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VNR VAN NOSTRAND REINHOLD COMPANY

Library of Congress Catalog Card Number: 84-2254
ISBN: 0-442-28281-8

Manufactured in the United States of America

Published by Van Nostrand Reinhold Company Inc.
135 West 50th Street
New York, New York 10020

Van Nostrand Reinhold Company Limited
Molly Millars Lane
Wokingham, Berkshire RG11 2PY, England

Van Nostrand Reinhold
480 Latrobe Street
Melbourne, Victoria 3000, Australia

Macmillan of Canada
Division of Gage Publishing Limited
164 Commander Boulevard
Agincourt, Ontario M1S 3C7, Canada

15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

Library of Congress Cataloging in Publication Data

Tarnopol'skiĭ, I͡U. M.
Static test methods for composites.

Includes bibliographical references and indexes.
1. Fibrous composites—Testing. I. Kincis, T. I͡A. (Talivaldis I͡Anovich) II. Title.
TA418.9.C6T37 1984 620.1'18 84-2254
ISBN 0-442-28281-8

Foreword

The rapid growth in the development and application of composits has reached the stage where these materials are no longer considered to be exotic, but are treated as practical engineering structures. In aircraft alone, the use of composites has gone up from 2–3% of the total weight of the plane to 10–15% and some, more advanced structures may use up to 40–60%.

To aid in introducing and utilizing these materials, numerous design and manufacturing processes have been developed to the point that structurally effective and durable parts are being economically fabricated and are expected to perform as well or better than the previously used metallic materials.

In working with composites, it is necessary to develop statistical design allowables similar to those used in the metal industry. To obtain these design allowables, extensive testing has been required and it was found early in the composites history that the test data scatter is much greater than that of metals, and the resulting figures have had to be greatly reduced. As is explained in the text of this book, the scatter is basically caused by the large variations in properties of the components of the composite materials, their orientation, process parameters, relative proportion of constituents and processing techniques.

It is no exaggeration when we claim that a specimen cut from a sheet of metal represents fairly closely the strength of the metal. In the case of composites, an individual specimen usually represents only the strength of that particular specimen and has merely a general relation to the strength of the final article fabricated from the particular composite.

This state of affairs has necessitated the need for destructive testing of the final molded part to prove the effectiveness of the design. This in turn frequently has resulted in overdesigned structures and minimal weight savings.

Precise strength data is essential for the design and economic fabrication of production composites of the future.

To try to resolve the problem of data variations, a group of engineers and scientists at the Institute of Polymer Mechanics of the Latvian SSR Academy of Sciences in Riga conducted a survey of all available literature on the testing of polymers and amplificied it by extensive additional research. The results of the survey constitute the material in this book. Here, all identifiable variables have been investigated where possible, and formulas for the development of design data have been either selected from literature or derived and modified by the authors with the help of the Institute personnel. These formulas are offered to the readers for use in designing composites together with an extended set of references including papers, books, publications and standards from all over the world. The effects of all fabrication parameters are discussed and the numerous test methods and test specimens described, evaluated and rated for accuracy and effectiveness.

After reading this book, one realizes how inadequate and incomplete are the sample preparation and testing techniques used by most laboratories. The old metal methods and the newer fiberglass technology are too unreliable to apply to modern composites and many new procedures have had to be introduced and perfected.

In my own experience I have found that much of the early data on composites is unreliable and a comparison of values generated on identical materials by different laboratories shows great scatter and variability. While the authors of this book do not offer magic solutions to all our problems, they shed much light on the hidden parameters and offer many suggestions on the choice of tests and material control.

Most books on composites or anisotropic materials deal with basic design concepts and the theory of elasticity of anisotropic structures. In this book, information is presented for the planning of destructive tests, determination of applicable variables and the verification and control of test results.

In selecting specimen shapes and fabricating operations, it is required that all manufacturing conditions and processes for the material, product or structure be properly simulated. Suggestions are offered on the relative importance and effects of most production variables. Test results on specimens with different configurations are discussed and recommendations made for optimum reliability.

Other subjects covered include the scale effect, stress concentrations, specimen conditioning and types of loading. A final recommendation includes a list of all information which should be a part of the test report.

George Lubin

Preface

Over the last decades, the possibility of industrial production of materials with properties assigned in advance has first arisen in human history. The fact is closely bound up with the creation, development and improvement of composites. The advent of composites has been prompted by contemporary technological demands on materials. At the basis of composites lies the concept of reinforcement—an idea unique in its simplicity, involving the combination of polar opposites as to their material properties, a compliant matrix and a strong and stiff reinforcement.

The idea has originated in nature, so far from extremely simplified forms. These are the stalks and leaves of plants, human and animal bones which behave as fiber-reinforced anisotropic materials—composites. It is noteworthy that the concept of reinforcement is broader than simply strength or workability. It involves also an increase in material reliability. Apparently composites are the only materials for which an increase in strength is accompanied by an increase in fracture toughness.

The mechanical properties of composites, in contrast to metals, are characterized by a multitude of constants. Their experimental evaluation is fraught with essential methodical difficulties. It should be borne in mind that the level of standardization of test methods for composites leaves much to be desired. In practice, a variety of specimen shapes and sizes, manufacturing methods of specimens and experimental techniques are being employed. This has resulted in incomparable results and contradictory judgements about the structural potential of composites. A realistic approach of mechanical testing requires strict regulation of the number and methods of evaluation of strength and stiffness of composites, increasing the necessity of a critical analysis of the existing methods, their evaluation and generalization.

In an effort to select and evaluate the most promising static test methods for advanced composites in tension, compression, shear and bending on flat and ring specimens, the book is based on world experience, mainly that of the USSR and USA. Selection of the test methods and their areas of application is substantiated by voluminous factual material. The majority of tables and illustrations contain references to works on which they have been based; these works contain all the necessary additional information. The references are particularly to Soviet scientific publications, with which American readers are less familiar.

It is up to the reader to judge the pros and cons of the book; we would only like to mention that all three Soviet editions were highly appraised by specialists and the scientific community. On our part, the American edition has been prepared by Elga A. Ozolina, Vladimir L. Kulakov and Lilly L. Volgina; their efforts are gratefully acknowleged by the authors. Thanks are also due to Susan Munger, Senior Editor of Van Nostrand Reinhold Company, Inc., for her help. It is also a pleasure to note that the American edition is being recommended to readers by Dr. George Lubin, one of the pioneers in composite mechanics and technology. The problem of new materials is a global problem. The future advances of mankind greatly depend on its solution.

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Introduction

In order to of estimate strength and stiffness, structural materials are subjected to mechanical testing. Historically, mechanical testing of structural materials, followed by practical application of test results, may be traced back to July 4, 1662 [77], when tows made from Riga and Holland yarns were compared [137]. Since then test procedures for materials, primarily metals, have attained a comparatively advanced level. The history of the development of test methods for technical materials is treated in detail in [235]. The advent and widely expanding use of composites in highly loaded primary structures have forced a revision of the subject of mechanical testing. New test methods are continuously being developed, already existing techniques verified and reexamined. The principal difficulties arising in the testing of composites have been analyzed in [198].

Research practice has far exceeded test methods specified by standards. So far there are only a few standards written in terms of anisotropy. Numerous investigations of composites by various techniques have resulted in ambivalent judgments about the potential capabilities of the materials. This fact still further emphasizes the need for a critical analysis of existing methods, their estimation and generalization.

Advanced fibrous composites with unidirectional, laminated, and multiply oriented reinforcement are nonhomogeneous, essentially anisotropic materials. For this class of materials the usual terms—tensile, compression, shear, and bending tests—become meaningless without specification of the direction between the load and the axes of elastic symmetry of the material. Material anisotropy and structural peculiarities cause a number of serious problems. First of all, the number of determinable strength and elastic characteristics necessary for complete description of the material depends on the type of material anisotropy. Selection of the loading scheme for which the material characteristics are most simply related to the experimentally determinable values, selection of the analytical apparatus for experimental data processing, and estimation of the range of their validity are of principal significance.

For fibrous composites it is difficult to establish a uniform state of stress in the characteristic volume of the specimen, even for the simplest types of tests. The difficulties increase with the anisotropy of the material, i.e., for materials with high-modulus and high-strength reinforcement (boron, carbon, and organic fiber reinforced composites). In composite testing, the measurable strain essentially depends on the boundary conditions, i.e., on the method of fastening and loading of specimens. This phenomenon is a characteristic of highly anisotropic materials and represents a specific case of Saint Venant's principle.

Anisotropy of elastic properties enhances the requirements imposed on specimen shape and size, elimination of end effect (proper choice of the distance from the grips to the reference section on a specimen), load transmission, fiber orientation, and angle of specimen cutting. Anisotropy of strength in the case of improper choice of the loading scheme and specimen fastening leads to alteration of the failure mode, for instance, to delamination or "shearing-off" of the specimen in grips under tension. A special problem is the selection of specimen width; it is important to avoid any edge effect, i.e., critical interlaminar stresses.

This book is devoted to methods of evaluation the elastic and strength characteristics of fibrous polymeric composites during short-term static tests under normal conditions. The authors have systematized and generalized worldwide experience in the field. Surveys published in recent years [27, 38, 39, 45, 194, 244, 266] and the experience accumulated at the Institute of Polymer Mechanics of the Latvian SSR Academy of Sciences, as well as numerous articles and reports presented at special conferences of the ASTM [10, 46–51], have been made good use of. The bibliography of this book does not claim to be comprehensive; however, it reflects sufficiently well the state of the art of mechanical testing of fibrous composites, advances made in the field, and the level of standardization achieved.

In spite of this progress, the degree of mastery and standardization is different for various methods. As before, shear stiffness and, especially, shear strength determination present difficulties. With the accumulation of experience a number of methods for estimation of strength and stiffness is in need of further corrections.

Test methods for annular specimens have been greatly extended during the last years. This fact allows us to consider test methods for flat and annular specimens in tension, compression, shear, and bending from a common standpoint—according to loading type. All the chapters include test methods and techniques for advanced composites with carbon, boron, and organic fiber reinforcement of various schemes. Attention has been focused on unidirectional materials which may be identified as laminae. Characteristics of a lamina must be determined not only for engineering certification of the material; they also form the basis for determining the properties of hybrid materials and composites with varying transverse reinforcement layups.

Among the composites which are discussed in this book, glass fiber composites with fibrous, laminated, and multidirectional reinforcement occupy the most important place. For substantiation of the test methods for glass fiber composites practically no experimental data are presented; these test methods are numerous and their accuracy is high. There is also no necessity to confirm and experimentally substantiate selection of the shape and size of a specimen, loading scheme, etc., for glass fiber composites with a traditional reinforcement scheme. For high-modulus materials the necessary experimental data have been presented, since the majority of problems are still under study. Test techniques for high-modulus and multidirectionally reinforced composites have not yet been refined.

This book is based on experience in testing of the "first generation" of fibrous composites with unidirectional, laminated, and multidirectional reinforcement, based on a polymeric matrix and reinforced with conventional and high-modulus fibers. Experience has shown that the methods evolved can be successfully applied to fibrous composites of the next generations—to carbon, metallic, and ceramic matrix based materials. However, experience in testing polymeric composites cannot directly be applied to modern materials without due regard for the specific properties of those matrices.

At the end of each chapter devoted to the analysis of an individual type of tests is a summary table. (See chapters 3, 4, and 5.) These tables are meant for fast visual orientation in the type of testing and for preliminary evaluation of the potential and selection of the optimum test method.

Knowledge of the properties of composites under uniaxial static loading is necessary but often insufficient for their rational use in primary structures. The development of methods for studying properties of fibrous composites under complex state of stress is a difficult task. There is a need for systematization and generalization of destructive as well as nondestructive methods for studying long-term static, dynamic, and fatigue properties of composites. The problems associated with peculiarities of testing at elevated and reduced temperatures, under conditions of increased humidity, under special environmental conditions, and in particular, prognostic methods of testing need special attention. Solution of all the above problems will form a scientific basis for future standardization of test methods for composites on an international scale.

In preparation of the first two editions significant assistance was lent to the authors by A.K. Mālmeisters. His advice and comments after having seen the outline of the book and the manuscript have greatly favoured the success of the work. The authors are truly grateful to I.G. Zhigun, who has analytically and experimentally evaluated a series of test methods for high-modulus and multidirectionally reinforced materials, and also to L.L. Volgina who has typed the manuscripts and prepared illustrations for all three editions.

Symbols

COORDINATES

x, y, z	structural axes, rectangular coordinate system
θ, z, r	structural axes, cylindrical coordinate system
1, 2, 3	material axes, rectangular or cylindrical coordinate system. In most cases treated in this book, they coincide with the structural axes in a rectangular or cylindrical coordinate system, which are preferred.

GEOMETRICAL CHARACTERISTICS

b, l, h	characteristic linear dimensions of the specimen, explained in the text
r	current radius
R, R_i, R_0	mean, inner, and outer radii, respectively, of ring or tube specimens
θ	fiber orientation or lamination angle

LOAD

P	concentrated load
P^u	concentrated load at specimen failure
p	uniform pressure
p^u	uniform pressure at the failure of a specimen
M	bending moment
M^u	bending moment at the failure of a specimen
M_T	the applied torque
M_T^u	the applied torque at the failure of a specimen

STRESSES AND STRENGTHS

σ	normal stresses: subscripts denote direction, superscripts denote type of loading
τ	tangential stresses: subscripts denote plane, super scripts denote type of loading
σ^u	strength due to normal stresses: subscripts denote direction, additional superscripts denote type of loading
τ^u	strength due to tangential stresses: subscripts denote plane, additional superscripts denote type of loading

DISPLACEMENTS AND STRAINS

u, v, w	displacements in the x, y, z or θ, z, r directions
ε	linear strains: subscripts denote direction, superscripts denote type of loading
γ	shear strains: subscripts denote plane
φ	angle of twist

MATERIAL CHANACTERISTICS

E	modulus of elasticity: subscripts denote direction or material constituents, superscripts denote type of loading
G	shear modulus: subscripts denote plane, superscripts denote type of loading
ν	Poisson's ratio: the first subscript denotes the loading direction, the second denotes transverse strain direction
V	volume content of material constituents, defined by subscripts

SUBSCRIPTS

x, y, z; θ, z, r	structural axes direction
$1, 2, 3$	material axes direction
xy, xz, yz; $\theta z, \theta r, zr$	shear planes in structural axes rectangular coordinate system

$0^\circ, 45^\circ, 60^\circ, 90^\circ \ldots$	orientation angles to the load direction
bear	bearing
break	breaking
cr	critical
exp	experiment
f	fiber; fictitious
h	horizontal
i	inner (inside)
m	matrix
mean	mean value
o	outer (outside)
shear	shearing
v	vertical; voids
L	longitudinal
T	transversal
τ	shear

SUPERSCRIPTS

b	bending
c	compression
t	tension

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