Composites forming technologies
Related titles:

*Geosynthetics in civil engineering*
Geosynthetics are essential to civil engineering and have a multitude of applications. The first part of the book looks at design principles for geosynthetics, their material properties and durability, and the range of national and international standards governing their use. Part II reviews the range of applications for synthetics as well as quality assurance issues. There are chapters on geosynthetic applications as filters, separators and barrier materials, in improving building foundations and landfill sites, and as limited design life materials.

*Multi-scale modelling of composite material systems*
This book focuses on the fundamental understanding of composite materials at the microscopic scale, from designing microstructural features to the predictive equations of the functional behaviour of the structure for a specific end-application. The papers presented discuss stress- and temperature-related behavioural phenomena based on knowledge of physics of microstructure and microstructural change over time.

*Durability of composites for civil structural applications*
This comprehensive book on the durability of FRP composites will make it easier for the practising civil engineer and designer to use these materials on a routine basis. It addresses the current lack, or inaccessibility, of data related to the durability of these materials, which is proving to be one of the major challenges to the widespread acceptance and implementation of FRP composites in civil infrastructure. The book should help further the acceptance of composites for civil structural applications by providing a source for practising engineers, decision makers, and students involved in architectural engineering, construction and materials, disaster reduction, environmental engineering, maritime structural technology, transportation engineering and urban planning.

Details of this book and a complete list of Woodhead’s titles can be obtained by:

- visiting our website at www.woodheadpublishing.com
- contacting Customer Services (e-mail: sales@woodhead-publishing.com; fax: +44 (0) 1223 893694; tel.: +44 (0) 1223 891358 ext. 130; address: Woodhead Publishing Limited, Abington Hall, Abington, Cambridge CB21 6AH, England)

If you would like to receive information on forthcoming titles in this area, please send your address details to: Francis Dodds (address, tel. and fax as above; e-mail: francisd@woodhead-publishing.com). Please confirm which subject areas you are interested in.
Composites forming technologies

Edited by
A. C. Long

The Textile Institute

CRC Press
Boca Raton  Boston  New York  Washington, DC

WOODHEAD PUBLISHING LIMITED
Cambridge England
Published by Woodhead Publishing Limited in association with The Textile Institute
Woodhead Publishing Limited
Abington Hall, Abington
Cambridge CB21 6AH, England
www.woodheadpublishing.com

Published in North America by CRC Press LLC
6000 Broken Sound Parkway, NW
Suite 300, Boca Raton FL 33487, USA

First published 2007, Woodhead Publishing Limited and CRC Press LLC
© 2007, Woodhead Publishing Limited
The authors have asserted their moral rights.

This book contains information obtained from authentic and highly regarded sources.
Reprinted material is quoted with permission, and sources are indicated. Reasonable
efforts have been made to publish reliable data and information, but the authors and
the publishers cannot assume responsibility for the validity of all materials. Neither the
authors nor the publishers, nor anyone else associated with this publication, shall be
liable for any loss, damage or liability directly or indirectly caused or alleged to be
caused by this book.

Neither this book nor any part may be reproduced or transmitted in any form or by
any means, electronic or mechanical, including photocopying, microfilming and
recording, or by any information storage or retrieval system, without permission in
writing from Woodhead Publishing Limited.

The consent of Woodhead Publishing Limited does not extend to copying for general
distribution, for promotion, for creating new works, or for resale. Specific permission
must be obtained in writing from Woodhead Publishing Limited for such copying.

Trademark notice: product or corporate names may be trademarks or registered
trademarks, and are used only for identification and explanation, without intent to infringe.

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

CRC Press ISBN-10: 0-8493-9102-4
CRC Press order number: WP9102

The publishers’ policy is to use permanent paper from mills that operate a sustainable
forestry policy, and which has been manufactured from pulp which is processed using
acid-free and elementary chlorine-free practices. Furthermore, the publishers ensure
that the text paper and cover board used have met acceptable environmental
accreditation standards.

Project managed by Macfarlane Production Services, Dunstable, Bedfordshire, England
(macfarl@aol.com)
Typeset by Godiva Publishing Services Ltd, Coventry, West Midlands, England
Printed by TJ International Limited, Padstow, Cornwall, England
## Contents

*Contributor contact details*  
xi  
*Introduction*  
 xv

### 1 Composite forming mechanisms and materials characterisation  
A C Long and M J Clifford, University of Nottingham, UK

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Intra-ply shear</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>Axial loading</td>
<td>9</td>
</tr>
<tr>
<td>1.4</td>
<td>Ply/tool and ply/ply friction</td>
<td>10</td>
</tr>
<tr>
<td>1.5</td>
<td>Ply bending</td>
<td>12</td>
</tr>
<tr>
<td>1.6</td>
<td>Compaction/consolidation</td>
<td>14</td>
</tr>
<tr>
<td>1.7</td>
<td>Discussion</td>
<td>19</td>
</tr>
<tr>
<td>1.8</td>
<td>References</td>
<td>19</td>
</tr>
</tbody>
</table>

### 2 Constitute modelling for composite forming  
R Akkerman and E A D Lamers, University of Twente, The Netherlands

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Introduction</td>
<td>22</td>
</tr>
<tr>
<td>2.2</td>
<td>Review on constitutive modelling for composite forming</td>
<td>22</td>
</tr>
<tr>
<td>2.3</td>
<td>Continuum based laminate modelling</td>
<td>29</td>
</tr>
<tr>
<td>2.4</td>
<td>Multilayer effects</td>
<td>34</td>
</tr>
<tr>
<td>2.5</td>
<td>Parameter characterisation</td>
<td>35</td>
</tr>
<tr>
<td>2.6</td>
<td>Future trends</td>
<td>43</td>
</tr>
<tr>
<td>2.7</td>
<td>References</td>
<td>44</td>
</tr>
</tbody>
</table>
## Contents

3 **Finite element analysis of composite forming**  
*P Boisse*, INSA de Lyon, France  

3.1 Introduction: finite element analyses of composite forming, why and where?  
3.2 The multiscale nature of composite materials and different approaches for composite forming simulations  
3.3 The continuous approach for composite forming process analysis  
3.4 Discrete or mesoscopic approach  
3.5 Semi-discrete approach  
3.6 Multi-ply forming and re-consolidation simulations  
3.7 Conclusions  
3.8 References  

4 **Virtual testing for material formability**  
*S V Lomov*, Katholieke Universiteit Leuven, Belgium  

4.1 Introduction  
4.2 Mechanical model of the internal geometry of the relaxed state of a woven fabric  
4.3 Model of compression of woven fabric  
4.4 Model of uniaxial and biaxial tension of woven fabric  
4.5 Model of shear of woven fabric  
4.6 Parametric description of fabric behaviour under simultaneous shear and tension  
4.7 Conclusions: creating input data for forming simulations  
4.8 References  

5 **Optimization of composites forming**  
*W-R Yu*, Seoul National University, Korea  

5.1 Introduction  
5.2 General aspects of optimization  
5.3 Optimization of composite forming  
5.4 Conclusions  
5.5 References  

6 **Simulation of compression moulding to form composites**  
*E Schmachtenberg*, Universität Erlangen-Nürnberg, Germany and *K Skrodolies*, Institut für Kunststoffverarbeitung, Germany  

6.1 Introduction  
6.2 Theoretical description of the simulation
6.3 Examples of use of the simulation 161
6.4 Measurement of the material data 172
6.5 References 174
6.6 Symbols 175

7 Understanding composite distortion during processing 177
M R WISNOM and K D POTTER, University of Bristol, UK
7.1 Introduction 177
7.2 Fundamental mechanisms causing residual stresses and distortion 177
7.3 Distortion in flat parts 181
7.4 Spring-in of curved parts 186
7.5 Distortion in more complex parts 192
7.6 Conclusions 194
7.7 References 195

8 Forming technology for composite/metal hybrids 197
J SINKE, Technical University Delft, The Netherlands
8.1 Introduction 197
8.2 Development of composite/metal hybrids 198
8.3 Properties of fibre metal laminates 201
8.4 Production processes for fibre metal laminates 205
8.5 Modelling of FML 213
8.6 Conclusions 218
8.7 References 219

9 Forming self-reinforced polymer materials 220
I M WARD and P J HINE, University of Leeds, UK and D E RILEY, Propex Fabrics, Germany
9.1 Introduction 220
9.2 The hot compaction process 220
9.3 Commercial exploitation 224
9.4 Postforming studies 225
9.5 Key examples of commercial products 232
9.6 Future developments 235
9.7 Acknowledgements 236
9.8 References 236
10 Forming technology for thermoset composites 239
R Paton, Cooperative Research Centre for Advanced Composite Structures Ltd, Australia
10.1 Introduction 239
10.2 Practicalities of forming thermoset prepreg stacks 240
10.3 Deformation mechanisms in woven fabric prepreg 241
10.4 Tape prepreg 247
10.5 Forming processes 248
10.6 Tooling equipment 250
10.7 Diaphragm forming tooling 251
10.8 Potential problems 252
10.9 Process capabilities 253
10.10 Future trends 253
10.11 References 254

11 Forming technology for thermoplastic composites 256
R Brooks, University of Nottingham, UK
11.1 Introduction 256
11.2 Thermoplastic composite materials (TPCs) for forming 256
11.3 Basic principles of TPC forming technologies 262
11.4 Forming methods 264
11.5 Some recent developments 273
11.6 Conclusions 275
11.7 References 275

12 The use of draping simulation in composite design 277
J W Klintworth, MSC Software Ltd, UK and A C Long, University of Nottingham, UK
12.1 Introduction 277
12.2 Zone and ply descriptions 277
12.3 Composites development process 278
12.4 Composites data exchange 281
12.5 Draping and forming simulation 282
12.6 Linking forming simulation to component design analysis 284
12.7 Conclusions 291
12.8 References 292
13 Benchmarking of composite forming modelling techniques

J L Górczyca-Cole and J Chen, University of Massachusetts Lowell, USA and J Cao, Northwestern University, USA

13.1 Introduction 293
13.2 Forming process and fabric properties 295
13.3 Experimental 297
13.4 Numerical analyses 313
13.5 Conclusions and future trends 315
13.6 Acknowledgements 316
13.7 References and further reading 317

Index 318
Contributor contact details

(* = main contact)

Editor
A.C. Long
School of Mechanical Materials and Manufacturing Engineering
University of Nottingham
University Park
Nottingham NG7 2RD
UK
E-mail: Andrew.Long@nottingham.ac.uk

Chapter 1
A.C. Long* and M.J. Clifford
School of Mechanical Materials and Manufacturing Engineering
University of Nottingham
University Park
Nottingham NG7 2RD
UK
E-mail: mike.clifford@nottingham.ac.uk

Chapter 2
R. Akkerman* and E.A.D. Lamers
Construende Technische Wetenschappen
Universiteit Twente – CTW
Postbus 217
7500AE Enschede
The Netherlands
E-mail: r.akkerman@ctw.utwente.nl

Chapter 3
P. Boisse
Laboratoire de Mécanique des Contacts et des Solides
UMR CNRS 5514
INSA de Lyon
France
E-mail: Philippe.Boisse@insa-lyon.fr

Chapter 4
S. Lomov
Department of Metallurgy and Materials Engineering
Kasteelpark Arenberg 44
BE-3001 Heverlee
Belgium
E-mail: stepan.lomov@mtm.kuleuven.be

Chapter 5
W.-R. Yu
Dept. of Materials Science and Engineering
College of Engineering
Chapter 6
E. Schmachtenberg
Universität Erlangen-Nürnberg
Lehrstuhl für Kunststofftechnik
Am Weichselgarten 9
91058 Erlangen-Tennenlohe
Germany
E-mail: Schmachtenberg@lkt.uni-erlangen.de

K. Skrodolies
Institute of Plastics Processing at RWTH Aachen University
Pantstraße 49
52062 Aachen
Germany
E-mail: zentrale@ikv.rwth-aachen.de

Chapter 7
M. R. Wisnom* and K. D. Potter
Professor of Aerospace Structures
University of Bristol
Advanced Composites Centre for Innovation and Science
Queens Building 0.64
University Walk
Bristol BS8 1TR
UK
E-mail: M.Wisnom@bristol.ac.uk

Chapter 8
J. Sinke
Faculty of Aerospace Engineering
Technical University Delft

Aerospace Materials and Manufacturing
Kluyverweg 1
2629HS, Delft
The Netherlands
E-mail: j.sinke@tudelft.nl

Chapter 9
I.M. Ward*, P.J. Hine and D.E. Riley
IRC in Polymer Science & Technology
School of Physics and Astronomy
University of Leeds
Leeds LS2 9JT
UK
E-mail: I.M.Ward@leeds.ac.uk
p.j.hine@leeds.ac.uk
Derek.Riley@propextfabrics.com

Chapter 10
R. Paton
Cooperative Research Centre for Advanced Composite Structures Ltd
506 Lorimer St, Fishermens Bend
Port Melbourne, 3207
Australia
E-mail: r.paton@crc-acs.com.au

Chapter 11
R. Brooks
School of Mechanical Materials and Manufacturing Engineering
University of Nottingham
University Park
Nottingham NG7 2RD
UK
E-mail: richard.brooks@nottingham.ac.uk
Chapter 12
J.W. Klintworth* and A.C. Long
MSC Software Ltd
MSC House
Lyon Way
Frimley
Camberley
Surrey GU16 7ER
UK
E-mail: john.klintworth@mscsoftware.com

Chapter 13
J.L. Gorczyca-Cole and J. Chen*
University of Massachusetts Lowell
One University Avenue
Lowell, MA 01854
USA
E-mail: Julie_chen@uml.edu

J. Cao
Department of Mechanical Engineering
Northwestern University
2145 Sheridan Road
Evanston, IL 60208-3111
USA
E-mail: jcao@northwestern.edu
Composite materials are available in many forms and are produced using a variety of manufacturing methods. A range of fibre types is used – primarily carbon and glass – and these can be combined with a variety of polymer matrices. This book concentrates on ‘long’ fibre composites, including fibres from a few centimetres in length (i.e. excluding injection moulding compounds). So the processing methods of interest include compression moulding of thermoplastic or thermoset moulding compounds; resin transfer moulding based on dry fibre preforms; forming and consolidation of thermoset prepreg and thermoplastic sheets; and forming of new material forms including composite/metal laminates and polymer/polymer (self-reinforced) composites.

Whatever the material form or manufacturing process, there is one common step: forming of initially planar material into a three dimensional shape. This is the focus of ‘Composite Forming Technologies’. The book includes descriptions of industrial forming processes, case studies and applications, and methods used to simulate composite forming. This description is intended for manufacturers of polymer composite components, end-users and designers, researchers in the fields of structural materials and manufacturing, and materials suppliers. Whilst the bulk of the text is devoted to modelling tools, the intention is to provide useful guidance and to inform the reader of the current status and limitations of both research and commercial tools. It is hoped that this will form essential reading for the users of such modelling tools, whilst encouraging others to ‘take the plunge’ and adopt a simulation approach to manufacturing process design.

This text may be considered broadly in two halves, with Chapters 1–7 covering the fundamental aspects of modelling and simulation, and Chapters 8–13 describing practical aspects including manufacturing technologies and modern practices in composites design. The first chapter provides a comprehensive introduction to the range of deformation mechanisms that can occur during forming for a range of materials, along with appropriate test methods and representative data. Chapter 2 describes fundamental constitutive models as required for composite forming, including the bases for commercial kinematic (draping) and mechanical (forming) simulations. The latter topic is
continued in Chapter 3, including a detailed description of finite element simulation techniques for forming of dry fabric preforms. The methodology here can be considered similar to that used for sheet metal forming, albeit with a more complex material model. Chapter 4 continues the modelling theme, with a description of ‘virtual testing’, whereby materials input data for forming simulation are predicted from the material structure. This topic is of particular interest, as it may offer the opportunity to select materials that are fit-for-forming, or even to design new materials with a specific component in mind. Chapter 5 details the use of modern simulation techniques for composite forming within an optimisation scheme, with the aim of selecting materials and process parameters to eliminate such defects as wrinkling or undesirable fibre orientations. Chapter 6 describes the methodology and current status of simulation tools for compression moulding, including applications to sheet moulding compound (SMC) and glass mat thermoplastic (GMT). The following chapter completes the initial treatment of simulation and modelling, with a description of composite distortion – notably the common phenomenon of ‘spring-in’ – caused by manufacturing induced stresses.

The second half of the book begins with four chapters describing forming technologies for a range of materials. This begins with a relatively new family of materials – composite/metal hybrids – which have recently found applications in the aerospace sector (notably as fuselage panels for the Airbus A380). Another new family is covered next, referred to as ‘self-reinforced polymers’. These materials include fibre and matrix from the same polymer material, addressing one of the current concerns for polymer composites – recycling. The next two chapters cover more conventional materials – thermoset prepreg and thermoplastic composite sheet. Prepreg forming technologies are described in detail, from the traditional hand lay-up and autoclave cure approach to current developments in automated tape placement and diaphragm forming. The thermoplastics chapter includes a detailed description of the range of material forms, along with their appropriate forming and consolidation techniques. Chapter 12 describes the current state-of-the-art in simulation software for composite forming within an industrial context, detailing the use of modern software tools to design the material lay-up, and describing how these tools can be integrated within the manufacturing environment. Finally Chapter 13 covers the issue of benchmarking of composite forming. This topic is particularly timely, drawing on current worldwide efforts to compare both formability characterisation tests and forming simulation tools for benchmark materials. It is hoped that this will lead to standardisation of formability testing – a key requirement for more widespread use of analysis tools – and guidelines on the accuracy of the range of simulation approaches that are currently available.
1

Composite forming mechanisms and materials characterisation

A C L O N G and M J C L I F F O R D, University of Nottingham, UK

1.1 Introduction

This chapter describes the primary deformation mechanisms that occur during composites forming. Experimental procedures to measure material behaviour are described, and typical material behaviour is discussed. The scope of this description is reasonably broad, and is relevant to a variety of manufacturing processes. While other materials will be mentioned, the focus here is on forming materials based on continuous, aligned reinforcing fibres. Specifically, materials of interest here include:

- Dry fabrics, formed to produce preforms for liquid composite moulding.
- Prepregs, comprising aligned fibres (unidirectional or interlaced as a textile) within a polymeric (thermoset or thermoplastic) matrix.

While other materials are also formed during composites processing, the above have received by far the most attention amongst the research community. The techniques described here can also be applied to polymer/polymer composites, although these materials present a number of challenges (see Chapter 9).

Moulding compounds such as glass-mat thermoplastics (GMTs) and thermoset sheet moulding compounds (SMCs) are formed by a compression (flow) moulding process; here formability is usually characterised by rheometry (see Chapter 6).

Focusing on continuous, aligned fibre materials, a number of deformation mechanisms during forming can be identified (Table 1.1). The remainder of this chapter will focus on methods for characterising materials behaviour. Materials testing typically has a number of objectives. Often the primary motivation is simply to understand materials behaviour during forming, and in particular to rank materials in terms of formability. If this can be related to the material structure, then this understanding may facilitate design of new materials or optimisation of manufacturing process conditions. Another aim may be to obtain materials data for forming simulation. For the most advanced codes, this may
<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Schematic</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Intra-ply shear            | ![Intra-ply shear](image) | - Rotation of between parallel tows and at tow crossovers, followed by inter-tow compaction  
- Rate and temperature dependent for prepreg  
- Key deformation mode (along with bending) for biaxial reinforcements to form 3D shapes |
| Intra-ply tensile loading  | ![Intra-ply tensile loading](image) | - Extension parallel to tow direction(s)  
- For woven materials initial stiffness low until tows straighten; biaxial response governed by level of crimp and tow compressibility  
- Accounts for relatively small strains but represents primary source for energy dissipation during forming |
| Ply/tool or ply/ply shear  | ![Ply/tool or ply/ply shear](image) | - Relative movement between individual layers and tools  
- Not generally possible to define single friction coefficient; behaviour is pressure and (for prepreg) rate and temperature dependent |
| Ply bending                | ![Ply bending](image) | - Bending of individual layers  
- Stiffness significantly lower than in-plane stiffness as fibres within tows can slide relative to each other; rate and temperature dependent for prepreg  
- Only mode required for forming of single curvature and critical requirement for double curvature |
| Compaction/consolidation   | ![Compaction/consolidation](image) | - Thickness reduction resulting in increase in fibre volume fraction and (for prepreg) void reduction  
- For prepreg behaviour is rate and temperature dependent |
require a full mechanical characterisation of the material under axial, shear and bending loads. The use of such data is described in detail in Chapter 3.

In almost all cases, test methods are non-standardised and have been developed by designers or researchers with a particular material and process in mind. This means that test methods, specimen dimensions, data treatment and presentation differ between practitioners. Here we will give a description of what we believe to be ‘best practice’, although this is clearly a subjective assessment. Benchmarking and comparison of results between laboratories is being addressed within an international exercise; this is discussed in detail in Chapter 13.

1.2 Intra-ply shear

This mechanism occurs when the material is subjected to in-plane shear. This essentially corresponds to relative sliding of parallel tows within a fabric layer or composite ply, and (for textile-based materials) rotation of tows at their crossovers. Intra-ply shear is usually considered to be the primary deformation mechanism for aligned fibre-based materials. Coupled with low bending resistance, the ability of materials to shear in this way allows them to be formed to three dimensional shapes without forming folds or wrinkles. A good analogy here is to compare a woven fabric to a sheet of paper. Both may have a similar bending stiffness, but unlike paper the ability of the fabric to shear allows it to be formed over shapes with double curvature.

Various experimental methods exist to characterise the shear resistance of dry textiles and aligned or woven composite materials. Early developments here were for apparel fabrics; of particular relevance is the ‘Kawabata Evaluation System for Fabrics (KES-F)’, a series of test methods and associated testing equipment for textile mechanical behaviour including tensile, shear, bending, compression and friction.\(^1\) However whilst this system has been used widely for clothing textiles, its application to reinforcement fabrics has been limited.\(^2\) This is probably due to the fact that KES-F provides single point data at relatively low levels of deformation, coupled with the limited availability of the (expensive) testing equipment.

Amongst the composites forming community, two widely used test methods are the picture frame test\(^3–9\) and the bias extension test.\(^8–12\) In this section we present a guide to the use of these test methods and how to make good use of the output data.

1.2.1 Picture frame test

The picture frame (or rhombus) test can be used to measure the force generated by shearing technical textiles and textile composites, including thermoplastic and thermoset based materials. Cross-shaped test samples can be cut or stamped