Stability and Analysis

The 2005 AISC *Specification* offers new options for rational stability design.

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There is no consensus among practicing engineers today as to what constitutes a "normal" or "standard" structural analysis. Advanced analysis methods that were regarded as research tools a few years ago have entered some design offices, while other practices are getting along just fine with the same (except bigger and faster) analysis tools they had a generation ago. This is especially true in the area of stability, where specification provisions for design cannot be separated from methods of analysis.

The 2005 AISC *Specification for Structural Steel Buildings* recognizes the wide range of analyses in common use. Chapter C, on Stability Analysis and Design, spells out the general safety- and reliability-based requirements that must be satisfied in all structural designs, and then gives designers the freedom to select or devise their own methods of analysis and design within these constraints. The *Specification* also offers designers specific, simple analysis and design procedures that are applicable to typical structures.

Chapter C specifies that the design of the structure for stability must consider all of the following:

- Flexural, shear, and axial deformations of members.
- All component and connection deformations that contribute to the lateral displacement of the structure.
- P-Δ effects, which are the effects of loads acting on the displaced location of joints or nodes in the structure. (In tiered building structures, this is the effect of loads acting on the laterally displaced location of floors and roofs.)
- P-δ effects, which are the effects of loads acting on the deformed shape of a member between joints or nodes.
- Geometric imperfections, such as initial out-of-plumbness.
- The reduction in member stiffness due to residual stresses and, in particular, the effect of this stiffness reduction on the stability of the structure.

When the required strengths of members have been determined from an analysis that considers all these effects, the members can be designed using the provisions for design of individual members (Chapters E, F, G, H, and I).

The *Specification* states explicitly that any method of analysis and design that considers all the specified effects is permissible, and then presents certain specific approaches that account for the last four of the listed effects (P-Δ effects, P-δ effects, geometric imperfections, and residual stresses).

Direct Analysis Method

The most generally applicable method of accounting for P-Δ and P-δ effects, geometric imperfections, and residual stresses is the **Direct Analysis Method** presented in Appendix 7 of the *Specification*. It is applicable to all types of structural systems; the provisions of the Direct Analysis Method do not distinguish between braced frames, moment-resisting frames, shear wall systems, and combinations of these and other structure types. In the Direct Analysis Method:

- P-Δ and P-δ effects are accounted for through second-order analysis (either explicit second-order analysis or second-order analysis by amplified first-order analysis, for which a procedure is presented in the *Specification*).
- Geometric imperfections are accounted for either by direct inclusion of imperfections in the analysis model or by the application of specified "notional loads" (which are a proportion of the gravity load applied laterally) as a minimum lateral load. (The notional loads are additive to other lateral loads under certain conditions.)
- Stiffness reductions due to residual stresses are accounted for by reducing the flexural and axial stiffnesses of members by specified amounts or, at the designer's option, by a combination of reduced member stiffness and additional notional loads.

Individual members are then designed using an effective length factor (K) of uni-

Should a Spec Cover Analysis?

There appears to be a near-consensus among practicing engineers today that a design specification should not cover analysis, and that the choice of method of analysis should be entirely up to the designer. The problem with this position is that analysis and design are closely intertwined. Indeed, almost every design-related specification provision is based on a particular type of analysis. This was brought home to the writer some time ago when a reviewer for a bridge project insisted on applying the specified $0.55F_y$ tensile stress limitation to the concentrated stress indicated by finite element analysis at the edge of a hole. He did not understand that the specified stress limit was meant to be applied to a simple "P/A" type of stress calculation, not to the result of finite element analysis.

Despite the close relationship between design and analysis, the expected type of analysis can remain implicit in a specification if there are no plausible alternatives. But where alternatives are readily available within the usual range of design-office practice (as in the area of stability today), the specification must spell out the type of analysis on which its design provisions are based or alternatively offer different design provisions corresponding to the different available analyses.

Comparison of Analysis Methods

	Direct Analysis Method	Effective Length Method	First-Order Analysis Method
Specification reference	Appendix 7	Section C.2.2a	Section C.2.2b
Limits on applicability?	No	Yes	Yes
Type of analysis	Second-Order	Second-Order	First-Order
Member stiffness	Reduced EI and EA	Nominal EI and EA	Nominal EI and EA
Notional lateral load?	Yes	Yes	Yes
Column effective length	$K = 1$	Sidesway buckling analysis	$K = 1$

ty in calculating the nominal strengths of members subject to compression.

The *Specification* provides enough direction to allow application of the Direct Analysis Method in "cook book" fashion. But it also lays out the logical basis for the provisions in a way that offers designers the option of tailoring the method to particular situations. For instance, it is spelled out that the specified 0.002 notional load coefficient to account for geometric imperfections is based on an assumed initial story out-of-plumbness ratio of 1/500; a different notional load can be used if the known or anticipated out-of-plumbness is different; and the imperfections can be modeled explicitly instead of applying notional loads.

AISC Task Committee 10 on Stability anticipates that in time, if not immediately, the Direct Analysis Method will become the "standard" method of stability design of steel building structures.

Limited Methods

For structures in which second-order effects are not very large (where the drift from a second-order analysis is not more than 1.5 times that from a first-order analysis), Chapter C of the *Specification* offers two alternatives to the Direct Analysis Method.

In the **Effective Length Method**, the structure is analyzed using the nominal geometry and nominal elastic stiffness of all members; required member strengths are determined from a second-order analysis (either explicit second-order analysis or second-order analysis by amplified first-order analysis). All gravity-only load combinations include a minimum lateral load at each frame level of 0.002 of the gravity load applied at that level. Effective length factors (K) or buckling stresses for calculating the nominal strengths of compression members must be determined from a sidesway buckling analysis, except that $K = 1$ may be used for braced frames or where the ratio of second-order drift to first-order drift is not more than 1.1.

The **First-Order Analysis Method** is applicable only when the required compressive strength is less than half the yield strength in all members whose flexural stiffnesses are considered to contribute to the lateral stability of the structure. In this method, the structure is analyzed using the nominal geometry and nominal elastic stiffness of all members; required member strengths are determined from a first-order analysis. All load combinations include an additional lateral load at each frame level of a magnitude based on the gravity load applied at that level and the lateral stiffness of the structure. The nominal strengths of compression members may be determined assuming $K = 1$; beam-column moments must be adjusted (using a formula that is provided) to account for non-sway amplification.

How to Do the Second-Order Analysis?

The Direct Analysis Method and the Effective Length Method both require a second-order analysis of the structure. The second-order analysis can take the form of an explicit second-order analysis that includes both P-Δ and P-δ effects. Alternatively, the second-order analysis can consist of amplified first-order analysis, for which a detailed procedure is provided in the *Specification*. (This is the "B1-B2" procedure familiar to designers from previous editions of the *Specification*.)

Since stability is an inherently nonlinear phenomenon, it is essential that all second-order analyses be carried out at the LRFD load level. To obtain the proper level of reliability when ASD is used, the analysis must be conducted under 1.6 times the ASD load combinations and the results must then be divided by 1.6 to obtain the forces and moments for member design by ASD. (The 1.6 load multiplier must also be used in ASD when checking the ratio of second-order drift to first-order drift, as required under certain provisions.)

User's Choice

Designers of steel structures now have a full menu of choices for stability analysis and design. The Direct Analysis Method is complete and rational and transparent in its logic. The Effective Length Method is closest to what engineers are used to from previous editions of the *Specification*, while the First-Order Analysis Method is a simple alternative for many structures. ★

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