16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 3722 (Abstract ID)
Registration Code: S-I1461794445

THE 2015 LOS ANGELES ALTERNATIVE PROCEDURE FOR SEISMIC ANALYSIS AND DESIGN OF TALL BUILDINGS

F. Naeim[1], L. D. Carpenter[2], T. Ghodsi[3], G. C. Hart[4], M. Lew[5], M. Mehrain[6], T. A. Sabol[7], J. W. Wallace[8]

(1) *President, Farzad Naeim Inc, farzad@fnaeim.com*
(2) *Principal Engineer, WHL Consulting Engineers, L_Carpenter@whl-international.com*
(3) *Principal, Englekirk, tony.ghodsi@englekirk.com*
(4) *Principal Emeritus, Thornton Tomasetti, GHart@ThorntonTomasetti.com*
(5) *Principal Engineer, Amec Foster Wheeler Environment & Infrastructure, marshall.lew@amecfw.com*
(6) *President, Mehrain Naeim International Inc, mehrain@MNIcorp.com*
(7) *Principal, Englekirk, tom.sabol@englekirk.com*
(8) *Professor, University of California Los Angeles, wallacej@ucla.edu*

Abstract

Building codes intend to provide for safe buildings by prescribing provisions that generally address all building and construction types. Tall buildings are a special class of structures that may need to be designed with a different approach to meet their specific safety and performance requirements, especially in regions of high seismicity. To meet this need, the Los Angeles Tall Buildings Structural Design Council (LATBSDC) has recently updated its alternative procedure for seismic analysis and design of tall buildings. LATBSDC has been developing the alternative design procedure over 12 years and has recently published the 2015 edition of this procedure.

Application of this performance-based alternative procedure requires an in-depth understanding of ground shaking hazards, structural materials behavior, and nonlinear dynamic structural response. The aims of the procedure are to provide: a more reliable seismic performance; reduced construction cost; relief from prescriptive design requirements that do not need to apply; accommodation of demanding architectural features; and use of innovative structural systems and materials not currently allowed by the building codes. LATBSDC has also recently published guidelines on the proper use of dual systems for tall buildings.

The following major updates have been implemented in the 2015 edition which is actively being used for design of tall buildings all over the west coast of the United States:

- Updated modeling requirements and acceptability criteria for reinforced concrete walls and coupling beams.
- Incorporation of sensitivity analysis requirements to bound the possible ramifications of the backstay effect.
- Incorporation of adjusted acceptability criteria for buildings in various seismic risk categories.
- Revised design ground motion criteria which permits the use of conditional spectra.

This paper describes the provisions of the 2015 edition and highlights the significance of the performance improvements that can be achieved using these new provisions for design of tall building structures.

Keywords: Tall buildings, performance-based engineering, seismic design, building codes, alternative procedure

1. Introduction

The 2015 LATBSDC procedure [1] provides a performance-based earthquake engineering (PBEE) approach for seismic design and analysis of tall buildings with predictable and safe performance when subjected to strong earthquake ground motions. The intent of the procedure is to result in more transparent and accurate identification of the relevant demands on tall buildings thus providing for structures that effectively and reliably resist earthquake ground motions. The performance-based alternative procedure requires an in-depth understanding of ground shaking hazards, structural materials behavior, and nonlinear dynamic structural response. In particular, the implementation of this procedure requires proficiency in structural and earthquake engineering including knowledge of: seismic hazard analysis and the selection and scaling of ground motions; nonlinear dynamic behavior of structural and foundation systems; mathematical modeling capable of dependable prediction of nonlinear behavior; capacity design principles; and detailing of elements to resist cyclic inelastic demands, and assessment of element strength, deformation and deterioration under cyclic inelastic loading.

The aim is to provide: a more dependable seismic performance; reduced construction cost; relief from prescriptive design requirements that do not apply; accommodation of architectural features; and use of innovative structural systems and materials not currently allowed by the building codes. The current editions of all United States building codes and standards allow for the use of alternative materials, design and methods of construction and equipment. This alternative means of compliance provides a vehicle by which "Performance-Based Earthquake Engineering" may be used to enable more accurate analysis based on well-established but complex principles of mechanics in lieu of prescriptive code provisions that will result in tall buildings which effectively and consistently resist earthquake forces.

The current approach to performance-based design in the United States relies on component-based evaluation as delineated in ASCE 41-06 [2] and ASCE 41-13 [3] documents. In the component-based approach, each component of the building (beam, column, wall segment, etc.) is assigned a normalized force/moment - deformation/rotation relation such as the one shown in Fig. 1 where segment AB indicates elastic behavior, point C identifies the onset of loss of capacity, segment DE identifies the residual capacity of the component, and point E identifies the ultimate inelastic deformation/rotation capacity of the component. Components are classified as primary (P) or secondary (S) and assigned with different deformation limits corresponding to various performance objectives. The vertical axis in this figure represents the ratio of actual force or moment to the yield force or moment. Primary components are those which are relied upon to provide lateral load resistance at maximum building deformation. Secondary elements are those that are relied upon to resist only gravity loads at maximum building deformation. Thus in a building with coupled shear walls, walls and coupling beams are primary components. The beam column framing system carrying gravity loading is secondary. IO, LS, and CP indicate the target building performance levels for Immediate Occupancy, Life Safety, and Collapse Prevention, respectively.

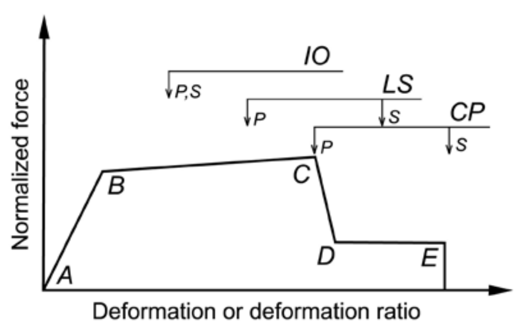

Fig. 1 – Generalized component force-deformation relations for depicting modeling and acceptance criteria in ASCE 41-06 and ASCE 41-13 documents

Although ASCE 41 is officially intended for seismic rehabilitation of existing structures, its component-based performance limits for NDP are routinely referenced by guidelines for performance based design of tall buildings. Engineers, who believe that ASCE 41 tabulated limits are not applicable or too conservative for their intended component, may perform laboratory testing and obtain confirmation of behavior for their component subject to approval by peer reviewers and approval agencies.

LATBSDC was the first United States organization to publish an alternative performance-based analysis and design procedure for tall buildings in 2005. Since then LATBSDC procedures have been revised and updated in 2008, 2011, 2014 and 2015. This paper summarizes the most recent updates to this procedure as published in 2014-2015 cycle. These updates include:

- incorporation of changes to provide consistency with relevant provisions of ASCE 7-10 [4], 2012 International Building Code (IBC) [5] and 2013 California Building Code (CBC) [6];
- incorporation of sensitivity analysis requirements to bound the possible ramifications of the backstay effect;
- revised modeling requirements and acceptability criteria for reinforced concrete walls and coupling beams;
- incorporation of adjusted acceptability criteria for buildings in various risk categories;
- revision of design ground motion criteria to permit use of conditional mean spectrum; and
- provisions for multiple towers on a common podium or basement.

2. Refined Methodology

The 2015 LATBSDC procedure is based on capacity design principles followed by a series of performance based design evaluations. First, capacity design principles are applied to ensure that the structure has a suitable ductile yielding mechanism, or mechanisms, under nonlinear lateral deformations. Linear analysis may be used to determine the required strength of the yielding actions.

The adequacy of the design and the attainment of acceptable building performance shall be demonstrated using two earthquake ground motion intensities:

A. Serviceable Behavior When Subjected to Frequent Earthquake Ground Motions. The service level design earthquake ground motions are taken as the ground motions having a 50% probability of being exceeded in 30 years (43-year return period). Structural models used in the serviceability evaluation shall incorporate realistic estimates of stiffness and damping considering the anticipated levels of excitation and damage. The purpose of this evaluation is to validate that the building's structural and nonstructural components retain their general functionality during and after such an event. Repairs, if necessary, are expected to be minor and could be performed without substantially affecting the normal use and functionality of the building. Subjected to this level of earthquake ground motion, the building structure and nonstructural components associated with the building shall remain essentially elastic. This evaluation shall be performed using three-dimensional linear or nonlinear dynamic analyses. Essentially elastic response may be assumed for elements when force demands generally do not exceed provided strength. When demands exceed provided strength, this exceedance shall not be so large as to affect the residual strength or stability of the structure.

B. Low Probability of Collapse when subjected to Extremely Rare Earthquake Ground Motions. The extremely rare earthquake motions shall be taken as the Risk Targeted Maximum Considered Earthquake (MCE_R) ground motions as defined by ASCE 7-10 and adopted by 2012 IBC and 2013 CBC. This evaluation shall be performed using three-dimensional nonlinear dynamic response analyses. This level of evaluation is intended to demonstrate a low probability of collapse when the building is subjected to the above-mentioned ground motions. The evaluation of demands includes both structural members of the lateral force resisting system and other structural members. Claddings and their connections to the structure must accommodate MCE_R displacements without failure. A reduction factor, κ_i , is applied to adjust the acceptance criteria for certain actions. This reduction factor is a function of building Risk Category as defined in Table 1.5-1 of ASCE 7-10.

The use of conditional mean spectrum (CMS) approach is permitted as long as a minimum of two suites of 7 pairs of site-specific ground motion time-histories are used for the nonlinear response history analysis. If only two suites are used then one suite shall characterize relatively short period motion, and the other suite shall characterize long period motion. The envelope of the two suites shall address periods ranging from $0.1T$ to $1.5T$ seconds to the satisfaction of the project's Seismic Peer Review Panel (T is the calculated fundamental period of the building).

3. Sensitivity Analyses for Backstay Effects

Where applicable (see Fig. 2), for collapse prevention evaluation, two sets of analyses are required to evaluate backstay effects:

1. A model which uses upper-bound (UB) stiffness assumptions for floor diaphragms at the podium and below.
2. A model which uses lower-bound (LB) stiffness assumptions for floor diaphragms at the podium and below.

Table 1 contains recommendations for numerical values of UB and LB Stiffness parameters for backstay sensitivity analyses. These values are likely to be reduced in the 2017 edition of the procedure. The sensitivity analyses, where applicable, shall be performed in addition to the analyses performed using stiffness properties provided elsewhere in the procedure.

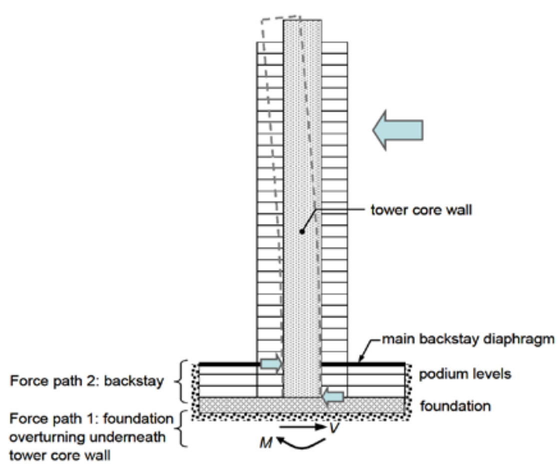

Fig. 2 – Backstay effect illustration (from ATC-72 [7])

Table 1. Stiffness parameters for Upper Bound and Lower Bound Models

Stiffness Parameters	UB	LB
Diaphragms at the podium and below		
$E_c I_{eff}$	0.5	0.20 to 0.25
$G_c A$	0.5	0.20 to 0.25

4. Modeling Reinforced Concrete Core Walls

4.1 Modeling of Flexural Behavior

Concrete stress-strain behavior for members modeled using fiber-element sections shall comply with the ASCE 41 backbone curves or shall be based on suitable laboratory test data. Approximations fitted to analytical curves defined by Collins and Mitchell [8], and adjustments made to allow for confinement effects as described by Mander et al. [9] and Saatcioglu and Razvi [10] are acceptable (see Fig. 3). Since high-strength concrete may have stress-strain relationships that are different from those for regular strength concrete, the high-strength concrete stress-strain relationship utilized shall be consistent with the requirements specified in the 2015 LATBSDC procedure.

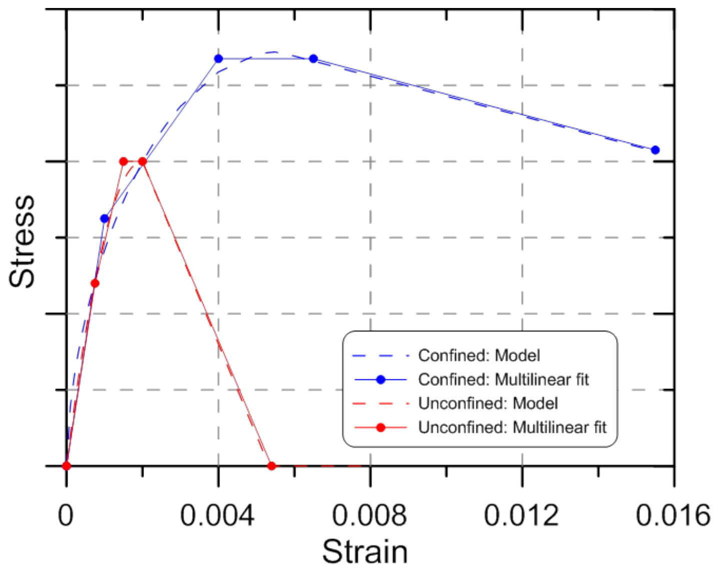

Fig. 3 – Examples of acceptable stress-strain models for concrete

4.2 Modeling of Main Reinforcing Steel

Reasonable bilinear approximation of steel stress-strain curve is acceptable (see Fig. 4).

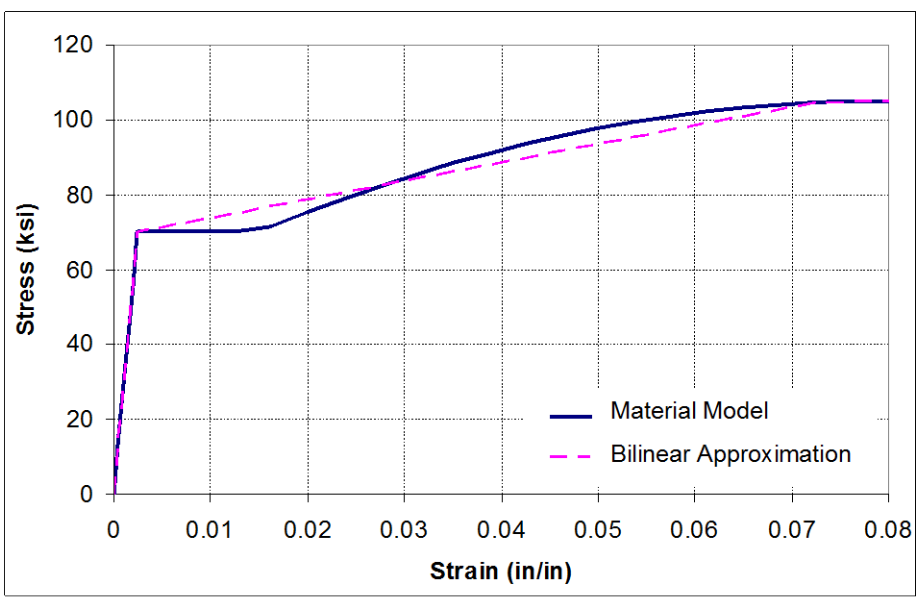

Fig. 4 – Example of an acceptable bilinear approximation of expected reinforcing steel stress strain curve

4.3 Modeling of Plastic Hinge Length

The effective plastic hinge length is used to monitor the compressive strain and ascertain the maximum dimensions of the wall elements in the analytical model. The expected value of the plastic-hinge length (l_p) in the walls for analyses purposes may be calculated from the maximum of the following formulas given by Paulay and Priestley [11]:

$$l_p = 0.2l_w + 0.03h_n \text{ or } l_p = 0.08h_n + 0.15f_y d_b \text{ (ksi units)}$$

where f_y is the expected yield stress, l_w is the wall length, h_n the wall height and d_b the nominal diameter of rebar. The height of the finite element used to model the plastic hinge shall not exceed the length, l_p, or the story height at the location of the critical section.

5. Adjusted Acceptability Criteria for Various Risk Categories

5.1 Service Level Design Earthquake

The service level design earthquake (SLE) is taken as an event having a 50% probability of being exceeded in 30 years (43 year return period). SLE is defined in the form of a site-specific, 2.5%-damped, linear, uniform hazard acceleration response spectrum and modal response spectrum analysis is usually used to evaluate the building performance under SLE.

The structure is deemed to have satisfied the acceptability criteria if none of the elastic demand to capacity ratios (ratio of demand to the applicable LRFD limits for steel members or USD limits for concrete members using ϕ = 1.0) exceed:

a) 1.50 for deformation-controlled actions for Risk Category I and II Buildings (ASCE 7-10 Table 1.5-1); 1.20 for deformation-controlled actions for Risk Category III Buildings; and a factor smaller than 1.20 as determined by the seismic peer review panel (SPRP) for Risk Category IV Buildings.

b) 0.70 for force-controlled actions.

5.2 Collapse Prevention Level Earthquake

Risk-targeted Maximum Considered Earthquake (MCE_R) ground motions determined in accordance with the site-specific procedure of Chapter 21 of ASCE 7-10 represent this level of hazard. A new risk reduction factor, κ_i, is introduced to adjust the acceptability criteria for various actions depending on the risk category of the building (see Table 2). The requirements in the previous editions are modified so that now they read as $F_{uc} \leq \kappa_i \phi F_{n,e}$ where F_{uc} is 1.5 times the mean value of demand for force-controlled critical actions and mean value of the demand for noncritical force-controlled and deformation-controlled actions.

Table 2. Risk Category Reduction Factor

Risk Category from ASCE 7-10 Table 1.5-1	Risk Reduction factor, κ_i
I	1.00
II	1.00
III	0.80
IV	Value to be established by SPRP

Where multiple towers on a common podium or base create a situation in which the number of occupants at or below the podium or ground level may exceed 5,000 persons, then:

1. The κ_i factor is also applied to all force-controlled actions including those of the podium diaphragm and below, including the foundations placed under the Risk Category III portion of the structure. The κ_i factor should be applied to all deformation-controlled and force-controlled elements of the tower passing through the Risk Category III portion of the project.
2. The same κ_i factor shall be also applied to all deformation-controlled actions of the first level of each tower immediately above the common podium. As this level is most likely a location of formation of plastic hinges, special ductile detailing and confinement shall also be provided.

6. Use of Conditional Spectra

The use of conditional mean spectrum (CMS) approach is permitted as long as Conditional Spectra that capture the building's response in each significant mode is utilized. A minimum of two CMS should be used one to capture the building's first mode translational response in each direction and the other second mode response. In structures where first or second mode periods in the two directions are widely separated, additional CMS are required. A minimum of 7 pairs of site-specific ground motion time histories are selected and scaled, or matched to each CMS and used for the nonlinear response history analysis. The envelope of the two suites shall address periods ranging from 0.1*T* to 1.5*T* seconds to the satisfaction of the project's Seismic Peer Review Panel (where *T* is the calculated fundamental period of the building). For purposes of evaluating acceptability of response, the mean response of each suite of motions should be separately evaluated.

Larger suites of appropriate ground motion time histories provide a more reliable statistical basis for analysis. Since three pairs of ground motions provide less statistical accuracy, the use of seven or more pairs of ground motions is required.

ASCE 7-10 does not specify how seed time histories are to be scaled for three-dimensional analyses except that each pair of selected and scaled ground motions shall be scaled such that in the period range of 0.2*T* to 1.5*T*, the average of the square root of the sum of the squares (SRSS) spectra from all horizontal component pairs does not fall below a target spectrum. Under previous editions of ASCE 7, the target spectrum was taken as 130% of that determined with the prescriptive approach of Section 11.4.5 or site-specific ground motions in accordance with Section 11.4.7. In recognition that MD ground motions are not appropriate for selection and scaling of ground motions for use in nonlinear response history analysis, ASCE 7-10 revised the target spectrum to 100% of that determined using either the prescriptive approach of Section 11.4.5 or the site-specific procedure of Section 11.4.7. Design teams should be cautious to select the appropriate scaling technique to the hazard definition used on a project. If geomean spectra are used, the target SRSS spectrum should be taken as 130% of the risk-targeted MCE geomean spectrum. If MD [maximum direction] spectra are used, the target SRSS spectrum should be taken as 100% of the risk-targeted MCE geomean spectrum.

When sites are within 3 miles (5 km) of the active fault that controls the hazard, each pair of ground motion components shall be rotated to the fault-normal and fault-parallel directions of the causative fault and be scaled so that the average of the fault-normal components is not less than the risk targeted MCE response spectrum for the period range from 0.2*T* to 1.5*T*.

It should be noted that ASCE 41-13 does give further guidance on ground motions. ASCE 41-13 Section 2.4.2.1 states that for sites located within 3 miles (5 km) of an active fault that controls the hazard of the site response spectra, the effect of fault-normal and fault-parallel motions shall be considered. ASCE 41-13 does not specify that the fault-normal component be scaled to the risk targeted maximum direction response spectrum and implies that the fault-normal and fault-parallel ground motions can be calculated by acceptable analytical methods. The time histories should be matched in such a way that the average response spectra of the fault-normal and fault-parallel components are not less than the respective target fault-normal and fault-parallel components.

The service level design earthquake ground motions may be based on geometric mean ground motions and need not consider maximum direction response.

7. Conclusion

The improvements implemented in the 2015 edition of the LATBSDC procedure were introduced and discussed. Further improvements are anticipated to be implemented in the next edition of this procedure scheduled for release in May of 2017 [12]. The authors welcome constructive criticisms and suggestions.

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