BENCHMARK STUDIES TO COMPARE FRAME STABILITY PROVISIONS

Jose M. Martinez-Garcia[1] and Ronald D. Ziemian[2]

ABSTRACT

The 2005 AISC *Specification for Structural Steel Buildings* provides engineers several opportunities to assess general requirements for the stability analysis and design of members and frames. Using eleven two- and three-dimensional structural systems, a comprehensive study was conducted that compares these opportunities. This paper will provide an overview of this research along with specific details for three of the frames investigated. As a basis for comparison, all results are calibrated against those obtained using advanced second-order inelastic analysis. General conclusions from this study are also provided.

INTRODUCTION

Structural engineers will be pleased to learn that the provisions for frame stability have been expanded in the

[1] Former Graduate Student at Bucknell University and currently Consulting Structural Engineer, APIA XXI S.A. Department of Structures, Santander, SPAIN
[2] Professor, Department of Civil and Environmental Engineering, Bucknell University, Lewisburg, PA 17837

upcoming 2005 American Institute of Steel Construction *Specification for Structural Steel Buildings* (AISC, 2005). Engineers should consider the following four factors in deciding which provisions to apply to their specific design:

- Main lateral resisting system employed. Braced frame, moment frame, shear wall, combined system, etc.
- Level of analysis being used as a basis for calculating second-order effects. First-order or second-order.
- Significance of second-order effects. Using an amplification factor (A.F.) such as a B_2 factor to define the ratio of second-order to first-order effects, this significance can be defined as low (A.F.<1.1), moderate (A.F.<1.5), or large (A.F.>1.5).
- Whether or not effective length (K) factors will be used to calculate the axial strength of compression members.

If the long-standing *Effective Length Method* is being employed, the Specification recognizes various methods for calculating effective lengths, which include the alignment charts, eigenvalue analysis, and story based methods. On the other hand, and new to this Specification, the engineer can now employ the *Direct Analysis Method* in which effective length factors do not need to be calculated. Instead, the unbraced length of the compression member (i.e. K=1) may be used to determine axial strength, P_n. To complete this method, two additional factors will need to be addressed

- How will the influence of material yielding or partial inelasticity be represented? Through the use of a defined stiffness reduction (τ-factor) or by the inclusion of notional loads.
- How will the influence of initial sway imperfections be represented? Through the use of equivalent notional loads or by actually distorting the geometry of the analysis model.

A summary of these two methods are provided in Table 1. Both methods require the consideration of second-order effects on the stability of the structure and its components. They both also require the use of the same interaction equation (Eq. H1-1) to confirm the strength of the member.

$$\frac{P_r}{\phi_c P_n} + \frac{8}{9} \cdot \frac{M_r}{\phi_b M_n} \leq 1.0 \quad \text{for } \frac{P_u}{\phi_c P_n} \geq 0.2$$

$$\frac{P_r}{2\phi_c P_n} + \frac{M_r}{\phi_b M_n} \leq 1.0 \quad \text{for } \frac{P_u}{\phi_c P_n} < 0.2$$

The difference in the two methods resides on how member inelasticity and geometric imperfections are represented. In the Effective Length Method, both of these effects are included through the column strength curve using an effective length (KL) to calculate the axial strength, P_n. In contrast, the Direct Analysis Method models both of these effects within the analysis and hence, the axial strength, Pn, can be determined by simply using the unbraced length of the member.

Table 1. Comparison of methods.

Effect	AISC 2005 Spec. Effective Length Method	AISC 2005 Spec. Direct Analysis Method	Advanced Analysis Approach
Member Inelasticity	Column Strength Curve	Reduce Stiffness or notional load	Inelastic Analysis
Initial Out-of-Plumbness (Erection Tolerance)	Column Strength Curve	Direct Modeling or notional load	Direct Modeling
Initial Out-of-Straightness (Fab. Tolerance)	Column Strength Curve	Column Strength Curve	Direct Modeling
Strength Check	Analysis / Interaction Eq. H1-1		Analysis
Axial Strength Term	P_n based on KL	P_n based on L (K=1.0)	N/A

Over the past several years, members of AISC's Task Committee 10-Stabilty have investigated several structural systems in developing and refining new stability provisions (AISC-SSRC, 2003) In addition, two extensive studies have been completed at the Georgia Institute of Technology (Maleck and White, 2003) and Bucknell University (Martinez-Garcia, 2003). Using benchmark studies performed in the latter study, the objective of this paper is to compare the frame stability provisions that will appear in the 2005 AISC *Specification for Structural Steel Buildings*.

MARTINEZ-GARCIA AND ZIEMIAN STUDY

In this study, eleven structural systems are investigated, ten that are modeled as two-dimensional and one as three-dimensional. All of the systems are analyzed using a rigorous second-order elastic analysis. Two Load and Resistance Factor Design (LRFD) approaches are compared, one based on the Effective Length Method and the other on the Direct Analysis Method.

For each system, twelve different design procedures are employed in investigating the Effective Length Method. These procedures are a result of using four different approaches for calculating effective lengths combined with three different ways of studying the impact of initial sway imperfections. Approaches employed for calculating effective lengths include the use of alignment charts, results from eigenvalue analyses, and two story-based methods, including

Story-Based Method 1:

$$P_e = \left(0.85 + 0.15R_L\right)\cdot \frac{P_u}{\sum_{all} P_u} \cdot \left[\frac{\sum_{non-leaner} HL}{\Delta_{oh}}\right] \le \frac{\pi^2 EI}{L^2}, \text{ where}$$

$$R_L = \frac{\sum_{leaner} P_u}{\sum_{all} P_u}$$

Story-Based Method 2:

$$P_e = P_u \left[\frac{\Delta_{2nd} / \Delta_{1st}}{\Delta_{2nd} / \Delta_{1st} - 1} \right] \leq \frac{\pi^2 EI}{L^2}$$

Initial sway imperfections are modeled either directly in the analysis by distorting the initial frame geometry, represented by equivalent notional loads, or simply neglected.

Four approaches are used in checking the designs by the Direct Analysis Method. These approaches come from all combinations of modeling initial imperfections (either by direct modeling or notional loads) and material yielding (through the use of stiffness reductions or equivalent notional loads).

For each of the eleven frames studied, all sixteen of the above design procedures are calibrated against results from advanced second-order inelastic analyses.

ANALYSIS DETAILS

Two levels of analysis are employed throughout this study, including second-order elastic and advanced second-order inelastic.

In accordance with the Specification, all of the above design approaches are based on second-order elastic analyses. The MASTAN2 software (Ziemian and McGuire, 2002) is employed with second-order effects being accounted for by the use of an updated Lagrangian formulation and geometric stiffness matrices (McGuire et al., 2000). In the Effective Length Method, the full elastic stiffness of the section (1.0EA and 1.0EI) is used. In the Direct Analysis Method, the stiffness of the system is reduced according to provisions set forth in the Specification. When using prescribed notional loads to represent material inelasticity, the stiffness of the sections is reduced to 0.8EA and 0.8EI. As an alternative to notional loads, member inelasticity is modeled directly in the analysis by using a modified stiffness of 0.8τEA and 0.8τEI, where $\tau=4(P/P_y)(1-P/P_y)$ when $P/P_y>0.5$. If initial sway imperfections are included they are either directly modeled by distorting the frame geometry according to H/500 where H is the height of the system or by equivalent notional loads prescribed by the Specification

As indicated above, advanced second-order inelastic analyses are used throughout the study to asses the adequacy of all design methods. These analyses are performed using two programs NIFA(2D) and NISFA(3D) that were both developed at the University of Sydney (Clarke, 1991, and Teh, 2002). Inelasticity is modeled through the use of a distributed plasticity model with thermal residual stresses directly incorporated. To capture effects of resistance factors, the material stiffness and strength are reduced by a factor of 0.9. Initial imperfections are included by distorting the model geometry according to the previously mentioned H/500. Imperfections are always included in the direction that compounds the lateral effects of the applied loads.

EXAMPLES

The results of the following three examples are representative of the eleven structural systems investigated in the Martinez-Garcia and Ziemian study. In all cases, the nominal loads shown have been scaled such that an advanced second-order inelastic analysis will indicate a limit of resistance just at application of the controlling factored load combination. All lateral loads and gravity loads are applied proportionally. It should also be noted that all of the example frames can be shown to satisfy standard serviceability requirements.

IRREGULAR TWO-BAY FRAME

The dimensions and member sizes for this frame are shown in Fig. 1. The geometry is taken from a set of frames originally studied at the Virginia Polytechnic and State University by Professor T. Murray and one of his graduate students (Schimizze, 2001). The frame is moderately sensitive to second-order effects with an amplification factor A.F. = $\Delta_{2nd}/\Delta_{1st}$ = 1.3. All members are oriented with their webs in the plane of the frame and assumed to be fully restrained against out-of-plane failure behavior.

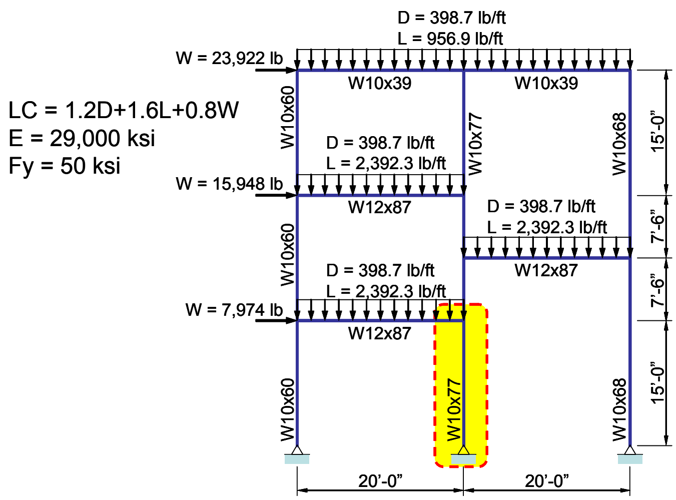

Figure 1. Irregular two-bay frame.

The advanced inelastic analysis results are shown in Fig. 2. At approximately 75% (APL=0.75) of the factored load, the upper portion of the lower story columns begin to yield. As a result of excessive yielding in this location, a significant redistribution of load occurs that eventually results in considerable yielding at the top of the left and center first-story columns. Additional lateral load is then resisted by only the right lower-story column and soon thereafter partial yielding of this column leads to a loss in the lateral stability of the frame.

It is clear from this analysis that a critical member, and in fact, the controlling member in checking the design of this frame is the first-story center column. Table 2 provides

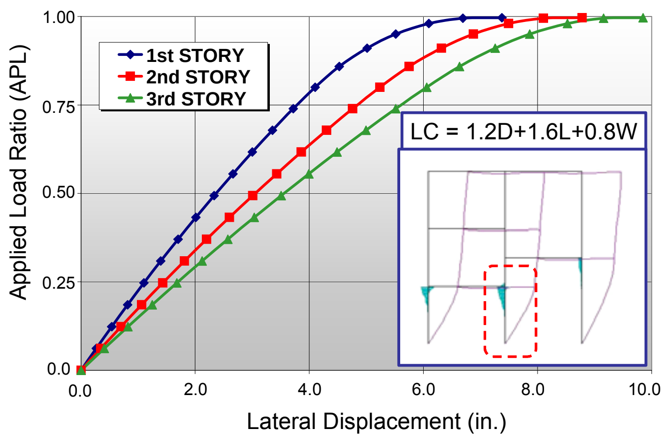

Figure 2. Results of advanced analysis.

Table 2. Design assessment of lower-story center column.

	AISC 2nd-Order Elastic Analysis/Design Methods	K	Eq. H1-1 APL = 1.0	APL @ Eq. H1-1 =1.00
Effective Length (Chapter C)	Alignment Chart	2.20	1.18	0.86
	Eigenvalue	1.84	1.13	0.90
	Story-Based 1	2.12	1.16	0.87
	Story-Based 2	1.97	1.14	0.89
Direct Analysis (Appendix 7)	NL:0.002Y_i & 0.8τEI	1.00	1.10	0.92
	Geom. Δ_o's & 0.8τEI	1.00	1.11	0.91
	NL:0.002Y_i & NL:0.001Y_i	1.00	1.10	0.92
	Geom. Δ_o's & NL:0.001Y_i	1.00	1.11	0.91

results obtained using a second-order elastic analysis to calculate the internal force distribution. Four design approaches are presented for each of the Effective Length and Direct Analysis Methods. Using these methods, the AISC interaction equation H1-1 is applied in two ways.

First, Eq. H1-1 is calculated for this column using internal forces or demands at application of the factored load combination (APL=1.0). Since all values exceed 1.0, all variations of both methods indicate that the column is inadequate. Since there is a disparity in the K-factors as a result of using different approaches to calculate effective lengths, the interaction equation values vary from 1.13 to 1.18. On the other hand, all four possibilities of the Direct Analysis Method provide consistent results which are acceptable and less conservative. This indicates that direct modeling of initial frame sway (Geom Δ_o's) and inelasticty ($0.8\tau EI$) is undistinguishable to applying equivalent notional loads (NL).

The study also investigated how much of the factored load could be applied before interaction Eq. H1-1 is exceeded. Since the frame response and corresponding analysis is nonlinear, these values cannot simply be taken as the reciprocal of the above results. As shown in the far right portion of Table 2, a second-order elastic analysis indicates that the lower-story center column becomes inadequate somewhere between 0.86 and 0.91 of the factored load depending on the design method employed. Since values less than 1.0 indicate conservative results, it is clear that slightly more variation and conservatism exists for the Effective Length Method.

BRACED FRAME WITH LEANER EXAMPLES

Two variations of the structural system shown in Fig. 3 are presented. In the first scenario the columns are oriented with their webs in the plane of the frame and in the second, the columns are assumed rotated 90° so that they experience minor-axis bending. Member sizes and loads in square brackets ([]'s) represent attributes of the minor-axis bending design. The frame geometry was originally suggested by Professor Joseph Yura at the University of Texas, Austin.

For the major-axis design, the factored lateral load combination LC2 controls. In this case, second-order effects are low-to-moderate with an amplification factor of A.F.=1.2. An advanced second-order inelastic analysis indicates that the limit of resistance of the structure is governed by the lower portion of the center column. Using an approach similar to the previous example, Table 3 compares the four variations of the Effective Length and Direct Analysis Methods. Again, small differences in the calculated effective length factors produce a slightly varied yet conservative range of interaction equation values for this column. On the other hand, the Direct Analysis Method is shown to be in remarkable agreement with the advanced analysis results. The consistency of the four possibilities of the Direct Analysis Method is also noteworthy.

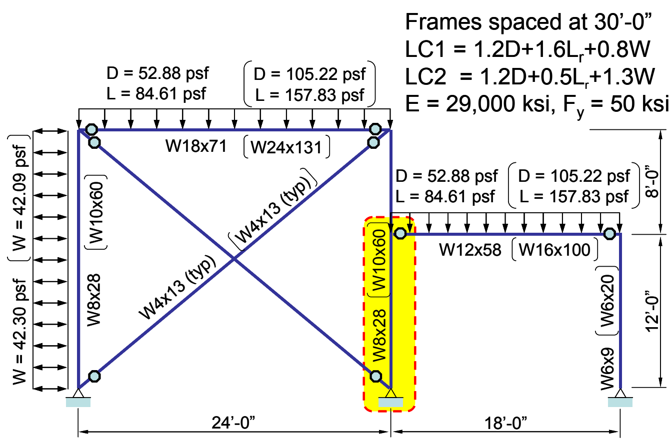

Figure 3. Braced frame with leaner.

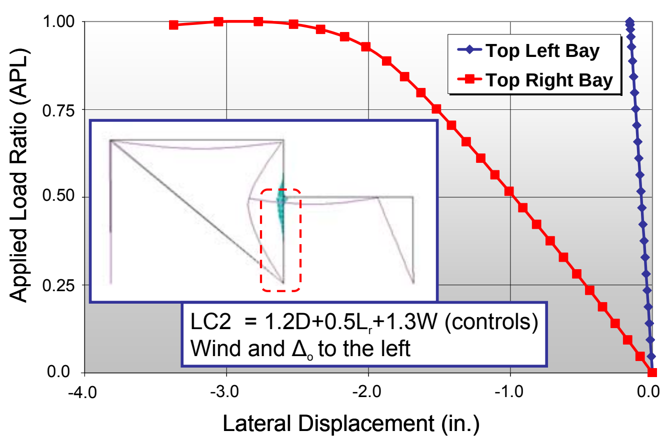

Figure 4. Results of advanced analysis (major-axis).

Table 3. Design assessment of center column (major-axis).

	AISC 2nd-Order Elastic Analysis/Design Methods	K	Eq. H1-1 APL = 1.0	APL @ Eq. H1-1 =1.00
Effective Length (Chapter C)	Alignment Chart	1.86	1.05	0.96
	Eigenvalue	1.60	1.02	0.99
	Story-Based 1	1.30	0.99	1.01
	Story-Based 2	1.56	1.01	0.99
Direct Analysis (Appendix 7)	NL:0.002Y_i & 0.8τEI	1.00	1.00	1.00
	Geom. Δ_o's & 0.8τEI	1.00	1.00	1.00
	NL:0.002Y_i & NL:0.001Y_i	1.00	1.00	1.00
	Geom. Δ_o's & NL:0.001Y_i	1.00	1.00	1.00

When all columns are rotated 90° so that they experience minor-axis bending, factored load combination LC1 controls. In this case, the second-order amplification factor is large at A.F.=1.8. Similar to the major-axis bending case, the effect of a leftward wind load combined with a natural leftward frame lean due to gravity loads results in excessive yielding in the center column.

Table 4 provides a summary of the interaction equation evaluation for this center column. There is significant variation in the effective length factors calculated by the different procedures. In fact, the authors doubt that Story-Based Method 1 should even be applied. Never the less, the Effective Length Method is shown to be accurate and slightly conservative as long as the correct effective length factor is determined. On the other hand, the Direct Analysis Method consistently appears to be slightly

Table 4. Design assessment of center column (minor-axis).

	AISC 2nd-Order Elastic Analysis/Design Methods	K	Eq. H1-1 APL = 1.0	APL @ Eq. H1-1 =1.00
Effective Length (Chapter C)	Alignment Chart	1.88	1.17	0.88
	Eigenvalue	1.60	1.05	0.98
	Story-Based 1 *	4.0*	1.26*	0.83*
	Story-Based 2	1.55	1.01	0.99
Direct Analysis (Appendix 7)	NL:0.002Y_i & 0.8τEI	1.00	0.96	1.03
	Geom. Δ_o's & 0.8τEI	1.00	0.97	1.02
	NL:0.002Y_i & NL:0.001Y_i	1.00	0.96	1.03
	Geom. Δ_o's & NL:0.001Y_i	1.00	0.97	1.02

* Upper portion of first-story center column controls

unconservative, indicating that this method suggests that the center column has a small amount of additional strength that is not predicted by a more advanced inelastic analysis.

SUMMARY AND CONCLUSIONS

This paper has presented a brief overview of two design approaches, the Effective Length Method and the Direct Analysis Method. Both approaches are appear in the 2005 AISC *Specification for Structural Steel Buildings* and viable alternatives that account for lateral stability. Three examples taken from a comprehensive comparative study of these methods is provided.

The following conclusions are made:

- In most cases the Effective Length and Direct Analysis Methods provide similar results. In other words, radically different designs are not expected when using one method instead of the other.
- The Effective Length Method tends to be slightly more conservative.
- As a consequence of employing different procedures for calculating effective length factors, a notable variation in the results obtained by the Effective Length Method can be observed. This variation tends to increase in situations when the axial force effect plays a more dominate role in the interaction equation.
- The Direct Analysis Method provides consistent results regardless of the Specification prescribed approaches for modeling inelasticity and geometric imperfections.
- The Direct Analysis Method may be slightly unconservative for beam-columns subjected to minor-axis bending.

Finally, and perhaps most importantly to the authors, the general approach and philosophy of the Direct Analysis Method provides an excellent transition for future design methods based on advanced analysis.

References

AISC (2005), *Specification for Structural Steel Build*ings, March 9, 2005, American Institute of Steel Construction, Inc., Chicago, IL.

AISC-SSRC (2003), "Background and Illustrative Examples on Proposed Direct Analysis Method for Stability Design of Moment Frames," Technical White Paper, AISC Technical Committee 10, AISC-SSRC Ad Hoc Committee on Frame Stability, American Institute of Steel Construction, Inc., Chicago, IL.

Clarke, M.J. (1991), *NIFA*, analysis software developed at the School of Civil and Mining Engineering, University of Sydney, Australia.

Maleck, A.E., and White, D.W. (2003), "Direct Analysis Approach for the Assessment of Frame Stability: Verification Studies," Proceedings of the Annual Technical Session and Meeting, Baltimore, MD, April 2-5, 2003, Structural Stability Research Council, Bethlehem, PA, pp. 423-442.

Martinez-Garcia, J.M. (2002), "Benchmark Studies to Evaluate New Provisions for Frame Stability using Second-Order Analysis," MS Thesis, Department of Civil and Environmental Engineering, Bucknell University, Lewisburg, PA, December.

McGuire, W., Gallagher, R.H., and Ziemian, R.D. (2000), *Matrix Structural Analysis*, 2nd edition, John Wiley and Sons, Inc., New York, NY.

Schimizze, A. (2001), "Comparison of P-Delta Analyses of Plane Frames Using Commercial Structural Analysis Programs and the AISC Specifications", MS Thesis, Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, May.

Ziemian, R.D. and McGuire, W. (2002), *MASTAN2*, Version 2.0, John Wiley and Sons, Inc., New York, NY.

Teh, L. (2002), *NISFA*, analysis software developed at the School of Civil and Mining Engineering, University of Sydney, Australia.