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Helen Chen

Chia-Ming Uang

Reidar Bjorhovde

Bonnie Manley

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Overview of the Standard for Seismic Design of Cold-Formed Steel Structural Systems – Special Bolted Moment Frames

by

Helen Chen[1], Chia-Ming Uang[2], Reidar Bjorhovde[3] and Bonnie Manley[4]

ABSTRACT

Cold-formed steel has been widely used for components and main force resisting systems in commercial, industrial, and residential buildings. Cold-formed steel structural members are designed using AISI S100, *North American Specification for the Design of Cold-Formed structures Members* [AISI, 2007]. For applications in high seismic regions, additional requirements may be needed. In fact, cold-formed steel design standards have been developed for applications in high seismic regions for both rack structures [RMI, 2004] and cold-formed steel light frame construction [AISI, 2007a]. In 2003, the American Iron and Steel Institute (AISI) established a seismic design committee. Composed of suppliers, manufacturers, engineers, researchers and professors, the committee is responsible for developing design standards applicable to cold-formed steel structural systems located in seismic regions. The first edition of the *Standard for Seismic Design of Cold-Formed Steel Structural Systems – Special Bolted Moment Frames* (hereinafter referred as the *Standard*) was finished in 2007. The *Standard* has also been approved by ANSI and an American National Standard. As the title indicates, this edition of the *Standard* focuses on the design of the seismic force resisting system for special bolted moment frames, which consist of tubular columns, cold-formed channel beams and bolted moment connections. A typical connection of a cold-formed steel special bolted moment frame (CFS-SBMF) is illustrated in Figure 1. This

[1] Senior Engineer at the American Iron and Steel Institute, Washington, DC, hchen@steel.org
[2] Professor of Civil Engineering at University of California – San Diego, La Jolla, CA, cuang@ucsd.edu
[3] President of The Bjorhovde Group, Tucson, AZ, rbj@bjorhovde.com
[4] Regional Director at the American Iron and Steel Institute, Construction Codes and Standards, Washington, DC, bmanley@steel.org

type of special bolted moment frame is widely used in industrial platform mezzanines such as the one shown in Figure 2.

The 2007 edition of the *Standard* is based on the 2005 edition of the ANSI/AISC 341, *Seismic Provisions for Structural Steel Buildings,* [AISC, 2007] and research work [Sato and Uang, 2007] on cold-formed steel special bolted moment frame systems as a seismic force resisting system. This paper will briefly review the design provisions included in the *Standard*.

APPLICABILITY

This edition of the *Standard* covers the cold-formed steel special bolted moment frames (CFS-SBMF), and is mandatory in seismic design categories D, E and F. For structures in seismic design categories A, B, and C, the designer may choose one of the following options:

1. To solely use AISI S100 and the response modification coefficient, R, given in the applicable building code or ASCE/SEI 7 [ASCE, 2005], or
2. To utilize a higher value for R in a system detailed for seismic resistance and follow the requirements of this *Standard*.

MATERIALS

To ensure a higher level of ductility and reserve strength for inelastic seismic response, the applicable steel grades are generally required to have a ratio of $F_u/F_y \geq 1.15$ and an elongation at fracture of not less than 12 percent in a 2 in. (50 mm) gage length, where F_u = specified minimum tensile strength and F_y = specified minimum yield stress.

To determine the expected yield stress, adjustments must be made to F_y considering not only the inelastic reserve capacity of a compact section, R_{re}, the increase in yield stress due to cold work of forming, R_{cf}, and the difference between stress level of the minimum yield stress and the expected yield stress, R_y. Taking these variables into account, the expected yield stress can be calculated as $R_{re}R_{cf}R_yF_y$. The expected tensile strength is calculated simply as R_tF_u, where R_t is the ratio of expected tensile strength to the specified minimum tensile strength.

The R_y and R_t values for different steels are provided in Table 1 below:

TABLE 1, R_y AND R_t VALUES FOR VARIOUS PRODUCT TYPES

Steel	R_y	R_t
Plates and bars:		
A36/A36M, A283/A283M	1.3	1.2
A242/A242M, A529/A529M, A572/A572M, A588/A588M	1.1	1.2
Hollow Structural Sections:		
A500 and A847	1.4	1.3
Sheet and strip (A606, A653/A653M, A792/A792M, A875, A1003/A1003M, A1008/A1008M, A1011/A1011M):		
F_y< 37 ksi (255 MPa)	1.5	1.2
37ksi (255MPa) ≤ F_y< 40 ksi (275 MPa)	1.4	1.1
40ksi (275MPa) ≤ F_y<50 ksi (340 MPa)	1.3	1.1
F_y ≥ 50 ksi (340 MPa)	1.1	1.1

COLD-FORMED STEEL – SPECIAL BOLTED MOMENT FRAMES (CFS-SBMF)

In order for CFS-SBMF to withstand the anticipated seismic forces, the CFS-SBMF is intended to dissipate seismic input energy through controlled inelastic deformation. Research work at the University of California-San Diego has revealed that the CFS-SBMF can experience substantial inelastic deformation during seismic events. Most of these deformations will take place in the bolted connections due to bolt slippage and bearing deformation as long as the beams and columns have sufficient strength when subjected to the forces resulting from the motion of the design level earthquake. This is accomplished by limiting the beam web flat width-to-thickness to a maximum of $6.18\sqrt{E/F_y}$ and the tubular column flat width-to-thickness to $1.58\sqrt{E/F_y}$, where E = modulus of elasticity = 29500 ksi (203000 MPa), and F_y = specified minimum yield stress of the steel.

Based on the unique behavior of the CFS-SBMF [Sato and Uang, 2007], the *Standard* provides methods for determining both the expected moment for beam-column connections and bolt bearing plates, and the appropriate seismic design coefficients.

The expected moments, M_e, at the beam-column connection of the CFS-SBMF and the bearing plate are determined by the following equation:

$$M_e = h(V_S+R_tV_B) \tag{1}$$

where h = story height
V_S = column shear corresponding to the slip strength of the bolt group
R_t = ratio of expected strength to specified minimum tensile strength
V_B = column shear corresponding to bearing strength of the bolt group

Equation (1) indicates that the column base shear due to earthquake is transferred to the beam-column connections through friction (slip strength) and bearing resistance. Based on the performance of the CFS-SBMF, the following equations are used to determine both V_S and V_B:

$$V_S = C_S kNT/h \tag{2}$$

$$\left(\frac{V_B}{V_{B,max}}\right)^2 + \left(1-\frac{\Delta_B}{\Delta_{B,max}}\right)^{1.43} = 1 \tag{3}$$

$$V_{B,max} = C_B N R_0/h \tag{4}$$

$$\Delta_{B,max} = C_{B,0} C_{DB} h \tag{5}$$

$$\Delta_B = \Delta - \Delta_S - \frac{nM_e}{hK} \geq 0 \tag{6}$$

$$\Delta_S = C_{DS} h_{os} h \tag{7}$$

where k = slip coefficient = 0.33
N = 1 for connection with a single-channel beam and 2 for connection with double-channel beams
T = 10 kips (44.5kN) for 1-in. (25.4 mm) diameter bolts
$V_{B,max}$ = column shear producing the maximum bearing strength of a bolt group

Δ	=	design story drift
Δ_B	=	component of design story drift causing bearing deformation in a bolt group
$\Delta_{B,max}$	=	component of design story drift corresponding to the deformation of the bolt group at maximum bearing strength
Δ_S	=	component of design story drift corresponding to bolt slip deformation
h_{os}	=	hole oversize
K	=	structural lateral stiffness
M_e	=	expected moment at a bolt group
n	=	number of columns in a frame line

Values of other variables C_S, C_B, C_{DS}, $C_{B,0}$, and C_{DB} that are related to the geometry of the bolt configurations are tabulated and provided in the *Standard*.

To increase the bearing strength of the bolted connection, bearing plates can be welded to the beam web. The expected moment for the bearing plate is determined by Equation (8) below:

$$M_{bp} = \frac{M_e}{N}\left(\frac{t_p}{t_w + t_p}\right) \quad (8)$$

where t_p = bearing plate thickness
t_w = beam web thickness.

Based on research [5], the response modification coefficient, R, for CFS-SBMF is 3.5, the deflection amplification factor, C_d, is 2.9, and the height limit for the system is 35 ft. The height limit is established based upon practical consideration of the system.

Once the expected moments are determined, the strengths of the members and connections are then designed in accordance with AISI S100, *North American Specification for the Design of Cold-Formed Steel Structural Members* [AISI, 2007]. For a typical CFS-SBMF, the following design procedures are recommended:

<u>Step 1</u> Perform the preliminary design of the beams, columns, and bolted connections by considering all basic load combinations found in the applicable building code, and using a value of 3.5 for Response Modification Coefficient, R. In determining the earthquake load, use a rational method to determine the structural period.

Step 2 Compute both the base shear (nV_S) that causes the bolt groups to slip and the slip range (Δ_S) in terms of story drift.

Step 3 Compute the design story drift, Δ. Follow the applicable building code to compute the design story drift, where the Deflection Amplification Factor is taken as 2.9.

Step 4 Determine the strength of beams and columns using AISI S100.

Step 5 Check P-Δ effects.

EXAMPLE

An example is provided to determine the expected moment through Equations (1) to (7). For a given one-story, two-bay CFS-SBMF, determine the expected moment of the beam-column connection at the center column. The beam and column cross-sections satisfy the flat width-to-thickness requirements for beams and columns, and are selected based on design outlined in Step 1. The beam web thickness = 0.135 in. (3.43 mm), the column wall thickness = 0.25 in. (6.35 mm), and the yield stress and tensile strength for both beam and column are 50 ksi (345 MPa) and 70 ksi (483 MPa), respectively. The bolted connection layout is shown in the elevation of Figure 1, where for bolt spacing, a = 3 in. (76 mm), b = 6 in. (152 mm), c = 4.25 in. (108 mm), and the bolt diameter = 1 in. (25.4 mm).

The frame analysis in Step 1 also provides the stiffness of the frame system as K = 6.17 kips/in. (0.175 kN/mm), and the drift corresponding to the design basis earthquake as Δ_{DBE} = 2.40 in. (61 mm). From there, the design drift is calculated as follows:

$\Delta = C_d\Delta_{DBE}$ = (2.9)(2.40) = 6.96 in. (177 mm)

Based on the bolt configuration, the following coefficients are obtained from the tables provided in the *Standard*:

C_S = 3.34 ft (1020 mm), C_{DS} = 3.61 ft^{-1} (0.0118 mm^{-1}), C_B = 5.88 ft (1790 mm), $C_{B,0}$ = 0.625 in./ft. (0.0521 mm/mm), and C_{DB} = 1.19.

The following variables are determined using Equations (2) and (4) through (7):

$V_S = C_S kNT/h$ = (3.34)(0.33)(2)(10)/(11.43) = 1.93 kips (8.59 kN)

$V_{B,max} = C_B NR_0/h$ = (5.88)(2)(9.45)/(11.43) = 9.72 kips (43.2 kN)

$\Delta_{B,max} = C_{B,0}C_{DB}h$ = (0.625)(1.2)(11.43) = 8.50 in. (200 mm)

$\Delta_S = C_{DS}\ h_{os}h$ = (3.61)(0.0625)(11.43) = 2.58 in (65.5 mm)

The expected moment, M_e, and the connection bearing shear force, V_B, are obtained via iteration of Equations (1) and (3). Some of the iteration results in the vicinity of the convergence are shown in the table below:

TABLE 2, ITERATION RESULTS

Given Δ_B in. (mm)	V_B Per Equation (3) Kips (kN)	M_e Per Equation (1) Kips-ft (kN-m)	New Δ_B Per Equation (6) In (mm)	Error
1.055 (25.85)	4.043 (17.98)	77.495 (105.1)	1.085 (26.57)	2.8%
1.06 (25.97)	4.052 (18.02)	77.62 (105.2)	1.079 (26.44)	1.8%
1.07 (26.22)	**4.071 (18.11)**	**77.88 (105.6)**	**1.068 (26.18)**	**0.16%**
1.08 (26.46)	4.089 (18.19)	78.13 (105.9)	1.058 (25.91)	2.1%

As shown in Table 2, the converged results are:

The expected moment at the connection, M_e = 77.88 kip-ft (105.6 kN-m);
The expected bearing shear force at the connection, V_B = 4.07 kips (18.11 kN);
The expected bearing deformation at the bolt connection, Δ_B = 1.07 in. (26.22 mm)
The expected total base shear $V_{total} = V_S + R_t V_B$

For Step 5, the P-Δ effect should be checked according to ASCE 7 [ASCE, 2005]. The frame members and connections should then be checked in accordance with AISI S100 to ensure the design strengths of the members and connections are greater than or equal to the expected moments and the shear forces. The design story drift of the frame should also be within the limit, 0.05h, as specified in the *Standard*.

FUTURE WORK

Cold-formed steel possesses higher strength and lower ductility than conventional hot-rolled steel. Since cold-formed steel members are relatively thin, they are susceptible to local, distortional and global buckling. Further research is needed to better understand the behavior of cold-formed steel members in seismic force resisting systems and to develop a more comprehensive seismic design standard for cold-formed steel. AISI will continue supporting research and partnering with interested organizations to expand the market for cold-formed steel.

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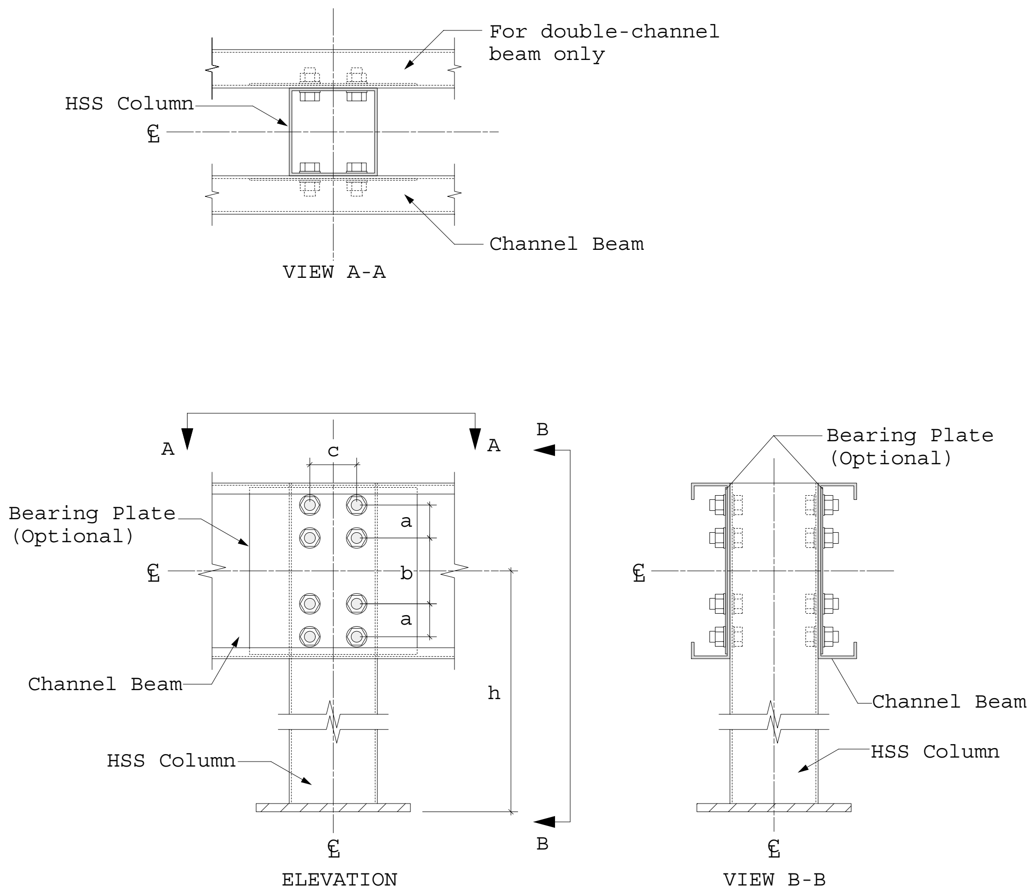

FIGURE 1 – TYPICAL CONNNECTION OF CFS-SBMF

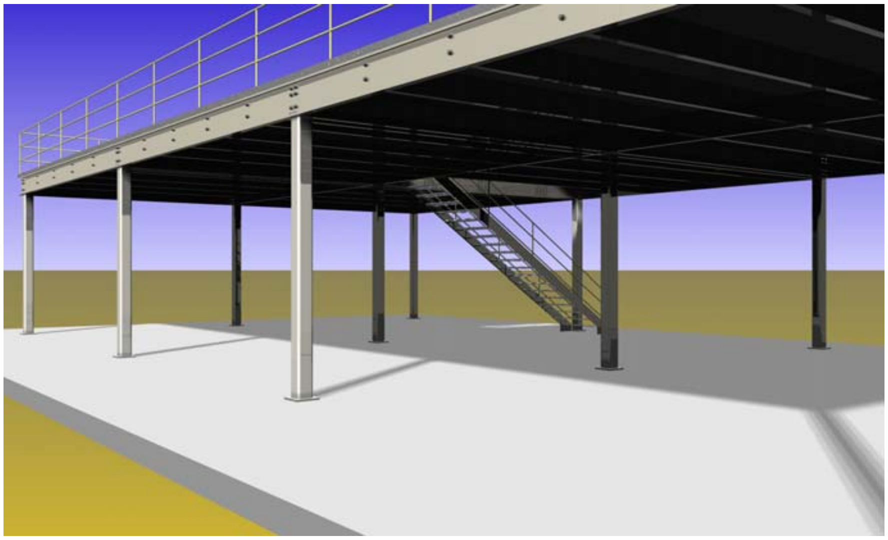

FIGURE 2 – TYPICAL CFS-SBMF USED AS INDUSTRIAL PLATFORM MEZZANINE