoxy composites [42]. Increasing amounts of microcapsules decreased the tensile strength and modulus, and increased the porosity [41, 42].

Much more research is needed. For CFRPs this includes developing more appropriate self-healing resins and survival of the encapsulated resins and catalysts during component manufacture.

14.7 Current Indian Scenario (*Contribution Partly by K. Vijaya Raju*)

Indian efforts in the development of CFRP products and components are summarised in this Section. Over the past three decades or so, a number of aerospace platforms have been developed in India. These include the Advanced Light Helicopter (ALH-Dhruv) from Hindustan Aeronautics Limited (HAL); the Light Combat Aircraft (LCA-TEJAS) developed by the Aeronautical Development

Agency with HAL as the principal partner; the Light Transport Aircraft (LTA-SARAS) and two-seater trainer aircraft (HANSA) developed by the National Aerospace Laboratories (NAL-CSIR); and a number of launch vehicles and satellites for the Indian Space Research Organisation (ISRO-DoS).

All these developments have employed composite materials for the realisation of efficient lightweight structures—mostly CFRP and glass fibre reinforced composites, and to a limited extent aramid (Kevlar) fibre reinforced composites.

14.7.1 Light Combat Aircraft TEJAS

The LCA-TEJAS is a multi-role combat aircraft and is the smallest aircraft in its class amongst contemporary aircraft. TEJAS has an unstable configuration and is controlled at all times by a fly-by-wire control system via on-board computers.

Among the important requirements for the airframe of such an aircraft are the lightweight construction, high degree of reliability over a long period, and the need to have aerodynamic shapes providing high aerodynamic efficiency under operating (flexed) conditions. It was realised that in order to meet these demands, it was necessary to have materials with high specific strength and stiffness that can take complex shapes easily and provide adequate fatigue and corrosion resistance.

Large-scale use of composites in TEJAS has provided effective solutions for such considerations. The TEJAS airframe consists of about 45 % CFRP that includes 90 % of the skin material. Illustrations of some of the CFRP components are given in the upper photomontage of Fig. 14.19. These include complex parts like the fin, rudder, centre fuselage and main landing gear doors, which are fabricated using co-curing and co-bonding.

The CFRP materials are mainly thermosets using epoxy resins. A high temperature CFRP is used for the engine bay door. Currently, carbon fibre prepregs are available both as unidirectional tapes (continuous carbon fibre tows embedded in partially cured matrix polymeric resin) and as bidirectionally woven fabrics embedded in partially cured matrix polymeric resin.

14.7.2 Light Transport Aircraft SARAS

The LTA-SARAS is a 14-seat twin-turboprop civilian light transport aircraft for general use. The airframe is about 35 % composites, mainly CFRP. Illustrations of some of the CFRP components are given in the lower photomontage of Fig. 14.19. These include the wing, horizontal and vertical stabilisers, the rear pressure bulkhead, front top skin, engine nacelles and flooring.

The CFRP wing is fabricated using a patented cost-effective manufacturing technology called VERITy (Vacuum Enhanced Resin Infusion Technology).

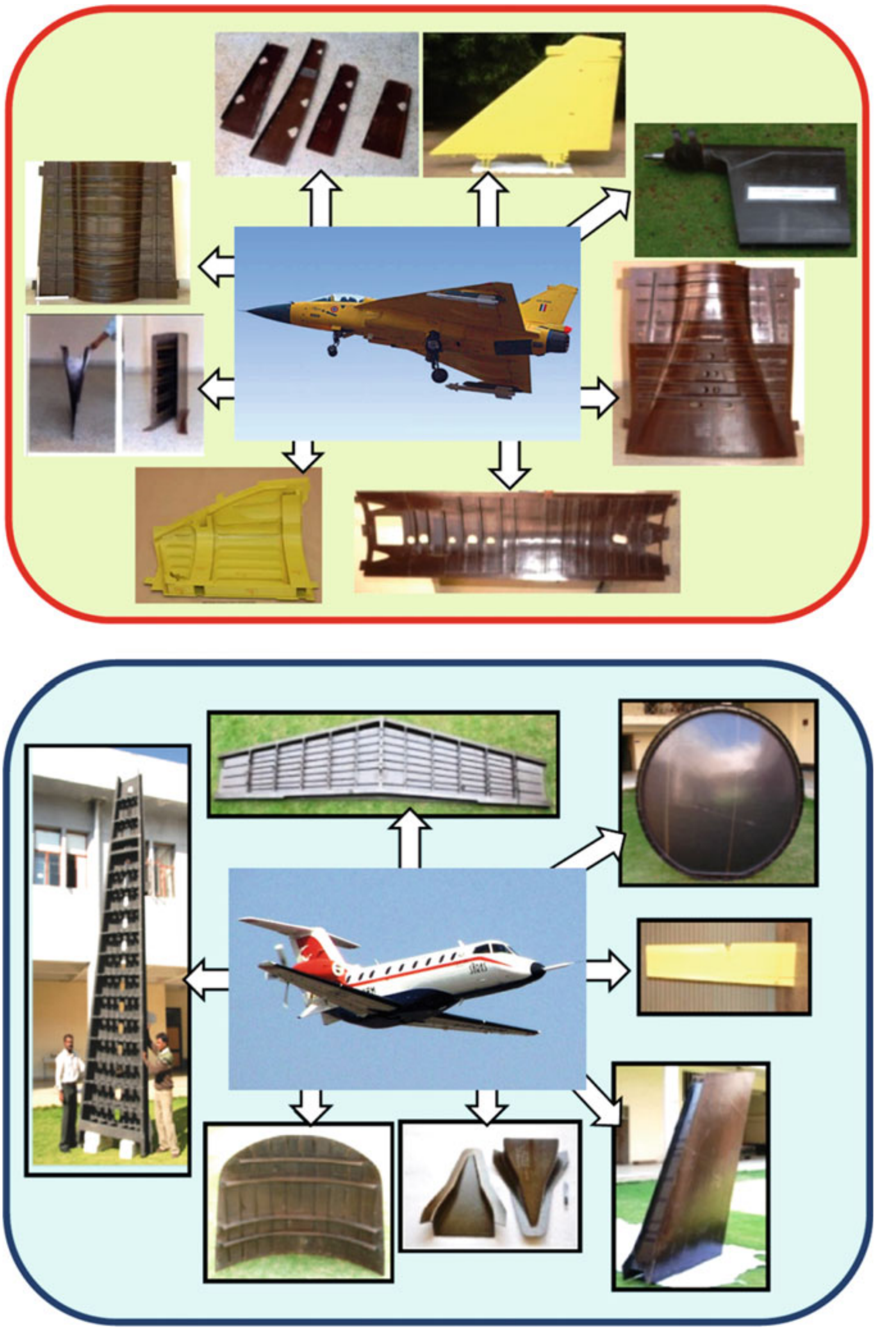


Fig. 14.19 Photomontages of CFRP composite parts in the Light Combat Aircraft TEJAS (*top*) and the Light Transport Aircraft SARAS (*bottom*). Source: Advanced Composites Division, CSIR-NAL, Bangalore, India

14.8 Summary

This chapter surveys the applications and properties of polymer matrix structural composites (PMCs), concentrating on carbon fibre reinforced composites (CFRPs), which are widely used in modern aerospace structures.

The discussion of CFRPs begins with considering the matrices and fibres and the production methods for aerospace components. Then some important CFRP properties and considerations are reviewed, namely the specific mechanical properties and their influences on practical weight savings and costs; and impact damage (to which CFRPS are very susceptible) and inspections and repairs of damage.

A complete Section is devoted to Safety and Damage Tolerance of CFRP components and structures. This is a complex topic and still very much an evolving discipline. The following Section mentions some 'old' but still current developments (high-modulus fibres and smart structures), and then discusses the newer developments of 3D fibre reinforcements and self-healing matrices. Especial attention is given to a NASA/Boeing demonstrator programme for a large 3D CFRP multi-bay pressure box simulating a centrally-located structure for an advanced Blended Wing Body aircraft.

The chapter ends with a contribution about the current CFRP scenario in India, highlighting the Light Combat Aircraft TEJAS and the Light Transport Aircraft SARAS, whose airframes consist of about 45 % and 35 % CFRPs, respectively.

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