DRAFT Provisions on Frame/Member Stability

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Prepared by AISC-SSRC Task Group on Stability

This document summarizes the key portions of new provisions for frame and member stability that have been developed by the AISC-SSRC Task Group operating under AISC TC 10. This draft has been prepared for discussion at the upcoming Task Group meeting (scheduled for Nov. 16-17, 2001) and to provide preliminary information to the main Specification committee. The task group co-chairs, Joe Yura and Greg Deierlein, welcome comments on the document.

As summarized in the following pages, most of the proposed changes involve Chapter C (Frames and Other Structures) and Chapter H (Members Under Combined Forces and Torsion) of the Specification. The task committee expects that the full implementation will require some minor changes in other chapters (e.g., Chapter E on compression members) along with further coordination with changes and restructuring being pursued by other task committees. It is envisioned, for example, that the requirements currently in Chapter C (Frames and Other Structures) may be incorporated in a new Chapter B (or C) dealing with general analysis and design requirements.

The provisions summarized in this draft focus on stability design requirements associated with the use of second-order elastic analysis, which represents the majority of present practice. The committee is continuing to develop companion provisions for use with inelastic analysis methods.

Material appearing in shaded regions is provided as commentary to explain how the provisions are intended to fit within the current Specification and/or information that would be included in the new commentary to the provisions.

CHAPTER C

FRAMES AND OTHER STRUCTURES

Sections C1 through C3 are intended to replace the current Sections C1 and C2. The current section C3 Stability Bracing would be renumbered to C4.

C1. TYPES OF CONSTRUCTION

This new section C1 is supplementary to the new stability provisions and clarifies how the stability requirements pertain to different types of framing systems. Most of the material included in this section is extracted from sections A2 and C2 of the 1999 Specification.

1. Lateral Framing Systems

The type of lateral framing system assumed in the analysis and design shall be indicated on the design drawings. The analysis and design of all members, connections, and other structural components shall be consistent with the assumption.

a. Braced-Frame Systems

Braced-Frame systems are those where the resistance to lateral load or frame instability is provided by a system of diagonals, beams, and columns that resist the lateral loads primarily through axial loads. The analysis and design of members and connections in braced-frame systems shall meet the requirements in Section C2.1.

b. Moment-Frame Systems

Moment-Frame systems are those where the resistance to lateral load or frame instability is primarily provided by flexural resistance of the beams, columns, and their connections. The analysis and design of members and connections in moment-frame systems shall meet the requirements in Section C2.2. The moment connections shall be designed as fully restrained (FR) or partially restrained (PR).

When FR moment connections are used, the connection stiffness shall be sufficient to maintain the angles between intersecting members. When PR moment connections are used, the connection stiffness need not be sufficient to maintain the angles between intersecting members, provided the strength, stiffness and ductility characteristics of the connection is incorporated into the analysis and design. These characteristics shall be documented in the technical literature or established by analytical or experimental means.

c. Shear-Wall Systems

Shear-Wall systems are those where the resistance to lateral load or frame instability is primarily provided by reinforced concrete, masonry, or steel shear walls. The analysis and design of members and connections in shear-wall systems shall meet the requirements Section C2.3.

d. Combined Systems

The analysis and design of members and connections in combined systems of braced-frames or shear-walls and moment-frames shall meet the requirements of their respective sections. Analysis for stability effects shall be according to the requirements for Moment-Frame systems in Section C2.2, considering interaction of the lateral system types.

2. Gravity Framing Systems

This is a place holder for a new section on gravity systems that will draw attention to analysis and design assumptions for the gravity systems that impact stability requirements.

C2. ANALYSIS REQUIREMENTS

Because stability requirements are tied to the type of analysis, this new section is added to define the types of analyses envisioned by the Specification. The commentary to this section will include further description of the analysis methods, including illustrative benchmark problems to demonstrate second-order effects. The B1 and B2 equations, which are currently in section C1, will be moved to the commentary. While these equations demonstrate one way by which second-order effects may be calculated, the expectation is that most users will perform second-order analyses directly with commercial computer programs.

Subject to the stability design requirements of Section C3, the following types of analyses are permitted by these provisions to calculate member and connection forces and deformations under the Design Loads:

First-Order Elastic: First-Order Elastic Analyses are those where equilibrium conditions are met on the undeformed structure and members and connections are nominally elastic.

Second-Order Elastic: Second-Order Elastic Analyses are those where equilibrium conditions are met on the deformed structure and members and connections are nominally elastic.

First-Order Elastic-Plastic: First-Order Elastic-Plastic Analyses are those where equilibrium conditions are met on the undeformed structure and inelastic response of members or connections is concentrated in discrete locations or elements of the analysis model.

Second-Order Elastic-Plastic: Second-Order Elastic-Plastic Analyses are those where equilibrium conditions are met on the deformed structure and inelastic response of members or connections is concentrated in discrete locations or elements of the analysis model.

Second-Order Distributed Plasticity Analysis: Second-Order Distributed Plasticity Analyses are those where equilibrium conditions are met on the deformed geometry of the structure and nonlinear inelastic response is modeled explicitly.

The specification provisions are primarily intended for use with Second-Order Elastic analyses. First-order analyses (elastic or inelastic) are only permitted where the amplification of member and connection forces due to second-order effects are shown to be negligible. Design using inelastic analyses requires that the inelastic deformation demand of yielding members be less than their deformation capacity.

The task group is currently developing guidelines for when second-order effects can safely be neglected and first-order analyses can be used. The intent is that these guidelines would be given in the Specification provisions or commentary.

C3. STABILITY DESIGN REQUIREMENTS

General stability shall be provided for the structure as a whole and for each of its elements. Consideration shall be given to the significant second-order effects of the loads on the deflected shape of the structure and its individual elements. Design shall be based on a second-order analysis, unless second-order effects are either shown to be negligible or accounted for by alternative means. All significant member and connection deformations, including axial, flexural, and shear deformations, shall be considered in the analysis.

The destabilizing influence of the Gravity Framing System on the Lateral Framing System shall be accounted for in analysis and design of the structure. Force transfer and load-sharing between elements of the Lateral Framing System shall be considered.

1. Braced-Frame Systems

Braced-frame systems shall be determined by structural analysis to be adequate to maintain stability of the structure under the Strength Load Combinations, taking into account initial geometric imperfections of the frame and its members.

1.a. Design by Second Order Elastic Analysis

Design of Braced-Frame Systems using Second-order Elastic Analysis shall meet the following requirements:

Braces shall satisfy the requirements of Section C4.2 (same as Section C3.2 of the 1999 Specification) and the minimum Required Strength calculated under the Strength Load Combinations. Alternatively, the requirements of Section C4.2 need not be checked if the destabilizing effects of an H/500 erection out-of-plumb (where H is the story height) are included in the second-order analysis by distorting the initial geometry of the analysis model or applying equivalent Notional Loads. For the purpose of modeling the initial out-of-plumb, Notional Loads equal to the following shall be applied in conjunction with the Design Loads:

$$NL = 0.002\, GL \qquad \text{(C3-1)}$$

where

NL is the notional lateral load applied at each floor level
GL is the total design gravity loads acting at that floor level

Compression strengths of columns, braces and laterally unsupported beams shall be determined according to Chapter E, where the elastic critical member load is determined for an effective buckling length equal to the unsupported member length, unless structural analysis shows that a smaller value may be used. Members subjected to appreciable bending and shear, in addition to axial forces, shall be proportioned as beam-columns according to Chapter H.

2. Moment-Frame Systems

Moment-frame systems shall be determined by structural analysis to be adequate to maintain the stability of the structure under the Strength Load Combinations, taking into account initial geometric imperfections of the frame and its members and the loss in stiffness due to material yielding under the Strength Load Combinations.

2.a. Design by Second-Order Elastic Analysis

Design of Moment-Frame Systems using Second-order Elastic Analysis shall be one of the following three methods:

1) **Critical Load Method:** Required Strengths for members and connections shall be calculated by a Second-Order Elastic Analysis for the Strength Load Combinations. To evaluate beam-column failure in the plane of the frame (Section H1.1a), member compression strengths shall be calculated from a critical load analysis in the plane of the Moment-Frame. To evaluate failure out of the plane of the frame (Section H1.1b), member compression strengths shall be calculated based on the laterally unsupported member lengths.

Commentary – this method is similar to that of the current procedures that require the calculation of effective buckling length factors for in-plane and out-of-plane column buckling. The provisions are rephrased to generalize the column strength calculation in terms of “elastic critical load” rather than “effective length” in order to emphasize that buckling is a system phenomena. The **commentary** will include the following two equations to estimate critical column loads using data from frame analyses:

$$Pe = 0.85Pu\left[\frac{\Delta_{ph} - \Delta_{oh}}{\Delta_{ph}/\Delta_{oh} - 1}\right] \le \pi^2 EI/L^2$$

or, alternatively

$$Pe = 0.85\frac{P_u}{\Sigma P_u}\left[\frac{\Sigma HL}{\Delta_{oh}}\right] \le \pi^2 EI/L^2$$

2) **Notional Load Method:** Required Strengths for members and connections shall be calculated by a Second-Order Elastic Analysis for the Strength Load Combinations applied in combination with Notional Loads to

account for frame out-of-plumb and inelastic softening at the Design Loads. To evaluate beam-column failure in the plane of the frame (Section H1.1a) or out of the plane of the frame (Section H1.1b), member compression strengths shall be calculated based on the unsupported member length.

To account for frame out-of-plumb and inelastic softening under the Design Loads, Notional Loads equal to the following shall be applied in conjunction with the Design Loads:

$$NL = 0.005\ GL \tag{C3-2}$$

where the terms are the same as defined previously for Equation C3-1.

3) **Modified Stiffness Method:** Required Strengths for members and connections shall be calculated by a Second-Order Elastic Analysis for the Strength Load Combinations with modifications to account for initial frame out-of-plumb and inelastic softening at the Design Load. To evaluate beam-column failure in the plane of the frame (Section H1.1a) or out of the plane of the frame (Section H1.1b), member compression strengths shall be calculated based on the unsupported member length.

Story out-of-plumb equivalent to H/500 (where H is the story height) shall be included by distorting the initial geometry of the analysis model or, alternatively, by applying Notional Loads equal to the following:

$$NL = 0.002\ GL \tag{C3-3}$$

where the terms are the same as defined previously for Equation C3-1.

To account for inelastic effects under the Design Load, flexural rigidities of members subjected to axial compression greater than 0.1Py shall be reduced as follows:

$$EI^* = \tau EI \text{ (for } M_n < 1.2\ M_y)$$
$$EI^* = 0.8\tau EI \text{ (for } M_n > 1.2M_y)$$

Where
M_n = nominal flexural capacity, kip-in (N-mm)
M_y = nominal yield moment (=FyS), kip-in (N-mm)
E = modulus of elasticity = 29,000 ksi (200 000 MPa)
I = moment of inertia about the axis of bending, in4 (mm4)
EI* = reduced flexural rigidity
τ = stiffness reduction factor
= 1.0 for P/Py < 0.5
= 4[P/Py (1-P/Py)] for P/Py > 0.5

2.a. Design by Second-Order Elastic-Plastic Analysis

The AISC-SSRC committee is working on provisions that will provide a straight forward extension of the Notional Load and Modified Stiffness approaches for second-order “plastic hinge” type analyses. These provisions will replace the existing requirements for “plastic design”.

It is anticipated that the main additions will be provisions to ensure adequate deformation capacity of the hinge locations in the frame.

3. Shear-Wall Systems

In concept this would be similar to braced-frame systems.

4. Combined Systems

Proposal would be to treat the analysis and design of combined braced-moment frame or wall-moment frame systems the same as for moment frame systems (section C3.2).

C4. STABILITY BRACING

Same as Section C3 of 1999 LRFD Specification

CHAPTER E

COLUMNS AND OTHER COMPRESSION MEMBERS

Section E2 employs the same column curve as the 1999 Specification, except that it is re-written in terms of elastic critical column strength rather than effective length and slenderness. Section E1 is rewritten to reflect the change in emphasis from "effective length" to "elastic critical load" and to reference the new stability requirements of Chapter C.

E1. ELASTIC CRITICAL COLUMN LOADS

In braced-frames, the elastic critical loads for calculating compression strengths shall be based on the unsupported member length, unless shorter lengths can be justified by a critical load analysis. For moment-frames, the elastic critical loads for calculating compression strengths shall be determined in accordance with Section C3.

E2. DESIGN COMPRESSIVE STRENGTH FOR FLEXURAL BUCKLING

The design strength for flexural buckling of compression members whose elements have width-thickness ratios less than λr from Section B5.1 is $\phi_c P_n$:

$$\phi_c = 0.85$$

$$P_n = A_g F_{cr} \qquad \text{(D1-1)}$$

(a) For $\sqrt{P_y / P_e} \le 1.5$

$$F_{cr} = \left(0.658^{Py/Pe}\right) F_y \qquad \text{(D1-2a)}$$

(b) For $\sqrt{P_y / P_e} > 1.5$

$$F_{cr} = 0.877 \frac{P_e}{A_g} \qquad \text{(D1-2a)}$$

where

P_e = elastic critical load in the direction of buckling, kips (N)
$P_y = A_g F_y$
A_g = gross area of member, in.^{2} (mm^2)
F_y = specified minimum yield stress, ksi (MPa)

CHAPTER H – Design for Combined Forces

The requirements for symmetric members are revised based on the proposed member/frame stability requirements in Chapter C. The following new Sections H1 and H2 replace the existing Section H1. The existing Section H2 and H3 would be renumbered to H3 and H4.

H1. SYMMETRIC MEMBERS SUBJECTED TO BENDING AND AXIAL TENSION

The interaction of flexure and tension in singly or doubly symmetric shapes shall be limited by Equations H1-1a and H1-1b. The required axial and flexural strengths shall be determined according to the provisions of Chapter C.

Comment – this section is unchanged from current specification, except for changes in chapter and section numbers. Where the bending strength is limited by local buckling or lateral-torsional buckling, it may be worthwhile to propose alternate formulae that account for the increased flexural strength due to the beneficial effect of tension.

For $\dfrac{P_u}{\phi_t P_n} \geq 0.2$

$$\frac{P_u}{2\phi_t P_n} + \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0 \qquad \text{(H1-1a)}$$

For $\dfrac{P_u}{\phi_t P_n} < 0.2$

$$\frac{P_u}{\phi_t P_n} + \frac{8}{9} \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0 \qquad \text{(H1-1b)}$$

where

P_u = required tensile strength, kips (N)
P_n = nominal tensile strength determined in accordance with Section D1, kips (N)
M_u = required flexural strength, kip-in (N-mm)
M_n = nominal flexural strength determined in accordance with Section F1, kips (N)
x = subscript relating symbol to strong axis bending
y = subscript relating symbol to weak axis bending
ϕ_t = resistance factor for tension (see Section D1)
ϕ_b = resistance factor for flexure (see Section F1)

H2. SYMMETRIC MEMBERS SUBJECTED TO BENDING AND AXIAL COMPRESSION

1. Uniaxial Bending: The interaction of uniaxial flexure and compression in singly or doubly symmetric shapes shall be limited by the in-plane and out-of-plane limit state provisions given by Equations H2-1a, H2-1b, and H2-2, respectively. The required axial and flexural strengths shall be determined according to Chapter C. Nominal compression strengths for the in-plane and out-of-plane limit state checks shall be calculated according to Sections C3 and E1.

1.a. In-plane limit state:

For $\dfrac{P_u}{\phi_c P_n} \geq 0.2$

$$\frac{P_u}{2\phi_c P_n} + \frac{M_u}{\phi_b M_n} \leq 1.0 \qquad \text{(H2-1a)}$$

For $\dfrac{P_u}{\phi_c P_n} < 0.2$

$$\frac{P_u}{\phi_c P_n} + \frac{8}{9}\frac{M_u}{\phi_b M_n} \leq 1.0 \qquad \text{(H2-1b)}$$

where

P_u = required tensile strength, kips (N)
P_n = nominal compression strength in the plane of bending determined in accordance with Sections B5 and D1, kips (N)
M_u = required flexural strength, kip-in (N-mm)
M_n = nominal flexural strength in the plane of bending determined in accordance with Section E1, kips (N)
ϕ_c = resistance factor for compression (see Section C1)
ϕ_b = resistance factor for flexure (see Section E1)

1.b. Out-of-plane limit state:

$$\frac{P_u}{\phi_c P_n} + \left(\frac{M_u}{\phi_b M_n}\right)^2 \Bigg/ \left[1 - \frac{P_u}{\phi_c P_{ez}}\right] \leq 1.0 \qquad \text{(H2-2)}$$

where, definitions are the same as for Equations G2-1a and G2-1b, except for the following modifications

P_n = nominal compression strength out of the plane of bending determined in accordance with Sections B5 and D1, kips (N)
M_n = nominal flexural strength out of the plane of bending determined in accordance with Section E1, kips (N)
P_{ez} = elastic torsional buckling strength

$$= \left(\frac{\pi^2 E C_w}{l^2} + GJ\right)\frac{1}{\bar{r}_o^{\,2}}$$

2. Biaxial Bending: The interaction of biaxial flexure and compression in singly or doubly symmetric shapes shall be limited by Equations G2-3a and G2-3b. Nominal compression strengths shall be the lesser of the compression strengths for the in-plane or out-of-plane limit state check, as specified in Section H2.1.

For $\dfrac{P_u}{\phi_c P_n} \geq 0.2$

$$\frac{P_u}{2\phi_c P_n} + \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0 \qquad \text{(H2-3a)}$$

For $\dfrac{P_u}{\phi_c P_n} < 0.2$

$$\frac{P_u}{\phi_c P_n} + \frac{8}{9}\left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0 \qquad \text{(H2-3b)}$$

where, definitions are the same as for Equations G2-1a and G2-1b, except for the following modifications

P_n = nominal compressive strength determined as the minimum of in-plane or out-of-plane failure in accordance with Sections H2.1, kips (N)
M_n = nominal flexural strength determined in accordance with Section F1, kips (N)
x = subscript relating symbol to strong axis bending
y = subscript relating symbol to weak axis bending

GLOSSARY

The following are glossary terms that are relevant to the analysis and stability provisions. Some of the terms are ones recently proposed by the AISC analysis subcommittee.

Nominal Loads. The magnitude of loads specified by the applicable building code.

Design Loads. General reference to the governing loading condition or combination whose specific meaning depends on the context in which it is used.

Modified Stiffness. Technique that assigns effective stiffness coefficients that account for softening of the structure that occurs due to residual stresses and partial yielding of members and connections under a specified load intensity.

Notional Load. Lateral load that is applied to the structure to approximate the effects of initial geometric imperfections and/or softening of the structure that occurs due to residual stresses and partial yielding of members and connections under a specified load intensity.

Required Strength. Load effects due either to LRFD or ASD strength load combinations.

Second-order Elastic Analysis. Analysis where equilibrium conditions are met on the deformed structure and where members and connections are nominally elastic.

Second-order Elastic-Plastic Analysis. Analysis where equilibrium conditions are met on the deformed structure and where members and connections are modeled as elastic-perfectly plastic, where their plastic strength is set equal to their design strength.

Strength Load Combinations. Factored load combination that is intended to determine the Required Strengths of members, connections and other elements as specified by the applicable building code.

Serviceability Load Combinations. Factored load combination that is intended to check a serviceability limit state condition as established by the design professional or otherwise specified by the applicable building code.