Design of Steel Buildings for Earthquake and Stability by Application of ASCE 7 and AISC 360

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Abstract

Design of steel buildings in the United States typically combines application of ASCE/SEI 7, *Minimum Design Loads for Buildings and Other Structures,* and ANSI/AISC 360, *Specification for Structural Steel Buildings*. For buildings designed for seismic effects, ANSI/AISC 341, *Seismic Provisions for Structural Steel Buildings,* may also be applicable. The ASCE 7 *Minimum Design Loads* standard includes specific design provisions related to stability under seismic loading which overlap and, in some instances, appear to conflict with the stability design requirements of the AISC *Specification*. This paper explores the areas of overlap and apparent conflict between ASCE 7 and AISC 360 and offers practical recommendations for seismic design incorporating the provisions of both.

Keywords: design loads, seismic design, structural stability.

Design of steel buildings in the United States typically combines application of ASCE/SEI 7, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2005), and ANSI/AISC 360, *Specification for Structural Steel Buildings* (AISC, 2005a; AISC, 2010). For buildings designed for seismic effects, ANSI/AISC 341, *Seismic Provisions for Structural Steel Buildings* (AISC, 2005b), may be applicable in conjunction with the *Specification*.

ASCE 7 is used, either directly or by reference from a building code, to define the loads for which the structure must be designed; AISC 360 and 341 are used to design the steel structure for those loads.

The ASCE 7 *Minimum Design Loads* standard, though generally focused on loads and not on design or the response of the structure to those loads, includes specific design provisions related to stability under seismic loading. These provisions overlap and, in some instances, appear to conflict with the stability design requirements of the AISC *Specification*. (The AISC *Seismic Provisions* do not include stability design requirements.)

This paper explores the areas of overlap and apparent conflict between ASCE 7 and AISC 360 and offers practical recommendations for seismic design incorporating the provisions of both.

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The paper does not attempt to correlate design with expected actual behavior beyond the degree of correlation implied by compliance with ASCE 7 and AISC 360. This is an important limitation. It is generally recognized that actual displacements in an earthquake could be much larger than the elastic displacements due to code-specified design loads, and the resulting second-order effects could be quite different from those predicted by specification-compliant analysis; exploration of this issue is beyond the scope of this paper.

STABILITY DESIGN BY AISC 360

The Direct Analysis Method of design for stability was introduced in the 2005 edition of the AISC *Specification*. The 2010 edition makes that method the primary means of design; alternative approaches have been moved to an appendix. The discussion in this paper will be limited to the Direct Analysis Method and its application in seismic design in conjunction with ASCE 7; other stability design methods permitted in the AISC *Specification* are not considered.

The rational basis of the Direct Analysis Method is explained in AISC-SSRC (2003); a simple introduction to the practical application of the method is provided in Nair (2009a). Notes on the modeling of structures for design by the Direct Analysis Method are provided in Nair (2009b).

Design for stability by the Direct Analysis Method involves a second-order analysis, use of reduced stiffness in the analysis, consideration of initial imperfections (either by direct modeling of the imperfections or by application of notional loads in the analysis) under certain circumstances, and strength check of components using an effective length factor, K, of unity for members subject to compression.

Second-Order Analysis

The analysis of the structure must be a second-order analysis that, in the most general case, includes both P-Δ effects, which are the effects of loads acting on the displaced locations of joints or nodes in the structure, and P-δ effects, which are the effects of loads acting on the deformed shapes of members. In tiered buildings, P-Δ effects are the effects of loads acting on the laterally displaced locations of floors and roofs.

The 2010 AISC *Specification* exempts most buildings from the need to consider P-δ effects in the analysis of the overall structure; a P-Δ–only analysis is sufficient in almost all cases. This is an important simplification relative to the 2005 *Specification,* which does require inclusion of P-δ effects in the analysis of most moment-frame buildings. Regardless of whether P-δ effects need to be considered in the analysis of the overall structure, the P-δ effects on individual beam-columns must always be considered in the strength check of those members.

The second-order analysis required by the Direct Analysis Method of design may be performed using a computer program formulated to provide a second-order solution. Alternatively, a second-order solution may be obtained by manipulating the results of a linear or first-order analysis to account for second-order effects by application of the B_1 and B_2 multipliers defined in the *Specification*.

In the B_1 and B_2 procedure, B_2 alters the results of a first-order analysis to account for P-Δ effects; the B_2 multiplier also accounts, in an approximate way (by application of the factor R_M in the calculation of B_2), for the overall softening of the structure's response due to P-δ effects in individual members. For a given vertical loading, there will be a single value of B_2 for each story and each direction of lateral translation, applicable to the forces and moments caused by lateral loading in all members and connections in that story. In the unusual case where gravity load causes lateral translation, B_2 is also applicable to the forces and moments caused by the side-sway component of gravity load. While B_2 is a story parameter, B_1 is a member parameter; a B_1 multiplier is applied to the moments in each beam-column to account for P-δ effects in that member.

Another approach, usable in the typical case where P-δ effects do not need to be considered in the analysis of the overall structure, is to obtain a P-Δ–only second-order solution from a computer program and then to apply B_1 multipliers to account for P-δ effects in individual members.

Given that in second-order analysis the effect of a load is not proportional to its magnitude (and the principle of superposition of loads does not apply), the second-order analysis must be performed at the Load and Resistance Factor Design (LRFD) load level: For design by LRFD, LRFD load combinations must be applied in the analysis; for design by Allowable Strength Design (ASD), ASD load combinations increased by a factor of 1.6 must be applied in the analysis and the results must be divided by 1.6 to get the forces and moments for proportioning of members and connections.

Reduced Stiffness

In the second-order analysis, all stiffnesses in the modeling of the structure must be reduced by applying a factor of 0.8. An additional reduction factor, τ_b, must be applied to the flexural stiffnesses of all members whose flexural stiffnesses are considered to contribute to the lateral stability of the building. Factor τ_b is unity when the LRFD-level required compression strength of the member is less than half the yield strength.

When the compression is high and τ_b is not unity, the designer may still avoid the complication of calculating and applying τ_b by applying, instead, a small notional lateral load (0.001 times the LRFD-level gravity load applied at each floor) in the analysis. This notional load will typically be so much smaller than seismic loads that it may reasonably be neglected when seismic loads are present. Thus, it should be possible to take τ_b as unity in all cases in seismic design; what remains is the 0.8 factor, applied to all stiffnesses.

Initial Imperfections

The effect of initial imperfections must be considered in the analysis, either by direct inclusion of the imperfections in the analysis model or by application of notional loads, if either (1) the load combination being considered is a gravity-only loading with no applied lateral load or (2) the ratio of second-order drift to first-order drift in any story of the building is more than 1.7.

For seismic design, there will always be applied lateral load and condition 1 will not apply; condition 2 will also typically not apply for buildings that satisfy the limits on stability coefficient, θ, specified in ASCE 7. Therefore, it will not typically be necessary in seismic design to consider initial imperfections, either explicitly or by application of notional loads.

Component Strength Check

For design by the Direct Analysis Method, once the appropriate analysis has been performed, members and connections are checked for strength with no further consideration of overall structure stability. The effective length factor, K, for members subject to compression is taken as unity (unless a lower value is justified by rational analysis).

SEISMIC DESIGN STABILITY PROVISIONS IN ASCE 7

Background and commentary on the seismic design provisions of the ASCE 7 *Minimum Design Loads* standard may be found in FEMA (2009). Specific requirements for stability in conjunction with seismic design are presented in the ASCE standard in a section titled "P-Delta Effects" (Section 12.8.7)*; these requirements are included as part of the "Equivalent Lateral Force Procedure" for seismic analysis (Section 12.8).

The P-Delta Effects section of ASCE 7 defines a stability coefficient, indicates when P-delta effects must be considered, places limits on the stability coefficient and specifies methods of accounting for P-delta effects.

Stability Coefficient, θ

The stability coefficient, θ, is approximately the ratio of the actual vertical force on a story of a building to the vertical force that would cause elastic lateral buckling of the story. An equation† is provided for the coefficient; the coefficient is calculated with nominal, unreduced stiffnesses and for load combinations with no individual load factor exceeding unity.

When Must P-delta Effects Be Considered?

Under ASCE 7, P-delta effects need be considered only when the stability coefficient, θ, is more than 0.10. This is roughly equivalent to an AISC B_2 multiplier (ratio of second-order story drift to first-order story drift) of 1.2, after accounting for the fact that θ is calculated with nominal stiffnesses and for load combinations with no individual load factor exceeding unity, while B_2 is calculated with reduced stiffnesses and for LRFD-level load combinations.

Limit on Stability Coefficient

The stability coefficient, θ, must never be higher than θ_{max}, which is variable (a function of β, the ratio of shear demand to shear capacity of the story, and of C_d, the deflection amplification factor), but never higher than 0.25. A θ of 0.25 is roughly equivalent to an AISC B_2 multiplier of 1.7 after correction for the different stiffnesses and loadings in the θ and B_2 calculations.

Method of Analysis for P-delta Effects

ASCE 7 specifies that when P-delta effects are required to be considered (i.e., when the stability coefficient, θ, exceeds 0.10), "the incremental factor related to P-delta effects on displacements and member forces shall be determined by rational analysis." Two types of rational analysis are envisioned: (1) nonlinear static (pushover) analysis and (2) nonlinear response history analysis, both of which require extensive, additional effort.

As an alternative to the rational analysis, "it is permitted to multiply the displacements and member forces by 1.0/(1 − θ)." This is analogous to application of the AISC B_2 multiplier with $R_M = 1$ in the equation for B_2, which amounts to neglecting P-δ effects in the analysis. However, given that θ is calculated with nominal stiffnesses and for load combinations with no individual load factor exceeding unity, while B_2 is calculated with reduced stiffnesses and at LRFD-level load combinations, the AISC approach will indicate significantly higher second-order displacements and forces.

Use of an analysis that included P-Δ effects (but not P-δ effects), and subsequent application of AISC B_1 multipliers to individual beam columns to account for P-δ effects, would also satisfy the requirement of ASCE 7.

Seismic Design by Modal Response Spectrum Analysis

The preceding discussion of stability-related requirements in the seismic design provisions of ASCE 7 was based on use of the Equivalent Lateral Force procedure. An alternative seismic analysis procedure prescribed in ASCE 7 (Section 12.9) is the Modal Response Spectrum Analysis approach. Design by Modal Response Spectrum Analysis is applicable to all structures of all Seismic Design Categories; the Equivalent Lateral Force procedure is not permitted for certain structures in Seismic Design Categories D through F.

Stability requirements are not presented independently in the Modal Response Spectrum Analysis section; the same P-delta requirements prescribed for the Equivalent Lateral Force procedure are incorporated by reference in the Modal Analysis section. There is an obvious complication here in that the Modal Analysis approach involves combining the results of analyses for different modes, but second-order analyses (i.e., analyses incorporating P-delta effects) cannot normally be combined. A means of overcoming this difficulty is suggested in the following section.

COMPARISON AND RECOMMENDATIONS

Selected features of the Direct Analysis Method of design for stability in the AISC *Specification* and provisions related to seismic design and stability in the ASCE 7 *Minimum Design Loads* standard, as discussed in the preceding sections, are summarized in Table 1. Clearly, there are areas of divergence between the two sets of requirements. Nonetheless, as outlined in the following, steel buildings may be designed for seismic effects and stability in general conformance with both the AISC *Specification* and ASCE 7.

* ASCE 7 does not explicitly differentiate between the P-Δ effects and P-δ effects recognized by the AISC *Specification*; the "P-delta" effects addressed in ASCE 7 are the P-Δ effects of AISC.

† There is an error in Equation 12.8-16, the equation for stability coefficient, θ, in ASCE 7-05. There should be I (for importance factor) in the numerator on the right-hand side of the equation. This has been corrected in ASCE 7-10.

Table 1. Comparison of Analysis and Stability Provisions in ASCE 7 and AISC 360

Subject	ASCE 7 Equivalent Lateral Force Procedure[a]	AISC 360 Direct Analysis Method	Recommendation for Seismic Design
Limit on P-Δ effect	Stability coefficient θ must not exceed θ_{max}.	No limit.	Observe ASCE limit, which corresponds to P-Δ multiplier of 1.33 or less.[b]
Must P-Δ effects be considered?	Only when θ is greater than 0.1.	Yes; in all cases.	Always consider P-Δ effects.
P-Δ effects by rational analysis?	Permitted.	Permitted.	Rational analysis may be used.
P-Δ effects by approximate analysis?	Permitted. [Multiply lateral load effects by $1/(1-\theta)$.]	Permitted. [Multiply lateral load effects by B_2.]	The AISC method may be used; note that $1/(1-\theta) \approx B_2$.
Must P-δ effects be considered in the analysis?	Not specified.	Generally yes in 2005; generally no in 2010.	Observe AISC 2010.[c]
Load in the stability analysis	Not specified for rational analysis. Load factor not greater than 1.0 for θ calculation.	LRFD load combinations for LRFD; 1.6 times ASD combinations for ASD.	Observe AISC: LRFD load combinations for LRFD; 1.6 times ASD load combinations for ASD.
Structure stiffness in the stability analysis	Not specified.	Apply factor of 0.8 τ_b to EI; 0.8 to all other stiffnesses.	Apply factor of 0.8 (no τ_b) to all stiffnesses.
Must initial imperfections be considered?	Not specified.	Yes, with exceptions; either model directly or apply notional loads.	Need not consider initial imperfections (neither direct modeling nor notional loads).
Analysis to assess conformance to drift limits	Elastic stiffness; same type of analysis as for strength.	Not specified.	Use of same analysis as for strength is permissible but may be too conservative; see text.
Analysis to determine period	Not specified, although upper limits are defined.	Not specified.	Use linear analysis (no P-Δ effects) with nominal, unreduced stiffnesses.

[a] See text for additional considerations for Modal Response Spectrum Analysis procedure.
[b] The stability coefficient, θ, is calculated at lower load than used in AISC stability analyses; therefore, P-Δ multipliers corresponding to the ASCE 7 thresholds are not strictly comparable to AISC 360 parameters.
[c] Regardless of whether it is considered in the analysis of the overall structure, P-δ must always be considered in the strength check of individual beam-columns.

General recommendations:

1. Observe the ASCE 7 limit on stability coefficient; θ must not exceed θ_{max}. The nominal (unreduced) stiffness of the structure and the ASCE 7 vertical load (with no individual load factor greater than 1.0) may be used in the calculation of coefficient θ.
2. In the analysis for assessing strengths, consider P-Δ effects in the analysis for all structures; also consider P-δ effects in the analysis where required by the AISC *Specification*. (Do not observe the ASCE 7 provision that exempts from P-delta considerations all buildings with a stability coefficient, θ, less than 0.10.)

Recommendations specific to seismic design by the Equivalent Lateral Force procedure:

1. Determine the fundamental period of the building either by analysis or by use of the approximate methods prescribed in ASCE 7. If determined by analysis, use first-order analysis (no second-order effects), with nominal (unreduced) stiffnesses.
2. Consider second-order effects either by second-order

analysis or by application of the AISC B_1 and B_2 multipliers to the results of first-order analysis. The options are:

a. Complete second-order analysis that considers both P-Δ and P-δ effects.

b. P-Δ–only second-order analysis, followed by application of B_1 to individual beam columns (not permissible in the unusual cases where inclusion of P-δ effects in the overall analysis is required by the AISC *Specification*).

c. First-order analysis, followed by application of B_2 and B_1 multipliers.

3. Perform the second-order analysis and/or calculate the B_1 and B_2 multipliers at LRFD-level loads; that is, use LRFD load combinations if design is by LRFD, use 1.6 times ASD load combinations if design is by ASD. (After second-order analysis under ASD, divide the analysis results by 1.6 for member and connection strength checks.)

4. Apply a factor of 0.8 to all stiffnesses in the second-order analyses and in the calculation of B_1 and B_2 multipliers. For load combinations that include seismic load, the additional stiffness reduction factor τ_b need not be applied.

5. In the analysis for load combinations that include seismic load, it is not necessary to model initial imperfections or to apply notional loads to account for the imperfections.

6. Perform strength checks in accordance with the AISC *Specification*, using an effective length factor, K, of unity for members subject to compression (unless a lower value is justified by rational analysis).

7. Conformance to ASCE 7 seismic drift limits may be checked using the same analysis used for strength checks (analysis at reduced stiffness, second-order analysis, second-order effects determined at LRFD-level loads). This may be excessively conservative, however, and it is permissible to base drift checks on an analysis using the full unreduced stiffness of the structure, with second-order effects determined at the lower loads specified by ASCE 7 for calculation of the stability coefficient, θ. The deflection amplification factor, C_d, should be applied in either case.

Recommendations specific to seismic design by the Modal Response Spectrum Analysis approach:

1. Determine modes and frequencies using first-order analysis, with nominal (unreduced) stiffnesses.

2. Determine member forces and moments due to gravity load by first-order analysis, with a factor of 0.8 applied to all stiffnesses.

3. Use the properties of each mode and the ASCE 7 design response spectrum to determine a set of lateral forces for that mode; using these lateral forces, perform a first-order analysis, with a factor of 0.8 applied to all stiffnesses, to determine member forces and moments. Repeat for all modes considered.

4. Calculate a single B_2 multiplier, applicable to all modes,‡ for each story and each direction of lateral translation, based on reduced stiffness (0.8 factor) and the full LRFD-level vertical load on the story.§

5. Combine first-order modal results (item 3) as specified in ASCE 7 Section 12.9.3. Apply B_2 multipliers to the combined results (member forces and moments caused by lateral loading). Then scale the combined results as specified in ASCE 7 Section 12.9.4. Algebraic signs will typically be lost in modal combinations; the member forces and moments due to seismic effects should, therefore, be considered reversible (i.e., use absolute values of forces and moments in the modal combinations and then consider the resulting overall forces and moments due to seismic effects to be fully reversible).

6. Combine the member forces and moment due to seismic effects (item 5) with the member forces and moments due to gravity load (item 2), with load factors as specified in ASCE 7.

7. Apply B_1 multipliers to the moments in beam-columns. The B_1 multiplier should be based on the full LRFD-level axial force in the member, including axial forces due to lateral loading, but need be applied only to that part of the moment in the beam-column that is caused by gravity loading. (Designers may use the conservative approximation of applying B_1 to the full moment to avoid the obvious bookkeeping difficulties involved in this calculation.)

8. Perform strength checks in accordance with the AISC *Specification*, using an effective length factor, K, of unity for members subject to compression (unless a lower value is justified by rational analysis).

‡ This is an approximation. If the B_2 calculations for all stories are based on story shears and drifts due to lateral load applied at the roof alone, the resulting B_2 values should be reasonably accurate or conservative (high) for all modes.

§ It should also be possible (as an alternative to the B_2 multiplier procedure used herein) to adapt the modified geometric stiffness approach for use with design by Modal Response Spectrum Analysis.

9. As in the Equivalent Lateral Force procedure, conformance to ASCE 7 seismic drift limits may be checked using either the same analysis used for strength checks (convenient, but potentially very conservative) or an analysis using the full unreduced stiffness of the structure, with second-order effects (B_1 and B_2 multipliers) determined at the lower loads specified by ASCE 7 for calculation of the stability coefficient, θ.

SUMMARY AND CONCLUSIONS

Provisions related to seismic design and stability in ASCE/SEI 7, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2005), and features of the Direct Analysis Method of design for stability in ANSI/AISC 360, *Specification for Structural Steel Buildings* (AISC, 2005a; AISC, 2010), have been explored and compared. While there are inconsistencies between the two sets of provisions, they are not fundamentally incompatible. Recommendations are offered for the design of steel buildings for seismic effects and stability in general conformance with both the AISC *Specification* and the ASCE 7 standard.

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