Software and the Direct Analysis Method

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Understanding how your software is doing its work will help you do yours better.

MUCH HAS BEEN WRITTEN in AISC's *Modern Steel Construction* magazine, the AISC *Engineering Journal* and elsewhere on the design of steel structures for stability. AISC also offers continuing education seminars that address this topic. The Direct Analysis Method of Appendix 7 in the 2005 AISC *Specification* is often the focus of these articles and seminars. Additionally, the AISC Steel Solutions Center frequently receives questions relating to this method and the selection and use of appropriate commercial software to implement it.

This article adds discussion of the use of some common commercial software in stability design and touches upon the important items design engineers must be aware of when using structural analysis software to carry out stability analysis and design. A sample generic computer design process flowchart is also presented to serve as a reference for design engineers.

Numerical Methods in the Marketplace

***P*-Δ and *P*-δ:** Sections C2.1 and A7.3(1) of the AISC *Specification* state that any second-order elastic analysis method that captures the effects of *P*-Δ and *P*-δ may be used. Section C2.1b provides an approximate method that can be used based upon first-order analysis forces amplified by B_2 and B_1 to satisfy the requirement. Finite element analysis methods also can be used to capture second-order effects in structures. In fact, any method that works can be used. The Commentary to Section 7.3 of Appendix 7 provides benchmark problems that can be used to determine the adequacy of numerical methods.

Most programs use either an iterative approach or a geometric-stiffness-based method. In both approaches, it is common that small deformations are assumed.

Iterative methods perform repeated linear-elastic evaluations as the structure deforms laterally to capture the increased moments and forces imposed on the structure. The iterations continue until convergence is reached—until the deformations stop increasing. If convergence does not occur, the structure is said to be unstable and needs to be stiffened. RISA Technologies' RISA-3D makes use of such an approach. Nodal deformations are first used to generate forces, which are then iterated until convergence is reached.

The *geometric stiffness* methods change the stiffness of the structure by altering the stiffness matrix to simulate the effects of the destabilizing gravity loads. When using this approach, iteration may not be required and the resulting analysis can be less computationally demanding. It also allows use of superposition and determination of dynamic properties that account for second-order effects. Bentley's RAM Structural System makes use of such an approach, as an alternative to the B_1-B_2 approximation method that it also provides. CSI's SAP 2000 allows the engineer to modify the stiffness matrix to customize the method for unique applications.

CSC's Fastrak Building Designer uses a combined approach with a two-step iterative analysis of a geometric stiffness method, in order to gain from the benefits of both approaches.

While both approaches have their strengths, designers should also consider their weaknesses. Iterative methods do not account for the lengthening of vibration periods due to second-order effects, and typically require more computational power. On the other hand, geometric stiffness methods require that the matrix be modified for a constant destabilizing load, typically a load combination. This means assuming a reasonable load as the basis for the geometric stiffness adjustment is important. Whichever approach a program uses, the design engineer must ensure that strength level loads are evaluated by the software analysis, as required in Sections C2.2a(2) and A7.3(1) of the *Specification*.

P-δ effects are caused by deformations (curvature) of individual members, but they also can affect the overall force amplification when lateral loads are introduced. Therefore, Sections C2.1a and A7.3(1) of the AISC *Specification* require that they be considered. In many cases, *P*-δ are small and may be neglected.

Software developers have proposed various methods to incorporate *P*-δ effects, where required, in second-order analysis. Among other approaches, this can be done by adding nodes between support points of members. RAM uses a B_1 factor with a geometric stiffness method to accomplish this.

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Computer Design Process Using the 2005 AISC Specification

Using the Provisions of Appendix 7

MODELING

1. Input Standards and Specifications
2. Input Material Properties
- **a.** Static analysis for forces and deformations used in:
  - **i.** Strength Check [see **ANALYSIS** for stiffness required]
  - **ii.** Serviceability Check [see **ANALYSIS** for stiffness required]
- **b.** Dynamic analysis [see **ANALYSIS** for stiffness required]
- **c.** Performance check [see **STRENGTH & SERVICEABILITY** for stiffness required]

3. Input Geometry [see **LOADING** and **Appendix 7 Notes**]
- **a.** Ideal
- **b.** Imperfections

4. Input Trial Shapes and Sizes

LOADING

1. Input Load Cases
- **a.** Gravity
- **b.** Notional Loads
- **c.** Wind
- **d.** Seismic

	Static	Dynamic
Linear	ELF	RSA
~~Non-Linear~~	~~Pushover~~	~~Time History~~

- **e.** Other

2. Define Load Combinations
- **a.** With strength level Notional Loads [see Ideal **MODELING**]
- **b.** Without Notional Loads [see **MODELING** with Imperfections]

ANALYSIS

	Static	Dynamic
Strength	Load Combinations	Load Case
	Reduced Stiffness	Nominal Stiffness
Serviceability	Drifts & Deflections	Vibration
	Nominal Stiffness	Nominal Stiffness
Comments	Second-Order Effects	Period
	Determination	Determination

Stable? no → **RESIZE** → **MODELING**; yes →

STRENGTH & SERVICEABILITY CHECK

1. Standard Specification [see **MODELING** for input]
2. Project Strength requirements [use Nominal Stiffness]
3. Project Serviceability requirements [use Nominal Stiffness]
4. Architectural and other requirements [see **MODELING** for input]
5. Shape selection and iteration [see **MODELING** for input]

N.G. → **RESIZE**; OK! →

VERIFICATION & OUTPUT

Appendix 7 Notes

1. Second-Order Effects **a.** P-δ **b.** P-Δ	**ANALYSIS**
2. Distabilizing Perterbations **a.** Notional Loads **b.** Imperfections	**MODELING & LOADING**
3. Reduced Stiffness	**ANALYSIS**

Deformations: Section C1.1 requires that all relevant deformations be considered. Most commonly used programs, at a minimum, account for flexural deformations because they contribute significantly to overall drift in moment frames. However, it is important that the contribution of other deformations be considered when they are significant, including axial and shear deformations. While most programs account for these deformations, other effects like panel zone deformations are typically not accounted for. Some software developers recommend modeling beams from column centerline-to-centerline—rather than face-to-face—as one way to account for panel zone deformations.

Appendix 7 Requirements

The Direct Analysis Method is a powerful approach that can be used to capture the effects of residual stresses and initial imperfections. The direct modeling approach for initial imperfections also can be used to account for temperature gradients and foundation settlements. In cases of second-order effects such that $\Delta_{2nd\ order} / \Delta_{1st\ order} > 1.5$, the Direct Analysis Method must be used.

Two deceptively simple tools in this method—notional lateral loads and stiffness reductions—account for a host of destabilizing influences on the structure.

Notional Lateral Loads: Section A7.3(2) states that notional lateral loads must be applied to all gravity only load combinations. Where $\Delta_{2nd\ order} / \Delta_{1st\ order} >$ 1.5, the notional load must be applied in all load combinations, even those with other lateral loads. These notional loads account for the effects of structure out-of-plumbness and are derived from the tolerances provided in the AISC *Code of Standard Practice*. However, the *Specification* also permits the use of notional loads that are smaller if a lesser out of plumbness is known to exist or can be ensured. Direct modeling of the actual geometric imperfections is also permitted.

Programs such as RISA-3D allow the user to input notional loads, while those like RAM and Fastrak automatically compute and add them to other lateral loads based on the gravity loads in the members. Automatic modeling of geometric imperfections is not provided by most structural analysis software developers at this time.

Stiffness Reductions: According to Sections A7.3(3) and A7.3(4), when calculating second-order effects a 20% reduction in axial and flexural stiffness must be made to all members that contribute to stabilizing the structure. A larger reduction applies to columns with high axial load, where τ_b is an additional multiplier; alternatively, an additional notional load of $0.001Y_i$ can be added in the analysis to maintain $\tau_b = 1$. These stiffness reductions must not be confused with the reductions that are made to the stiffness matrix by second-order analysis tools that use the geometric stiffness methods. One is mandated by the AISC *Specification* whereas the other is at the behest of the software developer; and the purposes of the two are different albeit related.

Inputting stiffness reduction is not difficult because it can simply be applied to the modulus of elasticity (E). However, the reductions in Section A7.3 are only required for purposes of generating design forces and drifts—amplified by second-order effects and notional loads—and not for strength checks, or evaluation of the system for serviceability.

This may require that programs differentiate between members that are part of the lateral system and those that are not. The program may then use two different sets of stiffness for those that are part of the lateral system; one for analysis and another for strength checks. RISA-3D, for instance, automates this entire process, including the calculation of τ_b for each member, while Fastrak automatically makes the 20% reduction but uses a τ_b value of 1.0 to avoid iteration by adding to the notional loads as permitted in section A7.3(3).

Conclusion

This article does not provide an exhaustive list of the items that design engineers must be aware of when selecting or using structural analysis software for stability design, but it does attempt to motivate communication between design engineers and their software providers. This is the only way the full capability and limitations of the programs can be known. Allen Adams of Bentley, Josh Plummer of RISA Technologies and Jason Ericksen of CSC provided invaluable input and guidance for this article.

An article on stability design of steel structures would be incomplete without recognizing the contribution to this topic by R. Shankar Nair of Teng and Associates, Inc. His two papers, "Simple and Direct" (*Modern Steel Construction*, January 2009) and "A Model Specification for Stability Design by Direct Analysis" (*Engineering Journal*, 1st Quarter 2009) are highly relevant to the topic of this article. Moreover, the AISC seminar "Design Steel Your Way II" by Louis F. Geschwindner expands on many of the topics raised herein. MSC

HOW TO USE THE COMPUTER DESIGN PROCESS CHART

The various phases involved in computer-based stability design are presented in this chart. The chart illustrates how all Appendix 7 requirements can be satisfied by using these phases, and how the phases affect each other. For instance, the modeling of a structure in step 3 of the **MODELING** phase can affect how the load combinations are defined in step 2 of the **LOADING** phase.

The process begins by listing the input parameters in the **MODELING** phase. The material properties to be input in this phase depend on the requirements of the **ANALYSIS** and **STRENGTH & SERVICEABILITY CHECK** phases. It then gives the more commonly used environmental loads in the **LOADING** phase. The choice of design process can influence this phase. Pushover and time-history analysis are not considered because non-linear seismic design methods are not addressed here.

In the **ANALYSIS** phase, computation of internal forces and deformations is carried out. A summary of the required stiffness for various analysis methods (static vs. dynamic) and purposes (strength vs. serviceability evaluation) is tabulated. This table shows that only second-order analysis to determine the forces in strength checks need use reduced stiffness values. Typically, even dynamic analysis for purposes of determining periods for use in strength checks should use nominal stiffness values. All other analysis to determine serviceability deformations and vibration periods should also use nominal stiffness values.

Finally the more common inputs required to asses the structural adequacy of the model are listed in the **STRENGTH & SERVICEABILITY CHECK** phase. In that phase it is shown that computations for purposes of both strength and serviceability checks utilize nominal stiffness values.