Integrated design and manufacture using fibre-reinforced polymeric composites

Edited by
M J Owen, V Middleton and I A Jones

CRC Press
Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Cambridge England

Published by Woodhead Publishing Limited, Abington Hall, Abington
Cambridge CB1 6AH, England
www.woodhead-publishing.com

Published in North and South America by CRC Press LLC, 2000 Corporate Blvd, NW
Boca Raton FL 33431, USA

First published 2000, Woodhead Publishing Ltd and CRC Press LLC

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data
A catalog record for this book is available from the Library of Congress.

Woodhead Publishing ISBN 1 85573 453 2
CRC Press ISBN 0-8493-0858-5
CRC Press order number: WP0858

Cover design by The ColourStudio
Typeset by Best-set Typesetter Ltd., Hong Kong
Printed by TJ International Ltd, Cornwall, England

This book is dedicated to the hundreds of people who have been involved over the last 37 years with the composites programme in the Mechanical Engineering Department at the University of Nottingham

Preface

This book is about fibre-reinforced polymers (FRPs) excluding rubber matrix materials. Although some contributors refer to 'composites', 'composite materials' or 'fibre-reinforced composite materials' the restriction to fibre-reinforced thermoplastic and thermosetting polymers still applies and rubber, metal and ceramic matrix composites are excluded. The overall intention is to show that material selection, manufacturing feasibility and material properties are strongly inter-related factors that have to be considered at an early stage in the design process in order to achieve cost-effective products. Often this can be done without recourse to elaborate calculations.

Following an introductory chapter that is intended to set the scene, there are three main parts to the book. Part I describes the main material constituents and the main manufacturing processes. Part II is based on case studies of some recent successful applications. The authors explain their development approach for both product and manufacturing process. Part II also includes chapters on adhesive technology and the growing importance of closed mould processes. Part III is an introduction to design methods with due regard to manufacturing feasibility. Three substantial appendices cover laminate analysis, sample material properties and a glossary of terms.

The provenance of the book lies in courses offered regularly by the Department of Mechanical Engineering, University of Nottingham, over the past 20 years. These comprise short intensive continuing professional development (CPD) courses and final year undergraduate and master's degree modules. CPD courses have also been presented at the premises of individual firms and trade associations both in the UK and around the world including South Africa, Singapore and other countries. The editors intend the book to be useful for similar courses and particularly to individual engineers, scientists and managers in industry who might be considering new products for which FRPs are unfamiliar candidate materials.

The editors have only acknowledged by name friends and colleagues who have made direct contributions to the book. However, over the years there have been hundreds of industrial collaborators, academic colleagues, research assistants and research students who have participated in sponsored research programmes, who have also helped with courses and who have made indirect contributions without which the present outcome would not have been possible.

About the contributors

Dr R Brooks

Dr Richard Brooks is a Senior Lecturer in the School of Mechanical, Materials, Manufacturing Engineering and Management at the University of Nottingham. Following a period in industry working for Courtaulds he gained a PhD in Engineering from the University of Cambridge in 1982 and joined the University of Nottingham in 1984 as a Lecturer in Polymer Applications. Since that time he has worked on the development of design procedures and high-volume manufacturing methods for thermoplastic composites. He has published extensively and has supervised a number of large collaborative research projects. Current research interests include orientation in short fibre composites and design with these materials, glass mat thermoplastics, co-mingled composites for structural automotive applications and the use of composites in sports equipment.

Mr P Bryant

Peter Bryant, now retired, was formerly Managing Director of Adams Hydraulics Ltd, York, manufacturers of sewage treatment equipment and purpose-designed composites products. Most recently he was Director responsible for Quality, R&D, and Project Manager for several DTI-sponsored development projects for highly stressed equipment constructed in composites. Prior to that, after training with C A Parsons & Co Ltd, Newcastle upon Tyne, manufacturers of turbo-generators, he worked for many years in Engineering and Production Management positions within the Baker Perkins group, becoming Managing Director of Baker Perkins (latterly APV) Chemical Machinery Ltd, Stoke on Trent, manufacturers of mixing, compounding and extrusion equipment for the plastics and chemical industries.

Dr J Dominy

John Dominy is a graduate of Middlesex University, gaining his PhD for work on high-speed transmissions. Following a period at Rolls-Royce, he first learned about composites during his time as a designer and race engineer for a Formula 1 racing team. He then returned to Rolls-Royce where, for the last ten years, he has been a specialist in the Composites Group. He has recently completed terms as Chairman of the two leading UK composites groups – the Nottingham University Composites Club and the Institute of Materials Polymer Composites Committee. In addition to his post at Rolls-Royce plc, he maintains a practical interest in composites as Chairman and Technical Director of Carbon Concepts Limited.

Dr G Eckold

Geoff Eckold was educated at University of Manchester Institute of Science and Technology. After completing a PhD thesis concerned with the design of filament wound structures he joined Plastics Design & Engineering (PDE) as a Design Engineer. His responsibilities covered the design, manufacture and installation of composite process plant. While at PDE he became involved in the development of design codes and standards for composite design. In 1984 he joined the Harwell Laboratory of AEA Technology and became involved in the design and prototype study of composite components for automotive, offshore, aerospace, process and engineering industries. He also was concerned with process modelling and the integration of CAD techniques for composite manufacture. Geoff Eckold is currently a Senior Manager within the engineering business of AEA Technology with overall responsibility for a wide range of materials and engineering projects within the industrial sector.

Mr N G Foster

Nevile Foster is a Principal Design Engineer at Slingsby Aviation. He graduated in Aeronautical Engineering at Kingston Polytechnic and completed an Engineering Apprenticeship at British Aircraft Corporation (now British Aerospace). He subsequently worked in the Acoustics Department of BAC and the Stress Departments of British Aerospace and Boeing, and for the past 11 years has specialised in composite structures at Slingsby Aviation. He is a Chartered Engineer and a Member of the Royal Aeronautical Society.

Mr A R Harrison

Alan Harrison is the supervisor for advanced materials and processing development in the Advanced Vehicle Technology Group of the Ford

Motor Company Ltd at Dunton, UK. He was an apprentice at Borg Warner (York Division) and subsequently had experience with them in component design and manufacturing quality control before joining Ford as a component engineer. For the past 15 years he has been involved in materials engineering, especially fibre-reinforced plastics. He has a BA degree in Materials Engineering from the Open University and an MSc degree in Advanced Automotive Engineering from the University of Loughborough.

Dr I A Jones

Arthur Jones is a Senior Lecturer in the School of Mechanical, Materials, Manufacturing Engineering and Management at the University of Nottingham. He studied Engineering Manufacture and Management at UMIST, during which time he gained experience of process industries with Vickers and ICI. On graduation he worked for two years for Rolls-Royce plc on the manufacture of civil aero-engines, before joining the lecturing staff at the University of Nottingham in 1989. Since then he has developed research interests in the design, manufacture and analysis of composite structures, with particular reference to the analysis of laminated shells and the development of novel composites for biomedical applications. He gained his doctorate as a staff candidate in 1993 for his research into finite element analysis of filament wound structures. He also conducts research into computer-aided experimental stress analysis.

Dr W A Lees

Bill Lees obtained both his BSc and PhD degrees in organic chemistry from Manchester University and after a brief period in the paint industry spent his working life in the field of engineering adhesives. He was instrumental in developing products for civil, mechanical, structural, electrical and electronic applications. As a founder member of the Permabond Division of NSC Ltd – now an ICI Group Company – and its Technical Director for more than 20 years he was responsible for the initial UK manufacture of both the cyanoacrylate and anaerobic adhesives. He also assisted in the establishment and exploitation of the now ubiquitous toughened adhesives. He is both author and editor and prepared the logic for both the PAL and EASel software – acknowledged expert systems for the selection of engineering adhesives. Dr Lees has served on a number of BS committees. Now recently retired, he is an independent consultant currently engaged in CEN on the preparation of Euro standards for structural adhesives. He is also a member of the DTI's Industrial Advisory Group.

Prof V Middleton

Vic Middleton is Professor of Engineering Design in the Division of Mechanical Engineering, University of Nottingham. He undertook his professional training with Rolls-Royce, Derby, as a University Apprentice during which time he graduated from the University of Nottingham with a BSc degree in Mechanical Engineering. He was subsequently awarded a PhD degree for research on dynamically loaded bearings before working for Glacier Metals. Since joining the university as a lecturer he has specialised in the application of composite materials and the design processes associated with this. He developed the CADFIL suite of software for filament winding composite components which was subsequently licensed to Crescent Consultants by the university and is marketed on a world-wide basis by that company. He has also been associated with the resin transfer moulding programmes with the Ford Motor Company within the Division. He is currently involved in the design and manufacturing programme for the application of structural composites in the water treatment industry. He has been a director of Crescent Consultants Ltd, a company specialising in the design and development of composite artefacts, since its inception in 1985.

Dr J A Nixon

After graduation in Metallurgy and Materials Science at Nottingham University in 1980 John Nixon conducted research into the flow and cure behaviour of sheet moulding compounds which led to a PhD in 1984. Following a further period of research into moulding and NDT techniques for thermoplastic composites at Bath University he joined Vosper Thornycroft (UK) Ltd to work on composite ship construction and the application of composites in the offshore oil and gas industry. He joined the Scott Bader Co Ltd in 1993 to work on fabrication process development where he now manages the Applications and Testing Group.

Prof M J Owen

Mike Owen was Professor of Reinforced Plastics in the Mechanical Engineering Department of the University of Nottingham until his recent retirement. After National Service he obtained a BSc in Mechanical Engineering from the University of Birmingham before spending three years in North America. After returning to Nottingham he was awarded a PhD degree for fatigue studies of gas turbine compressor disks and he was appointed to a lectureship. For over 30 years he was involved with FRP research projects in collaboration with industry, especially Ford Motor Company. He was the author of numerous publications, a director of several small companies, and for five years Dean of the Faculty of Engineering. In 1993 he was awarded a DSc degree for his work on fibre-reinforced plastics.

Dr P Thornburrow

Peter Thornburrow entered the composite materials industry nearly 30 years ago after gaining his PhD in Chemistry. Initially a research chemist with BP Chemicals, who manufactured polyester resins, his career developed through composites manufacturing process into applications development, before joining Vetrotex, the glass fibre manufacturer, in 1987. During his career with Vetrotex, his activities continued to be centred on the technical aspects of composite materials and processes, but also encompassed the field of reinforced thermoplastics, in which he has specialised for the last three years, Recently he has taken on responsibilities for developing new markets and applications for glass fibres, which will enable him to build on his previous experience from association with such projects.

Mr C J Wheatley

Chris Wheatley began working life as a foundry pattern maker in 1975. The demise of the foundry industry forced pattern makers into other industries. Chris found a need for pattern-making skills in the emerging composites industry manufacturing components for motor sport, aerospace and defence. He studied part time to achieve TEC level 3 in Mechanical Engineering and went on to graduate BEng (Hons) by studying full time as a mature student. After graduation, he worked as composites research and development engineer for Williams Grand Prix Engineering Ltd. During this time the company won the Formula 1 constructors championship five times. Chris is now Senior Composites Engineer at the Structural Materials Centre, DERA Farnborough.

1
Introduction

M J OWEN

This chapter serves as an introduction to the book. After reading it some readers may prefer to proceed to Part II, before reading Parts I and III.

1.1 What are fibre-reinforced polymers?

Fibre-reinforced polymers or fibre-reinforced plastics (FRPs) are combinations of fibres and/or particulate fillers in a polymeric matrix material. Generally the fibres and particles are regarded as reinforcements to carry load or to control strain, whereas the matrix is regarded as a bonding medium to transfer load and to provide continuity and structural integrity. The most common fibres are glass, carbon (graphite) or aramid although they may also be of natural, polymeric, metallic or ceramic origin. Commonly used fillers are of mineral origin such as chalk (calcium carbonate) or alumina trihydrate but other ground minerals, powdered metals, pigments, etc, are also used. Polymer matrices fall into two main classes, either thermosets or thermoplastics. Thermosets are liquid mixtures of chemical constituents which can be caused to react after combination with the reinforcement to form a solid matrix which can only be further shaped by a machining process. Thermoplastics can be softened or remelted by heat, thus permitting some reshaping. Processing covers the activities of combining the constituent materials and shaping them economically. The properties of FRPs depend on the properties of the constituents, the relative amounts of the constituents, their dispersion, and the processing route used to form the final shape of the desired artefact or component. The final FRP material and its properties are determined during the manufacturing operation for the desired component. Structural composites are load-bearing materials in which particulates or fibres are introduced to a matrix to achieve improved properties for the combined materials. Mechanical loads may be associated with electrical, thermal or chemical stress. It is wrong to restrict a definition of structural composites to 'high-tech' materials or to the needs of one particular industry.

In this book the words 'composites' and 'composite materials' are often used in place of 'FRP' as is common in some industries. According to the dictionaries the word 'composite' is an adjective conveying the meaning 'made up of various parts or elements'. The word came into regular use for 'composite materials' or 'composites' only in the late 1960s, apparently to enhance the image of glass-reinforced plastics and to encompass a wider range of materials, including metal and ceramic matrix materials. It is usual to exclude old-established materials such as rubber, plywood and reinforced concrete. In quantitative terms, FRPs are overwhelmingly glass fibre-reinforced thermoset or thermoplastic polymers.

1.2 Rationale

One of the main activities of engineers is to specify, design, manufacture and procure devices, structures and systems to meet customers' needs at competitive prices while achieving proper levels of profit. In fulfilling these aims, engineers must select materials that are the most appropriate in terms of properties and that can be used to achieve designs at the lowest accountable cost. There is no special place for FRP or 'composites' in this context. This book is about the exploitation of FRP in the design of engineering artefacts to produce cost-effective products for general industrial use. A knowledge of the relationships between basic material properties, processing, composite material properties, design and the performance of artefacts is required to achieve efficient low-cost designs in appropriate materials. The materials employed must be appropriate for the application and the design methods justifiable in terms of both cost and rigour. Frequently, FRP components will form only part of the total design.

The principal advantages of FRP may be expressed as follows:

- Design freedom.
- A wide range of materials.
- A wide range of properties.
- Low density.
- High specific strength and specific stiffness.
- Good corrosion and electrical resistance.
- Part consolidation.
- Choice of manufacturing routes.
- Nett shape manufacture.
- Choice of economical tool making methods.

The main disadvantages have been low modulus compared with steel and aluminium, the cost of developing design methods and obtaining design data, the need to develop and invest in new fabrication and production techniques, and the cost and lead-time to develop successful products.