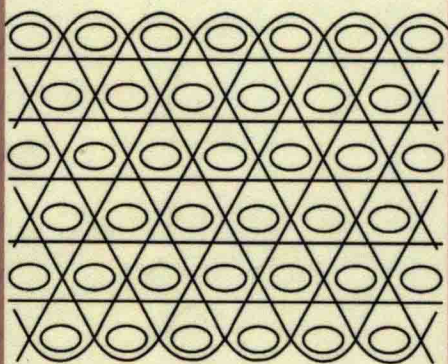


WOODHEAD PUBLISHING SERIES IN TEXTILES



# Woven textile structure

## Theory and applications

B. K. Behera and P. K. Hari



The Textile Institute

WP

Woodhead Publishing Series in Textiles: Number 115

# Woven textile structure

Theory and applications

---

Edited by  
B.K. Behera and P.K. Hari



The Textile Institute

**WP**

WOODHEAD  
PUBLISHING



Oxford   Cambridge   Philadelphia   New Delhi

Published by Woodhead Publishing Limited in association with The Textile Institute  
Woodhead Publishing Limited, 80 High Street, Sawston, Cambridge CB22 3HJ, UK  
www.woodheadpublishing.com  
www.woodheadpublishingonline.com

Woodhead Publishing, 1518 Walnut Street, Suite 1100, Philadelphia, PA 19102-3406, USA

Woodhead Publishing India Private Limited, G-2, Vardaan House, 7/28 Ansari Road,  
Daryaganj, New Delhi - 110002, India  
www.woodheadpublishingindia.com

First published 2010, Woodhead Publishing Limited  
Reprinted 2012

© Woodhead Publishing Limited, 2010

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 publisher cannot assume responsibility for the validity of all materials. Neither the authors nor the publisher, 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.

ISBN 978-1-84569-514-9 (print)

ISBN 978-1-84569-781-5 (online)

ISSN 2042-0803 Woodhead Publishing Series in Textiles (print)

ISSN 2042-0811 Woodhead Publishing Series in Textiles (online)

The publisher's 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 elemental chlorine-free practices. Furthermore, the publisher ensures that the text paper and cover board used have met acceptable environmental accreditation standards.

Typeset by Replika Press, Pvt Ltd, India

Printed by Lightning Source

## **The Textile Institute and Woodhead Publishing**

The Textile Institute is a unique organisation in textiles, clothing and footwear. Incorporated in England by a Royal Charter granted in 1925, the Institute has individual and corporate members in over 90 countries. The aim of the Institute is to facilitate learning, recognise achievement, reward excellence and disseminate information within the global textiles, clothing and footwear industries.

Historically, The Textile Institute has published books of interest to its members and the textile industry. To maintain this policy, the Institute has entered into partnership with Woodhead Publishing Limited to ensure that Institute members and the textile industry continue to have access to high calibre titles on textile science and technology.

Most Woodhead titles on textiles are now published in collaboration with The Textile Institute. Through this arrangement, the Institute provides an Editorial Board which advises Woodhead on appropriate titles for future publication and suggests possible editors and authors for these books. Each book published under this arrangement carries the Institute's logo.

Woodhead books published in collaboration with The Textile Institute are offered to Textile Institute members at a substantial discount. These books, together with those published by The Textile Institute that are still in print, are offered on the Woodhead web site at: [www.woodheadpublishing.com](http://www.woodheadpublishing.com). Textile Institute books still in print are also available directly from the Institute's website at: [www.textileinstitutebooks.com](http://www.textileinstitutebooks.com).

A list of Woodhead books on textile science and technology, most of which have been published in collaboration with The Textile Institute, can be found towards the end of the contents pages.

## The authors

---

Dr B. K. Behera is a Professor in the Department of Textile Technology, Indian Institute of Technology Delhi. His research interests include modeling and simulation, mechanics of textile structure, soft computing applications in the structure – property relationship of fabric, 3D weaving for composite applications and fabric handle and comfort. He has supervised more than 60 Masters and PhD students, published 110 research papers and presented more than 40 papers in various international conferences held in about 13 different countries. Professor Behera has completed 16 sponsored research projects and more than 50 industrial consulting projects as principal investigator. He has contributed a monogram on image processing applications in textiles published in *Textile Progress*. He has four patents to his credit. He has also contributed chapters in three other books being published by Woodhead Publishing Limited. Professor Behera is a regular contributor to the Textile Research Symposium held under the aegis of the Textile Machinery Society of Japan and has also contributed to the AUTEX world conference. Professor Behera has also worked as a specially-appointed Professor in the Global Centre of Excellence Programme at Shinshu University Japan (bijoy.behera@yahoo.com).

Dr P. K. Hari was Professor and Head of the Textile Department of the Indian Institute of Technology Delhi for over 30 years until his retirement. During his tenure at IIT Delhi, he supervised 10 PhD students in weaving, preparation and structure–property relationships of woven fabrics. Recently he has contributed to fabric structure and textile designing through web-based teaching. He has organised the International Textile Academia, a global forum for Textile Institutes with the sponsorship of Rieter Textile Machinery. He has contributed to Vision 2020 for the Indian Textile Industry sponsored by the Indian Government's Department of Scientific and Industrial Research. He has been a regular contributor to the international conferences, AUTEX and the Institute for Textile Technik. He has published over 60 papers in international textile journals. He is presently Professor Emeritus at TIT&S, Bhiwani and a textile consultant and can be reached at pk\_hari@hotmail.com.

## Woodhead Publishing Series in Textiles

---

- 1 **Watson's textile design and colour** Seventh edition  
*Edited by Z. Grosicki*
- 2 **Watson's advanced textile design**  
*Edited by Z. Grosicki*
- 3 **Weaving** Second edition  
*P. R. Lord and M. H. Mohamed*
- 4 **Handbook of textile fibres Vol 1: Natural fibres**  
*J. Gordon Cook*
- 5 **Handbook of textile fibres Vol 2: Man-made fibres**  
*J. Gordon Cook*
- 6 **Recycling textile and plastic waste**  
*Edited by A. R. Horrocks*
- 7 **New fibers** Second edition  
*T. Hongu and G. O. Phillips*
- 8 **Atlas of fibre fracture and damage to textiles** Second edition  
*J. W. S. Hearle, B. Lomas and W. D. Cooke*
- 9 **Ecotextile '98**  
*Edited by A. R. Horrocks*
- 10 **Physical testing of textiles**  
*B. P. Saville*
- 11 **Geometric symmetry in patterns and tilings**  
*C. E. Horne*
- 12 **Handbook of technical textiles**  
*Edited by A. R. Horrocks and S. C. Anand*
- 13 **Textiles in automotive engineering**  
*W. Fung and J. M. Hardcastle*
- 14 **Handbook of textile design**  
*J. Wilson*
- 15 **High-performance fibres**  
*Edited by J. W. S. Hearle*
- 16 **Knitting technology** Third edition  
*D. J. Spencer*
- 17 **Medical textiles**  
*Edited by S. C. Anand*
- 18 **Regenerated cellulose fibres**  
*Edited by C. Woodings*

- 19 **Silk, mohair, cashmere and other luxury fibres**  
*Edited by R. R. Franck*
- 20 **Smart fibres, fabrics and clothing**  
*Edited by X. M. Tao*
- 21 **Yarn texturing technology**  
*J. W. S. Hearle, L. Hollick and D. K. Wilson*
- 22 **Encyclopedia of textile finishing**  
*H-K. Rouette*
- 23 **Coated and laminated textiles**  
*W. Fung*
- 24 **Fancy yarns**  
*R. H. Gong and R. M. Wright*
- 25 **Wool: Science and technology**  
*Edited by W. S. Simpson and G. Crawshaw*
- 26 **Dictionary of textile finishing**  
*H-K. Rouette*
- 27 **Environmental impact of textiles**  
*K. Slater*
- 28 **Handbook of yarn production**  
*P. R. Lord*
- 29 **Textile processing with enzymes**  
*Edited by A. Cavaco-Paulo and G. Gübitz*
- 30 **The China and Hong Kong denim industry**  
*Y. Li, L. Yao and K. W. Yeung*
- 31 **The World Trade Organization and international denim trading**  
*Y. Li, Y. Shen, L. Yao and E. Newton*
- 32 **Chemical finishing of textiles**  
*W. D. Schindler and P. J. Hauser*
- 33 **Clothing appearance and fit**  
*J. Fan, W. Yu and L. Hunter*
- 34 **Handbook of fibre rope technology**  
*H. A. McKenna, J. W. S. Hearle and N. O'Hear*
- 35 **Structure and mechanics of woven fabrics**  
*J. Hu*
- 36 **Synthetic fibres: Nylon, polyester, acrylic, polyolefin**  
*Edited by J. E. McIntyre*
- 37 **Woollen and worsted woven fabric design**  
*E. G. Gilligan*
- 38 **Analytical electrochemistry in textiles**  
*P. Westbroek, G. Priniotakis and P. Kiekens*
- 39 **Bast and other plant fibres**  
*R. R. Franck*
- 40 **Chemical testing of textiles**  
*Edited by Q. Fan*
- 41 **Design and manufacture of textile composites**  
*Edited by A. C. Long*
- 42 **Effect of mechanical and physical properties on fabric hand**  
*Edited by H. M. Behery*

- 43 **New millennium fibers**  
*T. Hongu, M. Takigami and G. O. Phillips*
- 44 **Textiles for protection**  
*Edited by R. A. Scott*
- 45 **Textiles in sport**  
*Edited by R. Shishoo*
- 46 **Wearable electronics and photonics**  
*Edited by X. M. Tao*
- 47 **Biodegradable and sustainable fibres**  
*Edited by R. S. Blackburn*
- 48 **Medical textiles and biomaterials for healthcare**  
*Edited by S. C. Anand, M. Mirafteb, S. Rajendran and J. F. Kennedy*
- 49 **Total colour management in textiles**  
*Edited by J. Xin*
- 50 **Recycling in textiles**  
*Edited by Y. Wang*
- 51 **Clothing biosensory engineering**  
*Y. Li and A. S. W. Wong*
- 52 **Biomechanical engineering of textiles and clothing**  
*Edited by Y. Li and D. X-Q. Dai*
- 53 **Digital printing of textiles**  
*Edited by H. Ujiie*
- 54 **Intelligent textiles and clothing**  
*Edited by H. Mattila*
- 55 **Innovation and technology of women's intimate apparel**  
*W. Yu, J. Fan, S. C. Harlock and S. P. Ng*
- 56 **Thermal and moisture transport in fibrous materials**  
*Edited by N. Pan and P. Gibson*
- 57 **Geosynthetics in civil engineering**  
*Edited by R. W. Sarsby*
- 58 **Handbook of nonwovens**  
*Edited by S. Russell*
- 59 **Cotton: Science and technology**  
*Edited by S. Gordon and Y-L. Hsieh*
- 60 **Ecotextiles**  
*Edited by M. Mirafteb and A. Horrocks*
- 61 **Composite forming technologies**  
*Edited by A. C. Long*
- 62 **Plasma technology for textiles**  
*Edited by R. Shishoo*
- 63 **Smart textiles for medicine and healthcare**  
*Edited by L. Van Langenhove*
- 64 **Sizing in clothing**  
*Edited by S. Ashdown*
- 65 **Shape memory polymers and textiles**  
*J. Hu*
- 66 **Environmental aspects of textile dyeing**  
*Edited by R. Christie*



- 67 **Nanofibers and nanotechnology in textiles**  
*Edited by P. Brown and K. Stevens*
- 68 **Physical properties of textile fibres Fourth edition**  
*W. E. Morton and J. W. S. Hearle*
- 69 **Advances in apparel production**  
*Edited by C. Fairhurst*
- 70 **Advances in fire retardant materials**  
*Edited by A. R. Horrocks and D. Price*
- 71 **Polyesters and polyamides**  
*Edited by B. L. Deopora, R. Alagirusamy, M. Joshi and B. S. Gupta*
- 72 **Advances in wool technology**  
*Edited by N. A. G. Johnson and I. Russell*
- 73 **Military textiles**  
*Edited by E. Wilusz*
- 74 **3D fibrous assemblies: Properties, applications and modelling of three-dimensional textile structures**  
*J. Hu*
- 75 **Medical textiles 2007**  
*Edited by J. Kennedy, A. Anand, M. Mirafteb and S. Rajendran*
- 76 **Fabric testing**  
*Edited by J. Hu*
- 77 **Biologically inspired textiles**  
*Edited by A. Abbott and M. Ellison*
- 78 **Friction in textiles**  
*Edited by B. S. Gupta*
- 79 **Textile advances in the automotive industry**  
*Edited by R. Shishoo*
- 80 **Structure and mechanics of textile fibre assemblies**  
*Edited by P. Schwartz*
- 81 **Engineering textiles: Integrating the design and manufacture of textile products**  
*Edited by Y. E. El-Mogahzy*
- 82 **Polyolefin fibres: Industrial and medical applications**  
*Edited by S. C. O. Ugbolue*
- 83 **Smart clothes and wearable technology**  
*Edited by J. McCann and D. Bryson*
- 84 **Identification of textile fibres**  
*Edited by M. Houck*
- 85 **Advanced textiles for wound care**  
*Edited by S. Rajendran*
- 86 **Fatigue failure of textile fibres**  
*Edited by M. Mirafteb*
- 87 **Advances in carpet technology**  
*Edited by K. Goswami*
- 88 **Handbook of textile fibre structure Volume 1 and Volume 2**  
*Edited by S. J. Eichhorn, J. W. S. Hearle, M. Jaffe and T. Kikutani*
- 89 **Advances in knitting technology**  
*Edited by K.-F. Au*

- 90 **Smart textile coatings and laminates**  
*Edited by W. C. Smith*
- 91 **Handbook of tensile properties of textile fibres**  
*Edited by A. Bunsell*
- 92 **Interior textiles: Design and developments**  
*Edited by T. Rowe*
- 93 **Textiles for cold weather apparel**  
*Edited by J. T. Williams*
- 94 **Modelling and predicting textile behaviour**  
*Edited by X. Chen*
- 95 **Textiles for construction**  
*Edited by G. Pohl*
- 96 **Engineering apparel fabrics and garments**  
*J. Fan and L. Hunter*
- 97 **Surface modification of textiles**  
*Edited by Q. Wei*
- 98 **Sustainable textiles**  
*Edited by R. S. Blackburn*
- 99 **Advanced fibre spinning**  
*Edited by C. Lawrence*
- 100 **Fire toxicity**  
*Edited by A. Stec and R. Hull*
- 101 **Technical textile yarns**  
*Edited by R. Alagirusamy and A. Das*
- 102 **Nonwovens in technical textiles**  
*Edited by R. Chapman*
- 103 **Colour measurement in textiles**  
*Edited by M. L. Gulrajani*
- 104 **Textiles for civil engineering**  
*Edited by R. Figueiro*
- 105 **New product development in textiles**  
*Edited by B. Mills*
- 106 **Improving comfort in clothing**  
*Edited by G. Song*
- 107 **Textile biotechnology**  
*Edited by V. Nierstrasz*
- 108 **Textiles for hygiene**  
*Edited by B. McCarthy*
- 109 **Nanofunctional textiles**  
*Edited by Y. Li*
- 110 **Joining textiles**  
*Edited by I. Jones and G. Stylios*
- 111 **Soft computing in textiles**  
*Edited by A. Majumdar*
- 112 **Textile design**  
*Edited by A. Briggs-Goode and K. Townsend*

- 113 **Biotextiles as medical implants**  
*Edited by M. King and B. Gupta*
- 114 **Textile thermal bioengineering**  
*Edited by Y. Li*
- 115 **Woven textile structure**  
*B. K. Behera and P. K. Hari*

Engineering fabrics deals with the application of science to reveal the relationships between the raw material, process and the finished product to achieve desired functional or aesthetic effects in the fabric. The success of fabric engineering depends on reliable objective measurements, prediction and control of fabric quality and performance attributes. The prediction of fabric quality and performance attributes requires an efficient methodology to model the inherent non-linear relationships between fibre, yarn and fabric properties. The science of mechanics has provided the ability to predict quantitatively the mechanical performance of structures, but has rarely been applied to textile materials. Various mathematical models, such as geometrical and mechanistic models, based on forces in the fabric, energy minimization principles and empirical relationships between variables, can be used for the analysis of textile structures and processes to explain the underlying principles and predict fabric properties and behavior. Understanding the theoretical relationships between fabric parameters enables the fabric designer to play with different fibers, yarn tex, threads per centimeter and weave to vary texture and other fabric properties. These relationships provide simplified formulae to facilitate calculations which are of value for cloth engineering, problems of structure and mechanical properties.

The authors bring together expertise in fabric structure, mechanical properties of fabric, structure-property relationships and basic principles of design engineering as a tool to support product development, within the framework of fabric structural mechanics. This book is the culmination of teaching, research and methodology in presenting principles and applications related to structure of woven fabrics developed over several years at the Indian Institute of Technology (IIT) Delhi, India. It aims to give readers a good foundation in this area through an in-depth understanding of the principles of physical and mechanical properties of woven textile structures. It is designed as a textbook for graduates and postgraduates in textile technology and also as a reference book for research. The concepts and applications have been demonstrated by liberal use of examples. The book gives a flavor of the basics and builds up to predictive modeling of some fabric properties. The

book is broad-ranging in covering the physical and mechanical properties of the fabric, the fabric making-up process and applications in newer and emerging areas like sports, e-textiles, etc. SI units have been used throughout the book. Each chapter gives an abstract of the contents and is concluded, wherever possible, with how the contents can be used and applied in practical situations.

The book is broadly divided into four sections: Part I Fundamentals of woven fabric structure, Part II Mechanics of woven fabric structure, Part III Design engineering of woven fabrics and Part IV Practical applications. The first four chapters in Part I present the fundamentals of woven fabric structure and some derivatives including some special structures. They discuss the concept of a maximum weavability limit, crimp interchange phenomena, the mechanisms of fabric shrinkage and soft computing applications to predict fabric parameters using the relationship between fabric parameters based on geometrical models. Part II deals with mechanical properties of woven structure in which behavior of fabric under various kinds of deformations is discussed. In Part III, the concept of design engineering, fundamentals of modeling and simulation, modeling methodologies and soft computing application for prediction of fabric properties are described to enable textile researchers to understand the application of various methods for product engineering. Chapters in Part IV demonstrate how fundamental knowledge of theory of fabric structure can be helpful for practical applications in developing fabrics of special construction and achieving various performance characteristics in processing and use.

We wish to thank many students in the Textile Department, IIT Delhi for their unstinting support in making this endeavor a reality. We also owe our indebtedness to many others who are not mentioned for their indirect contribution in enhancing our knowledge and giving support. We would like to acknowledge Ms Kathryn Picking, Mr Francis Dodds and Woodhead Publishing Limited for their encouragement and assistance. Professor Hari would like to thank his wife Usha for the support and encouragement to take up this benevolent task for contribution of experience to textile technology. It is hoped that this book will fill the vacuum in the literature on woven structures since the last book on structural mechanics of fibres, yarn and fabrics was published in 1969. We welcome suggestions for any errors that may have crept into the book inadvertently.

B. K. Behera  
P. K. Hari

# Contents

---

<i>The authors</i>	<i>xi</i>
<i>Woodhead Publishing Series in Textiles</i>	<i>xiii</i>
<i>Preface</i>	<i>xix</i>
 <b>Part I Fundamentals of woven fabric structure</b>	
1	The basics of woven fabric structure 3
1.1	Introduction: woven fabric formation 3
1.2	Elements of woven fabric structure 5
1.3	Regular and irregular weaves 5
1.4	Modeling different weaves 6
1.5	References 8
2	Geometrical modeling of woven fabric structure 9
2.1	Introduction: woven fabric structure 9
2.2	A simple geometric model of woven fabric structure 9
2.3	Using the model to predict the fabric thickness, cover, mass and specific volume 17
2.4	Modeling maximum fabric cover 19
2.5	Calculating fabric properties: numerical examples 21
2.6	References 29
3	Using a geometric model to predict woven fabric properties 30
3.1	Introduction 30
3.2	Predicting woven fabric parameters 31
3.3	Predicting the weavability limit 41
3.4	Predicting cover in different woven structures 53
3.5	Calculating fabric properties: numerical examples 57
3.6	Application: calculating tightness values 70
3.7	References 72

4	Woven fabric properties after structural modifications	73
4.1	Introduction	73
4.2	Crimp interchange phenomena	73
4.3	Maximum fabric extension	75
4.4	Other structural changes	76
4.5	Structural design of woven fabrics using soft computing	76
4.6	Calculating fabric properties: numerical examples	82
4.7	Reference	105

## Part II Mechanics of woven fabric structure

5	Shrinkage in woven fabrics	109
5.1	Introduction	109
5.2	Mechanisms of fabric shrinkage	110
5.3	The relationship between cloth and yarn shrinkage	112
5.4	Predicting fabric shrinkage	113
5.5	Application of fabric shrinkage model	115
5.6	References	117
6	Yarn behavior in woven fabrics	118
6.1	Introduction	118
6.2	The yarn path in woven fabrics and inter-yarn forces	118
6.3	The crimp balance equation	121
6.4	Predicting the yarn path in woven fabrics	122
6.5	The effect of settings on yarn behavior	127
6.6	Crimp interchange and crimp balance equations	128
6.7	Calculating fabric properties: numerical examples	131
6.8	Practical applications	136
6.9	References	136
7	Tensile behavior of woven fabrics	137
7.1	Introduction	137
7.2	Fundamentals of axial deformation	138
7.3	Tensile properties of woven fabrics	142
7.4	Castigliano's theorem	149
7.5	The sawtooth model	152
7.6	Fabric extension in the bias direction	157
7.7	Factors affecting the tensile properties of woven fabrics	162
7.8	References	163
8	Buckling behavior of woven fabrics	164
8.1	Introduction	164

8.2	Buckling deformation of woven fabric	165
8.3	Buckling behavior of cloth under large deformation	166
8.4	Hysteresis in fabric deformation	172
8.5	Practical applications	172
8.6	References	172
9	Bending behavior of woven fabrics	173
9.1	Introduction	173
9.2	Fundamentals of bending deformation	174
9.3	Modeling bending behavior	176
9.4	The bending behavior of woven fabrics	178
9.5	Bending hysteresis	187
9.6	The effect of setting on bending behavior	190
9.7	Bending recovery	191
9.8	Bending at higher curvatures	191
9.9	The time effect in bending deformation	191
9.10	Bending in the bias direction	192
9.11	Practical applications	196
9.12	References	196
10	Creasing in woven fabrics	197
10.1	Introduction	197
10.2	Mechanisms of creasing	197
10.3	Deformation and crease recovery behavior	199
10.4	The effect of time on deformation and crease recovery	202
10.5	Factors affecting crease recovery of fabrics	203
10.6	References	204
11	Shear behavior of woven fabrics	205
11.1	Introduction	205
11.2	Fundamentals of shear deformation	206
11.3	Shear deformation in woven fabrics	207
11.4	Shear properties in various directions	215
11.5	Predicting shear properties: practical applications	216
11.6	References	216
12	Compression behavior of woven fabrics	217
12.1	Introduction	217
12.2	Fundamentals of compression	218
12.3	The compression behavior of textile structures	218
12.4	The exponential behavior of compressible fabrics	222
12.5	The low stress pressure–thickness curve	223
12.6	Predicting compression in woven fabrics	223



viii	Contents	
12.7	Practical applications	229
12.8	References	229
13	Friction and other aspects of the surface behavior of woven fabrics	230
13.1	Introduction	230
13.2	Fundamentals of friction and abrasion	231
13.3	Measuring roughness and other surface properties of woven fabrics	232
13.4	Factors affecting abrasion resistance	236
13.5	References	241

### Part III Design and engineering of woven fabrics

14	Textile product design methods	245
14.1	Introduction	245
14.2	The design process for textiles	246
14.3	Traditional design methods	247
14.4	Key issues in the design of textile products	248
14.5	Computer-assisted design (CAD) of woven fabrics	250
14.6	Design engineering using modeling	251
14.7	Reverse engineering	252
14.8	Expert systems in textile product design	252
14.9	References	257
15	Modeling for textile product design	260
15.1	Introduction	260
15.2	Principles of mathematical modeling	260
15.3	Modeling methodologies	262
15.4	Deterministic models	262
15.5	Nondeterministic models	264
15.6	Validation and testing of models	272
15.7	Summary	273
15.8	References	273
16	Building predictive models for textile product design	275
16.1	Introduction	275
16.2	Building empirical, mathematical and artificial neural network (ANN) models	276
16.3	Evaluating mathematical, empirical and artificial neural network (ANN) models	281
16.4	Summary	288
16.5	References	290