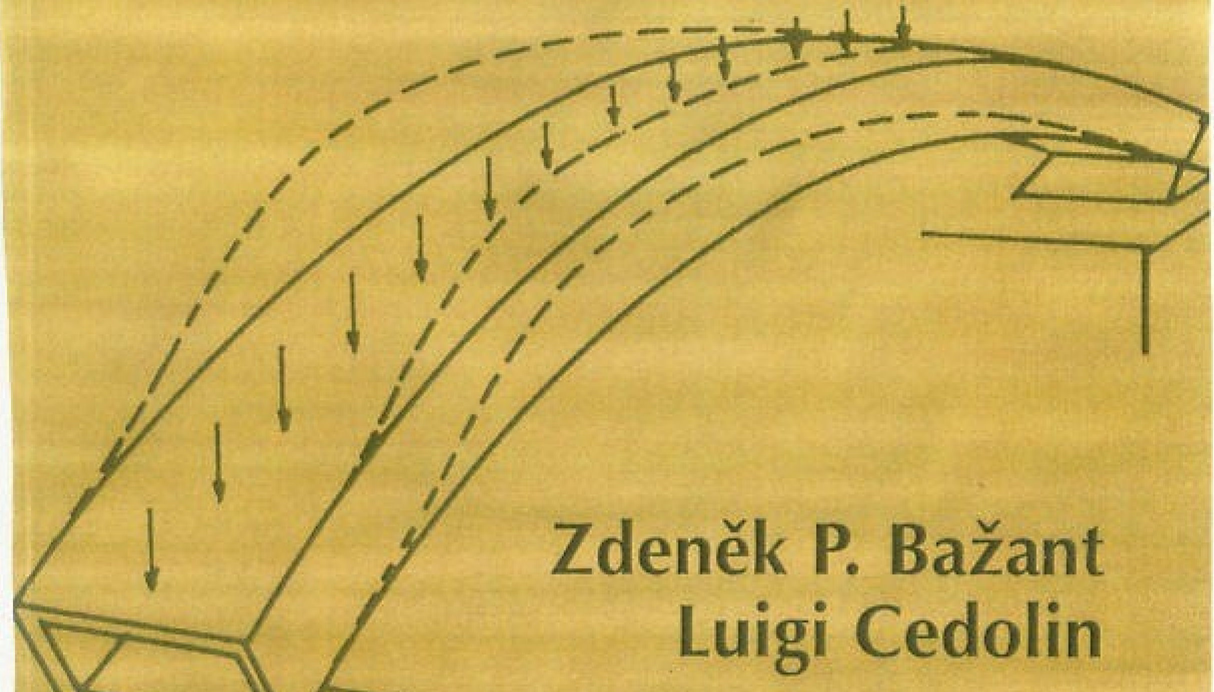
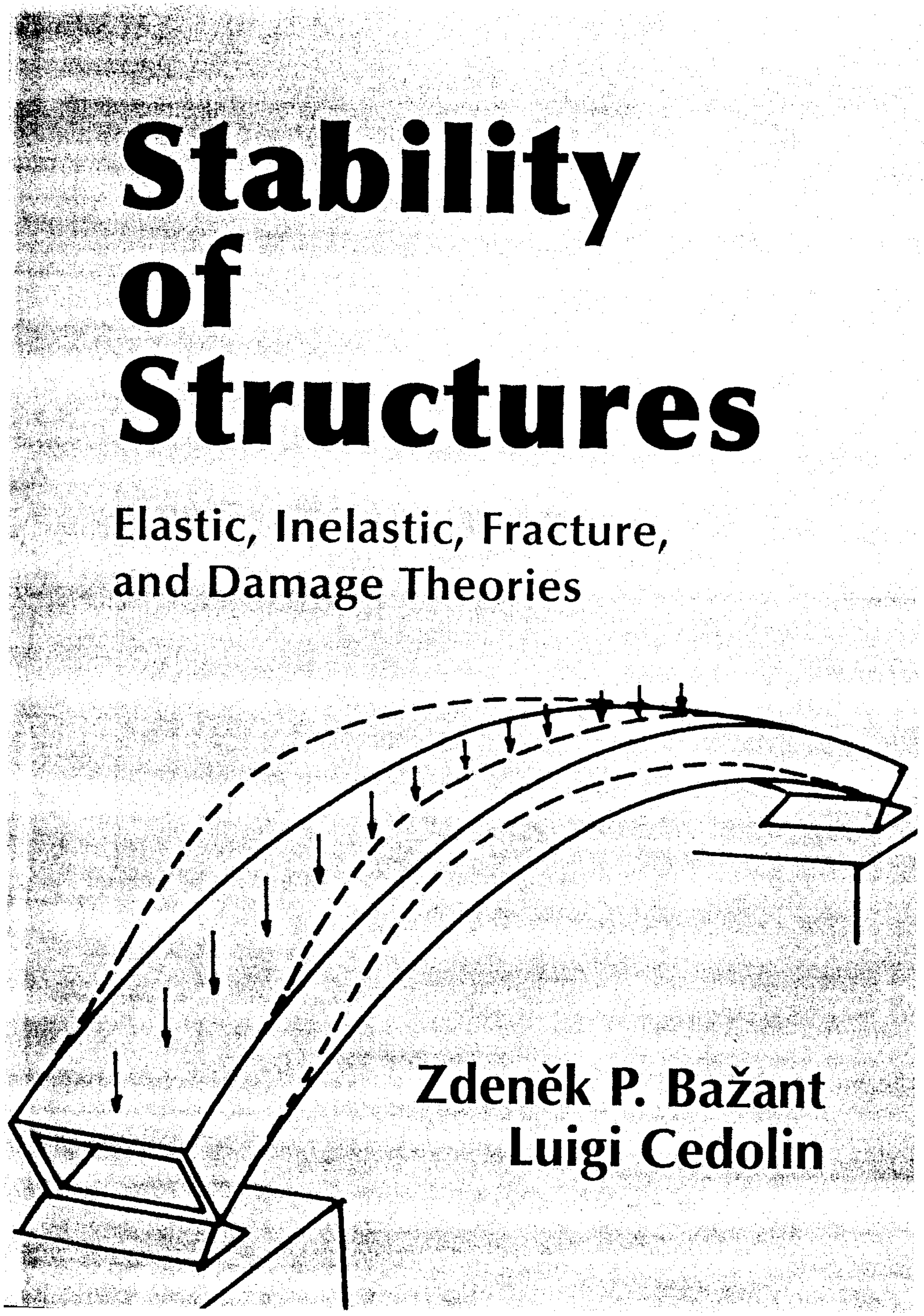
Stability of Structures

Elastic, Inelastic, Fracture, and Damage Theories



Zdeněk P. Bažant
Luigi Cedolin



STABILITY OF STRUCTURES

Elastic, Inelastic, Fracture, and Damage Theories

Zdeněk P. Bažant
Walter P. Murphy Professor of Civil Engineering
Northwestern University
Evanston, Illinois, USA

and

Luigi Cedolin
Professor of Structural Engineering
Politecnico di Milano
Milano, Italy

DOVER PUBLICATIONS, INC.
Mineola, New York

Preface

It is our hope that this book will serve both as a textbook for graduate courses on stability of structures and a reference volume for engineers and scientists. We assume the student has a background in mathematics and mechanics only at the level of the B.S. degree in civil or mechanical engineering, though in the last four chapters we assume a more advanced background. We cover subjects relevant to civil, structural, mechanical, aerospace, and nuclear engineering, as well as materials science, although in the first half of the book we place somewhat more emphasis on the civil engineering applications than on others. We include many original derivations as well as some new research results not yet published in periodicals.

Our desire is to achieve understanding rather than just knowledge. We try to proceed in each problem from special to general, from simple to complex, treating each subject as concisely as we can and at the lowest possible level of mathematical apparatus we know, but not so low as to sacrifice efficiency of presentation. We include a large number (almost 700) of exercise problems. Solving many of them is, in our experience, essential for the student to master the subject.

In some curricula, the teaching of stability is fragmented into courses on structural mechanics, design of steel structures, design of concrete structures, structural dynamics, plates and shells, finite elements, plasticity, viscoelasticity, and continuum mechanics. Stability theory, however, stands at the heart of structural and continuum mechanics. Whoever understands it understands mechanics. The methods of stability analysis in various applications are similar, resting on the same principles. A fundamental understanding of these principles, which is not easy to acquire, is likely to be sacrificed when stability is taught by bits, in various courses. Therefore, in our opinion, it is preferable to teach stability in a single course, which should represent the core of the mechanics program in civil, mechanical, and aerospace engineering.

Existing textbooks of structural stability, except for touching on elastoplastic columns, deal almost exclusively with elastic stability. The modern stability problems of fracture and damage, as well as the thermodynamic principles of stability of irreversible systems, have not been covered in textbooks. Even the catastrophe theory, as general is it purports to be, has been limited to systems that possess a potential, which implies elastic behavior. Reflecting recent research results, we depart from tradition, devoting about half of the book to nonelastic stability.

Various kinds of graduate courses can be fashioned from this book. The first-year quarter-length course for structural engineering students may, for example, consist of Sections 1.2–1.7, 2.1–2.4, 2.8, 3.1, 3.2, 3.5, 3.6, 4.2–4.6,

5.1–5.4, 6.1–6.3, 7.1–7.3, 7.5, 7.8, 8.1, 8.3, and 8.4, although about one-third of these sections can be covered in one quarter only partly. A semester-length course can cover them fully and may be expanded by Sections 1.8, 1.9, 2.7, 3.3, 4.5, 4.6, 5.5, 7.4, 7.8, 8.2, and 8.6. The first-year course for mechanical and aerospace engineers may, for example, be composed of Sections 1.1–1.5, 1.7, 1.9, 2.1–2.3, 3.1–3.7, 4.2–4.6, 5.1–5.4, 6.1–6.3, 7.1–7.3, 7.5, 7.8, 8.1–8.3, and 9.1–9.3, again with some sections covered only partly. A second-year sequel for structural engineering students, dealing with inelastic structural stability, can, for example, consist of Sections 8.1–8.6, 9.1–9.6, 10.1–10.4, 13.2–13.4, and 13.6, preceded as necessary by a review of some highlights from the first course. Another possible second-year sequel, suitable for students in theoretical and applied mechanics, is a course on material modeling and stability, which can be set up from Sections 11.1–11.7, 10.1–10.6, 13.1–13.4, 13.8–13.10, and 12.1–12.5 supplemented by a detailed explanation of a few of the constitutive models mentioned in Section 13.11. A course on Stability of Thin-Wall Structures (including plates and shells) can consist of a review of Sections 1.1–1.8 and detailed presentation of Chapters 6 and 7. A course on Inelastic Columns can be based on a review of Sections 1.1–1.8 and detailed presentation of Chapters 8 and 9. A course on Stability of Multidimensional Structures can be based on a review of Sections 1.1–1.9 and detailed presentation of Chapters 7 and 11. A course on Energy Approach to Structural Stability can be based on a review of Sections 1.1–1.8 and detailed presentation of Chapters 4, 5, and 10. A course on Buckling of Frames can be based on Chapters 1, 2, and 3. Chapter 3, along with Section 8.6, can serve as the basis for a large part of a course on Dynamic Stability.

The present book grew out of lecture notes for a course on stability of structures that Professor Bažant has been teaching at Northwestern University every year since 1969. An initial version of these notes was completed during Bažant's Guggenheim fellowship in 1978, spent partly at Stanford and Caltech. Most of the final version of the book was written during Professor Cedolin's visiting appointment at Northwestern between 1986 and 1988, when he enriched the text with his experience from teaching a course on structural analysis at Politecnico di Milano. Most of the last six chapters are based on Bažant's lecture notes for second-year graduate courses on inelastic structural stability, on material modeling principles, and on fracture of concrete, rock, and ceramics. Various drafts of the last chapters were finalized in connection with Bažant's stay as NATO Senior Guest Scientist at the Ecole Normale Supérieure, Cachan, France, and various sections of the book were initially presented by Bažant during specialized intensive courses and guest seminars at the Royal Institute of Technology (Cement och Betonginstitutet, CBI), Stockholm; Ecole des Ponts et Chaussées, Paris; Politecnico di Milano; University of Cape Town; University of Adelaide; University of Tokyo; and Swiss Federal Institute of Technology. Thanks go to Northwestern University and the Politecnico di Milano for providing environments conducive to scholarly pursuits. Professor Bažant had the good fortune to receive financial support from the U.S. National Science Foundation and the Air Force Office of Scientific Research, through grants to Northwestern University; this funding supported research on which the last six chapters are partly based. Professor Bažant wishes to express his thanks to his father, Zdeněk J. Bažant, Professor Emeritus of Foundation Engineering at the

Czech Technical University (ČVUT) in Prague and to his grandfather, Zdeněk Bažant, late Professor of Structural Mechanics at ČVUT, for having introduced him to certain stability problems of structural and geotechnical engineering.

We are indebted for many detailed and very useful comments to Leone Corradi and Giulio Maier, and for further useful comments to several colleagues who read parts of the text: Professors J. P. Cordebois, S. Dei Poli, Eduardo Dvorkin, Theodore V. Galambos, Richard Kohoutek, Franco Mola, Brian Moran, and Jaime Planas. Finally, we extend our thanks to M. Tabbara, R. Gettu, and M. T. Kazemi, graduate research assistants at Northwestern University, for checking some parts of the manuscript and giving various useful comments, to Vera Fisher for her expert typing of the manuscript, and to Giuseppe Martinelli for his impeccable drawings.

Evanston, Ill. Z. P. B. and L. C.
October, 1989

Contents

II INELASTIC, DAMAGE, AND FRACTURE THEORIES

Appendix to the Dover Edition

During the eleven years that have elapsed since the first edition of this book by Oxford University Press in 1991, we have collected a number of corrections and updates which we have hoped to implement in the second edition. Unfortunately, the first edition of this book by Oxford University Press in 1991 was produced by mechanical type-setting. In view of the subsequent universal switch to computerized book production, any corrections within the text have now become very difficult and prohibitively expensive.

Therefore, the present second edition of this book, produced by Dover, involves no corrections at all within the original text. The original text is reproduced exactly, and not even single-letter misprints are corrected. Instead, all the necessary corrections, as well as most of the pedagogically motivated updates and clarifications, are assembled in this Appendix. They are grouped in four sections, labeled as A, B, C and D.

Section A. These are *essential errata* which are not readily obvious and, if not corrected, could be misleading.

Section B. These are *minor errata*, which are almost obvious, can be readily guessed by thoughtful readers, and are not misleading. Their correction is nevertheless necessary for precise writing.

Section C. These are *minor updates* helpful to students, which provide brief observations or small improvements that enhance understanding but are not necessary for correctness.

Section D. These are *significant updates* providing further clarifications or better explanations, most of which are of pedagogical nature and result from our experience in using this book in teaching.

Since 1990, the year of completion of the original manuscript, many important research results have been contributed to the vast field of structural stability. This is particularly true for chapters 12 and 13. Despite this fact, any systematic coverage of these new results had to be ruled out. It would make this treatise much longer, yet it is already voluminous enough. Among extensive recent literature, we nevertheless wish to call attention to the excellent book by J. Singer, J. Arbocz, and T. Weller (*Buckling experiments*, J. Wiley, New York 1998), and to the perspicacious review by J.R. Rice (Rice, J.R.,1993, "Mechanics of solids". *Encyclopedia Britanica*, 15th ed., Vol.23, 737–747 and 773) characterized by an admirable combination of insight and brevity. Furthermore, a recent review article by Bažant in

ZAMM (Vol. 80, 2000, pp. 709–732, Prandtl's anniversary issue) can be regarded as a summary of the highlights of this book.

In the following listing of misprints, corrections and didactic clarifications, the locations of the required or recommended replacements are indicated by the page number followed by either a superscript, denoting the line number counted from the top, or a subscript, denoting the line number counted from the bottom of page. Alternatively, the page number is followed by an equation number or figure number in parentheses. In counting the lines from the top or bottom of the page, the figure captions and headings are included but the lines in separate equations are excluded (whether numbered or not).

A. Essential Errata

Location	As printed	Correction
5^{18}	midspan	quarterspan
22^{19}	P/e_1	Pe_1
22^{19}	P/e_2	Pe_2
28(1.6.5)	$M_{max} = ...C_2^2)$	$M_{max} = \sqrt{C_1^2 + C_2^2}$ if $C_1/C_2 <$ tankl, otherwise $M_{max} = M_2$
28(1.6.6)	$C_m = ...C_2^2)$	$C_m = (1 - \frac{P}{P_{cr_1}})\frac{M_{max}}{M_2}$
35(1.7.11)	$+E'_f I_f$	$+2E'_f I_f$
55(2.1.3)	$A(\cos\lambda - 1)$	$A\lambda(\cos\lambda - 1)$
65_{16}	$0.744P_E$	$0.748P_E$
114(2.8.10)	$M' - ..pR^2\theta = 0$	$M' + RV + pR^2\theta = 0$
146(3.1.9)	$A_n e^{-\lambda_n t}$	$A_n e^{\lambda_n t}$
167^6	$\frac{1}{2}w'^2$	$1 + \frac{1}{2}w'^2$
176(3.5.9)	$\leq \delta$	$\leq \delta^2$
176(3.5.9)	$< \epsilon$	$< \epsilon^2$
182(3.6.4)	$\frac{\partial\Psi}{\partial v_k} v_k$	$\frac{\partial\Psi}{\partial v_k} \dot{v}_k$
209(unnumbered equation)	for all δq_i	for some vector $\delta\mathbf{q}$
209(4.2.6)	for all i	(all i) for some vector $\delta\mathbf{q}$
210^3	potential energy	strain energy
210(4.2.7)	$\delta\Pi = 0$ .... all i	for some vector $\mathbf{q}$: $\frac{\partial\Pi}{\partial q_i} = 0$ (all i) or $\sum_i \frac{\partial\Pi}{\partial q_i}\bar{q}_i = 0$ (all vectors $\bar{\mathbf{q}}$)or $\delta\Pi = 0$ (all vectors $\bar{\mathbf{q}}$)
228(4.4.1)	$EAL/\cos q$	$EAL/\cos\alpha$