



**SEISMIC DESIGN OF
REINFORCED AND PRECAST
CONCRETE
BUILDINGS**

ROBERT E. ENGLEKIRK

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and

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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 |

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| 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 |

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| 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 |

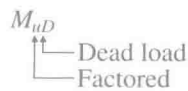
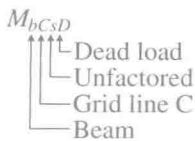
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|-------------------|---|
| β_1 | Factor that defines the relationship between the depth of the compressive stress block and the neutral axis depth, c ^[2.6] |
| γ_p | Postyield shearing angle |
| Γ | Participation factor |
| δ_u | Member or component 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:



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

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