Design and Analysis of Composite Structures

Christos Kassapoglou

Second Edition

Design and Analysis of Composite Structures

With Applications to Aerospace Structures

Aerospace Series

Editors: Peter Belobaba, Jonathan Cooper, Roy Langton, and Allan Seabridge

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DESIGN AND ANALYSIS OF COMPOSITE STRUCTURES
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DESIGN AND ANALYSIS OF COMPOSITE STRUCTURES
WITH APPLICATIONS TO AEROSPACE STRUCTURES

Second Edition

Christos Kassapoglou
Delft University of Technology, The Netherlands
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About the Author

Christos Kassapoglou received his BS degree in Aeronautics and Astronautics, and two MS degrees (Aeronautics and Astronautics and Mechanical Engineering) all from the Massachusetts Institute of Technology. He received his Ph.D in Aerospace Engineering from the Delft University of Technology. Since 1984, he has worked in the industry, first at Beech Aircraft on the all-composite Starship I and then at Sikorsky Aircraft in the Structures Research Group specializing on analysis of composite structures of the all-composite Comanche and other helicopters, and leading internally funded research and programs funded by NASA and the US Army. Since 2001, he has been consulting with various companies in the United States on applications of composite structures on airplanes and helicopters. He joined the faculty of the Aerospace Engineering Department of the Delft University of Technology (Aerospace Structures) in 2007 as an Associate Professor. His interests include fatigue and damage tolerance of composites, analysis of sandwich structures, design and optimization for cost and weight and technology optimization. He has over 40 journal papers and three issued or pending patents on related subjects. He is a member of AIAA, AHS and SAMPE.
Series Preface

The field of aerospace is wide ranging and covers a variety of products, disciplines, and domains, not merely in engineering but in many related supporting activities. These combine to enable the aerospace industry to produce exciting and technologically challenging products. A wealth of knowledge is contained by practitioners and professionals in the aerospace fields, which is of benefit to other practitioners in the industry, and to those entering the industry from University.

The *Aerospace Series* aims to be a practical and topical series of books aimed at engineering professionals, operators, users and allied professions such as commercial and legal executives in the aerospace industry. The range of topics is intended to be wide ranging, covering design and development, manufacture, operation and support of aircraft, as well as topics such as infrastructure operations and developments in research and technology. The intention is to provide a source of relevant information that will be of interest and benefit to all those people working in aerospace.

The use of composite materials for aerospace structures has increased dramatically in the last three decades. The attractive strength-to-weight ratios, improved fatigue and corrosion resistance and ability to tailor the geometry and fibre orientations, combined with recent advances in fabrication, have made composites a very attractive option for aerospace applications from both a technical and financial viewpoint. This has been tempered by problems associated with damage tolerance and detection, damage repair, environmental degradation and assembly joints. The anisotropic nature of composites also dramatically increases the number of variables that need to be considered in the design of any aerospace structure.

This book, *Design and Analysis of Composite Structures: With Application to Aerospace Structures*, Second Edition, provides a methodology of various analysis approaches that can be used for the preliminary design of aerospace structures without having to resort to finite elements. Representative types of composite structure are described, along with techniques to define the geometry and lay-up stacking sequence required to withstand the applied loads. The value of such a set of tools is to enable rapid initial trade-off preliminary design studies to be made, before using a detailed finite element analysis on the finalized design configurations.

Allan Seabridge
Jonathan Cooper
Peter Belobaba
Preface to First Edition

This book is a compilation of analysis and design methods for structural components made of advanced composites. The term “advanced composites” is used here somewhat loosely and refers to materials consisting of a high-performance fibre (graphite, glass, Kevlar®), etc. embedded in a polymeric matrix (epoxy, bismaleimide, PEEK, etc.). The material in this book is the product of lecture notes used in graduate-level classes in Advanced Composites Design and Optimization courses taught at the Delft University of Technology.

The book is aimed at fourth year undergraduate or graduate-level students and starting engineering professionals in the composites industry. The reader is expected to be familiar with classical laminated-plate theory (CLPT) and first ply failure criteria. Also, some awareness of energy methods and Rayleigh–Ritz approaches will make some of the solution methods easier to follow. In addition, basic applied mathematics knowledge such as Fourier series, simple solutions of partial differential equations and calculus of variations are subjects that the reader should have some familiarity with.

A series of attractive properties of composites such as high stiffness and strength-to-weight ratios, reduced sensitivity to cyclic loads, improved corrosion resistance and, above all, the ability to tailor the configuration (geometry and stacking sequence) to specific loading conditions for optimum performance has made them a prime candidate material for use in aerospace applications. In addition, the advent of automated fabrication methods such as advanced fibre/tow placement, automated tape laying, filament winding, has made it possible to produce complex components at costs competitive with if not lower than metallic counterparts. This increase in the use of composites has brought to the forefront the need for reliable analysis and design methods that can assist engineers in implementing composites in aerospace structures. This book is a small contribution towards fulfilling that need.

The objective is to provide methodology and analysis approaches that can be used in preliminary design. The emphasis is on methods that do not use finite elements or other computationally expensive approaches in order to allow the rapid generation of alternative designs that can be traded against each other. This will provide insight in how different design variables and parameters of a problem affect the result.

The approach to preliminary design and analysis may differ according to the application and the persons involved. It combines a series of attributes such as experience, intuition, inspiration and thorough knowledge of the basics. Of these, intuition and inspiration cannot be captured in the pages of a book or itemized in a series of steps. For the first attribute, experience, an attempt can be made to collect previous best practices which can serve as guidelines for future work. Only the last attribute, knowledge of the basics, can be formulated in such a way that the
reader can learn and understand them and then apply them to his/her own applications. And doing that is neither easy nor guaranteed to be exhaustive. The wide variety of applications and the peculiarities that each may require in the approach, preclude any complete and in-depth presentation of the material. It is only hoped that the material presented here will serve as a starting point for most types of design and analysis problems.

Given these difficulties, the material covered in this book is an attempt to show representative types of composite structure and some of the approaches that may be used in determining the geometry and stacking sequences that meet applied loads without failure. It should be emphasized that not all methods presented here are equally accurate nor do they have the same range of applicability. Every effort has been made to present, along with each approach, its limitations. There are many more methods than the ones presented here and they vary in accuracy and range of applicability. Additional references are given where some of these methods can be found.

These methods cannot replace thorough finite element analyses which, when properly set up, will be more accurate than most of the methods presented here. Unfortunately, the complexity of some of the problems and the current (and foreseeable) computational efficiency in implementing finite element solutions precludes their extensive use during preliminary design or, even, early phases of the detailed design. There is not enough time to trade hundreds or thousands of designs in an optimization effort to determine the “best” design if the analysis method is based on detailed finite elements. On the other hand, once the design configuration has been finalized or a couple of configurations have been downselected using simpler, more efficient approaches, detailed finite elements can and should be used to provide accurate predictions for the performance, point to areas where revisions of the design are necessary, and, eventually, provide supporting analysis for the certification effort of a product.

Some highlights of composite applications from the 1950s to today are given in Chapter 1 with emphasis on nonmilitary applications. Recurring and nonrecurring cost issues that may affect design decisions are presented in Chapter 2 for specific fabrication processes. Chapter 3 provides a review of CLPT and Chapter 4 summarizes strength failure criteria for composite plates; these two chapters are meant as a quick refresher of some of the basic concepts and equations that will be used in subsequent chapters.

Chapter 5 presents the governing equations for anisotropic plates. It includes the von Karman large deflection equations that are used later to generate simple solutions for post-buckled composite plates under compression. These are followed by a presentation of the types of composite parts found in aerospace structures and the design philosophy typically used to come up with a geometric shape. Design requirements and desired attributes are also discussed. This sets the stage for quantitative requirements that address uncertainties during the design and during service of a fielded structure. Uncertainties in applied loads and variations in usage from one user to another are briefly discussed. A more detailed discussion about uncertainties in material performance (material scatter) leads to the introduction of statistically meaningful (A- and B-basis) design values or allowables. Finally, sensitivity to damage and environmental conditions is discussed and the use of knockdown factors for preliminary design is introduced.

Chapter 6 contains a discussion of buckling of composite plates. Plates are introduced first and beams follow (Chapter 8) because failure modes of beams such as crippling can
be introduced more easily as special cases of plate buckling and post-buckling. Buckling under compression is discussed first, followed by buckling under shear. Combined load cases are treated next and a table including different boundary conditions and load cases is provided.

Post-buckling under compression and shear is treated in Chapter 7. For applied compression, an approximate solution to the governing (von Karman) equations for large deflections of plates is presented. For applied shear, an approach that is a modification of the standard approach for metals undergoing diagonal tension is presented. A brief section follows suggesting how post-buckling under combined compression and shear could be treated.

Design and analysis of composite beams (stiffeners, stringers, panel breakers, etc.) are treated in Chapter 8. Calculation of equivalent membrane and bending stiffnesses for cross sections consisting of members with different layups are presented first. These can be used with standard beam design equations and some examples are given. Buckling of beams and beams on elastic foundations is discussed next. This does not differentiate between metals and composites. The standard equations for metals can be used with appropriate (re)definition of terms such as membrane and bending stiffness. The effect of different end conditions is also discussed. Crippling, or collapse after very-short-wavelength buckling, is discussed in detail deriving design equations from plate buckling presented earlier and from semi-empirical approaches. Finally, conditions for inter-rivet buckling are presented.

The two constituents, plates and beams are brought together in Chapter 9 where stiffened panels are discussed. The concept of smeared stiffness is introduced and its applicability is discussed briefly. Then, special design conditions such as the panel breaker condition and failure modes such as skin–stiffener separation are analysed in detail, concluding with design guidelines for stiffened panels derived from the previous analyses.

Sandwich structure is treated in Chapter 10. Aspects of sandwich modelling, in particular, the effect of transverse shear on buckling, are treated first. Various failure modes such as wrinkling, crimping and intracellular buckling are then discussed with particular emphasis on wrinkling with and without waviness. Interaction equations are introduced for analysing sandwich structure under combined loading. A brief discussion on attachments including ramp downs and associated design guidelines close this chapter.

The final chapter, Chapter 11, summarizes design guidelines and rules presented throughout the previous chapters. It also includes some additional rules, presented for the first time in this book, that have been found to be useful in designing composite structures.

To facilitate material coverage and in order to avoid having to read some chapters that may be considered of lesser interest or not directly related to the reader’s needs, certain concepts and equations are presented in more than one place. This is minimized to avoid repetition and is done in such a way that reader does not have to interrupt reading a certain chapter and go back to find the original concept or equation on which the current derivation is based.

Specific problems are worked out in detail as examples of applications throughout the book. Representative exercises are given at the end of each chapter. These require the determination of geometry and/or stacking sequence for a specific structure not to fail under certain applied loads. Many of them are created in such a way that more than one answer is acceptable reflecting real-life situations. Depending on the assumptions made and design rules enforced, different but still acceptable designs can be created. Even though low weight is the primary objective of most of the exercises, situations where other issues are important and end up driving the
design are also given. For academic applications, experience has shown that students benefit the most if they work out some of these exercises in teams, so design ideas and concepts can be discussed and an approach to a solution formulated. It is recognized that analysis of composite structures is very much in a state of flux, and new and better methods are being developed (e.g. failure theories with and without damage). The present edition includes what are felt to be the most useful approaches at this point in time. As better approaches mature in the future, it will be modified accordingly.
Preface to Second Edition

The first edition of this book met with sufficient interest to justify an improved and enhanced second edition. Feedback from the readers of the first edition led to the addition of two new chapters, one on fittings and one with an example design problem of larger structural parts.

The objective of this book is to introduce basic design and analysis methods of composite structures with sufficient theoretical background for the reader to be able to (a) develop his/her own methods for other situations and (b) extend the present methods to improve their accuracy and applicability. Balancing this objective with the need to provide simple design equations is difficult. Invariably, in some areas the theoretical background will appear too extensive while, in other cases, equations are presented without sufficient derivation. In addition, people who have worked on any of the topics in any detail will, probably, complain that some of the approaches are oversimplified.

Trying to satisfy all the anticipated readers in all aspects covered in this book is simply impossible. If I can get about the same number of complaints at the two extremes of too detailed analysis and oversimplified analysis, I will have achieved my goal. After all, I only hope to give some guidelines for approaches I found useful that the reader can build on and apply to his/her own situations.

The changes from the first edition are (a) addition of more exercises in most chapters, (b) addition of the Puck failure criterion in Chapter 4, (c) addition of a chapter (Chapter 11) on analysis of simple fittings and (d) addition of a chapter (Chapter 13) with a detailed case study for designing a fuselage panel with three different design concepts. Furthermore, a diligent attempt was also made to correct typos of the first edition.

Perhaps, the most important and useful feature of this second edition is that it is accompanied by an App. The App is called CoDeAn (Composites Design and Analysis). Most equations and design procedures in the book have been incorporated in CoDeAn in a user-friendly and efficient manner. This allows iPhone and iPad users to perform analyses and design studies at the touch of a button. A material library with easy addition and modification options is available. Classical laminated-plate theory, first ply failure and buckling analysis are already available with this release. Future releases will include the rest of the book.
Applications of Advanced Composites in Aircraft Structures

Some of the milestones in the implementation of advanced composites on aircraft and rotorcraft are discussed in this chapter. Specific applications have been selected that highlight various phases that the composites industry went through while trying to extend the application of composites.

The application of composites in civilian or military aircraft followed the typical stages that every new technology goes through during its implementation. At the beginning, limited application on secondary structure minimized risk and improved understanding by collecting data from tests and fleet experience. This limited usage was followed by wider applications, first in smaller aircraft, capitalizing on the experience gained earlier. More recently, with the increased demand on efficiency and low operation costs, composites are being applied widely on larger aircraft.

Perhaps the first significant application of advanced composites was on the Akaflieg Phönix FS-24 (Figure 1.1) in the late 1950s. What started as a balsa wood and paper sailplane designed by professors at the University of Stuttgart and built by the students was later transformed into a fibreglass/balsa wood sandwich design. Eight planes were eventually built.

The helicopter industry was among the first to recognize the potential of the composite materials and use them on primary structure. The main and tail rotor blades with their beam-like behaviour were one of the major structural parts designed and built with composites towards the end of the 1960s. One such example is the Aerospatiale Gazelle (Figure 1.2). Even though, to first order, helicopter blades can be modelled as beams, the loading complexity and the multiple static and dynamic performance requirements (strength, buckling, stiffness distribution, frequency placement, etc.) make for a very challenging design and manufacturing problem.

In the 1970s, with the composites usage on sailplanes and helicopters increasing, the first all-composite planes appeared. These were small recreational or aerobatic planes. Most notable among them were the Burt Rutan designs such as the Long EZ and Vari-Eze (Figure 1.3). These were largely co-cured and bonded constructions with very limited numbers of fasteners. Efficient aerodynamic designs with mostly laminar flow and light weight led to a combination of speed and agility.
Up to that point, usage of composites was limited and/or was applied to small aircraft with relatively easy structural requirements. In addition, the performance of composites was not completely understood. For example, their sensitivity to impact damage and its implications for design only came to the forefront in the late 1970s and early 1980s. At that time, efforts to build the first all-composite airplane of larger size began with the LearFan 2100.
Figure 1.4 LearAvia LearFan 2100 (Copyright Thierry Deutsch; see Plate 4 for the colour figure)

(Figure 1.4). This was the first civil aviation all-composite airplane to seek FAA certification (see Section 2.2). It used a pusher propeller and combined high speed and low weight with excellent range and fuel consumption. Unfortunately, while it met all the structural certification requirements, delays in certifying the drive system and the death of Bill Lear the visionary designer and inventor behind the project, kept the LearFan from making it into production and the company, LearAvia, went bankrupt.

The Beech Starship I (Figure 1.5) which followed on the heels of the LearFan in the early 1980s was the first all-composite airplane to obtain FAA certification. It was designed to the new composite structure requirements specially created for it by the FAA. These requirements were the precursor of the structural requirements for composite aircraft as they are today. Unlike the LearFan which was a more conventional skin-stiffened structure with frames and stringers, the Starship fuselage was made of sandwich (graphite/epoxy facesheets with Nomex® core) and had a very limited number of frames, increasing cabin head room for a given cabin diameter and minimizing fabrication cost. It was co-cured in large pieces that were bonded together and, in critical connections such as the wing-box or the main fuselage joints, were also fastened. Designed also by Burt Rutan, the Starship was meant to have mostly laminar

Figure 1.5 Beech (Raytheon Aircraft) Starship I (Courtesy of Brian Bartlett; see Plate 5 for the colour figure)
flow and increased range through the use of efficient canard design and blended main wing. Two engines with pusher propellers located at the aft fuselage were to provide enough power for high cruising speed. In the end, the aerodynamic performance was not met and the fuel consumption and cruising speeds missed their targets by a small amount. However, structurally the Starship I proved that the all-composite aircraft could be designed and fabricated to meet the stringent FAA requirements. In addition, invaluable experience was gained in analysis and testing of large composite structures and new low-cost structurally robust concepts were developed for joints and sandwich structure in general.

With fuel prices rising, composites with their reduced weight became a very attractive alternative to the metal structure. Applications in the large civilian transport category started in the early 1980s with the Boeing 737 horizontal stabilizer which was a sandwich construction and continued with larger-scale application on the Airbus A-320 (Figure 1.6). The horizontal and vertical stabilizers as well as the control surfaces of the A-320 are made of composite materials.

The next significant application of composites on primary aircraft structure came in the 1990s with the Boeing 777 (Figure 1.7) where, in addition to the empennage and control surfaces, the main floor beams are also made out of composites.
Despite the use of innovative manufacturing technologies which started with early robotics applications on the A320 and continued with significant automation (tape layup) on the 777, the cost of composite structures was not attractive enough to lead to an even larger-scale (e.g. entire fuselage and/or wing structure) application of composites at that time. The Airbus A-380 (Figure 1.8) in the new millennium, was the next major application with glass/aluminium (glare) composites on the upper portion of the fuselage and glass and graphite composites in the centre wing-box, floor beams and aft pressure bulkhead.

Already in the 1990s, the demand for more efficient aircraft with lower operation and maintenance costs made it clear that more usage of composites was necessary for significant reductions in weight in order to gain in fuel efficiency. In addition, improved fatigue lives and improved corrosion resistance compared with aluminium suggested that more composites on aircraft were necessary. This, despite the fact that the cost of composites was still not competitive with aluminium and the stringent certification requirements would lead to increased certification cost.

Boeing was the first to commit to a composite fuselage and wing with the 787 (Figure 1.9) launched in the first decade of the new millennium. Such extended use of composites, about 50% of the structure (combined with other advanced technologies) would give the efficiency improvement (increased range, reduced operation and maintenance costs) needed by the airline operators.
The large number of orders (most successful launch in history) for the Boeing 787 led Airbus to start development of a competing design in the market segment covered by the 787 and the 777. This is the Airbus A-350, with all-composite fuselage and wings.

Another way to see the implementation of composites in aircraft structure over time is by examining the amount of composites (by weight) used in various aircraft models as a function of time. This is shown in Figure 1.10 for some civilian and military aircraft. It should be borne in mind that the numbers shown in Figure 1.10 are approximate as they had to be inferred from open literature data and interpretation of different company announcements [1–8].

Both military and civilian aircraft applications show the same basic trends. A slow start (corresponding to the period where the behaviour of composite structures is still not well understood and limited low risk applications are selected) is followed by rapid growth as experience is gained, reliable analysis and design tools are developed and verified by testing and the need for reduced weight becomes more pressing. After the rapid growth period, the applicability levels off as: (a) it becomes harder to find parts of the structure that are amenable to the use of composites; (b) the cost of further composite implementation becomes prohibitive; and (c) managerial decisions and other external factors (lack of funding, changes in research emphasis, investments already made in other technologies) favour alternatives. As might be expected, composite implementation in military aircraft leads the way. The fact that in recent years civilian applications seem to have overtaken military applications does not reflect true trends as much as lack of data on the military side (e.g. several military programs such as the B-2 have very large composite applications, but the actual numbers are hard to find).

It is still unclear how well the composite primary structures in the most recent programs such as the Boeing 787 and the Airbus A-350 will perform and whether they will meet the design
targets. In addition, several areas such as the performance of composites after impact, fatigue and damage tolerance are still the subjects of ongoing research. As our understanding in these areas improves, the development cost, which currently requires a large amount of testing to answer questions where analysis is prohibitively expensive and/or not as accurate as needed to reduce the amount of testing, will drop significantly. In addition, further improvements in robotics technology and integration of parts into larger co-cured structures are expected to make the fabrication cost of composites more competitive compared with metal airplanes.

References