Design by the Direct Analysis Method

Overview

The design of a portal frame is investigated for two options available within the Direct Analysis Method as defined in Chapter C of the AISC *Specification for Structural Steel Buildings* (2016). Rigorous second-order analyses are employed to check the adequacy of compact doubly symmetric members subject to flexure and axial force.

Learning Objectives

- Apply the Direct Analysis Method of design to assess the adequacy of a structural system.
- Employ rigorous second-order analyses to determine required strengths in beam-columns.
- Utilize notional loads in place of both direct modeling of initial imperfections and stiffness reduction due to partial yielding.
- Use an interaction equation to check the adequacy of members subject to the combination of flexure and axial force.
- Use the ratio of second- to first-order drifts as an indicator of a system's sensitivity to second-order effects.

Method

Begin by preparing <u>two</u> identical computational models of the portal frame shown in Fig. 1; one of these models will be modified and used in Case Studies 1 and 2, and the other model will be used in Case Study 3. The columns are W12x58 (A992) of length 12'-0" and oriented for minor-axis bending, and the beam is a W24x76 (A992) that is fully braced out-of-plane. Different values of Q_u will be used in the below studies, and in all analyses stiffness reduction shall be included by reducing E by a factor of 0.8. Initial member imperfections (out-of-straightness) need not be modeled. Begin by completing Table A.
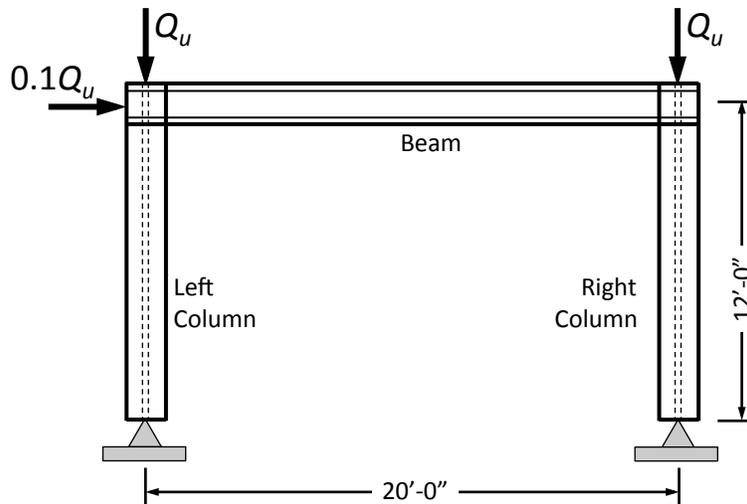

Figure 1.

Case studies:

1) Modify one of the models to include the effects of initial construction tolerance imperfections by assuming an out-of-plumbness ratio of H/500, where H is the story height. With Q_u = 100 kips, perform a second-order analysis that includes an additional stiffness reduction factor $0.8\tau_b$ per Section C.2.3 of the AISC *Specification for Structural Steel Buildings* (2016). Complete Table 1 using the analysis results and the information calculated in Table A.

2) Employing the same model and analysis parameters used in above study, determine the maximum value for Q_u that will satisfy the AISC interaction equation (Eq. H1-1a,b). This may take several trial and error iterations. Complete Table 2 for the analysis results that correspond to your maximum value of Q_u.

3) Using the second computational model (i.e., the one that has not been modified to include imperfections), perform a second-order elastic analysis with Q_u = 100 kips and a lateral load equaling the sum of $0.1Q_u$ and potentially two notional loads. The notional load of $0.002\Sigma Q_u$ represents the out-of-plumb imperfection, and the notional load $0.001\Sigma Q_u$ (if required) represents the additional stiffness reduction previously modeled by the τ_b factor. Complete Table 4 using the analysis results and information calculated in Table 1.

Table A. Applicable to all cases.

Member	K	L (in.)	Section	Axis	r (in.)	A_g (in.^{2})	Z (in.^{3})	$\phi_c P_n$	$\phi_b M_n$
Left Column	1.0	144	W12x58	minor					
Right Column	1.0	144	W12x58	minor					
Beam	1.0	240	W24x76	major					

Table 1.

1. Direct Analysis Method with imperfections modeled and τ_b included in analysis					0.8 E =		ksi
Gravity Load Q_u = 100 kips	Lateral Load $0.1Q_u$ = 10 kips	Model includes lateral imperfection of H/500 = in.			Additional stiffness reduction modeled by use of τ_b included in the analysis		
Member	P_u (kips)	$\phi_c P_n$ (kips)	M_u (kip-in)	$\phi_b M_n$ (kip-in)	AISC Eq. H1-1a/b	OK/NG?	
Left Column							
Right Column							
Beam							

Table 2.

2. Direct Analysis Method with imperfections modeled and τ_b included in analysis					0.8 E =		ksi
Gravity Load Q_u = kips	Lateral Load $0.1Q_u$ = kips	Model includes lateral imperfection of H/500 = in.			Additional stiffness reduction modeled by use of τ_b included in the analysis		
Member	P_u (kips)	$\phi_c P_n$ (kips)	M_u (kip-in)	$\phi_b M_n$ (kip-in)	AISC Eq. H1-1a/b	OK/NG?	
Left Column						OK	
Right Column						OK	
Beam						OK	

Table 3.

3. Direct Analysis Method with notional loads and no imperfections or τ_b included					0.8 E =		ksi
Gravity Load Q_u = 100 kips	Lateral Load $0.1Q_u$ = 10 kips	Imperfection Notional Load $0.002\Sigma Q_u$ = kips		Stiffness Notional Load $0.001\Sigma Q_u$ = kips		Total Lateral Load = kips	
Member	P_u (kips)	$\phi_c P_n$ (kips)	M_u (kip-in)	$\phi_b M_n$ (kip-in)	AISC Eq. H1-1a/b	OK/NG?	
Left Column							
Right Column							
Beam							

Hints:
1) Suggested units are kips, inches, and ksi.
2) Do not include the self-weight of the members.

MASTAN2 Details
The following suggestions are for those employing MASTAN2 to calculate the above computational strengths:
✓ Subdivide the members into 4 elements.
✓ By default MASTAN2 aligns the web (local y-axis) in the global X-Y plane. Use the *Re-orient Element(s)* option to rotate the member 90 degrees to investigate minor-axis bending of the columns.
✓ Initial imperfections (as needed) can be included by either extensive use of the *Move Node* option, or much more easily by "permanently bending" the frame through the combined use of a lateral load analysis and MASTAN2's post-processing option *Results-Update Geometry*.
✓ For Cases 1 and 2, employ second-order inelastic analyses[1] with:
   ▪ Planar frame analysis type
   ▪ Predictor-corrector solution scheme
   ▪ Load increment size of 0.05
   ▪ Maximum number of increments set to 100
   ▪ Maximum applied load ratio set to 1.0
   ▪ Modulus set to E_t (<u>not</u> E_{tm}; E_t employ's AISC's stiffness reduction τ_b factor)
✓ For Case 3, employ a second-order elastic analyses with:
   ▪ Planar frame analysis type
   ▪ Predictor-corrector solution scheme
   ▪ Load increment size of 0.05
   ▪ Maximum number of increments set to 100
   ▪ Maximum applied load ratio set to 1.0
✓ For Question 4 (below), employ a second-order inelastic analysis with:
   ▪ Planar frame analysis type
   ▪ Predictor-corrector solution scheme
   ▪ Load increment size of 0.05
   ▪ Maximum number of increments set to 100
   ▪ Maximum applied load ratio set to 5.0
   ▪ Modulus set to E_{tm} (MASTAN2's approximation for partial yielding/residual stresses)
✓ For Question 3 (below), prepare force-displacement curves using MASTAN2's MSAPlot feature.

Questions
1) Based on the results presented in Tables 1 and 3, what can you conclude about the two variations of the Direct Analysis Method? Include in your response the pros and cons of each variation.
2) For this system and based on the results recorded in Tables 1 and 2, what was the minimum value of the stiffness reduction factor τ_b employed in the analysis? Please interpret this number.
3) For the Case Study 1 computation model with Q_u = 100 kips, perform first- and second-order elastic analyses. Prepare a single plot that includes two curves (one for each analysis) with lateral deflection at the upper left corner of the frame as the abscissa and applied load Q_u as the ordinate. Record the maximum lateral deflection for each analysis.
   a. Based on the ratio of these second- to first-order drifts, what can you conclude about this system's sensitivity to second-order effects? Does the plot support your conclusion?
   b. If the first-order moment at one end of the beam was 1000 kip-in, use the above ratio to estimate this moment if equilibrium is formulated on the actual deformed shape of the system (i.e. based on an analysis that includes second-order effects)? Confirm your estimate by comparing actual moments taken from first- and second-order analyses of the system.

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[1] Although the Direct Analysis Method is based on second-order elastic analysis, MASTAN2 only provides access to the stiffness reduction τ_b factor in its second-order inelastic analysis feature.

      c.   Given that the beam resists a relatively small amount of axial force, explain why second-order effects are so significant in this member? In general beam design, when can second-order effects be neglected and when must they be included?

4)   What does a second-order inelastic analysis for Case Study 2 show? Per Appendix 1 of the AISC *Specification for Structural Steel Buildings* (2016), be sure to reduce the yield strength of the steel to 45 ksi and redefine *E* to 0.9 x 29000 ksi. Describe the frame's limit state behavior, including locations of yielding and maximum applied load ratio. Discuss these findings in relation to the data obtained in Table 2.

More Fun with Computational Analysis!
1. Repeat the above exercise with the column bases rigidly attached to the foundations.
2. Repeat the above exercise with the same beam size, but with HSS10x10x1/2 (A500Gr.B) columns.
3. Include additional case studies that are based on the effective length and first-order analysis design methods defined in Appendix 7 of the AISC *Specification for Structural Steel Buildings* (2016).

Additional Resources
    MS Excel spreadsheet: *9_DirectAnalysisMethod.xlsx*
    MASTAN2 – LM9 Tutorial Video [12 min]:
        http://www.youtube.com/watch?v=Poda7uKXAJQ
    MASTAN2 - How to re-orient elements for minor-axis bending [2 min]:
        http://www.youtube.com/watch?v=kqcPlDvw95U
    MASTAN2 - How to include an initial frame sway imperfection (out-of-plumb of H/500) [7 min]:
        http://www.youtube.com/watch?v=OTL3sx4W9TM
    MASTAN2 - How to account for partial yielding accentuated by residual stresses [1 min]:
        http://www.youtube.com/watch?v=m8ZXM02Cbu4
    MASTAN2 - How to plot response curves with MSAPlot [3 min]:
        http://www.youtube.com/watch?v=vS67MT0M1PQ
    AISC *Specification for Structural Steel Buildings and Commentary* (2016):
        https://www.aisc.org/publications/steel-standards/ - 30666
    MASTAN2 software:
        http://www.mastan2.com/