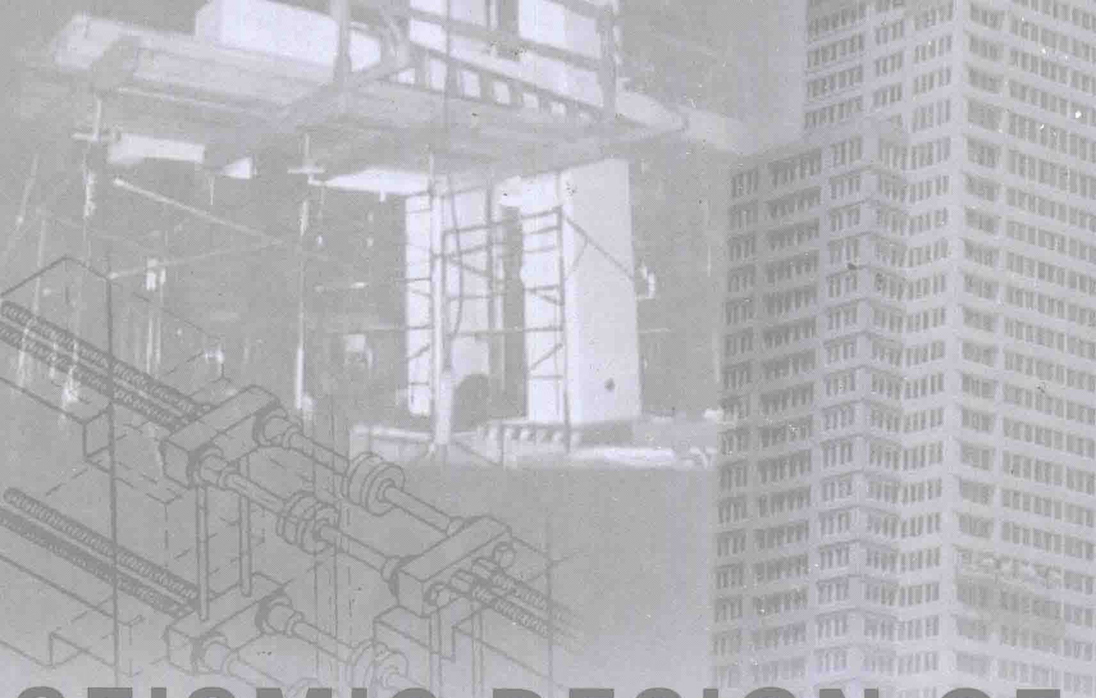

SEISMIC DESIGN OF REINFORCED AND PRECAST CONCRETE BUILDINGS

ROBERT E. ENGLEKIRK

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ROBERT E. ENGLEKIRK
Consulting Structural Engineer
and
Adjunct Professor
University of California at San Diego

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PREFACE

"Man's mind, once stretched by a new idea, never regains its original dimensions."
—Oliver Wendell Holmes

Knowledge and imagination are essential components of the design process. Imagination without knowledge will quite often produce designs that are dangerous. Knowledge absent imagination can only produce designs of limited scope. The development and integration of these themes is the objective of this book.

My hope is to advance the reader's ability to design by reducing existing experimentally developed conclusions to design-relevant relationships and limit states. The reduction of experimental data to a usable form is essential to the design process because an engineer, faced with a design decision, cannot confidently develop a design approach from experiment data or basic principles as a part of each design, especially if the basic principle is not a part of his or her working vocabulary. Behavior models must also be available to and accepted by the designer. To this end Chapters 1 and 2 review experimental evidence and selected fundamental principles in search of appropriate design processes and limit states.

My objective in Chapters 1 and 2 is to stretch the reader's mind, not constrain a design to a particular approach or set of limit states, for I believe that all design procedures must be thoroughly understood and accepted by the user if they are to be appropriately applied. Algorithms, whether contained in a black box or reduced to napkin form, are an essential part of the designer's vocabulary. The algorithms developed herein are presented in sufficient detail so as to allow the user to adapt them to his or her predilection or interpretation of experimental evidence, and this is because it is the engineer, not the algorithm, black box, or experimental data, who is responsible for the building design and safety of the building's occupants.

Engineers are generally characterized as unimaginative or pedantic in their approach to problems. This generalization is not supported by historical evidence, which from a structural perspective includes the creation of ancient structures, medieval cathedrals, and the modern structures of today, because none of these structures were developed from scientifically supportable data. Even today, in our modern scientifically based society that probes the universe, the scientific data used to support building design are more speculative than scientific. The existence of codified relationships expressed in four significant figures only tends to suppress an engineer's imagination by creating a scientific illusion. Imagination cannot be taught, but it can be released and encouraged by removing suppressants, and this is the objective of Chapters 3 and 4.

Imagination can and must be effectively used to apply basic concepts to complex problems. It is also effectively used to extend experimental evidence. The exploitation of precast concrete as a seismic resisting system clearly demonstrates how imagination can be used to create better structural systems. Exploring all possible uses of imaginative thinking is impossible so I have tried to develop several imaginative approaches by example and where possible relate these specific examples to a generalization of the design objective.

Building codes, like dictionaries, are essential tools of the trade. One writes with the assistance of a dictionary—we do not use the dictionary to write. So it should be with design, and it is for this reason that I do not choose to describe or explain design using the building code as a basis. The thrust of this book is to produce structural systems that can be shown by rational analysis and experimental evidence to be capable of attaining performance objectives when subjected to design-level earthquakes.

ACKNOWLEDGMENTS

Absent the dedicated efforts of Joan Schulte, who not only typed but managed the processing of this manuscript; Dan Shubin, who converted my crude sketches to an art form; and my cardiology team, Drs. Kahn, Natterson, and Robertson, this book would not exist.

The concepts explored in this book are more simply applied than explained. The assistance of my associates is gratefully acknowledged and especially that of Nagi Abo-Shadi, Richard Chen, Robert Liu, and Michael Riddell.

My thanks also to Kimberly Tanouye for her design contribution to the cover.

A special expression of gratitude is also extended to those who have taken the time and made the effort to translate ideas and research into the written word on the subject of concrete and earthquake engineering—my good friends and colleagues, Bob Park, Tom Paulay, and Nigel Priestley.

My hope is that the material contained herein will encourage the development of a dialogue that will result in a more rational approach to the seismic design of concrete buildings. The comments of you, the reader, will be appreciated.

I dedicate this book to my family and, in particular, to my wife, Natalie, whose patience and understanding allowed for its development.

NOMENCLATURE

I have chosen to use both English and metric units so as not to alter the graphic description of experimental data. The following conversions are standard:

$$1 \text{ m} = 39.37 \text{ in.}$$

$$1 \text{ kN} = 0.2248 \text{ kips}$$

$$1 \text{ kN-m} = 0.737 \text{ ft-kips}$$

$$1 \text{ MPa} = 1000 \text{ kN/mm}^2$$

ADOPTED NOMENCLATURE

A Area, usually subscripted for definition purposes

A_j Effective cross-sectional area within a joint in a plane parallel to plane of reinforcement generating shear in the joint. The joint depth is the overall depth of the column. The effective width will depend to a certain extent on the size of the beams framing into the joint.

A_{ps} Area of prestressed reinforcement in tension zone

A_s Area of nonprestressed tension reinforcement

A'_s Area of compression reinforcement

A_{sh} Total cross-sectional area of transverse reinforcement (including crossties) within spacings

A_{st} Total area of longitudinal reinforcement

A_1 Loaded area

A_2 The area of the lower base of the largest frustum of a pyramid, cone, or tapered wedge contained wholly within the support and having for its upper base the loaded area and having side slopes of 1 vertical to 2 horizontal

C Compressive force—subscripted when qualification is required

C_d Force imposed on the compression diagonal

D Dead loads; depth of frame

DR Drift ratio (Δ_x / h_x) or (Δ_n / H)

E Load effects of seismic forces, or related internal moments and forces; modulus of elasticity usually subscripted to identify material

EI Flexural stiffness

F Loads attributable to strength of provided reinforcement, usually subscripted to identify condition

F_y Yield strength of structural steel

H Overall height of frame

I_{cr} Moment of inertia of cracked section transformed to concrete

I_e Effective moment of inertia

I_g Moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement

L Live loads, or related internal moments and forces

M Moment in member, usually subscripted to identify loading condition, member, or stress state

M Mass subscripted when appropriate to identify (e) effective or (1) contributing mode

M_{bal} Nominal moment strength at balanced conditions of strain

M_{cr} Cracking moment

M_{el} Elastic moment

M_{pr} Probable flexural moment strength of members, with or without axial load, determined using the probable properties of the constitutive materials

N An integer usually applied to number of bays or number of connectors

P Axial load, usually subscripted to identify load type or strength state

P_b Nominal axial load strength at balanced conditions of strain

P_o Nominal axial load strength at zero eccentricity

P_{pre} Prestressing load applied to a high-strength bolt

Q Stability index for a story—elastic basis (see Section 4.3.1)

Q^* Stability index for a story—inelastic basis (see Section 4.3.1)

$\hat{R}$ Spectral reduction factor

S_a Spectral acceleration—in./sec

S_{ag} Spectral acceleration expressed as a percentage of the gravitational force g

S_d Spectral displacement

S_v Spectral velocity

SF	Square feet
U	Required strength to resist factored loads or related internal moments and forces
V	Shear force usually quantified to describe associated material or contributing load
V_c	Shear strength provided by concrete
V_{ch}	Nominal capacity of the concrete strut in a beam-column joint
V_N	Component of joint shear strength attributed to the axial load imposed on a column load
V_{sh}	Nominal strength of diagonal compression field
W	Wind load
W	Weight (mass) tributary to a bracing system

a	Depth of equivalent rectangular stress block, acceleration, shear span
b	Width of compression face of member
b_w	Web width
c	Distance from extreme compression fiber to neutral axis
c_c	Clear cover from the nearest surface in tension to the surface of the flexural tension reinforcement
d	Distance from extreme compression fiber to centroid of tension reinforcement
d	Displacement (peak) of the ground
$\dot{d}$	Velocity (peak) of the ground
$\ddot{d}$	Acceleration (peak) of the ground
d'	Distance from extreme compression fiber to centroid of compression reinforcement
d_b	Bar diameter
d_s	Distance from extreme compression fiber to centroid of tension conventional reinforcement
d_{ps}	Distance from extreme compression fiber to centroid of prestressed reinforcement
d_z	Depth of the plate
e	Eccentricity of axial load
f	Friction factor; measure of stress, usually subscripted to identify condition of interest
f'_c	Specified compressive strength of concrete
f'_{ci}	Compressive strength of concrete at time of initial prestress
$\sqrt{f'_{ci}}$	Square root of compressive strength of concrete at time of initial prestress
f_{cr}	Critical buckling stress
f_{ct}	Average splitting tensile strength of aggregate concrete

f_{cg}	Stress in the grout
f_{pse}	Effective stress in prestressed reinforcement (after allowance for all prestress losses)
f_{py}	Specified yield strength of prestressing tendons
f_r	Modulus of rupture of concrete
f_s	Calculated stress in reinforcement
f_{sc}	Stress in compression steel
f_y	Specified yield strength of reinforcement
f_{yh}	Specified yield strength in hoop reinforcing
h	Overall thickness of member
h_c	Cross-sectional dimension of column core measured center-to-center of confining reinforcement
h_n	Height of the uppermost level of a frame
h_w	Height of entire wall or of the segment of wall considered
h_x	Maximum horizontal spacing of hoop or crosstie legs on all faces of the column; story height
k	Effective length factor for compression members; system stiffness usually subscripted to identify objective
k_{el}	Elastic stiffness
k_{sec}	Secant stiffness
kd	Depth of neutral axis—elastic behavior is assumed
ℓ	Span length of beam center to center of supporting column
ℓ_c	Clear span of beam from face to face of supporting column
ℓ_d	Development length for a straight bar
ℓ_{dh}	Development length for a bar with a standard hook
ℓ_w	Length of entire wall or of segment of wall considered in direction of shear force
n	An integer usually applied to number of floors
r	Radius of gyration of cross section of a compression member
s	Spacing of transverse reinforcement
t_g	Thickness of grout
w	Unit weight
w_z	Width of steel plate
y_t	Distance from centroidal axis of gross section, neglecting reinforcement, to extreme fiber in tension
α	Factor in bar development length evaluation. 1.3 for top bars, 1.0 for bottom bars. See ACI,[2.6] Eq. 12.2.2
β	Coating factor. See ACI,[2.6] Eq. 12.2.2

β_1	Factor that defines the relationship between the depth of the compressive stress block and the neutral axis depth, c[2.6]
γ_p	Postyield shearing angle
Γ	Participation factor
δ_u	Member or component displacement
Δ	An increment of force, stress, or strain
Δ_n	Relative lateral deflection between the uppermost level and base of a building
Δ_x	Relative lateral deflection between the top and bottom of a story
ε	Strain—usually subscripted to describe material or strain state
ζ	Structural damping coefficient expressed as a percentage of critical damping
$\hat{\zeta}$	Total damping coefficient expressed as a percentage of critical damping
θ	Rotation
λ	Lightweight aggregate concrete factor
λ_o	Component or member overstrength factor that describes overstrength expected in a member
μ	Ductility factor usually subscripted; bond stress; friction factor
μ_Δ	Displacement ductility factor
μ_ε	Strain ductility factor
μ_θ	Rotation ductility factor
μ_ϕ	Curvature ductility factor
ρ	Ratio of nonprestressed tension reinforcement, A_s/bd
ρ'	Ratio of nonprestressed compression reinforcement, A'_s/bd
ρ_b	Reinforcement ratio producing balanced strain conditions
ρ_g	Ratio of total reinforcement area to cross-sectional area of column
ρ_s	Ratio of volume of spiral reinforcement to total volume of core (out-to-out of spirals) of a spirally reinforced compression member
ρ_v	Ratio of area of distributed reinforcement perpendicular to the plane of A_{cv} to gross concrete area A_{cv}
ϕ	Curvature, rad/in.; capacity-based reduction factor; strength reduction factor
ϕ_e	Normalized elastic displacement (Δ_i/Δ_u)
ϕ_k	Stiffness reduction factor
ϕ_p	Probable overstrength of the steel
ω	Reinforcement index $\rho f_y/f'_c$
ω'	Reinforcement index $\rho' f_y/f'_c$
ω_p	Reinforcement index $\rho_p f_{ps}/f'_c$
Ω_o	System overstrength factor

SPECIAL SUBSCRIPTS

Special subscripts will follow a notational form to the extent possible. Multiple subscripts will be used where appropriate, and they will be developed as follows:

1. s, u, n, p, pr, y, i, max, and M will be used to describe member strength or deformation state:

   s, service or stress limit state (unfactored)

   u, ultimate or factored capacity (strength)

   n, nominal capacity

   p, postyield

   pr, probable

   i, idealized

   y, yield

   max, maximum permitted

   min, minimum permitted

   M, mechanism
2. c, b, s, f, and p will be used to describe a member category or characterize a system behavior condition:

   c, column

   b, beam

   s, shear component of deformation

   f, flexural component of deformation

   p, postyield component of deformation
3. e, i will be used to describe a location; i will also be used to identify an idealized condition such as yield:

   e, exterior beam or column

   i, interior beam or column
4. L, D, E will be used to describe a load condition:

   L, live load

   D, dead load

   E, earthquake load
5. A, B, C, L, R and 1, 2 will be used to locate an event with reference to a specific plan grid or point:

   L, left

   R, right

Example:

M_{cui}
- i — Interior
- u — Ultimate or factored
- c — Column

M_{bCsD}
- D — Dead load
- s — Unfactored
- C — Grid line C
- b — Beam

M_{uD}
- D — Dead load
- u — Factored

6. Capitalized subscripts will be used to describe the stress class and its location:
   B, bottom
   C, compression
   CB, compression bottom
   CT, compression top
   T, top, tension, transverse
   TB, tension bottom
   TT, tension top
7. Special subscripts will be used to identify the following:
   a, attainable or average
   d, design, as in design basis
   D, degrading or diaphragm
   ed, energy dissipater
   g, grout
   SDOF, single-degree-of-freedom system

CONTENTS