COLD-FORMED STEEL RESEARCH CONSORTIUM

Test Report:
Cold-Formed Steel Gravity Walls with Bridging and/or Sheathing

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Abstract

The objective of this report is describe experiments conducted on cold-formed steel walls under axial loading with a variety of different bracing conditions. Cold-formed steel wall systems are commonly braced using small bridging channels that run through the web of the studs (discrete bracing) as well as by sheathing that is attached directly to the stud flanges. Previous research has shown that sheathing, on its own, can be a highly effective means of bracing studs; however, sheathing is not always present during construction and in some cases, e.g. a sprinkler system saturating a gypsum board panel, may not provide adequate restraint. As a result, discrete (all-steel) bracing systems are sometimes favored. All-steel bracing systems under ultimate applied loads can be costly – particularly if brace force accumulation, and commensurate loss of stiffness, is properly accounted for in the design. To better understand the flow of forces in cold-formed steel walls with combinations of discrete and sheathing bracing a set of pilot experiments have been conducted. The experiments consider (a) whether or not the discrete bracing is properly resolved at its end, (b) whether or not gypsum sheathing is in place, in addition to the discrete bracing, and (c) sequence of loading, i.e., when the gypsum sheathing is installed. Forces in the discrete bracing are directly measured as is displacement of the studs under load. The resulting tests indicate that bridging only plays a secondary role in bracing steel studs once sheathing is installed. It is intended to use these results to develop improved engineering guidance on the use of combined, steel bridging plus sheathing, bracing conditions for walls.

1 Introduction

Cold-formed steel gravity, load bearing, walls consist of vertical lipped channel studs capped with horizontal plain channel track – typically fastened together by self-drilling screws (see Figure 1). 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 would be severely limited.

The most common form of wall bracing are small channels, known as bridging, that are installed through holes (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 – these may be achieved in a variety of ways such as using kickers (direct axial members that go from the bridging to the floors) or strongback studs (members with high bending rigidity that can have the bracing force transmitted directly). 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 long-standing practice.

From a practical standpoint all CFS walls will have finish applied to both sides of the wall, this finish typically includes sheathing which is directly applied to the stud flanges. Gypsum board sheathing 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 Schafer (2013) and supported by the efforts in Vieira (2011), Vieira and Schafer (2013), Peterman (2012), and Peterman and Schafer (2014) 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 available 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 and are fully detailed in this report.

This report represents the experimental portion of a project funded by the American Iron and Steel Institute and the Steel Framing Industry Association to address “CFS Bracing Design Using Combinations of Discrete and Sheathing Bracing”. The other portion of the project is focused on potential design methods and their implementation.

2 Test Matrix

The basic wall selected for testing is motivated by past work on sheathing braced walls. The selected wall is an 8 ft × 8 ft (2.44 m × 2.44 m) CFS frame with 362S162-68 [50 ksi] studs as employed in Vieria and Schafer (2013). As shown in Figure 1, five 8-ft long 362S162-68 [50 ksi] studs are attached to two 8-ft long 362T125-68 [50 ksi] tracks with spacing of 2 ft center to center. When required, two 4 ft × 8 ft, ½ in. thick gypsum boards for each side of steel frame are installed vertically as sheathing bracing. A typical elevation of the CFS frame is provided in Figure 1, and a summary of the details of the conducted testing is provided in the Table 1 test matrix. Drawings for each test, providing complete details, are provided in Appendix 1.

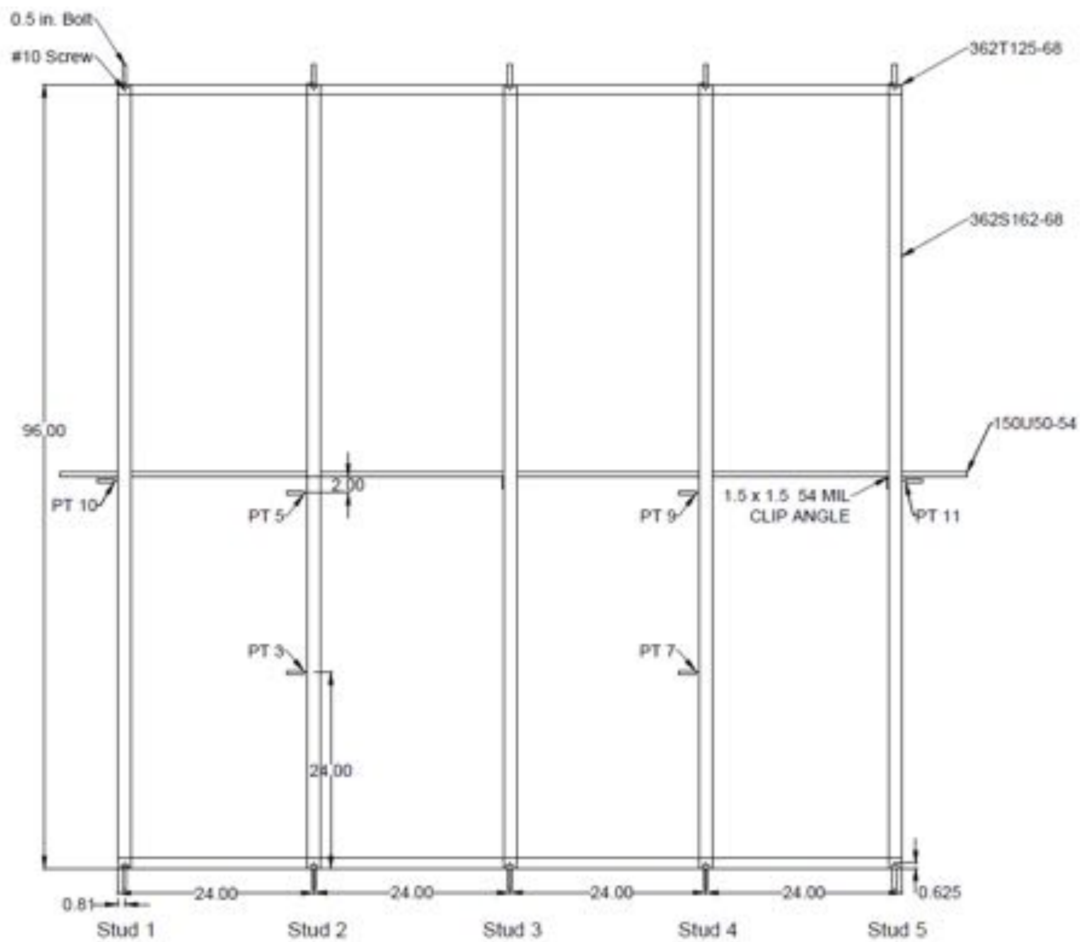


Figure 1. Elevation of Typical CFS Frame, Nomenclature, and Sensors

Table 1 Test Matrix

Type	Nomenclature	Load	Bridging	Resolution	Sheathing
All Steel	AS-1	~25 kips	None	None	None
	AS-2	"	150U50-54 [50]	None	None
	AS-3	"	"	Fixed Point	None
	AS-4	To Failure	"	"	None
Combined Bracing Resolved	CB-R-1	~25 kips	"	Fixed Point	1/2 in. Gyp (both sides)
	CB-R-2	To Failure	"	"	"
Combined Bracing Unresolved	CB-U-1	~25 kips	"	None	1/2 in. Gyp (both sides)
	CB-U-2	To Failure	"	None	"
Combined Bracing Construction Seq.	CB-C-1	~25 kips	"	Fixed Point	None
	CB-C-2	DL+Hold	"	"	"
	CB-C-3	DL+To Failure	"	"	1/2 in. Gyp (both sides)
Combined Bracing Unresolved	CB-G1U-1	~25 kips	"	None	1/2 in. Gyp (one side)
	CB-G1U-2	To Failure	"	None	"

Notes:
AS = All Steel, CB = Combined Bracing, R = Bridging resolved/fixed at one end, U = Unresolved bridging,
C = Construction Seq., G1=Gyp one side only;
Stud: 362S162-68 [50], Track: 362T125-68 [50]
Bridging clip detail: 1-1/2 x 1-1/2 x 3-3/8 54 mil, i.e., CD Easy Clip U-series U683, connected with #10 steel-to-steel
Stud-to-track detail: single #10 steel-to-steel self-drilling fasteners from track-to-stud
Stud should be fully seated, i.e. stud flanges in direct contact with corner radius or web of track during assembly
Gypsum Board: 1/2 in., 4 ft. x 8 ft. sheets (e.g. Sheetrock) installed vertical, #6 @ 12 in. o.c. perimeter and field
Punchout: 1 1/2 in. x 4 in. rounded, standard SFIA layout

3 Test Setup

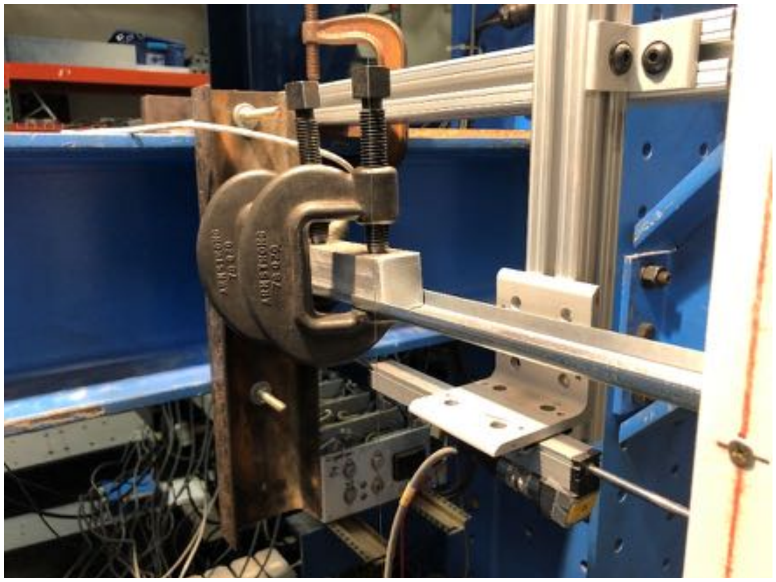
Testing was conducted in the multi-axis testing rig in the Thin-walled Structures Laboratory at Johns Hopkins University. A typical test in the rig is provided in Figure 2. The basic test setup is similar to Vieira and Schafer (2013). Thick plates are placed at each stud end and then connected to the distribution members in the testing rig. The plates are no wider than the track width insuring that the sheathing cannot contribute in direct bearing under the gravity load. The top of the rig is actuated, the bottom of the rig fixed.

(a) all steel specimen, elevation view of AS-4 (blue is testing rig, silver is specimen)

(b) sheathed specimen, elevation view of CB-R-2

Figure 2. Typical Test Specimens (a) all-steel, (b) sheathed

A key detail in the conducted testing is whether or not the mid-height bridging is resolved to a fixed end or left free at both ends – this detail is provided in Figure 3.



(a) bridging fixed at its end through clamping to block and attached to load cell

(b) bridging unattached at its ends

Figure 3. Resolution of Bridging Channel at Edge of Wall Specimen

Another detail should be mentioned is the clip connection of stud with bridging channel, a picture of this detail is provided in Figure 4.

Figure 4. Connection of Clip to Stud with Bridging Channel

4 Dimensions and Materials

Dimensions and section properties of the CFS studs are provided in Table 2. Nominal dimensions and section properties are cited from data of the 362S162-68 in CUFSM models and SFIA tables. One CFS stud of this batch was randomly selected to measure dimensions. Bare steel thickness, without zinc coating, is also measured after the zinc coating is removed by hydrochloric acid. Figure 5 shows typical materials for this test series.

Table 2. Stud Dimensions

	Nominal (CUFSM)	Measured (with coating)	Measured (without coating)
Length, L (in.)	96	95.94	
Width, h (in.)	3.625	3.6250	
Thickness, t (in.)	0.0713	0.0697	0.0691
Flange, b (in.)	1.625	1.6493	
Lip, d (in.)	0.5	0.4060	
Radius, r (in.)	0.10695	0.1122	
Hole Width, w (in.)	1.5	1.4985	
Hole Length, L_h (in.)	4	4.0006	
Hole Spacing, S_h (in.)	36	35.98	
Hole from End (in.)	12	12.0	

Gross Section Properties		
	Nominal (CUFSM)	Nominal (SFIA)
A_g (in^2)	0.52329	0.524
I_x (in^4)	1.0673	1.069
I_y (in^4)	0.18556	0.186
C_w (in^6)	0.51235	0.552
J (in^4)	0.000887	0.000887
X_o (in)	-1.264	-1.264

Net Section Properties	
	Nominal (CUFSM)
$A_{g,net}$ (in^2)	0.41632
$I_{x,net}$ (in^4)	1.0472
$I_{y,net}$ (in^4)	0.15208
$C_{w,net}$ (in^6)	0.50046
J_{net} (in^4)	0.000705
$X_{o,net}$ (in)	-1.2530

(a) stud: 362S162-68[50]

(b) track: 362T125-68[50]

(c) channel: 150U50-54[50]

(d) clip angle: U683 1-1/2”×1-1/2”×3-3/8”

(e) ½” gypsum board: ½”×4’×8’

(f) #10 screw

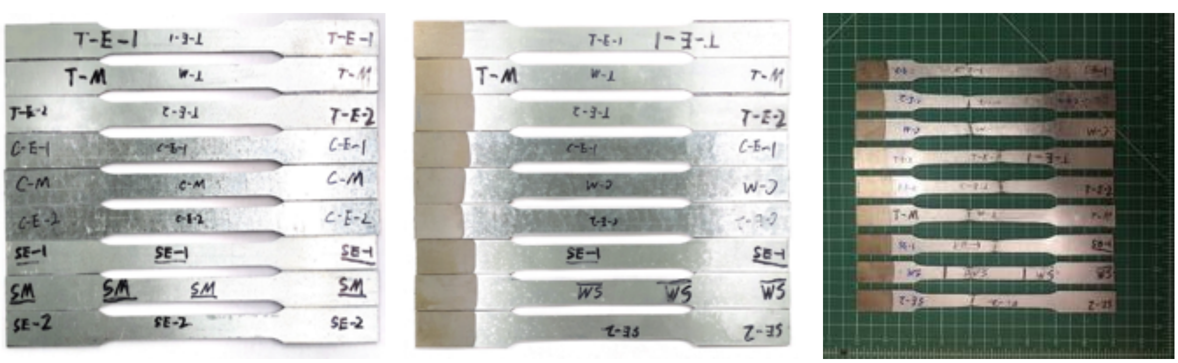
(g) #6 screw

Figure 5. Typical Test Materials

Yield strength of the cold-formed steel stud, track, and channel were determined following ASTM E8/E8M-Standard Test Methods for Tension Testing of Metallic Materials. Three coupon specimens from each type of CFS member are collected for the tension testing. The coupon specimens are shown in Figure 6a. To measure the exact thickness of the bare steel, one end of each coupon specimen's zinc coating is stripped, and the process of stripping described in Torabian (2016) is followed. Then, coupon testing in a servo-controlled MTS Criterion testing machine is completed, details of the tension test setup are shown in Figure 7. Pictures of the tension specimens after stripping and after testing are shown in Figure 6. A summary stress-strain plot of all coupon specimens is provided in Figure 8, complete details of the stress-strain plots for each specimen are provided in Appendix 3, and a summary table of coupon tension test results are given in Table 3.

Table 3. Summary of Coupon Tension Tests

Type	ID #	F_y (ksi)	avg. F_y (ksi)	std.	F_u (ksi)	avg. F_u (ksi)	std.
Stud	S-E-1	51.8			73.9		
(362S162-68 [50])	S-E-2	51.7	52.0	0.38	74.0	74.2	0.38
	S-M	52.4			74.6		
Track	T-E-1	52.5			73.6		
(362S125-68 [50])	T-E-2	52.9	52.6	0.26	73.7	73.6	0.15
	T-M	52.4			73.4		
Channel	C-E-1	53.7			64.2		
(150U50-54 [50])	C-E-2	53.6	53.6	0.10	64.2	64.1	0.12
	C-M	53.5			64.0		



(a) coupons (b) coupons after stripping (c) coupons after test

Figure 6. Coupon Specimens (original, one end zinc coating is removed, and after test)

(a) test setup

(b) details of extensometer and coupon

Figure 7. Tensile Test Setup and Details

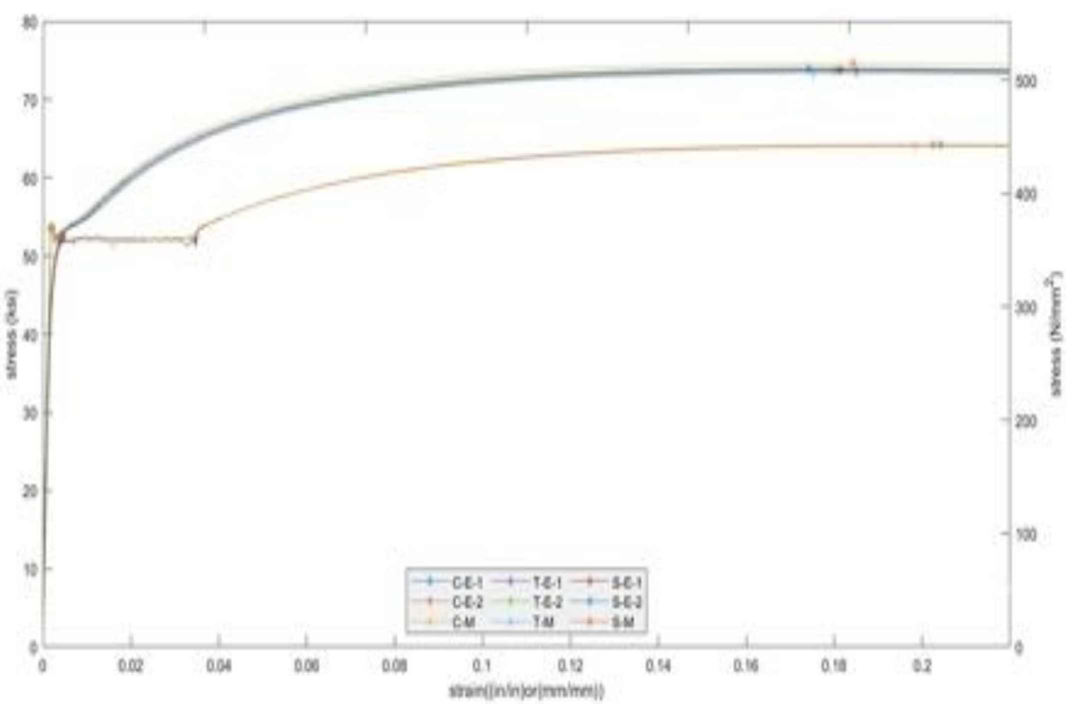


Figure 8. Coupon Tensile Test Result Plots Summary

5 Summary Test Results

Gravity load testing aligned with the test matrix of Table 1 are conducted in the multi-axis testing rig depicted in Section 2. Pictures and details of every specimen tested to failure are provided in Appendix 2. The results of specimens tested to failure are summarized in Table 4.

Overall wall deformations are summarized in plots of the axial displacement, sidesway displacement, and twist of one of the studs as provided in Figure 10 and Figure 11. The plots may be used, in part, to determine if minor-axis flexural or flexural-torsional buckling dominated the wall response.

The bracing force in the bridging channel is directly measured and provided in Figure 12. The force is approximately 1%P for the all-steel test and less than 0.5%P when the sheathing is in place, where P is the axial load on 5 wall studs.

The wall deformations for the four all-steel (AS) tests are summarized in Figure 13. The sidesway displacement is removed/minimized once the bridging is installed, and resolved to the support.

The CB-C test series considered the impact of applying dead load, before installing sheathing, on the brace forces in the bridging. Figure 14 depicts the brace force in the bridging over the testing time span.

Typically observed limit states for the tests are provided in Figure 15.

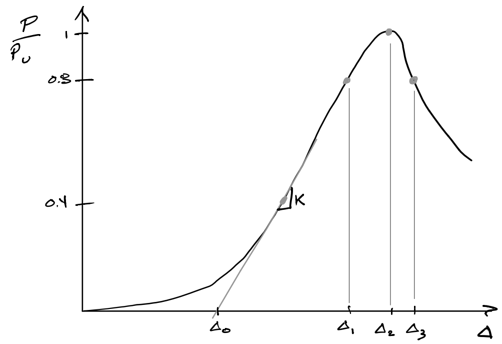


Figure 9. Definition of variables for force vs axial displacement response

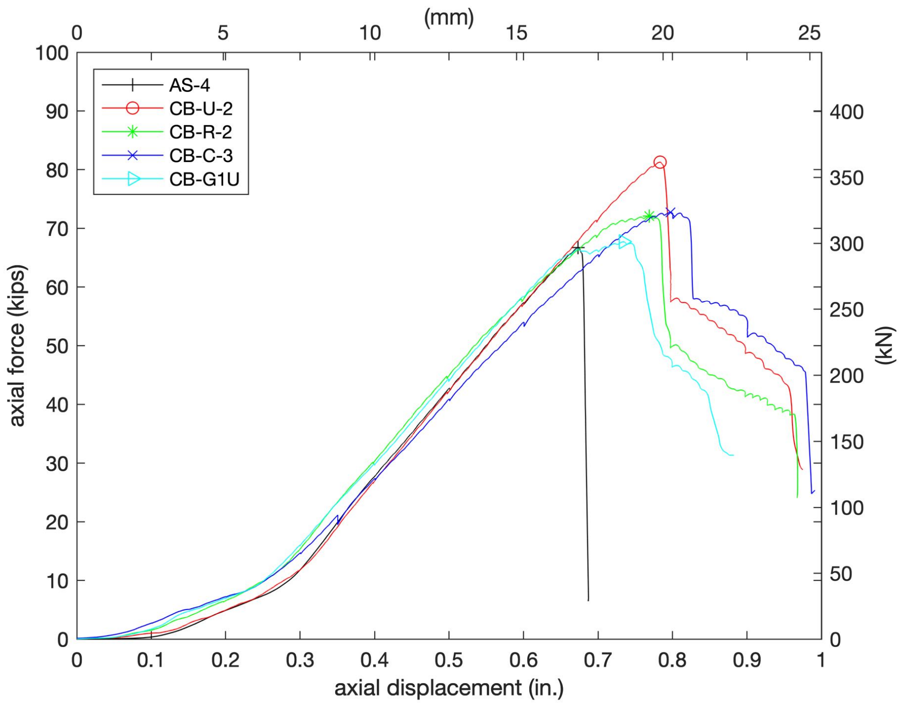
Table 4.Summary Results from Specimens Tested to Failure

id	Bridging	Sheathing	P_{max} (kip)	Limit State	$k_{40\%}$ (kip/in.)	Δ_0 (in.)	Δ_1 (in.)	Δ_2 (in.)	Δ_3 (in.)	$B(P_{max})$ (lbf)	max(|B|) (lbf)	B/P (%)
AS-4	end anchored	none	66.7	FTB2	150.8	0.22	0.57	0.67	0.68	604	677	1.0%
CB-U-2	no fixity	2 sided gyp	81.3	LB@Hole (FB/TB)	149.1	0.22	0.65	0.78	0.80	0	0	0.0%
CB-R-2	end anchored	2 sided gyp	72.1	LB@Hole (TB/FB)	137.9	0.18	0.60	0.77	0.79	-130	276	0.4%
CB-C-3	end anchored	2 sided gyp	72.7	LB@Hole (TB/FB)	131.8	0.19	0.64	0.80	0.83	79	490	0.7%
CB-G1U-2	no fixity	1 sided gyp	67.7	TB2	138.0	0.18	0.57	0.73	0.77	0	0	0.0%

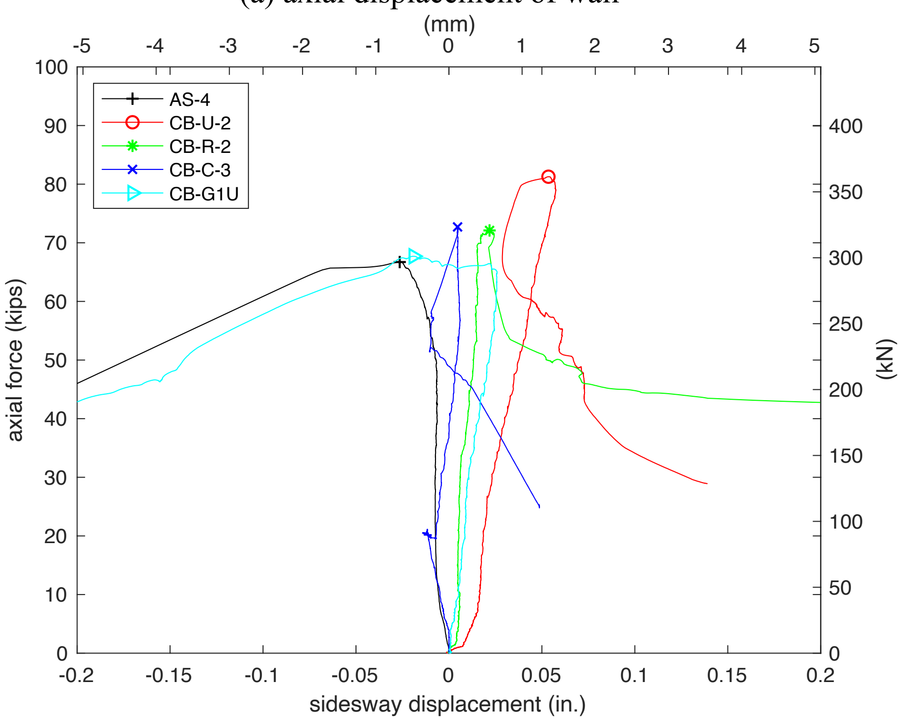
Notes: LS = limit state, P = axial force, B = bridging force, FTB = Flexural-torsional buckling, LB = Local buckling, FB = minor-axis flexural buckling, TB =torsional buckling, trailing 2 in LS indicates 2nd mode, () indicate secondary mode

id	Bridging	Sheathing	P_{max} (kN)	Limit State	$k_{40\%}$ (kN/mm)	Δ_0 (mm)	Δ_1 (mm)	Δ_2 (mm)	Δ_3 (mm)	$B(P_{max})$ (N)	max(|B|) (N)	B/P (%)
AS-4	end anchored	none	296.8	FTB2	26.4	5.47	14.51	17.10	17.31	2687	3011	1.0%
CB-U-2	no fixity	2 sided gyp	361.5	LB@Hole (FB/TB)	26.1	5.54	16.58	19.90	20.23	0	0	0.0%
CB-R-2	end anchored	2 sided gyp	320.7	LB@Hole (TB/FB)	24.1	4.54	15.21	19.54	20.03	-580	1228	0.4%
CB-C-3	end anchored	2 sided gyp	323.4	LB@Hole (TB/FB)	23.1	4.91	16.14	20.25	21.02	352	2179	0.7%
CB-G1U-2	no fixity	1 sided gyp	301.1	TB2	24.2	4.62	14.42	18.64	19.61	0	0	0.0%

Notes: LS = limit state, P = axial force, B = bridging force, FTB = Flexural-torsional buckling, LB = Local buckling, FB = minor-axis flexural buckling, TB =torsional buckling, trailing 2 in LS indicates 2nd mode, () indicate secondary mode

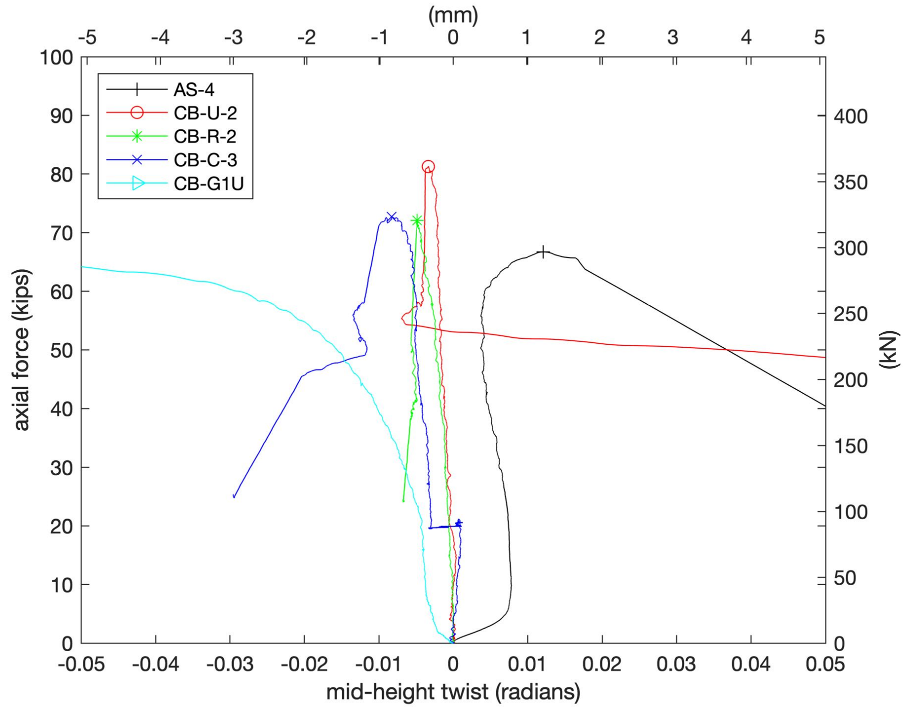


(a) axial displacement of wall

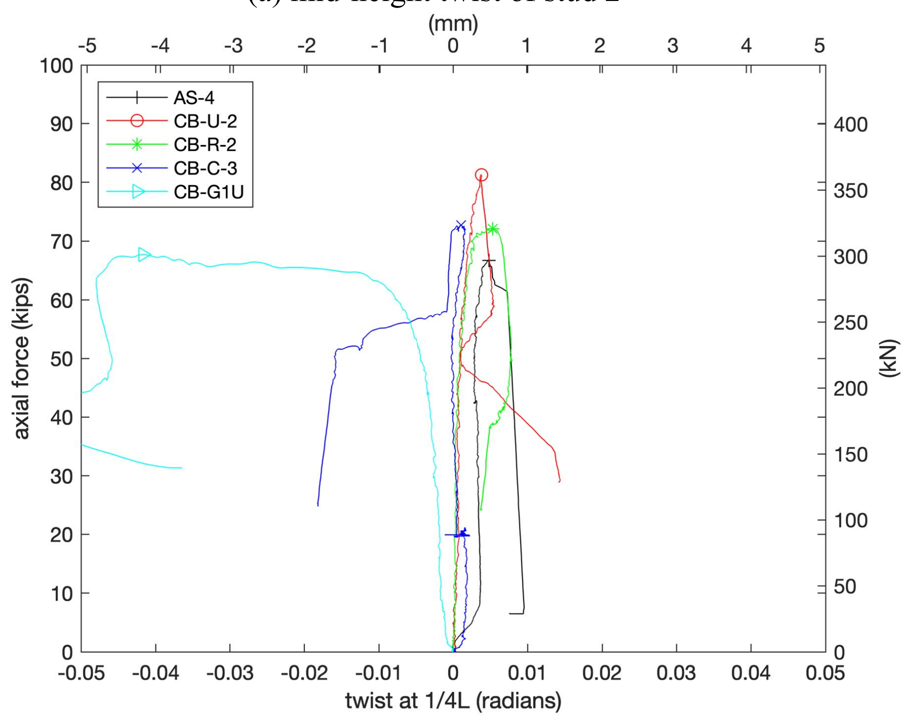


(b) sidesway displacement of wall

Figure 10.Summary force vs. displacement for specimens tested to failure

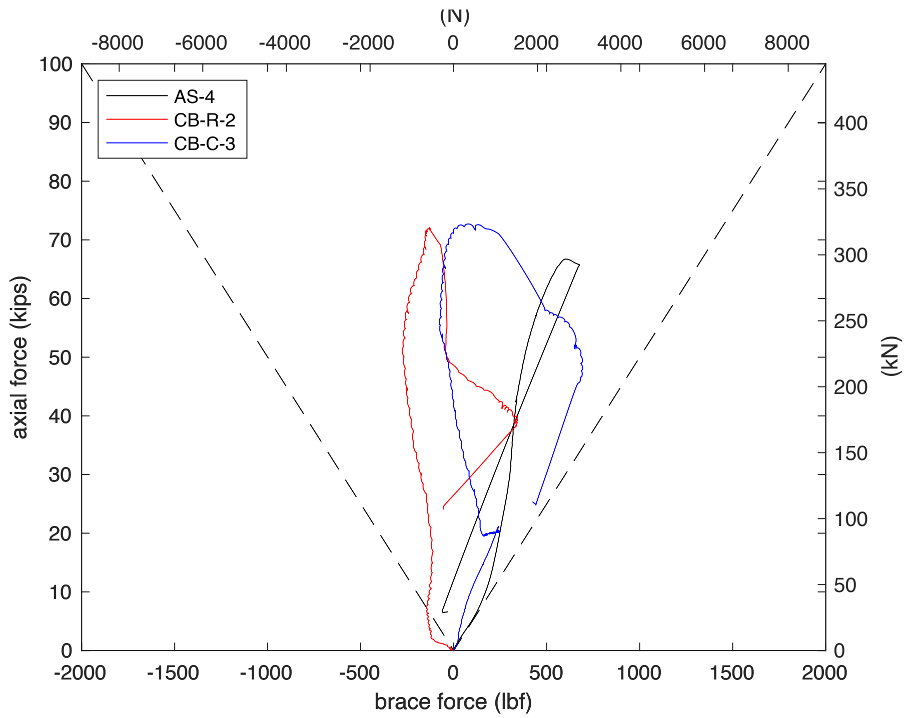


(a) mid-height twist of stud 2

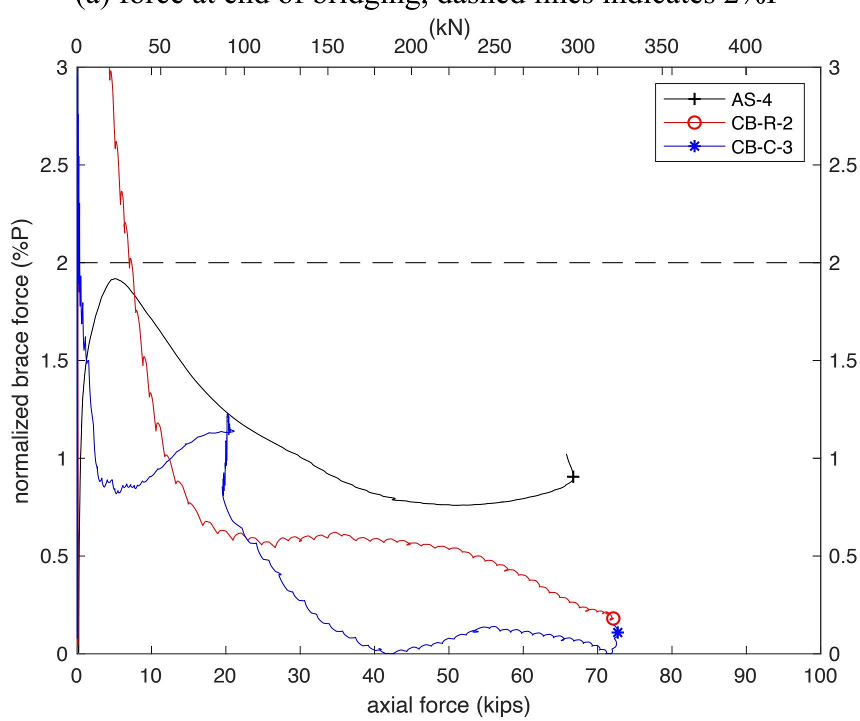


(b) quarter point twist of stud 2

Figure 11. Summary force vs. twist for specimens tested to failure

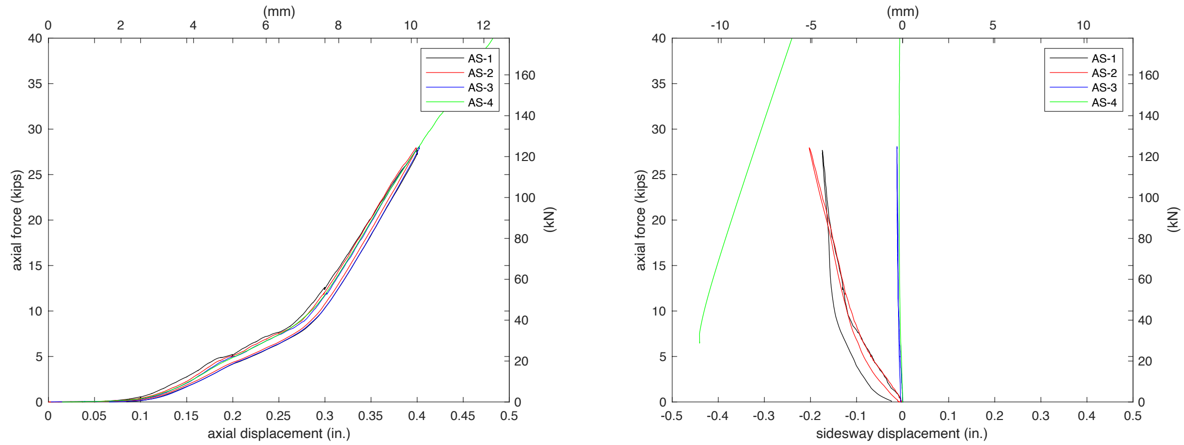


(a) force at end of bridging, dashed lines indicates 2%P



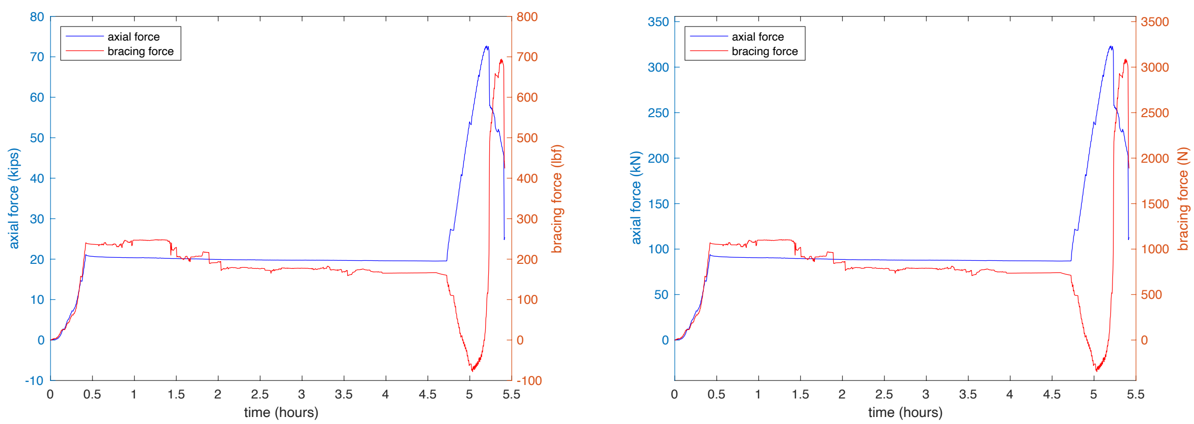
(b) normalized force at end of bridging

Figure 12. Brace force in specimens where bridging is fixed at its end and wall tested to failure



(a) axial displacement (b) mid-height sidesway displacement

Figure 13. Force displacement response of all steel (steel only) wall specimen



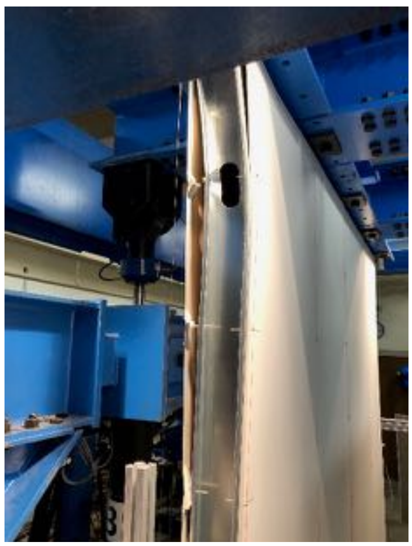
(a) imperial (b) SI

Figure 14. CB-C-1,2,&3 Construction Sequence Test – Axial Force and Bracing Force over Time (Gypsum sheathing installed at 0.5 hours – 2 hours)

(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 15. Limit State of Tested Specimens

6 Discussion of Test Results

The all steel test specimen (AS-1,2,3,4) has no sheathing in place and had the lowest observed axial capacity. However, these specimens unequivocally demonstrate the role of bridging in an all-steel wall system. Once the bridging is installed, even when not resolved (to a support) the twist of the studs is significantly reduced. However, unresolved bridging still allows large minor-axis flexure in the studs. When the bridging is resolved to a support the stud twist is further reduced, but the lateral deformation is nearly removed at the brace points. For the resolved bridging the axial force in the bridging is directly measured and at peak load is 1.0% of the axial load. At failure of AS-4, the all-steel specimen with fully resolved mid-height bridging the final primary limit state is 2nd mode flexural-torsional buckling. The bridging restraints flexure and torsion at the mid-height but not in the L/2 spans above and below. It should be noted that the flexural-torsional buckling is sudden and results in a significant load drop in the all-steel specimen.

When two-sided gypsum sheathing is applied to the walls (the CB-U, CB-R and CB-C series) the strength of the wall is increased substantially and the primary failure mode switches to local buckling in the stud holes located at the ¼L or ¾L knockouts. The failure is more gradual in the local bucking limit state with the sheathing applied than in the all-steel specimens without sheathing. In the sheathed specimens the importance of the bridging is dramatically reduced. In fact, the specimen with unresolved bridging (CB-U) had a higher ultimate capacity than the specimens with resolved/anchored bridging (CB-R, CB-C) though the limit state was essentially the same. In the conducted tests, if sheathing, even ½ in. gypsum board only fastened at 12 in. o.c., is on both sides of the stud, the bridging plays little to no role in the ultimate strength of the specimen.

A practical scenario of interest that is explored in the CB-C test series is what happens if dead load is applied to an all-steel wall and only at this point is the sheathing added to the walls. This would be consistent with on-site stick construction of the wall, or even panelized construction where the finish is applied in the field. The tests show that under the dead load the wall behaves like the typical all-steel system and the bridging supplies lateral bracing and develops a small (<1%P) bracing force. However, once the sheathing is applied and additional gravity load is added the bridging unloads and all brace forces move to the sheathing connections. Only after failure, does the bridging pick up any additional substantial force. Thus, a design practice where all-steel bridging is design for construction loads, and sheathing braced design is used for ultimate loads, would seem to have some merit.

Noting that for two-sided sheathing (CB-U) the bridging did not need to be resolved, we considered in a final scenario if one-sided sheathing (CB-G1U) could adequately resolve the bridging. The test indicated that one-sided sheathing performed as well, or even better, than no sheathing and a fully anchored bridging channel (AS-4). The strength in the one-sided sheathing case was slightly greater than the all-steel case and the failure mode, 2nd mode restrained-axes torsional buckling, was more benign than the all-steel 2nd mode flexural-torsional buckling failure. However, the one-sided sheathing did not sufficiently restrict torsion to allow the wall to develop the higher capacity associated with local buckling. The results suggest, that a design practice where discrete bridging is unresolved/unanchored may be adequate for construction loads so long as at least one side of the wall is sheathed.

It is important to note that the observations are only for a single wall.

7 Supplementary Stiffness Test

To determine the bridging system stiffness in the all-steel test a supplementary test was performed. An hydraulic hand jack was placed in-line with the load cell at the fixed support for the briding and exercised. The test setup is depicted in Figure 16 and details provided in Figure 17. To minimize error the specimen is tested 3 times and typical results are provided in Figure 18. Displacements are measured for the bridging channel itself at each end and for the middle two studs at mid-height and at the quarter point. The resulting measured displacements at an applied force of 200 lbf are provided in Table 5.

A planar frame element model of the test was created in MASTAN. The model uses actual properties for the stud, track, and bridging channel. A rotational spring is provided at the end of the studs to account for end fixity. A translational spring is provided between the bridging channel and the studs at each stud location to account for clip/fastener connection flexibility. Using displacement measurements from studs 2 and 4 it is determined that the stud ends are semi-rigid and a rotational stiffness of 28 k-in./rad leads to model results that most closely approximate the measured data. Using the displacement measurements directly from the bridging it is additionally found that a connection stiffness of 9.2 kips/in. in the model leads to the smallest error between the model and the testing. These values can be compared to the earlier testing of Green et al. (2006).

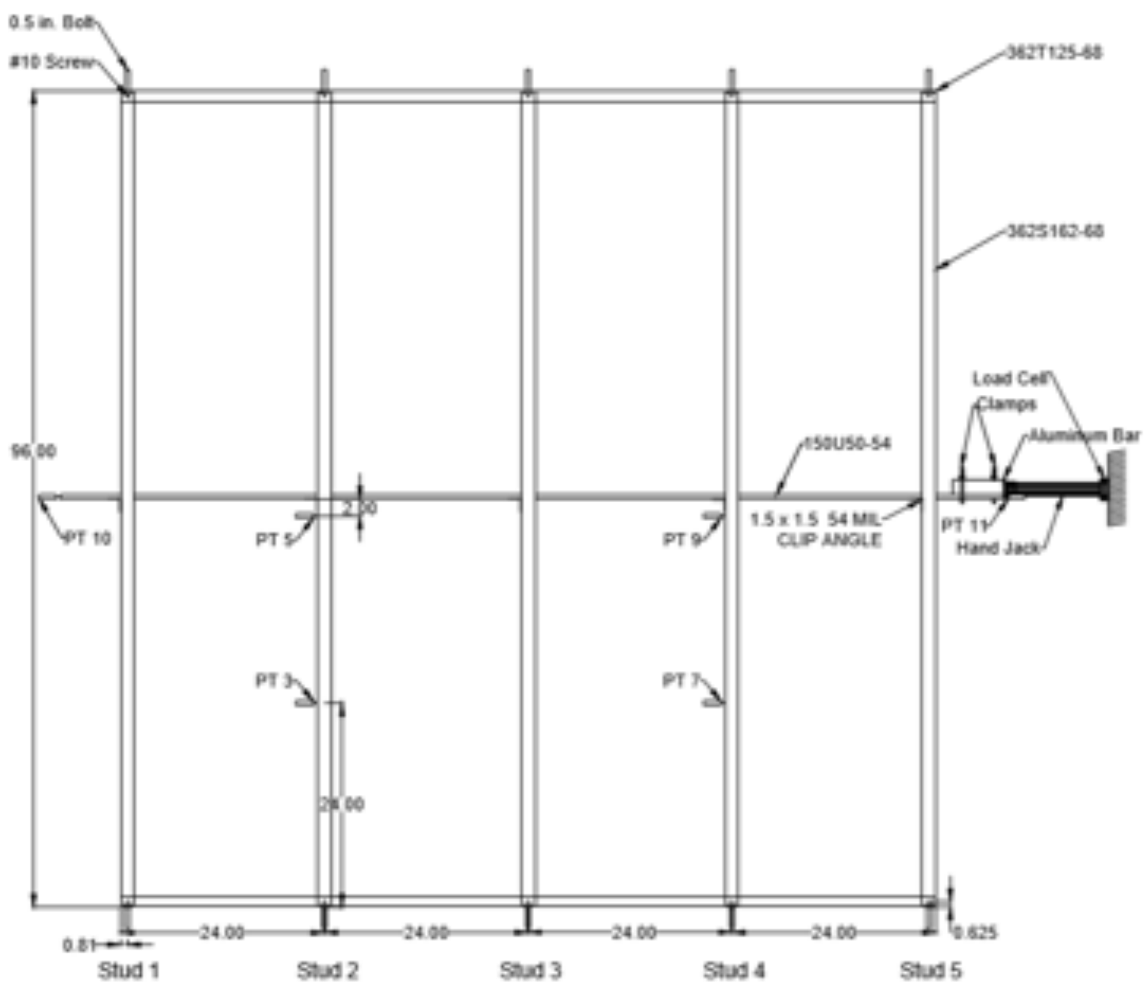
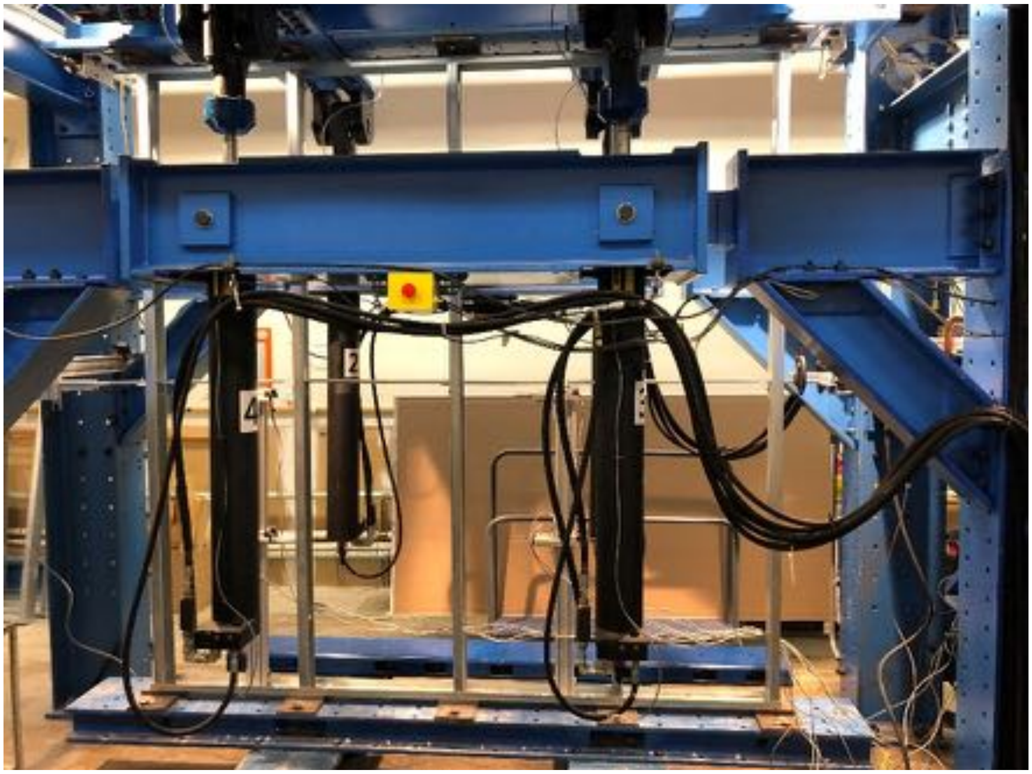


Figure 16. Drawing of Stiffness Test



(a) plan view of specimen

(b) detail of the end with jack and load cell

(c) detail of connection for bridging and stud

Figure 17. Details of Stiffness Test Setup

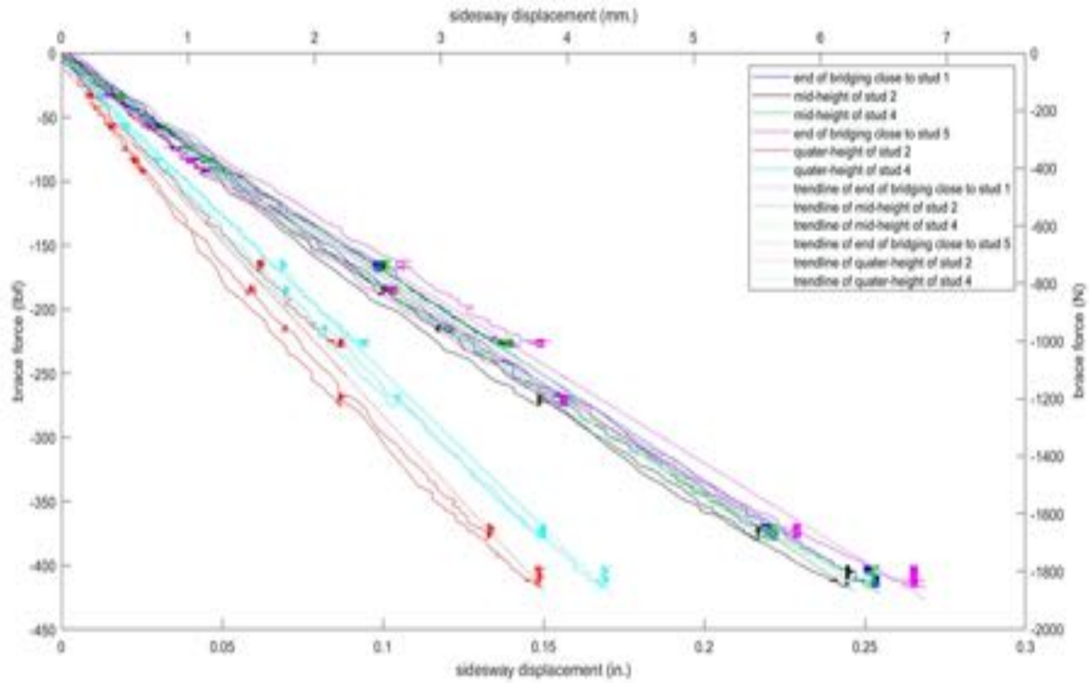


Figure 18. Plots of Sidesway Displacements in Stiffness Tests

Table 5. Summary of Sidesway Displacement when Brace Force is 200 lbf in Tests

Location of Position Transducers	Lateral Displacement (avg.) (in.)
end of bridging close to stud 1	0.118
2 in. below mid-point of stud 2	0.115
2 in. below mid-point of stud 4	0.119
end of bridging close to stud 5	0.122
quarter-point of stud 2	0.0695
quarter-point of stud 4	0.0802

Table 6. Summary of Stiffness Analysis by Mastan 2 at 200 lbf, and of Tested Response (final line)

K_x (k/in)	K_ϕ (k-in/rad)	Stud 2		Stud 4		bridging end of stud 1 (in.)	bridging end of stud 5 (in.)	Stud 2 and stud 4 MSE	bridging disp. MSE
		mid-point (in.)	quarte-point (in.)	mid-point (in.)	quarte-point (in.)				
19667	0	0.1333	0.0919	0.1345	0.0927				
19667	inf	0.0477	0.0268	0.0489	0.0274				
19667	28	0.1142	0.0775	0.1155	0.0784			2.02E-05	
9.2	28	0.1142	0.0775	0.1154	0.0784	0.119	0.121	2.04E-05	3.6E-07
Test results:		0.1150	0.0695	0.1190	0.0802	0.118	0.122		

8 Conclusions

Cold-formed steel stud walls benefit significantly from bracing. Conventional design favors all-steel solutions using discrete bridging channels for the bracing. Resolution of the accumulated bracing forces at the ends of walls is costly and design practice is not always aligned with analytical models used by design specifications to determine accumulated brace forces and minimum brace stiffness. Sheathing, such as gypsum board, is commonly applied to both sides of walls to provide necessary structural (e.g., fire) and non-structural (e.g., thermal and acoustic) performance. Previous testing has shown that the sheathing can serve as the bracing for the wall.

Tests conducted here show that if sheathing is present that bridging need not be resolved at the wall ends. Further, the tests indicate that sheathing, even ½ in. gypsum board with fasteners at 12 in. o.c., more effectively provides bracing than through the knockout bridging. 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. The tests also show that accumulated brace forces are low, less than 1% of the axial force applied to a 5 stud wall, and less than ½% if the wall has sheathing. Further, with respect to ultimate response, it is shown that the sheathing can be applied after 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 all-steel bracing system; however to achieve the most desirable limit state, strength, and post-peak response two-sided sheathing is favored.

The provided tests are a limited study of only a single wall stud section. Additional testing is needed. Comparisons between the predicted strength and observed strength are ongoing. In the future a design method whereby engineers can, when desired, account for the benefits of combined bracing, both sheathing and discrete, across all typical configurations is needed.

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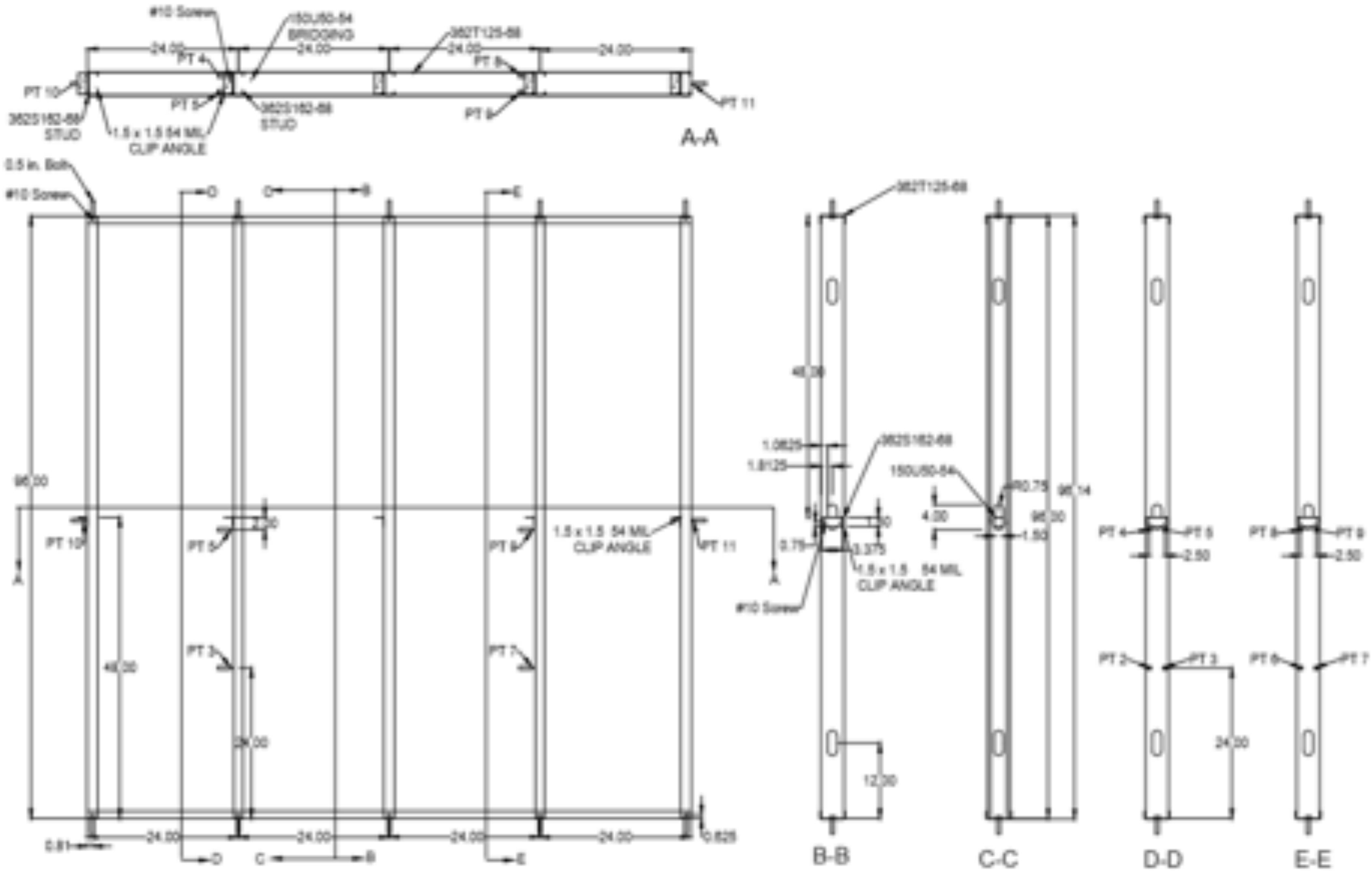
Vieira Jr., L.C.M. (2011) Behavior and design of cold-formed steel stud walls under axial compression, Department of Civil Engineering, Ph.D. Dissertation, Johns Hopkins University. (http://jhir.library.jhu.edu/handle/1774.2/40583)

Vieira Jr., L. C. M., & Schafer, B. W. (2013). “Behavior and design of sheathed coldformed steel stud walls under compression.” Journal of Structural Engineering (United States), 139(5), 772-786. 10.1061/(ASCE)ST.1943-541X.0000731.

Appendix 1: Drawings

Drawings for each of the conducted tests are provided on the following pages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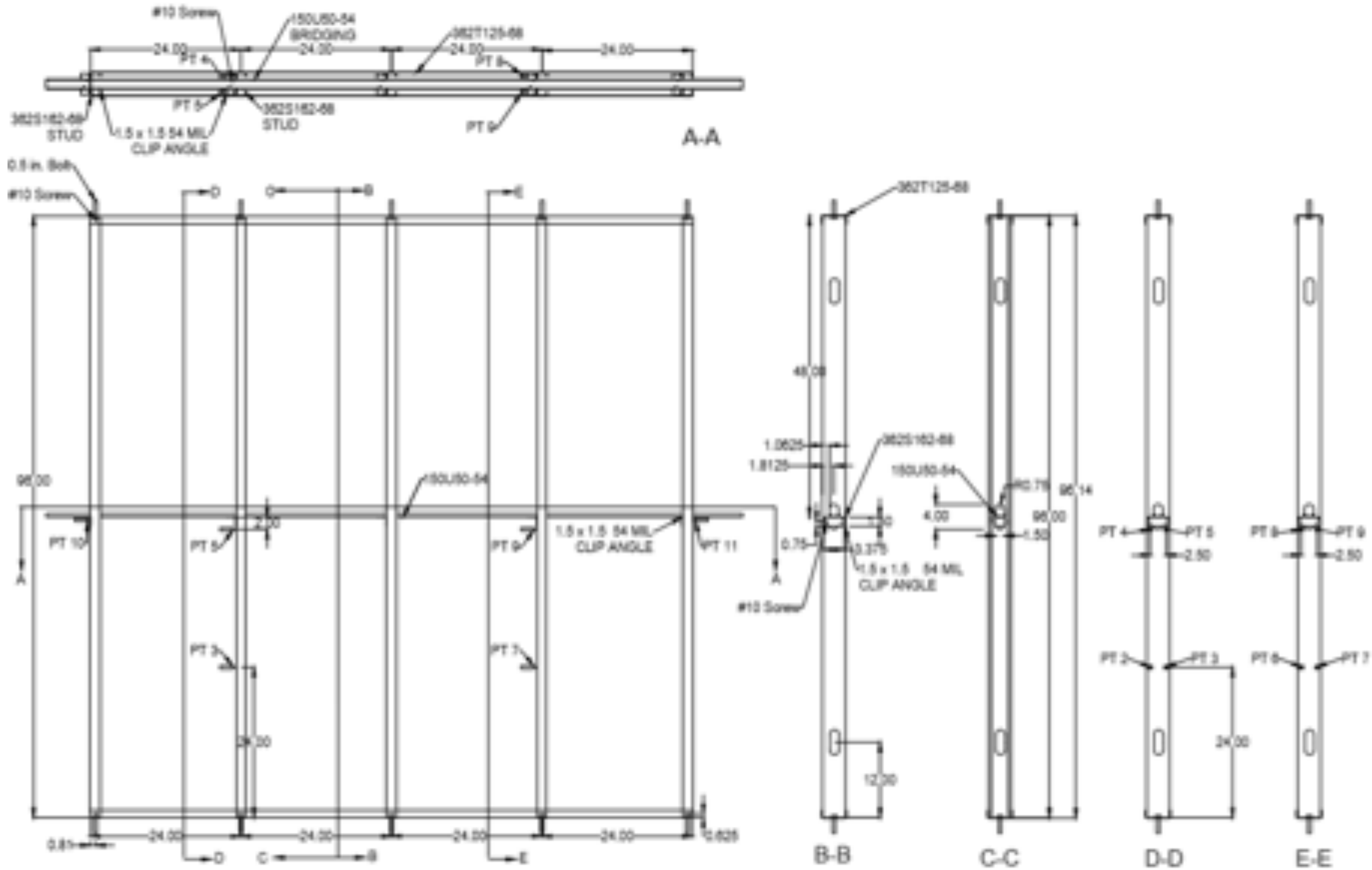
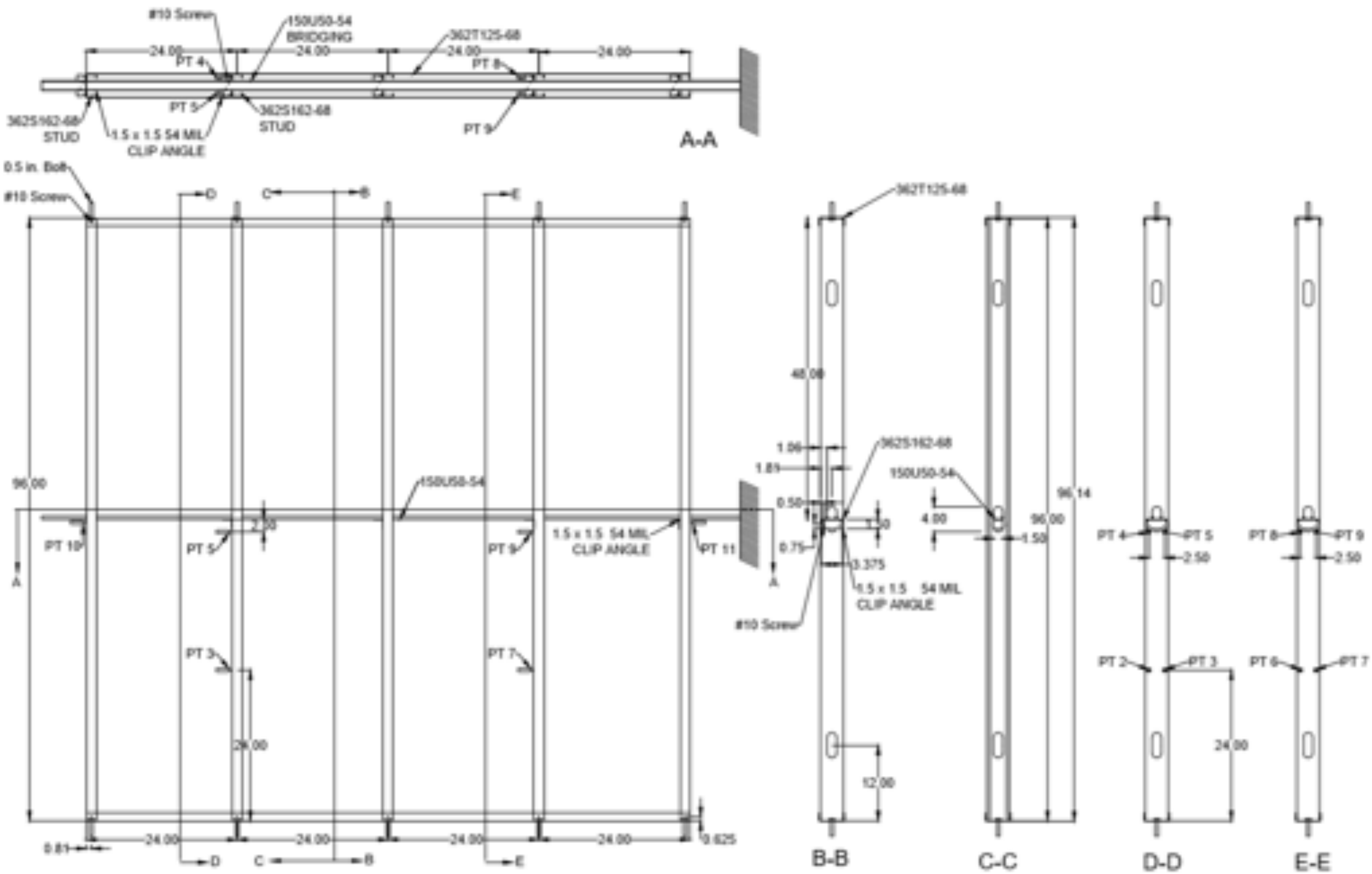
150U50-54
BRIDGING
362T125-68
PT 4
PT 8
PT 10
PT 5
PT 9
PT 11
362S162-68
STUD
1.5 x 1.5 54 MIL
CLIP ANGLE
A-A
0.5 in. Bolt
PT 3
PT 7
1.5 x 1.5 54 MIL
CLIP ANGLE
B-B
C-C
D-D
E-E

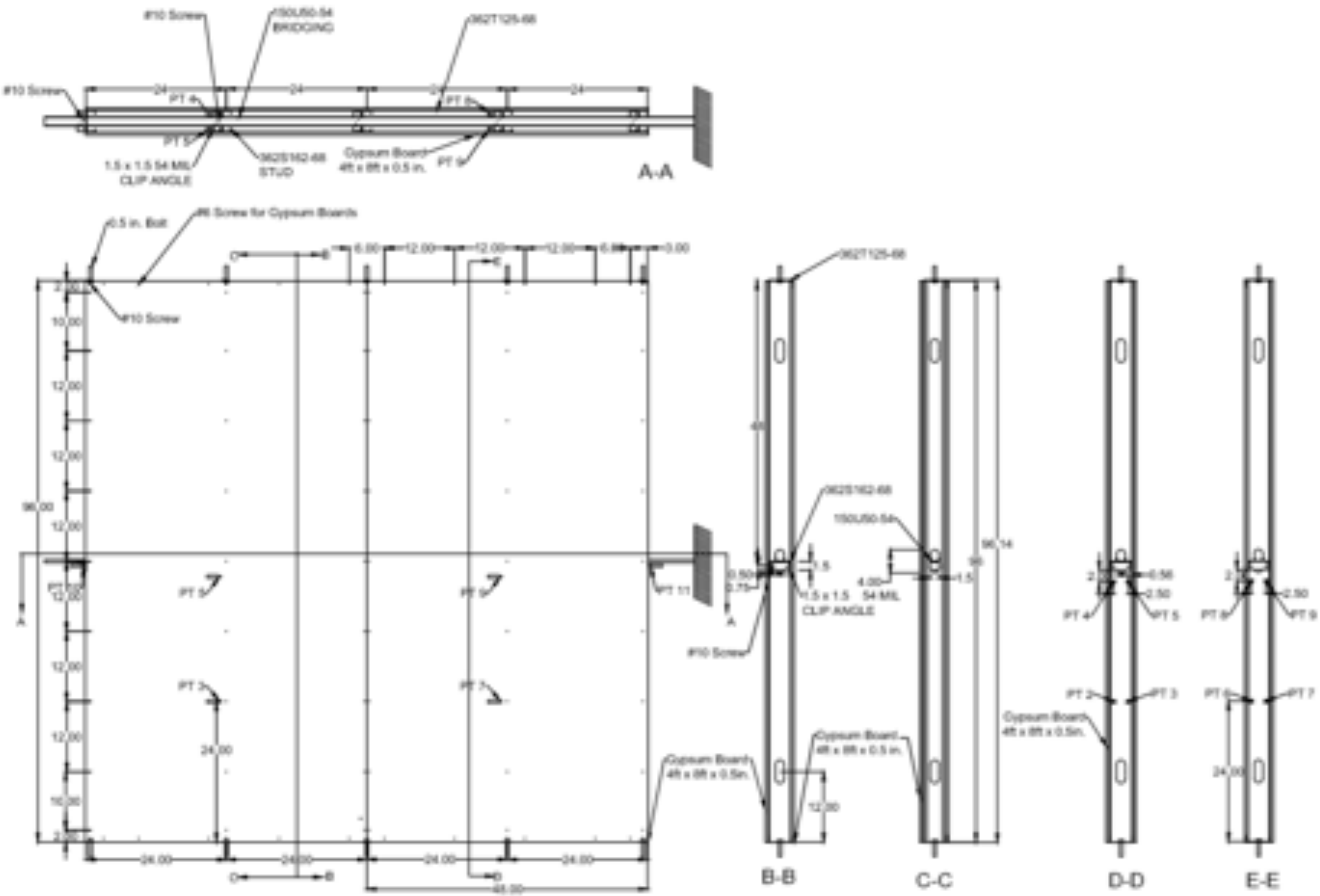
AS-1


#10 Screw
150U50-54
BRIDGING
362T125-68
24.00
PT 4
PT 8
PT 5
362S162-68
STUD
PT 9
1.5 x 1.5 54 MIL
CLIP ANGLE
A-A
0.5 in. Bolt
D
C
B
E
96.00
150U50-54
PT 10
PT 11
1.5 x 1.5 54 MIL
CLIP ANGLE
PT 3
PT 7
24.00
0.625
B-B
C-C
D-D
E-E
48.00
1.0625
1.8125
0.75
0.375
4.00
1.50
R0.75
96.14
12.00
2.50
PT 2
PT 6

AS-2

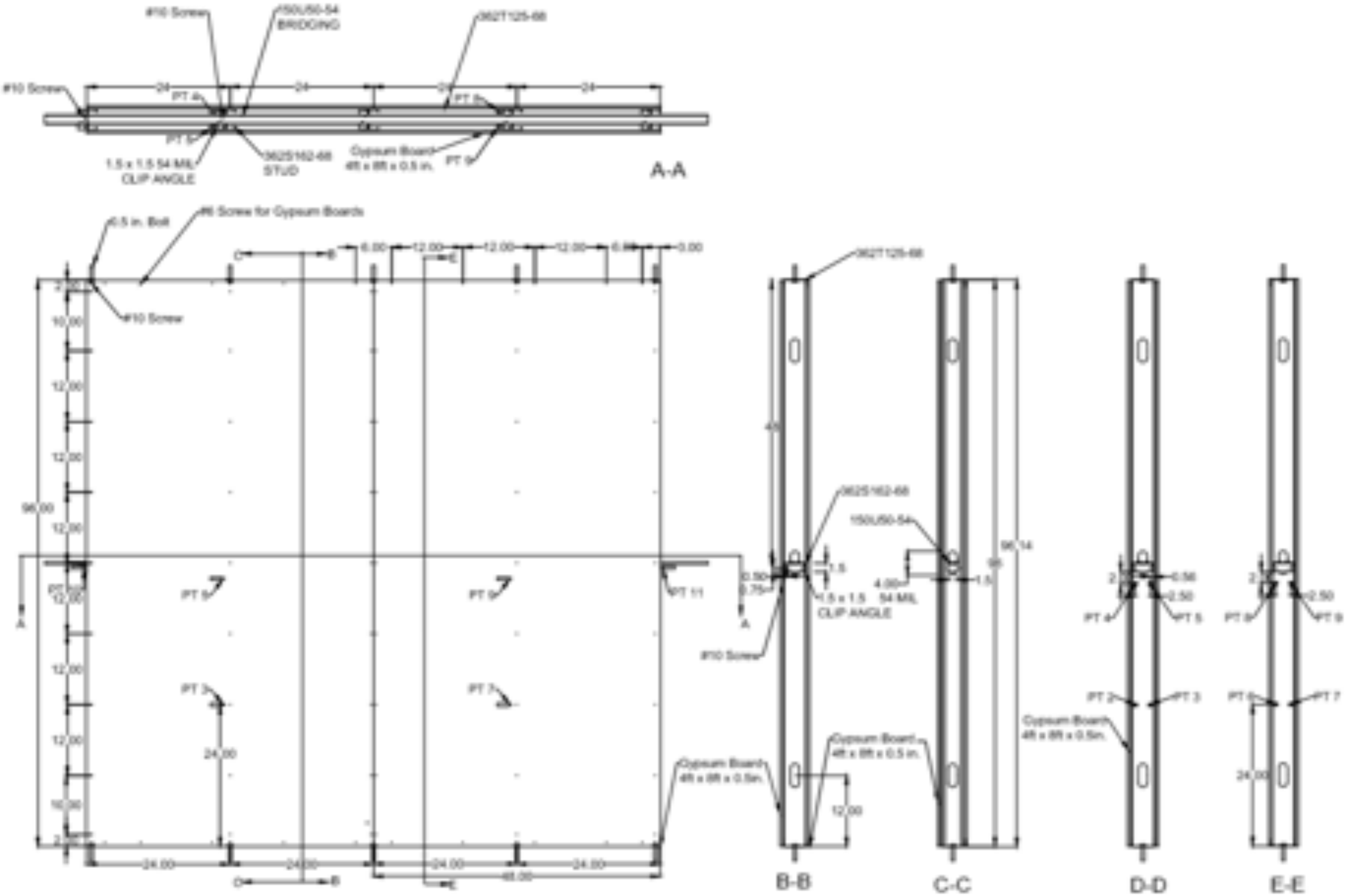

#10 Screw
150U50-54
BRIDGING
362T125-68
24.00
PT 4
PT 8
PT 5
362S162-68
STUD
PT 9
362S162-68
STUD
1.5 x 1.5 54 MIL
CLIP ANGLE
A-A
0.5 in. Bolt
#10 Screw
96.00
150U50-54
PT 10
PT 5
PT 9
1.5 x 1.5 54 MIL
CLIP ANGLE
PT 11
PT 3
PT 7
24.00
0.81
0.625
48.00
1.06
1.81
0.50
0.75
3.375
#10 Screw
12.00
B-B
C-C
96.14
96.00
4.00
1.50
D-D
PT 4
PT 5
2.50
PT 2
PT 3
E-E
PT 8
PT 9
PT 6
PT 7

AS-3 & AS-4

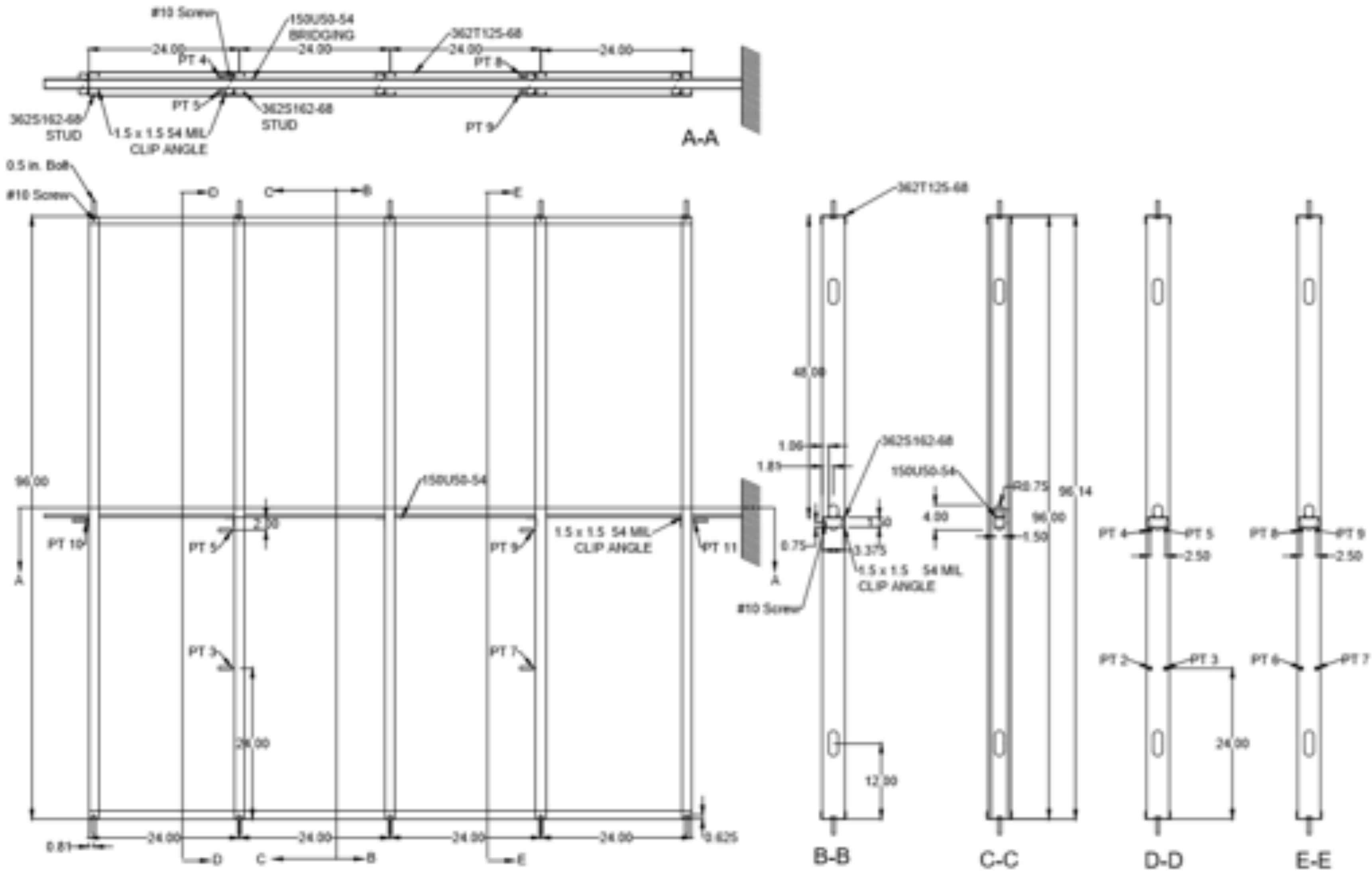


#10 Screw
150U50-54
BRIDGING
362T125-68
PT 4
PT 8
PT 5
PT 9
1.5 x 1.5 54 MIL
CLIP ANGLE
362S162-68
STUD
Gypsum Board
4ft x 8ft x 0.5 in.
A-A
0.5 in. Bolt
#6 Screw for Gypsum Boards
96.00
PT 11
PT 3
PT 7
24.00
48.00
B-B
C-C
D-D
E-E

CB-R-1 & CB-R-2

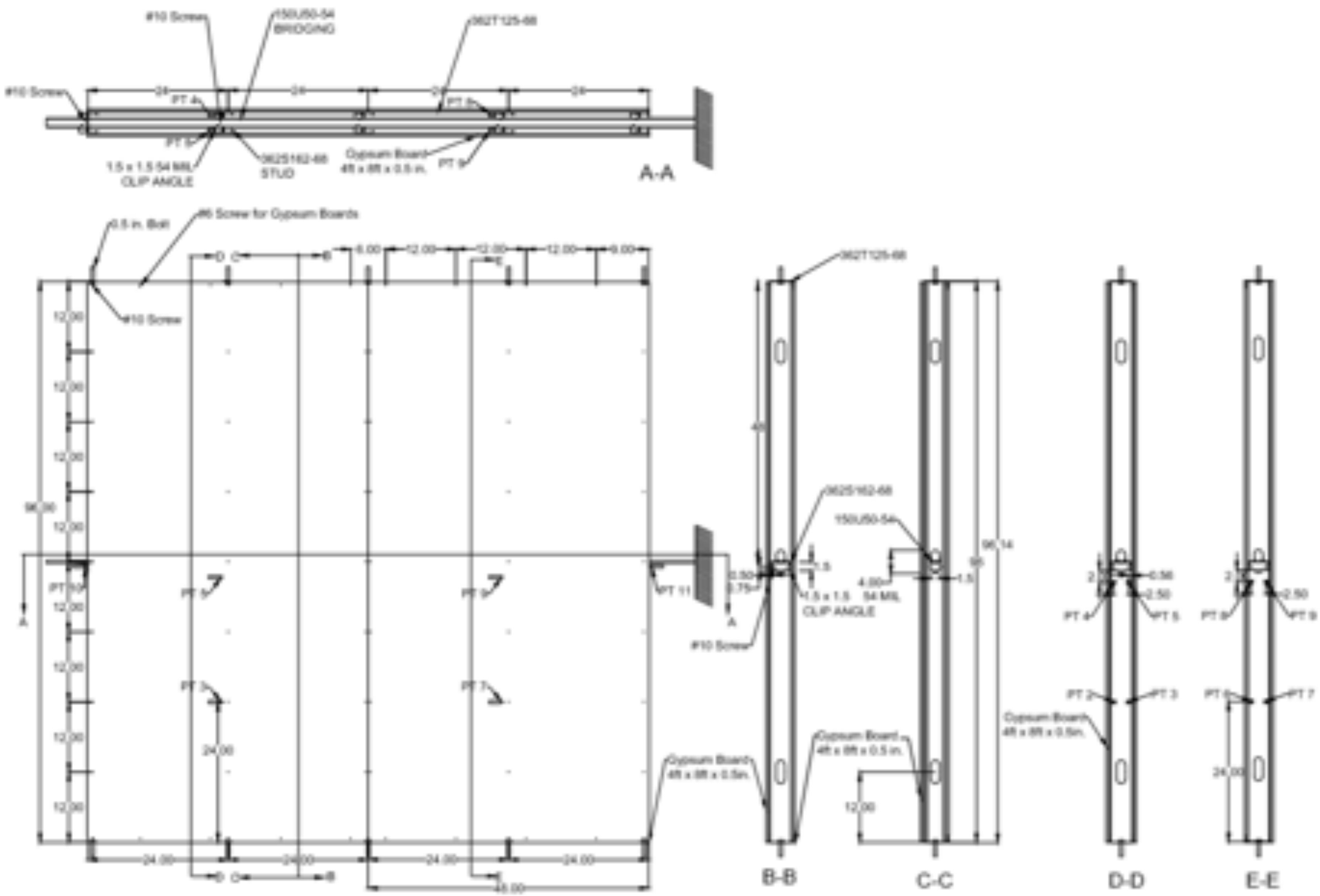


CB-U-1 & CB-U-2

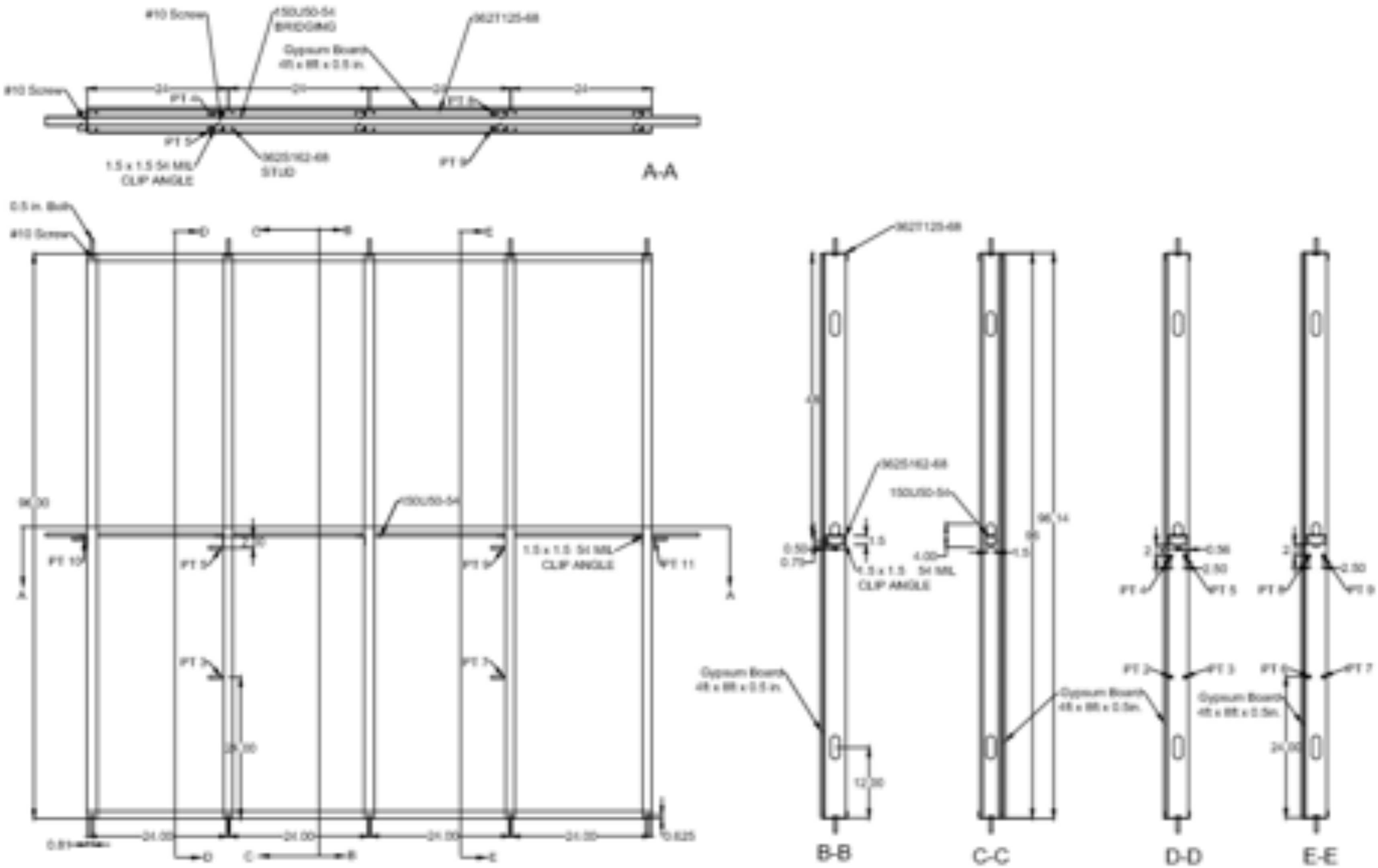


#10 Screw
150U50-54
BRIDGING
362T125-68
24.00
PT 4
PT 8
PT 5
362S162-68
STUD
PT 9
1.5 x 1.5 54 MIL
CLIP ANGLE
A-A
0.5 in. Bolt
D
C
B
E
96.00
150U50-54
PT 10
2.00
PT 11
A
PT 3
PT 7
24.00
0.81
0.625
48.00
1.06
1.81
0.75
3.375
4.00
R0.75
96.14
1.50
12.00
2.50
PT 2
PT 6
B-B
C-C
D-D
E-E

CB-C-1 & CB-C-2


#10 Screw
150U50-54
BRIDGING
362T125-68
#10 Screw
PT 4
PT 8
PT 5
1.5 x 1.5 54 MIL
CLIP ANGLE
362S162-68
STUD
Gypsum Board
4ft x 8ft x 0.5 in.
PT 9
A-A
0.5 in. Bolt
#6 Screw for Gypsum Boards
#10 Screw
PT 10
PT 11
PT 5
PT 9
PT 3
PT 7
B-B
C-C
D-D
E-E

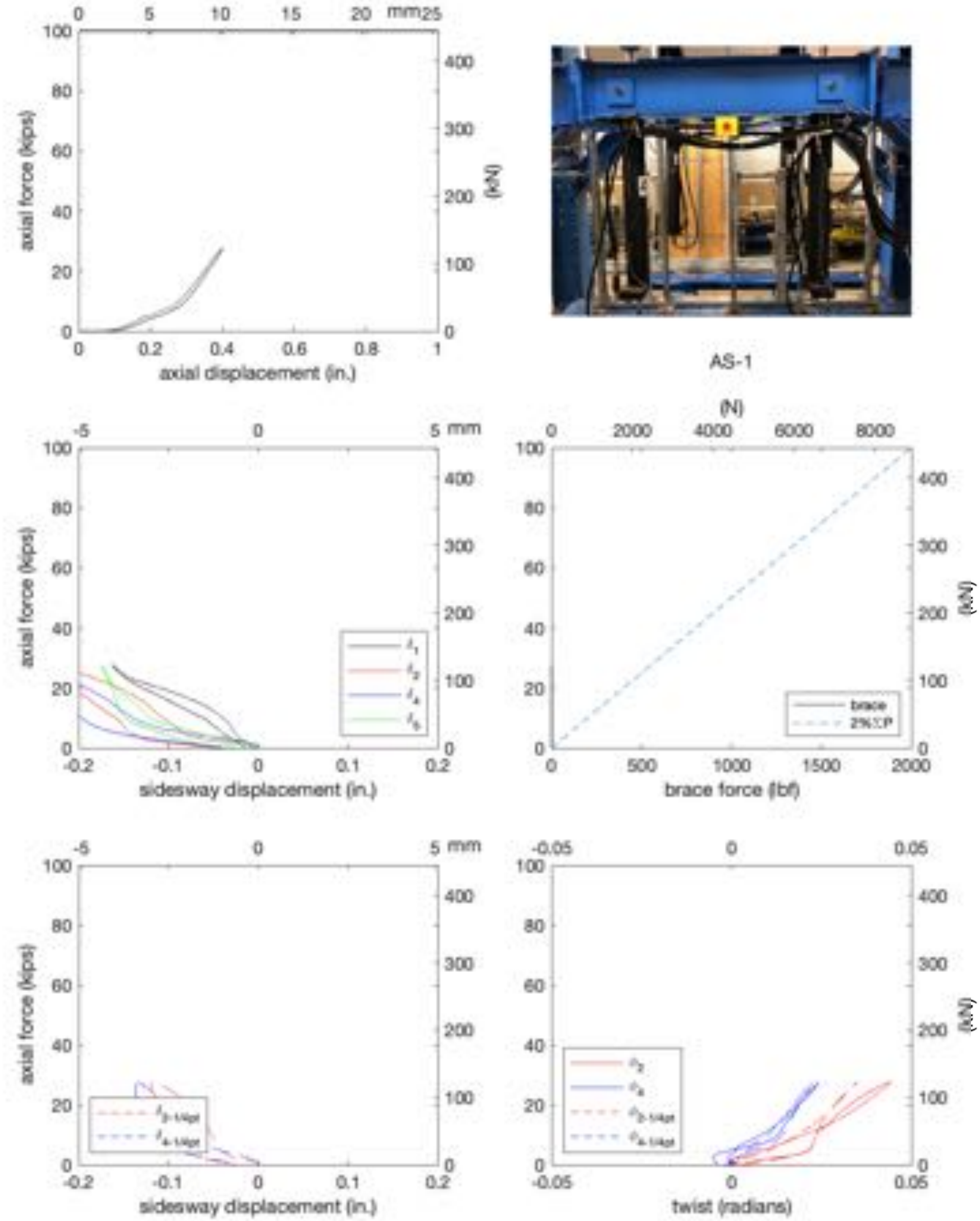
CB-C-3



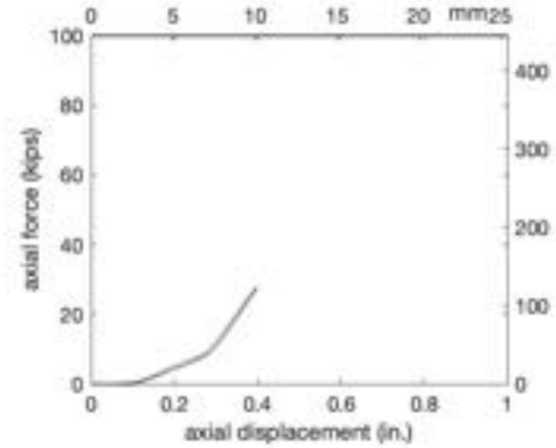
CB-G1U-1 & CB-G1U-2

Appendix 2: Test Reports

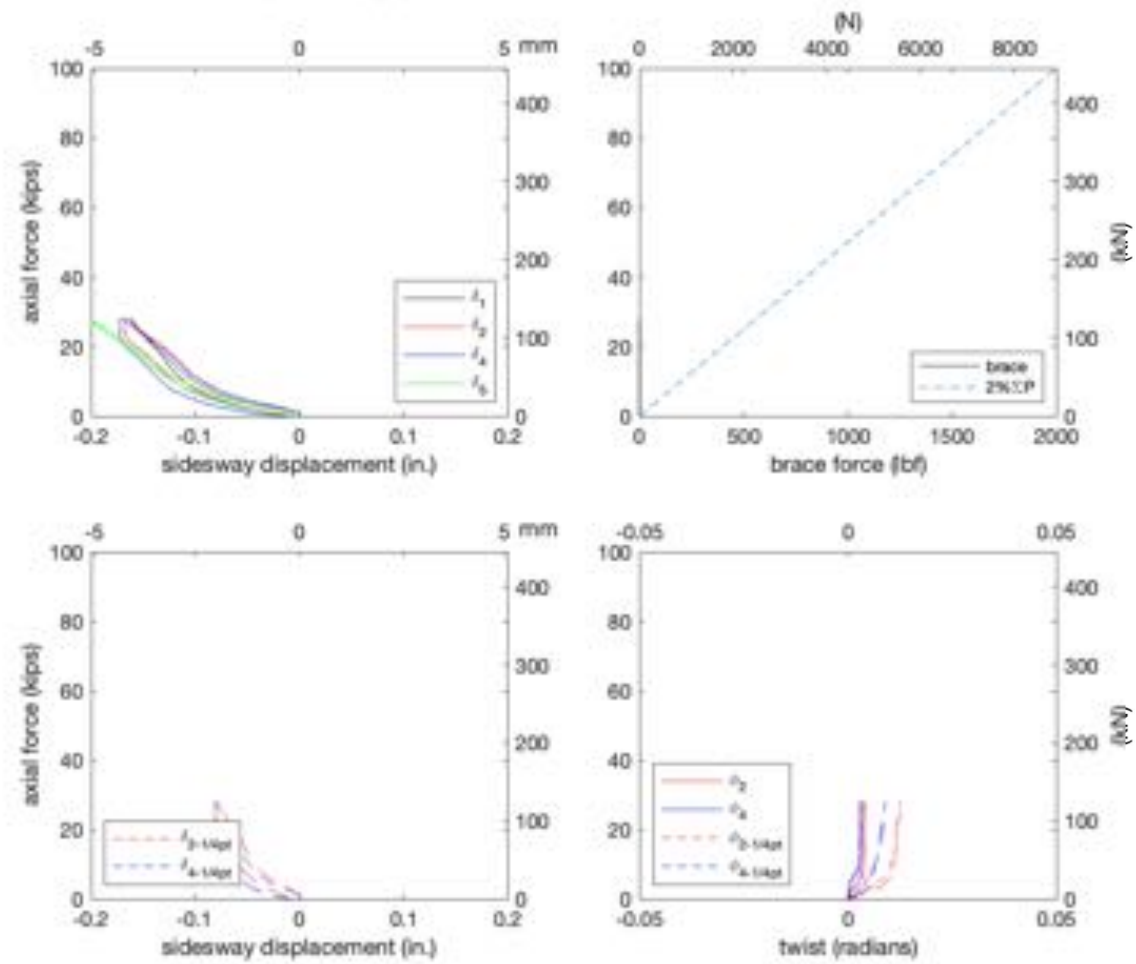
Summaries for each of the tests conducted are provided in this appendix.

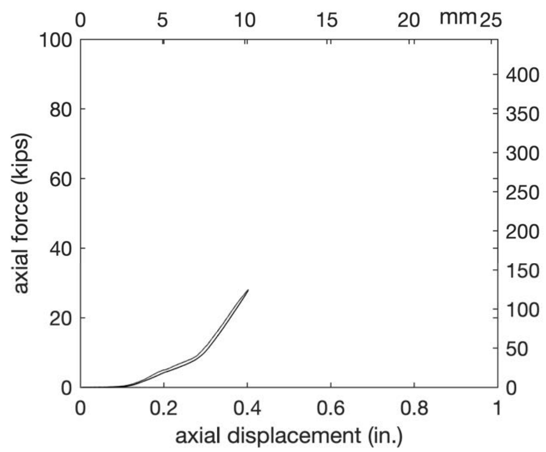


mm
axial force (kips)
(kN)
axial displacement (in.)
AS-1
(N)
sidesway displacement (in.)
brace
brace force (lbf)
twist (radians)

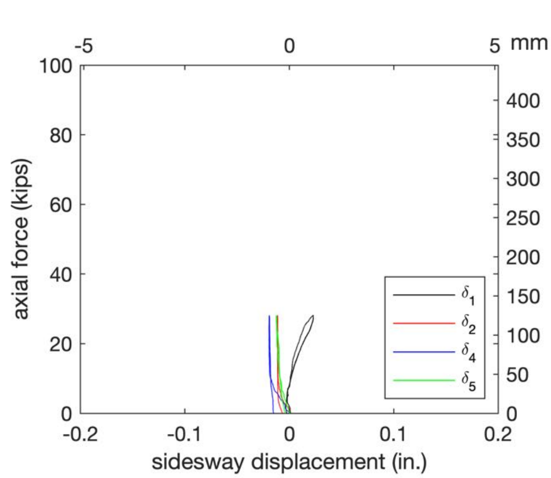

axial force (kips)
axial displacement (in.)
mm
(kN)

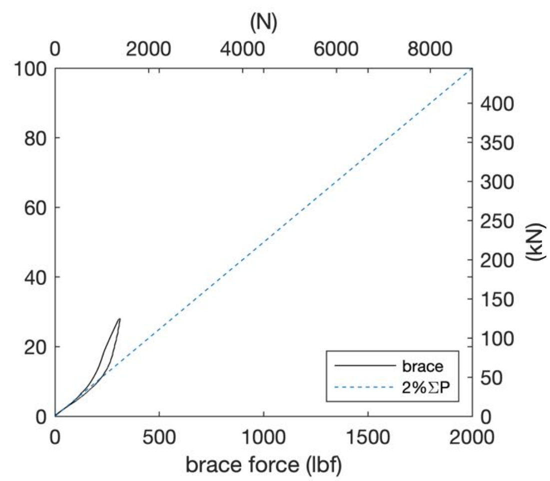
AS-2

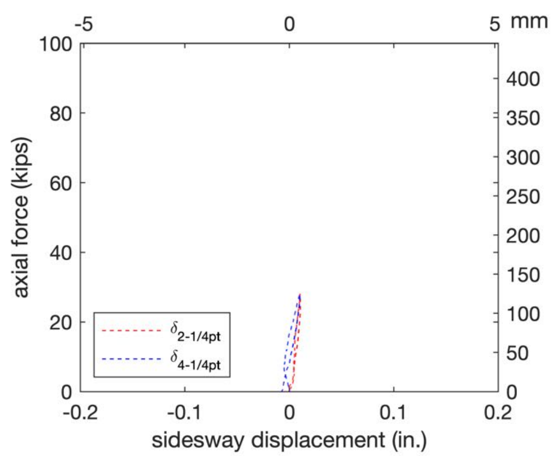

axial force (kips)
sidesway displacement (in.)
mm
(N)
brace force (lbf)
brace
2%ΣP
(kN)
twist (radians)

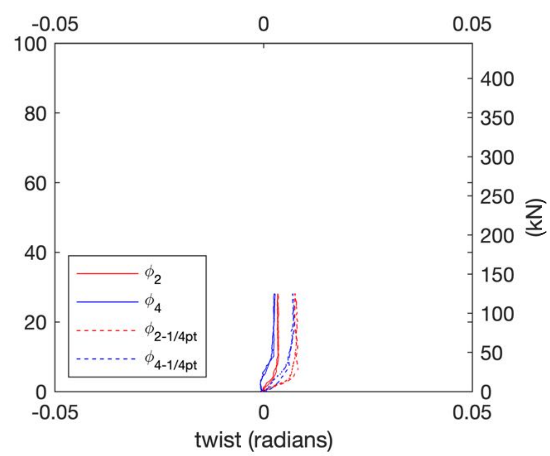

0 5 10 15 20 mm 25
axial force (kips)
(kN)
axial displacement (in.)

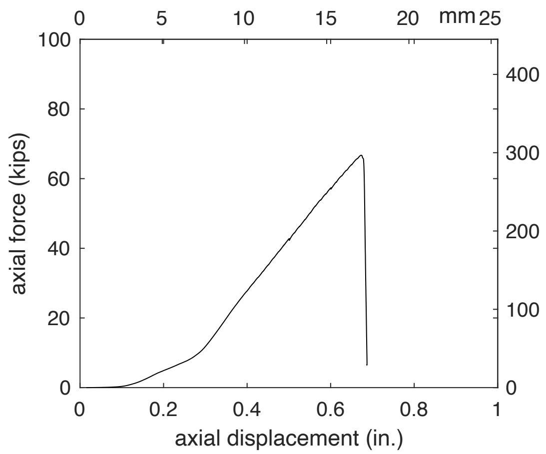
AS-3

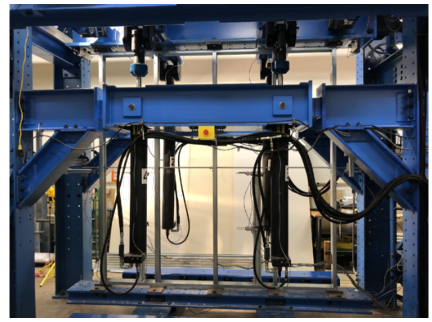

-5 0 5 mm
axial force (kips)
δ1
δ2
δ4
δ5
sidesway displacement (in.)


(N)
(kN)
brace
2%ΣP
brace force (lbf)

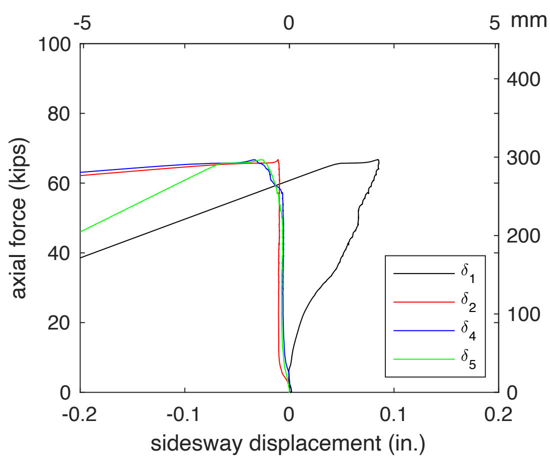

-5 0 5 mm
axial force (kips)
δ2-1/4pt
δ4-1/4pt
sidesway displacement (in.)

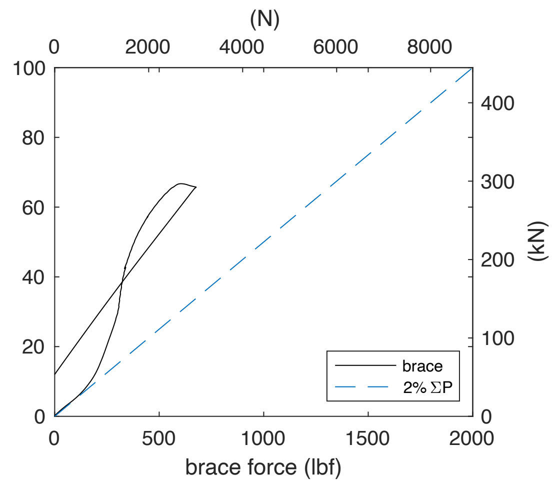

(kN)
φ2
φ4
φ2-1/4pt
φ4-1/4pt
twist (radians)

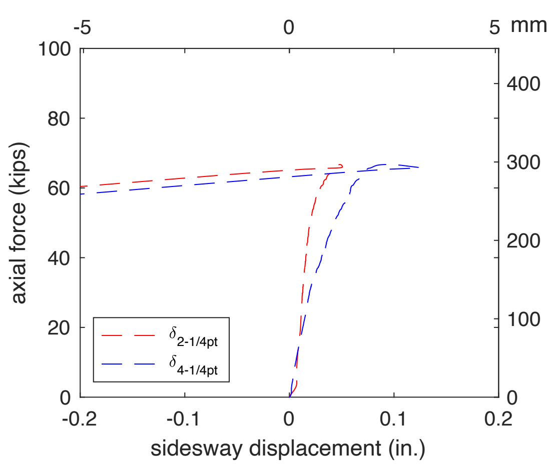

mm
axial force (kips)
(kN)
axial displacement (in.)

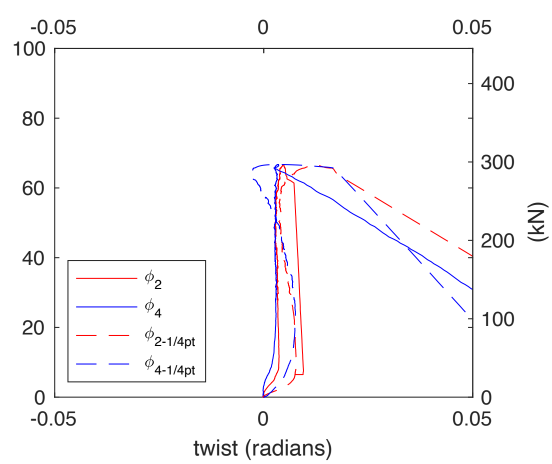


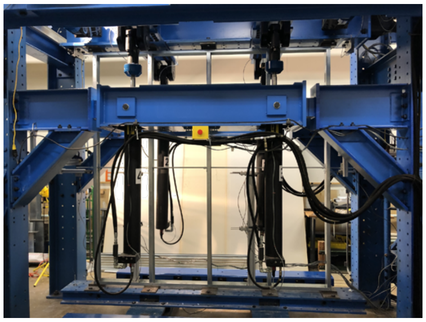
AS-4


mm
axial force (kips)
sidesway displacement (in.)
δ_1
δ_2
δ_4
δ_5


(N)
(kN)
brace force (lbf)
brace
2% ΣP

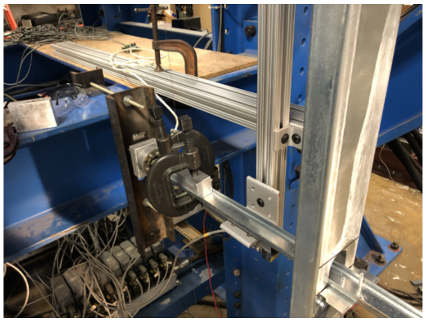

mm
axial force (kips)
sidesway displacement (in.)
$\delta_{2\text{-}1/4pt}$
$\delta_{4\text{-}1/4pt}$


(kN)
twist (radians)
ϕ_2
ϕ_4
$\phi_{2\text{-}1/4pt}$
$\phi_{4\text{-}1/4pt}$



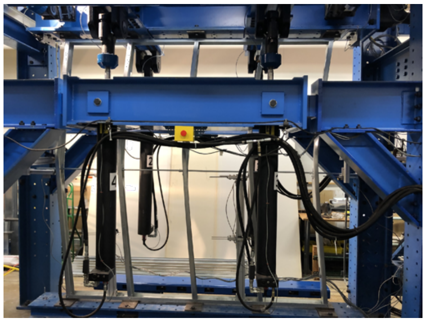
AS-4

isometric (typ.)



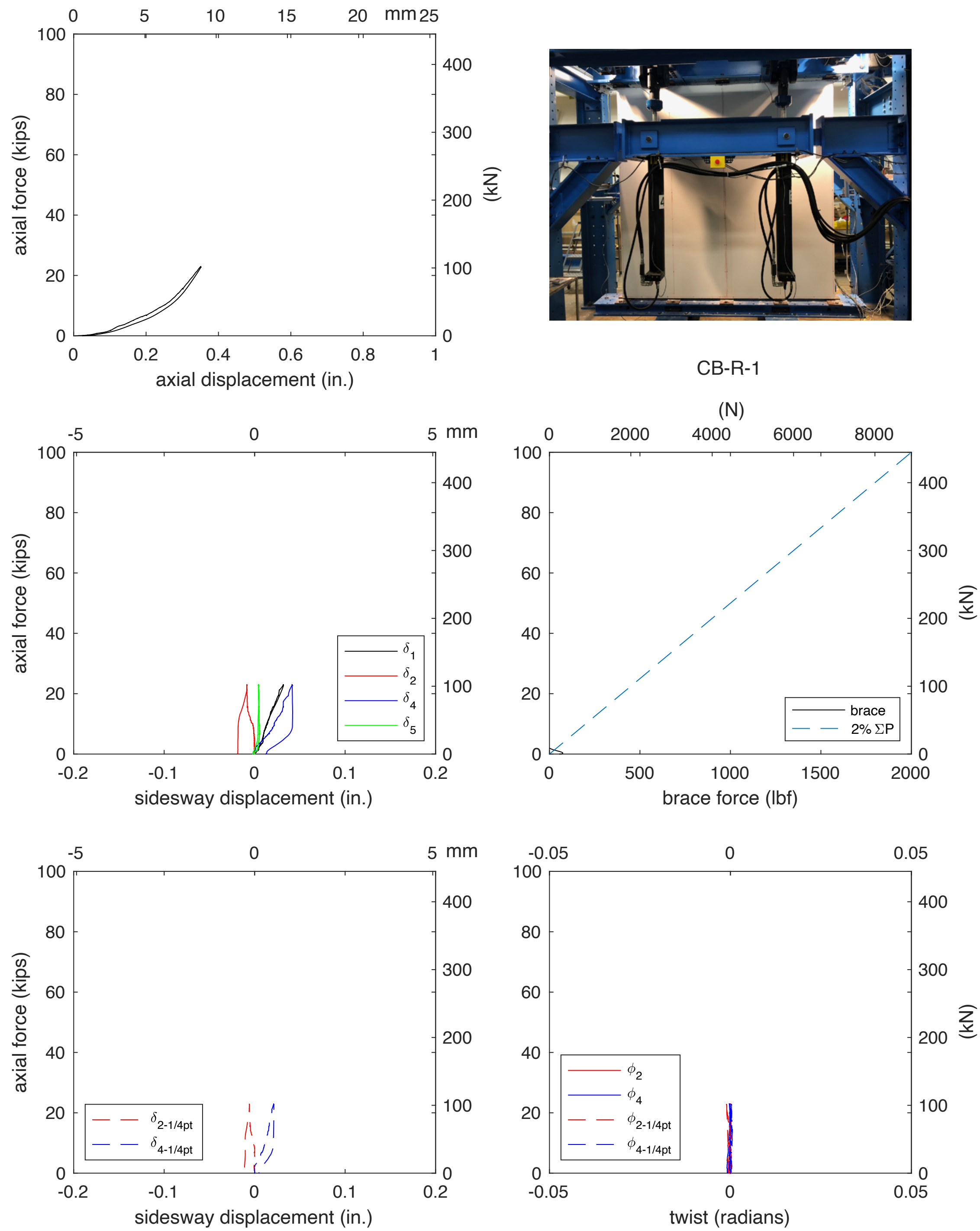
bridging connection

FTB at Stud 4(first)

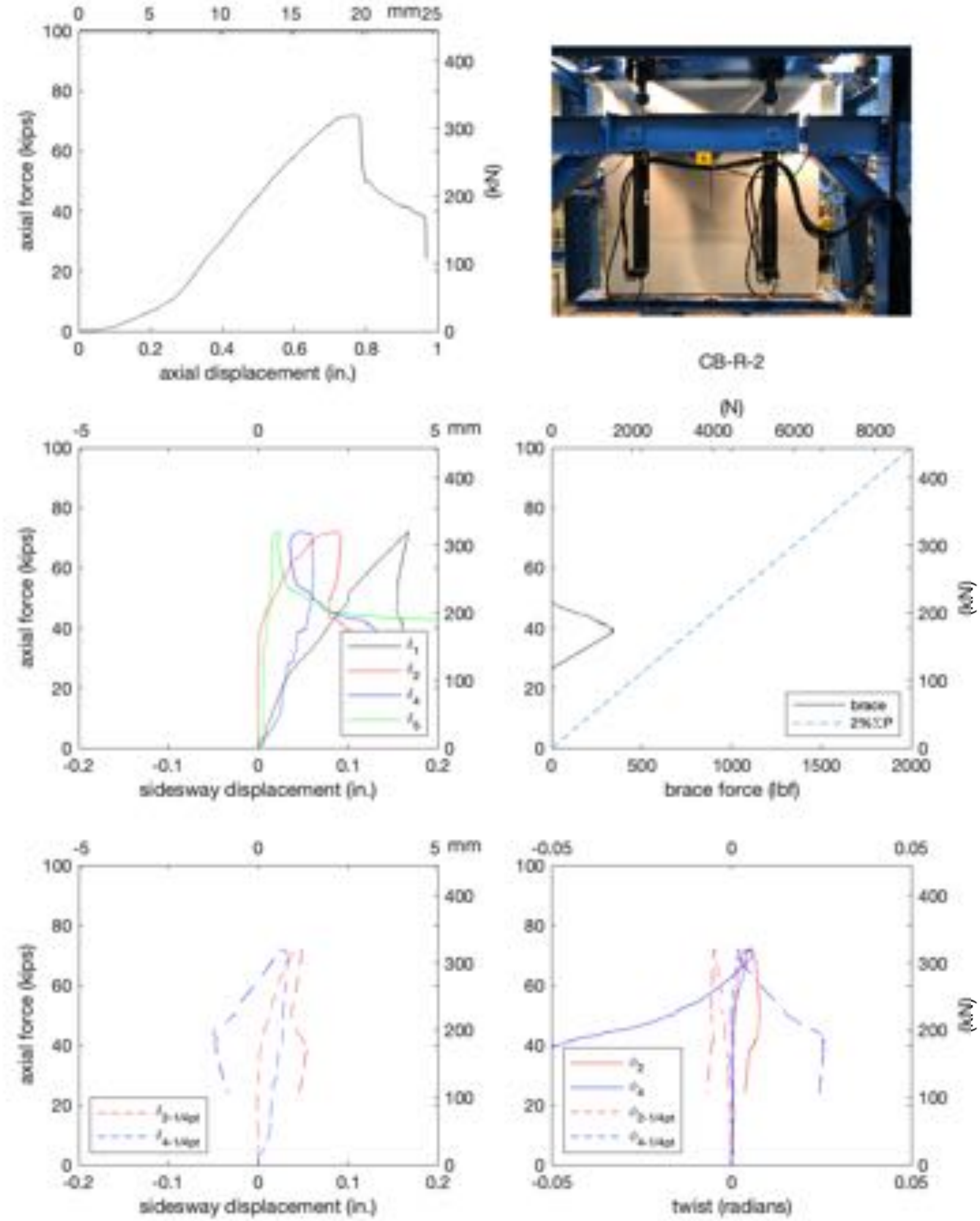


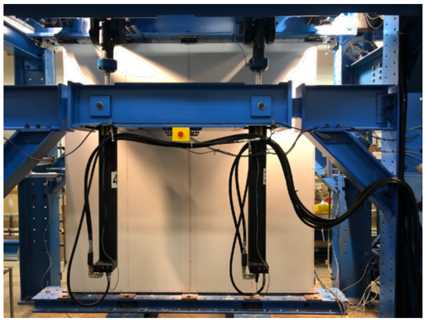
plan(post), FB-minor also observed

isometric(post), FTB 2nd mode



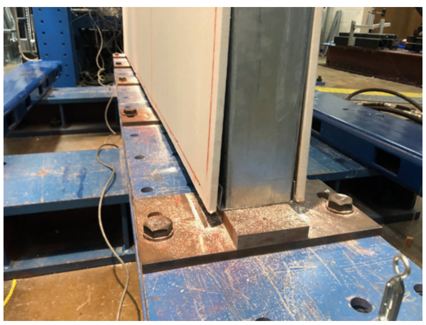
CB-R-1
axial force (kips)
(kN)
mm
axial displacement (in.)
sidesway displacement (in.)
δ_1
δ_2
δ_4
δ_5
(N)
brace
2% ΣP
brace force (lbf)
$\delta_{2\text{-}1/4pt}$
$\delta_{4\text{-}1/4pt}$
ϕ_2
ϕ_4
$\phi_{2\text{-}1/4pt}$
$\phi_{4\text{-}1/4pt}$
twist (radians)


axial force (kips)
axial displacement (in.)
mm
(kN)
CB-R-2
sidesway displacement (in.)
brace force (lbf)
(N)
brace
twist (radians)

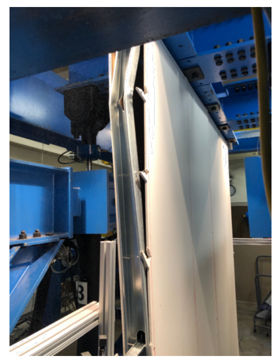


CB-R-2

isometric (typ.)

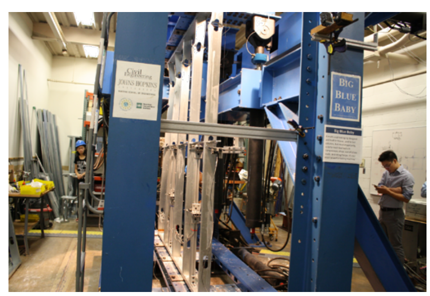


bottom corner of wall

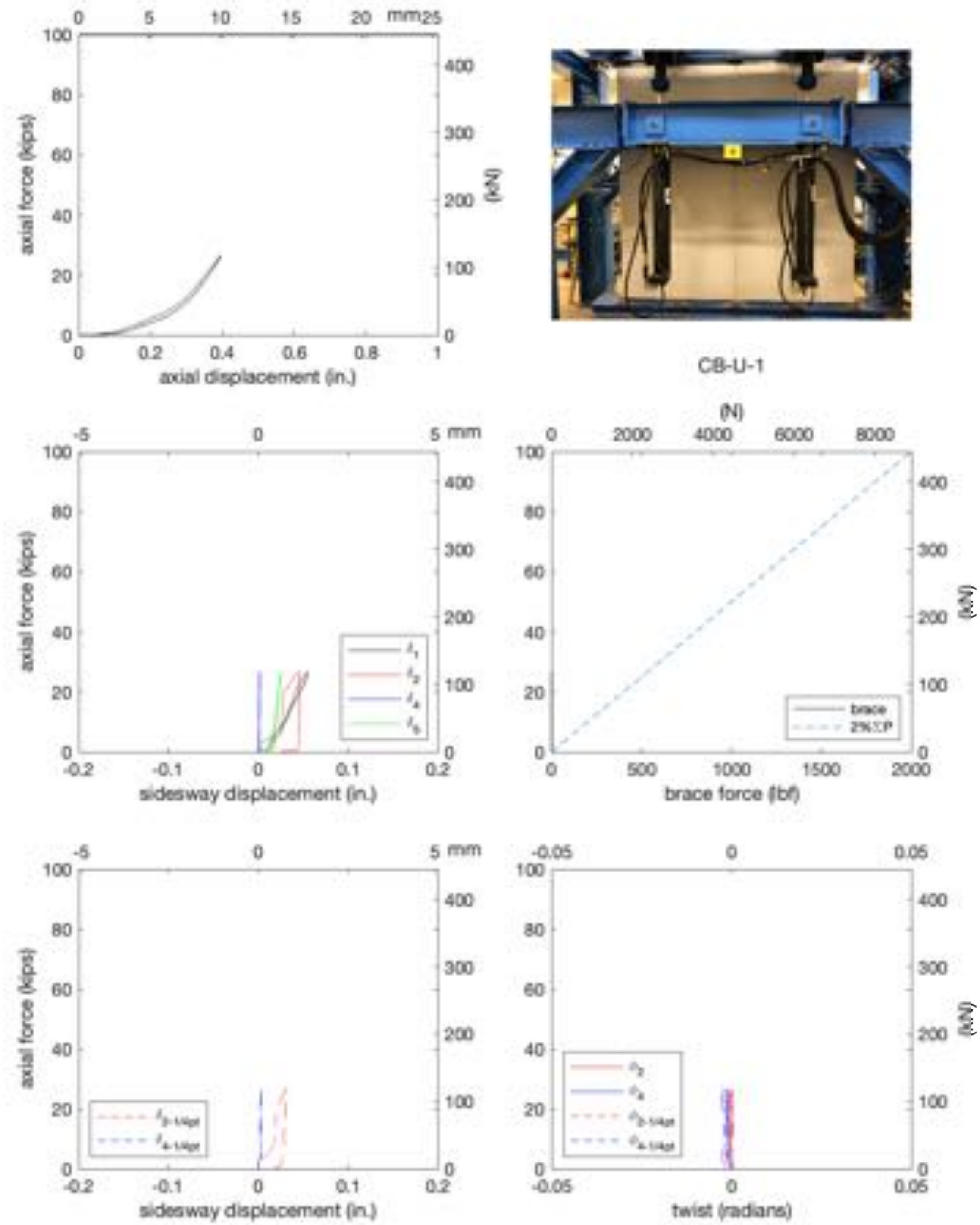


LB at upper hole(first)

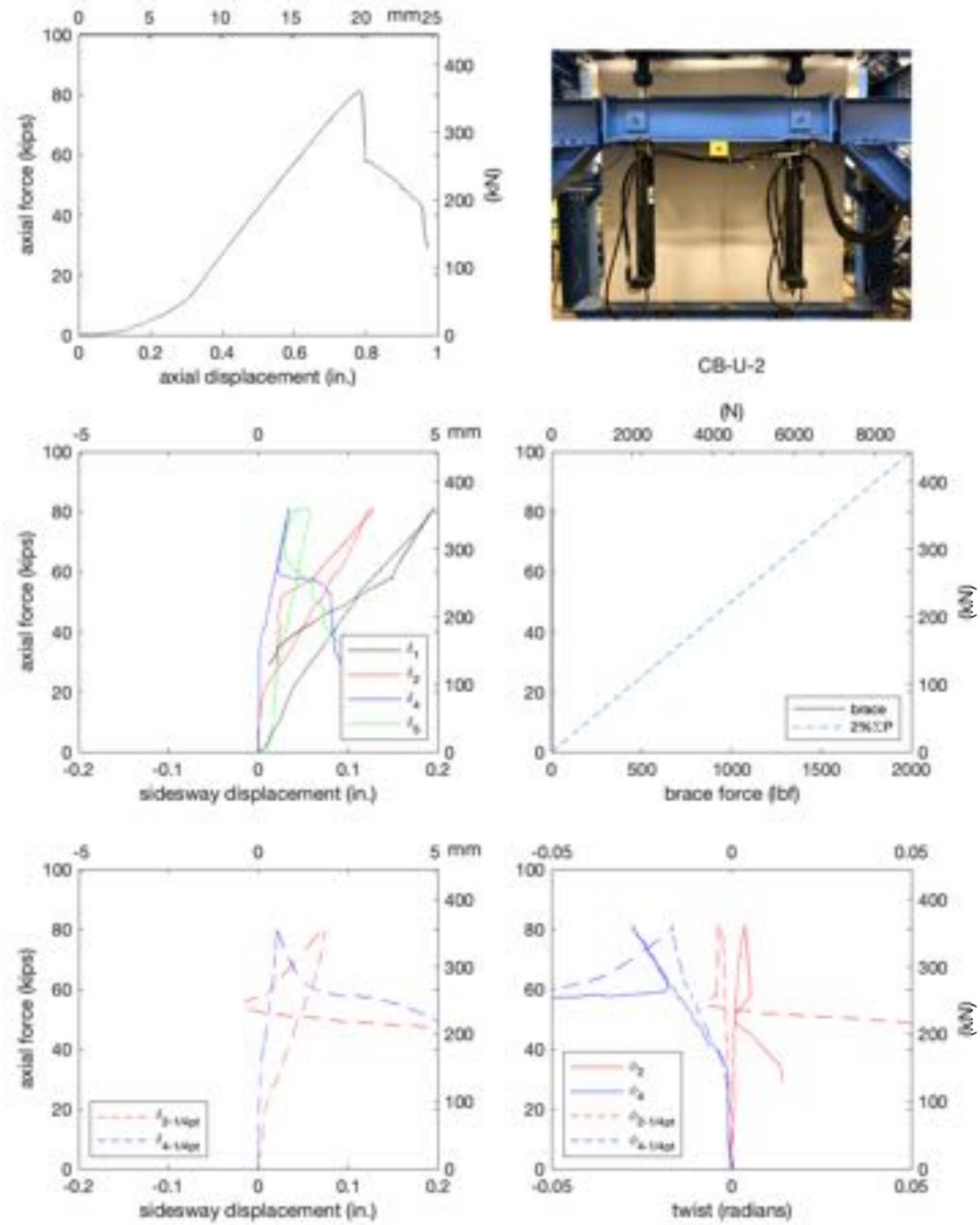
LB at upper hole

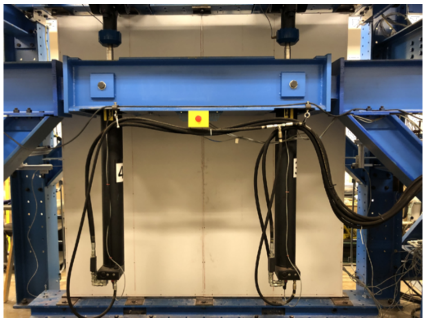


isometric(post), FB-minor follows LB

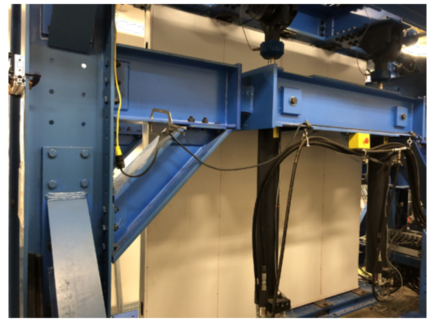

axial force (kips)
axial displacement (in.)
mm
(kN)
sidesway displacement (in.)
brace force (lbf)
(N)
brace
2%ΣP
twist (radians)

CB-U-1


axial force (kips)
axial displacement (in.)
mm
(kN)
CB-U-2
(N)
sidesway displacement (in.)
brace force (lbf)
brace
2%ΣP
twist (radians)



CB-U-2



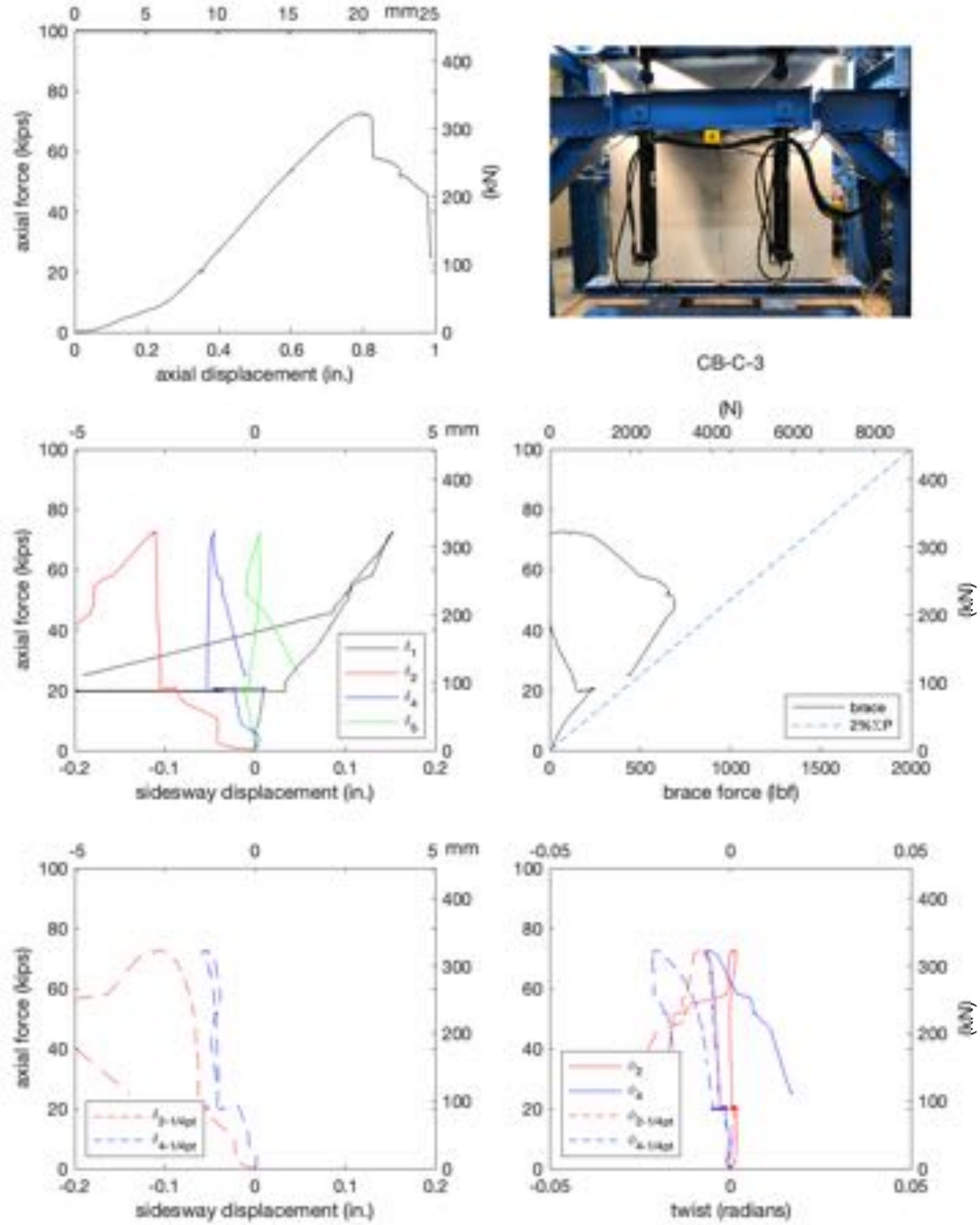
isometric (typ.)

bottom track is longer than 96 in.

LB at hole(first)

plan(post), edge TO of gyp

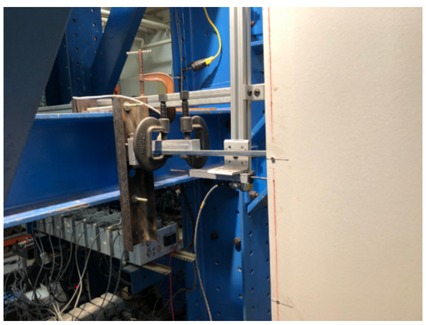
isometric(post), FB-minor follows LB


axial force (kips)
axial displacement (in.)
(kN)
mm
sidesway displacement (in.)
brace force (lbf)
(N)
brace
2%ΣP
twist (radians)

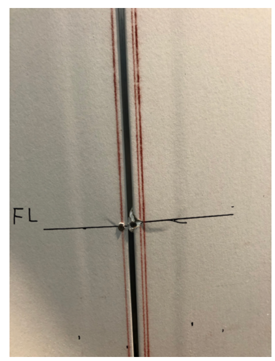
CB-C-3

CB-C-3

isometric (typ.)



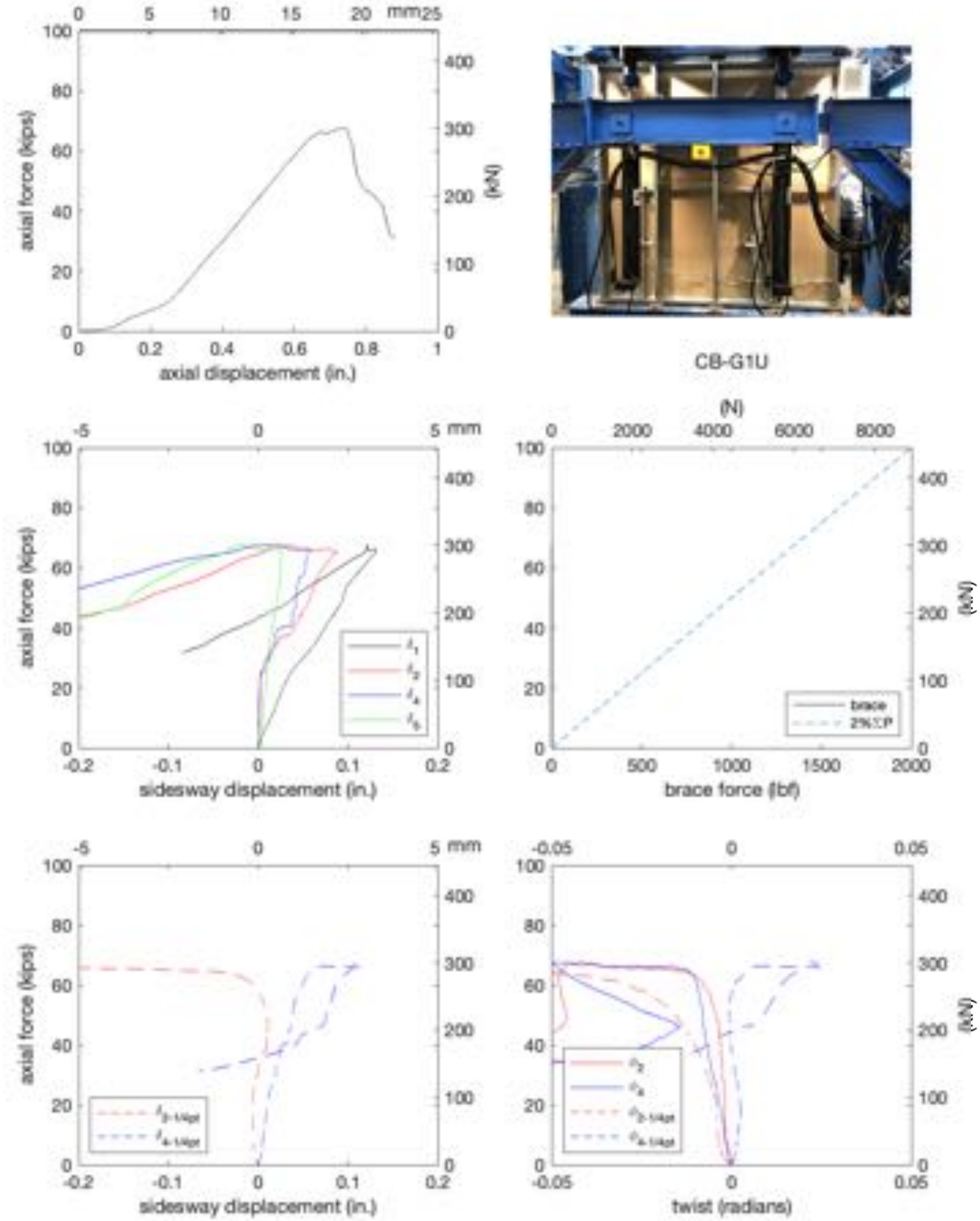
bridging connection

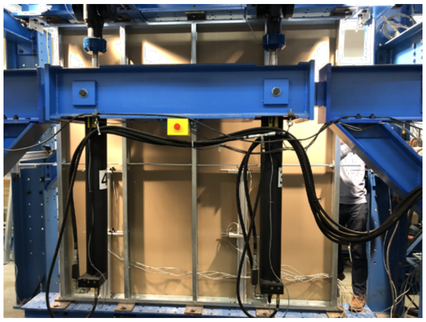


Gyp TO at Mid-Bottom Hole(first)

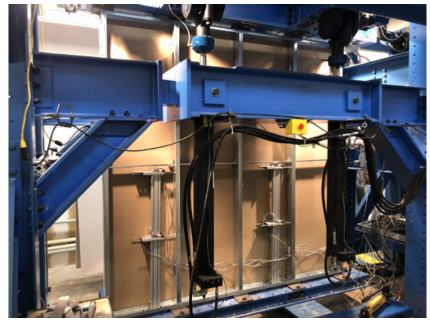
LB at upper hole(first)

isometric(post) GB after LB

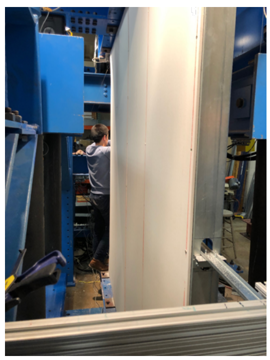

axial force (kips)
axial displacement (in.)
mm
(kN)
CB-G1U
sidesway displacement (in.)
brace force (lbf)
(N)
brace
2%ΣP
twist (radians)



CB-G1U



isometric (typ.)



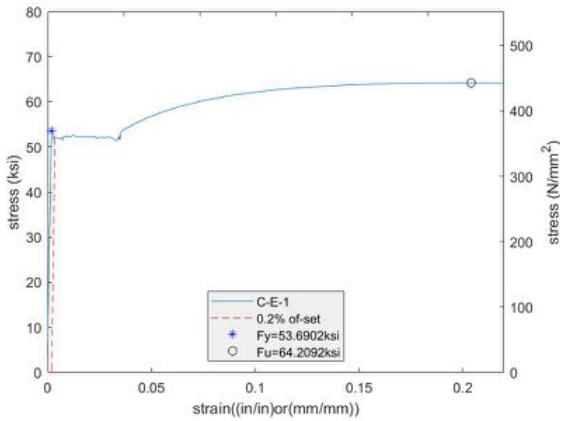
isometric (another side)

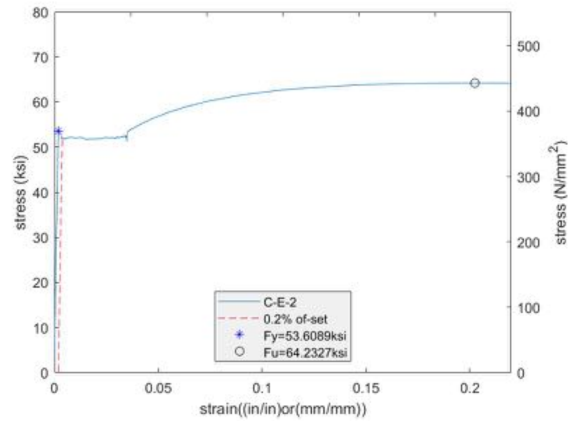
TB (first)

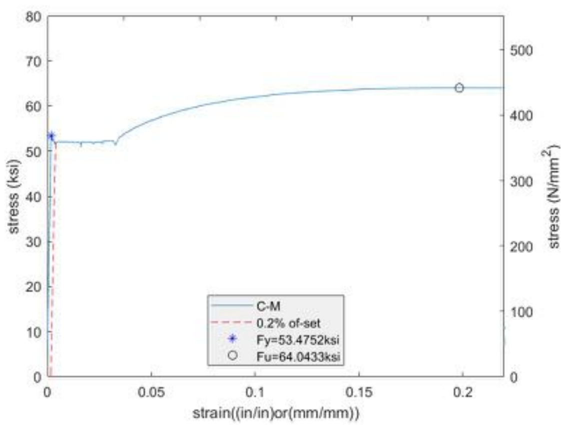
LB after TB

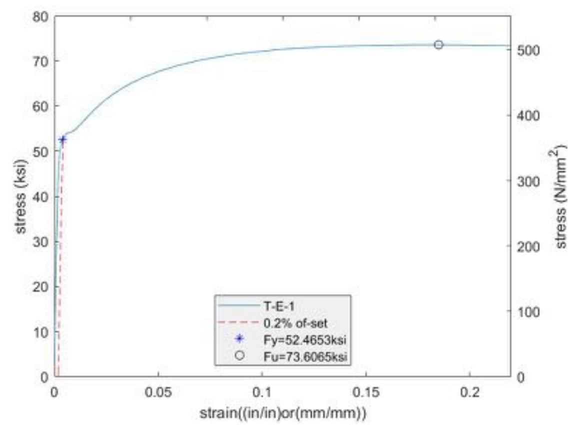
DB after TB

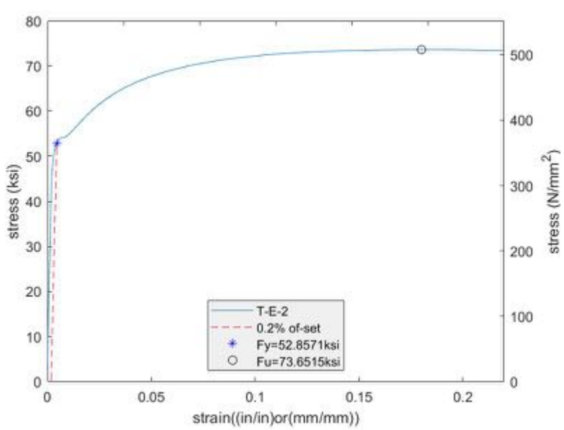
Appendix 3: Coupon Test Result

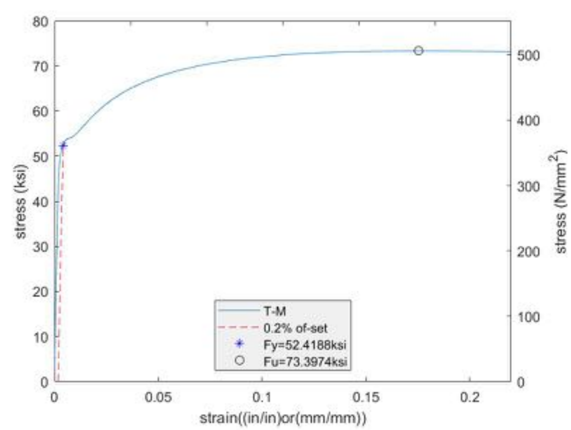


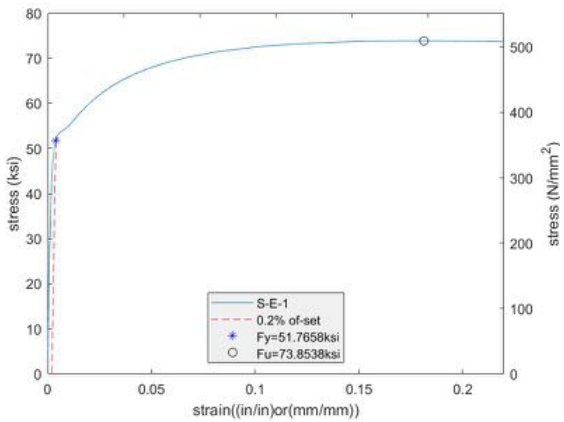


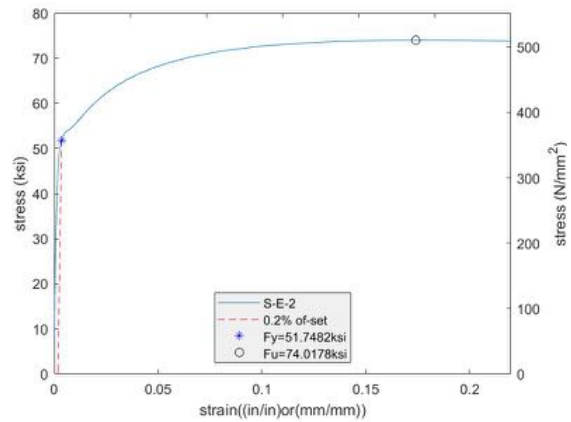


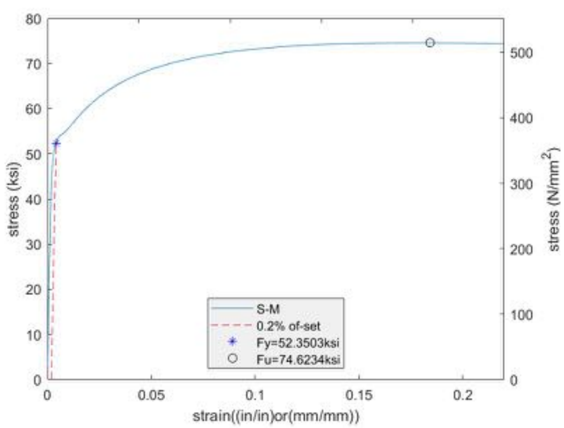







S-E-1
0.2% of-set
Fy=51.7658ksi
Fu=73.8538ksi
stress (ksi)
stress (N/mm^2)
strain((in/in)or(mm/mm))


S-E-2
0.2% of-set
Fy=51.7482ksi
Fu=74.0178ksi
stress (ksi)
stress (N/mm^2)
strain((in/in)or(mm/mm))


S-M
0.2% of-set
Fy=52.3503ksi
Fu=74.6234ksi
stress (ksi)
stress (N/mm^2)
strain((in/in)or(mm/mm))