Earthquake Design of Concrete Masonry Buildings:

Response Spectra Analysis and General Earthquake Modeling Considerations

Earthquake Design of Concrete Masonry Buildings:

Volume 1

Response Spectra Analysis and General Earthquake Modeling Considerations

Robert E. Englekirk

Gary C. Hart

Englekirk and Hart
Consulting Engineers, Inc.

and

The Concrete Masonry Association
of California and Nevada

PRENTICE-HALL, INC. Englewood Cliffs, New Jersey 07632

Library of Congress Cataloging in Publicatior

Englekirk, Robert E., 1936-
Earthquake design of concrete and masonry buildings.

Includes bibliographies and index.
Contents: v. 1. Response spectra analysis and general earthquake modeling considerations.
1. Earthquakes and building. 2. Concrete construction. 3. Masonry. I. Hart, Gary C. II. Concrete Masonry Association of California and Nevada. III. Title.
TH1095.E53 693.8'52 81-21141
ISBN 0-13-223065-8 (v. 1) AACR2

Editorial production/text design: Margaret McAbee
Manufacturing buyer: Joyce Levatino

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Prentice-Hall International, Inc., *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall of Canada, Ltd., *Toronto*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall of Southeast Asia Pte, Ltd., *Singapore*
Whitehall Books Limited, *Wellington, New Zealand*

PREFACE

The Concrete Masonry Association of California and Nevada recognizes that the safe and economical design of buildings often requires the structural engineer to perform an earthquake design that is state-of-the-art. Therefore, the Association has committed funding for the development of a three-book series on the earthquake design of concrete masonry buildings. Robert E. Englekirk and Gary C. Hart are writing the three books. Stuart Beavers is coordinating the efforts of the Concrete Masonry Association of California and Nevada.

This is the first book in the earthquake design series. The second book will describe earthquake design procedures for one- to four-story concrete masonry buildings. The third book will discuss earthquake design procedures for concrete masonry buildings taller than four stories. Many structural vibration books explain the response spectral analysis procedure, however, they do not show the necessary structural modeling assumptions, nor is the material presented in terms of the simplifications that can, and usually are, made for building applications. This text seeks to fill those needs. It is further intended to provide a foundation for two subsequent design books.

Only recently have U.S. Colleges and universities begun to include the structural dynamics of building design in their civil engineering curricula. Thus, two groups of structural engineers will be assisted by this text: the first group is composed of those now professional engineers who are currently involved in structural design and who are desirous of educating themselves in earthquake response spectra analysis; the second group is comprised of college students who require such material on earthquake design procedures.

Both authors have years of experience in structural analysis and the design of buildings in what is known as "earthquake country."

CONTENTS

	Preface		ix
1	**Introduction**		1
	1.1	General	1
	1.2	Structure of the Book	3
	1.3	Earthquake Design: An Overview	4
2	**Earthquake Ground Motion**		7
	2.1	General	7
	2.2	Time Histories of Earthquake Ground Motion	9
	2.3	Earthquake Response Spectrum	9
	2.4	Earthquake Design Spectrum	16
	2.5	Examples	20
	2.6	Additional Reading	26
3	**Static Earthquake Design Forces**		27
	3.1	General	27
	3.2	Base Shear Force (UBC)	28
	3.3	Lateral Story Forces (UBC)	33
	3.4	Proposed Static Design Procedures	34
	3.5	Examples	38
	3.6	Additional Reading	41

4 Modeling of Shear Wall Buildings 43

4.1 General 43
4.2 Looking at the Building System 43
4.3 Floor Diaphragms 46
4.4 Flexible Floor Diaphragms 50
4.5 Rigid Floor Diaphragms 52
4.6 Examples 53
4.7 Additional Reading 69

5 Shear Wall Response Using Elastic Response Spectra 71

5.1 General 71
5.2 Displacement of Shear Wall Substructure 72
5.3 Fundamental Mode Response Spectrum Analysis 73
5.4 Damping 75
5.5 Fundamental Period of Vibration 76
5.6 The Participation Factor 77
5.7 The Damage Level Earthquake Spectral Design Procedure 79
5.8 Ultimate Strength of Concrete Masonry Shear Walls 81
5.9 Examples 82
5.10 Additional Readings 90

6 Shear Wall Response Using Inelastic Response Spectra 91

6.1 General 91
6.2 Ductility 93
6.3 Construction of Inelastic Yield Spectra 96
6.4 Calculation of Shear Wall Forces 102
6.5 Calculation of Shear Wall Deflections 103
6.6 The Collapse Level Earthquake Spectral Design Procedure 104
6.7 Examples 104

Appendix A: The Geotechnical Consultant's Role 113

Appendix B: Multi-Degree-of-Freedom Response Spectra Analysis 123

Bibliography 142

Index 143

1

INTRODUCTION

1.1 GENERAL

This book, the first in a three-book series on the earthquake design of concrete masonry buildings, presents the essential background material for the calculation of earthquake loads on buildings by means of response spectrum analysis. Since we present the spectral analysis procedure in a general form, it also applies to other types of buildings.

Consider, for example, a shear wall building and isolate one shear wall for discussion. The base shear force that a single earthquake produces on this wall is denoted V_D. This base shear force can be visualized as the *base shear demand* on the wall. The concrete masonry wall has a strength that resists this force. This strength, called the *base shear capacity*, is denoted V_C. If for a single earthquake the base shear demand V_D exceeds the base shear capacity V_C, at the very least an undesirable structural performance known as failure occurs. Therefore if one defines

$$
\begin{aligned}
F &= (\text{capacity}) - (\text{demand}) \\
&= V_C - V_D
\end{aligned}
\tag{1.1}
$$

then failure will occur when F is less than or equal to zero.

This book addresses many of the important aspects of calculating V_D, the earthquake-induced demand on the building. A response spectrum analysis is used to calculate this demand. This book also presents the static equivalent load approach of the Uniform Building Code (UBC) [1.1] and the Applied Technology Council (ATC) [1.2].[1] These approaches are then compared with response spectrum load demands.

Although the structural engineer must rely on the geotechnical consultant to develop the response spectra for a specific building site, it is the structural engineer who uses these spectra together with the building model to evaluate the adequacy of member designs. Therefore it is the structural engineer who must ensure that the geotechnical consultant provides a spectrum whose risk is consistent with the structural design problem. Appendix A addresses the responsibilities of the geotechnical consultant in this regard.

The demand/capacity relationship in Equation (1.1) is the basis of modern code development. The load determined by static code formulas is multiplied by a factor that increases the load to ultimate levels. The capacity of the member according to code formulas is an estimate of nominal ultimate strength. This nominal capacity is multiplied by a reduction factor to obtain the design capacity of the member. Stated differently,

$$\begin{aligned}\text{Load demand} &= (\text{load factor}) \times (\text{code load})\\ \text{Member capacity} &= (\text{capacity reduction factor})\\ &\quad \times (\text{code nominal capacity})\end{aligned}$$

The load demand established in modern codes is independent of the capacity of the material. The capacity reduction factor depends on the material and on the accepted level of risk. In building codes this risk is quantified by using a term called the *reliability index*. These concepts will be discussed in more detail in Volumes II and III of this design series. In the present context, it is important for the structural engineer to realize that there are two main parts to a response spectrum analysis:

> *The Procedure:* This is the main topic of this book. The analysis procedure calculates the demand V_D for the building—for example, the moments, shears, and overturning forces to which its components will be subjected. These forces can be estimated by using a single-degree-of-freedom response spectrum.

[1] References are denoted [1.1], [1.2], and so on throughout. For bibliographic details see the References at the back of the book.

Definition of the Response Spectrum: The capacity reduction factors used in design depend on the level of risk established by society and quantified by means of the reliability index. Therefore the response spectrum used in design must be defined in a form consistent with this level of risk. This subject is dealt with separately in Appendix A, where we develop a response spectrum consistent with the level of risk currently considered acceptable by society.

1.2 STRUCTURE OF THE BOOK

The reader is not expected to have a knowledge of structural dynamics, but experience in structural design is desirable. Familiarity with earthquake terminology and design codes (such as the Uniform Building Code) is not essential.

Chapter 2 presents a brief introduction to the common terms used in earthquake engineering. The chapter also explains how to obtain an earthquake response spectrum from a record of earthquake ground motion.

Chapter 3 summarizes the present approach taken by the Uniform Building Code (UBC) and most standards, as well as those currently under consideration. These approaches use static forces to represent dynamic earthquake forces. We then compare these static earthquake design forces with the response spectra presented in Chapter 2.

Structural engineers must be able to develop analytic models of buildings. These models have varying degrees of complexity. Chapter 4 explains how the mass and stiffness of shear wall buildings are modeled for earthquake design.

Chapter 5 explains how to represent a shear wall building as a simple single-degree-of-freedom system. Such a representation is often very accurate, especially for preliminary design. In Chapter 5 the building is assumed to respond in a linear elastic manner. The chapter also discusses the calculation of response quantities such as story forces, story overturning moments, interstory displacements, and base shear.

Chapter 6 describes how inelastic, or ductile, response is incorporated into the response spectrum design. This design procedure helps the structural engineer to appreciate how earthquake-induced forces and displacements are influenced by yielding within the system.

Appendix A discusses the definition of response spectra that should be given to the geotechnical consultant so that designs meet the established level of risk. Appendix B extends the single-degree-of-freedom response spectrum analysis of Chapter 5 to a multi-degree-of-freedom response spectrum procedure.

1.3 EARTHQUAKE DESIGN: AN OVERVIEW

Figure 1.1 shows the five basic steps of the earthquake design procedure. Each step involves the structural engineer.

Step 1 usually requires minimal input from the structural engineer. It involves the selection of the building site by the developer and the definition of the building's function. The structural engineer does contribute to this step, however, if the site has unusual features that require special structural systems—for example, a special foundation to minimize potential damage from liquefaction.

Step 2 is performed by the geotechnical consultant, who must study the past earthquake activity of the region and the location of earthquake faults in the vicinity of the building site. The structural engineer must obtain at least two magnitude levels of earthquake ground motion characterization. The first—usually referred to as a *damage-level response spectrum*—characterizes the expected ground motion used in design to minimize damage. The second is a *collapse-*

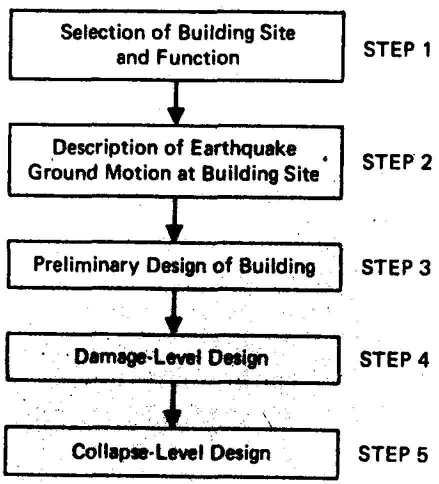

Figure 1.1 The earthquake design procedure

level response spectrum that characterizes the expected ground motion to ensure that the structure will not collapse.

Step 3 requires the structural engineer to determine preliminary sizes for all structural members. In this step, the structural engineer should use static force formulas (as in the UBC) together with an understanding of earthquake intensities to quantify the forces that the structure must withstand. The seismic load paths throughout the structure must then be developed.

In Step 4 the structural engineer analyzes the preliminary design developed in Step 3 by using the damage-level response spectra developed in Step 2. Members should be sized so that the potential for structural damage is minimized. Intrastory drifts should be determined so that components can be designed to accommodate them with a minimum amount of nonstructural damage.

Step 5 requires the structural engineer to reanalyze the design developed in Step 4 to ensure that the structure will not collapse if subjected to an intensity of earthquake ground motion consistent with that used to develop the collapse level response spectrum. The overall collapse of the structure must be prevented and life safety is of paramount concern. The designer must visualize the potential collapse modes (or limit states) of the structure so that the formation of a collapse mechanism can be avoided. Member strain levels may exceed yield levels, but they must be limited to levels less than ultimate to prevent component fracture. Connections must be designed to prevent premature brittle failure in members.

The performance of the above noted steps by the structural engineer can lead to a building design that meets society's needs from both economic and safety viewpoints.

2

EARTHQUAKE GROUND MOTION

2.1 GENERAL

Figure 2.1 is a simplified view of a cross section of the earth. The following terms in the figure should be defined:

Focus (or hypocenter): the center of the initial rupture causing the earthquake

Epicenter: a point on the earth's surface directly above the focus

Focal depth: the depth of the focus beneath the surface

There are two other terms that depend on the specification of a particular building site:

Epicentral distance: the distance from the epicenter to the site

Hypocentral distance: the distance from the focus or hypocenter to the site

Perhaps the most familiar term used to characterize an earthquake is its *Richter magnitude* (*M*). This magnitude is based on an experimental reading obtained on an instrument called a Wood-Anderson seismograph at a specified distance of 100 km from the

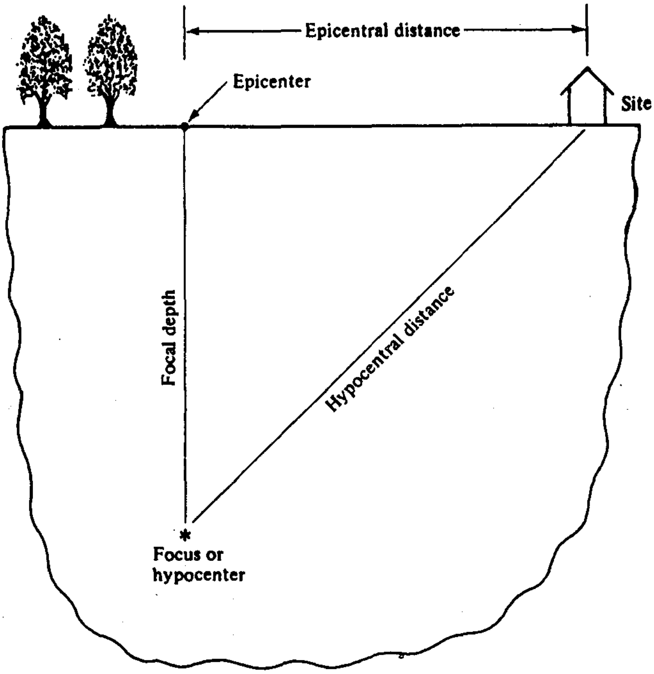

Figure 2.1 Cross-sectional view of Earth

Hart, G. C., *Uncertainty Analysis, Loads, and Safety in Structural Engineering.* Englewood Cliffs, NJ: Prentice-Hall, 1982.

epicenter of the earthquake. If there is no instrument at this distance from the epicenter, empirical formulas are used to estimate the 100-km reading. The Richter magnitude is a measure of the energy released by an earthquake. This energy can be estimated by using the formula

$$W = 10^{11.8 + 1.5M} \tag{2.1}$$

where W = energy in ergs.

The Richter magnitude has been empirically related to the relative displacement between the two sides of a fault at the ground surface and, also, to the total length of the fault rupture. Values of these two quantities provide a physical indication of the relative severity of earthquakes of different magnitude. For example, an empirical relation is

$$\log D = 0.57M - 3.39 \tag{2.2}$$

$$= 0.86 \log L - 0.46 \tag{2.3}$$

where D = relative fault displacement (feet)

L = length of fault rupture (miles)

A *modified Mercalli intensity* (MMI) is used to describe the observed effect of ground shaking at a particular site. Table 2.1 shows the MMI scale. The value of MMI, assigned after an earthquake at a particular site, is a subjective evaluation of damage made by an observer and is valuable in lieu of instrument records of ground motion.

2.2 TIME HISTORIES OF EARTHQUAKE GROUND MOTION

In recent years the acquisition of time histories of earthquake ground motion has become common. Instruments called *strong-motion accelerographs* are placed on the ground to measure earthquake-induced ground motions. The accelerograph measures the three orthogonal components of ground acceleration. Figure 2.2 shows a typical record obtained by an accelerograph; the integrated velocity and displacement time histories are also shown. An acceleration versus time trace is called an *accelerogram*. Figure 2.3 shows a representative accelerogram. The earthquake accelerogram can be interpreted directly to obtain estimates of peak ground acceleration, duration of strong ground shaking, and frequency content.

2.3 EARTHQUAKE RESPONSE SPECTRUM

Earthquake accelerograms show the irregularity of the accelerations as a function of time (Figures 2.2 and 2.3). Although the values for duration of strong shaking and peak ground acceleration provide basic information about the earthquake ground motion, the structural engineer must have a more meaningful characterization for use in structural design. This is provided by a *response spectrum*. The response spectrum is obtained from an accelerogram and indicates how a single-degree-of-freedom oscillator would respond if it were excited by the earthquake ground motion described in the accelerogram.

Figure 2.4 shows two commonly used schematics of a single-degree-of-freedom oscillator system. From both schematics, it is clear that the following quantities must be assigned numerical values before the relative-displacement time history can be calculated:

TABLE 2.1 Modified Mercalli Intensity Scale [Ref. 2.1]

MMI	*Description*
I	Not felt except under especially favorable circumstances.
II	Felt by persons at rest, on upper floors, or favorably placed.
III	Felt indoors. Hanging objects swing. Vibration like passing of light trucks. May not be recognized as an earthquake.
IV	Hanging objects swing. Vibration like passing of heavy truck or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. Wooden walls and frames creak.
V	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters and pictures move.
VI	Felt by all. Persons walk unsteadily. Windows, dishes, glassware broken. Knick-knacks, books, and so forth off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees and bushes shaken visibly or heard to rustle.
VII	Difficult to stand. Noticed by drivers of automobiles. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices, also unbraced parapets and architectural ornaments. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.
VIII	Steering of automobiles affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in floor or temperature of springs and wells. Cracks in wet ground on steep slopes.
IX	General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated area sand and mud ejected, earthquake foundations, and craters.
X	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI	Rails bent greatly. Underground pipelines completely out of service.
XII	Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Definition of Masonry A, B, C, D

Masonry A: Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, and the like; designed to resist lateral forces.

Masonry B: Good workmanship and mortar; reinforced but not designed in detail to resist lateral forces.

Masonry C: Ordinary workmanship and mortar; no extreme weaknesses (such as failing to tie in at corners) but neither reinforced nor designed against horizontal forces.

Masonry D: Weak materials, such as adobe; poor mortar; low standard of workmanship; weak horizontally.

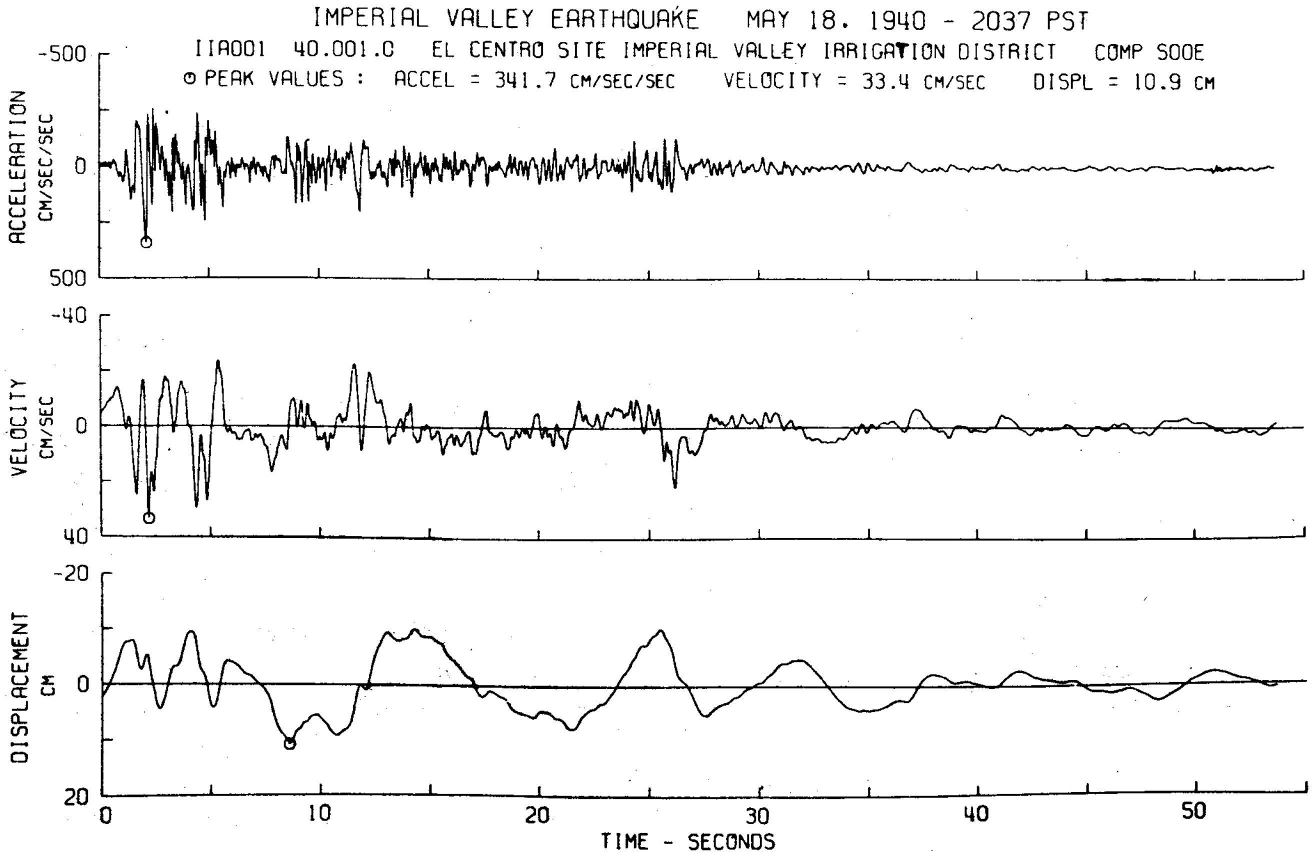

Figure 2.2 Ground acceleration and integrated ground velocity and displacement curves for a typical earthquake

Hart, G. C., *Uncertainty Analysis, Loads, and Safety in Structural Engineering.* Englewood Cliffs, NJ: Prentice-Hall, 1982.