Codes and Standards

updates and discussions related to codes and standards

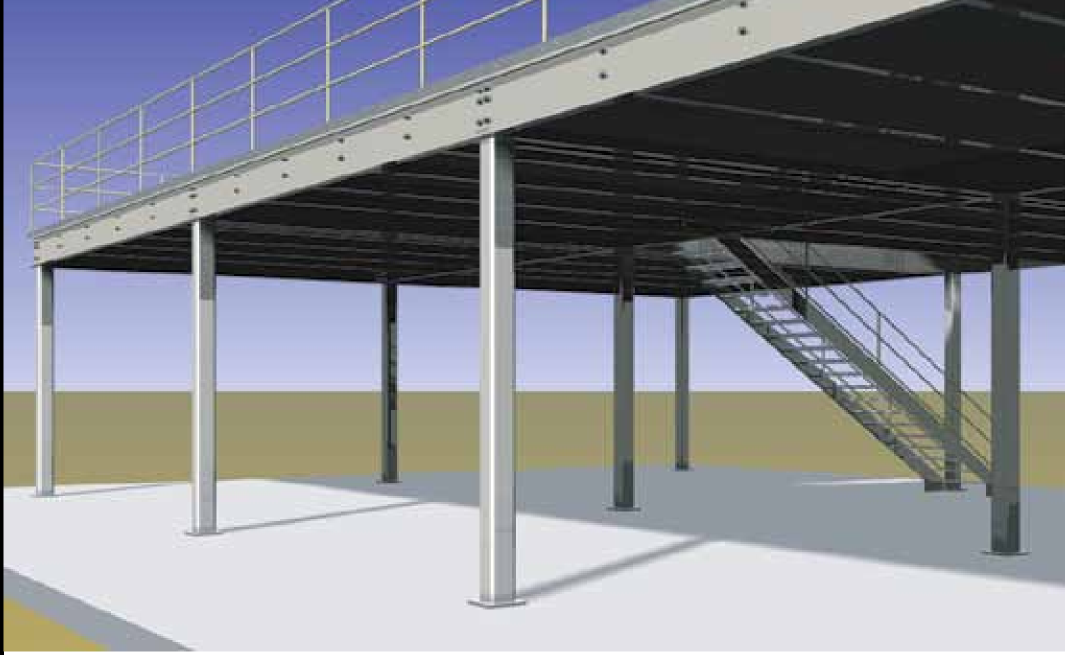

Figure 1: A Type of CFS-SBMF.

Cold-Formed Steel Special Bolted Moment Frames

Now a Code-Recognized System

By Chia-Ming Uang, Ph.D. and Atsushi Sato, Ph.D.

The American Iron and Steel Institute (AISI) recently issued a brand new standard S110, *Standard for Seismic Design of Cold-Formed Steel Structural Systems–Special Bolted Moment Frames*, which covers cold-formed steel seismic force-resisting systems. While there are plans to include additional cold-formed steel seismic force-resisting systems in the future, the first system introduced in this standard is called the Cold-Formed Steel Special Bolted Moment Frame (CFS-SBMF). This type of one-story framing system is commonly used for free standing mezzanines (industrial platform), elevated office support platforms, equipment support platforms, and small buildings in all seismic areas (*Figure 1*). The frame is typically composed of cold-formed Hollow Structural Section (HSS) columns and C-section beams. Beams are connected to the column by using snug-tight high-strength bolts (*Figure 2*). If needed, bearing plates are welded to the web of the beams in the connection region to increase the bearing strength at bolt holes.

The strong column-weak beam seismic design philosophy adopted in AISC 341, *Seismic Provisions for Structural Steel Buildings*, for Special Moment Frame is not applicable for a CFS-SBMF because cold-formed steel C-section beams usually do not satisfy the stringent

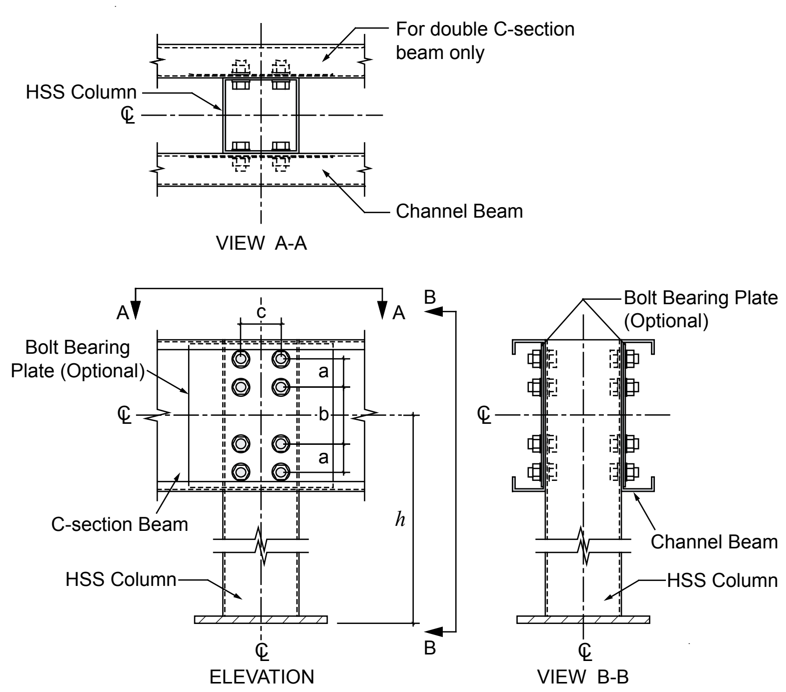

Figure 2: Typical CFS-SBMF Moment Connection.

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Table 1: Member Sizes and Bolted Connection Configuration.

Specimen No.	Beam	Column	Bearing Plate, in.	Bolted Connection		
				a (in)	*b* (in)	*c* (in)
1, 2	12CS3½×105	HSS8×8×¼	0.135	2.5	3	4.25
3	16CS3½×105	HSS8×8×¼	N/A	3	6	4.25
4	16CS3½×105	HSS8×8×¼	0.135	3	6	4.25
5, 6, 7	16CS3½×135	HSS8×8×¼	N/A	3	6	4.25
8, 9	20CS3½×135	HSS10×10×¼	N/A	3	10	6.25

seismic compactness requirement. Instead, the ductility capacity is provided through bolt slippage and bearing in bolted beam-to-column moment connections, and beams and columns are designed to remain elastic at the design story drift to resist the maximum force that can be developed in the moment connections. A cyclic testing program that verifies this concept was conducted. To calculate the maximum seismic effect in the beams and columns, an analytical model for the yielding element was then developed based on the concept of instantaneous center of rotation of a bolt group. To facilitate design, this analytical model was used to develop equations and tables for inclusion in AISI S110. A study based on the FEMA P695 methodology was also conducted to verify that the proposed seismic performance factors (R and C_d factors) can provide a sufficient margin against collapse for the Maximum Considered Earthquake. AISI S110 has been adopted by ASCE 7-10, and this system will be recognized in the 2012 International Building Code.

Test Program

A total of nine full-scale interior beam-column subassemblies were tested; see *Table 1* for the member sizes. The subassemblies simulated a portion of an 8-foot, 3-inch high CFS-SBMF with a bay width of 11 feet. *Figure 3* shows the test setup; the column was oriented horizontally to facilitate testing. Having assumed that the beam inflection point was at the mid-span, the beam length on each side of the column was half the bay width. The beam was connected to the column by eight 1-inch diameter, bearing type high-strength bolts. ASTM A607 Class 1, Gr. 50 steel was specified for the beams and ASTM A500 Gr. B steel was specified for the columns. The beams were galvanized with zinc, while the columns were coated with a zinc-rich paint.

The testing showed all specimens behaved in a very ductile manner, and the inter-story drift capacity was significantly higher than the 0.04 radian inter-story drift angle required by AISC 341 for Special Moment Frames (*Figure 4*). The cyclic behavior of all test specimens was dominated by the slip-bearing action in the bolted moment connection. The global response is characterized by three regions. Initially, the subassembly responded elastically with the bolted connection acting essentially as a rigid joint. Bolt slip was observed during the 0.75% through 2% drift cycles, which corresponded to the flat plateaus in the global response. Then the bolts started to bear against the beam and column webs at about 3% drift, which resulted in a significant hardening in strength.

The test matrix included some beam and column sizes with larger width-thickness ratios (w/t) to study the effect of local buckling. Specimens that experienced beam or column buckling still exhibited the same ductile hysteresis response as shown in *Figure 4*. Although local buckling occurred at a story drift beyond 4%, it is prudent to limit the w/t ratio to $6.18\sqrt{E/F_y}$ in order to control web local buckling of the C-section beams. For HSS columns, the limiting w/t ratio is $1.40\sqrt{E/F_y}$.

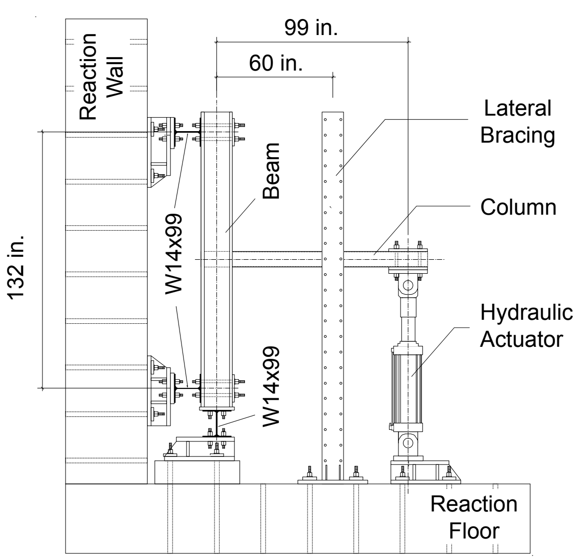

Figure 3: Test Setup.

Analytical Modeling of Moment Connection

Figure 5(b) (page 10) shows the free-body diagram of a column with a beam framing into it. With the pin-based column resisting a shear force, the bolt group in the connection region is subjected to a load, V_C, with a large eccentricity, h, which is the story height. The concept of instantaneous center (IC) of rotation can be used to compute the response of a bolted connection. The slip resistance, R_s, and bearing resistance, R_B, of a single bolt are:

$R_S = kT$ Equation 1

$R_B = R_{ult}[1-e^{-\mu\delta_{br}}]^{\lambda}$ Equation 2

where k (slip coefficient) = 0.19 for a galvanized surface condition, T = bolt tension force, R_{ult} (ultimate bearing strength) = $2.1dtF_u$, δ_{br} = bearing deformation (in.), e = 2.718, and μ, λ = regression coefficients. With the values of T = 17.5 kips, μ = 5, and λ = 0.55, response predicted by the instantaneous center of rotation method envelopes very well the cyclic response of the test specimens with varying member sizes and bolt configurations (*Figure 6, page 10*). The analysis procedure was also generalized to model the cyclic response for subsequent nonlinear time-history analysis.

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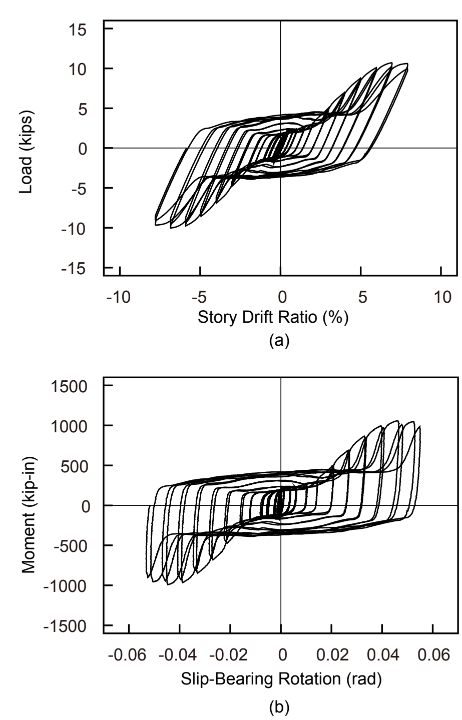

Figure 4: Typical Hysteresis Response: (a) Overall Response; (b) Bolted Moment Connection Component.

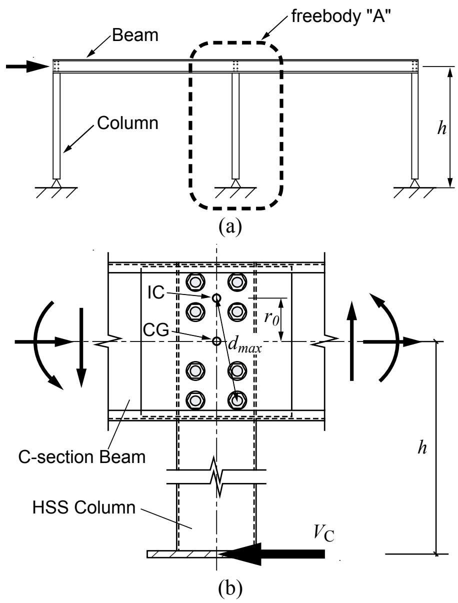

Figure 5: Bolt Group in Eccentric Shear: (a) CFS-SBMF; (b) Freebody "A".

Seismic Design Concept

Figure 7 shows the expected response of a CFS-SBMF. The elastic seismic force corresponding to the Design Basis Earthquake (DBE, point "e") is reduced by the R factor (= 3.5) to point "d" for sizing beams, columns, and bolted moment connections in accordance with the AISI S100. Unlike other steel seismic force-resisting systems where point "d" represents the first significant yielding event, CFS-SBMF actually would "yield" at a lower seismic force level (point "a") due to slippage of the bolts in moment connections. A horizontal plateau (points "a" to "b") would result due to the oversize of the bolt holes. As the story drift is increased, the lateral resistance of the frame starts to increase from point "b" once the oversized hole is overcome and the bearing action of the bolts starts to occur.

The designer amplifies the story drift at point "d" by the Deflection Amplification Factor C_d to estimate the maximum inelastic story drift (Δ at point "c") that is expected to occur in a Design Basis Earthquake event. To ensure that beams and columns will remain elastic, the challenge then is to evaluate the maximum seismic force corresponding to point "c" while considering the effect of significant hardening due to bolt bearing. This seismic force level, which is equivalent to the seismic load effect with overstrength, E_{mh}, in ASCE 7, represents the required strength for the beams and columns. Specifically, the required moment for both beam and column at the connection location is:

$M_e = h(V_S + R_t V_B)$ Equation 3

where h = story height, R_t = ratio of expected tensile strength to specified tensile strength. V_S and V_B represent the column shear components corresponding to the resistance of the eccentrically loaded bolt group due to bolt slip and bearing, respectively. Based on the analytical model presented earlier, equations and tables have been developed and provided in AISI 110 to calculate these two quantities.

Seismic Performance Factors

Based on the large ductility capacity observed from the cyclic testing of beam-column subassemblies, a value of 3.5 for the Response Modification Coefficient, R, was proposed. Recognizing that the hysteresis behavior of a CFS-SBMF exhibits a yield-like plateau that is followed by a significant hardening in the moment connection region, a statistical evaluation through nonlinear time-history analysis showed that the Newmark-Hall ductility reduction rule to account for the benefit of ductility is conservative. A revised rule was proposed, which was then used to derive the Deflection Amplification Factor, C_d. The derivation gave $C_d = R/1.2$ ($\approx$ 3.0). Conservatively, this value is adjusted up to 3.5 for adoption by ASCE 7-10.

Once the designer calculates the design story drift using the C_d factor, the AISI S110 design procedure then can be used to compute the maximum seismic force in the moment connection (point "c" in *Figure 7*). Although this procedure eliminates the need to specify an empirical System Overstrength Factor, Ω_0, for consistency with the format of other framing systems, a default value of 3.0 is adopted in ASCE 7-10. The adequacy of these proposed seismic performance factors to ensure a sufficient margin of safety against collapse under the Maximum Considered Earthquake has also been verified by FEMA P695, *Quantification of Building Seismic Performance Factors*.

In October 2009, AISI published Supplement No. 1 to AISI S110-07. In Supplement No. 1, revisions were made to the document adopting all the modifications included in ASCE 7-10, Chapter 14. The majority of these modifications ensure that the application of the design provisions remains within the configurations used in the initial research. AISI S110-07 with S1-09 was recently adopted as a reference in the 2012 International Building Code and is available for purchase online at AISI's Publications Bookstore at **www.steel.org/shopaisi**.▪

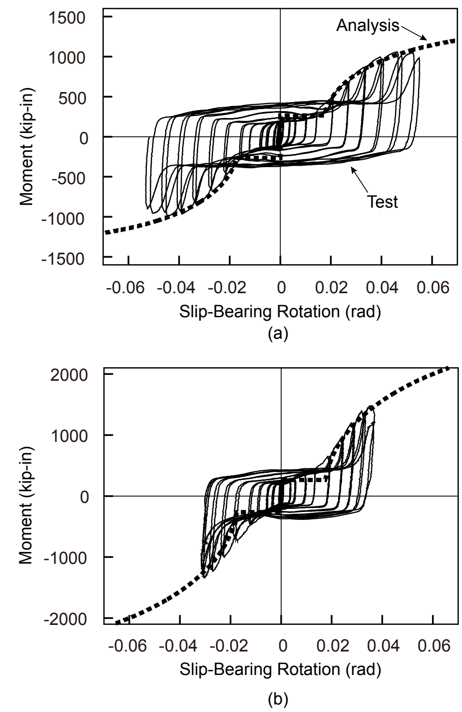

Figure 6: Measured versus Predicted Responses: (a) Specimen 3; (b) Specimen 4.

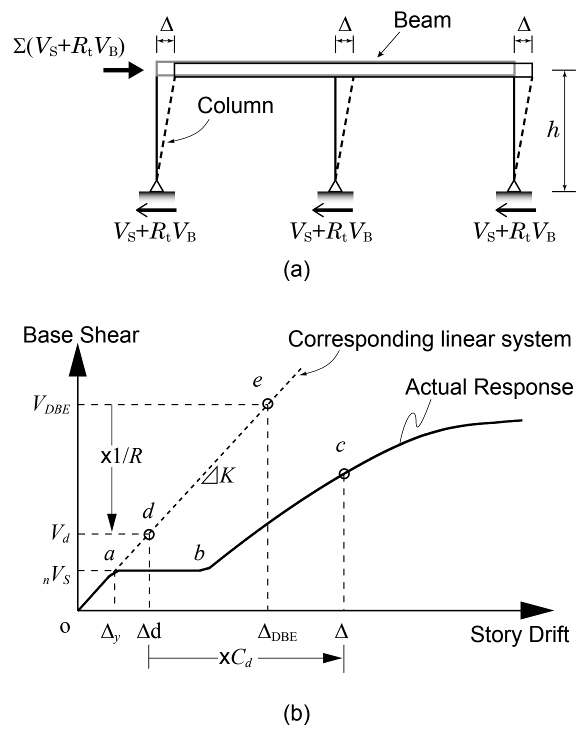

Figure 7: CBF-SBMF Expected Response: (a) Yield Mechanism and Column Shear Distribution; (b) General Structural Response.