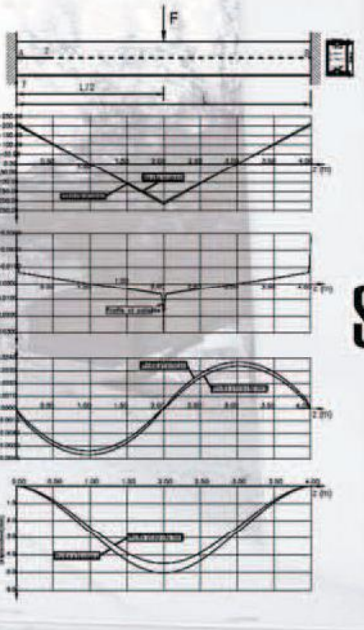
Seismic Design Aids for Nonlinear Analysis of Reinforced Concrete Structures



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Contents

Series Preface

The Advances in Earthquake Engineering series is intended primarily for the transformation of frontier technologies and research results, as well as state-of-the-art professional practices in earthquake engineering. It will encompass various topical areas such as multidisciplinary earthquake engineering, smart structures and materials, optimal design and lifecycle cost, geotechnical engineering and soil–structure interaction, structural and system health monitoring, urban earthquake disaster mitigation, postearthquake rehabilitation and reconstruction, innovative numerical methods, as well as laboratory and field testing.

This book, *Seismic Design Aids for Nonlinear Analysis of Reinforced Concrete Structures*, serves one of the aforementioned objectives. It provides nonlinear properties of reinforced concrete elements in a comprehensive form so that practicing engineers and researchers can use them readily without solving complex equations. With the step-by-step numerical procedures presented in the book, and also through supplemental electronic material found at http://www.crcpress.com/e_products/downloads/download.asp?cat_no=K10453, the reader will find the publication a very useful and practical handbook. The book is to serve not only as a reference for graduate students in civil, structural, and construction engineering, but also as a good research directory for academicians.

Franklin Y. Cheng, PhD, PE, ASCE Distinguished Member

Editor, Advances in Earthquake Engineering Series

Series Editor

Franklin Y. Cheng, PE, honorary member of ASCE, joined the University of Missouri-Rolla as an assistant professor in 1966. In 1987, the Board of Curators of the University appointed him curators' professor; he was honored as curators' professor emeritus in 2000. He is a former senior investigator, Intelligent Systems Center, University of Missouri-Rolla. Dr. Cheng received 4 honorary professorships abroad and chaired 7 of his 24 National Science Foundation (NSF) delegations to various countries for research and development cooperation. He has also been the director of international earthquake engineering symposia and numerous state-of-the-art short courses. His work has warranted grants from several funding agencies including more than 30 from NSF. He has served as either chairman or member of 37 professional societies and committees, 12 of which are ASCE groups. He was the first chair of the Technical Administrative Committee on Analysis and Computation and initiated the Emerging Computing Technology Committee and Structural Control Committee. He also initiated and chaired the Stability Under Seismic Loading Task Group of the Structural Research Council (SSRC).

Dr. Cheng has served as a consultant for Martin Marietta Energy Systems, Inc., Los Alamos National Laboratory, and Martin & Huang International, among others. The author, coauthor, or editor of 26 books and over 250 publications, Dr. Cheng's authorship includes two textbooks, *Matrix Analysis of Structural Dynamics: Applications and Earthquake Engineering,* and *Dynamic Structural Analysis.* Dr. Cheng is the recipient of numerous honors, including the MSM-UMR Alumni Merit, ASCE State-of-the-Art twice, the Faculty Excellence, and the Halliburton Excellence awards. After receiving a BS degree (1960) from the National Cheng-Kung University, Taiwan, and a MS degree (1962) from the University of Illinois at Urbana-Champaign, he gained industrial experience with C.F. Murphy and Sargent & Lundy in Chicago, Illinois. Dr. Cheng received a PhD degree (1966) in civil engineering from the University of Wisconsin-Madison.

Preface

Seismic Design Aids for Nonlinear Analysis of Reinforced Concrete Structures (with examples and computer coding) is an attempt toward clarifying and simplifying the complexities involved in estimating some basic input parameters required for such analyses. The necessity of safe seismic design of structures is becoming a big concern for the engineering community due to the increase in damage of buildings during recent earthquakes. Most existing buildings do not comply with the current seismic codes; therefore, it is necessary to assess their structural safety and to have clear answers to questions that raise doubts about their structural safety. For most of these buildings it is necessary to prevent structural failure, although the occurrence of limited damages is usually accepted. As a matter of fact, nonlinear structural analysis has been a fundamental tool for the past 30 years, but not one widely addressed in university courses and hence not currently employed by structural engineers comfortably. On the other hand, spreading of efficient and complete computer codes of structural analysis drives them toward a passive attitude that usually opposes the full verification of the design process. While nonlinear analysis methods like static pushover are commonly accepted and recommended as a reliable tool by international codes for seismic assessment of buildings, accuracy of the estimate of seismic capacity strongly depends on input parameters of such analysis. Some of the basic inputs, namely, (1) axial force–bending moment yield interaction, (2) moment-curvature, and (3) moment-rotation characteristics accounting for appropriate nonlinearity of constitutive materials of reinforced concrete elements, need to be readdressed for an accurate pushover analysis. The design curves and tables proposed in the book are the outcome of the studies conducted by the authors using a variety of nonlinear tools, computer programs, and software. During the course of teaching, researching, and short-term courses conducted on the subject, it is felt that an appropriate use of nonlinear properties of constitutive materials is not common among design engineers using software tools. They tend to use default properties of materials as input to nonlinear analyses without realizing that a minor variation in the nonlinear characteristics of the constitutive materials like concrete and steel could result in an unsatisfactory solution leading to wrong assessment and interpretation. The main reason for such ignorance can be due to complexities involved in deriving the material properties of reinforced concrete that constitute the basic input of the nonlinear analyses.

Seismic Design Aids spans five chapters on the topics (1) axial force–bending moment yield interaction (P-M), (2) bending moment-curvature relationship (M-ϕ), (3) bending moment-rotation characteristics (M-ϑ) for beams with different support conditions and loading cases, (4) collapse multiplier of seismic loads for regular framed structures using plastic theorems, both upper bound and lower bound limit analysis theorems, and (5) verification of plastic flow rule for the developed P-M interaction domains. A detailed mathematical modeling of P-M interaction of RC rectangular beams based on international codes, namely, Italian code, Indian code, and Eurocode, currently in prevalence by defining the boundaries of the subdomains and set of analytical expressions is proposed in the first chapter. Moment-curvature relationships for beams (with no axial force) and for columns (with different levels of axial forces) are presented in Chapter 2. In Chapter 3, some practical cases of beams with relevant support conditions and loading conditions are selected for which the collapse mechanism and plastic hinge extension are presented with complete analytical expressions for moment-rotation and ductility ratios. Chapter 4 deals with determination of collapse load multipliers using plastic theorems for a few selected examples that are common cases of frames with a weak-beam, strong-column type. The developed analytical modeling of P-M interaction is verified for plastic flow rule in Chapter 5. Though the material characteristics used in *Seismic Design Aids* are limited to a few international codes, readers can easily derive the required expressions in accordance to any other international code of their choice. This is made possible by presenting the step-by-step derivation of the expressions in the relevant chapters; simply by replacing a few equations addressing the material characteristics, one can readily arrive at the desired expressions. However, using the same algorithm, the authors are certain that design engineers and researchers can easily derive other cases not addressed in this book.

We also present a step-by-step procedure to carry out pushover analysis of an example frame using the proposed design curves and tables as input parameters. Two very simple relationships are proposed for upper and lower bounds of the seismic load multiplier for regular frames of the weak-beam, strong-column type. The forecasts, shown by means of their graphical representations, qualify an optimal agreement with the relevant values obtained by pushover analysis for all the regular framed structures analyzed. Knowledge of the foreseen static multipliers, also based on an easy analytical approach, is useful both for seismic assessment and design, since the structure will be safe, by definition, under the seismic loads amplified with static *lower bounds*. The computer codes used for nonlinear optimization of collapse multiplier using static theorem and for determining kinematic multipliers are given in the additional material found on the Web site; using the program, one can easily modify the input to determine the multipliers for other cases that are not addressed in *Seismic Design Aids*. The kinematic and static multipliers for collapse loads of frames are then compared with the results obtained using the nonlinear static pushover method to show the level of confidence in the results obtained using limit analysis.

Each chapter commences with a relevant brief literature review followed by a description of the detailed mathematical modeling. Using material characteristics of concrete and steel as proposed by the codes, analytical expressions are derived, based on classical theory of nonlinear mechanics. The developed equations are followed by treatment of structural components of building frames as example problems. Tables and design curves are proposed for appropriate combinations of cross-section dimensions of beams and columns with relevant sets of percentage of tensile and compression reinforcements commonly used in design offices. *Seismic Design Aids* can be useful for capacity assessment of reinforced concrete (RC) elements whose cross-sections are known and also for performing nonlinear analysis of RC structures using readily available computer programs. Design curves are given