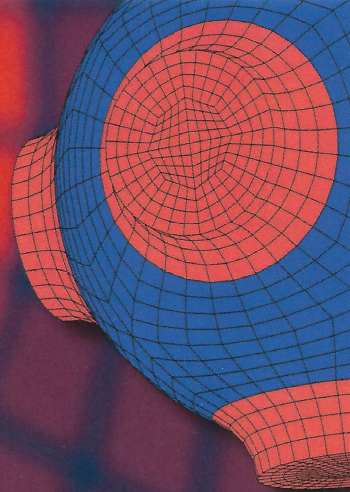


Advanced Structured Materials

Holm Altenbach
Julius Kaplunov
Hongbing Lu
Masayuki Nakada *Editors*



Advances in Mechanics of Time-Dependent Materials

 Springer


Holm Altenbach · Julius Kaplunov · Hongbing Lu ·
Masayuki Nakada
Editors

Advances in Mechanics of Time-Dependent Materials


 Springer

Editors

Holm Altenbach 
Lehrstuhl für Technische Mechanik, Institut
für Mechanik, Fakultät für Maschinenbau
Otto-von-Guericke-Universität
Magdeburg, Germany

Hongbing Lu 
University of Texas at Dallas
Richardson, TX, USA

Julius Kaplunov 
Department of Mathematics
Keele University
Keele, UK

Masayuki Nakada 
Materials System Res Lab
Kanazawa Institute of Technology
Hakusan, Ishikawa, Japan

ISSN 1869-8433

Advanced Structured Materials

ISBN 978-3-031-22400-3

<https://doi.org/10.1007/978-3-031-22401-0>

ISSN 1869-8441 (electronic)

ISBN 978-3-031-22401-0 (eBook)

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2023

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The book presents a variety of recent theoretical and experimental techniques for modelling of advanced viscoelastic materials. The book has a significant interdisciplinary flavour and reports on important achievements of the international academic community. This is a collection of selected chapters reporting on the current trends in Mechanics of Time Dependent Materials. The authors are renowned experts in the field affiliated with research intensive universities in Europe, North America and Far East.

The book covers a number of cutting-edge themes, such as characterization of linear and nonlinear mechanical behaviour of viscoelastic materials and their composites, taking into consideration finite deformations, dynamic loading, microstructure, phased transitions, along with failure and fracture phenomena. The contributions are inspired by advanced applications in modern technologies, e.g. injection moulding, extrusion etc. A variety of theoretical and experimental aspects addressed in the book will be of interest for a broad interdisciplinary audience, including but not restricted to mechanical, civil and chemical engineers, as well as material, bio and geoscientists. Postgraduate students in related areas will also find useful many of the chapters as additional literature sources.

The volume is dedicated to the 70th anniversary of Prof. Igor Emri. Prof. Emri is an internationally leading authority in mechanics of time-dependent materials and related topics. He originated numerous influential developments in this area and co-authored around 300 publications on the subject.



Professor Emri was born in Musrka Sobota, Slovenia in 1952. He graduated from the Faculty of Mechanical Engineering at the University of Ljubljana in 1977. He was awarded a Ph.D. from California Institute of Technology, USA, in 1981. For a long time, Prof. Emri was affiliated with the University of Ljubljana. He was promoted there to a Full Professorship in 1996. Soon after, he established the Department of Mechanics of Polymers and Composites leading it until his retirement in 2016.

Professor Emri is involved in a variety of important academic activities. In particular, he is one of the founders and Editor-in-Chief of the reputable international journal »Mechanics of Time Dependent Materials«, published by Springer-Nature. His outstanding achievements received a number of major awards and honours. He is an international member of USA National Academy of Engineering (NAE) and also a member of European Academy of Sciences and Arts, European Academy of Sciences, Slovenian Academy of Sciences and Arts and several others.

Professor Emri served as the Chairman of the Science Europe Scientific Committee on Engineering and Technology (ENGITECH), the Co-Chairman of the Science Europe Scientific Advisory Committee, the President of the Society of Experimental Mechanics (SEM), and the President of the International Committee on Rheology (ICR). In 1993 I. Emri jointly with his academic mentor W. G. Knauss from the California Institute of Technology, have created the new research field called "Mechanics of Time-Dependent Materials—MTDM". MTDM was first organized as Technical Division (TD) of SEM.

Another of his key contribution to the community service is related to the organization of numerous international scientific events. In particular, he launched the series of major conferences on Mechanics of Time-Dependent Materials taking place all over the world since 1995. Fruitful less formal workshops on Advances in Experimental Mechanics regularly hosted by Emri's research group in Slovenia are also worth to be mentioned.

Research activities of Prof. Emri are mainly focused on mechanics of dissipative systems with emphasis on studying the effect of the rate of changing of thermo-mechanical boundary conditions on processes of structure formation of polymeric materials and their macro-, micro- and nanocomposites, as well as on the behaviour of solid granular systems. He has developed a new nonlinear viscoelastic constitutive

model, known as the so-called Knauss-Emri model, which enables modelling of nonlinear behaviour of engineering polymers and composites subject to complex time-varying thermo-mechanical loading, and prediction of their long-time behavior (durability of polymer based products and structures).

Professor Emri and his group have shown that macroscopic properties of polymeric materials and their composites, can be controlled and modified either by changing material initial kinetics, i.e. molecular mass distribution and topology of molecules, or by varying thermo-mechanical conditions, including pressure and temperature, or by high rate mechanical loading.

The pioneering collaborative efforts by I. Emri together with W. G. Knauss and N. W. Tschoegl from the California Institute of Technologies resulted in an innovative theoretical-experimental approach for analysing the structure formation processes of multimodal polyamide materials under the influence of complex thermomechanical conditions. Emri's findings were patented and implemented by BASF in the production of polyamides. Later it was found that by using these materials one can manufacture osseointegrable implants with a gradient structure that mimics properties of bones and may be used in dental and orthopaedic surgery.

Among more recent Emri's scientific results there is the development of sound insulation structures involving granular materials. The underlying theory is based on the mechanism of a "force-network" formation. His invention has a substantial potential to be implemented in various modern industries including mechanical, automotive, electrical, aerospace, railway, naval and civil engineering. This piece of work has been also patented.

The list of a few selected publications by Prof. Emri illustrating a broad range of his research interests is given below.

- Knauss W.G., Emri I. Non-linear Viscoelasticity Based on Free Volume Consideration. *Computers & Structures*, 1981, 13 (1), 123–128.
- Knauss W.G., Emri I. Volume Change and the Nonlinearly Thermo-Viscoelastic Constitution of Polymers. *Polymer Engineering & Science*, 1987, 27 (1), 86–100.
- Emri I., Tschoegl N.W. Generating Line Spectra from Experimental Responses. Part I: Relaxation Modulus and Creep Compliance. *Rheologica Acta*, 1993, 32 (3), 311–322.
- Emri I., Tschoegl N.W. Generating Line Spectra from Experimental Responses. Part II: Storage and Loss Functions. *Rheologica Acta*, 1993, 32 (3), 322–327.
- Tschoegl N.W., Emri I., Generating Line Spectra from Experimental Responses. Part III: Interconversion between Relaxation and Retardation Behavior. *International Journal of polymeric materials*, 1992, 18, 117–127.
- Emri I., Tschoegl N.W. Generating Line Spectra from Experimental Responses. Part IV: Application to Experimental Data. *Rheologica Acta*, 1994, 33 (1), 60–70.
- Tschoegl N.W., Knauss W.G., Emri I. Poisson's Ratio in Linear Viscoelasticity—A Critical Review. *Mechanics of Time-Dependent Materials*, 2002, 6 (1), 3–51.

- Tschoegl N.W., Knauss W.G., Emri I. The Effect of Temperature and Pressure on the Mechanical Properties of Thermo-and/or Piezorheologically Simple Polymeric Materials in Thermodynamic Equilibrium—A Critical Review. *Mechanics of Time-Dependent Materials*, 2002, 6 (1), 53–99.
- Nikonov A., Davies A.R., Emri, I. The Determination of Creep and Relaxation Functions from a Single Experiment. *Journal of Rheology*, 2005, 49(6), 1193–1211.
- Emri I., Prodan T. A Measuring System for Bulk and Shear Characterization of Polymers. *Experimental Mechanics*, 2016, 46 (4), 429–439.
- Knauss W.G., Emri I., Lu H. *Mechanics of Polymers: Viscoelasticity*, Springer Handbook of Experimental Solid Mechanics, 2008, 49–96.
- Gergesova M., Zupančič B., Saprunov I., Emri I. The Closed Form tTP Shifting (CFS) Algorithm. *Journal of Rheology*, 2011, 55(1), 1–16.
- Emri I., Gonzalez-Gutierrez J., Gergesova M., Zupančič B., Saprunov I. Experimental Determination of Material Time-Dependent Properties. In Hetnarski, R.B. (ed.). *Encyclopedia of thermal stresses*. Dordrecht: Springer Reference, 2014, 1494–1510.
- Emri I., Voloshin A. *Statics: Learning from Engineering Examples*. New York: Springer, 2016. 570 p.
- Aulova A., Govekar E., Emri I. Determination of Relaxation Modulus of Time-Dependent Materials Using Neural Networks. *Mechanics of Time-Dependent Materials*, 2017, 21(3), 331–349.
- Aulova A., Oseli A., Bek M., Prodan T., Emri I. Effect of Pressure on Material Properties of Polymers. In: Altenbach H. (ed.), Öchsner A. (ed.). *Encyclopedia of continuum mechanics*. Berlin; Heidelberg: Springer, 2018, 1–14.
- Oseli A., Aulova A., Gergesova M., Emri I. Effect of Temperature on Material Properties of Polymers. In: Altenbach H. (ed.), Öchsner A. (ed.). *Encyclopedia of continuum mechanics*. Berlin; Heidelberg: Springer, 2018. 1–20.

Magdeburg, Germany
Keele, UK
Richardson, USA
Hakusan, Japan

Holm Altenbach
Julius Kaplunov
Hongbing Lu
Masayuki Nakada

Contents

1	Rheological Modeling—Historical Remarks and Actual Trends in Solid Mechanics	1
	Holm Altenbach	
1.1	Rheology as a Science	1
1.2	Development of Rheology as an Independent Scientific Branch	6
1.3	The Method of Rheological Modelling of Palmov	8
1.4	Two-Dimensional Rheological Modelling	10
1.5	Advanced Rheological Models	13
1.6	Summary and Outlook	14
	References	14
2	On Stieltjes Continued Fractions and Their Role in Determining Viscoelastic Spectra	17
	A. Russell Davies and Faris Alzahrani	
2.1	Introduction	17
2.2	Mathematical Background	18
2.3	The Continuous Relaxation Spectrum and Its Moments	20
2.3.1	Unimodal Spectra with a Finite Number of Moments	20
2.3.2	Unimodal Spectra with an Infinite Number of Moments	23
2.3.3	Multi-modal Spectra	24
2.4	The Stieltjes Moment Problem	25
2.4.1	The S-Series and S-Fraction	26
2.5	Dirichlet Series and Discrete Spectra	28
2.5.1	Spectral M-Sets	29
2.5.2	Spectral \mathbb{P} -Sets and Stieltjes Dictionaries	30
2.6	Two Case Studies	32
2.6.1	A Theoretical Spectrum	32
2.6.2	Polybutadiene	33

2.7	Discrete Retardation Spectra	34
2.8	Summary	36
	References	36
3	Modulation of the Viscoelastic Response of Hydrogels with Supramolecular Bonds	39
	Aleksey D. Drozdov	
3.1	Introduction	39
3.2	Constitutive Model	41
3.3	Fitting of Experimental Data	48
3.3.1	HA Gels with Hydrazine-Aldehyde Bonds	48
3.3.2	PEG Gels Cross-Linked by HIP and CB[7] Bonds	51
3.3.3	PAAm Gels Cross-Linked by HIP and CB[7] Bonds	52
3.4	Conclusions	54
	References	55
4	Igor Emri, a Student, a Colleague and a Friend	57
	Wolfgang G. Knauss	
	References	63
5	Numerical Simulation for Tensile Failure of Fiber-Reinforced Polymer Composites Based on Viscoelastic-Entropy-Damage Criterion	65
	Jun Koyanagi	
5.1	Introduction	65
5.2	Application of Thermodynamic Entropy for Continuum Damage Mechanics	68
5.3	Numerical Simulation for Discontinuous CFRP	70
5.3.1	Layer-Wise Method	70
5.3.2	Finite Element Analysis	72
5.3.3	Periodic Boundary Condition	75
5.3.4	Algorithm of Viscoelastic-Entropy-Damage Criterion	78
5.3.5	Numerical Results	78
5.4	Conclusion	80
	References	81
6	An Investigation of the Nonlinear Viscoelastic Behavior of PMMA Near the Glass Transition Using the Spectral Hole Burning Method	85
	Huiluo Chen, Sadeq Malakooti, Ren Yao, Stephanie L. Vivod, Gregory McKenna, and Hongbing Lu	
6.1	Introduction	85
6.2	Experiment Method	86
6.2.1	Mechanical Spectrum Hole Burning	86
6.2.2	Experiment	88

6.3	Results and Discussion	89
6.3.1	Linear Regime Determination	89
6.3.2	Exploration of Pump Amplitude and Frequency for PMMA	90
6.4	Experiments with Tuned Parameters	92
6.5	Conclusion	96
	References	97
7	Accelerated Testing Methodology for Life Prediction of Unidirectional CFRP Under Tension Load	99
	Masayuki Nakada and Yasushi Miyano	
7.1	Introduction	99
7.2	Generalization of Time-Temperature Superposition Principle for Strength of CFRP	101
7.3	Formulations Based on ATM	103
7.4	Experiments	107
7.4.1	CFRP Strands Employed as Unidirectional CFRP	107
7.4.2	Test Methods	109
7.5	Results and Discussion	109
7.5.1	Viscoelasticity of Matrix Resins	109
7.5.2	Statistical Static Strengths of CFRP Strands	111
7.5.3	Statistical Creep Strengths of CFRP Strands	113
7.5.4	Statistical Fatigue Strengths of CFRP Strands	113
7.5.5	Predictions of Long-Term Statistical Creep and Fatigue Strengths of CFRP Strands	115
7.6	Conclusions	115
	References	118
8	Application of Time-Temperature Superposition Principle for Polymer Lifetime Prediction	121
	Takenobu Sakai and Satoshi Somiya	
8.1	Introduction	121
8.2	Time-Influence Factor Superposition Principle	122
8.3	Time-Heat Treatment Conditions Superposition Principle	123
8.4	Time-Fiber Volume Fraction Superposition Principle	127
8.5	Time-Crystallinity Superposition Principle	129
8.6	Time-Crystallinity-Fiber Volume Fraction Superposition Principle	132
8.7	Conclusions	135
	References	136
9	Viscoelastic and Viscoplastic Behavior of Polymer and Composite	139
	Kenichi Sakaue	
9.1	Introduction	139
9.2	Viscoelastic-Viscoplastic Constitutive Model	140

9.2.1	Series-Connected Model of Viscoelastic and Viscoplastic Elements	140
9.2.2	Constitutive Equation of the Viscoelastic Elements	140
9.2.3	Constitutive Equation of the Viscoplastic Elements	141
9.3	Viscoelastic–Viscoplastic Behavior of PBT Resin	142
9.3.1	Viscoelastic Characteristics	142
9.3.2	Viscoplastic Characteristics	142
9.4	Viscoelastic–Viscoplastic Behavior of Short Glass Fiber-Reinforced PBT	145
9.4.1	Test Material	145
9.4.2	Prediction of Behavior of PBT Composite by Finite Element Analysis	145
9.5	Summary	149
	References	151
10	Using Asymptotic Homogenization in Parametric Space to Determine Effective Thermo-Viscoelastic Properties of Fibrous Composites	153
	A. N. Vlasov, D. B. Volkov-Bogorodsky, and V. L. Savatorova	
10.1	Introduction	153
10.2	Viscoelastic Fiber-Reinforced Composites. Maxwell's Model	155
10.3	Asymptotic Homogenization of the Equations with Complex Moduli in Parametric Space	157
10.4	The Solution of the Problem on Microscale	162
10.5	Numerical Results and Their Analysis	167
10.6	Conclusion	169
	References	169
11	Biomechanical Modeling and Characterization of Cells	173
	Arkady Voloshin	
11.1	Introduction	174
11.2	Materials and Method	175
11.2.1	HMSC Cell Culturing Conditions	175
11.3	Experiments	175
11.4	Elastic, Viscoelastic, and Tensegrity Models	176
11.4.1	Elastic and Viscoelastic Models	176
11.4.2	Modeling the Viscoelastic Cell Behavior Using Tensegrity	179
11.5	Results and Discussions	181
11.6	Conclusions	185
11.7	Definitions of Variables and Constants Used in this Paper	187
	References	187

12	Thermo-Rheological Analysis and Kinetic Modeling of Thermal and Thermo-Oxidative Degradation of Polyethylene	191
	Leslie Poh, Qi Wu, Esmacel Narimissa, and Manfred H. Wagner	
12.1	Introduction	192
12.2	Experimental	194
12.2.1	Materials	194
12.2.2	Sample Preparation	194
12.2.3	Differential Scanning Calorimetry	195
12.2.4	Thermogravimetric Analysis	195
12.2.5	Rheological Characterization	196
12.3	Kinetic Analysis	196
12.3.1	Model-Free Methods	198
12.3.2	Model-Fitting Method	199
12.4	Results and Discussion	199
12.4.1	Oxidative Induction Time in Differential Scanning Calorimetry and Thermogravimetric Analysis	199
12.4.2	Thermal and Thermo-Oxidative Degradation of Unstabilized and Stabilized LDPE in Nitrogen and Air	201
12.4.3	Kinetic Analysis of Non-isothermal TG Curves of Unstabilized and Stabilized LDPE	203
12.4.4	Thermorheological Analyses of Unstabilized and Stabilized LDPEs Using Time-Sweep Rheometry	206
12.5	Conclusions	209
	References	211
13	Quantitative Characterization of Cracks and Contact Stresses Using Photoviscoelasticity	215
	Satoru Yoneyama and Masahisa Takashi	
13.1	Introduction	215
13.2	Photoviscoelasticity	217
13.3	Evaluating Rolling Contact Stresses	219
13.3.1	Material Characteristics	219
13.3.2	Experimental Procedure	221
13.3.3	Finite Element Analysis	221
13.3.4	Results and Discussion	223
13.3.5	Summary	229
13.4	Evaluating Fracture Parameter	230
13.4.1	Material Characteristics	231
13.4.2	Specimen Geometry	232
13.4.3	Introducing Natural Crack	233
13.4.4	Experimental Procedure	234
13.4.5	Results for Stationary Cracks	234

13.4.6 Results for Moving Crack	236
13.4.7 Summary	243
13.5 Conclusions	244
References	245