Earthquake design practice for buildings

Second edition

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Contents

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.

Acknowledgements

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**
$\boldsymbol{a}_{\mathrm{g}}$	Peak ground acceleration: m/s^2
b	Width of compression flange of concrete beam: m
b_{f}	Breadth of flange of steel section: m
$\boldsymbol{c}_{\mathrm{u}}$	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
$\boldsymbol{F}$	Force: kN
$\boldsymbol{f}'_{\mathrm{c}}$	Cylinder strength of concrete: kN/m^2
$\boldsymbol{f}'_{\mathrm{cc}}$	Compressive strength of concrete under confining pressure $\boldsymbol{f}_1$: kN/m^2
$\boldsymbol{f}_1$	Hydrostatic confining pressure on an element of concrete: kN/m^2
$\boldsymbol{F}_{\mathrm{a}}$	Horizontal force on non-structural element: kN
$\boldsymbol{F}_{\mathrm{b}}$	Seismic shear at base of building: kN
$\boldsymbol{f}_{\mathrm{b}}$	Compressive strength of masonry: kN/m^2
$\boldsymbol{F}_{\mathrm{elastic}}$	Seismic force developing in an elastic (unyielding) system: kN
$\boldsymbol{F}_{\mathrm{i}}$	Force at level i: kN
$\boldsymbol{F}_{\mathrm{plastic}}$	Seismic force developing in a plastic (yielding) system: kN
$\boldsymbol{F}_{\mathrm{y}}$	Yield force: kN
$\boldsymbol{f}_{\mathrm{y}}$	Yield strength of steel: kN/m^2
g	Acceleration due to gravity n/s^2
$\boldsymbol{G}_0$	Shear modulus of soil at small strains: kN/m^2
$\boldsymbol{G}_{\mathrm{s}}$	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
$\boldsymbol{k}$	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
$\boldsymbol{M}_{\mathrm{A}}$, $\boldsymbol{M}_{\mathrm{B}}$	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
$\boldsymbol{M}_{\mathrm{p}}$	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
$\boldsymbol{P}$	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
$\boldsymbol{S}_{\mathrm{a}}$	Spectral acceleration: m/s^2

$\boldsymbol{S}_{\mathrm{ai}}$	Spectral acceleration corresponding to the period of mode i: m/s^2
S_{d}	Spectral displacement: m
$\boldsymbol{S}_{\mathrm{e}}(T)$	Spectral acceleration, based on elastic response, corresponding to structural period T: m/s^2
$\boldsymbol{S}_{\mathrm{v}}$	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
$T_{\mathrm{B}}, T_{\mathrm{C}}$	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
$\boldsymbol{u}_{\mathrm{elastic}}$	Seismic displacement of elastic (unyielding) system: m
$\boldsymbol{u}_{\mathrm{plastic}}$	Seismic displacement of a plastic (yielding) system: m
$\boldsymbol{u}_{\mathrm{ult}}$	Displacement at ultimate capacity: m
$\boldsymbol{u}_{\mathrm{y}}$	Displacement at yield: m
$\boldsymbol{v}$	Masonry shear strength under zero compressive load: kN/m^2
$\boldsymbol{V}_1, \boldsymbol{V}_2, \boldsymbol{V}_3$	Seismic shears at base of building corresponding to first, second, third modes: kN
$\boldsymbol{v}_{\mathrm{d}}$	Design in-plane shear strength of masonry: kN/m^2
$\boldsymbol{V}_{\mathrm{p}}$	Shear capacity of the shear link in an eccentrically braced frame (EBF): kN
$\boldsymbol{V}_{\mathrm{u}}$	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
$\phi_{\mathrm{i}}(x)$	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,

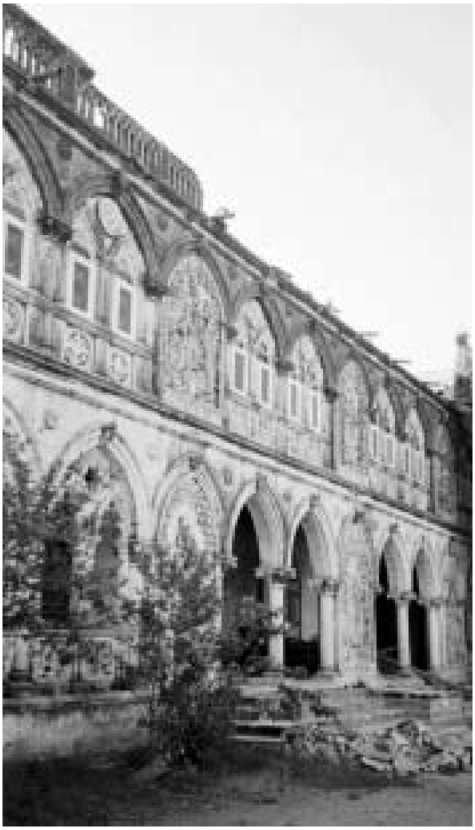

Fig. 10.1 Increase in seismic damage with height in a stone masonry building, Gujarat, India, 2001

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

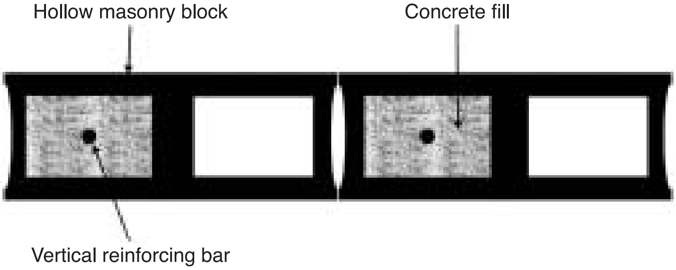

Fig. 10.3 Typical reinforced concrete hollow blocks

Index

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