CHAPTER

1

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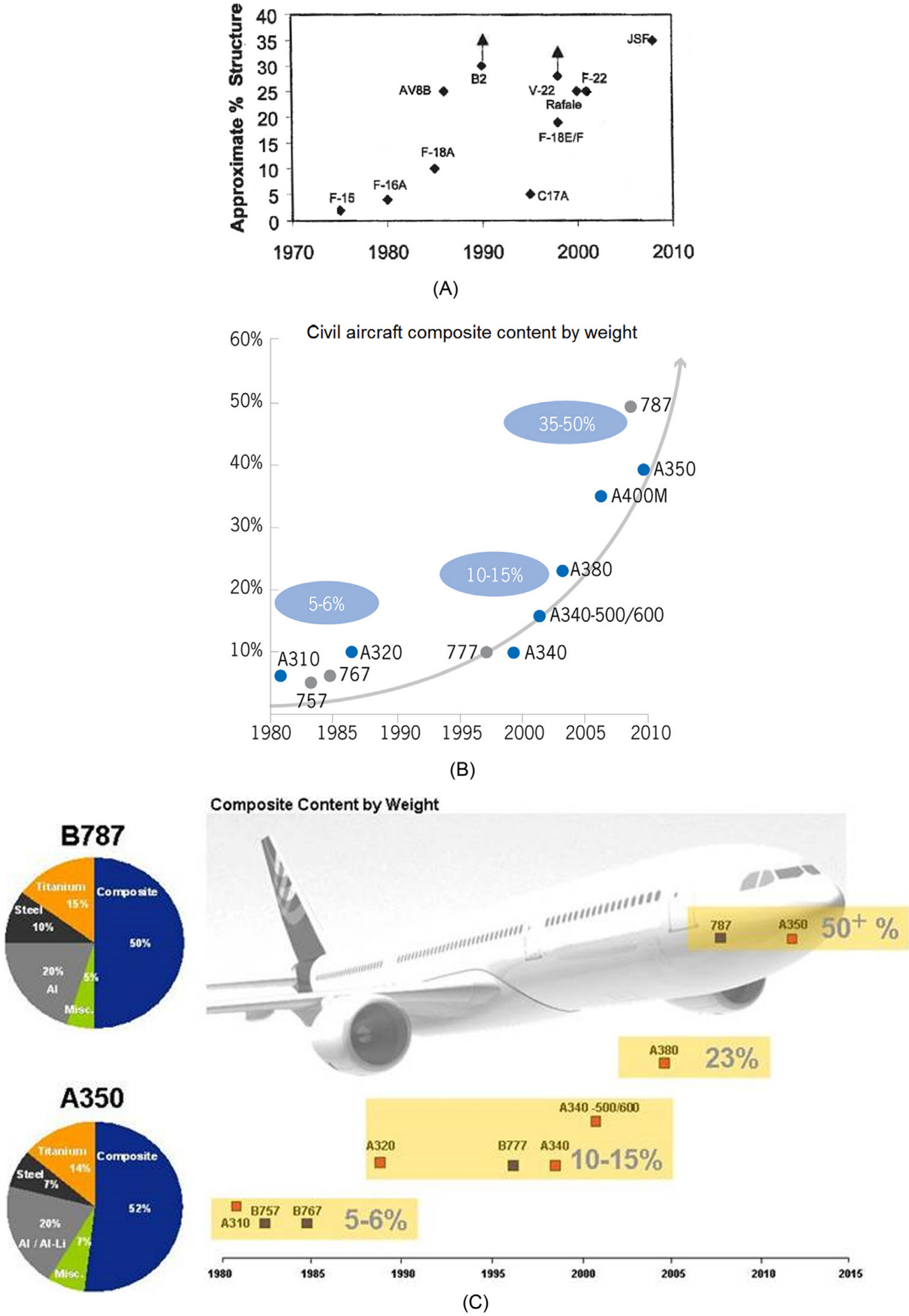
1.1 Preamble

The concept of *composites* has attracted the interest of both the engineers and the business professionals. To engineers, composites are the opportunity to create *designer materials* with palettes of properties that cannot be found in existing mineral materials. To the business professional, composites offer unprecedented business growth especially in areas where

Stress, Vibration, and Wave Analysis in Aerospace Composites
DOI: https://doi.org/10.1016/B978-0-12-813308-8.00006-5


Approximate % Structure
40
35
30
25
20
15
10
5
0
1970
1980
1990
2000
2010
JSF
B2
AV8B
V-22
F-22
Rafale
F-18E/F
F-18A
F-16A
F-15
C17A
(A)
Civil aircraft composite content by weight
60%
50%
40%
30%
20%
10%
35-50%
10-15%
5-6%
787
A350
A400M
A380
A340-500/600
A340
777
A320
A310
767
757
1980
1985
1990
1995
2000
2005
2010
(B)
Composite Content by Weight
B787
Titanium 15%
Composite 50%
Steel 10%
20% Al
5% Misc.
A350
Titanium 14%
Composite 52%
Steel 7%
20% Al / Al-Li
7% Misc.
787
A350
50+ %
A380
23%
A340 -500/600
A320
B777
A340
10-15%
A310
B757
B767
5-6%
1980
1985
1990
1995
2000
2005
2010
2015
(C)

unprecedented material properties are in high demand. Not surprisingly, the aerospace market is one of the largest and arguably the most important market to the composites industry. Commercial aircraft, military craft, helicopters, business jets, general aviation aircraft, and space craft all make substantial use of high-performance composites. The usage of high-performance composites by the aerospace market has experienced a continuous growth over several decades (Fig. 1.1).

Composites have good tensile strength and resistance to compression, making them suitable for use in aircraft manufacture. The tensile strength of the material comes from its fibrous nature. When a tensile force is applied, the fibers within the composite line up with the direction of the applied force, giving its tensile strength. The good resistance to compression can be attributed to the adhesive and stiffness properties of the matrix which must maintain the fibers as straight columns and prevent them from buckling.

1.2 Why use aerospace composites?

The primary needs for all the advanced composites used in aerospace applications remain the same, that is, lighter weight, higher operating temperatures, greater stiffness, higher reliability, and increased affordability. Some other special needs can be also achieved only with composites, such as good radio-frequency compatibility of fiberglass radomes and low-observability airframes for stealth aircraft.

High-performance composites were developed because no single homogeneous structural material could be found that had all of the desired attributes for a given application. Fiber-reinforced composites were developed in response to demands of the aerospace community, which is under constant pressure for materials development in order to achieve improved performance. Aluminum alloys, which provide high strength and fairly high stiffness at low weight, have provided good performance and have been the main materials used in aircraft structures over many years. However, both corrosion and fatigue in aluminum alloys have produced problems that have been very costly to remedy. Fiber-reinforced composites have been developed and widely applied in aerospace applications to satisfy the requirements for enhanced performance and reduced maintenance costs.

FIGURE 1.1 Increase of the weight content of composites in commercial aircraft structures over a 30-year time span: (A) trends in military aircraft composite usage [1]; (B) trends in civil aircraft composite usage [2]; (C) breakdown of weight content by material types in Boeing 787 and Airbus A350 XWB [3]. Source: *(A) From Baker, A., Dutton, S., & Kelly, D. (2004).* Composite materials for aircraft structures *(2nd ed.).* AIAA Education Series. *American Institute of Aeronautics and Astronautics. Reston, VA. (B) From Cookson, I. (2009).* Grant Thornton on United States Aerospace Component M&A, 2008. *Defense Industry Daily. <http://www.defenseindustrydaily.com/Grant-Thornton-on-UnitedStates-Aerospace-Component-MA-2008-05334/> Accessed November 2014 and <http://www.grantthornton.com/staticfiles/GTCom/files/Industries/Consumer%20&%20industrial%20products/Publications/Aerospace%20components%20MA%20update%202009.pdf> Accessed December 2014, figure on page 4. (C) From Anon.* Composites penetration—Step change underway with intermediate modulus carbon fiber as the standard. *Hexcel Corporation. <http://www.sec.gov/Archives/edgar/data/717605/000110465908021748/g97851bci012.jpg>.*

1.3 What are aerospace composites?

Aerospace composites are a class of engineered materials with a very demanding palette of properties. High strength combined with low weight and also high stiffness are common themes in the aerospace composites world. Nowadays, engineers and scientists thrive to augment these high-performance mechanical properties with other properties such as electric and thermal conductivity, shape change, and self-repair capabilities.

1.3.1 Definition of aerospace composites

From a pure lexical point of view, "composites" seem to have a variety of definitions and no universally accepted one exists as yet. One school prefers the word *composite* to include only those materials consisting of a strong structural reinforcement encapsulated in a binding matrix, while the purists believe that it should include everything except homogeneous or single-phase materials. In a generic sense, a composite material can be defined as a macroscopic combination of two or more distinct materials, having a recognizable interface between them. One material acts as a supporting matrix, while another material builds on this base scaffolding and reinforces the entire material. Thus the aerospace definition of composite materials can be restricted to include only those engineered materials that contain a reinforcement (such as fibers or particles) supported by a matrix material.

Fiber-reinforced composites, which dominate the aerospace applications, contain reinforcements having lengths much greater than their thickness or diameter. Most continuous-fiber (or continuous-filament) composites, in fact, contain fibers that are comparable in length to the overall dimensions of the composite part. Composite laminates are obtained through the superposition of several relatively thin layers having two of their dimensions much larger than their third.

High-performance composites are composites that have superior performance compared to conventional structural materials such as steel, aluminum, and titanium. Polymer matrix composites have gained the upper hand in airframe applications, whereas metal matrix composites, ceramic matrix composites, and carbon matrix composites are being considered for more demanding aerospace applications such as aeroengines, landing gear, and reentry nose cones. However, there are significant dissimilarities between polymer matrix composites and those made with metal, ceramic, and carbon matrices. Our emphasis in this book will be on polymer matrix composites for its applications in airframe.

Polymer matrix composites provide a synergistic combination of high-performance fibers and moldable polymeric matrices. The fiber provides the high strength and modulus, while the polymeric matrix spreads the load as well as offers resistance to weathering and corrosion. Composite tensile strength is almost directly proportional to the basic fiber strength, whereas other properties depend on the matrix–fiber interaction. Fiber-reinforced composites are ideally suited to anisotropic loading situations where weight is critical. The high strengths and moduli of these composites can be tailored to the high load direction(s), with little material wasted on needless reinforcement.

1.3.2 High-performance fibers for aerospace composites applications

Fiber composites offer many superior properties. Almost all high-strength/high-stiffness materials fail because of the propagation of flaws. A fiber of such a material is inherently stronger than the bulk form because the size of a flaw is limited by the small diameter of the fiber. In addition, if equal volumes of fibrous and bulk material are compared, it is found that even if a flaw does produce failure in a fiber, it will not propagate to fail the entire assemblage of fibers, as would happen in the bulk material. Furthermore, preferred orientation may be used to increase the lengthwise modulus, and perhaps strength, well above isotropic values. When this material is also lightweight, there is a tremendous potential advantage in strength-to-weight and/or stiffness-to-weight ratios over conventional materials.

Glass fibers were the first to be considered for high-performance applications because of their high strength when drawn in very thin filaments. Considering that bulk glass is quite brittle, the surprising high strength of these ultrathin glass fibers gave impetus to this line of research. Subsequently, a variety of other high-performance fibers have been developed: S-glass fibers (which are even stronger that ordinary E glass), aramid (Kevlar) fibers, boron fibers, Spectra fibers, etc.

The fiber that has eventually attained widespread usage in aerospace composites has been the carbon fiber (aka graphite fiber) that is used in carbon fiber-reinforced polymer (CFRP) composites. High-strength, high-modulus carbon fibers are about 5−6 μm in diameter and consist of small crystallites of "turbostratic" graphite, one of the allotropic forms of carbon. Two major carbon-fiber fabrication processes have been developed, one based on polyacrylonitrile (PAN) and the other based on pitch. Refinements in carbon-fiber fabrication technology have led to considerable improvements in tensile strength (~4.5 GPa) and in strain to fracture (more than 2%) for PAN-based fibers. These can now be supplied in three basic forms, high modulus (~380 GPa), intermediate modulus (~290 GPa), and high strength (with a modulus of ~230 GPa and tensile strength of 4.5 GPa). The tensile stress−strain response is elastic up to failure, and a large amount of energy is released when the fibers break in a brittle manner. The selection of the appropriate fiber depends very much on the application. For military aircraft, both high modulus and high strength are desirable. Satellite applications, in contrast, benefit from the use of high-modulus fibers that improve stiffness and stability of reflector dishes, antennas, and their supporting structures.

1.3.3 High-performance matrices for aerospace composites applications

The desirable properties of the reinforcing fibers can be converted to practical application when the fibers are embedded in a matrix that binds them together, transfers load to and between the fibers, and protects them from environments and handling. The polymeric matrices considered for composite applications include both thermosetting polymers (epoxy, polyester, phenolic, and polyimide resins) and thermoplastic polymers [polypropylene, Nylon 6.6, polymethylmethacrylate (aka PMMA), and polyetheretherketone (aka PEEK)]. In current aerospace composites, the epoxy thermosetting resin has achieved widespread utilization; however, efforts are under way toward the introduction of thermoplastic polymers which may present considerable manufacturing advantages.

The polymeric matrix of aerospace composites performs a number of functions such as (1) stabilizing the fiber in compression (providing lateral support), (2) conveying the fiber properties into the laminate, and (3) minimizing damage due to impact by exhibiting plastic deformation and providing out-of-plane properties to the laminate. Matrix-dominated composite properties (interlaminar strength, compressive strength) are reduced when polymer matrix is exposed to higher temperatures or to the inevitable absorption of environmental moisture.

1.3.4 Advantages of composites in aerospace usage

The primary advantage of using composite materials in aerospace applications is the weight reduction: weight savings in the range of 20%−50% are often quoted. Unitization is another advantage: it is easy to assemble complex components as unitized composite parts using automated layup machinery and rotational molding processes. For example, the concept of single-barrel fuselage used in Boeing 787 Dreamliner is a monocoque (single-shell) molded structure that delivers higher strength at much lower weight.

Aerodynamic benefits can be achieved with composites that were impossible with metals. The majority of aircraft control-lift surfaces have a single degree of curvature due to the limitation of metal fabrication techniques. But further improvements in aerodynamic efficiency can be obtained by adopting a double-curvature design, for example, variable-camber twisted wings. Composites and modern molding tools allow the shape to be tailored to meet the required performance targets at various points in the flying envelope.

The tailoring of mechanical properties along preferential stress directions is an extraordinary design advantage offered by aerospace composites that cannot be duplicated in isotropic metallic airframes. Aerospace composites can be tailored by "layup" design, with tapering thicknesses as needed to maintain optimal strength-to-weight ratio (Fig. 1.2A). In addition, local reinforcing layup can be placed at required orientation at design hot spots.

A further advantage of using composites in airplane design is the ability to tailor the aeroelastic behavior to further extend the flying envelope. This tailoring can involve adopting specialized laminate configurations that allow the cross-coupling of flexure and torsion such that wing twist can result from bending and vice versa. Modern analysis techniques allow this process of aeroelastic tailoring, along with strength and dynamic stiffness (flutter) requirements to be performed automatically with a minimum of postanalysis testing and verification

Thermal stability of composites is another advantage that is especially relevant in CFRP composites. The basic carbon fiber has a small negative coefficient of thermal expansion (CTE) which, when combined with the positive CTE of the resin, yields the temperature stability of the CFRP composite. This means that CFRP composites do not expand or contract excessively with rapid change in the environmental temperature (as, e.g., during the climb from a 90°F runway to −67°F at 35,000 ft altitude in a matter of minutes).

Another major advantage of using high-performance composites in aerospace application is that the problems of combined fatigue/corrosion that appear in conventional airframes are virtually eliminated. High-performance polymeric composites do not corrode and the fatigue life of fibrous materials is much higher than that of bulk materials. Nonetheless, environmental effects will eventually affect the matrix polymeric material and some form of fatigue (though different from that of metals) will develop in the composite. However, fracture of composite materials seldom occurs catastrophically without warning as it does in

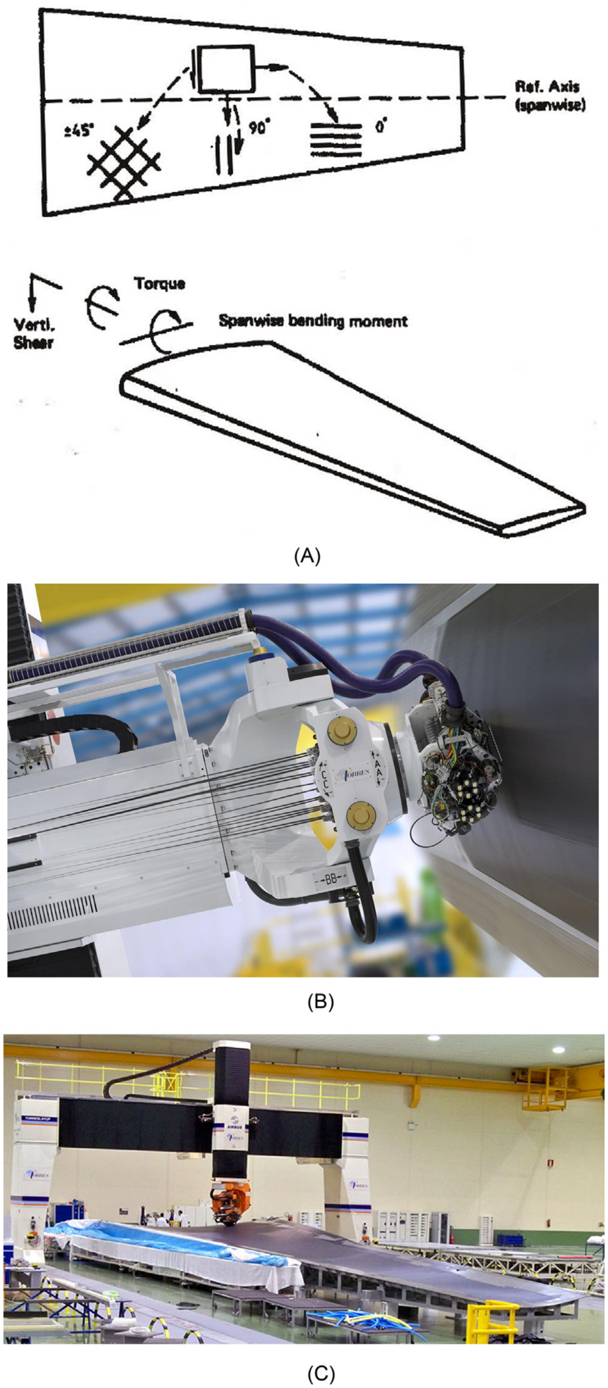


FIGURE 1.2 Unique advantages of using composites in aerospace structures: (A) the concept of strength and stiffness tailoring along major loading directions in an aircraft wing actual wing buildup processes [1]; (B) AFP [4]; (C) ATL [5]. *AFP*, automated fiber placement; *ATL*, advanced tape laying. Source*: (A) From Baker, A., Dutton, S., & Kelly, D. (2004).* Composite materials for aircraft structures *(2nd ed.).* AIAA Education Series. *American Institute of Aeronautics and Astronautics, Reston, VA, Fig. 1.1. (B) From Anon. (2014).* TORRESFIBERLAYUP—Automatic fiber placement machine. *M. Torres Group. <http://www.mtorres.es/en/aeronautics/products/carbon-fiber/torresfiberlayup#sthash.qgLshFMe.dpuf> picture 4, Accessed December 2014. (C) From M. Torres Group. (2014).* TORRESLAYUP—Automatic tape layer machine. *<http://www.mtorres.es/en/aeronautics/products/carbon-fiber/torreslayup> Accessed December 2014. picture 10.*

some metallic alloys. In composites, fatigue and fracture is a progressive phenomenon with substantial damage (and the accompanying loss of stiffness) being widely dispersed throughout the material before final failure takes place.

1.3.5 Fabrication of aerospace composites

Most carbon-fiber composites used in safety-critical primary structures are fabricated by placing uncured layer upon layer of unidirectional plies to achieve the design stacking sequence and orientation requirements. A number of techniques have been developed for the accurate placement of the composite layers in or over a mold, ranging from labor-intensive hand layup techniques to those requiring high capital investment such as automatic fiber placement (AFP, Fig. 1.2B) and in advanced tape laying (ATL, Fig. 1.2C) equipment. Large cylindrical and conical shapes can be obtained through AFP or ATL fabrication over rotating molding mandrels. AFP and ATL machines operate under numerical control and significant effort is being directed laying complicated contoured surfaces.

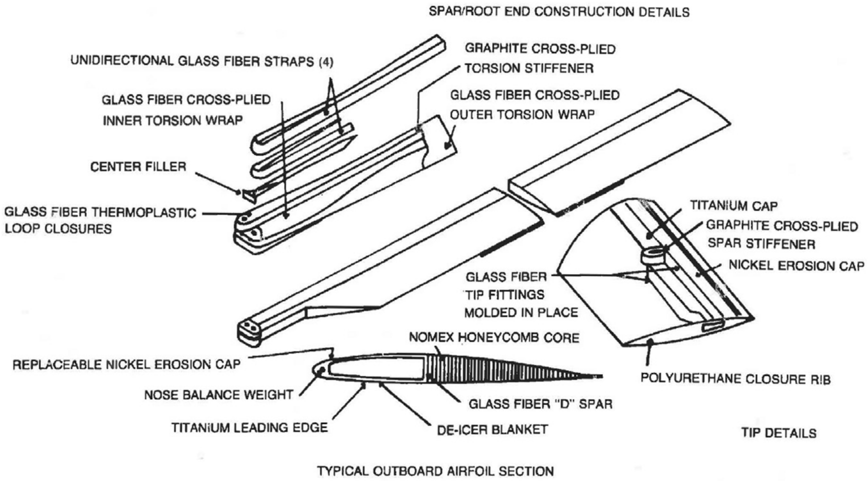
After being laid up in the mold, the uncured composite is subjected to polymerization by exposure to temperature and pressure. This is usually done in an autoclave, a pressure vessel designed to contain a gas under pressures and fitted with a means of raising the internal temperature to that required to cure the resin. Vacuum bagging is also generally used to assist with removing trapped air and organic vapors from the composite. The process produces structures of low porosity, less than 1%, and high mechanical integrity. Large autoclaves have been installed in the aircraft industry capable of housing complete wing or tail sections.

Alternative lower cost nonautoclave processing methods are also being investigated such as vacuum molding (VM), resin transfer molding (RTM), vacuum-assisted RTM, and resin film infusion. The VM processes make use of atmospheric pressure to consolidate the material while curing, thereby obviating the need for an autoclave. The RTM process lays out the fiber reinforcement as a dry preform into a mold and then lets the polymeric resin infiltrate into the preform. The composite systems suitable for vacuum-only processing are cured at 60°C−120°C and then postcured typically at 180°C to fully develop the resin properties. The RTM process is assisted by resin temperature fluidization, pumping pressure, and vacuum suction at specific mold vents.

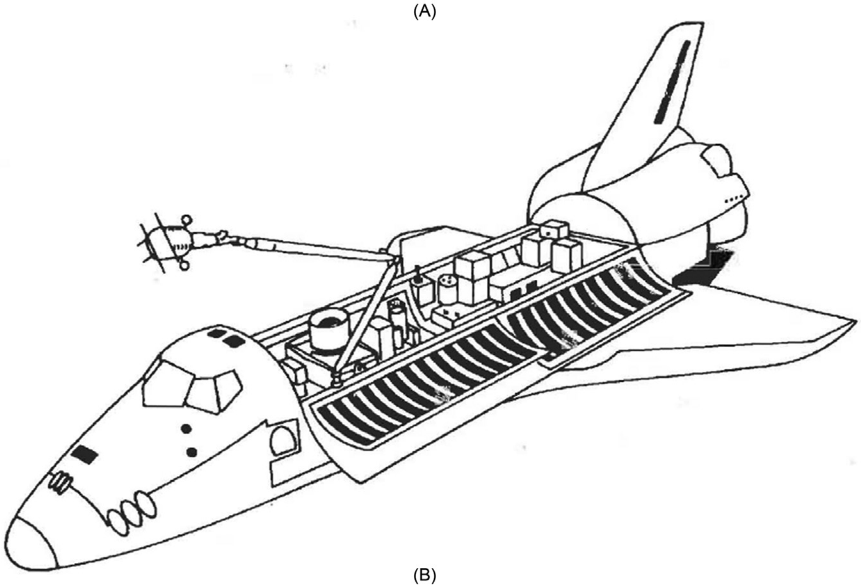
1.4 Evolution of aerospace composites

Development of advanced composites for aerospace use has been both costly and potentially risky, therefore, initial development was done by the military where performance is the dominant factor. The Bell-Boeing V-22 Osprey military transport uses 50% composites, whereas Boeing's C-17 military transport has over 7300 kg of structural composites. Helicopter rotor blades and the space program were among the early adopters of composites technology (Fig. 1.3).

As service experience with the use of advanced composites has accumulated, they have started to penetrate into the civilian aerospace usage. Composites have flown on commercial aircraft safety-critical primary structures for more than 30 years, but only recently have they conquered the fuselage, wing-box, and wings. This evolutionary process has recently culminated with the introduction of "all-composite" airliners, the Boeing 787



(A)



(B)

FIGURE 1.3 Early usage of composites in aerospace primary structures: (A) CH-46 helicopter main rotor blade and (B) composite bay-bay doors on the Space Shuttle [6]. Source*: (A) From Anon. (1989). Composites II: Material selection and applications.* Materials Engineering Institute course 31*. Materials Park, OH: ASM International, Figure 10.4. (B) From Anon. (1989). Composites II: Material selection and applications.* Materials Engineering Institute course 31*. Materials Park, OH: ASM International, Figure 10.7.*

Dreamliner and the Airbus A350 XWB, which have more than 80% by volume composites in their construction.

Early composite designs were replicas of the corresponding metallic parts and the resulting high production costs jeopardized their initial acceptance. Expensive raw materials ("exotic" fibers and specialty resins) as well as labor-intensive hand layup techniques contributed to these high initial costs. The production cost was further increased by the machining and drilling difficulties since these new fibrous materials behaved radically different than metals under these circumstances. Since this cost is in direct relation to the number of assembled parts, design and manufacturing solutions were sought to reduce the part count and the number of associated fasteners. Automated layup methods, integrally stiffened structures, cocured or cobonded of substructures, and the use of honeycomb sandwich solutions have decreased the part count by order of magnitudes while revealing the manufacturing advantages of using composites instead of conventional metals.

1.4.1 Early advances

World War II promoted a need for materials with improved structural properties. In response, fiber-reinforced composites were developed. By the end of the war, fiberglass-reinforced plastics had been used successfully in filament-wound rocket motors and in various other structural applications. These materials were put into broader use in the 1950s and initially seemed to be the only viable approach available for the elimination the problems of corrosion and crack formation observed in high-performance metallic structures.

1.4.2 Composite growth in the 1960s and 1970s

Although developments in metallic materials have led to some solutions to the crack and corrosion problems, fiber-reinforced composites continued to offer other benefits to designers and manufacturers. The 1960s and 1970s have experience a flurry of research into the development of a variety of advanced fiber for high-performance composites such as boron, S-glass, Spectra fiber, and Kevlar fibers. But the fiber that had eventually captured the market was the carbon fiber (aka graphite fiber) because of its excellent strength and modulus weight ratios and relative manufacturing ease. However, early industrial implementation of carbon-fiber development was not without surprises as, for example, their unique impact behavior, discovered by Rolls Royce in the 1960s when the innovative RB211 jet engine with carbon-fiber compressor blades failed catastrophically due to bird strikes.

In large commercial aircraft, composites have found application because of the weight considerations that were highlighted by the energy crisis of the 1970s. Spurred by these events, the use of composites in the aerospace industry has increased dramatically since the 1970s. Traditional materials for aircraft construction include aluminum, steel, and titanium. The primary benefits that composite components can offer are reduced weight and assembly simplification. The performance advantages associated with reducing the weight of aircraft structural elements has been the major impetus for military aviation composites development. Although commercial carriers have increasingly been concerned with fuel economy, the potential for reduced production and maintenance costs has proven to be a major factor in the push toward composites. Composites are also being used increasingly as replacements for metal parts and for composite patch repairs on older aircraft.

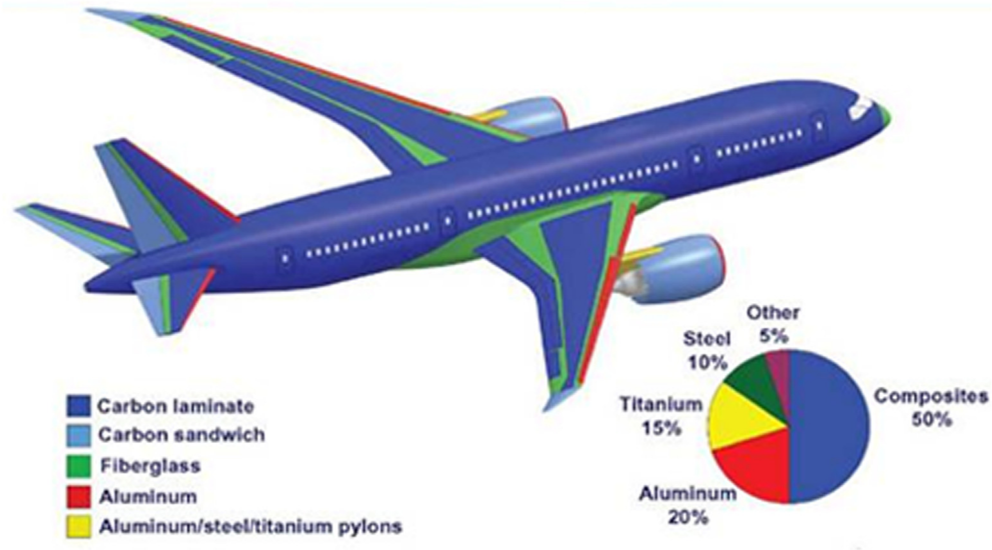
1.4.3 Composites growth since the 1980s

Since 1980s the use of high-performance polymer matrix fiber composites in aircraft structures has grown steadily, although not as dramatically as initially predicted. This is despite the significant weight-saving and other advantages that advanced composites could provide. One reason for the slower-than-anticipated advancement might be that the aircraft components made of aerospace composites have a higher cost than similar structures made from aerospace metals. Other factors include the high cost of certification of new components and their relatively low resistance to mechanical damage, low through-thickness strength, and (compared with titanium alloys) temperature limitations. Thus metals have continued to be favored for many airframe applications. CFRP composites have eventually emerged as the most favored advanced composite for aerospace applications. Although the raw material costs of this and similar composites are still relatively high, their advantages over metals in both strength-to-weight ratio, tailored design, and unitized manufacturability are increasingly recognized. Nonetheless, competition remains intense with continuing developments in structural metals such as aluminum alloys: improved toughness and corrosion resistance, new lightweight alloys (such as aluminum lithium), low-cost aerospace-grade castings, mechanical alloying leading to high-temperature alloys, and superplastic forming. For titanium, powder preforms, casting, and superplastic forming/diffusion bonding are to be mentioned. Advanced joining techniques such as laser and friction stir welding, automated riveting techniques, and high-speed (numerically controlled) machining also make metallic structures more affordable. And the use of hybrid metal-composite combinations (such as the GLARE[1] material used on Airbus A380) which seems to have the best of both worlds also gains popularity with certain designers.

1.5 Today's aerospace composites

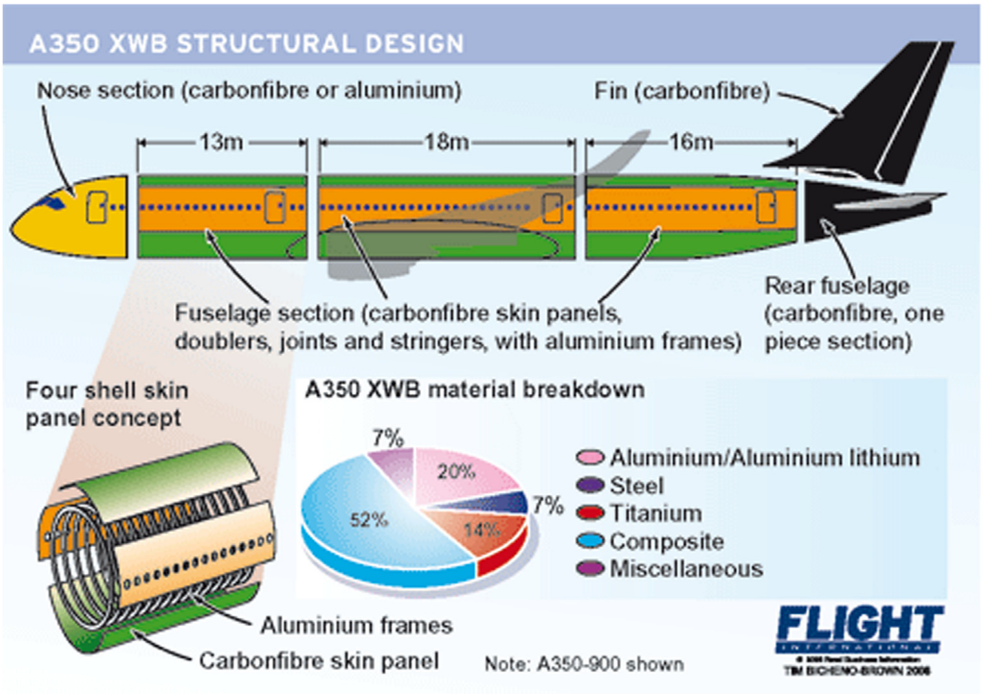
Though the growth has not been as fast as initially predicted, the penetration of high-performance composites into the civilian aerospace has been steady on a continuous upward trend. The drivers for lightweight aircraft structures have continued to push engineers and scientists in looking for unprecedented structural solutions and materials. These major drivers for lightweight structures have been nicely summarized in the 2001 study of the Advisory Council of Aeronautical Research in Europe (ACARE) which identified the aeronautical research needs to be achieved by 2020 [7]. The ACARE goals include (1) noise reduction to one-half of current average levels, (2) elimination of noise nuisance outside the airport boundary by quieter aircraft, (3) a 50% reduction in CO_2 emissions per passenger-kilometer (which means a 50% cut in fuel consumption in the new aircraft of 2020), and (4) an 80% reduction in nitrogen oxide (NO_X) emissions. A more detailed vision of the aerospace goals in the 2050 timeframe is given in the report "Flightpath 2050: Europe's Vision for Aviation" [8]. Similar requirements have been put forward in the United States and elsewhere. As a result, the civilian aerospace industry is now producing large almost all-composite passenger aircraft such as the Boeing 787 Dreamliner and

[1] GLARE is a proprietary glass-reinforced fiber metal laminate material



Carbon laminate
Carbon sandwich
Fiberglass
Aluminum
Aluminum/steel/titanium pylons
Other 5%
Steel 10%
Titanium 15%
Aluminum 20%
Composites 50%

(A)



A350 XWB STRUCTURAL DESIGN
Nose section (carbonfibre or aluminium)
Fin (carbonfibre)
13m
18m
16m
Fuselage section (carbonfibre skin panels, doublers, joints and stringers, with aluminium frames)
Rear fuselage (carbonfibre, one piece section)
Four shell skin panel concept
A350 XWB material breakdown
7%
20%
7%
52%
14%
Aluminium/Aluminium lithium
Steel
Titanium
Composite
Miscellaneous
Aluminium frames
Carbonfibre skin panel
Note: A350-900 shown
FLIGHT INTERNATIONAL
TIM BICHENO-BROWN 2006

(B)

FIGURE 1.5 Boeing 787 Dreamliner [12]. Source: *From Anon. (2014).* Boeing image gallery. *The Boeing Company. <http://www.boeing.com/boeing/companyoffices/gallery/images/commercial/787/index1.page,BoeingimageK63965-03_lg>.*

Airbus A350 XWB airliners (Fig. 1.4). These unprecedented engineering achievements have more than 80% composites by volume.

The main features of the Boeing 787 and Airbus A350 XWB are briefly discussed in the following sections.

1.5.1 Boeing 787 Dreamliner

The Boeing 787 Dreamliner (Fig. 1.5A) is a family of long-range, midsize wide-body, twin-engine jet airliners that can seat 242–335 passengers in a typical three-class seating configuration. This aircraft, the world's first major commercial airliner to use composite materials as the primary material in its airframe, is Boeing's most fuel-efficient airliner [11]. The Boeing 787 maiden flight took place on December 15, 2009 and completed flight testing in mid-2011. Final Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) type certification was received in August 2011 and the first 787-8 model was delivered to All Nippon Airways in September 2011.

The Boeing 787 aircraft is 80% composite by volume. By weight, the material contents is 50% composite, 20% aluminum, 15% titanium, 10% steel, and 5% other [11]. Aluminum is used for the wing and tail leading edges; titanium is used mainly on engines and fasteners, with steel used in various areas.

Each Boeing 787 aircraft contains approximately 32,000 kg of CFRP composites, made with 23 t of carbon fiber [11]. Composites are used on fuselage, wings, tail, doors, and interior. Boeing 787 fuselage sections are laid up on huge rotating mandrels (Fig. 1.6A). AFP and ATL

FIGURE 1.4 Composite content of all-composite airliners: (A) Boeing 787 Dreamliner has ~80% by volume (~50% by weight) composites [9] and (B) Airbus A350 XWB has ~83% by volume (~52% by weight) composites [10]. The lower by-weight ratio is due to the fact that other materials are much heavier than composites. Source: *(A) From Hale, J. (2006). Boeing 787 from the ground up.* Boeing Aero Magazine. *24, Q-04. <http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/index.html> Accessed December 2014. (B) From Kinsley-Jones, M. (2006).* Airbus's A350 vision takes shape—Flight takes an in-depth look at the new twinjet. *Flight International. <http://www.flightglobal.com/news/articles/airbus39s-a350-vision-takes-shape-flight-takes-an-in-depth-look-at-the-new-211028/> Accessed December 2014, Fig. 1.2.*

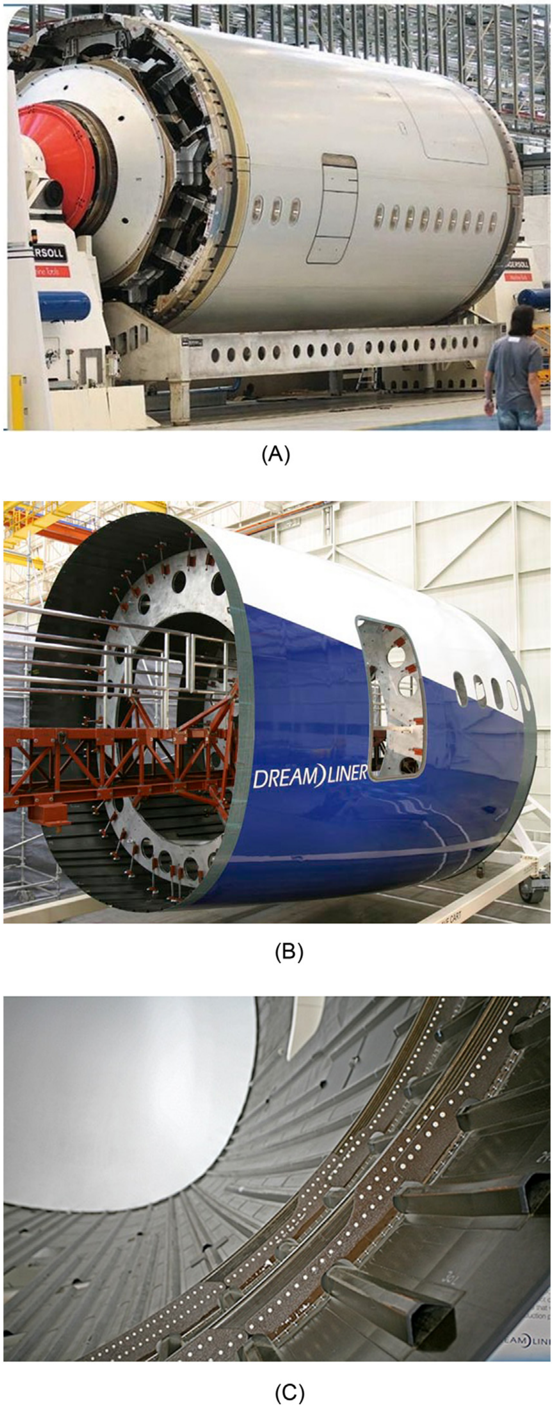


FIGURE 1.6 Composite fuselage of the Boeing 787 Dreamliner: (A) the fuselage barrel is a continuous construction build on a rotating mandrel through automated tape laying [13]; (B) the resulting monocoque shell has internal longitudinal stiffeners already built in [12]; and (C) the highly integrated internal structure of the fuselage requires orders of magnitude less fasteners than the conventional built-up airframes [11]. Source: *(A) From Norris, G., & Wagner, M. (2009).* Boeing 787 Dreamliner, *ISBN 0760328153, Zenith Press, MBI Pub. Co., Minneapolis, MN. <http://www.zenithpress.com>, Kindle book, location 1257. (B) From Anon. (2014).* Boeing image gallery. *The Boeing Company. <http://www.boeing.com/boeing/companyoffices/gallery/images/commercial/787/index1.page,photo#-k6321101_lg>. (C) From <http://upload.wikimedia.org/wikipedia/commons/2/2b/787fuselage.jpg>.*

robotic heads robotically layers of carbon-fiber epoxy resin prepreg to contoured surfaces. Reinforcing fibers are oriented in specific directions to deliver maximum strength along maximum load paths. The fuselage sections are cured in huge autoclaves. The resulting monocoque shell has internal longitudinal stiffeners already built in (Fig. 1.6B and C). This highly integrated structure requires orders of magnitude less fasteners than the conventional built-up airframes. Similar composite manufacturing techniques are applied to the wings.

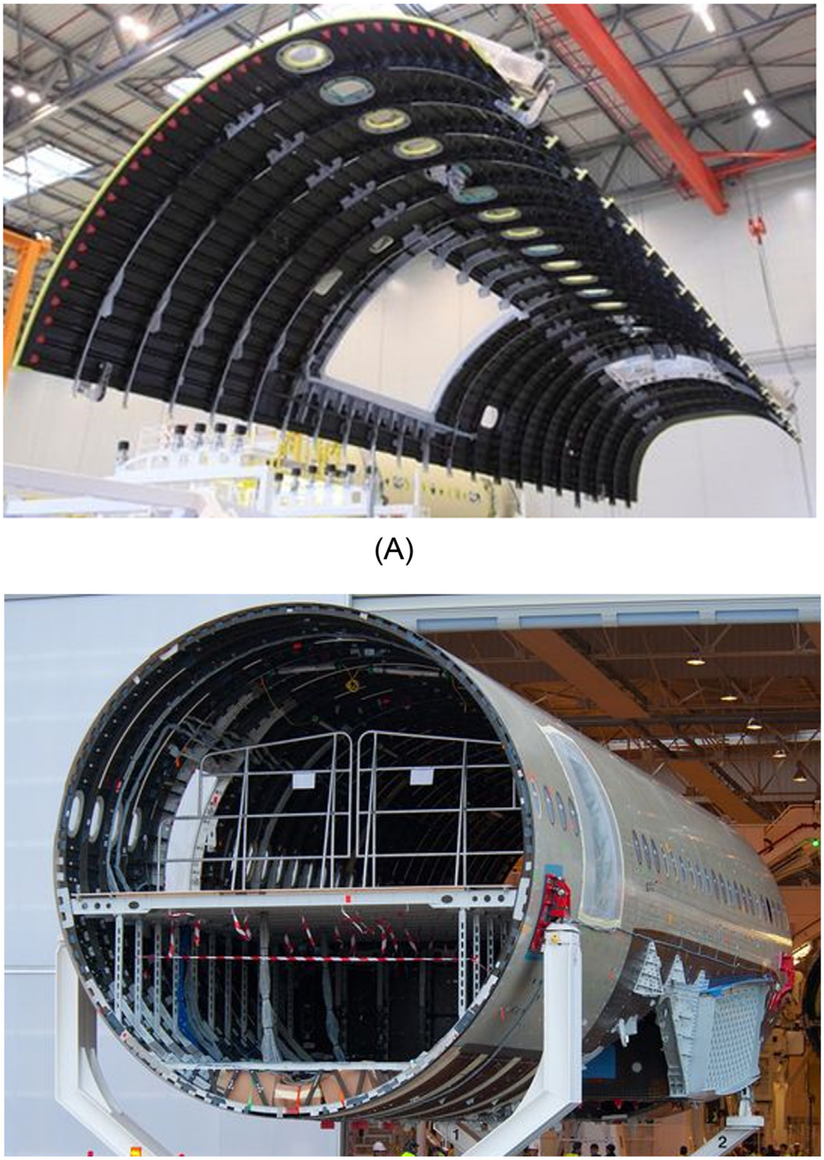
Boeing 787 has composite wings with raked wingtips where the tip of the wing has a higher degree of sweep than the rest of the wing. This aerodynamic design feature improves its fuel efficiency and climb performance while shortening takeoff length. It does this in much the same way that winglets do, by increasing the effective aspect ratio of the wing and interrupting harmful wingtip vortices thus decreasing the amount of lift-induced drag experienced by the aircraft. This capability of applying various camber shapes along the wingspan as well as a double-curvature configuration is particular to composite wings and cannot be efficiently achieved in metallic wings.

1.5.2 Airbus A350 XWB

The Airbus A350 XWB (Fig. 1.7) is a family of long-range, midsize wide-body twin-engine jet airliners that can seat 250–350 passengers in a typical three-class seating configuration. The Airbus A350 XWB maiden flight took place on June 14, 2013. The Airbus A350 XWB received EASA type certification in September 2014 and FAA certification in November 2014. The first Airbus A350 XWB was delivered to the Qatar Airways in December 2014 with the first commercial flight in January 2015 [14].

The Airbus A350 XWB airframe includes a range of advanced materials: composites in the fuselage, wings, and tail; aluminum–lithium alloys in floor beams, frames, ribs, and landing gear bays; and titanium alloys in main landing gear supports, engine pylons, and some attachments. The fuselage section of the Airbus A350 XWB has a four-panel construction such that the major fuselage sections are created by the assembly of four large panels which are joined with longitudinal riveted joints (Fig. 1.8). The fuselage composite panels are mounted on composite fuselage frames. Airbus designers see in this approach a better management of construction tolerances when the jetliner's composite fuselage

FIGURE 1.7 Airbus A350 XWB [15]. Source: *Anon. (2014).* Airbus photo gallery. <*http://www.airbus.com/galleries/photo-gallery/filter/a350-xwb-family/photoA350-MSN2-003*>.



(A)

(B)

FIGURE 1.8 Airbus A350 XWB four-panel concept: (A) one of the four panels [16] and (B) fuselage assembled from four panels [15]. Source: *(A) from Anon. (2012).* A350 XWB intelligent and aerodynamic airframe. *Airbus International. <http://www.a350xwb.com/advanced/fuselage/> Accessed December 2014. <http://www.a350xwb.com/advanced/fuselage/#four-panel-concept>. (B) from Anon. (2014).* Airbus photo gallery. *<http://www.airbus.com/galleries/photo-gallery/filter/a350-xwb-family/ photo A350-MSN2-003>. <http://www.airbus.com/galleries/photo-gallery/dg/idp/23464-a350-xwb-fal-start-1/?share = 1>.*

sections come together on the final assembly. Another perceived benefit of the four-panel concept might be the improved reparability in operational service, as an individual panel can be replaced in the event of significant damage—avoiding major repair work that could require extensive composite patching.

The Airbus A350 XWB has composite wings with blended tip winglets thus departing significantly from Airbus's traditional wingtip fences. The wings curve upward over the final 4.4 m in a "saber-like" shape. This capability of applying various camber shapes along the wingspan as well as a double-curvature configuration is particular to composite wings and cannot be efficiently achieved in metallic wings.

1.6 Challenges for aerospace composites

Though greatly popular and very attractive for development, the aerospace composites activity is not without challenges. Some of these challenges could be grouped in safety concerns, not surprisingly since the commercial use of composites in flight-critical primary structures is still at its inception. Other challenges are related to future developments, where composites are expected to deliver the "unobtainium" material that would make our engineering dreams come true. Both of these challenges are briefly discussed in the following sections.

1.6.1 Concerns about the aerospace use of composites

Several concerns have been voiced about the aerospace use of composites. One issue that has been raised concerns barely visible damage, that is, damage of the composite material that cannot be detected by preflight visual inspection (a routine procedure that identifies dents and other damages on current metallic aircraft). In fact, composite materials may suffer internal damage due to a low-velocity impact (e.g., a tool drop during routine maintenance) without any obvious changes to its surface.

Another often voiced concern is about the fact that the polymeric matrix constituent of the composite materials may collect moisture and change its properties over time. Moisture may also accumulate in matrix microcrack and minor delaminations between the layers of the composite laminate. As the aircraft goes at altitude and temperature drops below freezing, this trapped water would expand and promote further microcracking. Over several flight cycles, the freezing and unfreezing phenomenon will make cracks to expand and eventually cause delamination.

The aircraft designers are well aware of these issues and all necessary measures are being taken to maintain the aircraft safety and integrity. These measures have included extensive testing under accelerated climatic and environmental conditions to ensure that the composite will maintain its integrity over the whole design life of the aircraft. In some cases, these measures may also have included excessive design factors such that considerations other than pure operational stress and strain have been dominant in sizing some composite aircraft parts.

Recent technology has provided a variety of reinforcing fibers and matrices that can be combined to form composites having a wide range of very exceptional properties. In many instances, the sheer number of available material combinations can make selection of materials for evaluation a difficult and almost overwhelming task. In addition, once a material is selected, the choice of an optimal fabrication process can be very complex.

1.6.2 The November 2001 accident of AA flight 587

The November 2001 accident of AA flight 587 is one of the worst aviation accidents on United States soil, resulting in the death of all 260 people aboard the aircraft and 5 people on the ground [17]. On November 12, 2001 the Airbus A300−600 of American Airlines flight 587 crashed in Queens, New York City, shortly after takeoff [18]. The aircraft vertical stabilizer (tail fin) detached from the aircraft causing the aircraft to crash. The A300−600 vertical stabilizer is connected to the fuselage with six attaching points (Fig. 1.9). Each point has two sets of attachment lugs, one made of composite material, another of aluminum, all connected by a titanium bolt; damage analysis showed that the bolts and aluminum lugs were intact, but not the composite lugs [18]. This event as well as two earlier events in the life of the aircraft (namely, a delamination in part of the vertical stabilizer prior to its delivery from Airbus's Toulouse factory and an encounter with heavy turbulence in 1994) caused investigators to examine the use of composites [18].

The possibility that the composite materials might not be as strong as previously supposed was a cause of concern because they are used in other areas of the plane, including the engine mounting and the wings. Tests carried out on the vertical stabilizers from the aircraft that met the accident, and from another similar aircraft, found that the strength of the composite material had not been compromised, and the National Transportation Safety Board concluded that the material had failed because it had been stressed beyond its design limit, despite 10 previous recorded incidents where A300 tail fins had been stressed beyond their design limitation in which none resulted in the separation of the vertical stabilizer in-flight [18,20].

1.6.3 Fatigue behavior of composite materials

Although aerospace metals, such as aluminum, have a well-known fatigue behavior, the fatigue life of the composites is much more complicated and less understood. The aerospace metallic materials have been extensively studied and their fatigue behavior is well understood by now. The situation is drastically different in the case of composites. The fatigue life of a metallic aircraft part can be directly deduced from two basic ingredients: (1) knowledge of the aluminum fatigue data and (2) knowledge of cyclic stress distribution. In the case of metallic materials, the ingredient, that is, the material fatigue data, is well known and easily accessible. In the case of a composites, the ingredient, that is, the composite fatigue data, is far from being universally understood. In fact, the fatigue behavior of a composite material depends not only on that of its constituent fibers and matrix, but also on the layup sequence and hence it may vary from part to part. This observation explains in simple terms why the aerospace composites fatigue still remains a very fruitful research topic.

(A)

(B)

FIGURE 1.9 Composite vertical stabilizer lug (tail fin) broken during the AA flight 587 of Airbus A300−600 in Queens, New York City, November 12, 2001: (A) vertical stabilizer (tail fin) attachment point and (B) close-up of center vertical stabilizer attachment clevis at crash site [19]. Source*: From Anon. (2002).* NTSB schedules public investigative hearing on crash of American Airlines flight 587, for immediate release NTSB publication SB-02−31, file ntsb_020919*. pictures 3, 14.*

Nonetheless, the basic fatigue superiority of composites over the metals exists due to the fact that a fibrous material is less susceptible to catastrophic failure than a conventional metal. So far, the aircraft designers have relied on extensive certification tests and procedures to ensure that the composite materials used in their designs have an adequate fatigue behavior such that the aircraft safety is always ensured. However, these certification procedures are lengthy and expensive; for that reason, the introduction of other composite solutions is currently somehow retarded and certain conservatism exists with the tendency of using only the solutions that have been already certified and approved. This situation will persist until a better way of designing and in-service monitoring of aerospace composites is implemented.

1.6.4 The future of composites in aerospace

When it comes to aerospace, composite materials are here to stay. With ever increasing fuel costs and environmental regulations, commercial flying remains under sustained pressure to improve performance, and weight reduction is a key factor for achieving this goal. With their excellent strength-to-weight ratio, advanced composites are an obvious choice. Beyond the day-to-day operating costs, the aircraft maintenance programs are a heavy burden on the airline budgets. Aircraft maintenance can be simplified by the reduction of component count and elimination of corrosion issues. Again, composites are the obvious choice. The competitive nature of the aircraft construction business ensures that any opportunity to reduce operating costs is explored and exploited wherever possible. Competition also exists in the military, with continuous pressure to increase payload and range, flight performance characteristics, and "survivability," in both airplanes and missiles.

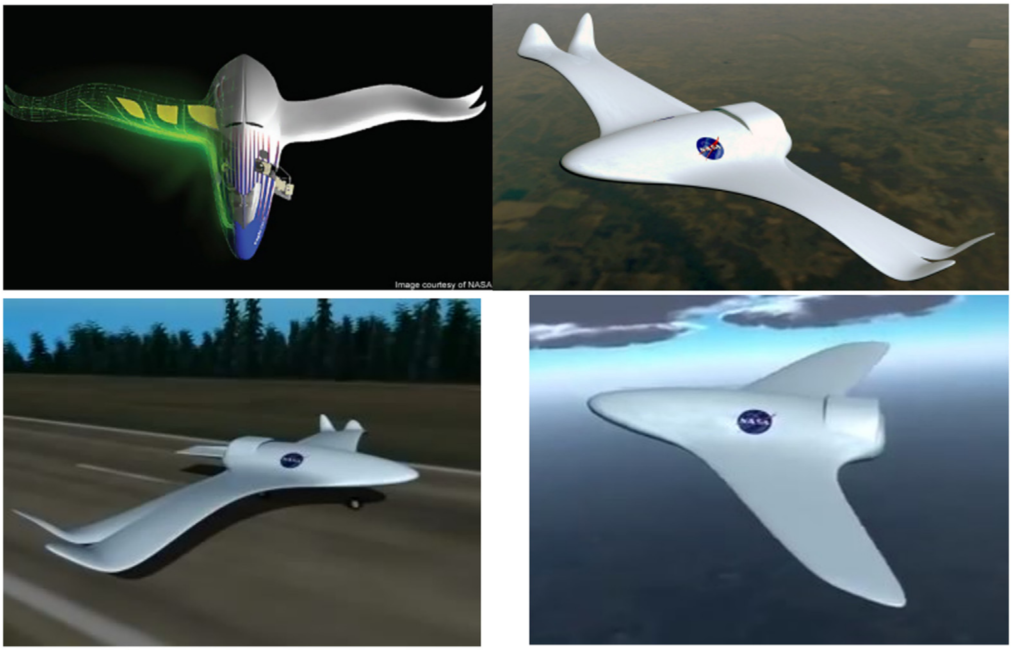
Composite technology continues to advance, and the advent of new fiber and matrix types as well as new manufacturing techniques is certain to accelerate and extend composite usage. Several research and development areas are of special interest to both scientists and engineers.

One technological shortcoming that requires a solution is the elimination of mechanical fasteners from the composite assemblies. At present, even the Boeing 787 and the Airbus A350 XWB still use thousands of mechanical fasteners during assembly. Why not use adhesive bonding? Because, in order to ensure safety, current certification requirements mandate that proof must be made that each and every *adhesively bonded* joint will not separate to cause structural failure should it reach its critical design load. Using mechanical fasteners is still the easiest and least expensive way to meet certification requirements. However, the full realization of cost and weight savings through composite materials will only be attained if our scientific understanding and technical trust in bonded joints reach the point where certification can be attained without additional fasteners.

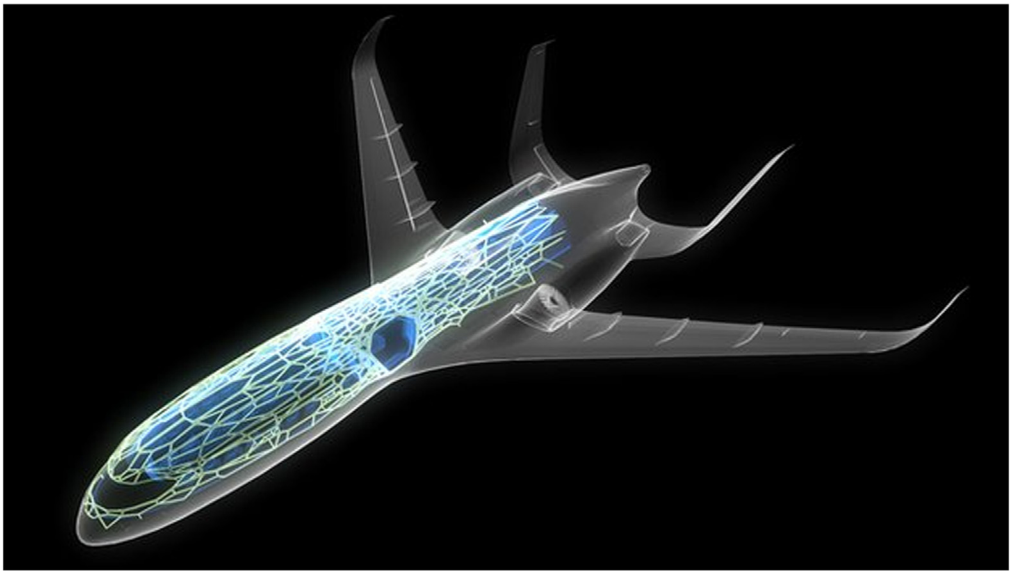
One of the most exciting upcoming opportunities for aerospace composites is in the commercial space flight arena. For example, the concepts of the Virgin Galactic LLC air-launch space travel consider all-composite solutions consisting of a space vehicle (VSS Enterprise) being launched at altitude from a carrier aircraft (the White Knight) [21].

Future composite aircraft are envisaged to be able to change their shape as required by the flight regime in which they operate. Fig. 1.10A shows several artist renderings resulting from NASA morphing aircraft program [22,23]; one notices that the straight wide-span double wings are needed for short takeoff and landing morph into a single swept-wing required for high-speed flight, as well as the appearance of individual winglets as required for fast maneuvers. Thus a morphing aircraft would be able to change its shape as needed by various flight profiles in which it has to operate.

Fig. 1.10B presents a futuristic aircraft concept originating from one of the major aircraft manufacturers [24]. Besides special aerodynamic contours that are only possible through the use of composites, this aircraft concept also displays a network of sensors and interconnects that, similar to the animal nervous system, would be able to collect data about the aircraft state of health, relay it to a central unit, and advise appropriate corrective actions and/or future maintenance scheduling. Such an aircraft nervous is also depicted in Fig. 1.10B, with the additional proviso that self-repairing aerospace composites are being considered in order to restore the composite aircraft to its full initial capability.



(A)



(B)

FIGURE 1.10 Composites-enabled future aircraft: (A) NASA morphing aircraft program aims at changing the aircraft shape as needed by various flight profiles [22,23] and (B) artist rendering of Airbus future composite aircraft concept [24]. Source: *(A) From Stories by Williams (2014).* The future of flight: Morphing wings. *<http://stories-bywilliams.com/2014/02/01/the-future-of-flight-morphing-wings/> Accessed December 2014. images 1 and 6. Anon. (2014). NASA morphing aircraft movie. <https://www.youtube.com/watch?v = vR3T8mdpdTI> Accessed December 2014, frame images captured from the video clip. (B) From Bowler, T. (2014).* Carbon fibre planes: Lighter and stronger by design. *BBC News Business. <http://www.bbc.com/news/business-25833264>, picture 5.*

1.7 About this book

This book addresses the field of structural health monitoring (SHM) and presents a review of the principal means and methods for SHM of aerospace composite structures. This very challenging issue is addressed is a step-by-step way such as the readers will become gradually aware of all the aspects of the problem as they progress through the book. The introductory chapter has given an overview of why and how composites are used in the aerospace industry.

The next chapters present a step-by-step approach to the analysis of composites behavior and response. Chapter 2 is dedicated to discussing the fundamental aspects of composite materials. This chapter will set up the mathematical framework in which the analysis of composite materials takes place. The basic equations of anisotropic elasticity in tensor and matrix notations are introduced and discussed. The induced-strain actuation analysis due to thermal, hygroscopic, and piezoelectric effects is introduced. The rotation of stress, strain, and stiffness matrices using the bond matrices is presented. The analysis of composites failure using various failure criteria and the safety factors and margin of safety is discussed.

Chapter 3 deals with the study of classical lamination theory (CLT) which is performed under the plane-stress assumption as appropriate to thin-wall aerospace composite structures. Plane-stress elastic properties of a composite layer are introduced and discussed. The Love–Kirchhoff theory for axial–flexural deformation of plates is recalled and then applied to composites. The CLT analysis of composite plates is developed yielding the ABD matrices that relate the stress resultants to strains and curvatures. The simplified forms that the ABD matrices take in the case of various laminates are derived, in particular for uniform laminates, symmetric laminates, antisymmetric laminates, crossply laminates, orthotropic laminates, and isotropic plates. The direct and inverse problems of composites' CLT analysis are posed and discussed. The induced-strain aspects of composites analysis related to thermal, hygroscopic, and piezoelectric effects are introduced into the CLT formulation. A unified CLT formulation for combined thermal, hygroscopic, and piezoelectric effects is developed. The progressive failure of laminated composites is presented consisting of allowing for further load increase beyond the first-ply failure. The progressive failure process is handled through degrading the elastic properties in the failed plies and updating the ABD matrices to account for the reduced load-carrying capacity of the partially failed composite laminate.

A large number of worked-out numerical examples are included. Basic CLT examples cover ply rotation and ABD matrices for various laminates, as well as induced-strain effects. The first-ply failure analysis is covered in several sets of worked-out examples such as axial-load failure with and without thermal effects, shear-load failure, quasi-isotropic composite failure, flexural failure, and twist failure. Some progressive failure examples cover the failure of crossply and quasi-isotropic composites under axial load with and without thermal effects. Other progressive failure examples include progressive failure under flexural and shear loads. Worked-out numerical examples for piezocomposites are also presented. A comparative discussion of the lessons learned from the worked-out examples is given. The chapter finishes with a set of problems and exercises and a rich list of cited references and extensive bibliography.

Chapter 4 is dedicated to the study of stress and displacement in aerospace composites under quasi-static conditions. The analysis presented in this chapter is done with the CLT which assumes a state of plane stress in the composite plies as discussed in Chapter 3. The kinematic and boundary-condition hypothesis of the Love−Kirchhoff plate theory are assumed. The main difference between the composite plate theory and the conventional Love−Kirchhoff plate theory is in the inherent coupling between the axial (in-plane) and flexural (out-of-plane) motions and deformations. In the isotropic plate, the axial and flexural motions and deformations are not coupled; hence, the axial analysis (aka membrane analysis) and flexural analysis (aka plate bending analysis) could be performed independently. In composite plates, the axial and flexural deformations are strongly coupled. If only one type of loading is applied, say, in-plane loading, then both axial and flexural deformations may appear due to the coupling effect. Similarly, out-of-plane loading may also generate not only flexural but also axial strains and deformation. This coupling situation is apparent in the differential equations that govern the composite plate behavior. However, the axial−flexural coupling disappears in the restrictive case of orthotropic composites. First, the series-expansion solution for the analysis of simply supported isotropic plates under flexural loads is reviewed. The displacement and stress solutions are derived and convergence studies are performed. Next, the same procedure is applied to the analysis of orthotropic composite plates in which coupling between axial and flexural deformations does not exist. Thermal and piezo effects are included. A large number of worked-out examples, problems and exercises, as well as references and bibliography are presented.

Chapter 5 deals with the vibration of composite structures. The axial and flexural vibrations of anisotropic composite plates are fully coupled, which is substantially different from the case of isotropic metallic plates in which the axial and flexural vibrations are decoupled and can be studied independently. The displacements and stress resultants are defined in terms of the motion and loading of composite plate mid-surface. The equations of motion are derived in terms of stress resultants. The strains were expressed in terms of mid-surface strains and curvatures. ABD matrices derived in Chapter 3 are used to express the relation between stress resultants and mid-surface strains and curvatures. Eventually, the vibration equations for an anisotropic laminated composite plate are derived in terms of displacements, mass distribution, and the ABD matrix components. The same approach is repeated for isotropic plates to allow direct comparison with the axial and flexural plate vibration formulations existing in literature. The composite plate vibration equations are solved for the special case of orthotropic composites which permit the decoupling between the axial and flexural motions. The flexural vibration of simply supported orthotropic composite plates is studied in order to derive natural frequencies and modeshapes. The dynamic response of simply supported orthotropic composite plates is studied through normal-mode expansion in terms of natural frequencies and modeshapes. Several worked-out numerical examples are presented, including unidirectional and crossply composite plates. Natural frequencies, modeshapes, and dynamic response for uniformly distributed excitation and point-load excitation are given. The calculations for similar isotropic aluminum plates are offered for comparison. Vibration of free composite plates is treated with the finite element method (FEM). Problems and exercises as well as a list of references and bibliography conclude the chapter.

Chapter 6 deals with the study of ultrasonic waves in bulk anisotropic composites. The analysis of bulk-wave propagation in an infinite anisotropic composite medium is examined. First, the wavefront propagation is studied in terms of wavespeed (aka phase velocity), particle-displacement polarization vector, wave phase, and wavefront. The attention is next given on harmonic waves. Wavelength, wavenumber, wavevector, and polarization of harmonic waves are discussed. The directional dependence of wavespeed and polarization vector is analyzed in terms of Christoffel equation and acoustic tensor. Solution of eigenvalue Christoffel equation is obtained as angle-dependent fundamental three wavemodes. Polar and surface plots of wavespeed and slowness are presented and discussed. Conditions for pure-wave modes are discussed. The excitation of ultrasonic waves in anisotropic bulk composites is analyzed under various conditions. It is shown that finite-footprint excitation may result in skew wave beams that propagate at an angle wrt the excitation direction. The concept of group velocity is introduced to account for this skew-propagation phenomenon. Expressions for calculating group velocity vector components are derived and the skew angle between group velocity and wavespeed is determined. Group velocity polar and surface plots are presented and discussed. The time-averaged wave energy and power flow are deduced. Expressions for Poynting vector and energy velocity are attained. The energy velocity is shown to be equivalent to group velocity in nondissipative media. The relations between slowness surface, ray surface, wavenumber, and group velocity are deduced and discussed. A large number of worked-out examples are presented in order to illustrate bulk-wave propagation in unidirectional and generally orthotropic CFRP composites in comparison with isotropic aluminum. Problems and exercises as well as cited references and bibliography are given at the end of the chapter.

Chapter 7 deals with the study of guided waves in aerospace composites. The analysis is performed with the semianalytical finite element (SAFE) method which performs FEM analysis of the vibration modes across the thickness while using analytical modeling of how these thickness vibration modes travel as guided waves. Straight-crested guided waves in composite plate are analyzed first. The elasticity relations are recalled and the variational formulation is introduced. The wave propagation along the plate with an assumed frequency ω and wavenumber ξ is applied. FEM discretization is implemented and strains inside the elements are calculated. A discretized variational formula is developed and the elemental stiffness and mass matrices are derived. The FEM assembly procedure is applied and the ω-dependent FEM eigenvalue problem is developed. A range of ω is explored and the eigenvalues and eigenvectors are extracted for each ω value. Then, the SAFE analysis is extended to arbitrarily crested guided waves with the wavevector pointing in a generic direction θ. A θ-dependent SAFE formulation is developed where the resulting eigenvalues and eigenvectors depend on both direction θ and frequency ω. The eigenvalues and eigenvectors are processed to yield the frequency−wavenumber dispersion curves and associated modeshapes. Wavespeed, energy velocity, and group velocity dispersion curves are derived. The skew angle between energy/group velocity and wavespeed is calculated. The modeshapes are processed in terms of displacement modeshapes and strain/stress modeshapes. The evanescent waves associated with imaginary wavenumbers as well as the waves associated with complex wavenumbers are discussed. The wavespeed, slowness, energy velocity, and group velocity polar plots associated with arbitrarily crested guided waves are derived and interpreted. A substantial number of worked-out examples, problems and exercises, and references are presented.

Chapter 8 covers the excitation of ultrasonic guided waves in aerospace composites. The analysis is performed with the SAFE method which performs FEM analysis of the vibration modes across the thickness while using analytical modeling of how these thickness vibration modes travel as guided waves. In previous Chapter 7 the SAFE method was used to study the guided-wave modes and characteristic wavenumbers in the absence of external excitation. In Chapter 8 the SAFE method is used to model how and external excitation would induce guided waves in an aerospace composite. The chapter starts with extension of the variational principle to include external excitation which then followed by the FEM setup in which the excitation is resolved in the form of nodal forces applied to the FEM nodes. Excitation representation in the wavenumber−frequency domain is generally assumed. Normal-mode expansion in terms of the guided-wave modes is assumed and the solution is sought in the form of wavenumber-dependent and frequency-dependent modal participation factors. The solution is obtained first in the wavenumber−frequency domain and the returned through an inverse Fourier transform to the space−frequency domain using the residue theorem. A further inverse Fourier transform is applied to deal with the frequency spectrum of the excitation such that the space−time domain solution is eventually obtained. For straight-crested guided waves, the solution depends only on a single wavenumber and the application of the residue theorem yields a closed-form solution. For the arbitrarily crested guided waves, the application of the residue theorem in the wavenumber−angle domain yields an angle-dependent integral that is evaluated in the far field using the stationary phase theorem. A substantial number of worked-out examples are presented. The chapter closes with problems exercises, and list of cited references and further-reading bibliography.

Chapter 9 discusses analytical methods for predicting guided waves in aerospace composites. The guided wave is modeled as an assembly of partial waves that share the same wavenumber parallel to the plate mid-surface but have different wavenumbers in the thickness direction. The problem setup is initiated by assuming six partial waves and imposing the coherence condition (generalized Snell's law) wrt the guided-wave propagation. The resulting Christoffel equation yields a nonlinear wavespeed-dependent eigenvalue problem. For every wavespeed, the constrained Christoffel equation yields six eigenvalues and eigenvectors that are used to assemble the displacement and stress field matrices. These are multiplied by the six partial-wave participation factors to assemble the physical displacements and stresses in each composite layer. The boundary conditions at the plate upper and lower faces and at the interfaces between the N layers yields a linear problem with $6N$ unknowns. If the $6N \times 6N$ problem is solved directly then one has the global matrix method (GMM). However, if the GMM problem is too large to solve direction, then one can apply a method of layer-by-layer transfer to reduce the problem size. If the transfer involves the displacement-stress-state vector then one has the 3×3 transfer matrix method (TMM), which is subject to numerical instability. If the layer transfer involves a recursive stiffness algorithm, then one has the 6×6 stiffness transfer method (SMM) which has a better numerical stability. In any case, the resulting search function is used to find the wavenumber−frequency−wavespeed combinations that give the guided-wave modes. The chapter contains a number of worked-out examples of solving the constrained Christoffel equation as well as the discussion of two software packages: (1) the GMM-based DISPERSE software from Imperial College, London, UK and (2) the GMM-TMM-SMM Dispersion Calculator (DC) software from ZLP-DLR in Augsburg, Germany.

Chapter 10 covers the application of stress, vibration, and wave analysis to the SHM and nondestructive evaluation (NDE) of aerospace composites. Numerous practical situations consisting of analytical and FEM simulations backed up by carefully conducted experiments are presented. Stress and strain monitoring of composite structures includes strain monitoring for delamination detection and buckling detection, and examples of stress and stress monitoring of actual aerospace vehicles. The chapter continues with the presentation of vibration methods for composite damage detection, including model-based vibration SHM, curvature/strain-mode vibration SHM, and an interesting application of the blister-mode method for composite delamination detection. Bulk-wave applications include NDE methods for the determination of composite material stiffness properties, delamination NDE, impact-damage NDE, and manufacturing-flaw NDE. The rest of the chapter is dedicated to various SHM and NDE methods utilizing guided-wave propagation in aerospace composites. The use of passive guided-wave monitoring for monitoring impact events is discussed with model-based impact monitoring and directional-sensor monitoring being presented. The discussion of active guided-wave monitoring for damage detection in composites starts with the study of wave-damage interaction coefficients, including examples in unidirectional and quasi-isotropic composites. Next, the use of angle-beam transducers (ABT) for guided-wave NDE of damage in various composite layups is presented. The ABT angle prediction of the generation of S0 and SH0 guided waves in crossply and quasi-isotropic composites of various thickness is predicted and experimentally verified. ABT methods for distinguishing between delaminations and actual impact damage are presented. Finally, acousto-ultrasonic methods and piezoelectric wafer active sensors[1] SHM of composite damage are presented and discussed.

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[1] PWAS = piezoelectric wafer active sensors

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