CFSRC
COLLOQUIUM

Proceedings of the Cold-Formed Steel Research Consortium Colloquium
20-22 October 2020 (cfsrc.org)

Performance of CFS Walls Braced with Bridging and Sheathing

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Abstract

The objective of this paper is to describe testing and analysis of cold-formed steel (CFS) stud walls braced by both discrete steel bridging and gypsum sheathing. A focused series of tests was conducted to determine the strength of a typical CFS wall with discrete bridging, both with and without sheathing in place. The bridging was instrumented such that the forces developed as the bridging braced the studs under increased axial load could be measured. Bridging forces were measured for walls where the sheathing was installed before loading, and for walls where the sheathing was applied after dead load – simulating panelized and stick construction sequences. It has been hypothesized that discrete bridging plays a limited role as bracing once wall sheathing has been applied – the test results conducted to date are consistent with this idea. Design methods exist for walls braced by discrete bridging or by sheathing, but methods do not exist for walls that rely on both bracing methods. An existing design philosophy is extended to provide a new design method for combined bracing. The proposed design method is fully supported by engineering tools (spreadsheets. etc.) and is compared to the conducted testing. Recommendations are made for additional testing and analysis to finalize an efficient design method and philosophy that would allow CFS walls to take advantage of discrete steel bridging during construction, but otherwise use the strength provided by wall sheathing to stabilize the walls studs.

1. Introduction

Cold-formed steel (CFS) gravity, load-bearing walls consist of vertical lipped channel studs capped with horizontal plain channel track – typically fastened together by self-drilling screws. The open cross-section lipped channel studs have relatively weak torsional stiffness and are oriented such that minor axis bending is in the plane of the wall. Without bracing of the studs, the wall capacity is limited.

The most common form of wall bracing are small channels, known as cold-rolled channel (CRC) bridging, that are installed through holes (punchouts/knockouts) in the stud web. These bridging channels provide minor-axis flexural bracing and depending on their stiffness and installation details can also restrict torsion of the stud. Of course, an isolated bridging channel must be resolved to a stiff member so that the bracing forces can be carried out of the wall. However, predictions of the accumulated brace force and stiffness requirements for an entire wall can be significant and result in design requirements that are not aligned with a long-standing practice in the U.S.

From a practical standpoint, most CFS walls will have finishes applied to both sides of the wall. This finish typically includes sheathing, which is directly applied to the stud flanges. Gypsum board sheathing attached with screws is the most common form of finish. Once installed, the gypsum board can also serve to brace the studs – particularly if installed on both sides. Such sheathing can be an effective restraint against both minor-axis and torsional deformations of the stud.

A comprehensive series of research on the role of sheathing in bracing cold-formed steel walls, summarized in [1] and supported by the efforts in [2-5] unequivocally demonstrated that sheathing bracing could effectively stabilize cold-formed steel stud walls, and developed a supporting design method. However, since many finish systems are non-structural, concerns persist as to whether such systems will be

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available during construction or during an overload or other critical loading condition (e.g., fire).

In practice, both steel discrete bridging and wall sheathing exist in a cold-formed steel stud wall. It is desired to know how these two systems work when under load and acting as bracing. What is the impact of not fully resolving (anchoring) the bridging? What is the impact of the construction sequence on the relative bracing forces between the bridging and the sheathing? When both bridging and sheathing are present, which system actually carries the bracing demands? A focused series of tests was developed to explore these questions.

The design method developed in [1] is relatively involved. Specifically, (a) the stiffness supplied by the sheathing to the stud as bracing must be calculated; (b) this stiffness must be included when solving for the global buckling load, which is now coupled in terms of major axis flexure, minor axis flexure, and torsion; (c) traditional column design with these buckling loads must be completed, and finally (d) the sheathing-to-stud connections must be checked for adequacy. It is desired to aid engineers with performing and understanding these steps, and so the method was implemented in a series of spreadsheets and extended to cover discrete bracing available in [6].

2. Testing

Compression testing was conducted on an 8 ft × 8 ft CFS frame with 362S162-68 [50 ksi] studs spaced 2 ft apart and attached at top and bottom to two 8-ft long 362T125-68 [50 ksi] tracks. The studs had standard obround punchouts with dimensions of 1 1/2 in. x 4 in. When specified 150U150-54 CRC bridging was supplied through the punchout at the mid-height of the stud. The bridging was attached to the studs with a 1 ½ in. x 1 ½ in. 54 mil angle connected with #10 steel-to-steel fasteners. When specified the CRC bridging was anchored to a fixed support at one end. When specified ½ in. lightweight sheetrock (installed vertically) with #6 @ 12 in. o.c. screw fasteners were added to one or both sides of the wall. The steel for a typical wall is provided in Figure 1.

Specimens in the testing rig are provided in Figure 2 and typically observed limit states in Figure 3. The test results are detailed in [7] and summarized in [8]. Please see these materials for details and key findings from the testing. Most importantly, the testing indicated definitively that bridging forces only accumulate for translation, not for torsion, and this accumulation only occurs when sheathing is not present. When sheathing is present, the sheathing, not the bridging, dominates the bracing response.

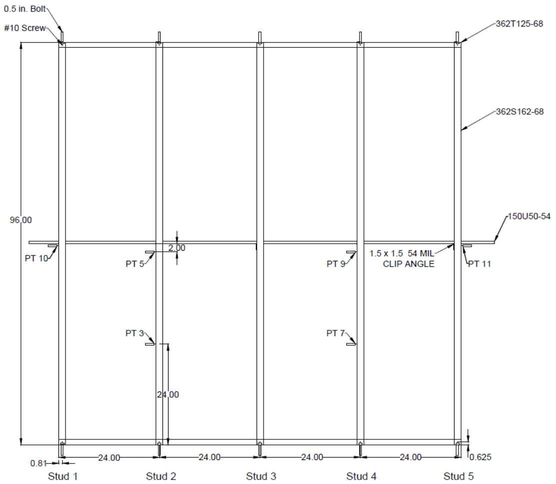
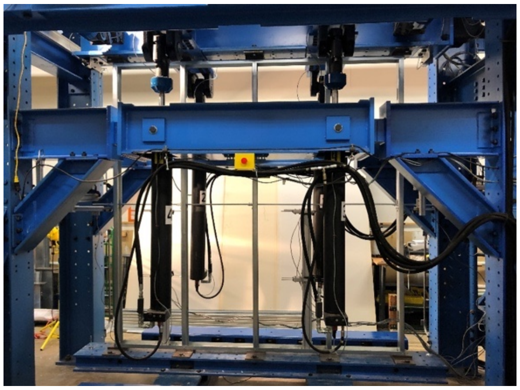


Figure 1. Elevation of Typical CFS Frame, Nomenclature, and Sensors



(a) all steel (AS-4) specimen in testing rig

(b) sheathed specimen (CB-R-2) in testing rig

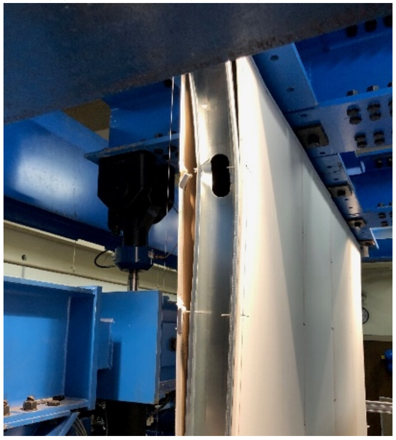
(c) detail of clip and bridging channel through knockout of the stud at mid-height

Figure 2. Typical test specimens

(a) 2nd mode FTB, AS-4

(b) LB at hole (FB/TB) CB-U-2

(c) LB at hole (TB/FB) CB-R-2



(d) LB at hole (TB/FB) CB-C-3

(e) 2nd mode TB CB-G1U-2

Figure 3: Limit states of tested specimens

3. Elastic Buckling Calculations/Spreadsheets

The elastic buckling calculations for a stud under compression, braced by discrete bridging, strapping, and/or sheathing and buckling in either local, distortional, and/or global buckling are provided through a series of spreadsheets available at [6] and include: 01_Pcre_analytical_v10.xlsm, 02_Pcrd_analytical_v2.xlsx, and 03_Pcrl_Pcrd_database_v2.xlsx. Note, these same elastic buckling values can be determined using general-purpose finite strip elastic buckling tools such as CUFSM, THIN-WALL, etc. or general-purpose plate/shell finite element tools such as ABAQUS, ANSYS, etc. The spreadsheets provide solutions without recourse to analysis tools and could be directly incorporated into in-house design solutions. A video has been developed to explain the use of the spreadsheets and is also available at [6]. Here we briefly describe the function of each spreadsheet and address the basic source material. Complete source references and full details are provided within the spreadsheets themselves.

3.1 Local ($\boldsymbol{P_{cr\ell}}$) and Distortional ($\boldsymbol{P_{crd}}$) Buckling (03_Pcrl_Pcrd_database_v2.xlsx)

Local and distortional buckling for pinned warping free boundary conditions was calculated for every structural section in the Steel Framing Industry Association (SFIA) product technical catalog [9] using CUFSM and provided as a database. In addition, the approximate finite strip method for members with holes recommended in AISI S100-16 Appendix 2 was adopted and provided for all SFIA sections with standard punchouts. This database provides the necessary local and distortional buckling loads for bare steel stud sections with and without punchouts.

3.2 Distortional Buckling ($\boldsymbol{P_{crd}}$) with Restraint ($\boldsymbol{k_{\phi}}$) (02_Pcrd_analytical_v2.xlsx)

AISI S100-16 Section 2.3.1.3 and 2.3.2.3 are implemented in this spreadsheet to provide the distortional buckling strength considering rotational restraint provided by sheathing.

3.3 Global Buckling ($\boldsymbol{P_{cre}}$) (01_Pcre_analytical_v10.xlsm)

Global buckling for a stud considering the beneficial restraint provided from bridging, discretely fastened sheathing, or strap are provided for all stud sections in this spreadsheet. This spreadsheet provides a number of ancillary calculations in addition to the final elastic buckling calculation that aid designers.

Gross and net section properties for any SFIA stud are automatically populated based on a database of properties provided in separate sheets within the spreadsheet.

For sheathing, based on the sheathing type, stud spacing, and fastener type and spacing the discrete restraint provided at the attachment points to the studs is calculated per [3] for shear restraint (k_x) per [3] for out-of-plane restraint (k_y), and per an adaptation of AISI S240 Appendix 1 for (k_{ϕ}). See [1] report for further details on sheathing bracing including illustrative examples for k_x, k_y and k_{ϕ} that can be compared with the spreadsheet output.

For bridging, only through the punchout CRC bridging attached by screw fastened clip angles is explicitly considered. For other cases there is an option to manually enter the provided bracing stiffness. The bracing stiffness is drawn from the work of Sputo and Green [10] as detailed in [11]. The bridging channel, connection (clip angle, fasteners, stud web), and kicker/strongback are considered as springs in series to determine the discrete stiffnesses (k_x) supplied to the stud. The connection stiffness, which is generally the weakest stiffness in the series, is based directly on the work of [11], but with interpolation allowed. For k_x the available data covers studs from 33 to 97 mil and webs from 3.62 to 8 in. deep. Separate tests on the rotational restraint of the connection are also available from [11] and these provide k_{ϕ} for screw fastened clip angles and CRC bridging attached to studs from 68 to 97 mil and webs from 3.62 to 6 in. deep. The final bridging stiffness values are automatically populated into the spreadsheet.

The spreadsheet also includes the condition of strap bracing, where screw fastened strap are attached to the stud flanges. For strapping, screwed to the flange of the studs, the in-plane bracing stiffness (k_x) is calculated using the same spring in series approach as for bridging, but with the connector stiffness based on AISI S310-16 Section D5.2.

The spreadsheet then solves the global buckling problem. Specifics of the buckling solution follow. The solution is adapted from [3] and [12]. The elastic buckling calculation is an eigenvalue problem:

$$(K_e - \lambda K_g)\phi = 0 \tag{1}$$

where the eigenvalue λ is the buckling load (P_{cre}) and the eigenvector ϕ is the buckling shape and where K_e is the elastic stiffness of the stud against xx and yy-axis bending (EI_{xx}, EI_{yy}) and torsion (GJ, EC_w) including additional stiffness supplied by *j* different bracing springs k_{xj}, k_{yj} and $k_{\phi j}$ located at h_{xsj}, h_{ysj} in the section and z_{sj} along the length and may be expressed as:

$$K_e = \begin{bmatrix} EI_{yy}I_4 + \sum_{j=1}^{n_s} k_{xj}I_{1j}^D & EI_{xy}I_4 \sum_{j=1}^{n_s} K_{xi}I_1^D & -\sum_{j=1}^{n_s} k_{xj}h_{ysj}I_{1j}^D \\ \sum_{j=1}^{n_s} K_{xi}I_1^D & EI_{xx}I_4 + \sum_{j=1}^{n_s} k_{yj}I_{1j}^D & \sum_{j=1}^{n_s} k_{yj}h_{xsj}I_{1j}^D \\ Sym - \sum_{j=1}^{n_s} K_{xi}I_1^D & \sum_{j=1}^{n_s} K_{xi}I_1^D & GJI_5 + EC_wI_4 + \sum_{j=0}^{n_s} I_{1j}^D\left[k_{xj}h_{ysj}^2 + k_{yj}h_{xsj}^2 + k_{\emptyset j}\right] \end{bmatrix} \tag{2}$$

where I_1 and I_4 are a function of the longitudinal shape function Z, which when a sine series is employed becomes:

$$Z_{[m]} = \sin\left(\frac{m\pi z}{L}\right), \tag{3}$$

$$I_1 = \int_0^L Z_{[m]}Z_{[n]}dz = \frac{L}{2}, \tag{4}$$

$$I_{1j}^D = Z_{[m]}(z_{sj})Z_{[n]}(z_{sj}) = \sin^2\left(\frac{m\pi z_{sj}}{L}\right), \text{ and} \tag{5}$$

$$I_4 = \int_0^L Z''_{[m]}Z''_{[n]}dz = \frac{m^4\pi^4}{2L^3} \tag{6}$$

and K_g is the load dependent geometric stiffness that degrades the elastic stiffness under axial load with x_o and y_o the distance from the shear center to the centroid in the cross-section plane:

$$K_g = \begin{bmatrix} I_5 & I_5 & -z_oI_5 \\ & I_5 & x_oI_5 \\ sym - & & r_o^2I_5 \end{bmatrix} \tag{7}$$

and the additional terms are:

$$r_o^2 = x_o^2 + y_o^2 + (I_{xx} + I_{yy})/A, \text{ and} \tag{8}$$

$$I_5 = \int_0^L Z'_{[m]} Z'_{[n]} dz = \frac{m^2\pi^2}{2L} \tag{9}$$

A lipped channel (C-shape) cross-section at longitudinal location z with a single set (j) of discrete springs attached to Face 1 of the section is depicted in Figure 4 the summation of these springs consistent with K_e, and the solution for various m longitudinal terms is provided in the spreadsheet.

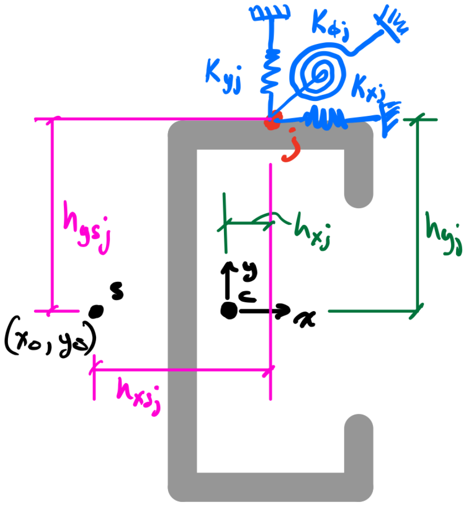


Figure 4. Cross-section with a set of discrete springs from bracing

The video provided with [6] covers additional practical details in the use of the spreadsheet and, for example, how to use the spreadsheet to develop the global buckling solution for an unbraced stud, a stud braced only with through the punchout CRC bridging, a stud braced with CRC bridging and gypsum board on one side, and finally a stud with CRC bridging and gypsum board on both sides.

4. Strength Prediction and Comparison to Testing

A spreadsheet is provided in [6] for the strength prediction: 04_Pn_DSM_v2.xlsx. This spreadsheet implements AISI S100-16 Chapter E for compression members without modification. The strength is a function of the gross and net squash load (P_y and P_{ynet}) and the local, distortional, and global buckling loads ($P_{cr\ell}, P_{crd}$ and P_{cre}). The buckling loads reflect the cross-section, including holes, and the presence of bridging, strapping, and sheathing and their calculation using the spreadsheets is detailed in the video with [6].

For the walls tested and reported in [7] Table 1 provides the yield loads, elastic buckling loads and characteristics, predicted strength, and observed strength. For the global elastic buckling mode the shape is summarized in terms of the components of its in-plane buckling deformation (**u** – minor axis flexure, **v** - major axis flexure, **f** - torsion/twist, and **m** – mode number). The global buckling load and mode changes dramatically as the bracing is introduced. The predicted strength and limit states are in good qualitative agreement with the testing, but strength agreement is not as good as previously conducted wall tests with sheathing alone (see [3]) and additional discussion is warranted.

Table 1 Predicted and observed compressive strength for CFS-framed wall tested in [7] with combinations of discrete CRC bracing and gypsum sheathing

	Yielding		**Buckling**							**Prediction****		**Observed**	
				Φ									
Condition	**P_y** (kips)	**P_{ynet}** (kips)	**P_{cre}** (kips)	**u**	**v**	**ϕ**	**m**	**P_{crd}** (kips)	**P_{crl}** (kips)	**P_n** (kips)	**LS**	**$P_{test}/5$** (kips)	**LS**
Unbraced	26.2	20.8	5.7	**1.0**	0.0	0.0	1	31.9	31.5	5.0	G1	not tested to failure	
CRC bridging (all steel)	26.2	20.8	18.1	0.0	-0.3	**1.0**	2	31.9	31.5	14.3	G2	13.3	FTB2
CRC* + 1 Side Gyp	26.2	20.8	22.5	0.4	-0.2	**0.9**	2	31.9	31.5	16.1	G2	13.5	TB2
CRC + 2 Side Gyp	26.2	20.8	32.6	0.0	**1.0**	-0.2	1	37.4	31.5	18.4 18.7	D (hole) G1	15.1	LB@Hole (TB/FB)

*note, the CRC is not anchored in this test – the gypsum sheathing must resolve the bridging force
**nominal predictions based on t = 0.0713 in. F_y = 50 ksi, measured stud t = 0.0691 in. F_y = 52 ksi

For the “CRC bridging” case of Table 1 (also known as the “all steel” case) the bridging successfully restrains minor-axis flexure (u) and the stud fails in a global (G) limit state of 2nd mode flexural-torsional (v-ϕ or FTB) buckling. AISI S100-16 Chapter E with the appropriate global buckling load accurately predicts the limit state and the observed strength is 93% (13.3 kips/14.3 kips) of the predicted strength. The section is “fully effective” in local buckling – i.e. no local-global interaction is predicted, and none is observed. The agreement for the all steel case is deemed acceptable – though broader study may be warranted.

For the case with (unresolved) CRC bridging and gypsum sheathing on 1 side of the wall, the test fails predominately in restrained-axis 2nd mode torsional buckling (TB2). The predicted limit state is also 2nd mode global buckling, dominated by torsion. However, in this case the test strength is only 84% of the predicted strength. The single stud test strength for the CRC bridging with one-side of gypsum (13.5 kips) is nearly the same as the CRC bridging alone (13.3 kips) perhaps leading on to think the gypsum board has little effect; however, the test with the gypsum had a different failure mode, sustained greater deformation, and had a much more benign post-peak response than the test with CRC bridging alone. The case with OSB sheathing only on one side in [3] did not have CRC bridging, but did have good agreement with this same basic method. A definitive explanation for the discrepancy between the predicted and tested strength has not been developed at this time.

For the case with CRC bracing and gypsum sheathing on both sides of the wall, the tested strengths per stud across the three tests in this category were 14.4, 14.5, and 16.3 kips vs. a predicted strength of 18.4 kips. Resulting in a test-to-predicted of 82% on average, ranging from 78% to 88%. For comparison, [3] tested similar walls with gypsum sheathing on both sides and the mean per stud strength was 19.3 kips, while isolated and sheathed studs had a mean stud strength of 21.4 kips – both exceeding the test results presented here. Key differences in the earlier testing included: studs did not have holes, normal weight gypsum attached at 6 in. o.c. was employed, CRC bridging was not present. Test-to-predicted ratios in [3] under these conditions were in good agreement.

5. Discussion

The project final report [6] provides potential specification language for AISI to adopt design methods consistent with those discussed here. However, given the test-to-predicted ratios are consistently less than 1.0 for the small testing sample this suggests some caution before adoption. Conservative adjustment of the resistance and safety factors may be possible, but additional testing should be conducted. The testing should consider 6 in. and potentially 8 in. deep studs that have greater reductions due to local buckling than the 362S162-68 [50ksi] tested here, and potentially those studs where distortional bucking (narrow flanges cause this) is predicted to control the capacity. Examination of studs with higher gravity loads (i.e. larger compressive capacity), and as a result higher connection forces, is also recommended.

Criteria for defining when sheathing can be considered in design is needed. Initial language as follows has been developed “sheathing that is in-place during construction and able to withstand sprinklers or other environmental conditions expected during the life of the assembly without substantial loss in stiffness.” This is useful but substantial loss in stiffness is not quantified. In the past the stiffness of gypsum board sheathing to steel shear connections under different humidity conditions has been examined and is known to be significant. With the elastic buckling tools now in place, it is possible to perform a parametric study to demonstrate the sensitivity of the predicted stud strength to degradation in sheathing stiffness – if targets for allowed strength degradation are established then it would be possible to quantify what is a “substantial loss in stiffness” and provide engineers with usable guidance. This study is recommended.

6. Conclusions

Cold-formed steel walls rely on both discrete bracing and sheathing bracing of the wall studs in real assemblies to achieve successful performance under gravity loads. When sheathing is not yet in place, e.g. during construction using on-site stick building methods, or when sheathing is compromised, e.g. due to sprinklers or prolonged high levels of humidity that degrade some sheathing materials, steel discrete bracing is critical; however, in all other situations, the relative stiffness of sheathing bracing is such that the sheathing is the primary means of bracing the stud. Design methods which consider only discrete bracing indicate large accumulation of forces in the provided braces; however, if sheathing is also present this accumulation does not readily occur. Combined discrete and sheathing bracing is an important benefit of typical cold-formed steel wall assemblies, but these benefits are not currently enabled in design through AISI S240 or AISI S100.

Compression tests of a typical wall assembly demonstrate that when sheathing is present the bridging need not be resolved at the wall ends. Gypsum sheathing on both sides of the wall leads to higher strength and a more favorable failure mode and post-peak response than fully resolved discrete bridging. Further, with respect to ultimate response, it is shown that the sheathing can be applied after service dead load without changing the bracing condition. Finally, we also show that one-sided sheathing can provide bracing at least as effective as a fully anchored discrete bridging; however, to achieve the most desirable limit state, strength, and post-peak response two-sided sheathing is favored.

A complete suite of spreadsheets was prepared for aiding the engineer in calculating the elastic local, distortional, and global buckling load of a wall stud considering both discrete bracing and sheathing bracing. The spreadsheets were utilized to predict the strength of the tested walls and it was found that the predictions of the walls tested in this effort with combined bracing are currently unconservative. This contrasts with previously tested walls with only sheathing bracing that were predicted conservatively. This result suggests at least a modest amount of additional work is needed.

7. Financial Acknowledgment

This work was completed in part based on a grant from the American Iron and Steel Institute and the Steel Framing Industry Association titled “CFS Bracing Design Using Combinations of Discrete and Sheathing Bracing”. Steel materials for testing were donated by ClarkDietrich. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the employers and sponsors.

8. Research Acknowledgment

The tests conducted here were assisted by Akhil Nayyar, whose help was much appreciated. In addition, the testing would not have been possible without staff support from Nick Logvinovsky. The spreadsheets developed for the project were completed in part through a subaward to Simpson Gumpertz & Heger, Inc.. The spreadsheets were also assisted by the work of Chu Ding. The project was monitored by volunteers from the AISI Committee on Specification and Committee on Framing Standards including: Pat Ford, Josh Buckholt, Nabil Rahman, Robert Glauz, Rob Madsen, Jay Larson, Jeff Klaiman, and Brian Mucha.

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