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Perry S. Green

Thomas Sputo

Viswanath Urala

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Bracing Strength and Stiffness Requirements for Axially Loaded Lipped Cee Studs

Perry S. Green[1], Thomas Sputo[2], and Viswanath Urala[3]

Abstract

An experimental testing program has been carried out on axially loaded cold-formed lipped cee-studs to determine their required flexural and torsional bracing strength and stiffness demand. The stud sizes ranged from 362S-125-33 mil to 800S-162-97 mil. Conventional bridging or nodal bracing has been simulated in the experiments using steel wires attached to the stud flanges at mid-height. A range of brace stiffness from less than 30 to greater than 4000 lbs/in. was simulated in the testing frame by using various diameters and lengths of wire. Brace strength was determined from the cross-sectional area of the steel wire and it's experimentally determined yield strength. The axial load, individual brace forces, axial shortening, and in-plane (weak-axis) and out-of-plane (strong-axis) lateral displacements were measured in each test. The required bracing stiffness was experimentally determined by varying the brace stiffness for a given stud size and was based on the ability of the stud to develop it's nominal axial compressive capacity as predicted by the 1996 AISI Cold-Formed Steel Specification (including 1999 supplement). The experimental results were compared to existing nodal bracing models, analytical prediction models, and the current column bracing provisions that are part of the 1999 AISC-LRFD Specification for Structural Steel Buildings.

[1]Assistant Professor, [2]Lecturer, and [3]Graduate Research Assistant, Dept of Civil and Coastal Eng., University of Florida, Gainesville, FL, USA

Introduction

Cold-formed steel studs have been widely used in structural and non-structural wall construction for more than 25 years, and can be found in residential commercial and industrial facilities. Their lighter weight makes them easier and more economical to mass-produce, transport and install than other building systems. Other advantages include resistance to pest attack, reduction in formwork, faster construction etc. Recently, there has been a drive to create more cost effective cold-formed steel (CFS) structural systems, and this current move to design axially loaded wall stud systems using an 'all-steel' approach, as an option to a sheathing braced approach, has led to the design and creation of wall stud systems which may be more sensitive to global stability limit states than previous designs. Ensuring global stability of axially loaded steel studs requires that the bracing system possess adequate strength and stiffness to allow them to develop their predicted axial strength.

Objectives of Research

In the current AISC-LRFD Specification (AISC 1999) nodal bracing strength and stiffness requirements have been prescribed based on a model developed by Winter (1960) and modified by Yura (1995). Whereas the most recent cold-formed steel design specification, the North American Specification (AISI 2001), does not contain any provisions for determining the nodal brace strength and stiffness requirements for axially loaded compression members. This research program was conducted to experimentally determine rational requirements for nodal bracing of lipped cee-studs subjected to axial compression and to formulate specification provisions that can be used for design purposes.

The main objectives of this research included: 1) Determine the minimum bracing strength and stiffness required for CFS members subjected to axial loading; 2) Predict the limit state or the governing buckling mode of CFS axial compression members; 3) Determine the effect of support fixity on global buckling of CFS axial compression members; 4) Evaluate the effect of slenderness ratio on the buckling behavior of the CFS members; and 5) Evaluate effective length factors based on unbraced length.

The strength and stiffness for bracing hot-rolled steel sections has been investigated by numerous researchers, which are based on physical experiments, analytical studies and practical design considerations. Research has been conducted on the buckling phenomena of cold-formed steel subjected to axial compression. This research has been directed towards establishing the strength and stiffness requirements of the bracing and bridging of CFS members.

Scope of Research

The scope of this research is limited to determining the strength and stiffness requirements for CFS lipped cee-studs subjected to axial compression. The studs were tested in a manner consistent with a typical field installation to determine their axial load capacity. With this as basis, the scope of the single column axial tests is described.

1. Standard lipped cee-studs that are widely used in structural and non-structural wall assemblies were tested. The section nominal web depths were 3.625, 6.00 and 8.00 in., the nominal thicknesses were 33, 43, 68 and 97 mil. The 33 mil studs had a flange width of 1.25 in. while the other studs had a flange width of 1.625 in.

2. The lipped cee-studs were mounted in industry standard tracks and attached with self-drilling screws. The length of each stud was 8'-0" for all the single axial column tests.

3. The number of nodal brace points was limited to one placed at the mid-height of the lipped cee-stud.

4. The support fixity was limited to a shallow track 1.25 in. deep, 12 in. long loosely held at each end with two bolts attached to a steel base plate; the stud being attached to the track with two self-drilling screws, one in each flange.

Background

While considerable effort has been directed at the problem of bracing hot-rolled structural steel columns, little published information exists specifically addressing the bracing requirements for CFS columns. Miller (1990) conducted a series of tests on CFS cee studs at Cornell University. Long column tests with lengths of 4' - 0" and 8' - 0" were performed on studs with depths of 3-5/8 and 6 inches. Load was applied to the studs both concentrically and eccentrically with the end conditions being either pin-ended or fixed. Several of the studs were tested with one or more perforations in the web. Geometric imperfections were measured and considered when comparing experimental results to analytical results. No bridging or bracing was installed as part of the test set-up.

Additionally, Miller conducted wall assembly axial tests on members with lengths of 4' - 0" and 8' - 0", spaced (typically) at 24 inches center-to-center and having depths of 3-5/8 and 6 inches. Bracing was applied to the wall members in one of three forms: continuous flat straps screwed to both flanges, continuous channel bridging installed through web perforations and gypsum sheathing screwed to one of the flanges of the members. As in the long column tests, end conditions of the studs were either pin-ended or fixed. Miller noted that the use of flat strap bracing and channel bridging resulted in similar ultimate axial loads and that the presence of mid-height bridging increased ultimate loads by at least 25% for 6 in. members and by at least 60% for 3-5/8 in. members.

Winter (1960) published the results of simple analytical models to calculate the required bracing stiffness and strength for both axially and flexurally loaded members. For an axially loaded column, a brace placed at mid-height can increase its axial load capacity only if the brace is stiff enough to restrain the column from displacing laterally and/or twisting (i.e. buckling). The minimum stiffness required for a lateral brace to effectively brace a member is defined as the ideal stiffness. If an axial member has an initial out-of-straightness (geometric imperfection), the required strength of the lateral brace increases with the magnitude of the imperfection, but the stiffness demand does not likewise increase. Winter calculated the ideal nodal brace stiffness for an axially loaded column to be

$$\beta_{ideal} = \frac{[4 - 2/n]P_n}{L_b} \tag{1}$$

and the required brace strength, assuming an initial out-of-straightness of L/500 to be

$$P_{brace} = 0.04\ P_n \tag{2}$$

where: β_{ideal} = Minimum required brace stiffness
L_b = Unbraced stud length
n = Number of equally spaced intermediate brace locations
P_{brace} = Minimum required brace strength

P_n = Nominal axial capacity when the assumed brace stiffness is greater than or equal to β_{ideal}

Experimental Program

For the purposes of this study, each tested stud was identified using a modified Steel Stud Manufacturers Association (SSMA) nomenclature:

DDD S FFF-TT-KKKK

where: DDD = Stud depth (362=3.62"; 600=6.00"; 800=8.00")
S = Lipped stud section
FFF = Flange width (125=1.25"; 162=1.62")
TT = Nominal steel thickness (mils; 1 mil=0.001")
KKKK = Axial stiffness of one brace wire in pounds per inch

The axial stiffness of a bracing wire was calculated as follows:

$$K = \frac{AE}{L} \tag{3}$$

where: A = Cross-sectional area of wire
E = Modulus of Elasticity of wire (29,000,000 psi)
L = Length of brace wire

Initial geometric imperfection measurements were taken on the majority of the axial test specimens. Measured camber was negligible in all the specimens except for the 600S162-43 series where it ranged from 0.0 to a maximum of 0.065 inches, or L/1500. The sweep measurements were more significant as these could directly influence the axial behavior of the cee studs during testing. The measured sweep ranged from 0.0 to 0.04 inches, or L/2400 for the 362S162-43 and 600S162-43 series; from 0.0 to 0.075 inches, or L/1300 for the 600S162-97 series; and from 0.0 to 0.14 inches, or L/700 for the 362S162-68 series. No geometric measurements were made of the 800S162-97 series studs.

The studs were axially loaded under displacement control using a mechanically driven Riehle Universal Testing Machine. Fig. 1 shows a plan view of a stud mounted in the testing machine. The figure also shows an adjustable frame attached to the testing machine that was used to hold the lateral/torsional bracing system in place. Bracing was modeled using high-strength steel wires of varying diameters and lengths. As indicated in the figure, the wires were attached to the corners of the flanges of the test specimens using #10 screws. The brace wires terminated at 250 pound capacity S-Beam load cells, which were used to measure the tension force in the brace wires during testing. Fig. 2 is a close-up of the stud cross-section and at mid-height shows the attachment points of the bracing wires and their corresponding Load Cells: A-NE BRACE (BF-1), B-SE BRACE (BF-2), C-NW BRACE (BF-3), and D-SW BRACE (BF-4).

The minor axis lateral displacement of the stud was measured by a complementary set of four linear potentiometers (LP-1,-2,-3,-4) positioned directly adjacent to the individual braces that made up the bracing system. The major axis lateral displacement was measured by a single linear potentiometer (LP-5) located along the minor axis attached to the south face of the stud, also at mid-height. Axial shortening of the stud was measured along the north face of the test specimen parallel to the longitudinal axis of the stud (LP-6).

To simulate actual field installation conditions, each stud was mounted in standard 43 mil (18 gage), 1-1/4" leg track. Fig. 3 shows a typical stud attached to track with a single #10 self-drilling screw on each flange. The track was then mounted to end bearing plates with two 0.150" diameter bolts to simulate attachment to concrete supports using 0.144" diameter drive pins. Fig. 3a shows the stud attached to the top end bearing plate being held in position against the movable cross-head of the testing machine. Fig. 3b shows the stud attached to the bottom end bearing plate that sits just above another plate holding a 150 kip axial load cell in place and resting on the fixed platen of the UTM. Fig. 4 shows how the bracing wires and instrumentation are attached to the stud at mid-height.

Experimental Results and Evaluation

Thirty-seven 8'-0" long single column axial load tests were conducted based on the following parameters:

- Cross-sections - 362S125-33, 362S162-43, 362S162-68
  - 600S125-33, 600S162-43, 600S162-97
  - 800S162-43, 800S162-97
- Unbraced Test Specimens versus Braced Test Specimens
- Bracing Stiffness
  - Under-Braced – less than ideal bracing
  - Ideally-Braced – equal to ideal bracing
  - Over-Braced – greater than ideal bracing

Table 1 gives the actual test matrix of the single column axially loaded cee-stud specimens. The table lists stud designation and number of studs tested with: a provided brace stiffness less than, approximately equal to, approximately equal to twice, and greater than twice β_{ideal}. The table also shows the series, 1 thru 8, that the studs were grouped.

Bracing Strength and Stiffness

The AISIWIN V5.0 program (AISIWIN 2002) was used to determine the axial capacities of each of the stud groups based on the average as-built properties of the eight groups of test specimens, using appropriate values of material yield and ultimate stress from tension coupon tests and measured geometric dimensions. Table 2 gives the coupon results, as-built cross-sectional areas, and as-built ultimate and unfactored capacities of each of the stud groups. The required ideal brace stiffness, for single nodal bracing (n=1), was then calculated (and provided in the table) as recommended by Yura (1995), where the unbraced length of the column was taken as the distance between the support and the point of bracing (L_b = 48.0 inches). At least one stud in each of the series was tested without bracing to provide baseline data to be used for comparison against the other test specimens in the same series where only the brace stiffness was changed.

Evaluation of Experimental Observations

Table 3 summarizes the experimental test results. The data provided in the table includes the stud designation, brace stiffness, calculated and experimental axial load capacity, as well as the observed failure mode of each of the cold-formed steel cee studs with or without mid-height lateral bracing. It can be observed that the maximum experimental loads were generally higher than the predicted capacities from AISIWIN (2002). This is because the AISIWIN program considers a perfect pin-ended support condition for both flexural and torsional buckling. The cee-studs were seated in standard track at both ends that provided end-conditions in the experimental investigation of partial fixity in weak axis flexural buckling and near full fixity in both strong axis flexural buckling and torsional buckling. These end restraints led to higher axial load capacities for the studs that failed by global buckling, i.e. flexural, flexural-torsional or torsional buckling.

The 600S125-33 and 600S 162-43 series of studs failed by distortional buckling at axial loads lower than were predicted by AISIWIN for a perfectly pin-ended stud. This necessitates the consideration of the distortional buckling as a controlling and critical limit state. The AISIWIN program does not consider a distortional buckling limit state while predicting the axial capacity of cold-formed lipped cee studs.

The labels used to identify the failure modes in Table 3 are $F^{[1]}$, $F^{[2]}$, $T^{[1]}$, $T^{[2]}$, $F^{[1]}T^{[1]}$, $F^{[1]}T^{[2]}$, $T^{[1]}F^{[1]}$, and $T^{[2]}F^{[1]}$ which descriptively mean first mode flexure, second mode flexure, first mode torsion, second mode torsion, first mode flexure with first mode torsion, first mode flexure with second mode torsion, first mode torsion with first mode flexure, and second mode torsion with first mode flexure, respectively. Fig. 5 qualitatively depicts the final lateral movements of various cross-sections along the length of a stud that correspond to the observed failure mode descriptors given above. The only other observed failure mode was a Distortional type failure that is not depicted in the figure.

The enhancement in the predicted load carrying capacity of the studs is directly related to the type of buckling failure that occurred. The percentage increase in the experimental load for the braced studs compared to its unbraced stud within the same series is also given in Table 3. The braced studs of the 362S125-33 series attained nearly 140% more than its unbraced stud, and the buckling was mainly global second mode flexural-torsional buckling. The braced studs of the 362S162-43 and 362S162-68 series showed an increase of about 35% and 115%, respectively. Though the 600S125-33 and 600S162-43 series studs failed by distortional buckling, they exhibited an average increase of 87%, and 34%, respectively while the 600S162-97 series showed an average increase of about 38%. The 800S162-43 and -97 series studs showed only a slight enhancement as their experimental maximum capacities were in the range of the predicted axial capacities.

Effect of brace stiffness on axial load capacity

The axial load vs. axial shortening plots for each series of the studs show that there is a considerable enhancement in the load carrying capacity of the braced studs in comparison to its unbraced stud. The same plots also indicate that when the brace stiffness provided is greater than the ideal bracing requirement, the experimental maximum loads attained in each of the tests remained nearly constant. Figs. 6 and 7 for the 362S162-68 series and the 600S162-97 series studs, respectively confirm these findings. The figures show a dotted line which represents the initial elastic stiffness for the given series and was calculated using:

$$k = \frac{A_g E}{L} \tag{4}$$

where: A_g = Gross cross-sectional area of the cee-stud
E = Young's Modulus = 29,500,000 psi
L = Length of an unbraced stud = 8'-0"

Detailed descriptions of the behavior of all of the test specimens and their failure modes can be found in Green, Sputo and Urala (2004). The report contains information on:

- Effect of brace stiffness on buckling type and mode;
- Effect of cross-sectional dimensions of cee-studs;
- Effect of brace stiffness on lateral displacement;
- Effect of brace stiffness on effective length of columns;
- Effect of brace strength (yielding brace) on axial capacity; and
- Other effects including geometric imperfections, mechanical properties of the stud material, track resistance and bearing ends of the stud.

Effect of experimental load on the brace stiffness and strength

As previously discussed, most of the unbraced studs failed at loads higher than the capacities predicted by the AISIWIN (2002) program. The higher capacities for the studs necessitate recalculating the ideal brace stiffness as per Yura (1995). Table 4 gives the required ideal brace stiffness based on these higher load capacities of the unbraced studs. The higher load capacity would require a higher demand on the lateral bracing as given in Table 4. This higher demand on the bracing stiffness renders some of the braced cee-studs to fall into the category of under-braced cee-studs since the provided brace stiffness is now less than the new ideal bracing requirement. The bracing strength however is satisfactory since the brace wires were capable of carrying the increased brace force.

The total measured brace forces and the corresponding weak axis lateral displacements at the maximum axial load for all the studs are tabulated in Table 5. It is observed that the calculated brace forces based on the measured displacements are higher than the corresponding values of the measured brace forces given in Table 5. This is because of the initial seating and possible slippage of the brace wires at the loops. Yura (1995) had proposed that the required brace strength to be 2.0% of the nominal axial capacity of the column. Table 5 gives the measured brace forces as a percentage of the maximum axial load. It is observed that the percentage of measured brace forces ranges from as low as 0.08% to as high as 1.34% of the tested axial capacity of the cee-studs.

Enhancement in the axial load carrying capacity of the cee-studs with an increase in the bracing stiffness can be seen in Fig. 8 for the 362, 600 and 800 series studs. The figure shows that there is a significant increase in axial capacity of the stud once it is braced, but that increasing the brace stiffness beyond that required to adequately brace the cee-stud only provides a slight increase in additional axial capacity.

Conclusions

Thirty-seven cold-formed steel lipped cee stud sections were loaded in axial compression to determine their maximum load carrying capacity, examine their deformation characteristics throughout the entire axial load-axial shortening history, report on the affects of varying the bracing stiffness on the axial strength of lipped cee studs, and determine the required strength of the bracing to achieve the measured results.

The following general observations are made from the testing:

- The field installation end conditions have significant impact on the long-wave buckling capacity of a stud. The stud mounted in a standard track assembly provides some degree of weak axis flexural restraint, and a significant degree of strong axis and torsional restraint. The strong axis and torsional restraint provided by the track connection approaches that of a fixed end condition. Ultimate capacities far in excess of those predicted by the usual stud design assumption of a pin-ended conditions were obtained.

- Torsional and/or flexural bracing stiffness has very little influence on the load carrying capacity of the compression member if distortional buckling of the cross-section is the controlling strength limit state. The bracing system only needs to be stiff and strong enough to develop the distortional buckling strength limit state.

- Global geometric imperfections have an observable influence on the behavior of the stud. Larger imperfections result in greater lateral deflections and higher brace forces, but have little influence on the ultimate load carrying capacity. This observation verifies the analytical predictions of Winter (1960).

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Table 1 Actual Test Matrix of the Single Column Axial Load Tests

Series	Stud Designation				Unbraced Studs	Total Bracing Stiffness of Braced Studs			
	D	S	B	t		$< \beta_{ideal}$	$\sim \beta_{ideal}$	$\sim 2\ \beta_{ideal}$	$> 2\ \beta_{ideal}$
1	362	S	125	33	1	0	1	2	2
2	362	S	162	43	1	0	1	1	1
3	362	S	162	68	1	0	0	1	2
4	600	S	125	33	1	1	1	0	1
5	600	S	162	43	2	2	0	1	1
6	600	S	162	97	1	2	0	1	1
7	800	S	162	43	1	1	1	1	0
8	800	S	162	97	1	0	1	1	1

Table 2 Average As-built Properties of the Test Specimens Using AISIWIN Program

Stud Designation				Tension Coupon Test Results		AISIWIN					Required Ideal Brace Stiffness
				Yield Stress	Ult. Stress	As-Built Section Area	As-Built Ultimate Capacity (P_u)		As-Built Unfactored Capacity (P_n)		
				F_y	F_u		Unbraced	Mid-Point Brace	No Brace	Mid-Point Brace	β_{ideal}
D	S	B	t	ksi	ksi	in^2	lbs	lbs	lbs	lbs	lb/in.
362	S	125	33	48.53	55.48	0.2028	704	1978	828	2327	97
362	S	162	43	47.04	58.20	0.3089	1688	4411	1986	5189	216
362	S	162	68	52.01	67.80	0.5154	3515	8448	4135	9939	414
600	S	125	33	24.03	45.24	0.2537	592	1548	696	1821	76
600	S	162	43	46.24	54.88	0.4135	2156	5832	2536	6861	286
600	S	162	43a	50.30	59.38	0.4346	2465	6721	2900	7907	329
600	S	162	97	60.20	70.21	0.9807	6277	19888	7385	23398	975
800	S	162	43	40.23	54.90	0.4829	1967	5180	2314	6094	254
800	S	162	97	42.50	67.49	1.1843	6686	17989	7866	21164	882

AISIWIN program was used to calculate the As-Built values of the test specimens
Ideal Brace Stiffness was obtained using Yura's Bracing Equation 2.14 (Yura 1995)
Design factor used in calculating the Unfactored Capacity is 0.85

Table 3 Summary of Experimental Test Results for Test Specimens

Stud Designation					Target Brace Stiffness	Axial Capacity			Observed Failure Mode	Percentage Increase in P_{max} of Braced Studs over Unbraced Studs
						Analytical		Experimental Load		
						No Brace	Mid-Pt Brace			
D		B	t	ID	lbs/in.	P_n (lbs)	P_n (lbs)	P_{max} (lbs)		%
362	S	125	33	5	0	828	-	1127	F[1] - T[1]	0.00
362	S	125	33	3	100	-	2327	2749	F[2] - T[2]	143.80
362	S	125	33	4	100	-	2327	2306	F[2] - T[2]	104.51
362	S	125	33	6	100		2327	2399	Distortional	112.79
362	S	125	33	1	200	-	2327	3012	F[2]	167.17
362	S	125	33	2	400	-	2327	2959	F[2] - T[2]	162.47
362	S	162	43	1	0	1986	-	5223	T[1] - F[1]	0.00
362	S	162	43	2	200	-	5189	7268	F[1] - T[2]	39.15
362	S	162	43	4	400	-	5189	7029	F[1] - T[2]	34.58
362	S	162	43	3	800	-	5189	6557	T[2]	25.54
362	S	162	68	5	0	4135	-	6451	F[1] - T[1]	0.00
362	S	162	68	3	500	-	10409	13384	T[1] - F[1]	107.47
362	S	162	68	4	750	-	10409	14029	T[2]	117.47
362	S	162	68	2	1000	-	10409	14792	T[2]	129.30
600	S	125	33	2	0	696	-	984	Distortional	0.00
600	S	125	33	4	30	-	1821	1951	F[1]	98.27
600	S	125	33	3	60	-	1821	2271	Distortional	130.79
600	S	125	33	1	200	-	1821	1302	Distortional	32.32
600	S	162	43	6	0	2536	-	5144	Distortional	0.00
600	S	162	43	6a	0	2900	-	4258	F[1]	0.00
600	S	162	43	5	30	-	6861	7163	Distortional	39.25
600	S	162	43	2	75	-	6861	6052	Distortional	17.65
600	S	162	43	1	250	-	6861	7308	Distortional	42.07
600	S	162	43	4	500	-	6861	7075	Distortional	37.54
600	S	162	97	5	0	7385	-	21029	F[1]	0.00
600	S	162	97	4	160	-	23398	28306	F[1] - T[1]	34.60
600	S	162	97	3	500	-	23398	30085	F[1] - T[1]	43.06
600	S	162	97	1	1000	-	23398	28553	T[1]	35.78
600	S	162	97	2	1500	-	23398	29472	T[1]	40.15
800	S	162	43	4	0	2314	-	4591	F[1]	0.00
800	S	162	43	2	75	-	6094	4306	F[1]	-6.21
800	S	162	43	3	150	-	6094	5333	Distortional	16.16
800	S	162	43	5	300	-	6094	6213	F[2]	35.33
800	S	162	97	3	0	7866	-	19703	F[1]	0.00
800	S	162	97	2	500	-	21164	21626	Distortional	9.76
800	S	162	97	1	1000	-	21164	23811	Distortional	20.85
800	S	162	97	4	2100	-	21164	23537	T[1]	19.46

Table 4 Required Brace Stiffness based on P_{max}

Stud Designation					Total Brace Stiffness	Brace Factor	AISIWIN Unfactored Load	Experimental Load	Required Total Stiffness	Brace Factor
					$\beta_{provided}$	$\beta_{provided}$ / β_{ideal}	P_n	P_{max}	$\beta_{required}$	$\beta_{provided}$ / $\beta_{required}$
D	S	B	t	ID	lb/in.		lbs.	lbs	lb/in.	
362	S	125	33	5	Not Braced	-	828	1127	-	-
362	S	162	43	1	Not Braced	-	1986	5223	-	-
362	S	162	68	5	Not Braced	-	4135	6451	-	-
600	S	125	33	2	Not Braced	-	696	984	-	-
600	S	162	43	6	Not Braced	-	2988	5144	-	-
600	S	162	43	6a	Not Braced	-	2900	4258	-	-
600	S	162	97	5	Not Braced	-	7385	21029	-	-
800	S	162	43	4	Not Braced	-	2314	4591	-	-
800	S	162	97	3	Not Braced	-	7866	19703	-	-
600	S	125	33	4	61	0.8	1821	1951	81	0.7
600	S	162	43	5	61	0.2	6861	7163	298	0.2
600	S	162	43	2	148	0.5	6861	6052	252	0.6
600	S	162	97	4	324	0.3	23398	28306	1179	0.3
800	S	162	43	2	149	0.6	6094	4306	179	0.8
600	S	125	33	3	123	1.6	1821	2271	95	1.3
600	S	162	97	3	1041	1.1	23398	30085	1254	0.8
800	S	162	43	3	299	1.2	6094	5333	222	1.3
800	S	162	97	2	1041	1.2	21164	21626	901	1.2
362	S	125	33	3	192	2.0	2327	2749	115	1.7
362	S	125	33	4	192	2.0	2327	2306	96	2.0
362	S	125	33	6	201	1.9	2327	2399	100	2.0
362	S	162	43	2	371	1.7	5189	7268	303	1.2
362	S	162	68	3	1023	2.5	9939	13384	558	1.8
600	S	162	43	1	497	1.7	6861	7308	305	1.6
600	S	162	97	1	2069	2.1	23398	28553	1190	1.7
800	S	162	43	5	602	2.4	6094	6213	259	2.3
800	S	162	97	1	2093	2.4	21164	23811	992	2.1
362	S	125	33	1	413	4.3	2327	3012	126	3.3
362	S	125	33	2	765	7.9	2327	2959	123	6.2
362	S	162	43	4	734	3.4	5189	7029	293	2.5
362	S	162	43	3	1478	6.8	5189	6557	273	5.4
362	S	162	68	4	1538	3.7	9939	14029	585	2.6
362	S	162	68	2	2046	4.9	9939	14792	616	3.3
600	S	125	33	1	402	5.3	1821	1302	54	7.4
600	S	162	43	4	990	3.5	6861	7075	295	3.4
600	S	162	97	2	3357	3.4	23398	29472	1228	2.7
800	S	162	97	4	4195	4.8	21164	23537	981	4.3

Table 5 Measured Values of Brace Force and Mid-height Displacement at P_{max}

Stud Designation					Target Brace Stiffness	Experimental Load	Measured Initial Bow	Measured Values at P_{max}				P_{br} as Percentage of P_{max}
								Brace Force	Weak Axis Displacement, Δ_W			
						P_{max}		P_{br}	N-Flange	S-Flange	Average	
D	S	B	t	ID	lbs/in.	lbs.	in.	lbs.	in.	in.	in.	%
362	S	125	33	5	0	1127	0.000	-	0.4065	0.8289	0.618	-
362	S	125	33	3	100	2749	0.000	9.55	0.0835	0.0661	0.075	0.35
362	S	125	33	4	100	2306	0.000	22.41	0.1577	0.0006	0.079	0.97
362	S	125	33	6	100	2399	0.000	14.47	0.0099	0.1561	0.083	0.60
362	S	125	33	1	200	3012	0.000	10.55	0.0173	0.0451	0.031	0.35
362	S	125	33	2	400	2959	0.000	32.43	0.0906	0.1925	0.142	1.10
362	S	162	43	1	0	5223	0.000	-	0.8281	0.0845	0.456	-
362	S	162	43	2	200	7268	0.000	19.37	0.1007	0.0411	0.071	0.27
362	S	162	43	4	400	7029	0.000	39.07	0.0815	0.0324	0.057	0.56
362	S	162	43	3	800	6557	0.010	34.67	0.0852	-0.0246	0.030	0.53
362	S	162	68	5	0	6451	0.100	-	2.8548	-0.2529	1.301	-
362	S	162	68	3	500	13384	-0.155	159.31	0.4032	-0.0366	0.183	1.19
362	S	162	68	4	750	14029	0.140	131.92	0.1315	0.0118	0.072	0.94
362	S	162	68	2	1000	14792	-0.187	144.26	0.0644	0.1814	0.123	0.98
600	S	125	33	2	0	984	0.130	-	0.7034	0.2548	0.479	-
600	S	125	33	4	30	1951	0.075	25.05	0.6312	0.2406	0.436	1.28
600	S	125	33	3	60	2271	0.120	11.86	-0.1936	-0.0529	-0.123	0.52
600	S	125	33	1	200	1302	0.100	1.10	-0.0146	-0.0208	-0.018	0.08
600	S	162	43	6	0	5144	0.015	-	0.3305	0.2255	0.278	-
600	S	162	43	6a	0	4258	0.090	-	-1.0398	-0.9219	-0.981	-
600	S	162	43	5	30	7163	0.075	15.51	0.0298	-0.4001	-0.185	0.22
600	S	162	43	2	75	6052	-	57.49	1.0127	0.0393	0.526	0.95
600	S	162	43	1	250	7308	-	7.43	-0.0378	-0.0064	-0.022	0.10
600	S	162	43	4	500	7075	-	14.85	0.0238	0.0102	0.017	0.21
600	S	162	97	5	0	21029	---	-	-0.1614	-0.9538	-0.558	-
600	S	162	97	4	160	28306	---	45.23	0.0961	-0.1869	-0.045	0.16
600	S	162	97	3	500	30085	0.000	137.53	-0.3179	0.0125	-0.153	0.46
600	S	162	97	1	1000	28553	0.110	171.51	-0.3955	-0.0472	-0.221	0.60
600	S	162	97	2	1500	29472	0.110	154.42	-0.0220	-0.2422	-0.132	0.52
800	S	162	43	4	0	4591	0.000	-	-0.4082	-0.8840	-0.646	-
800	S	162	43	2	75	4306	---	24.69	-0.0027	0.4608	0.229	0.57
800	S	162	43	3	150	5333	0.120	71.52	0.3110	-0.2260	0.042	1.34
800	S	162	43	5	300	6213	0.000	16.81	-0.0482	-0.0811	-0.065	0.27
800	S	162	97	3	0	19703	0.000	-	0.4080	0.3385	0.373	-
800	S	162	97	2	500	21626	0.000	85.60	0.1250	0.2550	0.190	0.40
800	S	162	97	1	1000	23811	0.000	115.45	0.2014	0.1889	0.195	0.48
800	S	162	97	4	2100	23537	0.000	69.64	0.2314	0.0723	0.152	0.30

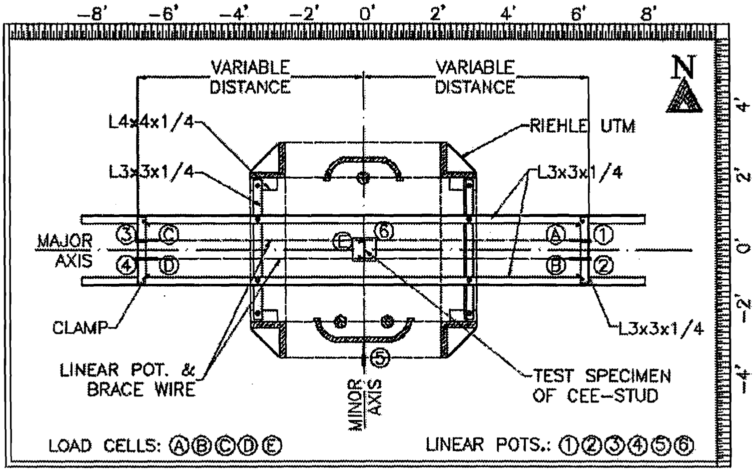


Fig. 1 Plan View of Single Column Axial Test Setup in Riehle UTM

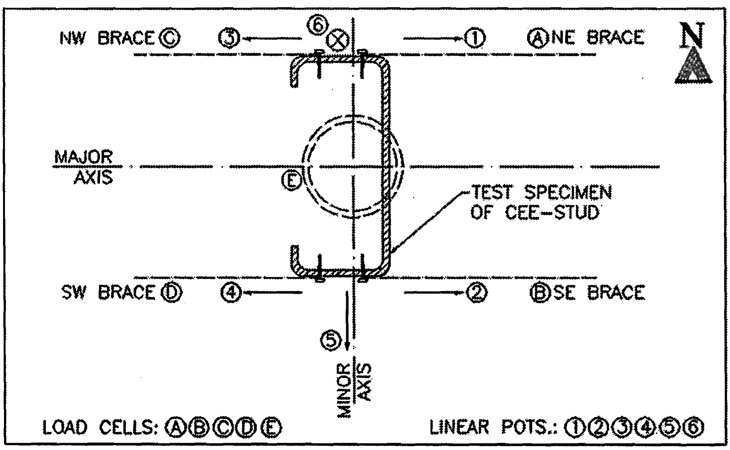


Fig. 2 Schematic Mid-height Bracing and Instrumentation Locations on Test Specimens

(a) (b)

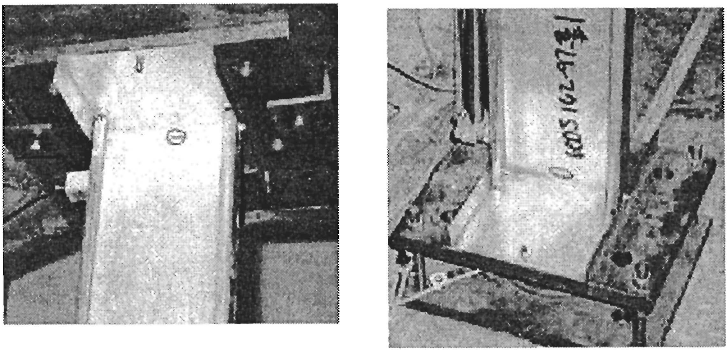


Fig. 3 Connection of Cee-Stud and Track (a) at Top, and (b) at Bottom

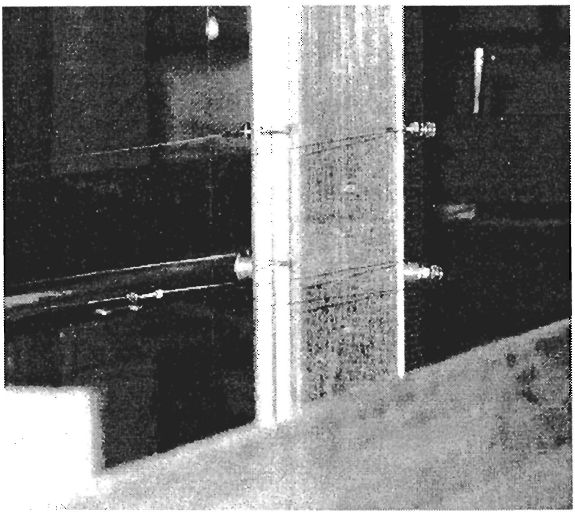


Fig. 4 Close-up View of the Location of Instrumentation (top screws) and Brace Wires (looped over bottom screws) at Mid-height of Cee-Stud

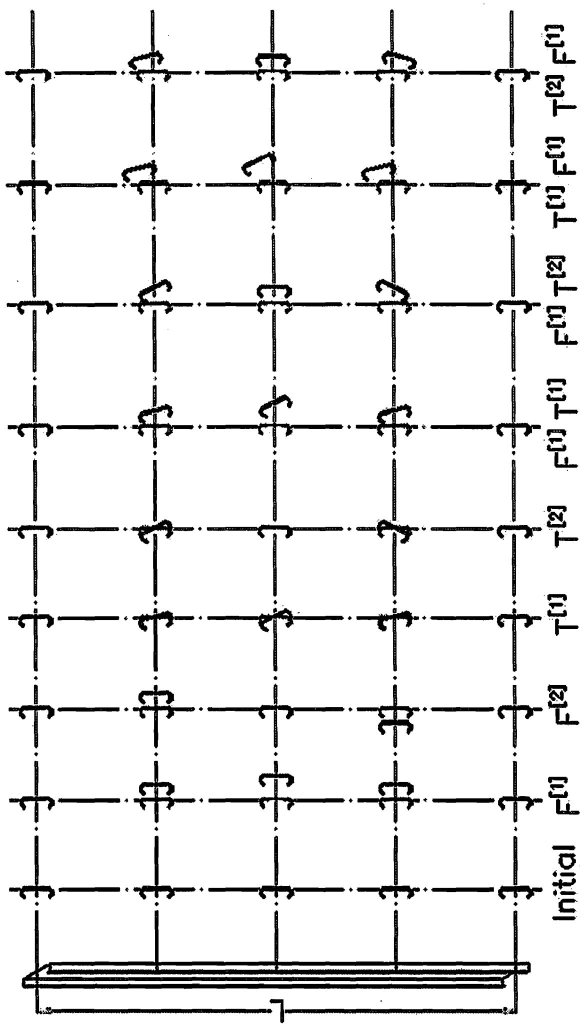


Fig. 5 Schematic Diagram Showing the Various Buckling Shapes and Buckling Modes Observed in the Experimental Testing

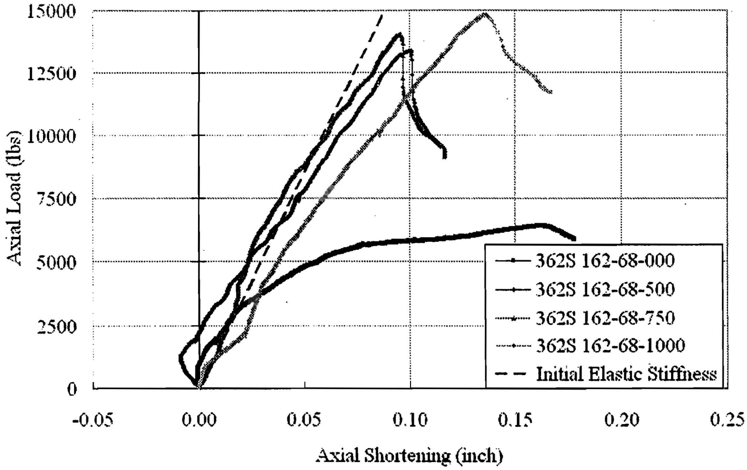


Fig. 6 Axial Load vs. Axial Shortening Behavior for the 362S162-68 Studs with Varying Brace Stiffness

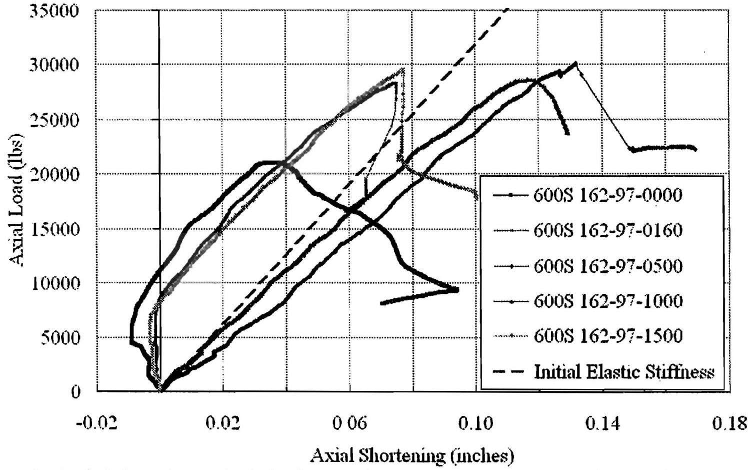
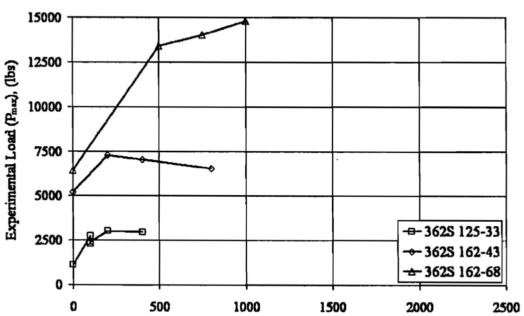


Fig. 7 Axial Load vs. Axial Shortening Behavior for the 600S162-97 Studs with Varying Brace Stiffness



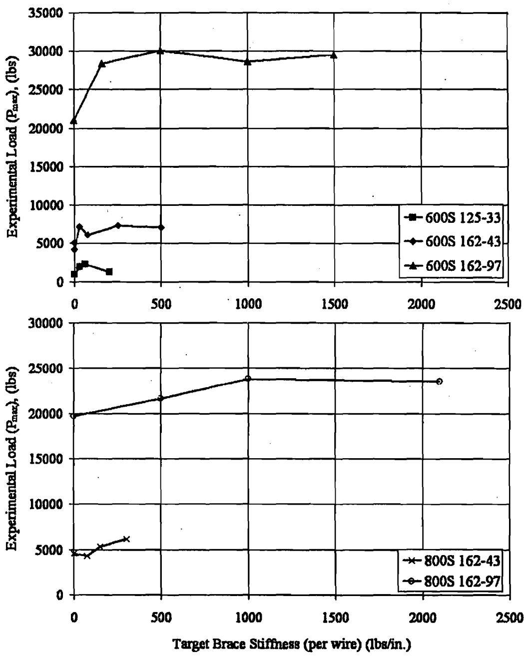


Fig. 8 Experimental Load vs. Target Brace Stiffness for the 362, 600 and 800 Series of Lipped Cee Studs