

Earthquake design practice for buildings

Second edition

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Contents

Sources for photographs	vii
Preface	ix
Scope of the book	ix
Outline	ix
Acknowledgements	x
Introduction to the first edition	xi
Introduction to the second edition	xiii
Foreword by Professor Robin Spence	xv
Notation	xvii
1 The lessons from earthquake damage	1
1.1 Damage studies	1
1.2 Ground behaviour	2
1.3 Structural collapse	4
1.4 Important categories of damage	9
1.5 Reinforced concrete	11
1.6 Structural steelwork	13
1.7 Masonry	15
1.8 Timber	16
1.9 Foundations	17
1.10 Non-structural elements	18
1.11 Bibliography	19
2 Ground motion	20
2.1 Primary and secondary sources of earthquake damage	20
2.2 Earthquake basics	21
2.3 Earthquake probability and return periods	24
2.4 Performance objectives under earthquake loading	25
2.5 Representation of ground motion	26
2.6 Site effects	30
2.7 Quantifying the risk from earthquakes	32
2.8 Design earthquake motions	34
2.9 References	37

3	The calculation of structural response	39
3.1	Introduction	39
3.2	Basic principles of seismic analysis	40
3.3	Linear elastic forms of seismic analysis	63
3.4	Non-linear analysis	67
3.5	Analysis for capacity design	75
3.6	Analysis of building structures	77
3.7	References	79
4	Analysis of soils and soil–structure interaction	80
4.1	Introduction	80
4.2	Soil properties for seismic design	80
4.3	Liquefaction	84
4.4	Site-specific seismic hazards	90
4.5	Soil–structure interaction	92
4.6	References	93
5	Conceptual design	96
5.1	Design objectives	96
5.2	Anatomy of a building	96
5.3	Planning considerations	97
5.4	Structural systems	102
5.5	Cost of providing seismic resistance	115
5.6	References	116
6	Seismic codes of practice	117
6.1	Role of seismic codes in design	117
6.2	Development of codes	118
6.3	Philosophy of design	118
6.4	Code requirements for analysis	119
6.5	Code requirements for strength	124
6.6	Code requirements for deflection	124
6.7	Load combinations	124
6.8	Code requirements for detailing	125
6.9	Code requirements for foundations	125
6.10	Code requirements for non-structural elements and building contents	126
6.11	Other considerations	126
6.12	References	127
7	Foundations	128
7.1	Design objectives	128
7.2	‘Capacity design’ considerations for foundations	129

7.3	Safety factors for seismic design of foundations	130
7.4	Pad and strip foundations	131
7.5	Raft foundations	133
7.6	Piled foundations	134
7.7	Retaining structures	136
7.8	Design in the presence of liquefiable soils	138
7.9	References	139
8	Reinforced concrete design	140
8.1	Lessons from earthquake damage	140
8.2	Behaviour of reinforced concrete under cyclic loading	141
8.3	Material specification	152
8.4	Analysis of reinforced concrete structures	154
8.5	Design of concrete building structures	158
8.6	Design levels of ductility	158
8.7	Design of reinforced concrete frames	159
8.8	Shear walls	169
8.9	Concrete floor and roof diaphragms	176
8.10	Unbonded prestressed construction	179
8.11	References	179
9	Steelwork design	182
9.1	Introduction	182
9.2	Lessons learned from earthquake damage	183
9.3	The behaviour of steelwork members under cyclic loading	185
9.4	Materials specification	191
9.5	Analysis of steelwork structures	192
9.6	Design of steel building structures	193
9.7	Design levels of ductility	194
9.8	Centrally braced frames (CBFs)	194
9.9	Eccentrically braced frames (EBFs)	196
9.10	Moment-resisting frames	198
9.11	Steel–concrete composite structures	204
9.12	References	204
10	Masonry	206
10.1	Introduction	206
10.2	Forms of masonry construction and their performance in earthquakes	206
10.3	Designing masonry for seismic resistance	209
10.4	Analysis of masonry structures	216
10.5	Simple rules for masonry buildings	216
10.6	References	218

11 Timber	219
11.1 Introduction	219
11.2 Characteristics of timber as a seismic-resisting building material	219
11.3 The lessons from earthquake damage	220
11.4 Design of timber structures	221
11.5 References	224
12 Building contents and cladding	225
12.1 Introduction	225
12.2 Analysis and design of non-structural elements for seismic resistance	226
12.3 Electrical, mechanical and other equipment	231
12.4 Vertical and horizontal services	231
12.5 Cladding	232
12.6 References	232
13 Seismic isolation	233
13.1 Introduction	233
13.2 Lessons from 30 years of seismic isolation	239
13.3 Seismic isolation systems	239
13.4 Design considerations	245
13.5 Analysis of seismic isolation systems	247
13.6 Testing of bearing systems	251
13.7 Active and semi-active systems	251
13.8 References	253
14 Assessment and strengthening of existing buildings	255
14.1 Introduction	255
14.2 Performance of strengthened buildings in earthquakes	256
14.3 Design strategies for strengthening	258
14.4 Surveying the seismic adequacy of existing buildings	261
14.5 Analysis methods	263
14.6 Assessing element strengths and deformation capacities	265
14.7 Methods of strengthening	266
14.8 Special considerations for strengthening earthquake-damaged buildings	270
14.9 Upgrading of historic buildings	271
14.10 Assessment of large groups of buildings	272
14.11 References	272
Index	275

Sources for photographs

(Note: where no source is indicated, the source is the authors.)

Fig. 1.1 Port and Airport Research Institute, Japan.

Fig. 1.2 Colin Taylor, Department of Civil Engineering, Bristol University.

Fig. 1.3 Edmund Booth.

Fig. 1.4 Earthquake Engineering Field Investigation Team (EEFIT), UK.

Fig. 1.6 Mike Winney.

Fig. 1.7 Edmund Booth.

Fig. 1.8 Edmund Booth.

Fig. 1.10 Antonios Pomonis (Cambridge University).

Fig. 1.13 J. Meehan. Courtesy of Karl V. Steinbrugge Collection, Earthquake Engineering Research Center, University of California, Berkeley.

Fig. 1.14 Robin Spence.

Fig. 1.16 EEFIT UK.

Fig. 1.18 Peter Yanev, courtesy of ABS Consulting.

Fig. 1.24 Peter Merriman, BNFL Ltd.

Fig. 2.9 James Jackson, University of Cambridge.

Fig. 4.6 Karl V. Steinbrugge Collection, Earthquake Engineering Research Center, University of California, Berkeley.

Fig. 5.3 David G. E. Smith.

Fig. 7.2 Jack Pappin.

Fig. 8.5 R. C. Fenwick.

Fig. 8.22 Peter Yanev, courtesy of ABS Consulting.

Fig. 9.2 Peter Yanev, courtesy of ABS Consulting.

Fig. 9.7 Courtesy of the SAC Project 7.03 – Georgia Tech (R. Leon and J. Swanson).

Fig. 10.2 Antonios Pomonis (Cambridge University)

Fig. 10.5 D. D'Ayala.

Figs 13.3, 13.4, 13.8 Courtesy of ALGA SpA.

Fig. 13.5 (a) Courtesy of Arup (b) courtesy of Frank la Riviere.

Fig. 13.6 L. Megget.

Fig. 14.3 C. Perry, E. Fierro, H. Sederat and R. Scholl (1993). Seismic upgrade in San Francisco using energy dissipation devices. *Earthquake Spectra*, Vol. 9, No. 3, pp. 559–579. Courtesy of EERI.

Preface

Scope of the book

This book is intended as a design guide for practitioners and advanced students with a sound knowledge of structural design who are not expert in seismic aspects of design, and perhaps are encountering the problem for the first time. Earthquake engineering is a vast subject and the intention of this book is not to provide a fully comprehensive treatment of all its aspects. Rather, it is to provide the practising engineer with an understanding of those aspects of the subject that are important when designing buildings in earthquake country, with references to sources of more detailed information where necessary. Many of the principles discussed also apply to the design of non-building structures, such as bridges or telecommunications towers, but the scope of this book is restricted to buildings.

Although earthquakes do not respect national boundaries, the practice of earthquake engineering does vary significantly between regions, and this is reflected in the differing formats and requirements of national seismic codes. The book is intended to be more general than to describe the approach in just one code, although it reflects the experience of the authors, particularly of the European seismic code Eurocode 8 and of US codes. Japanese practice is in many ways very different, and is scarcely mentioned here.

Outline

Earthquakes regularly occur which test buildings much more severely than their designers might reasonably have expected, and earthquake engineers should (and do) make use of this chance (found much more rarely in other disciplines) to find out whether the current theories actually work out in practice. The first chapter therefore reviews the lessons from earthquake damage for designers of buildings. Chapter 2 is a brief introduction to engineering seismology, including such matters as measuring earthquakes and the ground motions they produce. Chapter 3 outlines the important principles of structural dynamics applicable to seismic analysis, and Chapter 4 discusses the analysis of soils (a crucial issue where the soil provides the dual and conflicting roles of both supporting and also exciting the structures founded on it). Chapter 5 presents the fundamentally important issue of the conceptual design of buildings; if this is wrong, it is unlikely that the seismic resistance will be satisfactory. Chapter 6 gives an introduction to some seismic codes of practice. Chapter 7 discusses the design of foundations, while Chapters 8 to 11 discuss issues specific to seismic design in the four main materials used for building structures – concrete, steel, masonry and timber. So far, the book has concentrated on the primary structure of a building, but its

contents are also important and can suffer as much or even greater damage in an earthquake. Chapter 12 therefore discusses building contents and cladding. Chapter 13 introduces special measures to improve earthquake resistance, such as mounting buildings on base isolation bearings or introducing various types of devices to increase structural damping. Existing buildings without adequate seismic resistance pose a huge safety and economic threat in many parts of the world and the final chapter discusses how to assess and strengthen them.

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Assistance in preparing the text and illustrations is gratefully acknowledged from many friends and colleagues. Particular thanks are due to Richard Fenwick for permission to base parts of Chapter 8 on material originally prepared by him, and to Jack Pappin in a similar way for material used in Chapters 4 and 7. Richard and Jack also provided many helpful and detailed comments on the text, as did Dina D'Ayala, Ahmed Elghazouli, James Jackson, David Mallard, Agostino Marioni, Alain Pecker, Bryan Skipp, Robin Spence and David Trujillo.

Introduction to the first edition

This book deals with earthquakes, which are natural disasters. In a letter to *The Times*, on 13 July 1984, the Archbishop of York wrote

‘Disasters may indeed be messengers, in that they force us to think about our priorities. They drive us back to God. They remind us of mistakes and failures, and they call forth reserves of energy and commitment which might otherwise remain untapped. Disasters also remind us of the fragility of life and of our human achievements.’

Designing for earthquake resistance is difficult, not because the basic steps in the process are necessarily hard, but because the fundamental concept of earthquake resistance is different from design for other loadings, such as wind pressure or gravity loads. It is different in two important respects. Firstly, it is a dynamic loading involving a number of cyclic reversals, so that the behaviour of the structure involves an understanding of structural dynamics. Secondly, normal design practice accepts that, in response to a major earthquake, a building structure may suffer major damage (but should not collapse), whereas for wind and gravity loads even minor damage is not acceptable.

Earthquake-resistant design is not widely taught. For the practising engineer it is a difficult subject to come to grips with, not because there is a shortage of information, but because there is a surfeit. It is a subject where it is possible to drown in information and to starve for knowledge. Professor G. Housner, in an address to the participants at the Eighth World Conference on Earthquake Engineering in 1984, suggested that, if the current logarithmic increase in the number of papers presented at the four-yearly World Conferences continued, by the 19th it would take four years to present the papers.

The author himself (David Key) has struggled over many years to develop a sound approach to the design of structures in earthquake zones. This book is intended to guide others not only in the basic procedures of design but also to point out sources of specialised information on the subject when it is beyond the scope of this work.

Earthquake engineering has to a large extent slipped out of the hands of the practical designer, and into the hands of the specialist, who usually employs a suite of computer programs to provide great quantities of unnecessarily precise information on such subjects as the ground motion spectrum or the dynamic response of the building to some long past earthquake which can only bear the vaguest resemblance to any ground motion to which the building could be subjected. In the author’s view the principal ingredients in an earthquake-resistant design can be categorised as follows.

Essential

- (a) a sound structural concept
- (b) an understanding of the way in which the structure will behave when primary structural elements have yielded
- (c) an approximate idea of the peak ground acceleration likely to be experienced, and the predominant frequency
- (d) the application of engineering common sense to the fact that the building may be violently shaken
- (e) good detailing
- (f) good quality construction and inspection.

Useful

- (a) detailed elastic analysis of the structure
- (b) dynamic analysis of simple models
- (c) a soil–structure interaction study when justified by the soil and structure properties
- (d) estimates of the ground motion spectrum.

The designer is in the end the person who puts all the theory into steel and concrete, and who bears the responsibility for it.

This book assumes a competent knowledge of structural design by the reader. It is intended as a guide to the normal processes of design, and to provide directions for further study when the structural problem is out of the ordinary.

David Key, 1988

Introduction to the second edition

Many things have changed since David Key wrote his introduction to the first edition in 1988, but his approach as outlined above remains just as valid. The major changes in seismic engineering can be listed as follows.

- (1) Publication of a European seismic code of practice and significant developments in codes elsewhere, including the USA.
- (2) A vast increase in the number, availability and quality of earthquake ground motion recordings, and a better understanding of the influence of soils and earthquake characteristics on ground motion.
- (3) A greater appreciation of the factors that need to be accounted for in the seismic design of steel structures.
- (4) Transformation of non-linear time-history analysis from a specialist research method to a potentially useful (and actually used) tool for practising engineers.
- (5) Development of non-linear static (pushover) techniques of analysis.
- (6) Development of practical methods for assessing and improving the seismic resistance of existing structures.
- (7) Much greater use and experience of seismically isolated structures and those with added structural damping, although they still represent only a tiny minority of structures actually built.
- (8) Improved ability to predict the response of soils to earthquake loading, including their potential for liquefaction.

The second edition has therefore retained the same basic structure and intention of the original edition, but all sections have been partially or (in most cases) wholly rewritten to reflect the changes noted above. The scope has been limited to buildings, so the chapter in the first edition covering bridges, tanks, towers and pipelines has been removed, and replaced with one on the assessment and strengthening of existing buildings.

Edmund Booth, 2005

Foreword

In the introduction to the first edition of *Earthquake design practice for buildings*, David Key memorably wrote

‘Earthquake engineering has to a large extent slipped out of the hands of the practical designer, and into the hands of the specialist, who usually employs a suite of computer programs to provide great quantities of unnecessarily precise information . . .’

and it was partly for this reason that he directed that first edition to the needs of the practical designer, not to those of the earthquake specialist.

In the intervening 17 years the science of earthquake engineering has advanced enormously, and today it is inconceivable that a large building project would be built in an earthquake area without the advice of a specialist. Indeed Edmund Booth who, with David Key, has so admirably expanded and updated this book, is one of today’s leading earthquake engineering specialists. But the resulting book is not written for the specialist. It is remarkable in the way it adheres to the main goal which motivated David Key in the first place – to make earthquake engineering intelligible and interesting to the non-specialist, practical designer.

Today there is of course much more ground to cover than there was in 1988 – the development of codes, the improved understanding of ground motion, new methods of analysis and many innovations in providing for earthquake resistance – and these are all succinctly covered in this new edition with admirable clarity.

But the key features that made the first edition so valuable are still present. First, that the approach to earthquake engineering presented derives from the authors’ direct observation of the damage to buildings in large earthquakes; the principal modes of damage are clearly identified, and many very well chosen photographs are used to illustrate these. This experience is used to inform the design guidance given.

Second, the book does not depend on a heavily mathematical approach. Rather, equations are used sparingly and the authors rely on good, clear descriptions of structural behaviour, backed by excellent diagrams, making the text accessible to all those who have to deal with the design of buildings structures for earthquake areas, whether as engineers or architects.

Third, the book is based on long personal experience by both authors of the design of buildings in earthquake areas worldwide, and can thus give authoritative advice on the appropriate codes, design procedures and structural arrangements to adopt for both highly seismic areas and areas of low seismicity. This is advice we can rely on.

Special features of this edition which will make it particularly valuable to engineering designers are:

- its timely account of the Eurocodes, now finally becoming published documents and soon to become mandatory in some areas, with which Edmund Booth has been closely involved
- the excellent chapter on conceptual design, setting out some fundamentals which should be thought about while a building's form and siting are still being developed, and which architects as well as engineers will find illuminating
- a valuable new chapter on the assessment and strengthening of existing buildings, an activity whose importance is already growing in many countries, as we look for ways to protect our urban centres from future earthquake disasters
- an excellent state of the art on seismic isolation, rightly identified by the authors as 'an idea whose time has come'.

However, as well as being a practical guide to design, the book is also a valuable reference work, offering excellent bibliographies on all the major topics, and valuable suggestions for follow-up study where needed.

For these reasons and many more this book will be appreciated – and enjoyed – by all those who have responsibility for the design, construction and maintenance of buildings in earthquake areas, both in the European area and worldwide.

*Professor Robin Spence
President, European Association for Earthquake Engineering
Cambridge
July 2005*

Notation

Notes

- (1) The units shown for the parameters are to indicate the dimensions of the parameters, but other consistent systems of units (involving for example the use of millimetres instead of metres) would also be possible.
- (2) Notation not given in this table is defined at the point of occurrence in the text.

Symbol	Description
a_g	Peak ground acceleration: m/s^2
b	Width of compression flange of concrete beam: m
b_f	Breadth of flange of steel section: m
c_u	Undrained shear strength of soil: kN/m^2 ; Dimensionless coefficient in the US code ASCE 7 relating to the upper limit on calculated period of a building
d	Effective depth to main reinforcement in a concrete beam: m; Diameter of bolt or other fastener joining timber members: m
d_b	Diameter of reinforcing steel in concrete: m
d_r	Relative displacement between points of attachment of an extended non-structural element: m
e	Length of the shear link in an eccentrically braced frame (EBF): m
F	Force: kN
f'_c	Cylinder strength of concrete: kN/m^2
f'_{cc}	Compressive strength of concrete under confining pressure f_1 : kN/m^2
f_1	Hydrostatic confining pressure on an element of concrete: kN/m^2
F_a	Horizontal force on non-structural element: kN
F_b	Seismic shear at base of building: kN
f_b	Compressive strength of masonry: kN/m^2
$F_{elastic}$	Seismic force developing in an elastic (unyielding) system: kN
F_i	Force at level i: kN
$F_{plastic}$	Seismic force developing in a plastic (yielding) system: kN
F_y	Yield force: kN
f_y	Yield strength of steel: kN/m^2
g	Acceleration due to gravity n/s^2
G_0	Shear modulus of soil at small strains: kN/m^2
G_s	Shear modulus of soil at large shear strain: kN/m^2
H	Building height: m
h	Minimum cross-sectional dimension of beam: m; Greater clear height of an opening in a masonry wall: m

h_{ef}	Effective height of a masonry wall: m
h_s	Clear storey height of shear wall between lateral restraints: m
h_w	Overall height of shear wall: m; cross-sectional depth of beam: m
k	Spring stiffness: kN/m; Dimensionless exponent in equation 6.2 for distribution of seismic forces with height; Dimensionless empirical constant in Table 10.5
K_{eff}	Secaut stiffness of a non-linear system at a given deflection: kN/m (see Figure 3.24)
L	Length of a masonry wall: m
l	Effective unrestrained length of a beam or column: m
L^*	Critical span of beam corresponding to formation of plastic hinges within span under lateral loading: m
L'	Clear span of beam: m
l_{av}	Average length of shear walls in a building: m (see Table 10.5)
L_i	Structural property defined in equation 3.11: tonnes
L_{pl}	Effective plastic hinge length: m
L_v	Bending moment to shear force ratio at the critical section of a plastic hinge forming in a concrete member
M	Magnitude of earthquake; Mass: tonnes
M_s	Magnitude of earthquake measured using the surface wave scale
$m(x)$	Mass per unit length at height x : kN/m
M_A, M_B	Plastic hinge moments forming at either end of a beam: kNm
M_i	Structural property defined in equation 3.12: tonnes
m_i	Mass at level i : tonnes
M_p	Flexural strength of the shear link in an eccentrically braced frame (EBF): kN-m
M_u	Bending moment in a plastic hinge under ultimate conditions: kNm
N	Blow count per 300 mm in the Standard Penetration Test (SPT)
N_1 (60)	Corrected SPT blow count: see section 4.3.2(d-f)
n	Number of storeys in a building
P	Axial load in a column: kN
P_1	Probability of exceedence in one year
P_y	Probability of exceedence in y years
q	'Behaviour' or force reduction factor for structural systems in Eurocode 8
q_a	'Behaviour' or force reduction factor for non-structural elements in Eurocode 8
R	'Response modification' or force reduction factor for structural systems in the US code IBC; Radius of a friction pendulum isolation bearing: m
r_y	Radius of gyration of a beam or column about its minor axis: m
S	Soil amplification factor in Eurocode 8
S_a	Spectral acceleration: m/s^2

S_{ai}	Spectral acceleration corresponding to the period of mode i : m/s^2
S_d	Spectral displacement: m
$S_e(T)$	Spectral acceleration, based on elastic response, corresponding to structural period T : m/s^2
S_v	Spectral velocity: m/s
T	Return period: years; Structural period: s
T_1, T_2, T_3	Periods of first, second, third modes of building: s
T_a	Fundamental vibration period of non-structural element: s; Empirically determined vibration period of a building: s
T_B, T_C	Periods defining the peak of the design response spectrum in Eurocode 8: s
t_{ef}	Thickness of a masonry wall: m
T_{eff}	Effective period of a non-linear system at a given displacement: s
t_f	Thickness of flange of steel section: m
$u_{elastic}$	Seismic displacement of elastic (unyielding) system: m
$u_{plastic}$	Seismic displacement of a plastic (yielding) system: m
u_{ult}	Displacement at ultimate capacity: m
u_y	Displacement at yield: m
v	Masonry shear strength under zero compressive load: kN/m^2
V_1, V_2, V_3	Seismic shears at base of building corresponding to first, second, third modes: kN
v_d	Design in-plane shear strength of masonry: kN/m^2
V_p	Shear capacity of the shear link in an eccentrically braced frame (EBF): kN
V_u	Shear force in a plastic hinge under ultimate conditions: kN
W_a	Weight of non-structural element: kN
X	Dimensionless reduction factor
x	Height above fixed base: m
z	Total height of building above base: m
z_i	Height above base of level i : m
α_{sl}	Dimensionless empirical constant in equation 8.4 for plastic hinge length
δ	Lateral deflection: m
$\phi_i(x)$	Modal deflection at height x in mode i
ϕ_p	Curvature of a plastic hinge at rotation θ_p : radians/m
ϕ_u	Ultimate curvature of a plastic hinge: radians/m
ϕ_y	Curvature of a plastic hinge at first yield: radians/m
γ	Shear strain
γ_a	Importance factor for non-structural element, in Eurocode 8
γ_m	Partial factor on material strength
η	Correction factor to adjust response for damping other than 5%
μ	Displacement ductility; Coefficient of friction
ν	Reduction factor in Eurocode 8 to convert design displacements at ultimate limit state to serviceability limit state

θ_p	Plastic rotation of a plastic hinge: radians
θ_u	Ultimate rotation at a plastic hinge: radians
θ_y	Rotation at a plastic hinge at yield: radians
ρ	Ratio of tension reinforcing steel area to cross-sectional area of concrete member;
	Ratio of force demand on an element to capacity of the element
ρ'	Ratio of compression reinforcing steel area to cross-sectional area of concrete member
σ_v	Vertical stress in masonry due to permanent loads: kN/m^2
σ_{vo}	Total vertical stress in soil at the level of interest due to gravity loads: kN/m^2
σ'_{vo}	Effective vertical stress in soil at the level of interest due to gravity loads: kN/m^2
τ_e	Effective shear stress in soil under design earthquake loading: kN/m^2
ξ	Percentage of critical damping
Ω	Minimum ratio of resistance moment to design moment at plastic hinge position

10 Masonry

‘Masonry materials – mortar and stones or bricks – are stiff and brittle, with low tensile strength, and are thus intrinsically not resistant to seismic forces. However, the earthquake resistance of masonry as a composite material can vary between good and poor, depending on the materials used . . . [and] . . . the quality of workmanship.’

Sir Bernard Feilden. In: *Between Two Earthquakes – Cultural Property in Seismic Zones*. ICCROM, Rome/Getty Conservation Institute, Marina del Rey, CA, 1987

This chapter covers the following topics.

- The lessons from earthquake damage
- Characteristics of masonry as a seismic-resisting material
- Material specification
- Special considerations for analysis
- Masonry walls
- Floors and roofs in masonry buildings
- Masonry as non-structural cladding

10.1 Introduction

Brick and stone masonry is a widely available, low-energy material, and the skills are found all over the world to use them for creating highly practical and often beautiful buildings. However, its low tensile strength limits the available ductility and places reliance on its ability to sustain high compressive stresses during an earthquake. If the compressive strength is low (as is the case for example with earth bricks or ‘adobe’) then the consequences in an earthquake can be disastrous, and often have been (Fig. 1.9). However, well-designed buildings made from good-quality brick or stone can perform well. In US practice, all new masonry buildings in areas of high seismicity have to be reinforced with steel. By contrast, Eurocode 8 permits the use of unreinforced masonry to withstand strong earthquakes, although it is unlikely that a building taller than one or two storeys could be made to comply with the code if the seismicity is high.

10.2 Forms of masonry construction and their performance in earthquakes

Masonry consists of blocks or bricks, usually bonded with mortar. A wide variety of forms exist. The weakest is where cohesive soil is placed in a mould and

sun-dried to form a building block. This type of construction (called adobe in Latin America and elsewhere) is cheap, widely available and requires only basic skills to form, but cannot be relied on to resist strong ground motion. Stabilising the soil with lime or other cementitious material improves matters.

Random rubble masonry consists of rough cut or natural stones held in a matrix of soil or mortar. It may form the core of a wall with a cladding of dressed (i.e. cut) stone, called ashlar. The seismic resistance depends on the matrix holding the stones together; if this is weak, the seismic performance will be poor or very poor.

Carefully cut rectangular blocks of stone (dressed stone) of good quality arranged to resist lateral resistance without developing tensile stresses can possess surprisingly good earthquake resistance. Here, the presence of vertical prestress, usually coming from the weight of masonry above, is important for two reasons. First, seismically induced tensile stresses may not develop if the prestress is great enough. Second, the shear strength of dressed stone relies primarily on friction; the higher the contact forces between stones, the higher the shear strength. Since compressive gravity loads are higher at the base of a building, often the seismic resistance is also greater, and so often the damage observed in dressed stone masonry is less at the bottom of a building than at the top (Fig. 10.1). By contrast,



Fig. 10.1 Increase in seismic damage with height in a stone masonry building, Gujarat, India, 2001



Fig. 10.2 Poor performance of hollow clay tile masonry in Erzincan, Turkey, 1992

the opposite is usually the case for structures in steel and concrete because the highest seismic forces occur at the bottom of the building (as they do in masonry buildings) but the gravity preload is likely to weaken steel and concrete structures, rather than strengthening them as it can do in stone masonry. Inducing compressive stresses by introducing vertical or inclined steel prestressing cables is thus a powerful way to improve the seismic resistance of good-quality stone masonry buildings (see Beckmann and Bowles 2004, section 4.5.10)

Manufactured bricks or blocks can approach the compressive strength of natural stone without requiring the special skills and equipment needed to dress natural stone. They may be reinforced with steel laid in some of the horizontal mortar bed joints (e.g. every third joint) and with vertical reinforced concrete elements, particularly at corners and around openings; this can form a satisfactory seismic resisting system. Hollow clay bricks are lighter but much weaker and have not performed well seismically unless reinforced or confined within a beam–column frame (Fig. 10.2). Concrete hollow blocks, often made with lightweight aggregates, are cast with central voids, which can be reinforced and concreted to form a strong, monolithic system (Fig. 10.3). Proprietary brick systems have

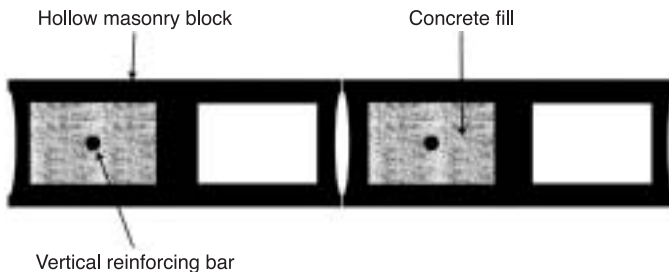


Fig. 10.3 Typical reinforced concrete hollow blocks

Index

Page references in italics are to illustrations and diagrams. Place names refer to earthquakes cited in the text.

- acceleration spectra 47–48, 47, 48
- active systems, seismic isolation 251–252
- adjacent buildings
 - buffeting 6, 9
 - separation 100
- adobe, weaknesses 15, 206–207
- amplification
 - soil effects 30–31, 30, 90
 - topographical effects 31, 91
- Anchorage (USA, 1964) 2–3, 89, 89
- anchorage
 - flexural steel 166–167
 - reinforcements 143–144
- ashlar masonry 15, 15, 207–208, 207, 214, 215
- automatic shutdown valves, services 231–232
- avalanches, consequential 2–3, 20

- Baguio (Phillipines, 1990) 14
- bahareque* construction 223
- bamboo construction 223–224, 223
- base isolation, seismic 235
- base shear 53, 53
- Bauschinger effect 141, 185
- beam-column joints
 - see also* moment-resisting frames
 - failures 11
 - flexural steel, anchorages 166–167
 - forces at 76, 77
 - moment-resisting frames 160–161, 165, 165
 - steel-framed structures 201–202, 202, 203, 203
- beams
 - see also* beam-column joints; plastic hinges
- capacity design 75–76, 76
- ductile
 - code requirements 163–164
 - detailing 160, 161
- elongation, deflection/rotation 146–147, 147
- moment-resisting frames 199–200
- moments of inertia 154–155
- shear deformation 144, 145
- blocks, compressive strength 210
- blockwork infill 63
 - moment-resisting frames 106
- boundary elements, shear walls 173
- bricks, compressive strength 210
- bridges
 - foundations 130
 - piles, superstructure failures 17–18, 18
 - seismic isolation 115, 238, 242
- Bucharest (1978) 112
- buildings
 - see also* cladding; floors; foundations; non-structural elements; roofs
 - adjacent
 - buffeting 6, 9
 - separation 100
 - appendages, failure 9–10, 9
 - categories of functions 96–97
 - contents, inertial forces of 102
 - damping 43–45
 - deflections, limiting 101–102
 - earthquake resistance 113–114
 - earthquake-damaged 261–263, 271
 - existing
 - performance 256–258, 257
 - strengthening 255–256
 - groups 272
 - historic, restoration 271

- buildings — contd.
 - mass
 - distribution 100
 - equivalent static design 120
 - normal, performance objectives 25
 - periods 41, 44, 121–122
 - seismic analysis 77–78
 - seismic isolation 114–115, 245–247
 - strengthening
 - analysis 263–265
 - cost–benefit analysis 259
 - methods 266–270, 267, 269, 270
 - performance targets 258–259
 - structural irregularities, earthquake susceptibility 100
 - surveying 261–262
- capacity design
 - advantages 76–77
 - beam shear strength 75–76, 76
 - beam/column dimensions 160
 - definitions 75
 - diaphragms 178
 - flexural strength, framing 76, 77
 - foundations 129–131
 - overstrength 75
- capacity displacement spectra 48–49, 49
- capacity spectrum method (ATC-40)
 - non-linear static analysis 70–73, 72
 - interpretation 73, 74–75, 75
- Chile (1985) 91, 136, 137, 174
- cladding
 - displacement sensitive 226, 226, 227–228
 - effects of 63
 - glass 232
 - masonry 232
 - pre-cast panels 232
- classifications, soils 97–99
- clay brick houses, collapse 8
- clay tiles, hollow, performance 208, 208
- clays
 - damping effects 83
 - stiffness 82–83, 82
 - strength 84
- coefficient of permeability, soils 137–138
- cohesive soils 84, 98–99
- columns
 - see also* beam-column joints
 - cyclic loadings, compression 149–150
 - deflection resistance 101–102
 - ductile 160, 162
 - code requirements 163–164
 - masonry, earthquake resistance 214, 215
 - moment-resisting frames 200–201
 - moments of inertia 154–155
 - plastic hinges, prevention 76, 77
 - reinforced concrete, failures 12
 - shear walls as 110–111
- centrally braced frames (CBF)
 - definition 107
 - diagonal 107, 108, 193, 195
 - K-braced 107, 109, 193, 196
 - steel-framed structures 193–196, 193
 - V-braced 107, 108–109, 193, 195
 - X-braced 107–108, 107, 108, 193, 195
- concrete
 - see also* reinforced concrete
 - confined 142–143, 143
 - panel buildings 13, 13
 - precast frames 169
 - prestressed 151–152, 152
 - unbonded 179
 - shear panels 175–176, 175
 - specifications 152–154
 - stress–strain properties 142
 - as structural material 103
- concrete–steel composite structures 204
- confined concrete 142–143, 143, 156
- confined masonry 209, 212
- contents *see* non-structural elements
- Coulomb dampers 241
- coupled lateral–torsional responses 54, 54
- Dagupan (Philippines, 1990) 17
- Dalambert force 65
- damping
 - causes of 43–44
 - determination 44–45
 - energy storage and dissipation 43, 43
 - in reinforced concrete structures 155
 - soils 82, 92, 92
 - timber structures 219–220
 - viscous 42–43, 42
- deflection ductility, definitions 55, 56, 57
- deflections
 - limiting 101–102
 - limits 124
 - storey drift 199
- design objectives, foundations 128–129
- design strength, seismic codes of practice 124

- diaphragms
 - capacity design 178
 - flexibility 178
 - floors as 176, 177
 - roofs as 176, 177
 - strength 179
 - transfer forces 176, 177, 178
- displacement spectra 47–48, 47
- displacement-based design *see* non-linear static analysis
- ductile beams 160, 161, 163–164
- ductile columns 160, 162, 163–164
- ductile frames 168
 - beam/column dimensions 159–160
- ductile yielding 101
- ductility
 - deflection, definitions 55, 56, 57
 - earthquake resistance 101
 - foundations, capacity design 129
 - reinforced concrete structures 158–159
 - shear walls 110
 - soft-storeys 55, 56, 57
- ductility demand, definitions 57
- ductility reduction factors, steel-framed structures 192
- ductility supply, definitions 57
- ductility-modified spectra
 - construction of 58–59, 59
 - multiple degrees of freedom 61
 - single degree of freedom 57–60, 57, 59
 - storey drifts 61
- dynamic responses
 - damping 42–44, 42, 43
 - non-linear 40
 - resonance 40–41, 41
- earthquake resistance 113–114
 - ashlar masonry 15, 15, 214, 215
- earthquake susceptibility, structural irregularities 100
- earthquake-damaged buildings
 - foundations 271
 - groups, strengthening policies 272
 - historic 271
 - strengthening 261
 - surveying 262–263
- earthquakes
 - fatalities due to 22, 23
 - fault planes 20, 21, 21
 - ground motion
 - response spectra 26–28, 28
 - time histories 26, 27
 - hazard assessments 33–34, 33, 34
 - human responses 1–2
 - intensity scales 22
 - magnitude scales 21–22
 - numbers, by magnitude 22
 - past, records of 23–24, 33–34
 - peak ground acceleration 29
 - peak velocity 29
 - probability 24
 - return periods 24–25, 32–33, 120
 - torsional ground motions 29
 - types 120
 - unpredictability of responses 39
 - vertical motions 29
 - and wind resistance 1
- eccentrically braced frames (EBF) 109, 109
 - steel-framed structures, link rotation 196–198, 196, 197
- El Centro (1940, USA) 42, 45
- elastic displacements 3–4
- equivalent linear static analysis 63–65
- equivalent static design 120
- equivalent static forces 65
- Erzincan (Turkey, 1992) 5, 8, 11, 13, 14
- Eurocode 8
 - see also* seismic codes of practice
 - IBC, comparisons 120–126
- existing buildings
 - performance 256–258, 257
 - shear walls, retrofitting 256–257, 257
 - strengthening 255–256
- fatalities
 - due to earthquakes 22, 23
 - due to natural disasters 22, 23, 24
- fault planes 20–21, 21
 - ruptures along 91
- fires, timber structures 16, 20, 220
- flange buckling, structural steel 188–190, 189, 190
- floors
 - as diaphragms 176, 177
 - flexibility 178
 - joist failures 10, 11
 - preliminary sizing 176–177
 - strengthening 268–269
 - timber structures 220
 - transfer forces 176, 177, 178

- foundations
 - see also* piles; retaining structures
 - bridges 130
 - capacity design
 - ductility 129
 - load factors 130
 - soil responses 129–130
 - soil strengths 130–131
 - design objectives 128–129
 - earthquake-damaged 271
 - footing ties 132–133
 - pad and strip, failures 131–132, 132, 133
 - raft 133–134, 133
 - seismic resistance factors 102–103
 - soil liquefaction 3, 17, 17, 138–139
- Fourier acceleration spectra 48, 48
- friction pendulum bearings 243, 245, 245
- Friuli (Italy, 1980) 11
- glass cladding 232
- granular soils, strength 83–84
- ground-storeys *see* soft-storeys
- Gujarat (India, 2001)
 - ashlar stability 15, 15, 214, 215
 - parapet failure 9, 207–208, 207
 - rubble masonry collapse 7
- hazard assessments, probabalistic 33–34, 33, 34
- high damping rubber bearings 242–243, 243, 244, 251
- historic buildings, restoration 271
- historic masonry, overturning 212, 213, 214
- historical records, past earthquakes 24
- hospitals
 - continuous functioning 225
 - performance objectives 25–26, 121
 - plant items 227
 - seismic isolation 239
- hysteristic dampers, seismic isolation 241, 241, 268, 269
- IBC
 - see also* seismic codes of practice
 - Eurocode 8, comparisons 120–126
- intermediate-storey collapse 6
- internal structure, lateral loadings 168
- interstorey drifts
 - ductility-modified spectra 61
 - estimating 199
 - seismic isolation 234, 234
- isolation gaps 235–236
- Japan, seismic codes of practice 119
- knee-braced frames 109–110, 110
- Kobe (Japan, 1995)
 - fires 16, 220
 - liquefaction-induced failures 128
 - port damage 3, 3
 - seismic isolation 115, 239
 - steel structures, failure 107, 108, 183–184, 191
 - timber structures 220
- Kocaeli (Turkey, 1999) 20, 116, 117, 256–257
- landslips, consequential 2–3, 20, 91
- lead–rubber bearings 242, 243
- life safety levels 258–260
- linear static analysis, equivalent 63–65
- linear time-history analysis 66
 - frequency domain 66–67
- liquefaction
 - assessing potential for 84–89, 85
 - consequences of 89–90, 89
 - definitions 84
 - foundation failures 3, 17, 17
 - loss of intergranular stability 2–3, 20
 - and porewater pressures 84
- Loma Prieta (USA, 1989) 175, 175
- masonry
 - adobe, weaknesses 15, 206–207
 - ashlar, stability 15, 15, 207–208, 207, 214, 215
 - blocks/bricks, compressive strength 210
 - cladding 232
 - clay tiles, hollow 208, 208
 - columns, earthquake resistance 214, 215
 - confined 209, 212
 - free-standing, toppling 16, 16
 - historic, overturning 212, 213, 214
 - in-plane failures 16
 - in-plane shear strength 210–211
 - infill panels 169, 203
 - out-of-plane
 - failure mechanisms 212, 213, 214
 - strengths 211–212
 - principles of 216–218

- reinforced 212
 - shear strength 211
 - steel requirements 209
- reinforced concrete blocks 208–209, 208
- rubble 15, 207
 - failure 7
- seismic reduction factors 216
- shear wall areas 217
- slender 211, 212
- strengthening, by guniting 270
- as structural material 103
- unreinforced 209, 212, 257–258
 - shear strength 211
- mass distribution, buildings 100
- mechanical systems 18–19
- Mexico City (Mexico, 1985)
 - cladding failure 226, 226
 - foundations, bearing capacity failure 133, 133
 - reinforced structure collapses 4, 6–7
 - shear wall performance 256, 257
 - soil conditions 30, 30, 81
 - steel-framed structure collapse 8, 183, 183
- modal response spectrum analysis 65–66
- moment-resisting frames
 - advantages 104
 - beam-column joints 160–161, 165, 165
 - blockwork infill 106
 - grid frame 105, 105
 - height-to-base ratios 104–105
 - internal structure 168
 - masonry infill panels 169, 203
 - perimeter frame 105–106, 105
 - potential problems 104
 - precast 106
 - shear walls 112
 - steel-framed structures 199–201
- multiple degrees of freedom (MDOF)
 - ductility-modified spectra 61, 602
 - modal responses 49–51, 50
 - base shear 53, 53
 - peak acceleration 51
 - spectrum analysis 52–53, 52
- non-cohesive soils 2–3, 98–99
- non-ferrous reinforcements 152
- non-linear dynamic responses 40
- non-linear static analysis 68–69
 - capacity spectrum method 70–73, 72, 74–75, 75
 - static pushover analysis 69, 69, 70
 - target displacement method 69–70, 73, 74–75, 75
- non-linear time-history analysis 67–68
- non-structural elements
 - see also* cladding
 - acceleration-sensitive 226–227
 - analysis 228–229
 - floor response spectra 229–230
 - testing 227, 230
 - displacement-sensitive 226, 226, 227–228
 - heavy, within roofs 18
 - interaction 102
 - nuclear plant 230–231
 - seismic codes of practice 126
 - services 231–232
 - tank design 231
- Northridge (USA, 1994)
 - column bursting 12
 - response spectra 27–28, 28
 - seismic isolation 115, 239
 - steel structures, failure 183, 184–185, 184, 191
 - time histories 26, 27
- nuclear facilities 115, 230–231
- openings, failure triggers 173–174, 174
- overstrength, capacity design 75
- overturning, historic masonry 212, 213, 214
- P-delta effects 55, 55
- pad and strip foundations
 - bearing capacity failures 131, 132, 133
 - rotational failures 131, 132
 - sliding failures 131, 132
 - structural failures 132, 132
- partial seismic isolation 250
- peak deflection, derivation 45–46, 46
- peak ground accelerations (pga) 29
 - and seismic codes of practice 34–35
- peak spring force, derivation 45–46, 46
- peak velocity 29
- periods
 - structural
 - determination 44, 121–122
 - fundamental 41
- permeability coefficient, soils 137–138
- Peru (1970) 2, 3
- piles
 - bridges, superstructure failures 17–18, 18
 - confinement steel 135
 - detailing measures 135

- piles — contd.
 - horizontal effects 134–135, 134
 - plastic hinge formation 135
 - raking 135–136, 136
 - seismic resistance 102–103
 - vertical effects 134
- plant rooms, high level 18, 100
- plastic deformations, structural steel 182–183
- plastic hinges
 - beams
 - definitions 157–158, 158
 - formation 144
 - reversing 144, 145
 - rotational 146–148, 147, 157–158, 157, 158
 - cyclic loadings 147–149, 148
 - piles 135
 - prevention of 268
 - reverse, sliding 144, 146, 146
- plastic yielding 101
- porewater pressure, and soil liquefaction 84
- precast concrete
 - cladding 232
 - frames 169
 - panel buildings 13, 13
 - tilt-up panels 175, 175
- prestressed concrete 151–152
 - cyclic responses 152, 152
 - unbonded 179
- probabilistic hazard assessments 33–34, 33, 34
- radiation damping 92, 92
- raft foundations 133–134, 133
- raking piles 135–136, 136
- reinforced concrete
 - see also* reinforced concrete structures; reinforcements
 - beam–column joints, failure 11
 - beams 144, 145, 146–149, 148
 - capacity design 75–76, 76
 - plastic hinge rotation 157–158, 157, 158
 - columns 149–150
 - failures 12
 - curvature–moment relationships 156–157, 156
 - cyclic loading behaviour 141
 - shear walls 150–151, 150
- reinforced concrete blocks 208–209, 208
- reinforced concrete structures
 - see also* moment-resisting frames; shear walls
 - complete collapse 4
 - damping in 155
 - ductility 158–159
 - earthquake damage in 140–141
 - frames, design of 159–160
 - rotational capacity, elemental 155–158, 156, 157
 - shear resistance 144, 145
 - stiffness modelling 154–155
 - upper-storey collapse 6
- reinforced masonry 212
 - shear strength 211
 - steel requirements 209
- reinforcements
 - anchorage 143–144
 - mild steel
 - cyclic behaviour 141–142, 141
 - specifications 152–154
 - stress–strain relationships 141
 - non-ferrous 152
 - reverse cycle loadings 143
- resonance
 - definition 40
 - steady-state response 40–41, 41
- response spectra 28
 - absolute and relative values 47
 - acceleration spectra 47–48, 47
 - Fourier 48, 48
 - advantages 26–28, 28
 - analysis 45
 - capacity displacement spectra 48–49, 49
 - displacement spectra 47–48, 47
 - and peak deflection 45–46, 46
 - and peak spring force 45–46, 46
 - in seismic codes of practice 34–35
 - seismic isolation 250
 - site-specific 35–36
 - velocity spectra 48, 48
- response spectrum analysis, modal 65–66
- retaining structures
 - active and passive 136–137
 - fluid pressures on 137–138
 - soil liquefaction 136, 137
- return periods
 - earthquakes 24–25, 32–33, 120
 - hazard assessments 33, 33
- reverse plastic hinges, sliding shear failures 144, 146, 146

- roofs
 - as diaphragms 176, 177
 - flexibility 178
 - massive 18, 100
 - preliminary sizing 176–177
 - transfer forces 176, 177, 178
- rubble masonry 7, 15, 207

- St Johns (Antigua, 1974) 12, 16
- San Fernando (USA, 1971) 10, 10
- San Francisco (USA, 1906) 1
- San Francisco (USA, 1989) 16, 220
- sands
 - damping effects 83
 - stiffness 82
 - strength 83–84
- seismic analysis
 - buildings
 - methods 78
 - models 78
 - objectives 77–78
- seismic codes of practice
 - combined horizontal forces 126
 - deflection limits 124
 - design strength 124
 - development of 118
 - equivalent static design 120–122
 - Eurocode 8/IBC comparisons 120–126
 - foundations 125–126
 - Japan 119
 - load combinations 124–125
 - non-structural elements 126
 - performance goals 118–119
 - response spectra in 34–35
 - seismic isolation 239
 - timber structures 221–223
 - universal adoption 117
 - vertical forces 126
- seismic isolation
 - active systems 251–252
 - analysis
 - axial rotation 249–250
 - response spectra 250
 - rigid isolation layer 248–249
 - applications 236, 237, 238, 238
 - base isolation 235, 250
 - basic principles 234–235, 234
 - bearings
 - friction pendulum 243, 245, 245
 - high damping rubber 242–243, 243, 244
 - lead–rubber 242, 243
 - testing 251
 - bridges 115, 238, 242
 - building design constraints 245–247
 - codes of practice 239
 - Coulomb dampers 241
 - effects of 235–236, 235
 - emergency facilities 239
 - history of 233–234
 - horizontal flexibility 240, 240
 - hysteretic dampers 241, 241, 268, 269
 - isolation gaps 235–236
 - nuclear facilities 115
 - partial 250
 - performance 239
 - positioning 247
 - re-centring 236, 241–242
 - retrofitting 238, 238, 247, 250, 270, 270
 - semi-active systems 252–253, 252
 - services 235
 - stepping columns 240, 240
 - structural suitability 114–115
 - systems 239–240
 - vertical motion 236
 - viscous dampers 241
- seismic reduction factors, masonry walls 216
- seismic resistance
 - economics of 115–116
 - foundations 102–103
 - isolation 114–115
- seismicity, areas of 32, 32, 34
- semi-active systems, seismic isolation 252–253, 252
- services
 - automatic shutdown valves 231–232
 - buried 231
 - displacement damage 19
 - electrical 18–19
 - seismic isolation 235
- shear behaviour, soils 81–82, 81
- shear failures, sliding, reverse plastic hinges 144, 146, 146
- shear movements, subsurface 3, 4
- shear strength, reinforced concrete 144, 145
- shear walls
 - bending moments 150–151, 150
 - boundary elements 173
 - compression failures 13, 14
 - concrete 103
 - as strength columns 110–111
 - coupled 112–113, 114

- shear walls—contd.
 - cross-wall construction 111, *111*
 - ductility 110
 - external, retrofitting 256
 - failure 151
 - frame-wall systems 112
 - outriggers 112, *113*
 - isolated, aspect ratio 111
 - masonry 217
 - moment-resisting frames 112
 - openings, as failure triggers 173–174, *174*
 - precast 111–112
 - precast panels, large 175–176, *175*
 - sizing 169
 - slender
 - definition 150
 - failures 151
 - flexural strength 170, *170*, *171*
 - shear strength 170, *170*, *171*, *172*
 - tension shift 170–171, *172*
 - squat 151, 173
 - strength, torsional movements 7
 - strengthening buildings by 266–267, *267*
 - wind motions, control 112, *113*
- Shinhang dam (Taiwan, 1999) 4
- slender masonry walls 211, 212
- slender shear walls
 - definition 150
 - failures 151
 - flexural strength 170, *170*, *171*
 - shear strength 170, *170*, *171*, *172*
 - tension shift 170–171, *172*
- slender struts
 - cyclic loading effect 186–187, *187*
 - intermediate 187–188, *188*
- sliding shear failures, reverse plastic hinges 144, 146, *146*
- slope stability, soils 91
- soft-storeys
 - collapse 5, 100, 220
 - cross-walls, discontinuation 111
 - ductility 55, 56, 57
 - prevention of 160
- soils
 - amplification effects 30–31, *30*, *31*, 90
 - classification of 97–99, 120–121
 - clays
 - damping effects 83
 - stiffness 82–83, 82
 - coefficient of permeability 137–138
 - cohesive 84, 98–99
 - compression effects 81
 - damping effects 82
 - radiation 92, 92
 - foundations, liquefaction potential 138–139
 - granular, strength 83–84
 - inertia 81
 - influence on planning 97–100
 - liquefaction
 - assessing potential for 84–89, 85
 - consequences of 89–90, 89
 - definitions 84
 - foundation failures 3, 17, *17*
 - and intergranular stability 2–3, 20
 - and porewater pressures 84
 - potential for 84–85, 85, 138–139
 - retaining structures 136, *137*
 - non-cohesive 98–99
 - responses, foundations 129–130
 - sands
 - damping effects 83
 - stiffness 82
 - strength 83–84
 - shear behaviour 81–82, *81*
 - slope stability 91
 - strength parameters, foundations 130–131
 - structure interaction 31
 - foundations 92–93, 92
- Spitak (Armenia, 1988) 13, *13*, 106, 112
- squat shear walls 151, 173
- static pushover analysis 69, *69*, *70*
- steel
 - compressive stresses, reversing loads 185
 - reinforcements
 - cyclic behaviour 141–142, *141*
 - specifications 152–154
 - stress–strain relationships 141
 - specifications 191
 - structural 103
 - flange buckling 188–190, *189*, *190*
 - plastic deformations 182–183
 - suitability 182–183
 - types of damage 13, 15
 - struts
 - slender 186–188, *187*, *188*
 - stocky 186, *186*
 - welds
 - brittle failures at 184–185, *184*
 - low-cycle fatigue 185, 190–191
 - specifications 191–192

- steel–concrete composite structures 204
- steel-framed structures
 - beam–column joints
 - bolted 203, 203
 - welded 201–202, 202
 - collapse 8, 183, 183
 - centrically braced frames 193, 193
 - capacity design 195
 - diagonal and V-braced 193, 195
 - effects of 194
 - K-braced 193, 196
 - X-braced 193, 195
 - ductility 192, 194
 - eccentrically braced frames 196–197, 197
 - link rotation demands 196–198, 196
 - flexural hinges 192
 - moment-resisting frames
 - beams 199–200
 - columns 200
 - panel zones 200–201
 - preliminary sizing 198–199
 - scale effects 191
 - unbraced, flexibility 192–193
 - welded box columns, failures 183
- stepping columns, seismic isolation 240, 240
- stocky struts 186
 - reversing loads 186, 186
- strengthening buildings
 - analysis 263–265
 - by confining jackets 268
 - cost–benefit analysis 259
 - by cross-bracing 267–268
 - by floor strengthening 268–269
 - groups, policies 272
 - masonry walls, guniting 270
 - by passive dampers 268
 - performance targets 258–259
 - plastic hinges, prevention of 268
 - by seismic isolation 270, 270
 - by shear walls 266–267, 267
 - wall-to-floor connections, improving 269
- structural collapse, causes 4, 9
- structural irregularities, earthquake
 - susceptibility 100
- structural materials, choice of 103
- structural walls *see* shear walls
- struts
 - slender
 - cyclic loading effect 186–187, 187
 - intermediate 187–188, 188
 - stocky 186
 - reversing loads 186, 186
- target displacement method
 - non-linear static analysis 69–70
 - interpretation 73, 74–75, 75
- tectonic plate boundaries 32, 32
- tilt-up precast concrete panels 175, 175
- timber, uses of 219
- timber structures 16
 - advantages 103
 - bamboo 223–224, 223
 - damping ratios 219–220
 - decay 220
 - fires 16, 220
 - floors, as strength members 220
 - frames 220
 - joints 220, 222
 - pancake collapse 220
 - seismic codes of practice 221–223
 - soft-storey failure 220
- time-histories 26, 27
 - analysis
 - artificial 36
 - floor response spectra 229–230
 - low seismicity areas 36–37
 - past events 36
 - disadvantages 26
 - linear analysis 66–67
 - non-linear analysis 67–68
- Tokyo (Japan, 1923) 16, 220
- topographical effects, amplification 31, 91
- torsional ground motions 29
- tsunamis 20
- Umbria-Marche (Italy, 1997) 257–258
- unbonded prestressed concrete 179
- unreinforced masonry 209, 212, 257–258
 - shear strength 211
- upper-storey collapse, reinforced concrete
 - structures 6
- velocity spectra 48, 48
- vertical forces 29
 - seismic codes of practice 126
 - seismic isolation 236
- viscous dampers, seismic isolation 241
- wall openings, as failure triggers 173–174, 174

weak storeys *see* soft storeys

welds

beam-column joints 201–202, 202

brittle failures at 184–185, 184

low-cycle fatigue 185, 190–191

specifications and procedures

191–192

wind

motions, control 112, 113

seismic isolation 115

yielding responses

dealing with 62–63

significant 62