Composite Materials in Aircraft Structures

EDITED BY

D H MIDDLETON

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Longman Scientific & Technical

Copublished in the United States with
John Wiley & Sons, Inc., New York

Longman Scientific & Technical,
Longman Group UK Limited,
Longman House, Burnt Mill, Harlow,
Essex CM20 2JE, England
and Associated Companies throughout the world.

First published 1990

British Library Cataloguing in Publication Data
Composite materials in aircraft structures.
1. Airframes. Composite materials
I. Middleton, Don, *1921–*
629.134'31

ISBN 0-582-01712-2

Set in Linotron 202 9½/12pt Ehrhardt Roman

Produced by Longman Singapore Publishers (Pte) Ltd.
Printed in Singapore

ACKNOWLEDGEMENTS

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Butterworth & Co. (Publishers) Ltd. and the author, F. L. Matthews for fig. 9.8 from fig. 5 (Matthews, Kilty & Godwin, 1982) © 1982 Butterworth & Co (Publishers) Ltd.; Cambridge University Press for figs. 6.9 & 6.15–17 from figs. 6.16, 7.39, 8.13 & 8.21 on pp. 122, 168, 187 & 184 (Hull, 1981); Chapman & Hall for figs. 6.6 & 6.7 (Bailey & Parvizi, 1981), 6.11 & 6.12 (Manders *et al.*, 1983), 6.14 (Parvizi & Bailey, 1978); The Design Council for fig. 7.1 from fig. 1.1, p. 2 in *Conceptual Design for Engineers* by M. J. French © 1986 Michael J. French/The Design Council; Elsevier Applied Science Publishers Ltd. for figs. 9.3, 9.4 & 9.5 from figs. 9, 13 & 19 (Collings, 1986), 9.6, 9.9, 9.10 & 9.11 from figs. 24, 2, 11 & 24 (Hart-Smith, 1987); The Controller of Her Majesty's Stationery Office for fig. 6.2 (McCrum, 1971); Institute of Physics Publishing Ltd. and the author, F. L. Matthews for figs. 9.1 & 9.2 from figs. 2 & 3 by Matthews, p. 15 of *Proceedings of Conference* on "New Materials and their Applications", (University of Warwick, 1987); the author, Dr. K. T. Kedward for figs. 7.5 & 7.15 (Kedward, 1985); The Plastics & Rubber Institute and the author, F. L. Matthews for fig. 9.7 from fig. 5 by Matthews, Kilty & Godwin in *Plastics and Rubber Processing and Applications*, Vol 2, p. 21 (1982).

PREFACE

The history of the aerospace industry has been marked by a series of 'signposts' initiating a major leap forward in technology. The retractable undercarriage, all-metal construction, the gas turbine, supersonic flight and the American space programme have opened up new vistas for the designer.

In the present decade the twin technologies of electronics and composite materials have linked to create a revolution in aircraft design, construction and, through the medium of avionics, control of aircraft which can now be built to lower load factors in the knowledge that avionics will protect the airframe from excessive stress.

The use of advanced composites permits a useful reduction in structural weight and virtually eliminates fatigue and corrosion, two considerations of vital significance.

The pioneering work of Dr Norman de Bruyne before the war and the RAE team, under Leslie Phillips, which developed carbon fibre, has given Britain a leading position in this relatively new industry while the powerful research and development resources available in Europe and the United States of America are providing a sound base for future developments. Later aircraft in the Airbus range are outstanding examples of the use of advanced composites in primary structures while the Lockheed project to build the wing box of the massive C130 Hercules in composites is another major step forward.

In common with all new technologies composites has its 'grey areas' and differences of opinion among its practitioners which only experience can resolve.

In this book some of the world's leading experts in composites engineering contribute their collective wisdom which will be of value to the designer, the manager, the technician and the student. To the General Editor it has been a stimulating and rewarding experience to work with all the contributors and his thanks must go to all of them and to their organisations. The interest and co-operation shown by Dr John Fozard and Mr Colin Wilson of British Aerospace in arranging meetings at the appropriate plants are particularly appreciated while the advice and assistance given by the College of Aeronautics, Cranfield, British Airways Training School, CSE Training School, Kidlington, Marshalls, Cambridge, Training School, the Universities of Southampton and Surrey, and other engineers, too numerous to mention, was most valuable as was the advice and comment offered by Mr John Saull, Director and Chief Surveyor of the Civil Aviation Authority.

D. H. Middleton
General Editor

GLOSSARY

ADHEREND	Surface to be joined with adhesive.
ADSORPTION	The taking up of one substance at the surface of another.
ANISOTROPY	Exhibiting different mechanical properties such as strength and stiffness along different axes.
AQAP	Allied Quality Assurance Procedures.
ARAMIDS	A group of strong, high-temperature resistant man-made fibres (Aromatic polyamides).
AREAL WEIGHT	Weight per unit of area.
AUTOCLAVE	A chamber which can be heated and/or pressurised to cure adhesives or matrix materials in composites.
CARBON BMI	Carbon bismaleimide.
CAA	Civil Aviation Authority (UK).
CAD/CAM	Computer Aided Design/Computer Aided Manufacture.
CO-CURE	Simultaneous curing of parts of an assembly of composite materials.
COHERENT/INCOHERENT ILLUMINATION	Coherent – all light waves in phase as in a laser. Incoherent – normal white light.
COMINGLING	The random mixing of fibres of different materials.
COMPRESSION MOULDING	The shaping of a component by laying material into a two-part mould which provides pressure as heat is applied to it.
COUPON SPECIMEN	Specimen of cured material used for test purposes.
COMPUTER AIDED TOMOGRAPHY	Industrial application of brain-scan techniques.
CRACK BLUNTING	Procedure by which sharp cracks are made less sharp or made to change direction to reduce stress concentration.
CRYOGENIC	Operation at very low temperature.
CSDU	Constant-Speed Drive Unit.
CTM	Centrifugal Twisting Moment.
DEBULK	Remove excess resin from assembled prepregs or material in mould.
DECORATED	The presence at a chemical site of a substance which makes the site detectable but which may or may not take part in subsequent chemical reactions.
DEFIBRILLATE	To divide longitudinally into fibres of smaller diameter.
DEFLASH	To remove surplus material from the edges of a cured component.
DF	Degradation Factor.
DWELL TIME	The time within the cure cycle of a matrix/fibre system whereby the temperature and/or pressure are held at lower than the final values to enable de-gassing to take place, resin flow to occur, viscosity to build up or to prevent excessive exotherm.

EMI/RFI	Electro-Magnetic/Radio Frequency Interference.
EPOXY	A chemical compound containing a resin, with epoxide groups and a hardener which forms a durable, solid thermoset material.
EQUILIBRIUM WATER UPTAKE	Point at which the rate of increase of water uptake is virtually nil.
EUTECTIC MIXTURE	A mixture of two or more substances in such a ratio that it has the lowest melting point of any other combination.
EXOTHERMIC	Accompanied by the generation of heat.
FIBRE DISPERSION	Fine distribution of fibres.
FIBREGLASS BMI	Glassfibre bismaleimide.
FILAMENT WINDING	A fabrication process achieved by winding a continuous reinforcing fibre impregnated with resin, around a rotating and removable form known as the mandrel.
FOD	Foreign Object Damage.
FPF	First Ply Failure.
FRP	Fibre Reinforced Plastics.
GLASS TRANSITION TEMPERATURE	Temperature at which a polymer changes from a rigid glassy state to a rubbery compliant state.
GRAPHITE/EPOXY	American terminology for carbon/fibre epoxy.
GREENSTICK FRACTURE	Fracture where the crack does not go right through the material but is deflected part-way through, allowing the remainder of the cross-section to deform elastically.
HACKLES	Raised strips or striations on a fracture surface caused by an array of small cracks produced during a shear failure.
HOLOGRAM	Three-dimensional photograph produced by interference between two sets of coherent light waves.
HOMOPOLYMERISED	A condition whereby a monomeric material is polymerised only with itself.
HYBRID COMPOSITE	A composite material with two or more reinforcing fibres.
ILSS	Inter-Laminar Shear Strength.
INHOMOGENEOUS	Consisting of more than one phase, e.g, discrete regions of different materials.
INJECTION MOULDING	The production of a composite component by the injection of resin or a fibre/resin mix into a closed mould.
KERNMANTEL ROPE	High strength sheathed rope.
LATENCY	The characteristic of a resin system whereby it remains relatively inactive at ambient temperature and below, but reacts quickly at its cure temperature.
LAYUP	A stage in the production cycle of some composite components when the reinforcing fibre material or prepreg is located in the correct position in the mould.
LIQUID COUPLANT	Liquid interface between transducer and the subject of a non-destructive test.
LOCUS OF FAILURE	Site of failure.
LONGERON	Main stress-bearing longitudinal member of an aircraft fuselage.
LPF	Last Ply Failure.
MANDREL	A profiled form around which filament wound and pultruded composite structures are shaped.
MATRIX	The material produced to bind the filaments used in the composite material.
METROLOGY	The science of precise measurement.
MONOMER	Molecules of low molecular weight which join together to form polymers.

MORPHOLOGY	Shape, form, external structure or arrangement.
NAPKIN RING SPECIMEN	Test pieces in the form of rings produced to the specification of the UK Naval Ordnance Laboratory.
NC MACHINES	Numerically controlled machines, programmed by computer.
NOTCH SENSITIVITY	The product of the following calculation: failure stress without notch divided by the failure stress over the net section in the presence of the notch.
OUT TIME	The time that a matrix/fibre system can be stored at ambient temperature and still produce satisfactory laminates when cured.
PAN (Abbrevn)	Polyacrylonitrile, used as a base material for certain carbon fibres.
PEEL STRESS	Localised high stress resulting from peeling a laminate with the load not parallel with the load line.
POLAR ROBOTS	Robots capable of universal movement of the work holding elements.
POLYAMIDE	A polymer in the hydrocarbon family which contains repeated groupings of hydrogen and nitrogen.
POLYIMIDE	Similar to a POLYAMIDE but with different numbers of hydrogen molecules in the groupings. A special case is POLYBISMALEIMIDE in which the precursor anhydride is malein anhydride.
POLYMER	A giant molecule formed by the combination of a large number of smaller molecules (monomers) in a regular pattern.
PREPREG	Pre-impregnated reinforcing material. It is impregnated with resin and partly cured.
PRVT	Production Readiness Verification Testing.
PULTRUSION	The manufacture of composite components of constant cross-section in a continuous process. The fibre reinforcing material is drawn through a resin impregnation bath and through a shaping die in which the resin is finally cured.
QUASI-ORTHOTROPIC	Following orthotropic principles.
QUENCHED LAYER	To fix a layer by quenching.
RELEASE CLOTH	Cloth impregnated with a release agent.
RESIN TRANSFER	A compression moulding technique using dry fibres and resin injection.
RHL	Rudder Hinge Line.
RIVER MARKINGS	Markings on the surface of a fracture parallel with the direction of the crack growth.
SORPTION	Generic term for the processes of absorption, adsorption, chemisorption and persorption.
SPECKLE PHOTOGRAPHY	Non-holographic photography by laser.
SPECTRAL or SPECTROMETRIC ANALYSIS	The analysis of the spectrum of the light emitted as, for example, a test substance is burned in an electric arc.
SPLASH or FACILITY MEDIUM	An intermediate stage tool produced for moulding composite materials.
STABILISER	The horizontal stabiliser of an aeroplane is the tailplane, the vertical one is the fin.
SYNTACTIC CORE	A lightweight core material produced by using hollow or solid spheres of glass, ceramics, plastics or carbon in the resin.
THERMAL EXCURSION	Variation in temperature.
THERMAL SPIKE	Unacceptable thermal excursion.
THERMOPLASTIC	A type of plastic material or resin which is capable of being repeatedly softened by heating and repeatedly hardened by cooling.

THERMOSET	A type of plastic material or resin which when cured by heat or chemical means is changed into a virtually infusible and insoluble material.
TRANSDUCER	Device for the translation of energy from one form to another, for example, the conversion of movement into electrical energy.
TURBOSTRATIC GRAPHITE	Graphite consisting of parallel planes of hexagonally arranged carbon atoms but without the third direction ordering required for normal graphite.
ULTRASONIC INSPECTION	Inspection by sound waves at frequencies from 500 kHz to 25 MHz.
VACUUM BAGGING	A moulding process using a film placed over the lay-up in the mould and sealed so that a vacuum can be applied to permit atmospheric pressure to assist in forming the composite.
VOLUME FRACTION	Fraction by volume of fibre to resin.
WET-OUT	The application of resin to the matrix to ensure good interaction and elimination of voids.
WIP	Work In Progress.

CONTENTS

CHAPTER 1 ORIGINS OF COMPOSITE MATERIALS

J. E. BAILEY.

Appointed Dyson Professor and Head of Department of Ceramics, Glasses and Polymers at the University of Sheffield in 1984 and subsequently Chairman of the School of Materials within the Faculty of Engineering in 1987. Gained B.Sc. in Physics at Bristol University and Ph.D. at Cambridge where he carried out research on metal physics. He is also Chairman of Redland Technology Ltd.

Career includes periods at Berkeley Nuclear Laboratories of the Central Electricity Generating Board, and the School of Engineering Science at Bangor. In 1964 he was appointed Research Director of Morgan Crucible Company, and in 1968 was appointed Professor of Materials Technology at the University of Surrey.

Professor Bailey is a Chartered Engineer and Fellow of the Institutes of Physics, Ceramics, and Metals and of the Plastics and Rubber Institute. He has wide-ranging interests in ceramics, hydraulic cements, carbon and composite materials which have been his main pre-occupation for two decades.

The use of fibrous structures for load-bearing purposes has its origin in nature. The structure of a tree consists of long strong cellulose fibres bonded together with a protein-like substance called lignin; the fibres run up the trunk of the tree and along the branches which are the directions of the principal stresses. Wood remains one of man's major structural materials and one might expect therefore that structural engineers should be well acquainted with the use of fibre-reinforced materials in design. However, the advent of strong, tough metals, especially iron (steel) and aluminium alloys has meant that in recent times sophisticated structures have used these materials and there are overridingly important differences between them and fibre composites; namely that they are isotropic in behaviour whereas fibre composites can be highly anisotropic. It is difficult to fracture wood across the grain but it is easy to do so along it. Plywood reduces this anisotropy by the process of lamination. For structural engineering purposes metals usually have similar properties in all directions within the material. The use of anisotropic fibre composites materials in structural design requires more complex analysis because, as will become apparent in this book, it is possible and necessary to design both the composite material and the structure for a given application for maximum efficiency.

In the pioneering days of flight, aircraft structures were composite, being composed largely of wood, wire and fabric. Light aluminium alloys took over in the 1930s and have dominated the aircraft industry to the present time. Wooden structures did however persist until the Second World War (Fig. 1.1), and the famous de Havilland Mosquito aircraft (Figs. 1.2, 1.3) constructed of a

Fig. 1.1 A 1937 venture into composite construction. The de Havilland DH91 Albatross airliner was moulded as a ply-balsa-ply sandwich, carapace construction, upon a male mould. The photograph shows the completed fuselage being mated to the wing. A similar technique was used in the Mosquito to achieve the superb aerodynamic form apparent in both aircraft. *British Aerospace plc Hatfield*

plywood–balsa–plywood sandwich laminate probably represents the highpoint of engineering design with wood.

The emergence of a new class of fibre composite materials for use in aircraft has its origin in a number of technical and scientific developments, the starting point being the discovery last century of synthetic organic materials derived originally from vegetation and coal. These developments have produced plastics, rubbers, adhesives and paints, and oil is now a major source for them. A major step forward was the production of phenolic resins (Bakelite) around 1908 by Dr Leo Baekeland. Since then a whole range of thermosetting resins and adhesives have been developed, for example, apart from the phenolics, there are polyesters, epoxies, polyimides and silicones. It was soon apparent that for structural use these materials were often too brittle and too flexible, and to overcome these deficiencies fillers such as wood with other cellulosic fibres, paper and asbestos were used.

The development of phenolic resins led, in the 1920s, to the production of the well-known facing board Formica, which is a laminate of Kraft paper impregnated with phenolic resin, and can be regarded as the precursor for modern high performance fibre-reinforced plastics. A similar material known as Gordon Aerolite and also based on phenolic resin incorporating untwisted flax fibres was developed in the late 1930s by Dr Norman de Bruyne at Aero Research, Cambridge, UK for aircraft applications. A fuselage was made out of this material for the Spitfire fighter during the Second World War (Figs. 1.4, 1.5). To save time no attempt was made to fully develop the constructional technology of the material so the

Fig. 1.2 The DH98 Mosquito prototype just before its first flight at Hatfield in November 1940 *British Aerospace plc Hatfield*

aluminium alloy structure was followed as far as possible even to the extent of assembly by rivetting. The weight of the fuselage in Aerolite was the same as the aluminium one and load tests at RAE Farnborough were entirely satisfactory.

De Bruyne's interest in good adhesives for laminated sandwich structures involving bonding to aluminium alloys led to the development of the thermoplastic modified phenolic adhesives called 'Redux' resins, first used around 1943 in the de Havilland Hornet fighter aircraft. Similar developments occurred in the USA during this period which produced cloth phenolic composites for a wide range of uses, and perhaps the most significant of these was the introduction of polyester resins. A serious problem with composites containing cellulose materials is durability in the presence of moisture, which puts them in a similar category to wood itself. The more rapid development of thermosetting resins for structural purposes hung upon another key technical development, namely the production of glass fibres. It is not widely appreciated that glass fibres were produced in the last century, around 1840, in France, and that C. V. Boys in 1889 was probably the first person to realise their high load-bearing capability. These early glass fibres were produced for fabrics, for which they are unsuited because of poor abrasion resistance, and consequently failed to develop. Present day E-glass fibre production began in the 1930s. Originally the requirement was for an electrically insulating tape capable of withstanding high temperatures. At about the same time as these high strength fibres were being produced, polyester thermosetting resins that could be cured without high pressure were becoming available in the USA.

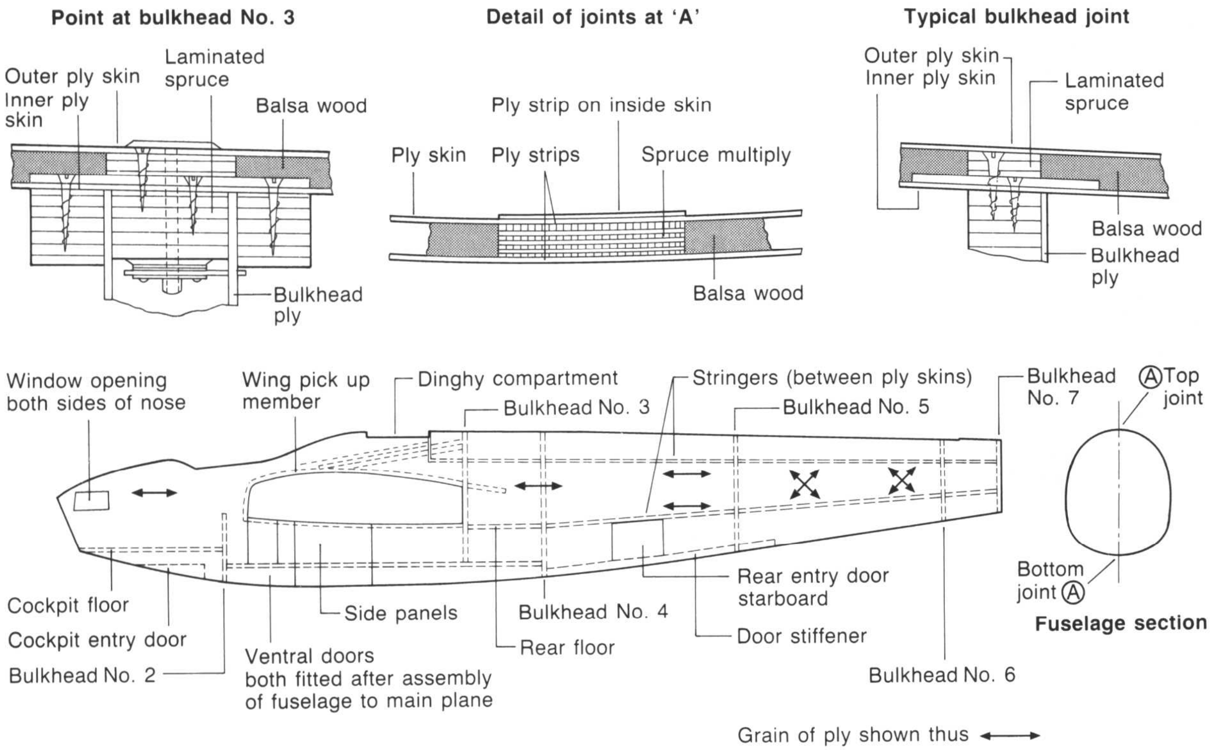

Fig. 1.3 Mosquito fuselage construction *Michael J. F. Bowyer*

These polyester resins, when combined with continuous glass fibres, produced good quality (low porosity) laminates with extremely attractive mechanical properties, and high strength and stiffness to weight ratios. It was in 1943 that the aft fuselage of a training aircraft was built in the USA from a sandwich construction of glass fibre-reinforced polyester laminate incorporating a honeycombed core. The machine flew successfully in March 1944.

The development of the superior epoxy resins resulted in the replacement of polyester resins for most structural applications in the postwar period. The introduction of glass fibre-reinforced polyester and epoxy resins ensured the rapid development of applications and to this day glass fibre dominates the market because of the combination of mechanical properties and cost.

The early development of fibre-reinforced plastics owed very little to scientific understanding of the strength potential of materials. It was, however, studies of high strength glass fibres that enabled A. A. Griffith, around 1920, to take a major step forward in our understanding of strength by showing that fine cracks introduced during manufacture controlled the strength of glass. During the drawing of glass fibres the probability of producing large cracks of a size that control the strength of bulk glass is reduced drastically and there is therefore a large increase in strength. The greater understanding of the strength of materials that has developed since Griffith's experiments has undoubtedly stimulated the more recent developments in high performance composite materials. The materials we now use in bulk form have strengths several orders of magnitude smaller than that to be expected from the known force laws between atoms. Bulk materials are as weak as they are either because of the effect of defects in the fine regular arrangement of the atoms or because of the presence of cracks of the kind identified by Griffith. It is found that the potentially strongest materials are those with high stiffness

Fig. 1.4 The Spitfire fuselage designed and built of Gordon Aerolite material by Aero Research Ltd, Duxford in 1940. Metal was used only in the mainspar members and certain pick-up fittings. Aerolite was composed of untwisted flax fibres impregnated with phenolic resin and made into 6 in wide bands. To produce sheet material the bands were placed edge to edge on moulds with others at right angles to build up thickness. The pack was then hot pressed. *Ciba-Geigy Plastics*

(Young's modulus) which itself is highest for a solid consisting of small closely spaced strongly bonded atoms. When the Periodic Table for these elements is examined it is found that among the lightest examples are beryllium, boron, carbon, nitrogen, oxygen, aluminium and silicon.

These elements and compounds of them are expected therefore to be candidate materials in their perfect form for the production of high strength materials. Other attractive properties follow because high bond strength and lightness give high thermal stability and low density. Very fine, near perfect fibrous crystals known as whiskers have been produced that show exceptional strength. For example, alumina, silicon carbide and carbon (graphite) whiskers have been produced but the results are very variable because fine defects accidentally arise which reduce the strength to varying degrees. Whisker technology is still in its infancy. The major developments have been in producing continuous filaments of alumina, boron, carbon, silicon carbide and highly oriented organic polymers. It is possible to control and thereby limit the effect that defects and fine cracks have in reducing strength in these continuous filaments in much the same way as for glass fibres.

The potentially very high strength and stiffness to weight ratio of these fibres have led to their development for aerospace applications and both boron and carbon fibre became available in limited quantities during the 1960s.

Boron fibre was developed in the USA using chemical vapour deposition tech niques by which boron is deposited upon a very fine tungsten wire. The method produces a comparatively thick fibre and the process is considered to be in-