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Guide to Nonlinear Modeling Parameters for Earthquake-Resistant Structures

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Guide to Nonlinear Modeling Parameters for Earthquake-Resistant Structures

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Guide to Nonlinear Modeling Parameters for Earthquake-Resistant Structures

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This guide provides information regarding nonlinear modeling of components in special moment frame and structural wall systems resisting earthquake loads. The reported modeling parameters provide a modeling option for licensed design professionals (LDPs) performing nonlinear analysis for performance-based seismic design of reinforced concrete building structures designed and detailed in accordance with ACI 318.

Keywords: backbone curve; beams; columns; coupling beams; earthquake-resistant structures; flexure; joints; modeling parameters; nonlinear analysis; performance-based engineering; seismic design; shear; special concrete moment frames; special concrete shear walls; special structural walls.

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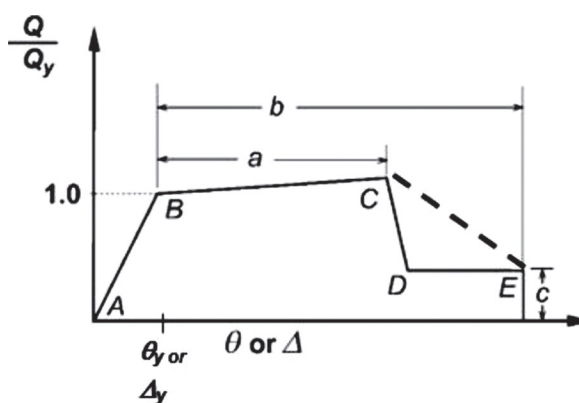
CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

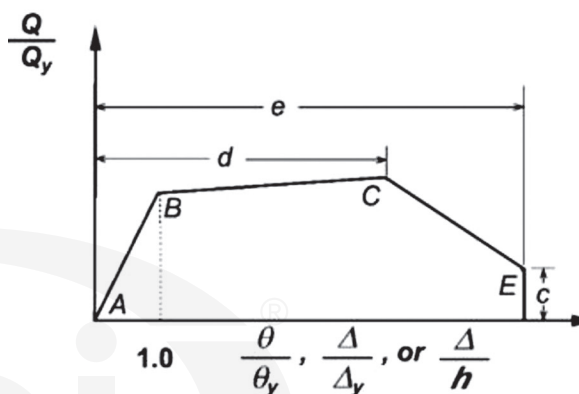
This guide provides nonlinear modeling parameters that will assist the licensed design professional (LDP) in the use of performance-based seismic design of new concrete buildings. Performance objectives are assigned for the given structure and compliance with the performance objectives are then evaluated based on the deformation of structural elements rather than evaluated based on strength under prescriptive requirements. Deformations in structural components allow the LDP to understand damage levels related to seismic hazards.

There are currently several documents that provide general analysis procedures for the design of new buildings using performance-based engineering (ASCE/SEI 7; Structural Engineers Association of Northern California [SEAONC] 2008; Los Angeles Tall Buildings Structural Design Council [LATBSDC] 2014; Pacific Earthquake Engineering Research Center [PEER] [PEER/ATC 2010]). Although these documents provide a means for seismic design indicative of earthquake hazards and acceptance criteria that are similar to ASCE/SEI 41, they do not provide the required information for modeling nonlinear behavior of a structural component based on detailing conditions, such as the development of force-deformation backbone curves shown in Fig. 1.1. This guide provides modeling parameters that can be used to generate the backbone curves of structural members of special moment frame and structural wall systems detailed per Chapter 18 of ACI 318-14.

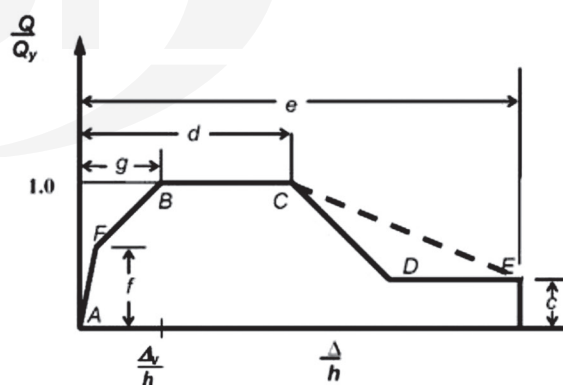
For example, an engineer modeling the nonlinear deformation of a structural wall with specific reinforcement configurations for new design can select from the following three alternatives: 1) develop modeling parameters from existing experimental data; 2) develop and implement a new testing program; or 3) create force-deformation curves using the information in the existing building standard (ASCE/SEI 41) or guideline (ACI 369R) developed for seismic evaluation and rehabilitation. The existing experimental data, however, are not always available, and new testing programs may be limited by budget and project schedule. In addition, the modeling parameters in the existing building standard do not always adequately represent the behavior of components designed according to current codes. Furthermore, they may not be directly applied to new design due to incongruities



(a) Plastic deformation



(b) Deformation ratio or drift



(c) Deformation ratio or drift – Tri-linear response

Fig. 1.1—Generalized force-deformation relations for structural concrete components (ASCE/SEI 41). (Note: a, b, d, e, f, and g are deformations as defined in the reported nonlinear modeling parameter tables.)

in parameter definition and requirements across documents. This guide provides a set of nonlinear modeling parameters that can be used without performing one of the three alternatives given.

1.2—Scope

This guide provides information about nonlinear modeling parameters for:

(a) Special moment frames extracted from ASCE/SEI 41, for which definitions and requirements are converted to those of the codes for the design of new concrete buildings

(b) Special structural walls and coupling beams extracted from ASCE/SEI 41, for which definitions and requirements are converted to those of the codes for the design of new concrete buildings

(c) Special moment frames and structural walls developed from the latest experimental databases of structural components compliant with the requirements of Chapter 18 (ACI 318-14) for earthquake-resistant structures.

In regards to (c), the mean and mean minus one standard deviation modeling parameter values are provided for these code-compliant specimen databases in an effort to demonstrate a quantitative representation of data distribution for the LDP. The LDP can select modeling parameters based on ASCE/SEI 41, or the experimental database, depending on project constraints, jurisdiction requirements, or both.

The modeling parameters in this guide are meant to be used for the analytical modeling of structural components in earthquake-resistant systems as described. The guide, however, does not describe global behavior or provide interaction between different systems in the buildings, for example, diaphragms and moment frames.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_{cv} = gross area of concrete section bound by web thickness and length of section in the direction of shear force considered, in. ² (mm ²)	h_c = average height of the beams framing into the joint in the direction of applied shear, in. (mm)
A_g = gross area of concrete section, in. ² (mm ²)	h_{eff} = effective shear span of wall, in. (mm)
A_j = effective cross-sectional area within a joint in a plane parallel to plane of beam reinforcement generating shear in the joint, in. ² (mm ²) (ACI 318-14 Section 18.8.4.3)	h_w = height of entire wall from base to top, or clear height of wall segment or wall pier, in. (mm)
A_s = area of nonprestressed longitudinal tension reinforcement, in. ² (mm ²)	I_{cr} = moment of inertia of cracked section transformed to concrete, in. ⁴ (mm ⁴)
A'_s = area of compression reinforcement, in. ² (mm ²)	I_g = moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement, in. ⁴ (mm ⁴)
A_v = area of shear reinforcement within spacing s , in. ² (mm ²)	L = length of member along which deformations are assumed to occur, in. (mm)
b = width of compression face of member, in. (mm)	ℓ_d = development length in tension of deformed bar, deformed wire, or plain wire reinforcement, in. (mm)
b_w = web width, or diameters of circular section, in. (mm)	ℓ_p = assumed plastic hinge length, minimum of the following: $0.5\ell_w$, the first-story height, and $0.5h_w$ for wall segments, in. (mm)
d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in. (mm)	ℓ_w = length of entire wall, or length of wall segment or wall pier considered in direction of shear force, in. (mm)
E = effect of horizontal and vertical earthquake-induced forces	M_n = nominal flexural strength at section, in.-lb (N-mm)
E_c = modulus of elasticity of concrete, psi (MPa)	M_{pr} = probable flexural strength of members, with or without axial load, determined using the properties of the member at the joint faces assuming a tensile stress in the longitudinal bars of at least $1.25f_y$ and a strength reduction factor ϕ of 1.0, in.-lb (N-mm)
E_s = modulus of elasticity of reinforcement and structural steel, psi (MPa)	P = design axial force obtained from design load combinations that include overstrength factor or determined from limit-state analysis, lb (N)
f'_c = specified compressive strength of concrete, psi (MPa, $\sqrt{f'_c}$ in MPa = $12\sqrt{f'_c}$ in psi)	Q = generalized force demand in a component
f_y = specified yield strength of reinforcement, psi (MPa)	Q_y = yield strength of a component
h = height of member along which deformations are measured, in. (mm)	s = center-to-center spacing of transverse reinforcement, in. (mm)
h_b = subgrade dimension from absolute base of wall to grade level, in. (mm)	V = design shear force obtained from design load combinations that include overstrength factor or determined from limit-state analysis, lb (N)
	V_e = design shear force for load combinations including earthquake effects, lb (N) (refer to ACI 318-14 Sections 18.6.5.1 and 18.7.6.1.1)
	V_n = nominal shear strength, lb (N)
	V_o = shear strength of a column per ASCE/SEI 41 Eq. (10-3), lb (N)
	V_p = shear demand on a column at flexural yielding of plastic hinges per ASCE/SEI 41 Section 10.4.2.2.2, lb (N)
	V_{si} = nominal shear strength provided by shear reinforcement, lb (N)
	Δ = generalized deformation, in. (mm)
	Δ_y = generalized yield deformation, in. (mm)
	ϵ_y = yield strain of reinforcement, in./in. (mm/mm)
	θ = generalized deformation, radians
	θ_y = generalized yield deformation, radians
	ϕ = strength reduction factor
	ϕ_y = yield curvature at section, 1/in. (1/mm)
	ρ = ratio of nonprestressed tension reinforcement
	ρ' = ratio of nonprestressed compression reinforcement
	ρ_b = ratio of A_s to bd producing balanced strain condition
	ρ_v = ratio of A_v to b_ws



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Ω_0 = amplification factor to account for overstrength of the seismic-force-resisting system (overstrength factor)

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <https://www.concrete.org/store/productdetail.aspx?ItemID=CT16>. Definitions provided herein complement that source.

acceptance criteria—limiting values of properties, such as drift, strength demand, and inelastic deformation, used to determine the acceptability of a component at a given performance level.

drift—horizontal deflection at the top of the story relative to the bottom of the story.

effective stiffness—stiffness of a structural member accounting for cracking, creep, and other nonlinear effects.

licensed design professional—an individual who is licensed to practice structural design as defined by the statutory requirements of the professional licensing laws of the state or jurisdiction in which the project is to be constructed, and who is in responsible charge of the structural design.

modeling parameter—deformation parameter that defines the shape of the nonlinear force-deformation envelope curve of a structural component.

performance objective—one or more pairings of a selected seismic hazard level with both a target structural performance level and a target nonstructural performance level.

probable strength—strength of a member determined using the properties of the member assuming a tensile stress in the reinforcing bars of at least $1.25f_y$ and a strength reduction factor ϕ of 1.0.

special moment frame—a cast-in-place beam-column frame complying with 18.2.3 through 18.2.8 and 18.6 through 18.8 of ACI 318-14.

special structural wall and coupling beam—a cast-in-place structural wall and connecting the structural walls in accordance with 18.2.3 through 18.2.8 and 18.10 of ACI 318-14.

CHAPTER 3—GENERAL

3.1—General

In the following sections, tables of nonlinear modeling parameters are provided for components of special moment frames, special structural walls, and special coupling beam components designed in accordance with Chapter 18 of ACI 318. An experimental database of component specimens compliant with the detailing requirements of ACI 318 was available for columns (Ghannoum and Sivaramakrishnan 2012a,b) and flexure-controlled structural walls (Birely 2012) only. Therefore, while tables derived from ASCE/SEI 41 are available for all component types including columns, beams, beam-column joints, and shear-controlled wall elements, tables derived from the test database are only available for columns and flexure-controlled walls.

The nonlinear force-deformation response of a component can be generalized as a backbone curve by a series of linear relations dictated by the provided nonlinear modeling parameters. This guide adopted the generalization methods

Table 3.1—Effective initial stiffness (ASCE/SEI 41-13 Table 10-5, modified)

Component	Flexural rigidity	Shear rigidity
Beams*	$0.3E_cI_g$	$0.4E_cA_w$
Columns with compression due to design gravity loads $\geq 0.5A_gf_c^{\dagger}$	$0.7E_cI_g$	$0.4E_cA_w$
Columns with compression due to design gravity loads $< 0.1A_gf_c$ or with tension [†]	$0.3E_cI_g$	$0.4E_cA_w$
Beam-column joints	Rigid column offsets and non-rigid beam offsets based on the beam stiffness (Fig. 4.2a)	
Structural walls	Constant stiffness coefficient method: Refer to 5.1.1.1	$0.4E_cA_{cv}$
	Constant yield curvature method: Refer to 5.1.2.1	$0.4E_cA_{cv}$

*For T-beams, I_g can be taken as twice the value of I_g of the web alone. Otherwise, I_g is based on the effective width as defined in Section 6.3 of ACI 318-14.

[†]For columns with axial compression falling between the limits provided, flexural rigidity is determined by linear interpolation.

used in ASCE/SEI 41. Figure 1.1 presents examples of general force-deformation backbone curves and modeling parameters. A typical backbone curve is described by a linear response from Point A (unloaded deformation) to Point B (effective yield), then a linear response from Point B to C (post-yield deformation without degradation of strength), followed by a linear response from Point C to D (strength degradation), and a final line from Point D to E (total loss of strength and deformation capacity limit). The slope from Point A to B (initial stiffness) is selected according to Table 3.1. The stiffness values presented for flexure-controlled elements are meant to represent a secant to yield level forces, neglecting initial stiffness properties prior to flexural cracking. The initial variation of stiffness is not a critical factor for estimation of plastic deformation capacity and is generally lost after the first significant cycle of dynamic loading. It is critical that the effective stiffness values presented be used instead of the stiffness values from Section 6.6.3 of ACI 318 because the modeling parameters based on ASCE/SEI 41 (plastic rotations) were calculated as total deformation minus yield deformation, based on the effective stiffness values defined in this document. The yield strength Q_y of a component is defined as the nominal strength—that is, M_n or V_n calculated in accordance with ACI 318 Chapter 18, without the inclusion of a strength reduction factor ϕ . The slope from Point B to C corresponds to the increase of the component strength, considering the difference between nominal strength and the probable strength associated with strain hardening of the steel reinforcement—that is, $1.25f_y$. The linear relations between Points C, D, and E are determined by the modeling parameters representing the strength degradation at higher deformations. Although ASCE/SEI 41 general backbone curves in Fig. 1.1(a) and (c) show a sudden strength loss from Point C to D, a more realistic approach for concrete compo-