

# FUNDAMENTALS OF EARTHQUAKE ENGINEERING

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# About the Authors

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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.

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# 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 heart-warming praise alongside some scathing criticism. These are, in alphabetical order, Nicholas Ambrose, 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

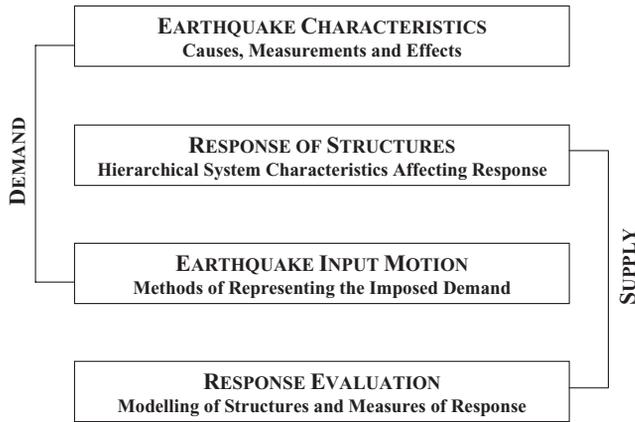
Earthquakes are one of the most devastating natural hazards that cause great loss of life and livelihood. On average, 10,000 people die each year due to earthquakes, while annual economic losses are in the billions of dollars and often constitute a large percentage of the gross national product of the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

$H_{\text{eff}}$  = effective height

$h$  = height

$I$  = intensity

= moment of inertia

$I_i$  = Modified Mercalli intensity of the  $i$ th isoseismal

$I_{\text{JMA}}$  = intensity in the Japanese Meteorological Agency (JMA) scale

$I_{\text{max}}$  = maximum intensity

$I_{\text{MM}}$  = 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

$k_{\text{eff}}$  = 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  
 $M_{\text{eff}}$  = effective mass  
 $M_L$  = local (or Richter) magnitude  
 $M_{\text{JMA}}$  = 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  $n$ th mode  
 $T_y$  = yield period  
 $t_r$  = reference time period  
 $V_{\text{base}}$  = 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  
 $\alpha_s$  = shear span ratio  
 $\Gamma_i$  = modal participation factor for the  $i$ th mode  
 $\gamma_D, \gamma_E, \gamma_L$  = load factors  
 $\gamma_I$  = importance factor  
 $\Delta$  = global lateral displacement  
 $\Delta_y$  = global yield lateral displacement  
 $\Delta_u$  = global ultimate lateral displacement  
 $\delta$  = lateral displacement  
 $\delta_i$  = storey lateral displacement  
 $\delta_{\text{top}}$  = top lateral displacement  
 $\delta_u$  = ultimate lateral displacement

$\delta_y$  = yield lateral displacement  
 $\varepsilon$  = strain  
 $\varepsilon_c$  = concrete strain  
 $\varepsilon_{cu}$  = concrete crushing strain  
 $\varepsilon_u$  = ultimate strain  
 $\varepsilon_y$  = yield strain  
 $\theta$  = rotation  
 $\theta_p$  = plastic rotation  
 $\theta_u$  = ultimate rotation  
 $\theta_y$  = yield rotation  
 $\mu$  = ductility  
 $\mu_a$  = available ductility  
 $\mu_d$  = ductility demand  
 $\mu_\Delta$  = global displacement ductility  
 $\mu_\delta$  = displacement ductility  
 $\mu_\varepsilon$  = material ductility  
 $\mu_\theta$  = rotation ductility  
 $\mu_\chi$  = curvature ductility  
 $\nu$  = Poisson's ratio  
 $\xi$  = damping  
 $\xi_{eff}$  = effective damping  
 $\xi_{eq}$  = equivalent damping  
 $\rho$  = density  
 $\sigma$  = normal stress  
 $\sigma_y$  = yielding normal stress  
 $\chi$  = curvature  
 $\chi_u$  = ultimate curvature  
 $\chi_y$  = yield curvature  
 $\Psi$  = combination coefficient  
 $\Omega_d$  = observed overstrength  
 $\Omega_i$  = inherent overstrength  
 $\omega$  = natural circular frequency  
 $\omega_i$  = circular frequency relative to the  $i$ th mode

Fundamentals of Earthquake Engineering combines aspects of engineering seismology, structural and geotechnical earthquake engineering to assemble the vital components required for a deep understanding of response of structures to earthquake ground motion, from the seismic source to the evaluation of actions and deformation required for design. The nature of earthquake risk assessment is inherently multi-disciplinary. Whereas Fundamentals of Earthquake Engineering addresses only structural safety assessment and design, the problem is cast in its appropriate context by relating structural damage John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, 2008. - 374 p. ISBN:0470024836. Fundamentals of Earthquake Engineering combines aspects of engineering seismology, structural and geotechnical earthquake engineering to assemble the vital components required for a deep understanding of response of structures to earthquake ground motion, from the seismic source to the evaluation of actions and deformation required for design. The nature of earthquake risk assessment is inherently multi-disciplinary.