FUNDAMENTALS OF EARTHQUAKE ENGINEERING

Fundamentals of Earthquake Engineering Amr S. Elnashai and Luigi Di Sarno
© 2008 John Wiley & Sons, Ltd. ISBN: 978-0-470-02483-6

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WILEY
A John Wiley & Sons, Ltd, Publication

This edition first published 2008

Registered office

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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Library of Congress Cataloging-in-Publication Data
Elnashai, Amr S.
Fundamentals of earthquake engineering / Amr S. Elnashai and Luigi Di Sarno.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-02483-6 (Hbk) 1. Earthquake engineering. I. Di Sarno, Luigi. II. Title.
TA654.6.E485 2008
624.1'762–dc22

2008033265

ISBN: 978-0-470-02483-6 (Hbk)

A catalogue record for this book is available from the British Library.

Set in 9 on 11pt Times by SNP Best-set Typesetter Ltd., Hong Kong
Printed in England by Antony Rowe Ltd, Chippenham, Wilts.

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About the Authors

Professor Amr Elnashai

Professor Amr Elnashai is Bill and Elaine Hall Endowed Professor at the Civil and Environmental Engineering Department, University of Illinois at Urbana-Champaign. He is Director of the National Science Foundation (NSF) multi-institution multi-disciplinary Mid-America Earthquake Center. He is also Director of the NSF Network for Earthquake Engineering Simulation (NEES) Facility at Illinois. Amr obtained his MSc and PhD from Imperial College, University of London, UK. Before joining the University of Illinois in June 2001, Amr was Professor and Head of Section at Imperial College. He has been Visiting Professor at the University of Surrey since 1997. Other visiting appointments include the University of Tokyo, the University of Southern California and the European School for Advanced Studies in Reduction of Seismic Risk, Italy, where he serves on the Board of Directors since its founding in 2000. Amr is a Fellow of the Royal Academy of Engineering in the United Kingdom (UK-equivalent of the NAE), Fellow of the American Society of Civil Engineers and the UK Institution of Structural Engineers.

He is founder and co-editor of the *Journal of Earthquake Engineering*, editorial board member of several other journals, a member of the drafting panel of the European design code, and past senior Vice-President of the European Association of Earthquake Engineering. He is the winner of the Imperial College Unwin Prize for the best PhD thesis in Civil and Mechanical Engineering (1984), the Oscar Faber Medal for best paper in the Institution of Structural Engineering, and two best paper medals from the International Association of Tall Buildings, Los Angeles. He is the administrative and technical team builder and director of both the MAE Center and NEES@UIUC Simulation Laboratory, at Illinois.

Amr is President of the Asia-Pacific Network of Centers of Earthquake Engineering Research (ANCER), a member of the FIB Seismic Design Commission Working Groups and two Applied Technology Council (ATC, USA) technical committees. He founded the Japan–UK Seismic Risk Forum in 1995 and served as its director until 2004. He leads a FEMA project for impact assessment for the eight central US states, was advisor to the UK Department of the Environment, advisor to the Civil Defense Agency of Italy, and review panel member for the Italian Ministry of Research and the New Zealand and Canadian Science Research Councils.

Amr's technical interests are multi-resolution distributed analytical simulations, network analysis, large-scale hybrid testing, and field investigations of the response of complex networks and structures to extreme loads, on which he has more than 250 research publications, including over 110 refereed journal papers, many conference, keynote and prestige lectures (including the Nathan Newmark Distinguished Lecture), research reports, books and book chapters, magazine articles, and field investigation reports. Amr has successfully supervised 29 PhD and over 100 Masters Theses. Many of his students hold significant positions in industry, academia and government in over 12 countries. He has a well-funded research group, with a large portfolio of projects from private industry, state agencies, federal agencies, and international government and private entities. Amr taught many different subjects both at Illinois and at Imperial College. He is recognized as an effective teacher and has been on the ‘incomplete list of teachers considered excellent by their students’ twice at UIUC.

He has contributed to major projects for a number of international companies and other agencies such as the World Bank, GlaxoWellcome (currently GSK), Shell International, AstraZeneca, Minorco, British Nuclear Fuels, UK Nuclear Installations Inspectorate, Mott MacDonald, BAA, Alstom Power, the Greek, Indonesian and Turkish Governments, and the National Geographic Society. He is currently working on large projects for the Federal Emergency Management Agency (FEMA), State Emergency Management Agencies, Istanbul Municipality, US AID, Governments of Pakistan and Indonesia, among others. Amr enjoys scuba-diving and holds several certificates from the British Sub-Aqua Club and the US Professional Association of Diving Instructors. He also enjoys reading on history, the history of painting and film-making.

Dr Luigi Di Sarno

Dr. Luigi Di Sarno is Assistant Professor in Earthquake Engineering at the University of Sannio (Benevento), and holds the position of Research Associate at the Department of Structural Engineering (DIST), University of Naples, Federico II in Italy. He graduated cum laude in Structural Engineering from the University of Naples, Federico II. He then obtained two MSc degrees in Earthquake Engineering and Structural Steel Design from Imperial College, London. In 2001 Dr. Di Sarno obtained his PhD from University of Salerno in Italy and moved to the University of Illinois at Urbana Champaign in 2002 where he worked as a Post-doctoral Research Associate. He has been Visiting Professor at the Mid-America Earthquake Center at Illinois since 2004. His research interests are seismic analysis and design of steel, reinforced concrete and composite structures, and the response of tall buildings to extreme loads, on which he has written more than 60 research publications, including over 15 refereed journal papers, many conference papers, research reports, book chapters and field investigation reports. Dr. Di Sarno continues to work with the active research group at the University of Naples, with a large portfolio of projects from private industry, state agencies, and international government and private entities. He taught several courses at Naples, Benevento and the Mid-America Earthquake Center. He is currently working on large projects funded by the Italian State Emergency Management Agency (DPC) and the Italian Ministry of Education and Research, amongst others. Dr. Di Sarno enjoys reading on history, science and art. He also enjoys playing tennis and swimming.

Foreword

Congratulations to both authors! A new approach for instruction in Earthquake Engineering has been developed. This package provides a new and powerful technique for teaching – it incorporates a book, worked problems and comprehensive instructional slides available on the web site. It has undergone numerous prior trials at the graduate level as the text was being refined.

The book, in impeccable English, along with the virtual material, is something to behold. 'Intense' is my short description of this book and accompanying material, crafted for careful study by the student, so much so that the instructor is going to have to be reasonably up-to-date in the field in order to use it comfortably. The writer would have loved to have had a book like this when he was teaching Earthquake Engineering.

The text has four main chapters and two appendices. The four main chapters centre on (a) Earthquake Characteristics, (b) Response of Structures, (c) Earthquake Input Motions and (d) Response Evaluation, with two valuable appendices dealing with Structural Configurations and Systems for Effective Earthquake Resistance, and Damage to Structures. The presentation, based on stiffness, strength and ductility concepts, comprises a new and powerful way of visualizing many aspects of the inelastic behaviour that occurs in structures subjected to earthquake excitation.

The book is written so as to be appropriate for international use and sale. The text is supplemented by numerous references, enabling the instructor to pick and choose sections of interest, and to point thereafter to sources of additional information. It is not burdened by massive reference to current codes and standards in the world. Unlike most other texts in the field, after studying this book, the students should be in a position to enter practice and adapt their newly acquired education to the use of regional seismic codes and guidelines with ease, as well as topics not covered in codes. Equally importantly, students who study this book will understand the bases for the design provisions.

Finally, this work has application not only in instruction, but also in research. Again, the authors are to be congratulated on developing a valuable work of broad usefulness in the field of earthquake engineering.

William J. Hall
Professor Emeritus of Civil Engineering
University of Illinois at Urbana-Champaign

Preface and Acknowledgements

This book forms one part of a complete system for university teaching and learning the fundamentals of earthquake engineering at the graduate level. The other components are the slide sets, the solved examples, including the comprehensive project, and a free copy of the computer program Zeus-NL, which are available on the book web site. The book is cast in a framework with three key components, namely (i) earthquake causes and effects are traced from Source to Society; (ii) structural response under earthquake motion is characterized primarily by the varying and inter-related values of stiffness, strength and ductility; and (iii) all structural response characteristics are presented on the material, section, member, sub-assemblage and structural system levels. The four chapters of the book cover an overview of earthquake causes and effects, structural response characteristics, features and representations of strong ground motion, and modelling and analysis of structural systems, including design and assessment response quantities. The slide sets follow closely the contents of the book, while being a succinct summary of the main issues addressed in the text. The slide sets are intended for use by professors in the lecture room, and should be made available to the students only at the end of each chapter. They are designed to be also a capping revision tool for students. The solved examples are comprehensive and address all the important and intricate sub-topics treated in the four chapters of the book. The comprehensive project is used to provide an integration framework for the various components of the earthquake source, path, site, and structural features that affect the actions and deformations required for seismic design. The three teaching and learning components of (i) the book, (ii) the slide sets and (iii) the solved examples are inseparable. Their use in unison has been tested and proven in a top-tier university teaching environment for a number of years.

We have written this book whilst attending to our day jobs. We have not taken a summer off, or gone on sabbatical leave. It has therefore been difficult to extract ourselves from the immediate and more pressing priorities of ongoing academic and personal responsibilities. That authoring the book took four years has been somewhat frustrating. The extended period has however resulted in an improved text through the feedback of end-users, mainly graduate students of exceptional talent at the University of Illinois. Our first thanks therefore go to our students who endured the experimental material they were subjected to and who provided absolutely essential feedback. We are also grateful for a number of world-class researchers and teachers who voluntarily reviewed the book and provided some heartwarming praise alongside some scathing criticism. These are, in alphabetical order, Nicholas Ambraseys, Emeritus Professor at Imperial College; Mihail Garevski, Professor and Director, Institute of Seismology and Earthquake Engineering, University of Skopje ‘Kiril and Methodius’; Ahmed Ghobarah, Professor at McMaster University; William Hall, Emeritus Professor at the University of Illinois; and Sashi Kunnath, Professor at University of California-Irvine. Many other colleagues have read parts of chapters and commented on various aspects of the book, the set of slides and the worked examples. Finally our thanks go to six anonymous reviewers who were contacted by Wiley to assess the book proposal, and to all Wiley staff who have been invariably supportive and patient over the four years.

Amr S. Elnashai
Luigi Di Sarno

Introduction

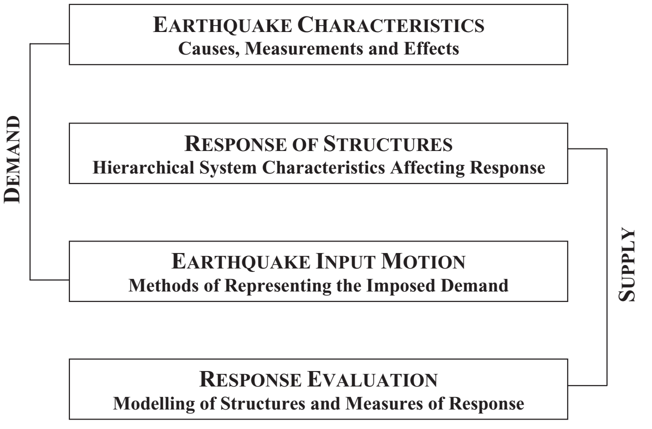
Context, Framework and Scope

Earthquakes are one of the most devastating natural hazards that cause great loss of life and livelihood. On average, 10,000 people die each year due to earthquakes, while annual economic losses are in the billions of dollars and often constitute a large percentage of the gross national product of the country affected.

Over the past few decades, earthquake engineering has developed as a branch of engineering concerned with the estimation of earthquake consequences and the mitigation of these consequences. It has become an interdisciplinary subject involving seismologists, structural and geotechnical engineers, architects, urban planners, information technologists and social scientists. This interdisciplinary feature renders the subject both exciting and complex, requiring its practitioners to keep abreast of a wide range of rapidly evolving disciplines. In the past few years, the earthquake engineering community has been reassessing its procedures, in the wake of devastating earthquakes which caused extensive damage, loss of life and property (e.g. Northridge, California, 17 January 1994; $30 billion and 60 dead; Hyogo-ken Nanbu, Japan, 17 January 1995; $150 billion and 6,000 dead).

The aim of this book is to serve as an introduction to and an overview of the latest structural earthquake engineering. The book deals with aspects of geology, engineering seismology and geotechnical engineering that are of service to the earthquake structural engineering educator, practitioner and researcher. It frames earthquake structural engineering within a framework of balance between ‘Demand’ and ‘Supply’ (requirements imposed on the system versus its available capacity for action and deformation resistance).

In a system-integrated framework, referred to as ‘From Source-to-Society’, where ‘Source’ describes the focal mechanisms of earthquakes, and ‘Society’ describes the compendium of effects on complex societal systems, this book presents information pertinent to the evaluation of actions and deformations imposed by earthquakes on structural systems. It is therefore a ‘Source-to-Structure’ text. Source parameters, path and site characteristics are presented at a level of detail sufficient for the structural earthquake engineer to understand the effect of geophysical and seismological features on strong ground-motion characteristics pertinent to the evaluation of the response of structures. Structural response characteristics are reviewed and presented in a new framework of three quantities: stiffness, strength and ductility, which map onto the three most important limit states of serviceability, structural damage control and collapse prevention. This three-parameter approach also matches well with the consequential objectives of reducing down time, controlling repair costs and protecting life. By virtue of the fact that the text places strong emphasis on the varying values of stiffness, strength and ductility as a function of the available deformation capacity, it blends seamlessly with deformation-based design concepts and multi-limit state design, recently referred to as performance-based design. The book stops where design codes start, at the stage of full and detailed evaluation of elastic and inelastic actions and deformations to which structures are likely to be subjected. Emphasis is placed on buildings and bridges, and material treatment is constrained to steel and concrete. The scope of the book is depicted in the figure below.



Scope of the book

Chapter 1 belongs to the Demand sub-topic and is a standard exposé of the geological, seismological and earth sciences aspects pertinent to structural earthquake engineering. It concludes with two sections; one on earthquake damage, bolstered by a detailed Appendix of pictures of damaged buildings and bridges categorized according to the cause of failure. The last section is on earthquake losses and includes global statistics, as well as description of the various aspects of impact of earthquakes on communities in a regional context.

Chapter 2, which belongs to the Supply or Capacity sub-topic, establishes a new framework of understanding structural response and relating milestones of such a response to (i) probability of occurrence of earthquakes and (ii) structural and societal limit states. Viewing the response of structures in the light of three fundamental parameters, namely Stiffness, Strength and Ductility, and their implications on system performance opens the door to a new relationship between measured quantities, limit states and consequences, as described in Table 2.1. The two most important 'implications' of stiffness, strength and ductility are overstrength and damping. The latter two parameters have a significant effect on earthquake response and are therefore addressed in detail. All five response quantities of (1) Stiffness, (2) Strength, (3) Ductility, (4) Overstrength and (5) Damping are related to one another and presented in a strictly hierarchical framework of the five levels of the hierarchy, namely (i) material, (ii) section, (iii) member, (iv) connection and (v) system. Finally, principles of capacity design are demonstrated numerically and their use to improve structural response is emphasized.

Chapter 3 brings the readers back to description of the Demand sub-topic and delves into a detailed description of the input motion in an ascending order of complexity. It starts with point estimates of peak ground parameters, followed by simplified, detailed and inelastic spectra. Evaluation of the required response modification factors, or the demand response modification factors, is given prominence in this chapter, to contrast the capacity response modification factors addressed in Chapter 2. The chapter concludes with selection and scaling of acceleration time histories, as well as a discussion of the significance of duration on response of inelastic structures.

Chapter 4 concludes the Supply sub-topic by discussing important aspects of analytically representing the structure and the significance or otherwise of some modelling details. The chapter is presented in a manner consistent with Chapter 2 in terms of dealing with modelling of materials, sections, members, connections, sub-assemblages and systems. The final section of Chapter 4 presents expected and important outcomes from analytical modelling for use in assessment of the adequacy of the structure under consideration, as well as conventional design forces and displacements. The chapter also includes a brief review of methods of quasi-dynamic and dynamic analysis pertinent to earthquake response evaluation.

Use Scenarios

Postgraduate Educators and Students

As discussed in the preceding section, the book was written with the university professor in mind as one of the main users, alongside students attending a graduate course. It therefore includes a large number of work assignments and additional worked examples, provided on the book web site. Most importantly, summary slides are also provided on the book web site. The slides are intended to be used in the classroom, and also to be used in final revision by students. The book and the slides have been used in teaching the postgraduate level course in earthquake engineering at the University of Illinois at Urbana-Champaign for a number of years, and are therefore successfully tested in a leading university environment. Parts of the book were also used in teaching short courses on a number of occasions in different countries. For the earthquake engineering professor, the whole book is recommended for postgraduate courses, with the exception of methods of analysis (Section 4.5 in Chapter 4) which are typically taught in structural dynamics courses that should be a prerequisite to this course.

Researchers

The book is also useful to researchers who have studied earthquake engineering in a more traditional context, where strength and direct assessment for design were employed, as opposed to the integrated strength-deformation and capacity assessment for design approach presented in this book. Moreover, structural earthquake engineering researchers will find Chapter 3 of particular interest because it bridges the conventional barriers between engineering seismology and earthquake engineering, and brings the concepts from the former in a palatable form to the latter. From the long experience of working with structural earthquake engineers, Chapter 3 is recommended as an essential read prior to undertaking research, even for individuals who have attended traditional earthquake engineering courses. Researchers from related fields, such as geotechnical earthquake engineering or structural control, may find Chapter 2 of value, since it heightens their awareness of the fundamental requirements of earthquake response of structures and the intricate relationship between stiffness, strength, ductility, overstrength and damping.

Practitioners

Practising engineers with long and relatively modern experience in earthquake-resistant design in high-seismicity regions will find the book on the whole easy to read and rather basic. They may however appreciate the presentation of fundamental response parameters and may find their connection to the structural and societal limit states refreshing and insightful. They may also benefit from the modelling notes of Chapter 4, since use is made of concepts of finite element representation in a specifically earthquake engineering context. Many experienced structural earthquake engineering practitioners will find Chapter 3 on input motion useful and practical. The chapter will aid them in selection of appropriate characterization of ground shaking. The book as a whole, especially Chapters 3 and 4 is highly recommended for practising engineers with limited or no experience in earthquake engineering.

Abbreviations

AI = Arias Intensity
AIJ = Architectural Institute of Japan
ASCII = American Standard Code for Information Interchange
ATC = Applied Technology Council
BF = Braced Frame
CBF = Concentrically Braced Frame
CEB = Comité Euro-international du Beton
CEUS = Central and Eastern United States
COSMOS = Consortium of Organisations for Strong-Motion Observation Systems
COV = Coefficient Of Variation
CP = Collapse Prevention
CQC = Complete Quadratic Combination
CSMIP = California Strong-Motion Instrumentation Program
CSUN = California State University Northridge
CTBUH = Council on Tall Building and Urban Habitat
CUE = Conference on Usage of Earthquakes
DC = Damage Control
DL = Dead Load
EBF = Eccentrically Braced Frame
EERI = Earthquake Engineering Research Institute
ELF = Equivalent Lateral Force
EPM = Elastic-Plastic Model
EPP = Elastic Perfectly-Plastic
EMS = European Modified Scale
EQ = Earthquake
FE = Finite Element
FEMA = Federal Emergency Management Agency
FRP = Fibre-Reinforced Plastic
FW = Frame-Wall structure
GNP = Gross National Product
HF = Hybrid Frame
HPGA = Horizontal Peak Ground Acceleration
ICSMD = Imperial College Strong-Motion Databank
ID = Inter-storey Drift
IDA = Incremental Dynamic Analysis
IF = Irregular Frame
JMA = Japanese Meteorological Agency

KBF = Knee-Braced Frame
K-NET = Kyoshin Net
LEM = Linear Elastic Model
LENLH = Linear Elastic-plastic with Non-Linear Hardening
LEPP = Linear Elastic-Perfectly Plastic
LESH = Linear Elastic-plastic with Strain Hardening
LL = Live Load
LQ = Love wave
LR = Rayleigh wave
LRH = Linear Response History
LS = Limit State
MCS = Mercalli-Cancani-Seiberg
MDOF = Multi-Degree-Of-Freedom
MM = Modified Mercalli
MP = Menegotto-Pinto model
MRF = Moment-Resisting Frame
MSK = Medvedev-Sponheuer-Karnik
NGA = New Generation Attenuation
NLEM = Non-Linear Elastic Model
NRH = Non-linear Response History
NSP = Non-linear Static Pushover
OBF = Outrigger-Braced Frame
PA = Pushover Analysis
PGA = Peak Ground Acceleration
PGD = Peak Ground Displacement
PGV = Peak Ground Velocity
PEER = Pacific Earthquake Engineering Research Center
PL = Performance Level
RC = Reinforced Concrete
RO = Ramberg-Osgood model
RF = Regular Frame
RSA = Response Spectrum Analysis
SCWB = Strong Column-Weak Beam
SDOF = Single-Degree-Of-Freedom
SH = Shear Horizontal
SI = Spectral Intensity
SL = Serviceability Limit
SPEAR = Seismic Performance Assessment and Rehabilitation
SRSS = Square Root of the Sum of Squares
SV = Shear Vertical
SW = Structural Wall
TS = Tube System
URM = Unreinforced masonry
USA = United States of America
USEE = Utility Software for Earthquake Engineering
USSR = Union of Soviet Socialist Republics
VPGA = Vertical Peak Ground Acceleration
WCSB = Weak Column-Strong Beam.

Symbols

Symbols defined in the text that are used only once, and those which are clearly defined in a relevant figure or table, are in general not listed herein.

A_v = effective shear area
C_M = centre of mass
C_R = centre of rigidity
d = distance from the earthquake source
E = Young's modulus
E_0 = initial Young's modulus (at the origin)
E_t = tangent Young's modulus
f_c = concrete compression strength
f_t = concrete tensile strength
f_u = steel ultimate strength
f_y = steel yield strength
G = shear modulus
G_b = shear modulus of the bedrock
g = acceleration of gravity
H = total height
H_{eff} = effective height
h = height
I = intensity
= moment of inertia
I_i = Modified Mercalli intensity of the ith isoseismal
I_{JMA} = intensity in the Japanese Meteorological Agency (JMA) scale
I_{max} = maximum intensity
I_{MM} = intensity in the Modified Mercalli (MM) scale
I_0 = epicentral intensity
J = torsional moment of inertia
K = stiffness
K_s = secant stiffness
K_t = tangent stiffness
K_0 = initial stiffness (at origin)
K = connection rotational stiffness
k_{eff} = effective stiffness
k_f = flexural stiffness
k_s = shear stiffness

L_p = plastic hinge length
L_w = wall length
M = magnitude
 = bending moment
m_b = body wave magnitude
M_{eff} = effective mass
M_L = local (or Richter) magnitude
M_{JMA} = Japanese Meteorological Agency (JMA) magnitude
m_r = rotational mass
M_S = surface wave magnitude
m_t = translational mass
M_w = moment magnitude
N = axial load
q = force reduction factor
R = focal distance
 = force reduction factor
r_i = radius of the equivalent area enclosed in the *i*th isoseismal
S_a = spectral acceleration
S_d = spectral displacement
SI_H = Housner's spectral intensity
SI_M = Matsumura's spectral intensity
S_v = spectral velocity
T = period of vibration
T_h = hardening period
T_R = return period
T_S = site fundamental period of vibration
$T_{S,n}$ = site period of vibration relative to the nth mode
T_y = yield period
t_r = reference time period
V_{base} = global base shear
V_e = elastic shear
V_i = storey shear
V_y = yield shear
V_d = design base shear
V_u = ultimate shear
v_{LQ} = velocity of Love waves
v_{LR} = velocity of Rayleigh waves
v_P = velocity of P-waves
v_S = velocity of S-waves
α_s = shear span ratio
Γ_i = modal participation factor for the *i*th mode
γ_D, γ_E, γ_L = load factors
γ_I = importance factor
Δ = global lateral displacement
Δ_y = global yield lateral displacement
Δ_u = global ultimate lateral displacement
δ = lateral displacement
δ_i = storey lateral displacement
δ_{top} = top lateral displacement
δ_u = ultimate lateral displacement

δ_y = yield lateral displacement
ε = strain
ε_c = concrete strain
ε_{cu} = concrete crushing strain
ε_u = ultimate strain
ε_y = yield strain
θ = rotation
θ_p = plastic rotation
θ_u = ultimate rotation
θ_y = yield rotation
μ = ductility
μ_a = available ductility
μ_d = ductility demand
μ_Δ = global displacement ductility
μ_δ = displacement ductility
μ_ε = material ductility
μ_θ = rotation ductility
μ_χ = curvature ductility
ν = Poisson's ratio
ξ = damping
ξ_{eff} = effective damping
ξ_{eq} = equivalent damping
ρ = density
σ = normal stress
σ_y = yielding normal stress
χ = curvature
χ_u = ultimate curvature
χ_y = yield curvature
Ψ = combination coefficient
Ω_d = observed overstrength
Ω_i = inherent overstrength
ω = natural circular frequency
ω_i = circular frequency relative to the *i*th mode