SHEAR AND COMPRESSION STRENGTH OF COLD-FORMED STEEL CLIP ANGLES SUBJECTED TO DIFFERENT SCREW PATTERNS

Zhishan Yan

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APPROVED:

Cheng Yu, Major Professor
Huseyin Bostanci, Committee Member
Seifollah Nasrazadani, Committee Member
Enrique Barbieri, Chair of the Department of Engineering Technology
Costas Tsatsoulis, Dean of the College of Engineering
Victor Prybutok, Dean of the Toulouse Graduate School

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This thesis presents experiments and numerical analysis of the cold-formed steel clip angle in three different limit states which are shear, compression, and combination of the screw connection. A previous cold-formed steel clip angle test program (which is Phase 1) developed design methods for clip angle. Therefore, the object of this thesis is to further investigate the behavior and design methods of loading-bearing cold-formed steel clip angles under different screw pattern. For each limit state, a test program was conducted to investigate the behavior, strength, and deflection of the clip angle. The test result were compared with previous CFS clip angle design method. Amending existing CFS clip angle method were developed by each of the four limit states studied in this project.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

An angle clip, which is shown in Figure 1.1, is a hardware device used to join two or more structural components within a building, bridge, or other object. This device is made from steel plates that are bent at 90-degrees to form an L-shape. The terms "angle clip" and "clip angle" are often used interchangeably to refer to this type of hardware. An angle clip also features pre-drilled holes to accommodate screws or bolts. These holes may be staggered on each "wing" of the clip so that angle clips can be installed on both sides of an object. For any structural system, not only connection method but also its details are always the critical elements for achieving the desired structural behavior and ensuring the minimum safety level defined by building codes and design specifications [1]. The connections in CFS structures are similar to those in any other structural system, and are even more critical as fasteners are most commonly used and sometimes have dual responsibilities: load bearing and energy dissipation [2]. Among the various connections and connectors, a thin-walled CFS clip angle is a common method used in CFS framing. A CFS clip angle can be subjected to shear, axial, bending, and a combination of those three [3].

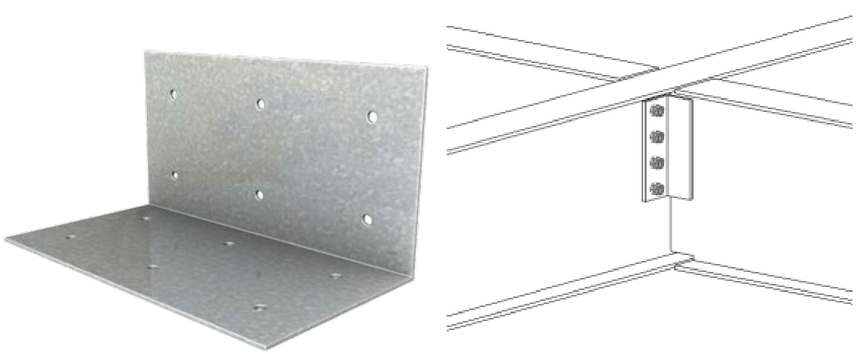


Figure 1.1: Clip Angle Design [4] [5]

CHAPTER 2

LITERATURE REVIEW: CLIP ANGLE UNDER DIFFERENT LOADING METHODS

2.1 Shear Strength of Clip Angles

Clip angle are usually used in the beam-to-column connections and therefore subjected to a shear force, shown in Figure 2.1. The two observed failure modes were lateral-torsional buckling and local buckling failure, as shown in Figure 2.2. For thin clip angle with large aspect ratios (L/B>0.8), a lateral-torsional buckling mode dominated the behavior and failure mechanism. For thick clip angles with small aspect ratio (L/B<0.8), a local buckling failure could be observed [6].

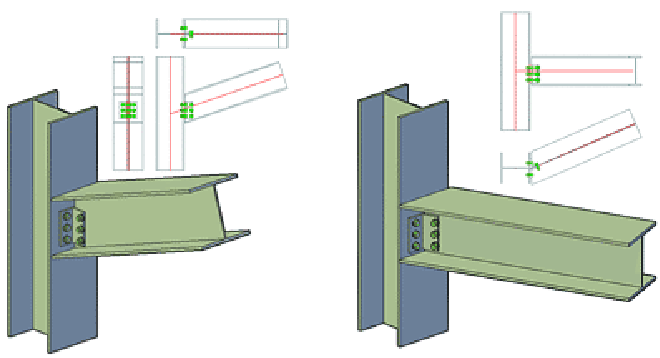


Figure 2.1: Clip Angle subjected to shear force [2]

(a) Later-torsional buckling (b) local buckling failure

Figure 2.2 Failure modes of clip angle under shear loading

2.2 Compression Strength of Clip Angle

Under severe earthquake excitation of a braced steel frame. High axial forces can arise in the horizontal members, particularly those forming part of the horizontal load resisting system. As a result, compression force may arise in clip angle, as shown in Figure 2.3. The flexural buckling was the primary failure mode for the tested clip angles under compression. Typical flexural buckling of a clip angle is shown in Figure 2.4.

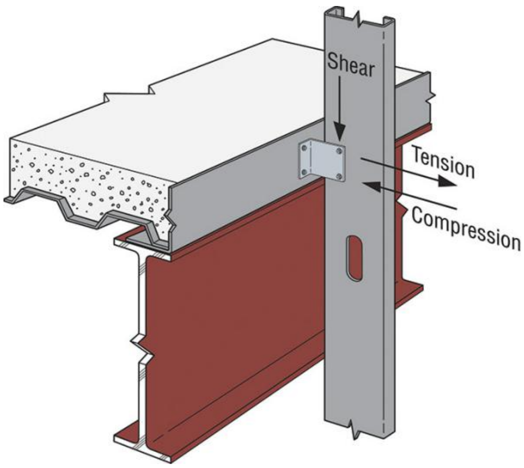


Figure 2.3: Clip angle subjected to various loading

Figure 2.4: Failure modes of clip angle in compression

2.3 Tension (Pull-Over) Strength of Clip Angle

Pull-over failure, also known as pull-through failure is a typical failure mode of clip angle under tension [7]. The different between tension and compression is the loading direction. Clip angles demonstrate three behavior stages in the pull-over [8]. The initial stage has relatively small stiffness, the tension resistance is provided by the bending capacity of the angle. As the clip is continuously being pulled up, the tensile strength of the clip angle begins to contribute to the resistance to applied force and later become the loading bearing mechanism. In this stage, the stiffness of the clip angle increases significantly. The clip angle finally fails by the pull-over failure at the screws. Figure 2.5 shows a typical behavior of a CFS clip angle subjected to a tension force.

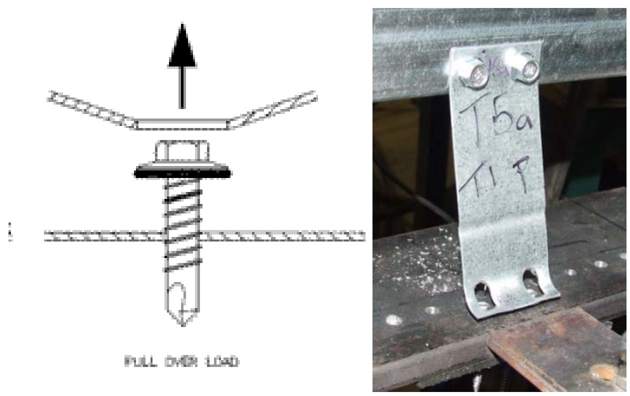


Figure 2.5: Failure modes of clip angle under tension [9] [10]

2.4 Previous Research and Experimental Investigations

Richard G el. al. (1984) [11] conducted a test program on clip angle subjecting to cyclic loads following test methods in ASTM325 [12] and ASTM 490 [13]. The test result showed that these clip angle connections retain their ductility and exhibit considerable reserve of strength and ductility after 15 cycles of tension-compression loading at load amplitudes considerably in excess of normal factored design load magnitudes. However, only one type of connection detail was considered in this research and these conclusion did not necessarily apply to other details of the influence of shearing force is needed.

To investigate the strength and the behavior of the block shear of coped beams with welded end connections, Yam et al. (2007) [13] [14] conducted a test program of ten full-scale coped beam. The test parameters included the aspect ratio of the clip angle, the web shear and tension area around the clip angle, the web thickness , beam section depth, cope , length, and connection position. The test result indicated that the specimens failed, developing either tension fractures of the wed near the bottom of the clip angles or local web buckling near the end of the cope. Although the final failure mode of the six specimens was local web buckling, it was observed during the tests that these specimens exhibited a significant deformation of the block shear type prior to reach their final failure mode. No shear fracture was observed in all of the tests. A comparison was made between the ultimate loads in the test and the predictions using the current design equations from current design standards, such as the AISC-LEFR, CSA-S16-01, Eurocode 3, BS5950-1:2000, AIJ and GB50017. In 2015, a research project was conducted Yu et al. [15] at the University of North Texas to develop design methods for three limit states of cold-formed steel clip angle: shear, compression, and tension. For each limit state, a test program was conducted to investigate the behavior, strength, and deflection of the clip angles. The test results were compared with existing design methods for members similar to, but not exactly the same as, cold-formed steel clip angles. It was found that none of the existing methods worked well for the tested clip angles, therefore new design methods were developed for each of the three limit states studied in the project. LRFD and LSD resistance factors and ASD safety factors were provided to apply to the proposed design equations for nominal strength.

CHAPTER 3

THESIS OBJECTIVES

The objective of this project is to investigate the behavior and design methods of load-bearing cold-formed steel clip angles with thickness ranging from 33 mils to 118 mils. Research will focus on (1) the fastener screw pattern effects on the behavior and strength of clip angles; (2) serviceability of clip angles subjected to compression; (3) design of clip angles subjected to combined shear and bending with different boundary conditions. Compare all the test result with pervious cold-formed steel clip angle tests Phase 1 (which is the same test methods as Phase 2) to further investigate and amend pervious cold-formed clip angle strength design method.

3.1 Shear Strength of Clip Angles

The shear test program was aimed at identifying the failure mechanism and determining the shear strength of the cantilevered leg of CFS clip angle subjected to in-plane transverse shear forces. The test setup ensured the failure would occur in the clip angle, and fastener failures were prevented. The test results were initially compared with the pervious cold-formed clip angle design. It was found that large variations existed between the test results and those determined using the Phase 1 methodology. A new design method was proposed that would more accurately predict the shear strength of the CFS clip angles than other pervious methods. To address the deflection limit, a design method with consideration of the deformation limit was also developed.

3.2 Test Setup and Test Procedure

The test programs were performed in the Structural Testing Laboratory at the Discovery Park of the University of North Texas. The entire test apparatus was constructed on a structural reaction frame. Figure 3.1 shows the overall view and close-up view of the shear test setup respectively.

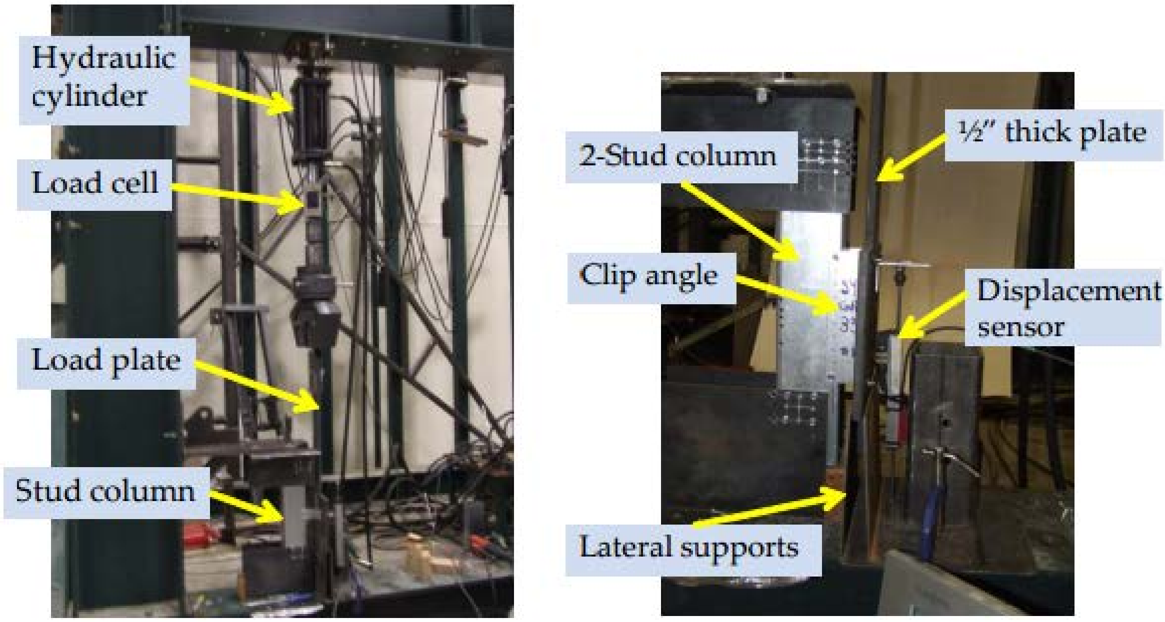


Figure 3.1: Test setup of shear test

In each shear test, two identical clip angles were used in the specimen assembly. The cantilevered leg of each clip angle was fastened to a 54 mil or 118 mil 20 in. long CFS stud column (one clip on each side of the column) using No. 14-14×1 self-drilling self-tapping screws. The other leg of the clip angle (anchored leg) was fixed to a loading plate by No. 10-24×1 Button Head Socket Cap (BHSC) screws. The loading plate was made of ½ in. thick structural steel which had pre-drilled holes to accommodate the BHSC screw connections. The 20 in. long CFS stud column was fixed to a set of specially designed steel fixtures on both ends by No. 14 screws. The stud column was made of two identical CFS stud members face-to-face welded together by spot welds along the flanges. For 54 mil and thinner clip angles, a 54 mil or thicker stud column was used. For 68 mil and thicker clip angles, a 118 mil stud column was used. The upper end of the loading plate was attached to a mechanical grip via a pin connection.

The other end of the loading plate was constrained by two lateral supports, as shown in Figure 3.1, so that the out-of plane movement of the loading plate was prevented. A 50 kip universal compression/tension load cell was installed between the hydraulic rod and the mechanical grip. A position transducer was used to measure the vertical displacement of the loading plate. The data acquisition system consisted of a PC with Labview and a National Instruments® unit (including a PCI6225 DAQ card, a SCXI1100 chassis with SCXI1520 load cell sensor module and SCXI1540 LVDT input module). The applied force and the clip angle displacement were measured and recorded instantaneously during the test. An 8 in. stroke hydraulic cylinder was used to apply the shear load to the clip angle. The cylinder was supported by a hydraulic system with a built-in electrical servo valve to control the hydraulic flow rate. The shear tests were conducted in a displacement control mode. In each test, the hydraulic cylinder moved the loading plate upwards at a constant speed of 0.3 in. per minute. The selected loading speed was found satisfactory for achieving the desired failure mode of test specimens meanwhile allowing accurate readings of displacement and load measurement devices. The testing speed was slow enough to have no effect to the test results.

3.3 Test Specimens

The research focused on failures in the clip angles; therefore, the tests that failed in other modes such as fastener failures were not included in the analyses. The shear test program included a total of 40 valid shear tests with the thickness range of the clip angles between 33 mil and 97 mil. All the clip angles in the research project had pre-punched holes for screw installation. For the shear tests, No. 14-14×1 self-drilling self-tapping screws were used on the cantilevered leg of clip angles. No. 10-24×1 BHSC screws were used on the anchored leg of clip angles. The screws were placed uniformly along the line of the holes and the two end holes were always used for screws. Table 3.1 lists the measured dimensions related to tested material properties, and the number of screws used in each clip angle. The test specimen designations used in this test program were the same as the original product labels from the manufacturer. In Figure 3.2, the L measures the flat length of the cantilevered leg between the center of the first line of screws and the bend line, if it is two line test, the L measures the flat length of the cantilevered leg between the centers of the second line of screws. The thickness, t, is the uncoated thickness of materials. The yield stress Fy, and tensile strength, Fu, were obtained from coupon tests following ASTM A370 Standard Test Method and Definitions for Mechanical Testing of Steel Products [17]. Figure 3.3 illustrates the measured dimensions. The distance between the center of the holes and edges are constantly 0.375 inch. The distance between two holes on cantilevered leg are constantly 0.75 inch also. The distance between the center of the holes and edges on anchored leg are constantly 1 inch. Furthermore, α, which is spacing ratio, equal to B divide by screw spacing S.

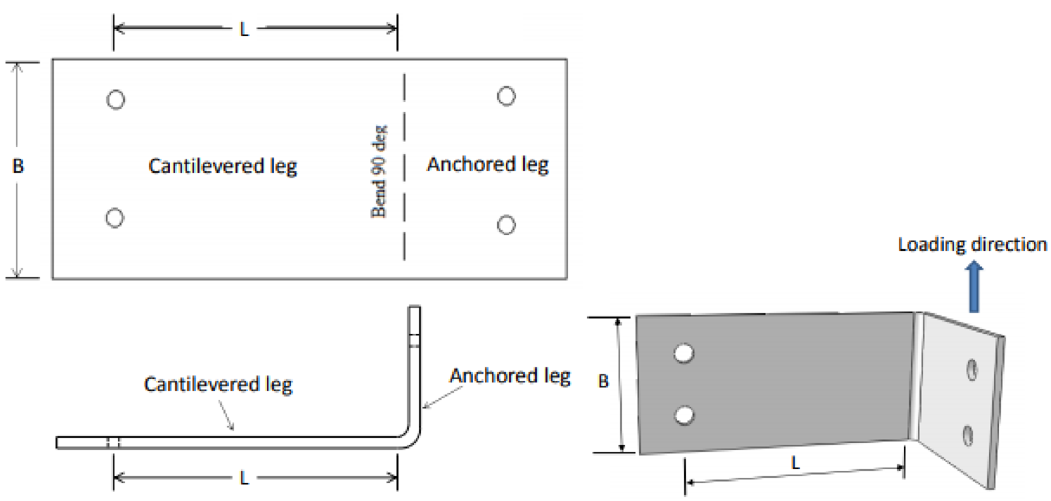


Figure 3.2: Clip angle overall view

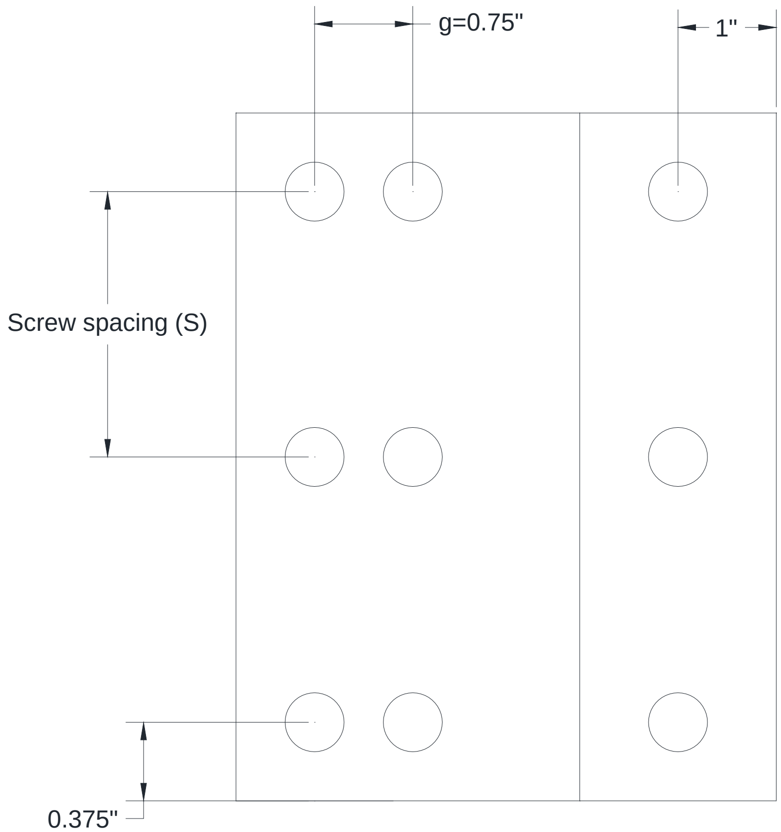


Figure 3.3: Measured Dimensions

Table 3.1: Properties of clip angles in theshear test program

Test label	B (in.)	L (in.)	t (in.)	F_y (ksi)	F_u (ksi)	# Screws on cantileg	# Bolts on Anchleg	α
S3 #1	5.252	1.391	0.0584	45.7	50.1	7	7	0.750
S3 #2	5.220	1.391	0.0584	45.7	50.1	7	7	0.750
S6 #1	3.004	2.425	0.0465	46.4	51.2	4	4	0.750
S6 #2	3.004	2.425	0.0465	46.4	51.2	4	4	0.750
S8 #1	5.244	2.388	0.0465	46.4	51.2	7	7	0.750
S8 #3	5.244	2.388	0.0465	46.4	51.2	7	7	0.750
S9 #2	7.540	2.405	0.0349	49.9	55.8	10	10	0.754
S9 #3	7.540	2.405	0.0349	49.9	55.8	10	10	0.754
S9 #1	7.540	1.665	0.0349	49.9	55.8	6	10	3.395
S9 #2	7.540	1.665	0.0349	49.9	55.8	6	10	3.395
S9 #2	7.540	1.665	0.0349	49.9	55.8	10	10	1.700
S9 #3	7.540	1.665	0.0349	49.9	55.8	10	10	1.700
S9 #1	7.540	2.405	0.0349	49.9	55.8	5	10	1.698
S9 #3	7.540	2.405	0.0349	49.9	55.8	5	10	1.698

Test label	B (in.)	L (in.)	t (in.)	F_y (ksi)	F_u (ksi)	# Screws on cantileg	# Bolts on Anchleg	α
S10 #1	7.497	2.403	0.0349	45.7	50.1	5	10	1.687
S10 #2	7.497	2.403	0.0349	45.7	50.1	5	10	1.687
4.5D#1	4.501	3.300	0.0583	46.1	63.7	2	2	3.751
4.5D#2	4.501	3.300	0.0583	46.1	63.7	2	2	3.751
4.5 D#1	4.501	3.300	0.0583	46.1	63.7	4	4	1.250
4.5 D#2	4.501	3.300	0.0583	46.1	63.7	4	4	1.250
4.5 D#1	4.501	2.534	0.0583	46.1	63.7	4	4	3.751
4.5 D#2	4.501	2.534	0.0583	46.1	63.7	4	4	3.751
8.5 A#2	8.499	2.811	0.0583	46.1	63.7	5	11	1.937
8.5 A#3	8.499	2.811	0.0583	46.1	63.7	5	11	1.937
8.5 A#1	8.499	2.031	0.0583	46.1	63.7	6	6	3.875
8.5 A#2	8.499	2.031	0.0583	46.1	63.7	6	6	3.875
S6 #1	3.004	1.675	0.0465	46.4	51.2	4	4	2.254
S6 #2	3.004	1.675	0.0465	46.4	51.2	4	4	2.254
10.5 A #1	10.500	2.800	0.0583	46.1	63.7	14	14	0.750
10.5 A #2	10.500	2.800	0.0583	46.1	63.7	14	14	0.750
10.5 A #1	10.500	2.800	0.0583	46.1	63.7	8	14	1.393
10.5 A #3	10.500	2.800	0.0583	46.1	63.7	8	14	1.393
10.5 A #2	10.500	2.060	0.0583	46.1	63.7	8	14	1.393
10.5 A #3	10.500	2.060	0.0583	46.1	63.7	8	14	1.393
6.5B T #1	6.500	3.407	0.0583	46.1	63.7	5	5	1.438
6.5B T #2	6.500	3.407	0.0583	46.1	63.7	5	5	1.438
8.5B T #1	8.499	3.407	0.0583	46.1	63.7	5	5	1.937
8.5B T #2	8.499	3.407	0.0583	46.1	63.7	5	5	1.937
10.5B T#1	10.500	3.886	0.0583	46.1	63.7	14	14	0.750
10.5B T#2	10.500	3.886	0.0583	46.1	63.7	14	14	0.750

3.4 Test Results

For each specimen configuration, minimum of two tests were conducted. If the difference in the peak load between the first two tests was greater than 10% of the average result, a third test would be performed. All the clip angles have been test had small aspect ratios (L/B<0.8). Local buckling failure could be observed. Figure 3.4 shows the test result of a 54mil clip angle. Local buckling can be failure can be observed in Figure 3.4.

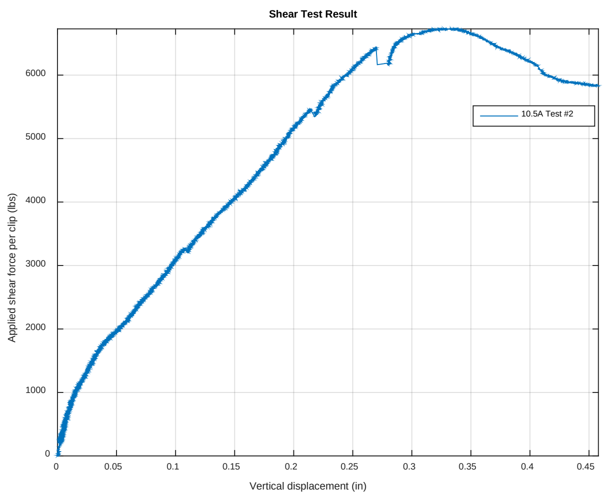


Figure 3.4: Test result of clip angle 10.5A T#2

Table 3.2 provides the test result. V_{test} is the peak load per clip angle and V1/8 is the maximum load per clip angle in the deflection range between 0 and 1/8 inch. The deflection, Δ, is the displacement of the loading plate at the peak load

Table 3.2: Results of shear tests

Table Label	V_{test} (lbs)	Δ (in.)	$V_{1/8}$ (lbs)
S3 #1	4648	0.243	3975
S3 #2	5081	0.239	3689
S6 #1	1416	0.225	1129
S6 #2	1460	0.265	1165
S8 #1	2200	0.172	2102
S8 #3	2077	0.168	1904
S9 #2	3190	0.084	2859
S9 #3	3246	0.118	2773
S9 #1	3503	0.161	3176
S9 #2	3261	0.185	2549
S9 #2	4470	0.218	2764
S9 #3	4471	0.151	4120
S9 #1	2069	0.095	1937
S9 #3	2173	0.105	2098
S10 #1	4922	0.267	3228
S10 #2	4850	0.238	4107
4.5D#1	1342	0.234	1012

Table Label	V_{test} (lbs)	Δ (in.)	$V_{1/8}$ (lbs)
4.5D#2	1311	0.167	1230
4.5 D#1	1664	0.309	1016
4.5 D#2	1821	0.376	1142
4.5 D#1	2706	0.222	1917
4.5 D#2	2650	0.147	2493
8.5 A#2	4525	0.264	2637
8.5 A#3	4136	0.508	2716
8.5 A#1	5620	0.571	3075
8.5 A#2	5272	0.419	2923
S6 #1	1636	0.225	1075
S6 #2	1526	0.164	1302
10.5 A #1	7426	0.676	6506
10.5 A #2	7842	0.178	6126
10.5 A #1	5836	0.425	4466
10.5 A #3	6178	0.328	2889
10.5 A #2	6999	0.314	3549
10.5 A #3	7579	0.357	4162
6.5B T #1	3451	0.235	3166
6.5B T #2	3197	0.191	3084
8.5B T #1	4747	0.251	4175
8.5B T #2	4328	0.192	4320
10.5B T#1	7403	0.861	7259
10.5B T#2	7391	0.260	7231

3.5 Comparison with Proposed Shear Design Method for CFS Clip Angles without Consideration of Deformation from Phase 1

In Phase 1[6], a shear design method was proposed. The design method for determining shear nominal shear strength without consideration of deformation of CFS clip angles was developed using the peak load results from the shear test program. The proposed shear strength method is listed below

$$Vn = 0.17\lambda^{-0.8}FyBt \leq 0.35FyBt$$

where

$\lambda = \sqrt{\frac{Fy}{Fcr}}$ - slenderness ratio

$Fcr = \frac{k\pi^2 E}{12(1-\mu^2)}(\frac{t}{B})^2$- Critical elastic buckling stress

E – Modulus of elasticity of steel, 29500 ksi

μ- Poisson's ratio for steel

$k = 2.569(\frac{L}{B})^{-2.202}$ – buckling coefficient

t - design thickness of clip angle B - depth of clip angle as shown in Figure 3.4

L - flat width of clip angle, distance between the centers of first line of screws to the bend line as shown in Figure 3.4.

The above equations shall be valid within the following range of parameters and boundary conditions:

Clip angle design thickness: 33 mils to 97 mils,

Clip angle design yield strength: 33 ksi to 50 ksi,

L/B ratio: 0.18 to 1.40, the fastener pattern shall allow full engagement of the cantilevered leg in bearing the shear load.

Table 3.3 shows the comparison test result from Phase 1 and 2 in same clip angle. The table points out that in the same specimen by adding more screws on one line gives more strength than less screws pattern.

Table 3.3: Comparison Phase 1 and 2 test result in same clip angle

	Test label	Screw pattern	P_{test} per clip(lbs)	Δ (in.)
Phase 1	S3 #1	1 line 3 screws	3793	0.401
	S3 #2	1 line 3 screws	3753	0.342
	S6 #1	1 line 2 screws	1050	0.361
	S6 #2	1 line 2 screws	982	0.297
	S8 #3	1 line 3 screws	2053	0.258
	S8 #4	1 line 3 screws	1912	0.236
	S9 #2	1 line 3 screws	1786	0.225
	S9 #3	1 line 3 screws	1669	0.197
	S10 #1	1 line 3 screws	3268	0.358
	S10 #2	1 line 3 screws	3421	0.256
Phase 2	S3 #1	1 line 7 screws	4647	0.242
	S3 #2	1 line 7 screws	5080	0.239
	S6 #1	1 Line 4 Screws	1416	0.332

	S6 #2	1 Line 4 Screws	1460	0.388
	S8 #1	1 line 7 screws	2200	0.172
	S8 #3	1 line 7 screws	2076	0.168
	S9 #2	1 line 10 screws	3190	0.084
	S9 #3	1 line 10 screws	3245	0.118
	S10 #1	1 Line 5 Screws	4922	0.266
	S10 #2	1 Line 5 Screws	4850	0.237

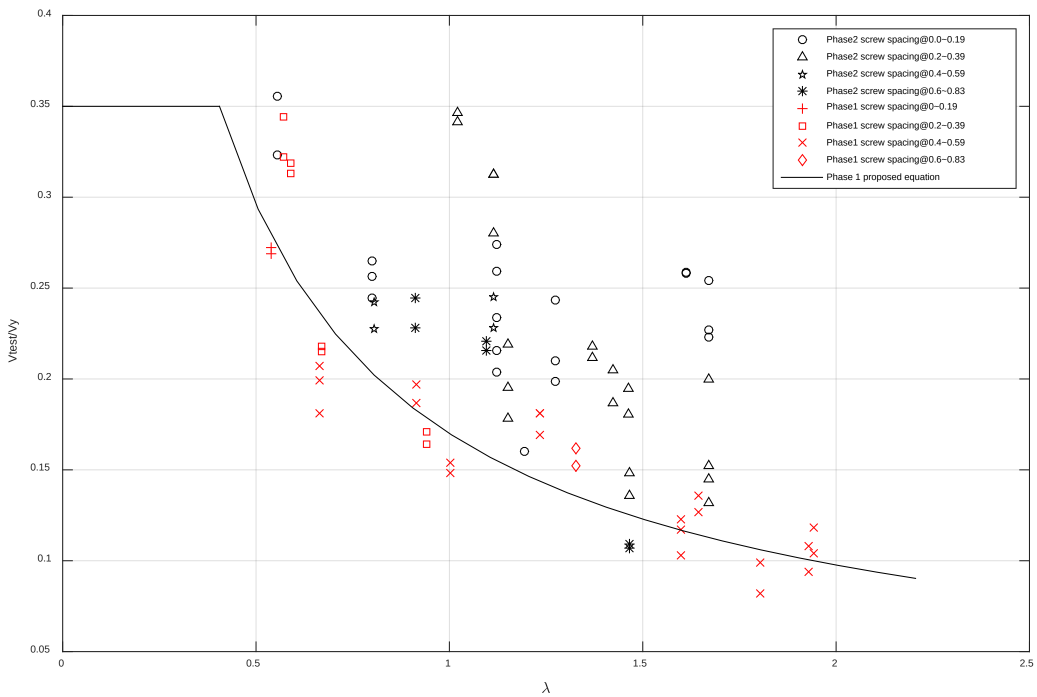


Figure 3.5: Comparison of shear test results from Phase1 and Phase2 with previous proposed method

Figure 3.5 shows the comparison (grouped by screw spacing) between test result from Phase1 and Phase 2 and proposed equation method. Based on the comparison, Phase2 test result did not match the proposed equation by changing the screws spacing.

As a result, screw spacing ratio α, (which is the value of screw spacing divide by B), needs to be involved in the new proposed equation.

Comparison the test result by spreading screw spacing ration to four groups (which are 0~0.19, 0.2~0.39, 0.4~0.59, and 0.6~0.83), as shown in Figure 3.5.

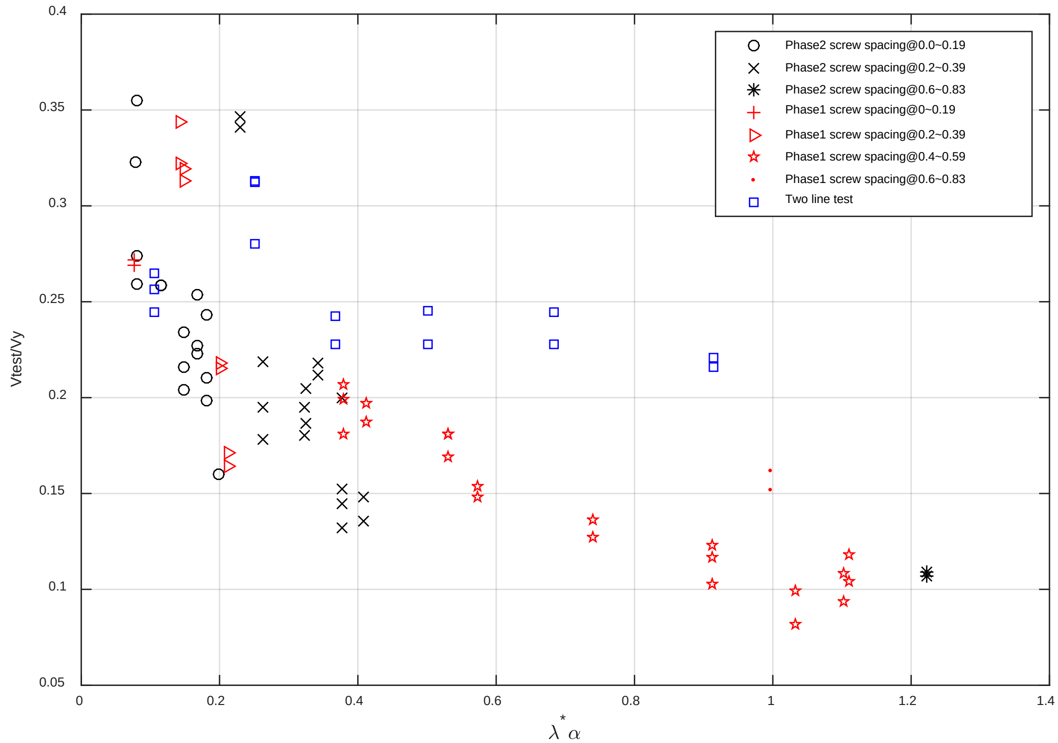


Figure 3.6: Comparison test result by spreading in different screw spacing ratio α

Furthermore, during in the Phase 2 test, two line test were involved. In Figure 3.6, square marked points are 2 line test, and other points are 1 line test. It indicates 2 line tests did not match the proposed equation as well.

3.6 New Proposed Equation

3.6.1 Without Consideration of Two Line Test

Figure 3.7 shows the comparison of 1 test result from Phase 1 and Phase 2, and it indicates that all Phase 1 line test give a reasonable variation; therefore, a new proposed equation was proposed.

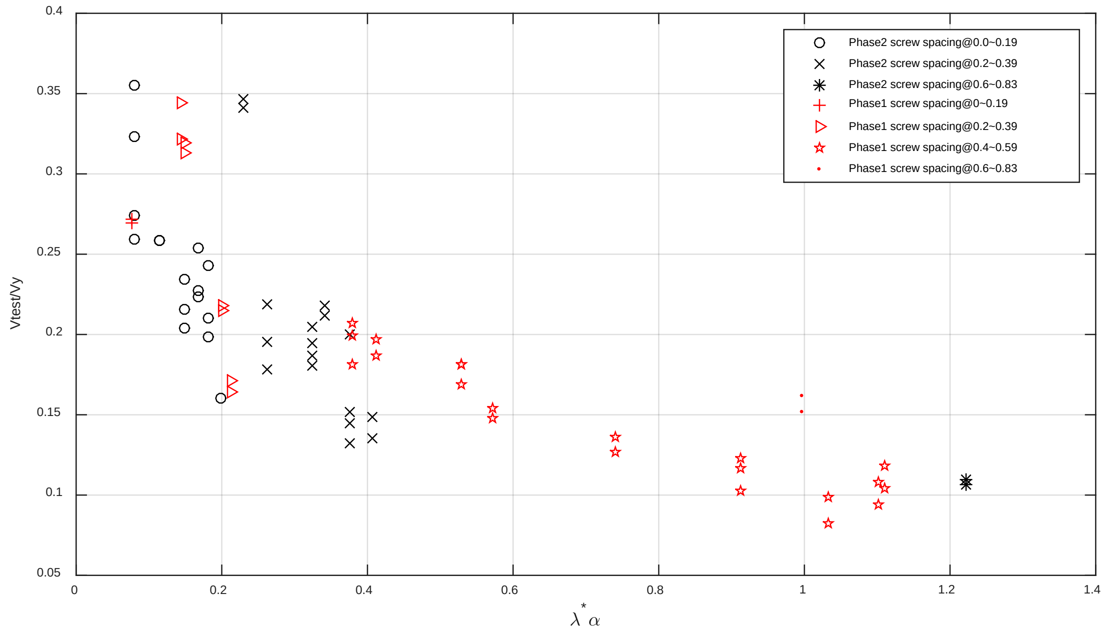


Figure 3.7: Comparison 1 line test result

The new proposed equation:

$$V_n = 0.12(\lambda\alpha)^{-0.384} F_y B_t \leq 0.35 F_y B_t \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} \quad (1)$$

Where

$\lambda = \sqrt{\frac{F_y}{F_{cr}}}$ – slenderness ratio

$\alpha = \frac{S}{B}$ – Screw saping ratio

$F_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)} (\frac{t}{B})^2$ – critical elastic buckling stress

E – Modulus of elasticity of steel, 29500 ksi

μ- Poisson’s ratio for steel

$k = 2.569(\frac{L}{B})^{-2.202}$

t - Design thickness of clip angle

B - Depth of clip angle as shown in Figure 3.4

L - Flat width of clip angle, distance between the centers of first line (or the line closest to the corner of the clip angle) of screws to the bend line as shown in Figure 3.4

The above equations shall be valid within the following range of parameters and boundary conditions:

Clip angle design thickness: 33 mils to 97 mils,

Clip angle design yield strength: 33 ksi to 50 ksi,

L/B ratio: 0.18 to 1.40, the fastener pattern shall allow full engagement of the cantilevered leg in bearing the shear load

The comparison between the test result and the calculated nominal shear strength by the new proposed design method is listed in Table 3.4 and illustrated in Figure 3.8. It can be seen that the proposed method has a good agreement with the test result.

The LRFD and LSD resistance factors and the ASD safety factors for the proposed shear design method were calculated following Chapter K of the North American Specification for the Design of Clod-Formed Members (AISI S100, 2016). Two types of components listed in Table K of AISI S100, Flexural member – Shear and Web Crippling and Other Connectors or Fasteners were chosen for the statistical analysis. The result are listed in Table 3.5.

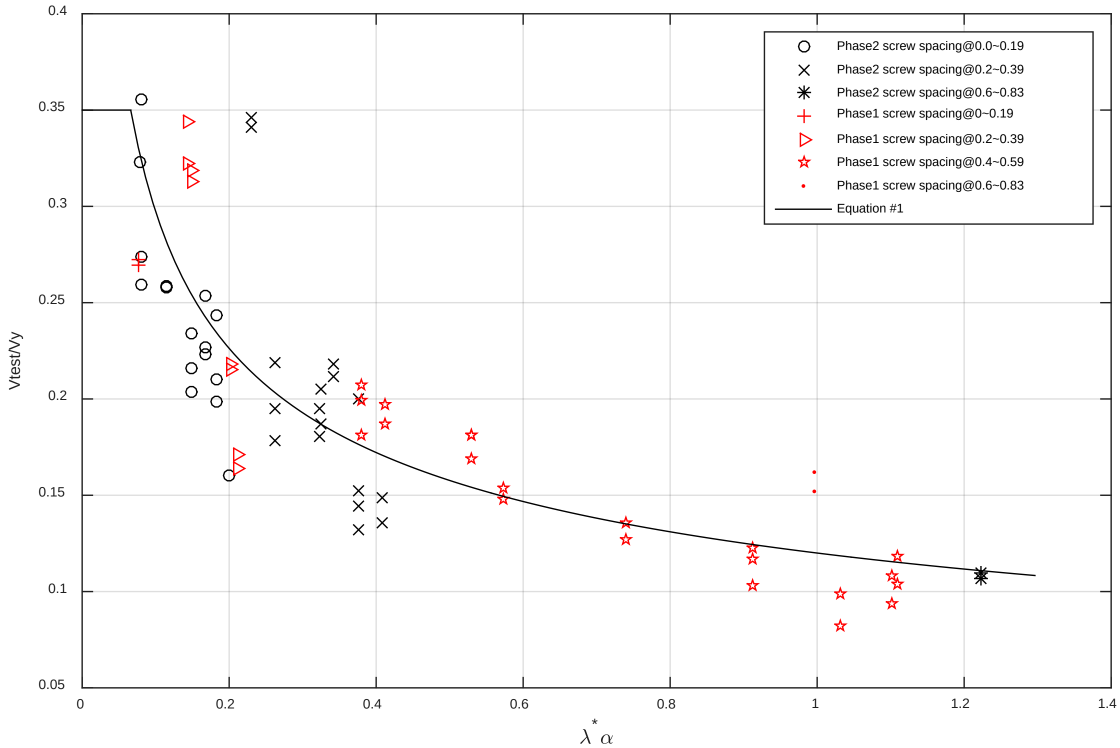


Figure 3.8: Comparison test result with new design equation

Table 3.4: Comparison of Phase 1 and 2 shear test result with the new proposed design method

Test Label	α	λ	V_n (lbs)	V_{test} (lbs)	V_{test}/V_y	V_{test}/V_n
S3 #1	0.142	0.554	4449	4648	0.323	1.045
S3 #2	0.143	0.555	4410	5081	0.355	1.152
S6 #1	0.249	1.37	1174	1416	0.211	1.206
S6 #2	0.249	1.369	1174	1460	0.218	1.244
S8 #1	0.143	1.273	2611	2200	0.21	0.843
S8 #3	0.143	1.273	2611	2077	0.198	0.795
S9 #2	0.1	1.671	3136	3190	0.223	1.017
S9 #3	0.1	1.671	3136	3246	0.227	1.035
S9 #1	0.225	1.671	2296	2069	0.144	0.901
S9 #3	0.225	1.671	2296	2173	0.152	0.947
S10 #1	0.225	0.977	2568	4922	0.346	1.149
S10 #2	0.225	0.977	2568	4850	0.341	1.132
4.5D#1	0.833	1.466	1345	1342	0.109	0.998
4.5D#2	0.833	1.466	1345	1311	0.106	0.975
4.5 D#1	0.277	1.466	2051	1664	0.135	0.811
4.5 D#2	0.277	1.466	2051	1821	0.148	0.888
8.5 A#2	0.227	1.152	4583	4525	0.195	0.987
8.5 A#3	0.227	1.152	4583	4136	0.178	0.902

Test Label	α	λ	V_n (lbs)	V_{test} (lbs)	V_{test}/V_y	V_{test}/V_n
10.5 A #1	0.071	1.123	8928	7426	0.259	0.832
10.5 A #2	0.071	1.123	8928	7842	0.273	0.878
10.5 A #1	0.132	1.123	7039	5836	0.203	0.829
10.5 A #3	0.132	1.123	7039	6178	0.215	0.878
6.5B T #1	0.221	1.463	3235	3451	0.194	1.067
6.5B T #2	0.221	1.463	3235	3197	0.18	0.988
8.5B T #1	0.227	1.424	4225	4747	0.204	1.124
8.5B T #2	0.227	1.424	4225	4328	0.186	1.024
10.5B T#1	0.071	1.611	7772	7403	0.258	0.953
10.5B T#2	0.071	1.611	7772	7391	0.258	0.951
T5a #1	0.571	1.941	352	318	0.104	0.902
S4 #3	0.449	0.914	2207	2581	0.197	1.17
S4 #4	0.449	0.914	2207	2445	0.187	1.108
S6 #1	0.75	1.328	779	1050	0.162	1.349
S6 #2	0.75	1.328	779	983	0.151	1.262
S8 #3	0.428	1.235	1736	2054	0.181	1.183
S8 #4	0.428	1.235	1736	1912	0.168	1.101
S9 #2	0.45	1.643	1771	1787	0.135	1.009
S9 #3	0.45	1.643	1771	1670	0.127	0.943
S3 #1	0.142	0.537	4483	3794	0.272	0.846
S3 #2	0.142	0.538	4483	3753	0.269	0.837
S10 #1	0.224	0.94	4355	3268	0.163	0.75
S10 #2	0.224	0.94	4355	3421	0.171	0.786
S8 #5	0.428	1.235	1736	2048	0.18	1.18
S5 # 3	0.3	0.669	3605	3534	0.217	0.98
S5 # 4	0.3	0.669	3605	3488	0.215	0.967
T3 # 1	0.572	0.664	813	845	0.18	1.039
T3 # 2	0.572	0.664	813	967	0.206	1.189
T5b # 1	0.571	1.805	362	250	0.081	0.691
T5b # 2	0.571	1.805	362	303	0.099	0.838
T5a # 2	0.571	1.941	352	359	0.117	1.02
T1b # 1	0.57	1.599	379	358	0.117	0.945
T1b # 2	0.57	1.599	379	315	0.103	0.832
T1a # 1	0.57	1.93	352	288	0.094	0.817
T1a # 2	0.57	1.93	352	328	0.107	0.931
T4 # 2	0.571	1.002	995	1028	0.153	1.033
T4 # 3	0.571	1.002	995	993	0.148	0.998
S7 #1	0.25	0.591	3465	4339	0.312	1.252
S7 #3	0.25	0.591	3465	4425	0.319	1.277
S1 #4	0.25	0.57	2040	2594	0.322	1.272
S1 #5	0.25	0.57	2040	2767	0.343	1.356
T1b #3	0.57	1.599	379	373	0.122	0.986
T3 #3	0.572	0.664	813	932	0.199	1.146

Test Label	α	λ	V_n (lbs)	V_{test} (lbs)	V_{test}/V_y	V_{test}/V_n
Mean						1.009
St.Dev						0.157
COV						0.156

Table 3.5: Resistance factors and safety factors for the proposed shear design method without two line tests

	Considered as Shear and Web Crippling	Considered as other Connections
Quantity	73	73
Mean	1.01	1.01
Std.Dev.	0.17	0.17
COV	0.17	0.17
M_m	1.10	1.10
V_m	0.10	0.10
F_m	1.00	1.00
P_m	1.01	1.01
V_f	0.05	0.15
C_p	1.10	1.10
β(LRFD)	2.50	3.50
β(LSD)	3.00	4.00
V_q	0.21	0.21
φ(LRFD)	0.80	0.53
φ(LSD)	0.65	0.48
Ω(ASD)	1.99	3.00

3.6.2 With Consideration of Two Line Test

Figure 3.9 indicates that the comparison of all the tests result from Phase 1 and Phase 2, and also includes two line tests. Based on the comparison, there was no a good agreement between 1 line and 2 line tests from both Phase 1 and Phase 2; therefore, a second new equation was proposed for two line test. Furthermore, the second included a new factor which is g distance between the centers of screw line on cantilevered legs.

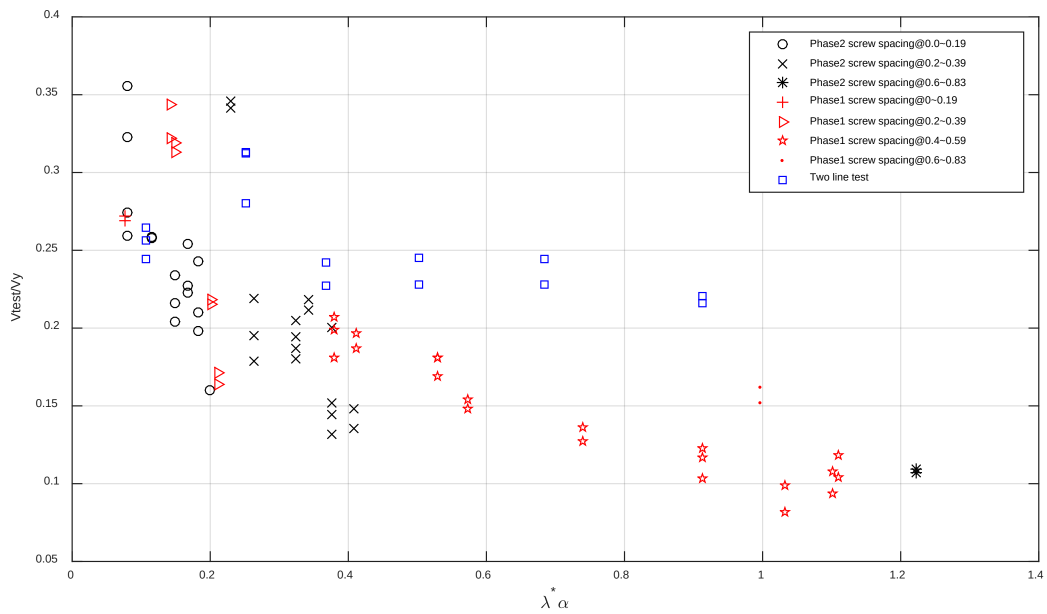


Figure 3.9: Comparison test result includes two line test

In Phase 2, there were not too many two line tests data and g constantly equal to 0.75 inches, therefore, the proposed equation which based on two line test has a limit. Figure 3.10 shows the comparison between tests result including two lines test and proposed equation 2, and there is an agreement between equation 2 and all the test data.

Proposed equation:

V_n =0.12$[\lambda\alpha(1-\frac{g}{L})^2]^{-0.394}F_yB_t \leq 0.35F_yB_t$ and when g=0.75’_________________ (2)

Where

$\lambda = \sqrt{\frac{F_y}{F_{cr}}}$ – slenderness ratio

$F_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)}(\frac{t}{B})^2$ – critical elastic buckling stress

E – Modulus of elasticity of steel, 29500 ksi

μ- Poisson’s ratio for steel

k=2.569$(\frac{L}{B})^{-2.202}$

$$\alpha = \frac{S}{B} \quad - \quad Screw\ saping\ ratio$$

t - design thickness of clip angle B - depth of clip angle as shown in Figure 3.4

L - flat width of clip angle, distance between the centers of first line (or the line closest to the corner of the clip angle) of screws to the bend line as shown in Figure 3.4.

g – Distance between the centers of screw line on cantilevered legs.

The above equations shall be valid within the following range of parameters and boundary conditions:

Clip angle design thickness: 33 mils to 97 mils,

Clip angle design yield strength: 33 ksi to 50 ksi,

L/B ratio: 0.18 to 1.40, the fastener pattern shall allow full engagement of the cantilevered leg in bearing the shear load.

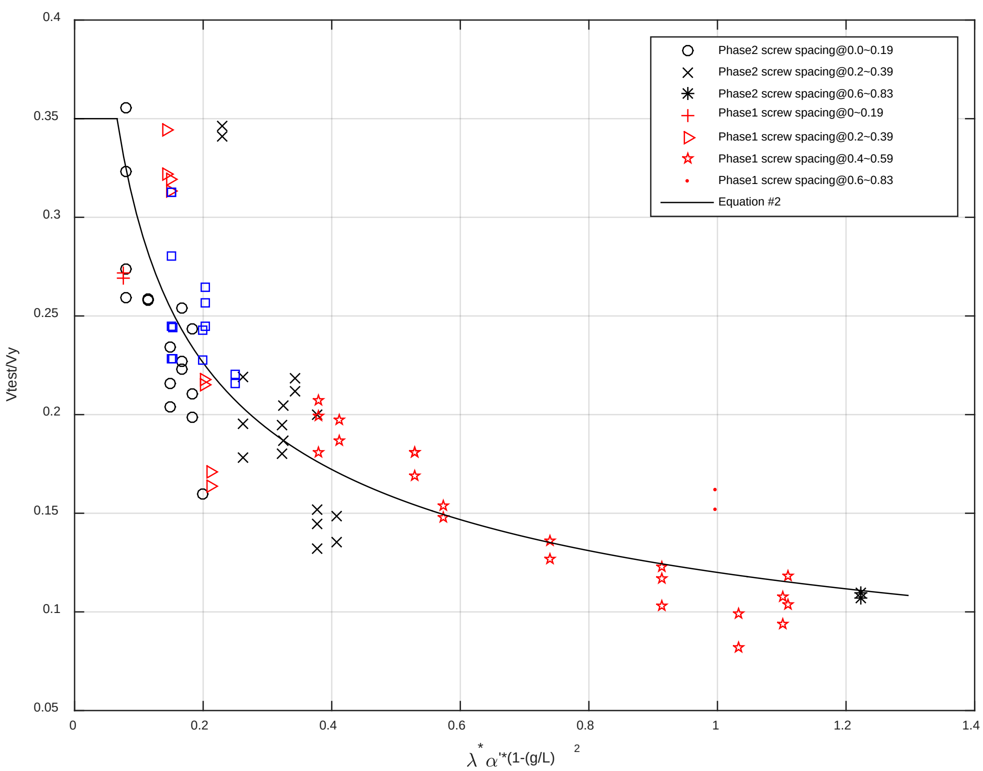


Figure 3.10: Comparison test result including two line tests with new design equation

Table 3.6: Comparison of Phase 1 and 2 shear test result including two line tests with the new proposed design method

Test Label	α	λ	V_n (lbs)	V_{test} (lbs)	$V_{tes}t/V_y$	V_{test}/V_n
S3 #1	0.143	0.555	4449	4648	0.323	1.045
S3 #2	0.144	1	4410	5080	0.355	1.152
S6 #1	0.250	1	1174	1416	0.212	1.206
S6 #2	0.250	1	1174	1460	0.218	1.244
S8 #1	0.143	1	2611	2200	0.210	0.843
S8 #3	0.143	1	2611	2076	0.198	0.795
S9 #2	0.100	2	3136	3190	0.223	1.017
S9 #3	0.100	2	3136	3245	0.227	1.035
S9 #1	0.225	2	2296	2069	0.145	0.901
S9 #3	0.225	2	2296	2173	0.152	0.947
S10 #1	0.225	1	2568	4922	0.346	1.149
S10 #2	0.225	1	2568	4850	0.341	1.132
4.5D#1	0.833	1	1345	1342	0.109	0.998
4.5D#2	0.833	1	1345	1310	0.107	0.975
4.5 D#1	0.278	1	2051	1663	0.136	0.811
4.5 D#2	0.278	1	2051	1821	0.148	0.888
8.5 A#2	0.228	1	4583	4525	0.195	0.987
8.5 A#3	0.228	1	4583	4135	0.178	0.902
10.5 A #1	0.071	1	8928	7426	0.259	0.832
10.5 A #2	0.071	1	8928	7842	0.274	0.878
10.5 A #1	0.133	1	7039	5836	0.204	0.829
10.5 A #3	0.133	1	7039	6177	0.216	0.878
6.5B T #1	0.221	1	3235	3451	0.195	1.067
6.5B T #2	0.221	1	3235	3196	0.180	0.988
8.5B T #1	0.228	1	4225	4747	0.205	1.124
8.5B T #2	0.228	1	4225	4327	0.187	1.024
10.5B T#1	0.071	2	7772	7403	0.259	0.953
10.5B T#2	0.071	2	7772	7391	0.258	0.951
S9 #1(2 Line 3 Screws	0.450	1	3317	3502	0.245	1.056
S9 #2(2 Line 3 Screws	0.450	1	3317	3261	0.228	0.983
S9 #2(2 Line 5 Screws	0.225	1	4357	4469	0.313	1.026
S9 #3(2 Line 5 Screws	0.225	1	4351	4471	0.313	1.028
4.5 D#1(2 Line 2 Screws)	0.833	1	1985	2705	0.220	1.363
4.5 D#2(2 Line 2 Screws)	0.833	1	1985	2649	0.216	1.335
8.5 A#1(2 Line 3 Screws)	0.456	1	5852	5619	0.243	0.960
8.5 A#2(2 Line 3 Screws)	0.456	1	5852	5272	0.228	0.901
S6 #1 (2 Line 2 Screws)	0.750	1	1442	1635	0.244	1.135
S6 #2 (2 Line 2 Screws)	0.750	1	1442	1526	0.228	1.059
10.5 A #2(2 Line 8 Screws)	0.133	1	11709	6999	0.244	0.598
10.5 A #3(2 Line 8 Screws)	0.133	1	11709	7578	0.265	0.647
T5a #1	0.572	2	352	317	0.104	0.902

Test Label	α	λ	V_n (lbs)	V_{test} (lbs)	$V_{tes}t/V_y$	V_{test}/V_n
S4 #3	0.45	1	2207	2581	0.197	1.17
S4 #4	0.45	1	2207	2445	0.187	1.108
S6 #1	0.75	1	779	1050	0.162	1.349
S6 #2	0.75	1	779	982	0.152	1.262
S8 #3	0.429	1	1736	2053	0.181	1.183
S8 #4	0.429	1	1736	1912	0.169	1.101
S9 #2	0.45	2	1771	1786	0.136	1.009
S9 #3	0.45	2	1771	1669	0.127	0.943
S3 #1	0.143	1	4483	3793	0.272	0.846
S3 #2	0.143	1	4483	3753	0.269	0.837
S10 #1	0.225	1	4355	3268	0.164	0.75
S10 #2	0.225	1	4355	3421	0.171	0.786
S8 #5	0.429	1	1736	2048	0.181	1.18
S5 # 3	0.3	1	3605	3534	0.218	0.98
S5 # 4	0.3	1	3605	3487	0.215	0.967
T3 # 1	0.572	1	813	845	0.181	1.039
T3 # 2	0.572	1	813	967	0.207	1.189
T5b # 1	0.572	2	362	250	0.082	0.691
T5b # 2	0.572	2	362	303	0.099	0.838
T5a # 2	0.572	2	352	359	0.118	1.02
T1b # 1	0.571	2	379	357	0.117	0.945
T1b # 2	0.571	2	379	315	0.103	0.832
T1a # 1	0.571	2	352	287	0.094	0.817
T1a # 2	0.571	2	352	328	0.108	0.931
T4 # 2	0.572	1	995	1028	0.154	1.033
T4 # 3	0.572	1	995	993	0.148	0.998
S7 #1	0.251	1	3465	4339	0.313	1.252
S7 #3	0.251	1	3465	4424	0.319	1.277
S1 #4	0.251	1	2040	2594	0.322	1.272
S1 #5	0.251	1	2040	2766	0.344	1.356
T1b #3	0.571	2	379	373	0.123	0.986
T3 #3	0.572	1	813	932	0.199	1.146
Mean	1.009					
St.Dev	0.169					
COV	0.167					

Table 3.7: Resistance factors and safety factors for the proposed shear design method

	Considered as Shear and Web Crippling	Considered as other Connections
Quantity	73	73
Mean	1.01	1.01
Std.Dev.	0.17	0.17
COV	0.17	0.17
M_m	1.10	1.10
V_m	0.10	0.10
F_m	1.00	1.00
P_m	1.01	1.01
V_f	0.05	0.15
C_p	1.10	1.10
β(LRFD)	2.50	3.50
β(LSD)	3.00	4.00
V_q	0.21	0.21
φ(LRFD)	0.80	0.53
φ(LSD)	0.65	0.48
Ω(ASD)	1.99	3.00

CHAPTER 4

COMPRESSION STRENGTH OF CLIP ANGLE

The compression test program was to investigate the compression capacity of the clip angle

Fastened to CFS members. The test results were compared with previous cold-formed clip angle design method (Phase 2). New compression test (Phase 2) were comparable with Phase 1.

4.1 Test Setup and Test Procedure

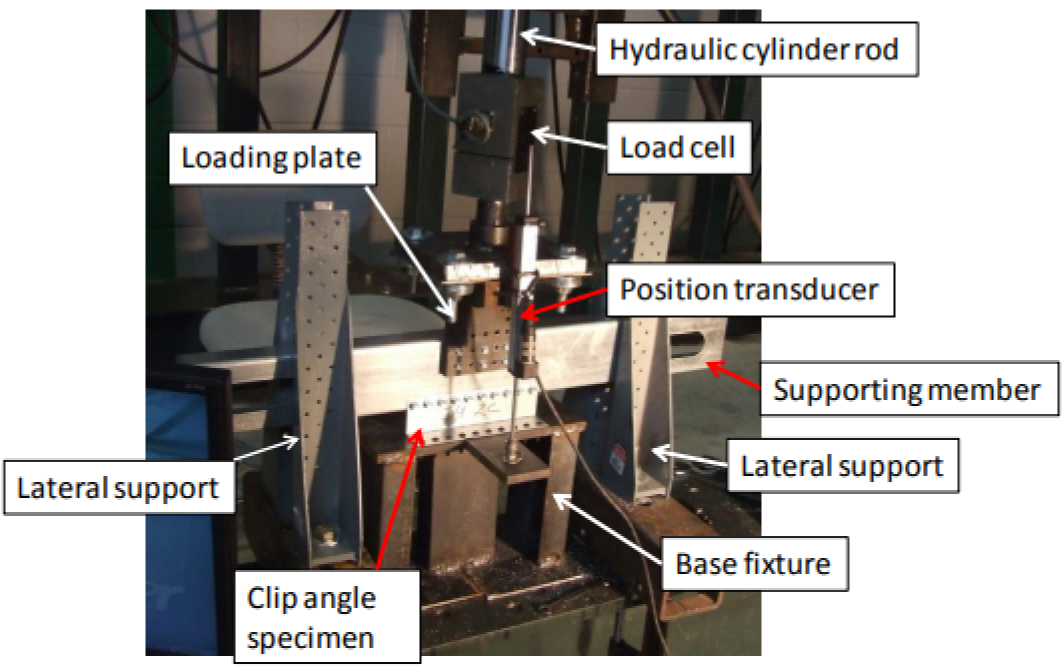


Figure 4.1: Test setup for compression tests

Figure 4.1 shows the setup for the compression tests. The anchored leg of the cold-formed steel clip angle was fixed to a steel base fixture by No. 10-24×1 Button Head Socket Cap (BHSC) screws. The cantilevered leg of the clip angle was fastened to a 54 mil to 118 mil 20 inch long CFS stud member using No. 14-14×1 self-drilling screws. For clip angles with a thickness of 33 mil, a 54 mil stud member was used. For clip angles with a thickness 54 mil, a 68 mil stud member were used. For clip angles with thickness 68 or greater, a 118 mil stud member were used.

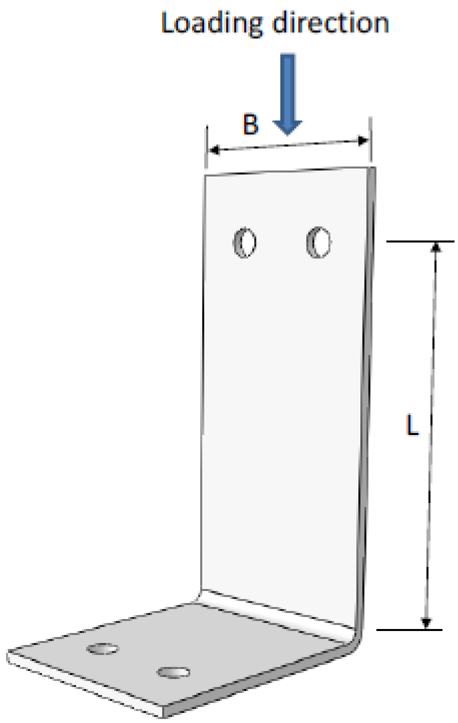


Figure 4.2: Loading direction and measured dimensions for compression tests

The data acquisition system and the hydraulic loading system were the same as used in the shear tests. The compression tests were conducted in a displacement control mode. In each test, the hydraulic cylinder moved the loading plate downwards at a constant speed of 03 in. per minute. The loading rate was the same as used in shear tests since it was found that the selected loading static compression loads were successfully captured by the apparatus, and the testing speed was slow enough to have no impact to the test result. Loading direction shown in Figure 4.2.

4.2 Test Specimens

The compression test program included a total of 36 tests with the clip angles thickness range between 33 mil and 118 mil. The measured dimensions and tested material properties are provided in Table 4.1. The definitions of the measured dimension in the Table 4.1 are the same as those defined in the shear test program. All the pre-punched holes in each clip angle were used for screws connections.

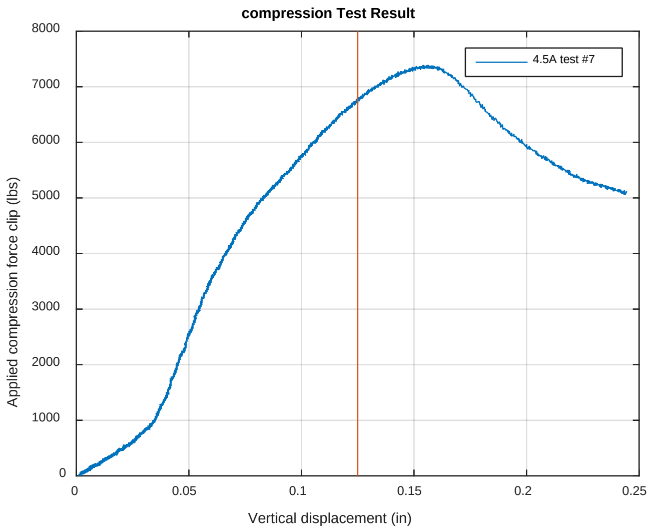
Table 4.1: Properties of clip angles in the compression test program

Test label	B (in.)	L (in.)	Thickness w/o Coating (in.)	F_y (ksi)	F_u (ksi)	Screw spacing (in.)
S3 T#1	5.253	1.352	0.0584	45.6	50	2.25
S3 T#2	5.253	1.35	0.0584	45.6	50	2.25
S3 T#3	5.253	1.35	0.0584	45.6	50	2.25
S9 T#1	7.5	2.341	0.0349	49.9	55.8	0.96
S9 T#2	7.5	2.358	0.0349	49.9	55.8	0.96
S9 T#1	7.5	2.341	0.0349	49.9	55.8	1.35
S9 T#2	7.5	2.358	0.0349	49.9	55.8	1.35
4.5A Test #5	4.501	1.623	0.0989	54.2	63.9	1.25
4.5A Test #7	4.501	1.623	0.0989	54.2	63.9	1.25
4.5D Test #1	4.501	3.3	0.0583	46.1	63.7	3.75
4.5D Test #2	4.501	3.3	0.0583	46.1	63.7	3.75
4.5D Test #3	4.501	3.3	0.0583	46.1	63.7	3.75
4.5D Test #1	4.501	3.3	0.0583	46.1	63.7	1.25
4.5D Test #2	4.501	3.3	0.0583	46.1	63.7	1.25
4.5D Test #3	4.501	3.3	0.0583	46.1	63.7	1.25
4.5D Test #4	4.501	3.3	0.0583	46.1	63.7	1.25
4.5D Test #1	4.501	2.534	0.0583	46.1	63.7	3.75
4.5D Test #2	4.501	2.534	0.0583	46.1	63.7	3.75
4.5D Test #3	4.501	2.534	0.0583	46.1	63.7	3.75
8.5A Test #1	8.499	2.811	0.0583	46.1	63.7	1.94
8.5A Test #2	8.499	2.811	0.0583	46.1	63.7	1.94
8.5A Test #3	8.499	2.811	0.0583	46.1	63.7	1.94
8.5A Test #1	8.499	2.811	0.0583	46.1	63.7	0.77
8.5A Test #2	8.499	2.811	0.0583	46.1	63.7	0.77
8.5A Test #3	8.499	2.811	0.0583	46.1	63.7	0.77
8.5A Test #1	8.499	2.071	0.0583	46.1	63.7	3.87
8.5A Test #2	8.499	2.071	0.0583	46.1	63.7	3.87
8.5B Test #1	8.499	3.53	0.0583	46.1	63.7	0.77
8.5B Test #2	8.499	3.53	0.0583	46.1	63.7	0.77

Test label	B (in.)	L (in.)	Thickness w/o Coating (in.)	F_y (ksi)	F_u (ksi)	Screw spacing (in.)
8.5B Test #3	8.499	3.53	0.0583	46.1	63.7	0.77
8.5B Test #1	8.499	2.79	0.0583	46.1	63.7	1.94
8.5B Test #2	8.499	2.79	0.0583	46.1	63.7	1.94
10.5A Test #1	10.5	2.8	0.0583	46.1	63.7	1.39
10.5A Test #2	10.5	2.8	0.0583	46.1	63.7	1.39
10.5A Test #3	10.5	2.8	0.0583	46.1	63.7	1.39
10.5A Test #1	10.5	2.8	0.0583	46.1	63.7	0.75
10.5A Test #2	10.5	2.8	0.0583	46.1	63.7	0.75
10.5A Test #1	10.5	2.04	0.0583	46.1	63.7	3.25
10.5A Test #2	10.5	2.04	0.0583	46.1	63.7	3.25
10.5A Test #3	10.5	2.04	0.0583	46.1	63.7	3.25
10.5B Test #1	10.5	2.14	0.0583	46.1	63.7	0.75
10.5B Test #2	10.5	2.14	0.0583	46.1	63.7	0.75
10.5B Test #1	10.5	1.38	0.0583	46.1	63.7	1.39
10.5B Test #2	10.5	1.38	0.0583	46.1	63.7	1.39
S9 Test #1	5.253	0.6	0.0584	49.9	55.8	2.25
S9 Test #2	5.253	0.6	0.0584	49.9	55.8	2.25
T3 Test #1	1.753	0.754	0.0583	45.6	50	1
T3 Test #1	1.753	0.754	0.0583	45.6	50	1
T6 1 Test #1	1.748	2.336	0.1352	49.6	53.2	0.5
T6 1 Test #2	1.748	2.336	0.1352	49.6	53.2	0.5

4.3 Test Result

For each specimen configuration, a minimum of two tests were conducted. If the difference in the peak load between the first two tests was greater than 10% of the average result, a third test would be performed. The test program showed that the flexural buckling was the primary failure mode for the tested clip angle under compression. Figure 4.3 indicates the result of a 97 mil clip angle. Figure 4.4 shows the result of a 54 mil clip angle.



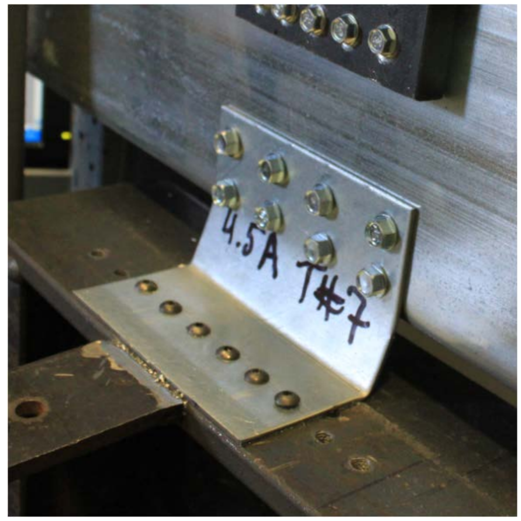
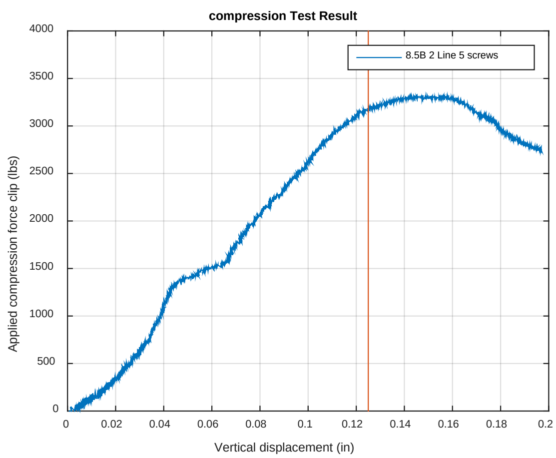


Figure 4.3: Test result of 4.5A #7



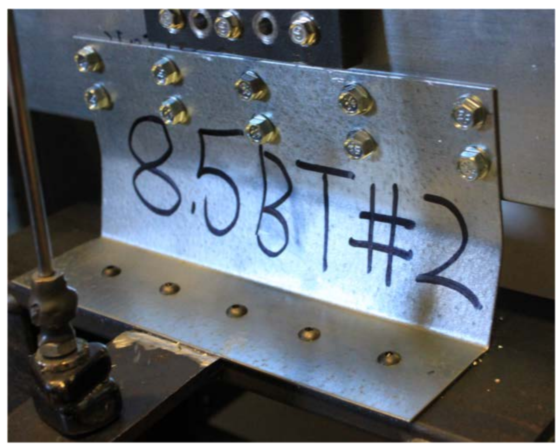


Figure 4.4: Test result of 8.5B #2

Table 4.2: Result of compression test

Test lable	P_{test} - per clip (lbs)	Δ (in.)
S3 T#1	2355	0.136
S3 T#2	3216	0.187
S3 T#3	2964	0.194
S9 T#1	1238	0.196
S9 T#2	1118	0.099
S9 T#1	1388	0.054
S9 T#2	1549	0.084
4.5A Test #5	7056	0.136
4.5A Test #7	7390	0.154
4.5D Test #1	1970	0.16

Test lable	P_{test} - per clip (lbs)	Δ (in.)
4.5D Test #2	1682	0.112
4.5D Test #3	2142	0.099
4.5D Test #1	1956	0.12
4.5D Test #2	1665	0.083
4.5D Test #3	2300	0.095
4.5D Test #4	2322	0.071
4.5D Test #1	2015	0.118
4.5D Test #2	1615	0.239
4.5D Test #3	1988	0.091
8.5A Test #1	3819	0.161
8.5A Test #2	3114	0.123
8.5A Test #3	3886	0.156
8.5A Test #1	3758	0.088
8.5A Test #2	3070	0.077
8.5A Test #3	4141	0.102
8.5A Test #1	3902	0.117
8.5A Test #2	3948	0.138
8.5B Test #1	4197	0.08
8.5B Test #2	3576	0.084
8.5B Test #3	3996	0.089
8.5B Test #1	3574	0.11
8.5B Test #2	3323	0.147
10.5A Test #1	4337	0.172
10.5A Test #2	3856	0.131
10.5A Test #3	4169	0.079
10.5A Test #1	4737	0.142
10.5A Test #2	4392	0.182
10.5A Test #1	5260	0.148
10.5A Test #2	4243	0.183
10.5A Test #3	5586	0.191
10.5B Test #1	4106	0.024
10.5B Test #2	4001	0.087
10.5B Test #1	3993	0.044
10.5B Test #2	4158	0.117
S9 Test #1	1475	0.113
S9 Test #2	1418	0.075
T3 Test #1	1136	0.046
T3 Test #1	1167	0.068
T6 1 Test #1	4115	0.135
T6 1 Test #2	4144	0.125

4.4 Compared with Previous Proposed Deign Method from Phase 1

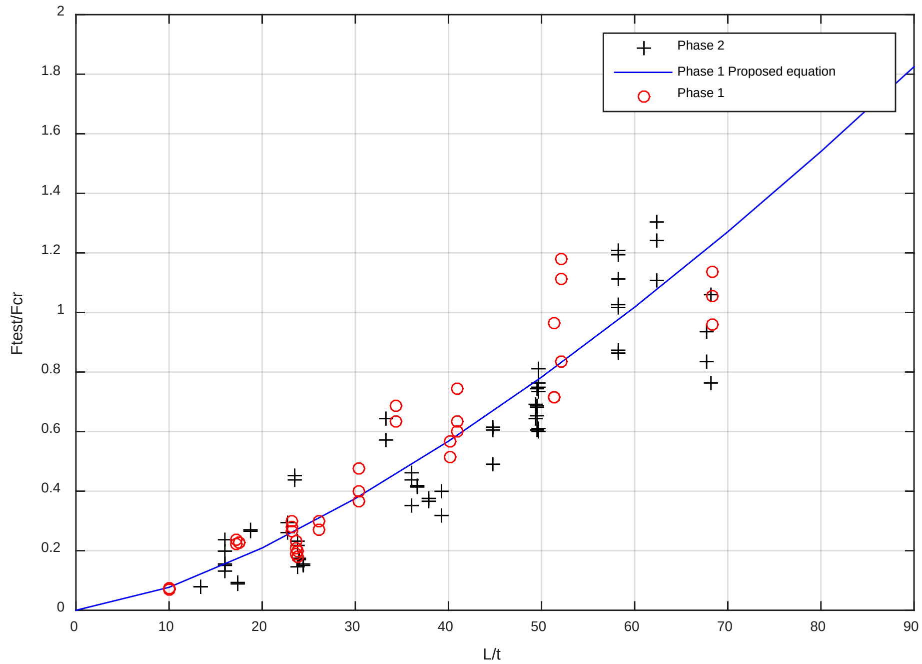


Figure 4.5: Compare Phase 1 and Phase 2 test result with pervious proposed equation

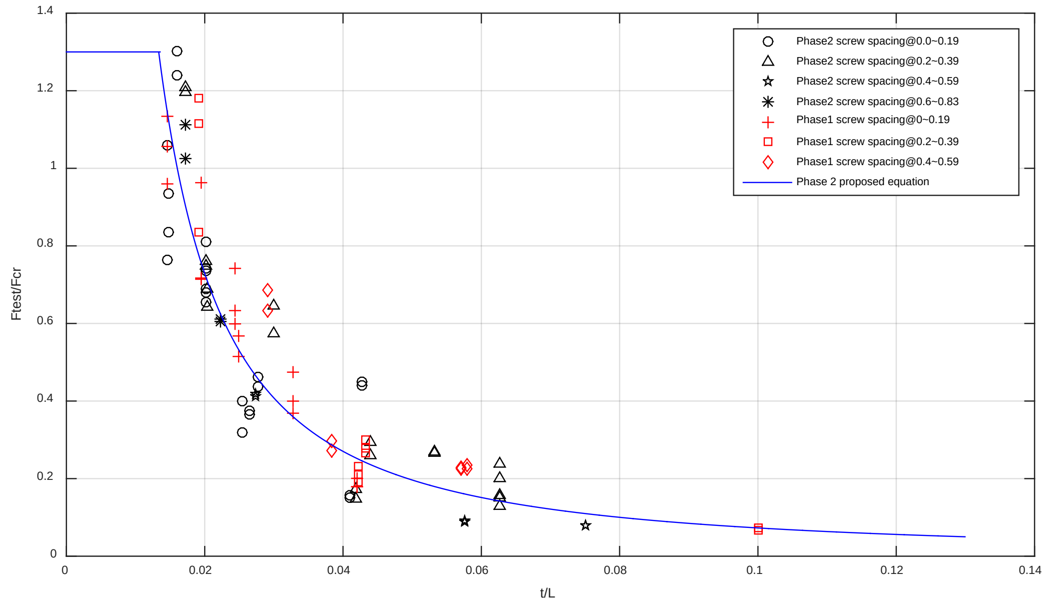


Figure 4.6: Compare test result from Phase 1 and 2 in different screw spacing ratio with Phase 2 proposed equation

The compression tests showed that the CFS clip angles behaved in a similar manner as a plate columns, where the flexural buckling dominated the failure mechanism. The pervious proposed design method from Phase 1 for the compression strength of CFS clip angles was developed considering the column theory of the AISI design which express the column strength as a function of slenderness (KL/r). Furthermore, Figure 4.5 shows the test result comparison between Phase 1 and Phase 2 with the pervious proposed equation. Figure 4.6 shows the test result comparison between Phase 1 and Phase 2 in different screw spacing ratio (same definition as in shear test).

$P_n = F_n A_g$ ____ (3)

where:

$P_n = B't$

$F_n = 0.0027\lambda^{-1.431} F_{cr} \leq 1.3F_{cr}$

$\lambda = \frac{L}{t}$

$F_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)}(\frac{t}{L})^2$ – Critical elastic buckling stress

E – Modulus of elasticity of steel, 29500 ksi

M- Poisson's ratio for steel, 0.3

K – Buckling coefficient can be found by interpolation (Table 4.3).

t – Design thickness of clip angle

B' – shall be taken as the lesser of the actual clip angle width (Figure 3.4) or the Whitemore section width (Figure 4.7)

L – Flat width of clip angle, distance between the first lines of screws to the bend line (Figure 3.4).

The above equations are valid within the following range of established test parameters:

Clip angle design thickness: 33 mils to 118 mils

Clip angle design yield strength: 33 ksi to 50 ksi

L/B ratio: 0.1 to 1.4

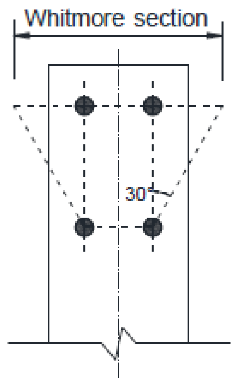


Figure 4.7: Whitmore section width

Table 4.3: Theoretical K values

L/B	K
0.1	0.993
0.2	0.988
0.3	0.983
0.4	0.978
0.5	0.973
0.6	0.969
0.7	0.964
0.8	0.960
0.9	0.956
1	0.952
1.5	0.938
2	0.929

Table 4.3 lists the comparison between the test results (P_{test}) and the predicted strength by the proposed design method (Pn). In the Table 4.4, F_{test} is the applied stress, $F_{test}= P_{test}/ (Bt)$.

Table 4.4: Comparison of test with the proposed design method

Test label	L/t (in.)	F_{cr} (ksi)	F_{test}/F_{cr}	P_{test}/P_n
S3 T#1	23.89	46	0.173	0.643
S3 T#2	23.85	46.9	0.147	0.545
S3 T#2	23.85	46.1	0.234	0.868
S3 T#3	23.85	46.1	0.215	0.8
S9 T#1	67.67	5.7	0.834	0.689
S9 T#2	68.16	5.6	0.764	0.625

Test label	L/t (in.)	F_{cr} (ksi)	F_{test}/F_{cr}	P_{test}/P_n
S9 T#1	67.67	5.7	0.935	0.772
S9 T#2	68.16	5.6	1.058	0.865
S4 T#1	39.2	17.1	0.318	0.577
S4 T#2	39.2	17.1	0.399	0.724
4.5A T#1	23.43	47.1	0.45	1.714
4.5A T#2	23.43	47.1	0.439	1.673
4.5A T#5	15.96	102.6	0.15	0.993
4.5A T#6	15.96	102.6	0.129	0.858
4.5D T#1	58.3	7.5	1.024	1.048
4.5D T#3	58.3	7.5	1.113	1.14
4.5D T#3	58.3	7.5	1.196	1.224
4.5D T#4	58.3	7.5	1.207	1.236
4.5D T#1	44.77	12.9	0.612	0.917
4.5D T#3	44.77	12.9	0.604	0.905
8.5A T#1	49.66	10.6	0.748	0.965
8.5A T#3	49.66	10.6	0.761	0.982
8.5A T#1	49.66	10.6	0.736	0.949
8.5A T#3	49.66	10.6	0.811	1.046
8.5A T#1	36.59	19.6	0.413	0.827
8.5A T#2	36.59	19.6	0.418	0.837
8.5B T#1	62.37	6.7	1.302	1.21
8.5B T#3	62.37	6.7	1.239	1.152
8.5B T#1	49.29	10.7	0.689	0.899
8.5B T#2	49.29	10.7	0.641	0.836
10.5A T#1	49.47	10.7	0.68	0.882
10.5A T#3	49.47	10.7	0.653	0.848
10.5A T#1	49.47	10.7	0.743	0.963
10.5A T#2	49.47	10.7	0.689	0.893
10.5A T#1	36.04	20.2	0.436	0.892
10.5A T#3	36.04	20.2	0.463	0.948
10.5B T#1	37.81	18.4	0.375	0.716
10.5B T#2	37.81	18.4	0.365	0.697
10.5B T#1	24.38	44.4	0.151	0.543
10.5B T#2	24.38	44.4	0.157	0.565
S9 T#1	17.34	87.9	0.092	0.541
S9 T#2	17.34	87.9	0.088	0.52
T3 T#1	13.32	146.7	0.078	0.669
T3 T#1	13.32	146.7	0.08	0.687
T4 T#1	33.3	22.6	0.573	1.316
T4 T #2	33.3	22.6	0.644	1.477
T4 T#1	22.76	49.1	0.259	1.03
T4 T#2	22.76	49.1	0.293	1.165
T6 1 T#1	18.81	71	0.266	1.393

Test label	L/t (in.)	F_{cr} (ksi)	F_{test}/F_{cr}	P_{test}/P_n
T6 1 T#2	18.81	71	0.268	1.403
S9 #1 C	68.35	5.6	1.134	0.923
S9 #2 C	68.35	5.6	0.958	0.78
S9 #3 C	68.35	5.6	1.057	0.861
S1 #1 C	23.67	46.4	0.232	0.873
S1 #2 C	23.67	46.4	0.19	0.713
S1 #3 C	23.67	46.4	0.209	0.785
S7 #1 C	23.14	47.8	0.301	1.166
S7 #2 C	23.14	47.8	0.266	1.032
S7 #3 C	23.14	47.8	0.279	1.08
S4 #1 C	40.1	16.3	0.567	0.996
S4 #2 C	40.1	16.3	0.515	0.905
S5 #1 C	30.44	28.4	0.474	1.238
S5 #2 C	30.44	28.4	0.367	0.96
S6 #1 C	52.12	9.4	0.834	1.003
S6 #2 C	52.12	9.4	1.114	1.34
S6 #3 C	52.12	9.4	1.179	1.419
S10 #1 C	40.88	15.6	0.742	1.266
S8 #1 C	51.38	9.8	0.962	1.181
S8 #2 C	51.38	9.8	0.716	0.879
S8 #3 C	51.38	9.8	0.712	0.875
T3 #1 C	26.08	37.5	0.271	0.885
T3 #2 C	26.08	37.5	0.297	0.971
T4 #1 C	34.31	21.3	0.6853	1.505
T4 #2 C	34.31	21.3	0.633	1.391
S10 #2 C	40.88	15.6	0.634	1.082
S10 #3 C	40.88	15.6	0.598	1.022
S2 #1 C	9.99	260.7	0.068	0.886
S2 #2 C	9.99	260.4	0.074	0.966
T2 #1 C	17.53	81.6	0.229	1.324
T2 #2 C	17.53	81.6	0.225	1.302
T6 #1 C	17.28	84.1	0.235	1.389
T6 #2 C	17.28	84.1	0.224	1.326
S3 #1 C	23.82	46.2	0.179	0.667
S3 #2 C	23.82	46.2	0.199	0.741
S3 #3 C	23.82	46.2	0.179	0.666
S5 #3 C	30.44	28.4	0.4	1.046
Mean				0.978
St.Dev				0.268
COV				0.274

CHAPTER 5

COMBINED JOIST TEST

Combined clip angle joist test investigated the behavior and strength of cold-formed steel clip angles subjected to combined bending moments and shear forces. The two types of boundary conditions, rigid and semi-rigid, for the cantilevered leg of clip angles will be studied. Design methods were developed for those configurations. The test setup ensured the failure would occur in the clip angle, fastener failures were prevented as shear test. The test result were compared with the phase 2 clip angle shear design procedure. It was found that a good agreement between the test result and Phase 2 clip angle shear force design.

5.1 Test Setup and Test Procedure

The test setup consist of 54 mil or 118 mil thick cold-formed steel joists and two supporting members representative of filed conditions as shown Figure 5.1, and 54 mil clip angle and fasteners to be evaluated. Supporting member which is HSS beam were long enough to provide the intended contact surface for the clip angle. Joist were 28 inch long to prevent contact between clip angle and any material other than the attached supporting members and joists. A horizontal clear distance were greater than 1/3 the joist depth. A minimum gap of 1/8 were provided between the end of each joist and abutting material to avoid friction between the joist and supporting member. Load transfer block members at the area of load application was permitted to prevent member failure in local-buckling, global-buckling, shear, or web crippling at the applied load to ensure a failure of clip angle at the joist connecters. A HSS beam block were put into the middle of joist beam to equally transfer load to each end on the clip angle as shown in Figure 5.2 and 5.3. To prevent rotation of the supporting members inward toward the joist, bracing were provided at every 3 inch. The loading speed is 0.3 inch per minute.

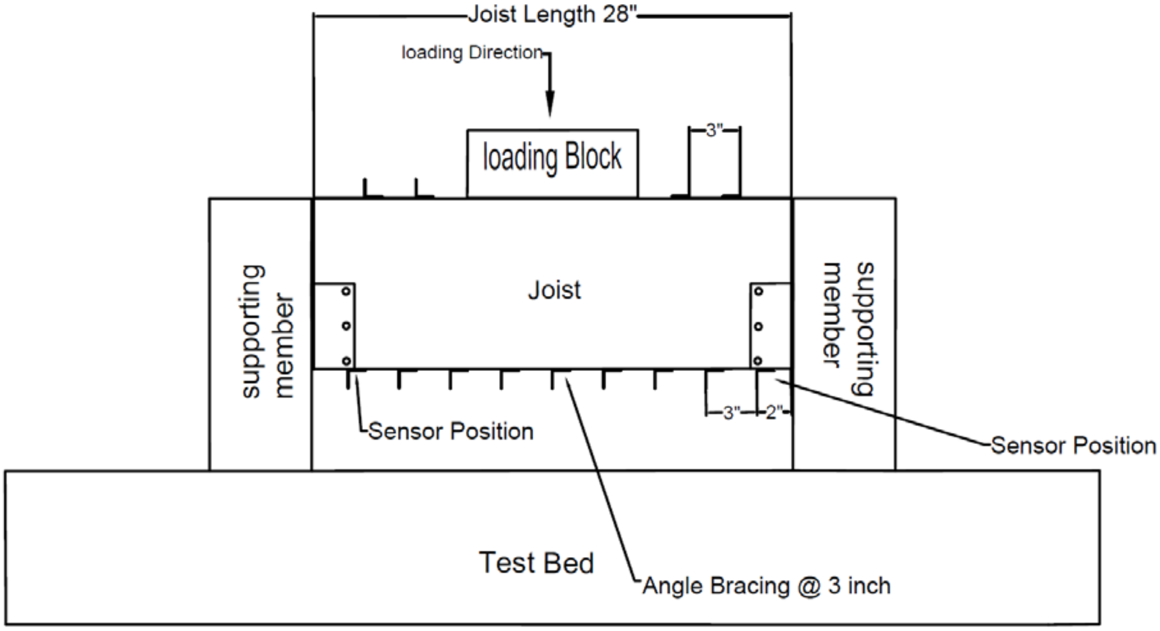


Figure 5.1: Joist test setup

Figure 5.2: Test Setup

Figure 5.3: Test Setup

5.2 Test Specimens

The combined test program included a total of 14 tests with the clip angle's thickness 54 mil. The measured dimension and tested material properties are provided in Table 5.1. The definitions of measured dimensions in Table 5.1 are the same as those defined in the shear test program. All pre-punched holes in each clip angle were used for screws connections. All the clip angle in the test were in order from left to right, and marked as 1, 2, 3, and 4.

Table 5.1: Properties of clip angle in the combination test

Test Specimen &Test No.	B (in.)	L (in.)	T (in.)	F_y (ksi)	F_u (ksi)	Joist spec
4.5D T#1	4.5	3.157	0.058	46.1	63.7	600S250-97(12GA)
4.5D T#2	4.5	3.157	0.058	46.1	63.7	600S250-97(12GA)
4.5F T#1	4.5	3.407	0.058	46.1	63.7	600S250-54(16GA)
4.5F T#2	4.5	3.407	0.058	46.1	63.7	600S250-54(16GA)

6.5A T#1	6.5	3.094	0.058	46.1	63.7	800S250-54(16GA)
6.5A T#2	6.5	3.094	0.058	46.1	63.7	800S250-54(16GA)
6.5B T #1	6.5	3.407	0.058	46.1	63.7	800S250-54(16GA)
6.5B T #2	6.5	3.407	0.058	46.1	63.7	800S250-54(16GA)
8.5B T #1	8.5	3.407	0.058	46.1	63.7	1000S165-54(16GA)
8.5B T #2	8.5	3.407	0.058	46.1	63.7	1000S165-54(16GA)
8.5B T #3 (thicker joist)	8.5	3.407	0.058	46.1	63.7	1000S250-97(12GA)
8.5B T #4 (thicker joist)	8.5	3.407	0.058	46.1	63.7	1000S250-97(12GA)
10.5B T#1	10.5	3.886	0.058	46.1	63.7	1200S165-54(16GA)
10.5B T#2	10.5	3.886	0.058	46.1	63.7	1200S165-54(16GA)
10.5B T#3 (thicker joist)	10.5	3.886	0.058	46.1	63.7	1200S250-97(12GA)
10.5B T#4 (thicker joist)	10.5	3.886	0.058	46.1	63.7	1200S250-97(12GA)

5.3 Test Result

For each specimen configuration, a minimum of two tests were conducted. If the difference in the peak load between the first two tests was greater than 10% of the average result, a third test would be performed. During the test, only one failure mode which is local buckling failure mode was observed. Failure mode can be seen in Figure 5.4, and test result shown in Figure 5.5.

Figure 5.4: Test result of clip angle 8.5B

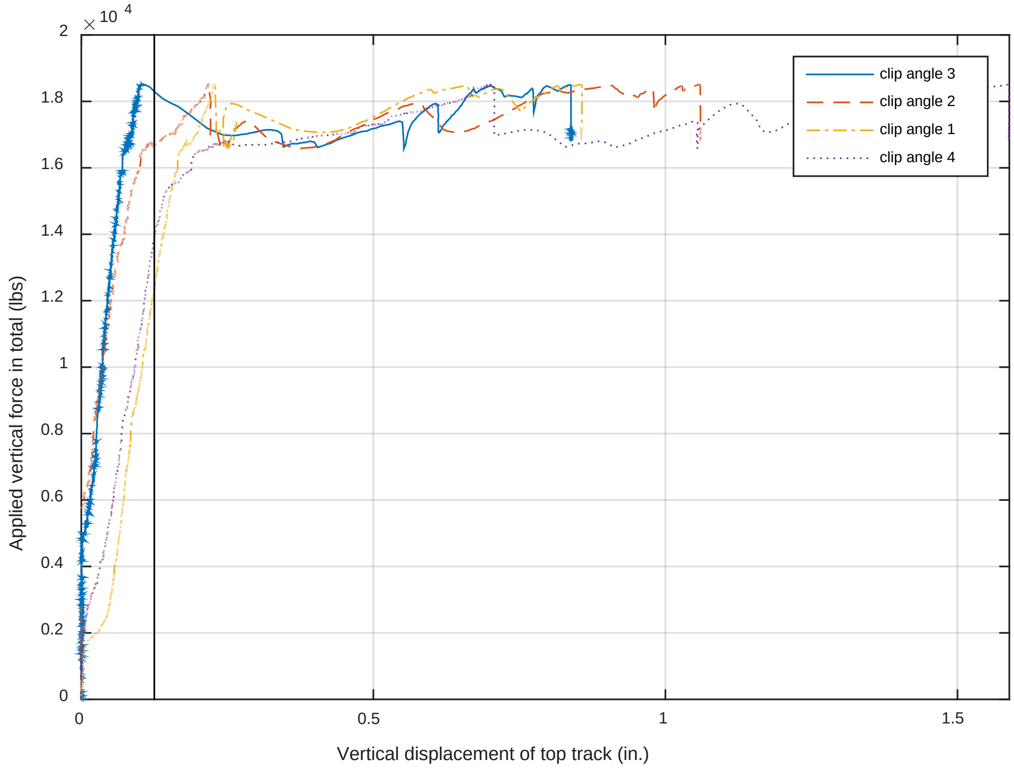


Figure 5.5: Test result of clip angle 8.5B

The test result are provided in Table 5.2 in which V_{test} is the peak load per clip angle. The deflection, Δ, is the displacement of the loading plate at the peak load. Δ can be considered as the first deflection of the failed clip angles as two identical angles were used in each test.

Table 5.2: Results of combination tests

Table Label	V_{test} per clip angle (lbs)	Δ (in.)
4.5D T#1	1742	0.226
4.5F T#1	1671	0.217
4.5F T#2	1589	0.091
6.5A T#1	3257	0.187
6.5A T#2	3188	0.296
6.5B T #1	2576	0.151
6.5B T #2	2940	0.129
8.5B T #1	3447	0.161
8.5B T #2	3808	0.088
8.5B T #1	3446	0.025
8.5B T #2	3808	0.088
8.5B T #3	4627	0.701

8.5B T #4	5395	0.114
10.5B T#1	4960	0.145
10.5B T#2	4915	0.074
10.5B T#3	8282	0.180
10.5B T#4	9038	0.154

5.4 Comparison with Phase 2 Shear Force Clip Angle Design without Consideration of Deformation

A design method for determining the nominal shear strength without consideration of deformation of CFS clip angles was developed using the peak load results from joist test program. The methodology is the same as shear test program. For the 8.5B and 10.5B test, at first, 54 mil joists were used for tests; therefore, failure not only happened on clip angle, but also can be seen on joists. The test purpose is to focus on clip angle, so 97 mil thick joist were used for additional test. Figure 5.6 shows the failure on joist. Furthermore, Table 5.3 illuminates that using 97 mil joist for clip angle have higher strength than using 54 mil joist.

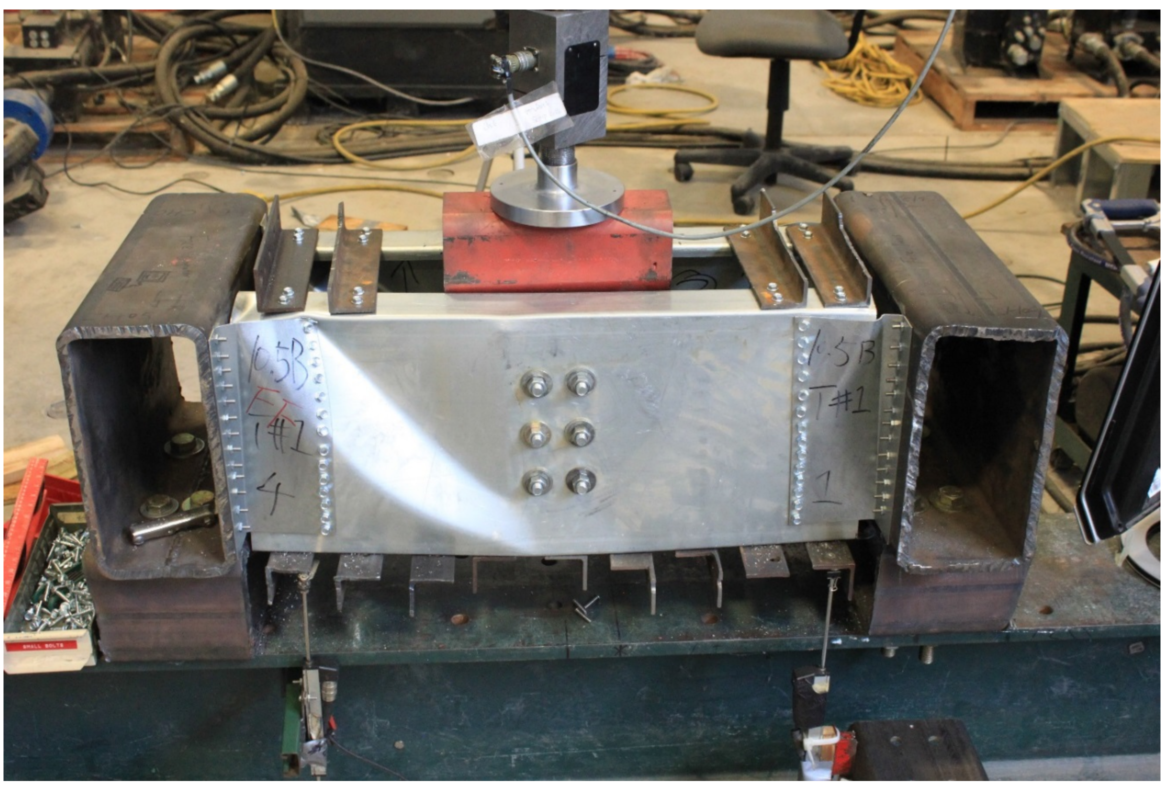


Figure 5.6: Clip angle 10.5B test with 54 mil joist

Table 5.3: Comparison of test result between joists and shear tests

	Test Label	B (in.)	L (in.)	T (in.)	F_y (ksi)	F_u (ksi)	Screw spacing (in.)	Ptest - per clip (lbs)	Δ (in.)Peak load
Combined Tests	4.5D T#1	4.5	3.2	0.058	46.1	63.7	0.94	1743	0.227
	4.5F T#1	4.5	3.4	0.058	46.1	63.7	0.94	1671	0.218
	4.5F T#2	4.5	3.4	0.058	46.1	63.7	0.94	1590	0.09124(bad sensor)
	6.5A T#1	6.5	3.1	0.058	46.1	63.7	1.44	3258	0.187
	6.5A T#2	6.5	3.1	0.058	46.1	63.7	1.44	3188	0.297
	6.5B T #1	6.5	3.4	0.058	46.1	63.7	1.44	2576	0.151
	6.5B T #2	6.5	3.4	0.058	46.1	63.7	1.44	2940	0.130
	8.5B T #1	8.5	3.4	0.058	46.1	63.7	1.94	3447	0.025
	8.5B T #2	8.5	3.4	0.058	46.1	63.7	1.94	3809	0.088
	8.5B T #3(thicker joist)	8.5	3.4	0.058	46.1	63.7	1.94	4628	0.702
	8.5B T #4(thicker joist)	8.5	3.4	0.058	46.1	63.7	1.94	5395	0.114
	10.5B T#1	10.5	3.9	0.058	46.1	63.7	0.75	4960	0.146
	10.5B T#2	10.5	3.9	0.058	46.1	63.7	0.75	4915	0.074
	10.5B T#3(thicker joist)	10.5	3.9	0.058	46.1	63.7	0.75	8283	0.181
	10.5B T#4(thicker joist)	10.5	3.9	0.058	46.1	63.7	0.75	9038	0.154
Shear Tests	4.5 D#1	4.5	3.3	0.058	46.1	63.7	1.25	1664	0.309
	4.5 D#2	4.5	3.3	0.058	46.1	63.7	1.25	1821	0.376
	6.5B T #1	6.5	3.4	0.058	46.1	63.7	1.44	3451	0.235
	6.5B T #2	6.5	3.4	0.058	46.1	63.7	1.44	3197	0.191
	8.5B T #1	8.5	3.4	0.058	46.1	63.7	1.94	4747	0.251
	8.5B T #2	8.5	3.4	0.058	46.1	63.7	1.94	4328	0.192
	10.5B T#1	10.5	3.9	0.058	46.1	63.7	0.75	7403	0.861
	10.5B T#2	10.5	3.9	0.058	46.1	63.7	0.75	7391	0.260

Figure 5.7: Clip angle 6.5 shear test

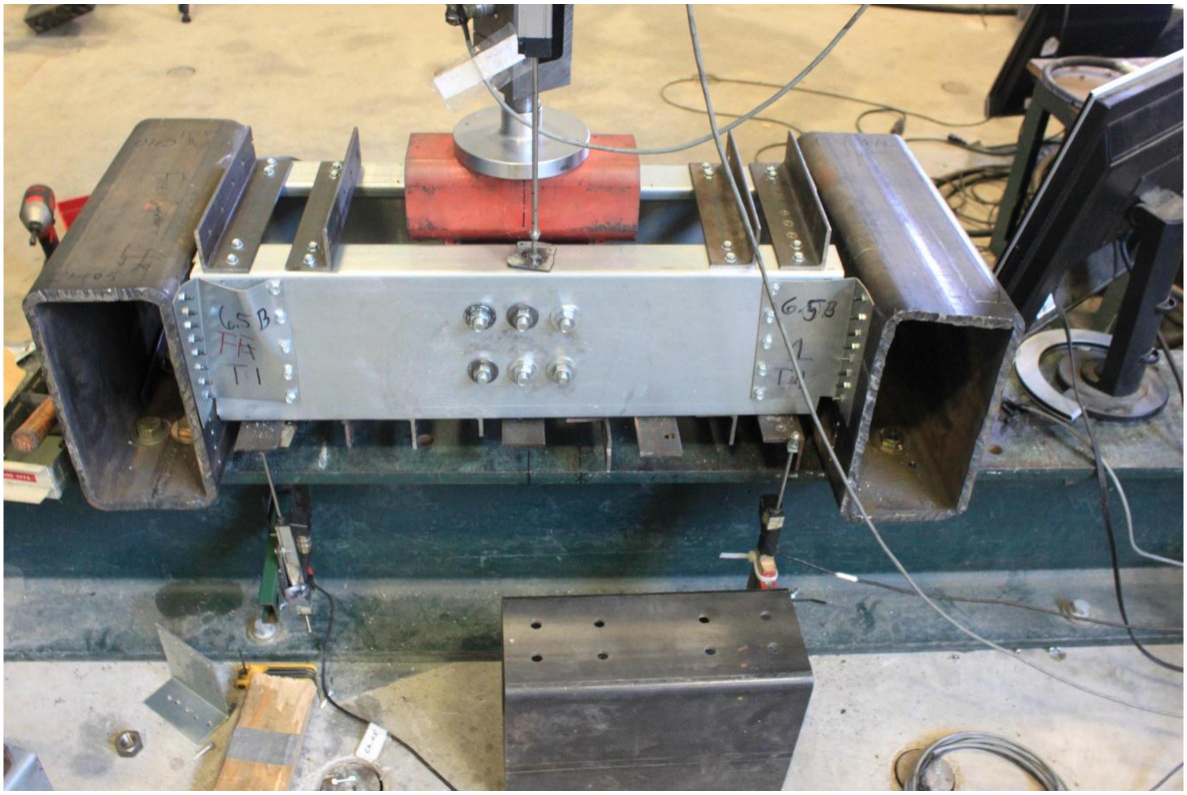


Figure 5.8: Clip angle 6.5B joist test

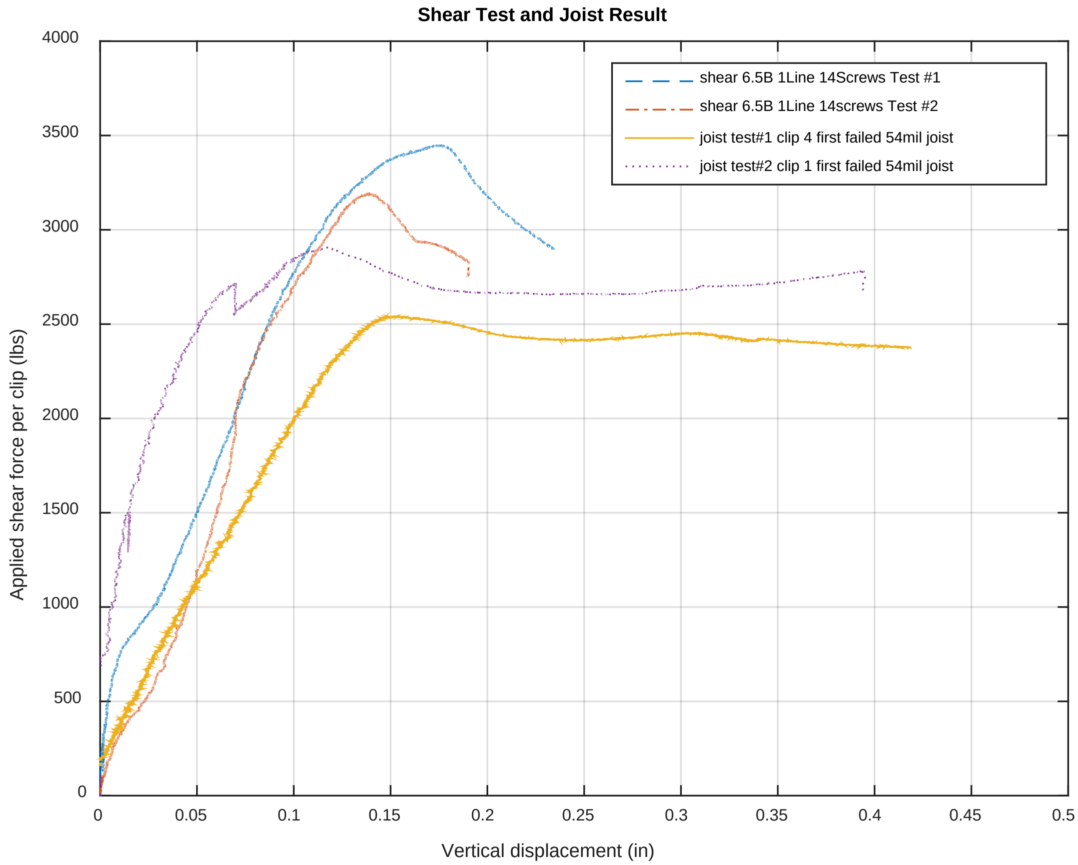


Figure 5.9: Test result of clip angle 6.5B in shear and joist test

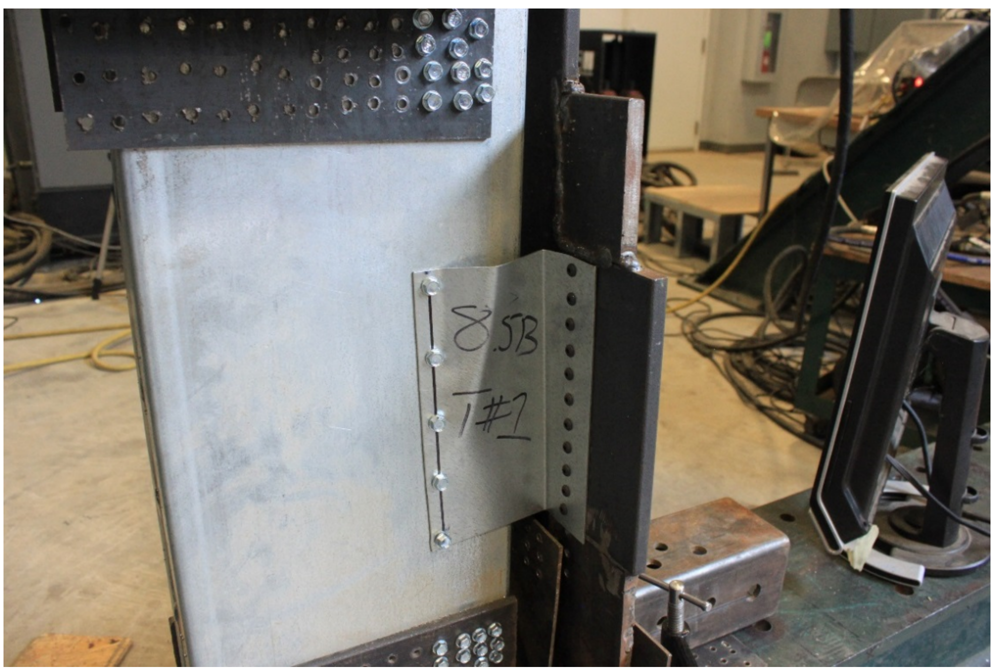


Figure 5.10: Clip angle 8.5B shear test result

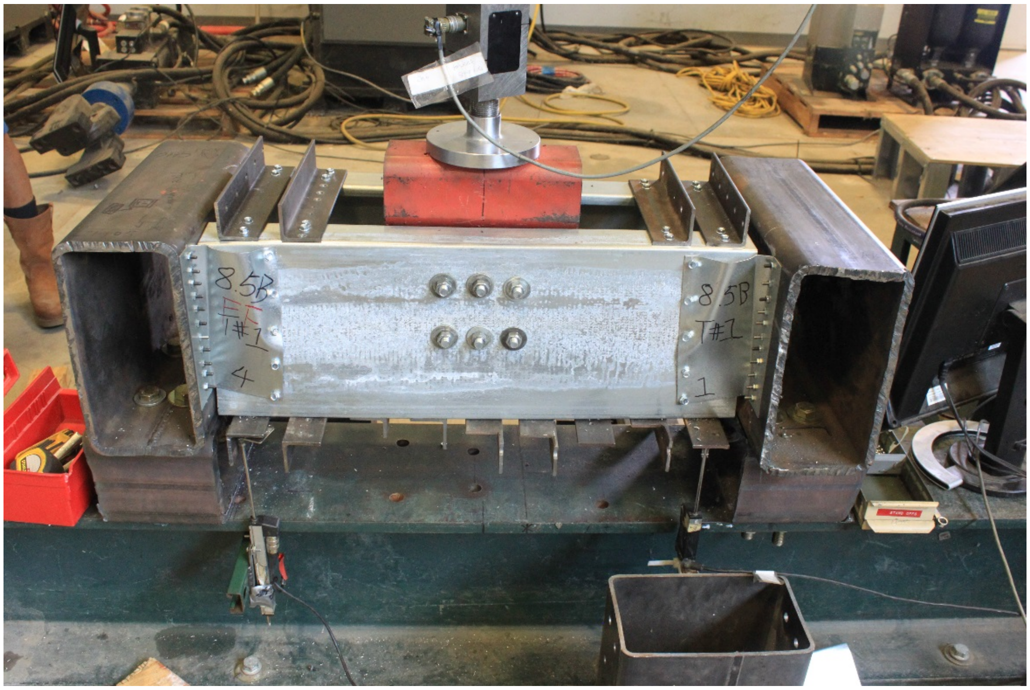


Figure 5.11: Clip angle 8.5B joist test result with 54 mil joist

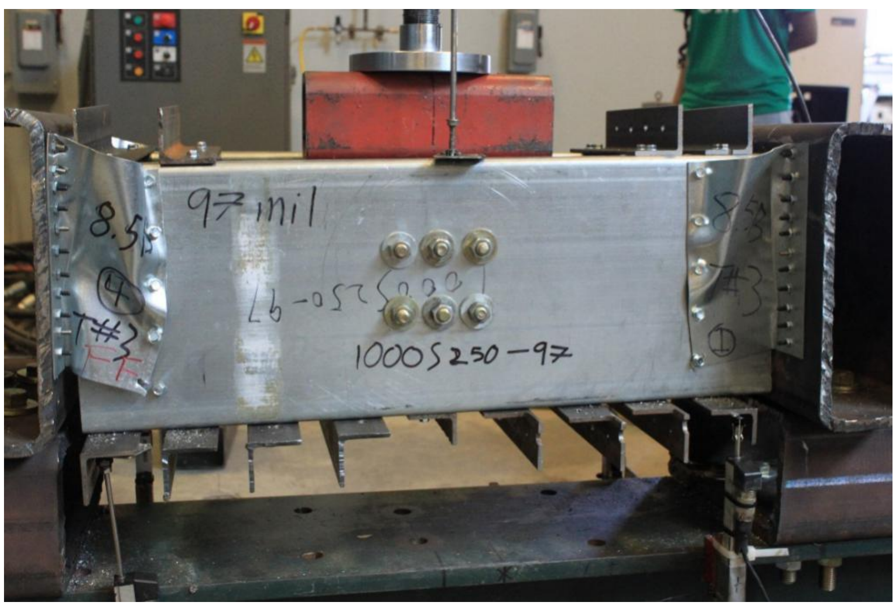


Figure 5.12: Clip angle 8.5B joist test result with 97 mil joist

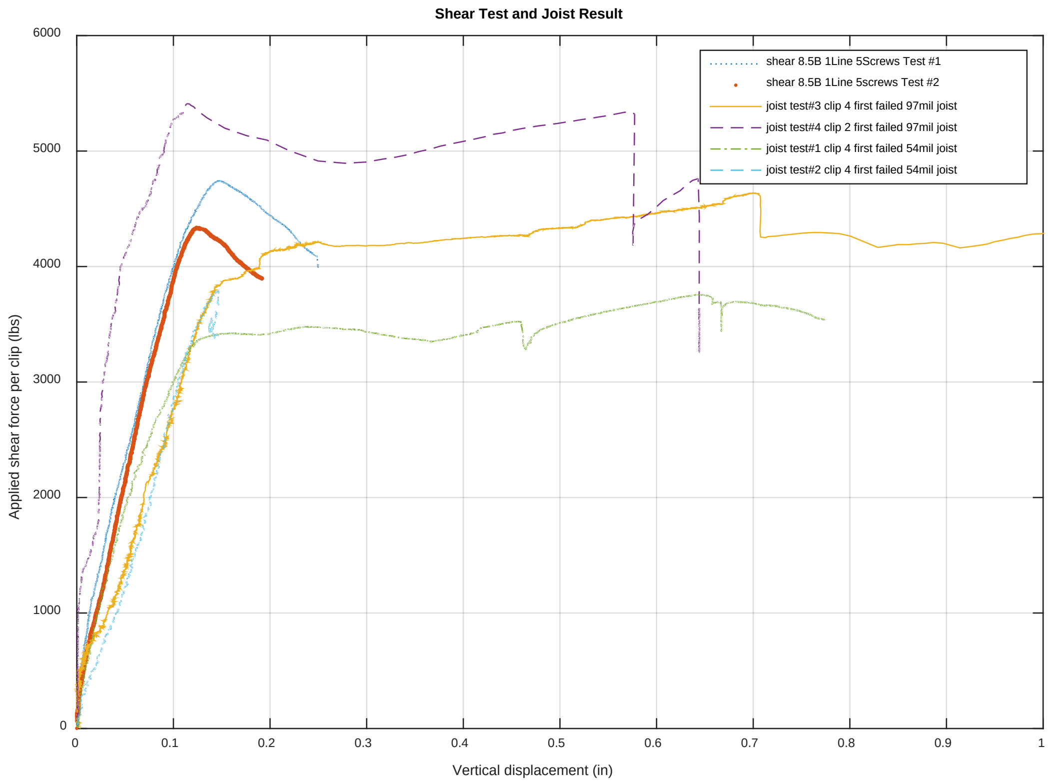


Figure 5.13: Clip angle 8.5B test result in shear and joist tests

Table 5.3 shows the comparison of clip angle test results between joists and shear tests. Figures 5.7, 5.8, and 5.9 show the test result of clip angle 6.5B in shear and joist tests. Figures 5.10, 5.11, 5.12, and 5.13 indicate clip angle 8.5B test result in shear and joist tests. It can be seen that the test result of clip angle joist tests have a relatively good agreement with the test result of clip angle shear test. Clip angle yield at the same level as clip angle shear test; therefore, shear design clip angle is a applicable of clip angle subjected to realistic boundary conditions.

CHAPTER 6

CONCLUSION AND FUTURE RESEARCH

Three series of tests on CFS clip angles were conducted to investigate the behavior, strength, and deflection for three limits states: shear of clip angle, compression of clip angle, and combination of clip angle screw connection. The test result were compared with existing Phase 1 design method. It was found that not all of the existing methods provided reasonable predictions for the nominal strength of clip angles for those three limit states. New design methods for determining the nominal strength of the CFS clip angles were developed for the three limit states respectively. For clip angle shear strength, different screw pattern affect the clip angles' shear strength capacity. The new proposed equation in this thesis is based on Phase 1 design method to account for the different screw spacing in the loading direction. For the two lines test in shear part, it also has significant effect to the shear strength. A preliminary equation was proposed. Due to limited data, additional research is needed to develop a comprehensive design equation to account for the screw spacing in both parallel and perpendicular direction to the loading direction. For the clip angles' compression strength test, the research found that the screw spacing did not have significant effect to the compression strength of clip angles. The Phase 1 design method works. For the combined loading tests, it shows the joist stability has significant effect to the shear strength of the clip angle. With adequate support from the joists, the clip angle yielded similar shear strength as those tested in the pure shear tests. The shear strength design method works for the clip angles when subjected to realistic boundary conditions. The LRFD and LSD resistance factors and the ASD safety factors for the proposed design method were calculated following Chapter K of the North American Specification for the Design of Clod-Formed Members (AISI S100, 2016).

The following subjects can be considered in the future research efforts:

- Clip angle using multiple screws pattern line. In this research, two lines screw pattern were tested, and the data is limited. Additional tests on clip angles with multiple screw pattern line can be conducted to verify the proposed design method.
- Clip angle using welded connections. In this research, screw connection were used in all tested clip angle. The clip angles using welded connection may demonstrate different behavior and strength.

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