国际著名力学图书 —— 影印版系列 3

Advanced Strength and Applied Stress Analysis

Second Edition

# 高等材料力学和实用应力分析

## 第2版

Richard G. Budynas

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# Computer-Controlled Systems

## Theory and Design

THIRD EDITION

Karl J. Åström

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**Advanced Strength and Applied Stress Analysis**

**(Second Edition)**

# 影印版序

我国高等学校工科专业大学生所学的力学基础知识是理论力学和(初等)材料力学(土木工程系还增加结构力学),这对毕业后从事应力分析和强度设计的工程师和研究人员来说是远远不够的。他们经常感到理论基础不够,需要在工作中自学许多固体力学专业的课程,例如弹性力学、有限元法、断裂力学、实验应力分析等,然而每门课程都有一本厚厚的教科书,而且往往使用较深的数学知识。许多科技工作者都希望读到一本能简明易懂地综合介绍与应力分析和强度设计密切相关的固体力学基础知识的教材。在国外也存在着类似的情况。本书正是为此目的而编写,它以大学本科生的力学和数学知识为基础,系统地讲述了从事应力分析和强度设计工作所必备的理论、实验和计算三方面的基础知识,概念清楚、叙述简明、内容丰富、选材恰当,每章后面附有供读者检验自己掌握程度的习题和答案,附录中还为读者补充了数学预备知识和便于查找的图表,是一本既可供讲授又适于自学的优秀教材和专业参考书。

书中首先系统介绍力、应力、应变、位移等基本概念,坐标转换关系和平衡、协调等基本方程,为读者掌握后面的高等专题打下坚实基础。然后沿理论、实验和计算三方面深入展开。理论方面篇幅最大,包括高等材料力学(薄壁管扭转,非对称梁,剪力中心,复合梁,曲梁,平板,厚壁筒及旋转圆盘,接触应力,应力集中等)、弹性力学(平面问题和柱形杆扭转问题)、能量法(卡氏第一、第二定理,余能定理,虚载荷法,瑞利-里兹法等)和强度设计基础(强度与安全系数,强度理论、断裂力学、疲劳分析、结构稳定性、非弹性响应、静不定问题的工程方法)四大部分。实验方面首先讲述实验模型设计的量纲分析原理,接着详细介绍了实验应力分析中应用最广泛的电阻应变片和光弹性(包括光弹性贴片)两种实验技术。计算方面作者用两章篇幅集中介绍工程计算中最有效的有限元法,前一章选择一维杆、梁单元和最典型的二维平面单元讲述有限元法的基本概念和基本方法,这是熟悉材料力学的读者最容易理解的讲授方式,后一章介绍更为实用的有限元模型化技术和商用有限元软件包的应用方法。本书重点放在静力强度设计,对动力强度设计(如结构抗震设计)感兴趣的读者需要参考其他教材和专著。

本书目的是指导读者实现从材料力学到固体力学必备基础知识的顺利过渡,可用作工程硕士研究生班教材,对于从事应力分析和强度设计的科技工作者、讲授高等材料力学和应力分析课程的教师以及高等工业院校的高年级学生和研究生,本书也是一本很好的参考书。

陆明万

清华大学工程力学系

*To my friend, my love, my companion, my wife, Joanne,*
*without whom this book and the first edition never would have been written.*

# PREFACE

## APPROACH

When dealing with a design or redesign problem the design engineer knows that the design must (1) function according to some prescribed requirements and (2) have an acceptable level of structural integrity. *Stress analysis* is that part of the design process which strives to ensure that each element of a given system will not fail to meet the structural requirements of the design throughout the specified life of the system. Stress analysis tools range from the countless theoretical techniques employed in elementary and advanced mechanics of materials and the mathematical theory of elasticity, to computer-based numerical procedures such as the finite element method and to the wide variety of available experimental techniques. Whole industries exist which are exclusively devoted to supplying experimental or numerical materials to the stress analysis community. This book was originally devoted to expand the theoretical, experimental, and numerical background of the reader beyond that covered in a first course in elementary mechanics of materials. This edition continues to adhere to this purpose where the author has attempted to improve the presentation of the practical topics of the first edition while infusing important additional subject matter and procedures.

Practical stress analysis problems range from problems which closely resemble simple models which have known closed-form solutions to complex problems which are not easily adaptable to the various classical techniques. For the complex problem, the analyst must either obtain an approximation from a theoretical analysis, seek a numerical solution, perform an experimental analysis, or carry out a combination of these approaches. In order to be versatile, the analyst should have a good working knowledge of the theoretical, numerical, and experimental procedures employed in the field of stress analysis. No single book could ever completely cover this wide range of concepts. However, this book covers the fundamental aspects of each area with a sufficient amount of depth at the mathematical level of a junior undergraduate to first-year graduate engineering student. References are cited throughout the book where, if desired, the reader can obtain additional information in a specific area.

## CONTENTS

Although it is assumed that the reader has completed a first course in elementary mechanics of materials, it cannot be assumed that the reader is comfortable exploring a more advanced book straightaway. The object of an advanced book is to build upon elementary concepts and processes that have been *mastered*. Many of the subjects in Chapters One and Three should be a review for the reader. However, many of the examples and problems in these chapters are designed to test the mastery of the subject material.

Chapter One provides the basic definitions and relationships between the fundamental state properties of force, stress, strain and displacement. Chapter Two extends the basic concepts by presenting the various three-dimensional stress and strain relationships which include transformations, equilibrium, and compatibility. Chapters Four and Five extend the elementary theoretical processes of Chapter Three to techniques from the mathematical theory of elasticity and advanced mechanics of materials, respectively. Topics in Chapter Five include single- and multiple-celled thin-walled tubes in torsion, bending of unsymmetrical beams, shear center, composite beams, curved beams, plates, thick-walled cylinders, contact stress, and stress concentrations. Chapter Six provides a very extensive presentation of energy methods pertaining to deflection analysis. Chapter Seven is devoted to strength theories and design methods which include the concept of strength; the design factor and uncertainty; strength theories for ductile and brittle materials; introductions to fracture mechanics, fatigue analysis, structural stability, and inelastic behavior; and engineering approximations used in statically indeterminate problems. Chapter Eight is devoted to experimental stress analysis which includes dimensional analysis, analysis techniques, strain gages and instrumentation, and transmission and reflection photoelastic techiniques. Finally, Chapters Nine and Ten provide an introduction to the numerical finite method and finite element modeling techniques used in practice.

The author has attempted to present a modern and concise development of the fundamental areas of stress analysis using consistent notation with well-defined coordinate systems. In addition, an ample and comprehensive collection of examples and exercise problems, equally in SI and U.S. customary units, are included.

## NEW TO THIS EDITION

Two changes in the sequence of material from that of the first edition have been incorporated in this edition. Based on reviewer input, (1) three-dimensional transformations, equilibrium equations, and compatibility were moved to the beginning of the book (Chapter Two) as a part of the fundamental subject material, and (2) the concepts from the theory of elasticity were also moved forward (Chapter Four) to provide an earlier insight to the more mathematical approach of the concepts and to provide some results which can be used with some of the topics of advanced mechanics of materials in Chapter Five. If using this book at the junior undergraduate level, the instructor may wish to postpone or selectively organize the coverage of the more mathematical rigor of the material provided in Chapters Two and Four.

The significant changes incorporated in this edition include

- A rearrangement of all the basic concepts including three-dimensional considerations to the beginning of the text in Chapters One and Two.
- A significant elevation in the degree of difficulty of some of the examples and problems in the review of elementary mechanics of materials covered in Chapter Three. The intent is to test the mastery of the prerequisite material.
- Addition of several classical problems in the theory of elasticity using the Airy stress function in polar coordinates (Chapter Four).
- Included in the significant changes in Chapter Five, *Topics from Advanced Strength of Materials,* are the additional topics: torsion of multiple cell thin-walled tubes, shear center for open unsymmetric and closed thin-walled beams, approximate and numerical calculation of the offset of the centroidal and neutral axes of curved beams, and contact stresses between curved surfaces. The section on the bending of unsymmetrical beams has been significantly clarified and expanded and the section on the bending of thin flat plates completely rewritten presenting many cases of rectangular and annular plates.
- Chapter Seven, *Strength Theories and Design Methods,* includes new sections on fracture mechanics and structural stability.
- Chapter Nine, *Introduction to the Finite Element Method,* has been completely rewritten with improved notation and *additional* topics such as the Rayleigh-Ritz formulation, the assembly partitioning process, skew supports, two- and three-dimensional transformations, distributed and thermal loading, hinges, the frame element in two- and three-dimensional space, load-stiffening and buckling of beams, and the two-dimensional isoparametric quadrilateral element.
- Chapter Ten, *Finite Element Modeling Techniques,* is a new chapter which provides insight into the application of commercial finite element software to static structural problems. Commercial finite element software has become quite commonplace in the engineering environment, yet there is very little literature, notwithstanding manufacturer's literature, which discloses actual modeling practices. Topics include: the planning and creation of the finite element model (preprocessing), element selection and mesh strategy, load application, constraints, preprocessing checks, processing, and postprocessing.
- A significant increase in the number of problems are included at the end of each chapter. In addition to the standard closed-form solutions, computer-oriented problems are also provided at the end of the problem sections of most chapters.

## SUPPLEMENT

An Instructor's Solutions Manual is available to adopters. It contains detailed solutions to all the end-of-chapter problems except most of the open-ended computer problems.

## ACKNOWLEDGMENTS

A great many of the changes included in this edition came about from the many suggestions made by readers over the years for which the author is most appreciative. A special thanks to Dr. David Lineback of Measurements Group, Inc., Raleigh, North Carolina, for his review and input on the treatment of strain gages and instrumentation given in Chapter Eight. The author is also thankful for the many helpful suggestions made by the following reviewers:

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Last, but not least, I lovingly dedicate this book to my wife, Joanne, for her continued understanding and support during the writing of this and the first edition.

*Richard G. Budynas*

# LIST OF SYMBOLS

| | |
|---|---|
| $A$ | area, area of cross section, light-wave vector amplitude, analyzer filter axis |
| $\bar{A}$ | area bounded by perimeter centerline of a thin-walled tube |
| $a$ | dimension, crack width, varying amplitude of a light-wave vector |
| $b$ | dimension, beam width |
| $b_e$ | equivalent width of a composite beam section |
| $C$ | material calibration constant for transmission photoelasticity |
| $C_1$ | correction factor for photoelastic coatings |
| $c$ | distance from the neutral axis to an outer beam fiber, speed of light, strain pulse speed |
| $D$ | flexural rigidity of a thin plate, diameter |
| $d$ | diameter |
| $d_x$, $d_y$, $d_z$ | directional numbers of a plane |
| $E$ | modulus of elasticity, voltage |
| $\mathbf{E}$ | modulus of elasticity scale factor |
| $e$ | eccentricity, distance from the centroidal axis to the neutral axis of a curved beam |
| $F$ | concentrated force |
| $\mathbf{F}$ | force scale factor |
| $F_e$ | equivalent concentrated force |
| $\bar{F}_x$, $\bar{F}_y$, $\bar{F}_z$ | body forces per unit volume |
| $f$ | material calibration constant for photoelastic coatings, finite element nodal force, coefficient of friction |
| $f_s$ | strength uncertainty factor |
| $f_\sigma$ | stress uncertainty factor |
| $G$ | shear modulus, Griffith energy release rate |
| $g$ | gravitational constant |
| $h$ | dimension, depth of beam |
| $h_p$ | depth of plastic region |
| $I$, $I_y$, $I_z$, $I_{yz}$ | second-area moments (area moments of inertia) of a cross section |
| $I_m$, $I_n$ | principal second-area moments (area moments of inertia) of a cross section |
| $I_1$, $I_2$, $I_3$ | stress invariants |
| $\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$ | unit vectors in the $x$, $y$, $z$ directions respectively |
| $J$ | polar second-area moment (polar moment of inertia) of a cross section |
| $J_e$ | equivalent polar second-area moment (polar moment of inertia) of a cross section |
| $K$ | column support factor |
| $K_f$ | fatigue stress concentration factor |
| $K_I$ | stress intensity factor |
| $K_{Ic}$ | critical stress intensity factor |
| $K_t$ | static stress concentration factor, strain gage transverse sensitivity factor |
| $k$ | spring constant, form correction factor for shear, stress optic coefficient |

| | |
|---|---|
| $L$ | length |
| $\mathbf{L}$ | length scale factor |
| $l, m, n$ | directional cosines |
| $l_g$ | strain gage length |
| $l_p$ | strain pulse length |
| $M$ | applied or reaction concentrated bending moment (couple) |
| $\mathbf{M}$ | moment scale factor |
| $M_P$ | limit (plastic) moment |
| $M_r, M_\theta$ | plate bending moments per unit length in polar coordinates |
| $M_x, M_y, M_{xy}$ | plate bending and twisting moments per unit length in rectangular coordinates |
| $M_Y$ | yield moment |
| $M_y, M_z$ | net internal bending moments about axes parallel to the $y$ and $z$ axes respectively |
| $m$ | mass, margin of safety |
| $m, n$ | axes of the principal second-area moments |
| $N$ | normal force, number of cycles, photoelastic isochromatic fringe order, shape functions |
| $N_\theta$ | photoelastic isochromatic fringe order at an angle of incidence $\theta$ |
| $n$ | design factor, index of refraction, angular speed (rpm) |
| $n_x, n_y, n_z$ | directional cosines |
| $P$ | concentrated force, polarizer filter axis |
| $\mathbf{P}$ | pressure scale factor |
| $P_{cr}$ | critical buckling load |
| $P_L$ | limit force |
| $p$ | pressure, press-fit interference pressure |
| $Q$ | first-area moment of a partial area of a beam section |
| $q$ | shear force per unit length, distributed load intensity, notch sensitivity factor |
| $R$ | reaction force, radius, crack resistance force, electrical resistance |
| $R_g$ | strain gage nominal resistance |
| $r$ | radius |
| $r, \theta, z$ | cylindrical coordinates |
| $r_c$ | the distance from the center of curvature to the centroidal axis of a curved beam |
| $r_g$ | radius of gyration |
| $r_n$ | the distance from the center of curvature to the neutral axis of a curved beam |
| $r_p^*$ | plastic zone radius |
| $S$ | elastic section modulus |
| $\bar{S}$ | perimeter length of the centerline of a closed thin-walled tube |
| $S_a$ | strain gage axial sensitivity |
| $S_E$ | endurance strength |
| $S_F$ | fatigue strength |
| $S_g$ | strain gage factor |
| $S_t$ | strain gage transverse sensitivity |
| $S_Y$ | yield strength |
| $S_U$ | ultimate strength |
| $s$ | position, curvilinear coordinate |

| | |
|---|---|
| $SF$ | beam shape factor |
| $T$ | torsional moment (couple), temperature |
| $t$ | thickness, time |
| $t_p$ | pulse time |
| $t_x$, $t_y$, $t_z$ | directional cosines of the net shear stress on an isolated surface |
| $U$ | strain energy |
| $u$ | strain energy per unit volume |
| $u$, $v$, $w$ | displacements in the $x$, $y$, $z$ directions respectively |
| $u_r$, $u_\theta$, $u_z$ | displacements in the $r$, $\theta$, $z$ directions respectively |
| $V$ | net internal shear force, input voltage |
| $V_r$ | plate shear force per unit length in polar coordinates |
| $V_x$, $V_y$ | plate shear forces per unit length in rectangular coordinates |
| $V_y$, $V_z$ | beam shear forces in rectangular coordinates |
| $v_c$ | displacement of beam centroidal axis |
| $W$ | weight, work |
| $W_c$ | complementary work |
| $W_p$ | work potential |
| $w$ | force per unit length, work per unit volume, width, weighting factor |
| $x$, $y$, $z$ | rectangular coordinates |
| $Z$ | inelastic section modulus |

**Greek**

| | |
|---|---|
| $\alpha$ | angle, coefficient of thermal expansion, angular location of the neutral plane for unsymmetrical bending relative to the $m$ axis |
| $\beta$ | angle, angular location of the neutral plane for unsymmetrical bending relative to the $y$ axis |
| $\Delta$ | change, shift in phase of light waves |
| $\delta$ | deflection, press-fit radial interference |
| $\boldsymbol{\delta}$ | deflection scale factor |
| $\delta_{ij}$ | Kronecker delta |
| $\varepsilon$ | normal strain |
| $\boldsymbol{\varepsilon}$ | strain scale factor |
| $\varepsilon_a$ | axial strain |
| $\varepsilon_t$ | transverse strain |
| $\gamma$ | shear strain, weight density, temperature coefficient of resistivity |
| $\Theta$ | angular deflection |
| $\theta$ | angle, angular deflection |
| $\theta'$ | angular deflection per unit length |
| $\lambda$ | wavelength, Lamè constant |
| $\mu$ | Lamè constant |
| $\nu$ | Poisson's ratio |
| $\xi$, $\eta$ | natural coordinates |
| $\Pi$ | potential energy |
| $\rho$ | radius of curvature, mass density, resistivity |
| $\rho'$ | Neuber constant |
| $\sigma$ | normal stress |
| $\sigma_a$, $\sigma_m$ | alternating and mean stresses in fatigue applications |
| $\boldsymbol{\sigma}$ | stress scale factor |
| $\sigma_1$, $\sigma_2$, $\sigma_3$ | principal stresses |

| | |
|---|---|
| $\sigma_{cr}$ | critical buckling stress |
| $\sigma_{vM}$ | equivalent von Mises stress |
| $\tau$ | shear stress |
| $\tau_{Tresca}$ | equivalent Tresca shear stress |
| $\Phi$ | Airy stress function, complementary strain energy |
| $\Psi$ | Prandtl's stress function |
| $\phi$ | angle, helix angle of twist |
| $\omega$ | angular speed (rad/s) |

**Mathematical**

| | |
|---|---|
| $\nabla^2$ | Laplacian operator |
| $[\mathbf{J}]$ | Jacobian matrix |
| $[\mathbf{T}]$ | Transformation matrix |

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