research report

Load Bearing Clip Angle Design — Phase II

Report RP18-4

October 2018
(Revised March 30, 2021)

American Iron and Steel Institute

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Load Bearing Clip Angle Design – Phase II

Report No. UNT-GP20000

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August 9, 2018
(Revised, March 30, 2021)

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ABSTRACT

The report presents the second phase of a research project aimed at developing design methods for three limit states of CFS clip angles: shear, compression, and pull-over of the screw connections. In the Phase II work, the research focus was on investigating (1) the fastener pattern effects on the behavior and strength of clip angles; (2) the serviceability of clip angles subjected to tension; (3) the strength and behavior of clip angles subjected to combined shear and bending. Based on the research findings, revision to the Phase I method was proposed to account for the impact of the fastener spacing. Analytical approach to evaluate the serviceability of clip angles in tension was developed. The experimental results of the combined loading verified design equations proposed in this research project.

Table of Contents

Abstract i

1 Research Objectives 1

2 Shear Strength of Clip Angles 2

2.1 Test Setup and Test Procedure 2

2.2 Test Specimens 3

2.2.1 Test Specimens with a Single Line of Screws on the Cantilevered Leg 3

2.2.2 Test Specimens with a Double Line of Screws on Cantilevered Leg 5

2.3 Test Results 6

2.3.1 Test Specimens with a Single Line of Screws on Cantilevered Leg 6

2.3.2 Test Specimens with a Double Line of Screws on Cantilevered Leg 8

2.4 Finite Element Analysis 9

2.4.1 Finite Element Modeling and Verification 9

2.4.2 Results of Finite Element Analysis 11

2.5 Comparison with Design Methods 12

2.5.1 Comparison with Phase I Design Method 12

2.5.2 Revised Design Method for Single Screw Line Configuration 15

2.5.3 Revised Design Method for Clip Angles with either a Single or a Double Line of Screws 20

2.6 Shear Design Method for CFS Clip Angles with Consideration of Deformation 23

3 Compression Strength of Clip Angles 26

3.1 Test Setup and Test Procedure 26

3.2 Test Specimens 27

3.3 Test Results 30

3.4 Comparison with Phase I Design Method 32

4 Serviceability of Clip Angles in Tension 37

4.1 Test Setup and Test Procedure 37

4.2 Test Specimens 37

4.3 Test Results 39

4.4 Proposed Tensile Strength for CFS Clip Angles at the Deformation Limit of Serviceability 40

4.4.1 Analytical Model 40

4.4.2 Design Equation for Nominal Strength at Deflection Limit 42

5 CFS Joist Tests 44

5.1 Test Setup and Test Procedure 44

5.2 Test Specimens 46
5.3 Test Results 46
6 Summary of Proposed Design Provisions 52
6.1 Nominal shear strength of the cantilevered leg of clip angle without consideration of deformation 52
6.2 Nominal shear strength of the cantilevered leg of a clip angle with consideration of serviceability 53
6.3 Nominal axial compression strength of the cantilevered leg of a clip angle 53
6.4 Nominal pull-over strength of the anchored leg of a clip angle 54
6.5 Nominal tension strength of a clip angle with consideration of serviceability 55
7 Conclusions and Future Research 56
Acknowledgements 57
References 58

1 RESEARCH OBJECTIVES

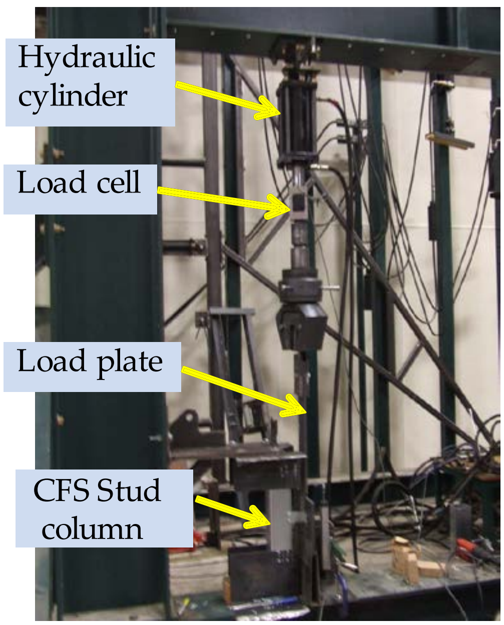
The objective of this project is to continue the Phase I research to further investigate the behavior and design methods of load-bearing cold-formed steel (CFS) clip angles with thickness ranging from 33 mils to 97 mils. The Phase I research conducted experiments to study three limit states of CFS clip angles: shear, compression, and pull-over of the screw connections. The test results were compared with existing design methods for members similar to, but not exactly the same as, CFS clip angles. It was found that none of the existing methods worked well for the tested clip angles, therefore new design methods were developed in Phase I for each of the three limit states. LRFD and LSD resistance factors and ASD safety factors were also provided to apply to the proposed design equations for nominal strength. The Phase I research is documented in Yu et al. (2015, 2017) and Zhang et al. (2018). The Phase II research presented in this report focused on (1) the fastener pattern effects on the behavior and strength of clip angles; (2) serviceability of clip angles subjected to tension; (3) design of clip angles subjected to combined shear and bending with different boundary conditions. Finite element analysis was employed to supplement the experimental work on relatively thicker clip angles. Based on the research findings, the Phase I methods were revised to account for the fastener spacing in the shear strength design method. A new closed-formed design method was also developed to evaluate the serviceability limit of the clip angle in tension.

2 SHEAR STRENGTH OF CLIP ANGLES

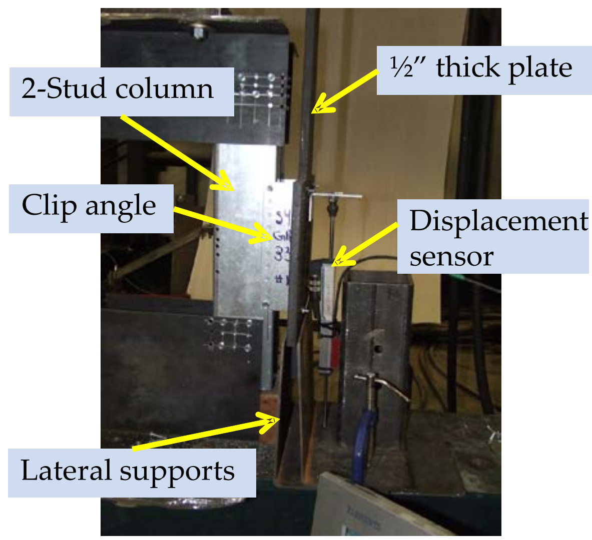
The shear test program was aimed at identifying the failure mechanism and determining the shear strength of the cantilevered leg of CFS clip angles subjected to in-plane transverse shear forces. An adequate number of screws were installed in each specimen so that fastener failures were prevented in the test program. Besides the clip angle's dimensions, the Phase II specimens also included variations in the screw spacing and the number of screw lines.

2.1 Test Setup and Test Procedure

The shear tests in the Phase II project used the same setup as that for Phase I. The tests 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. Figures 2.1 (a) and (b) show the overall view and close-up view of the shear test setup respectively.



(a) Overall view



(b) Close-up view

Figure 2.1: Shear test setup

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 as shown in Figure 2.1. The stud column was made of two identical CFS stud members face-to-face welded together by arc spot welds along the flanges. For 54 mil and thinner clip angles, a 54 mil 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 2.1(b), 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. 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 noticeable effect on the test results.

2.2 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 mils and 68 mils. All the clip angles in the research project had pre-drilled 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 shear specimens were divided in two groups depending on the number of screw lines on the cantilevered leg: one group with a single line of screws, and the other group with two lines of screws. All the specimens were manufactured by the Simpson Strong-Tie Company.

2.2.1 Test Specimens with a Single Line of Screws on the Cantilevered Leg

A total of 28 test specimens had a single line of screws on the cantilevered leg. Figure 2.2 illustrates the measured dimensions. Table 2.1 lists the measured dimensions, tested material properties, and the number of screws used in each clip angle. In Table 2.1, the L measures the flat length of the cantilevered leg between the center of the first line of screws and the bend line, as illustrated in Figure 2.2. On the cantilevered leg, the edge distance of the holes were constantly 0.375 inch. The thickness, t, is the uncoated thickness of materials. The yield stress F_y, and tensile strength, F_u, were obtained from coupon tests conducted following ASTM A370 Standard Test Method and Definitions for Mechanical Testing of Steel Products (2014).

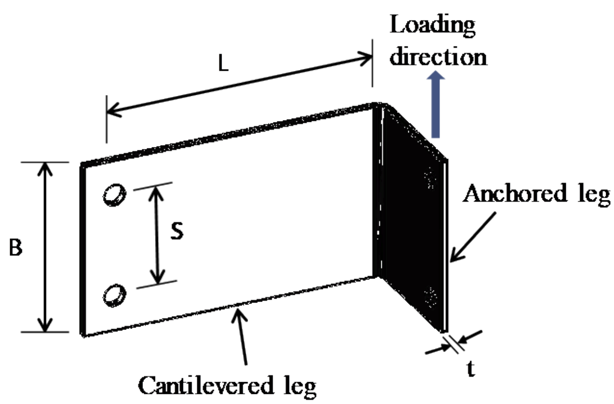


Figure 2.2: Measured dimensions for clip angles with a single line of screws

Table 2.1: Properties of clip angles with a single line of screws in the shear test program

Test Label	B (in.)	L (in.)	t (in.)	S (in.)	F_y (ksi)	F_u (ksi)	# Screws on C-leg	# Bolts on A-leg
IIS3 #1	5.252	1.391	0.0584	0.750	45.7	50.1	7	7
IIS3 #2	5.220	1.391	0.0584	0.750	45.7	50.1	7	7
IIS6 #1	3.004	2.425	0.0465	0.750	46.4	51.2	4	4
IIS6 #2	3.004	2.425	0.0465	0.750	46.4	51.2	4	4
IIS8 #1	5.244	2.388	0.0465	0.750	46.4	51.2	7	7
IIS8 #2	5.244	2.388	0.0465	0.750	46.4	51.2	7	7
IIS9 #a1	7.540	2.405	0.0349	0.754	49.9	55.8	10	10
IIS9 #a2	7.540	2.405	0.0349	0.754	49.9	55.8	10	10
IIS9 #b1	7.540	2.405	0.0349	1.698	49.9	55.8	5	10
IIS9 #b2	7.540	2.405	0.0349	1.698	49.9	55.8	5	10
IIS10 #a1	7.497	2.403	0.0584	1.687	45.7	50.1	5	10
IIS10 #a2	7.497	2.403	0.0584	1.687	45.7	50.1	5	10
II4.5 #a1	4.501	3.300	0.0583	3.751	46.1	63.7	2	2
II4.5 #a2	4.501	3.300	0.0583	3.751	46.1	63.7	2	2
II4.5 #b1	4.501	3.300	0.0583	1.250	46.1	63.7	4	4
II4.5 #b2	4.501	3.300	0.0583	1.250	46.1	63.7	4	4
II8.5 #1	8.499	2.811	0.0583	1.937	46.1	63.7	5	11
II8.5 #2	8.499	2.811	0.0583	1.937	46.1	63.7	5	11
II10.5 #a1	10.500	2.800	0.0583	0.750	46.1	63.7	14	14
II10.5 #a2	10.500	2.800	0.0583	0.750	46.1	63.7	14	14
II10.5 #b1	10.500	2.800	0.0583	1.393	46.1	63.7	8	14
II10.5 #b2	10.500	2.800	0.0583	1.393	46.1	63.7	8	14
II6.5 #1	6.500	3.407	0.0583	1.438	46.1	63.7	5	5
II6.5 #2	6.500	3.407	0.0583	1.438	46.1	63.7	5	5
II8.5 #b1	8.499	3.407	0.0583	1.937	46.1	63.7	5	5
II8.5 #b2	8.499	3.407	0.0583	1.937	46.1	63.7	5	5
II10.5 #c1	10.500	3.886	0.0583	0.750	46.1	63.7	14	14
II10.5 #c2	10.500	3.886	0.0583	0.750	46.1	63.7	14	14

Note: C-leg: Cantilevered leg; A-leg: Anchored leg.

2.2.2 Test Specimens with a Double Line of Screws on Cantilevered Leg

A total of 12 test specimens had a double line of screws on the cantilevered leg. Figure 2.3 illustrates the measured dimensions. Table 2.2 lists the measured dimensions, tested material properties, and the number of screws used in each clip angle. For all clip angles with a double line of screws, the center-to-center distance between the two lines of screws was consistently 0.75 in.

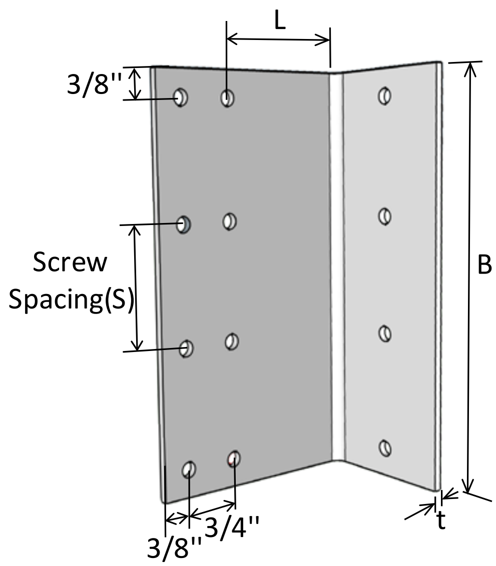


Figure 2.3: Measured dimensions for clip angles with a double line of screws

Table 2.2: Properties of clip angles with a double line of screws in the shear test program

Test Label	B (in.)	L (in.)	t (in.)	S (in.)	F_y (ksi)	F_u (ksi)	# Screws on C-leg	# Bolts on A-leg
IIS9D #a1	7.540	1.665	0.0349	3.395	49.9	55.8	6	10
IIS9D #a2	7.540	1.665	0.0349	3.395	49.9	55.8	6	10
IIS9D #b1	7.540	1.665	0.0349	1.700	49.9	55.8	10	10
IIS9D #b2	7.540	1.665	0.0349	1.700	49.9	55.8	10	10
II4.5D #1	4.501	2.534	0.0583	3.751	46.1	63.7	4	4
II4.5D #2	4.501	2.534	0.0583	3.751	46.1	63.7	4	4
II8.5D #1	8.499	2.031	0.0583	3.875	46.1	63.7	6	6
II8.5D #2	8.499	2.031	0.0583	3.875	46.1	63.7	6	6
IIS6D #1	3.004	1.675	0.0465	2.254	46.4	51.2	4	4
IIS6D #2	3.004	1.675	0.0465	2.254	46.4	51.2	4	4
II10.5D #1	10.500	2.060	0.0583	1.393	46.1	63.7	8	14
II10.5D #2	10.500	2.060	0.0583	1.393	46.1	63.7	8	14

Note: C-leg: Cantilevered leg; A-leg: Anchored leg.

2.3 Test Results

2.3.1 Test Specimens with a Single Line of Screws on Cantilevered Leg

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 was performed. In the shear test program, two failure modes were observed. In the Phase II tests, all clip angles had relatively small aspect ratios (L/B < 0.81), the local buckling failure was the dominant failure mode. Figure 2.4 shows the results of a 54 mil clip angle (II10.5 #b1), and a local buckling failure can be observed in the test. Figure 2.5 shows a direct comparison of a 43 mil clip angle (S6) in both phases. With additional screws in the cantilevered leg, the clip yielded higher initial stiffness and greater peak load. It indicates that the screw spacing may have significant impact on the behavior and strength of a CFS clip angle in shear. At the beginning of the Phase II test program, a confirmatory test on a Phase II S6 clip angle was conducted to verify the test setup. The confirmatory test, as shown in Figure 2.5, matched the Phase I tests.

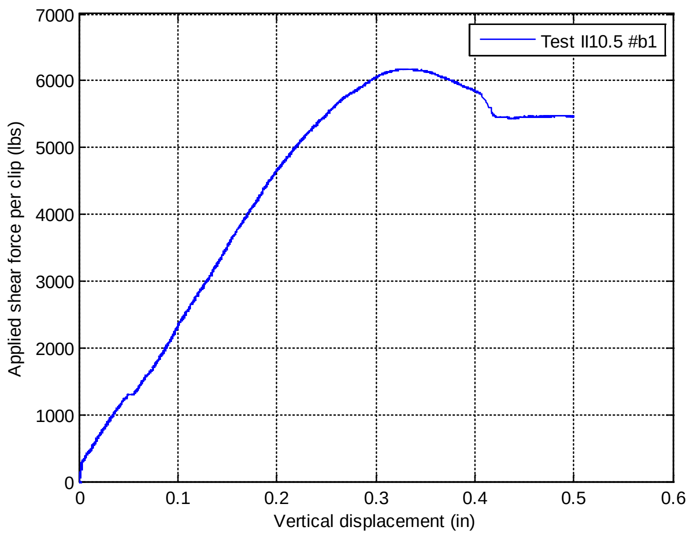


Figure 2.4: Test result of clip angle II10.5 b #1

The test results for clip angles with a single line of screws are provided in Table 2.3 in which V_{test} is the peak load per clip angle and $V_{1/8}$ is the maximum load per clip angle in the deflection range between 0 and 1/8 in. The deflection, Δ, is the displacement of the loading plate at the peak load. Δ can be considered as the average vertical deflection of the two clip angles used in each test.

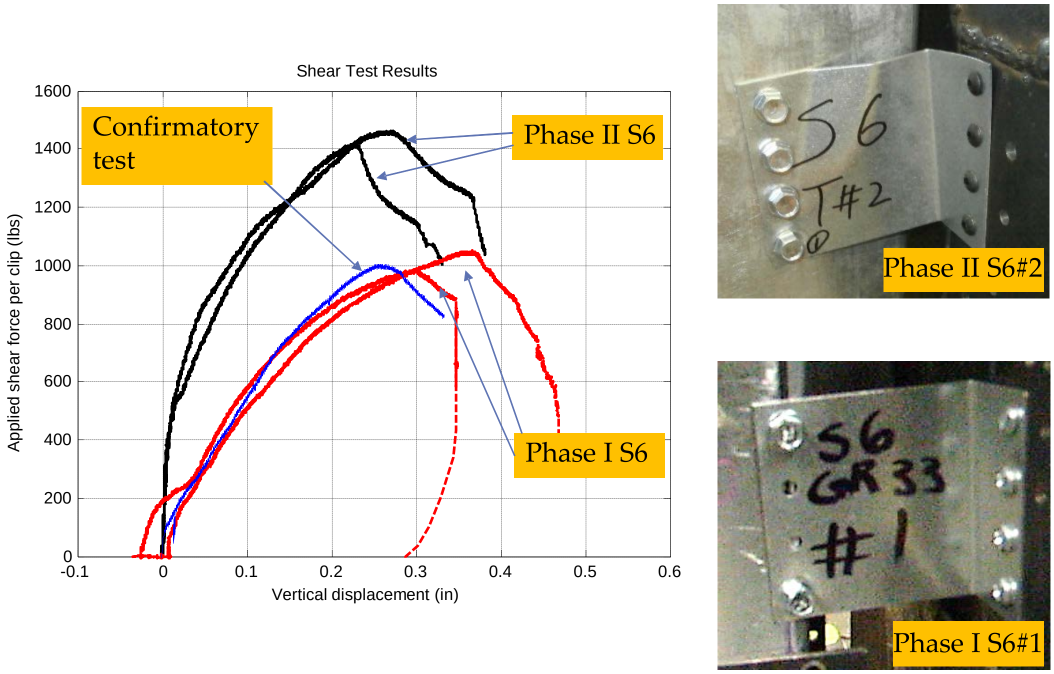


Figure 2.5: Test results of S6 clip angles

Table 2.3: Results of shear tests with a single line of screws

Test Label	V_{test} (lb)	Δ (in.)	$V_{1/8}$ (lb)
IIS3 #1	4648	0.243	3975
IIS3 #2	5081	0.239	3689
IIS6 #1	1416	0.225	1129
IIS6 #2	1460	0.265	1165
IIS8 #1	2200	0.172	2102
IIS8 #2	2077	0.168	1904
IIS9 #a1	3190	0.084	2859
IIS9 #a2	3246	0.118	2773
IIS9 #b1	2069	0.095	1937
IIS9 #b2	2173	0.105	2098
IIS10 #a1	4922	0.267	3228
IIS10 #a2	4850	0.238	4107
II4.5 #a1	1342	0.234	1012
II4.5 #a2	1311	0.167	1230
II4.5 #b1	1664	0.309	1016
II4.5 #b2	1821	0.376	1142
II8.5 #1	4525	0.264	2637
II8.5 #2	4136	0.508	2716
II10.5 #a1	7426	0.676	6506
II10.5 #a2	7842	0.178	6126
II10.5 #b1	5836	0.425	4466
II10.5 #b2	6178	0.328	2889
II6.5 #1	3451	0.235	3166
II6.5 #2	3197	0.191	3084
II8.5 #b1	4747	0.251	4175
II8.5 #b2	4328	0.192	4320
II10.5 #c1	7403	0.861	7259
II10.5 #c2	7391	0.26	7231

2.3.2 Test Specimens with a Double Line of Screws on Cantilevered Leg

When two lines of screws were installed on the cantilevered leg, the unbraced width of the cantilevered leg, L, was reduced which led to increased shear strength in the clip. The double line of screws also provided a more rigid boundary condition than that by a single line of screws. Figure 2.6 shows test results on a 54 mil clip angle with two different numbers of screw lines. Table 2.4 provides the test results for the shear tests with a double line of screws.

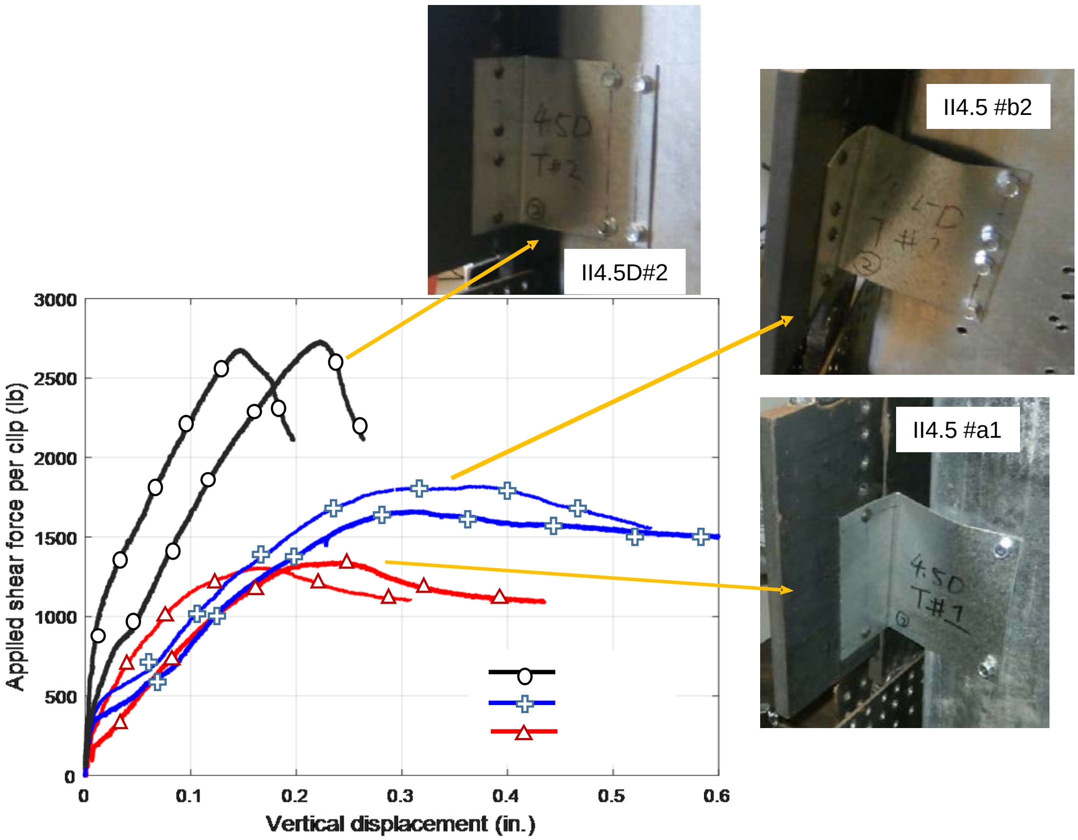


Figure 2.6: Test results of a 54 mil clip angle with different numbers of lines of screws

Table 2.4: Results of shear tests with a double line of screws

Test Label	V_{test} (lb)	Δ (in.)	$V_{1/8}$ (lb)
IIS9D #a1	3503	0.161	3176
IIS9D #a2	3261	0.185	2549
IIS9D #b1	4470	0.218	2764
IIS9D #b2	4471	0.151	4120
II4.5D #1	2706	0.222	1917
II4.5D #2	2650	0.147	2493
II8.5D #1	5620	0.571	3075
II8.5D #2	5272	0.419	2923
IIS6D #1	1636	0.225	1075
IIS6D #2	1526	0.164	1302
II10.5D #2	6999	0.314	3549
II10.5D #3	7579	0.357	4162

2.4 Finite Element Analysis

In the shear test program, 97 mil clip angles were also tested. However, all the tested 97 mil clip angles failed by screw failures. A failure in the cantilevered leg of 97 mil clip angles could not be achieved. Therefore, finite element models were developed in this research to investigate the strength of 97 mil clip angles.

2.4.1 Finite Element Modeling and Verification

The commercially available finite element software ABAQUS was used for the finite element modeling and analysis. The clip angle, screws, bolts, stud column and loading plate were modeled using 8-node linear brick solid elements with reduced integration and hourglass control (C3D8R). The top surface of the loading plate was coupled to a reference point to which the displacement was applied while the bolts connected to the clip angle and the loading plate. Surface-to-surface contact was set between the clip angle and the stud column, the loading plate and the screws. A friction formulation was adopted between the screw and the holes. There were two steps in the ABAQUS modeling: The first step was to increase the temperature of the screws to simulate the pressure when installing the self-drilling self-tapping screws. The second step was to apply the load to the loading plate through a forced displacement of the reference point.

Figure 2.7 shows the comparison between the ABAQUS results and the test results on II4.5#a clip angles. The deviation of the peak load between the finite element results and the tests is 5.8%. Figure 2.8 shows the comparison of the deformation shape at the peak load.

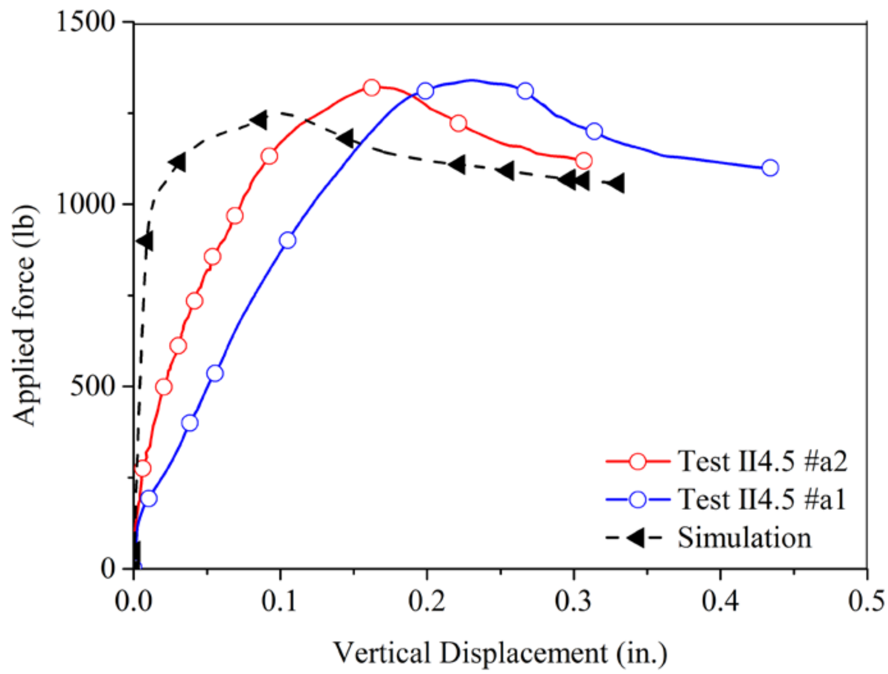
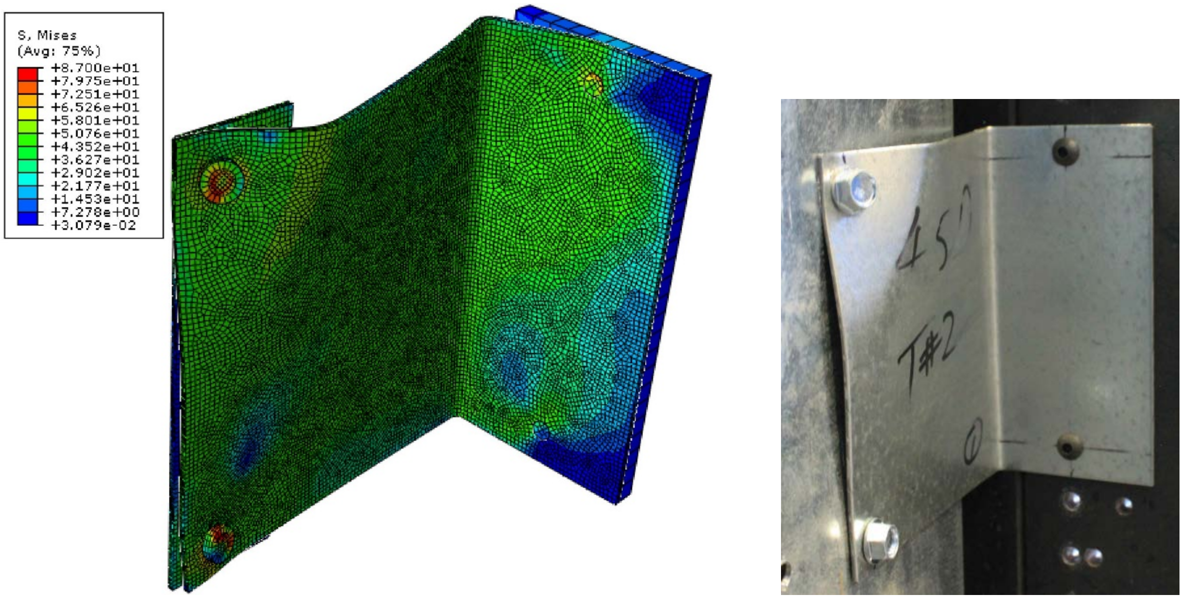


Figure 2.7: Load-displacement curves



ABAQUS model (b) Experiment

Figure 2.8: Failure mode (II4.5 #a2)

Figures 2.9 and 2.10 provide a comparison between the finite element model and the tests of an 8.5 in. deep clip angle. The difference between the finite element results and the test results is 13.5%.

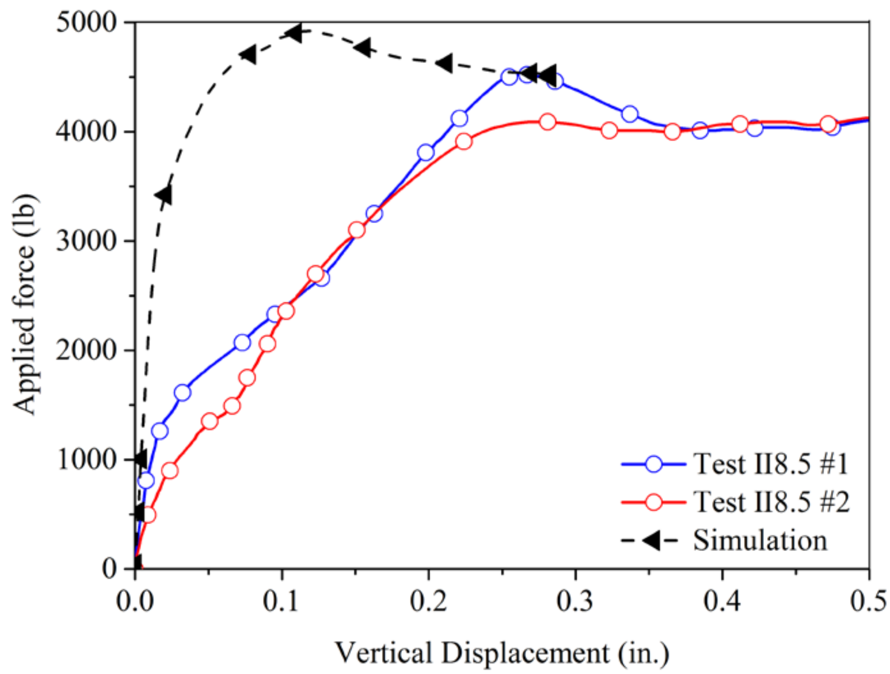
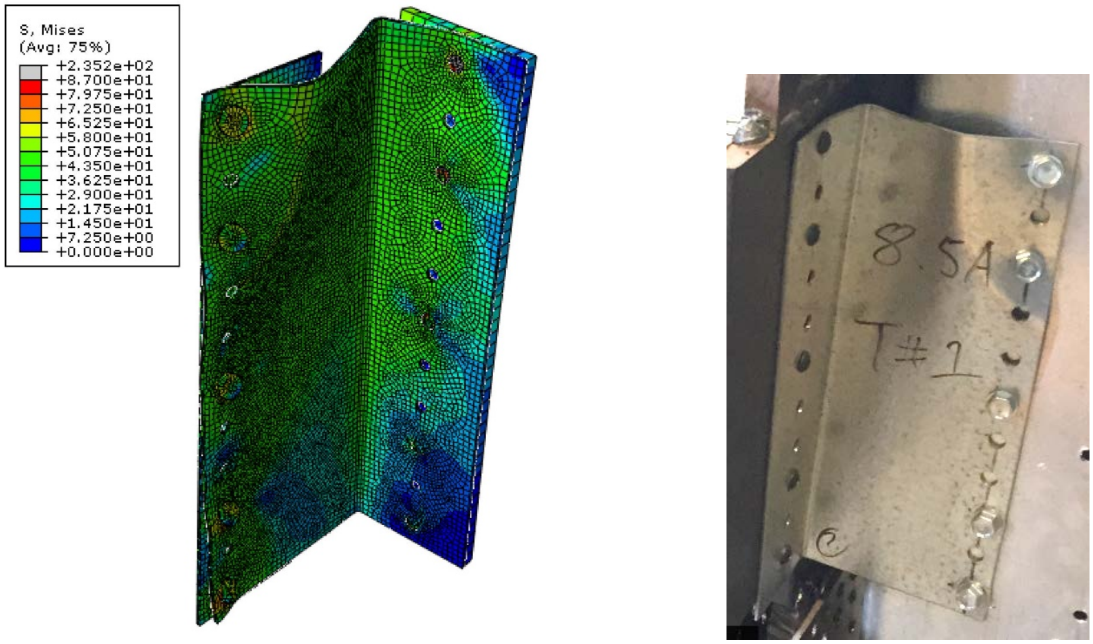


Figure 2.9: Load-displacement curves (Test 1 - II8.5 #1, Test 2 – II8.5 #2)



ABAQUS model (b) Experiment

Figure 2.10: Failure mode (Test II8.5 #1)

2.4.2 Results of Finite Element Analysis

The ABAQUS model proposed in this project was able to predict the shear strength of the CFS clip angles within a 15% variation. However, agreement on the initial stiffness was not reached. One possible reason could be the tilting of the screws was not successfully represented in the ABAQUS model. The finite element model was used to predict the shear strength of 97 mil clip angles with a single line of screws in this research. Table 2.5 summarizes the ABAQUS results. The actual material properties of the 97 mil clip angles were used in the ABAQUS models. The ABAQUS results have not been directly used in any of the test data calibrations subsequently being developed.

Table 2.5: Results of finite element analysis

Clip Label	B (in.)	L (in.)	t (in.)	S (in.)	F_y (ksi)	F_u (ksi)	# Screws on C-leg	# Bolts on A-leg	V_{FEA} (lb)
4.5F	4.5	3.3	0.097	0.750	52	60	6	6	5797
8.5F	8.5	3.3	0.097	0.775	52	60	11	11	13900
10.5F	10.5	3.3	0.097	0.750	52	60	14	14	19878
S3F	5.25	1.891	0.097	0.750	52	60	7	7	11315
S9F	7.536	2.405	0.097	0.754	52	60	10	10	15449
6.5F	6.5	3.407	0.097	0.719	52	60	5	5	8289

Note: C-leg: Cantilevered leg; A-leg: Anchored leg.

2.5 Comparison with Design Methods

2.5.1 Comparison with Phase I Design Method

A design method for determining the nominal shear strength without consideration of deformation of CFS clip angles with a single line of screws was developed in the Phase I project (Yu et al. 2015). The Phase I shear strength method is listed as follows:

Nominal shear strength

$$V_n = 0.17\lambda^{-0.8}F_yBt \leq 0.35F_yBt \tag{2.1}$$

Where $\lambda = \sqrt{\frac{F_y}{F_{cr}}}$ - Slenderness ratio (2.2)

$F_{cr} = \frac{k\pi^2E}{12(1-\mu^2)}(\frac{t}{B})^2$ - Critical elastic buckling stress (2.3)

E - Modulus of elasticity of CFS, 29500 ksi

μ - Poisson's ratio for steel, 0.3

$k = 2.569\left(\frac{L}{B}\right)^{-2.202}$ - Buckling coefficient (2.4)

t - Design thickness

B - Depth of clip angle

L - Flat width of clip angle, distance from the center of first line of screws to the bend line

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

Clip angle nominal thickness: 33 mils to 97 mils

Clip angle nominal yield strength: 33 ksi to 50 ksi

L/*B* ratio: 0.18 to 1.40

The Phase I and II test results were compared with the Phase I design method and the results are provided in Table 2.6. V_{test} is the tested peak load, V_n is the predicted nominal shear strength using the Phase I method. Figure 2.11 illustrates the comparison between the shear test results and the Phase I design method. The Phase I specimens had relatively large screw spacing on the cantilevered leg, while the Phase II specimens were designed to have various screw patterns and the screw spacing was generally closer than those of the Phase I specimens. Therefore, the Phase II specimens yielded higher shear strength than the Phase I specimens, as shown in Figure 2.11. The yield strength, V_y, in Figure 2.11 is defined as follows:

$$V_y = F_yBt \tag{2.5}$$

The shear design method proposed in Phase I gave conservative predictions for the majority of the Phase II tests. The screw spacing does have a significant impact on the shear strength of the CFS clip angle, and the design method will be revised to include the screw spacing in the equations as shown in Section 2.5.2.

Table 2.6: Comparison of test results with Phase I design method

	Test Label	V_{test} (lb)	V_n (lb)	V_{test}/V_n
Phase I	S1 #4	2594	2106	1.232
	S1 #5	2767	2102	1.316
	S3 #1	3794	3011	1.260
	S3 #2	3753	3012	1.246
	S4 #3	2581	2243	1.151
	S4 #4	2445	2239	1.092
	S5 # 3	3534	3144	1.124
	S5 # 4	3488	3146	1.109
	S6 #1	1050	779	1.348
	S6 #2	983	777	1.265
	S7 #1	4339	5012	0.866
	S7 #3	4319	4895	0.882
	S8 #3	2054	1756	1.169
	S8 #4	1912	1751	1.092
	S8 #5	2048	1751	1.169
	S9 #2	1787	1779	1.005
	S9 #3	1670	1780	0.938
	S10 #1	3268	3374	0.969
	S10 #2	3421	3387	1.010
	T1a #1	288	354	0.814
	T1a #2	328	351	0.935
	T1b #1	358	381	0.940
	T1b #2	315	381	0.827
	T1b #3	373	377	0.988
	T3 #1	845	825	1.024
	T3 #2	967	826	1.171
	T3 #3	932	828	1.126
	T4 #2	1028	1001	1.027
	T4 #3	993	1006	0.987
	T5a #1	319	353	0.903
	T5a #2	359	350	1.025
	T5b #1	250	361	0.692
	T5b #2	303	363	0.835

Table 2.6: Comparison of test results with Phase I design method (Continued)

	Test Label	V_{test} (lb)	V_n (lb)	V_{test}/V_n
Phase II (clips with a single line of screws only)	IIS3 #1	4648	3913	1.188
	IIS3 #2	5081	3887	1.307
	IIS6 #1	1416	878	1.613
	IIS6 #2	1460	878	1.663
	IIS8 #1	2200	1625	1.354
	IIS8 #2	2077	1625	1.278
	IIS9 #a1	3190	1490	2.141
	IIS9 #a2	3246	1490	2.178
	IIS9 #b1	2069	1490	1.388
	IIS9 #b2	2173	1490	1.458
	IIS10 #a1	4922	3552	1.386
	IIS10 #a2	4850	3552	1.366
	II4.5 #a1	1342	1551	0.865
	II4.5 #a2	1311	1551	0.845
	II4.5 #b1	1664	1551	1.073
	II4.5 #b2	1821	1551	1.174
	II8.5 #1	4525	3550	1.275
	II8.5 #2	4136	3550	1.165
	II10.5 #a1	7426	4477	1.659
	II10.5 #a2	7842	4477	1.752
	II10.5 #b1	5836	4477	1.304
	II10.5 #b2	6178	4477	1.380
	II6.5 #1	3451	2243	1.539
	II6.5 #2	3197	2243	1.425
	II8.5 #b1	4747	2997	1.584
	II8.5 #b2	4328	2997	1.444
	II10.5 #c1	7403	3354	2.207
	II10.5 #c2	7391	3354	2.203
Mean				1.242
St. Dev.				0.345
COV				0.278

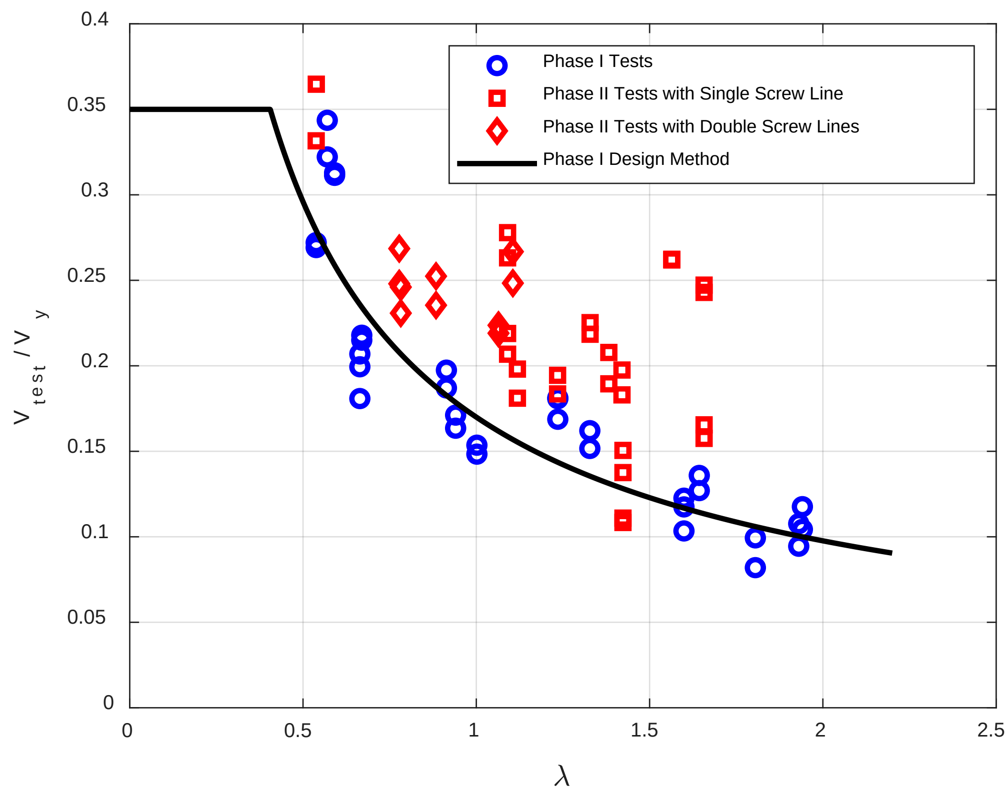


Figure 2.11: Comparison of test results with Phase I design method

2.5.2 Revised Design Method for Single Screw Line Configuration

To take account of the influence that screw spacing has, a screw spacing ratio, α, is defined as follows:

$$\alpha = S/B \tag{2.6}$$

Where, S is the screw spacing on the cantilevered leg and B is depth of clip angle. The α ratio is introduced and a modified design equation can be obtained by using nonlinear regression analysis of the test results from both phases for clip angles with a single line of screws:

Nominal shear strength

$$V_n = 0.12(\gamma)^{-0.4} F_y B t \leq 0.35 F_y B t \tag{2.7}$$

Where $\gamma = \alpha\lambda$ (2.8)

$$\lambda = \sqrt{\frac{F_y}{F_{cr}}} \text{ – Slenderness ratio} \tag{2.2}$$

$$\alpha = \frac{S}{B} \quad - \quad \text{Screw spacing ratio} \tag{2.6}$$

$F_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)}(\frac{t}{B})^2$ – Critical elastic buckling stress (2.3)

E – Modulus of elasticity of CFS, 29500 ksi

μ- Poisson's ratio for steel

$$k = 2.569(\frac{L}{B})^{-2.202} \quad (2.4)$$

t - Design thickness of clip angle

B - Depth of clip angle

S - Screw spacing on the cantilevered leg

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.

The above equations are valid within the following range of parameters and boundary conditions which are based on the specimens in both phases:

Clip angle nominal thickness: 33 mils to 97 mils

Clip angle nominal yield strength: 33 ksi to 50 ksi

L/*B* ratio: 0.18 to 1.40

The revised design method is based on the test results of clip angles with a single line of screws. Figure 2.12 illustrates the comparison between the design method with the test results. The revised method provides reasonable predictions for clip angles tested in both phases where a single line of screws was used.

The clip angles with a double line of screws yielded greater strength than the clip angles with a single line of screws, therefore the number of screw lines shall also be considered in the design. However, the test program had only a limited number of specimens with more than one line of screws, and only the configuration of two lines of screws was tested. Therefore, the revised design method (Eq. 2.7) does not take the number of screw lines into consideration, the revised design method gives conservative prediction for the clip angles with more than one line of screws on the cantilevered leg. Figure 2.23 show the comparison between the revised design method with the test and FEA results of the clip angles. Table 2.7 compares the test results with the revised design method. Only the results of clip angles with a single line of screws were used to develop the revised design equation (Eq. 2.7), therefore Table 2.7 lists only those clip angles.

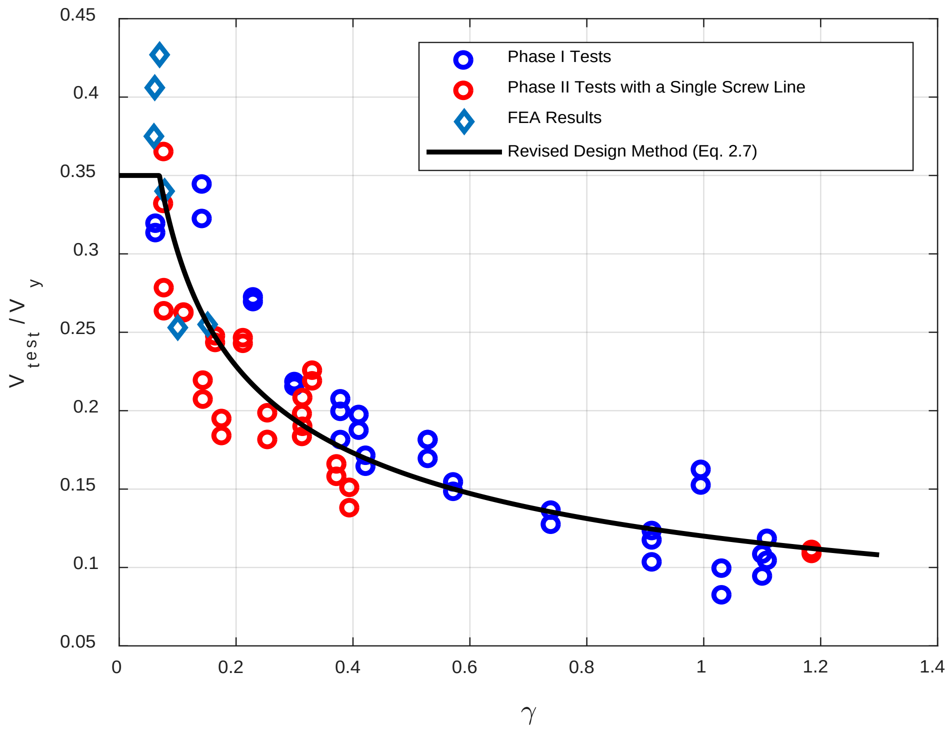


Figure 2.12: Comparison of the revised design method with test and FEA results of clip angles with a single line of screws

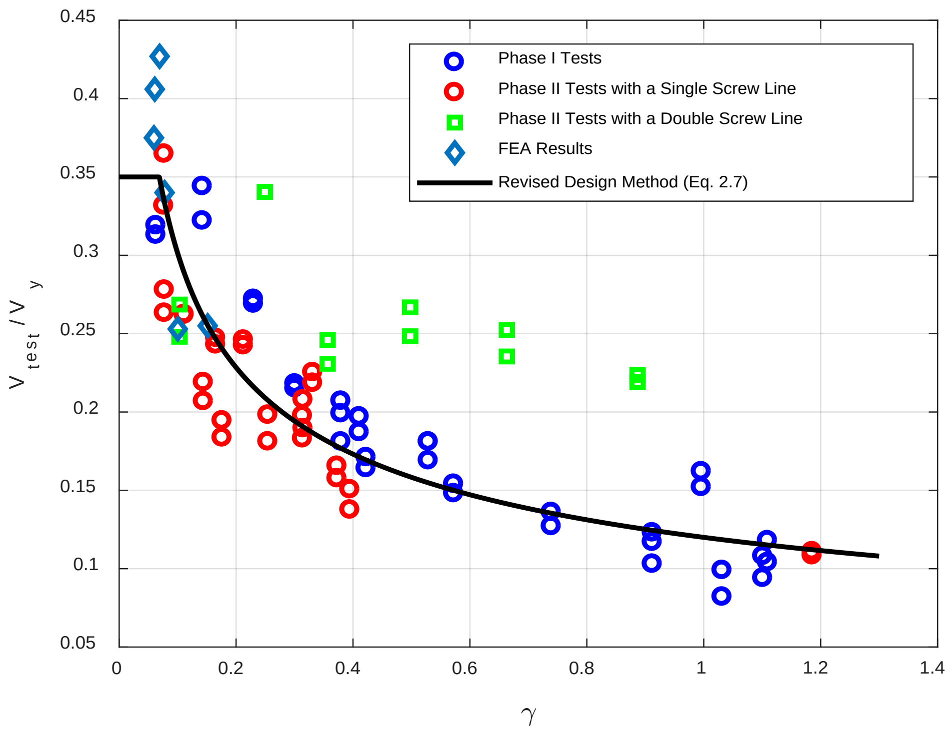


Figure 2.13: Comparison of the revised design method with test and FEA results of all clip angles

Table 2.7: Comparison of test results with the revised design method

	Test Label	γ	V_{test} (lb)	V_n (lb)	V_{test}/V_n
Phase I	S1 #4	0.143	2594	2106	1.232
	S1 #5	0.143	2767	2102	1.316
	S3 #1	0.230	3794	3011	1.260
	S3 #2	0.230	3753	3012	1.246
	S4 #3	0.411	2581	2243	1.151
	S4 #4	0.411	2445	2239	1.092
	S5 # 3	0.301	3534	3144	1.124
	S5 # 4	0.301	3488	3146	1.109
	S6 #1	0.996	1050	779	1.348
	S6 #2	0.996	983	777	1.265
	S7 #1	0.063	4339	5012	0.866
	S7 #3	0.063	4319	4895	0.882
	S8 #3	0.529	2054	1756	1.169
	S8 #4	0.529	1912	1751	1.092
	S8 #5	0.529	2048	1751	1.169
	S9 #2	0.740	1787	1779	1.005
	S9 #3	0.740	1670	1780	0.938
	S10 #1	0.423	3268	3374	0.969
	S10 #2	0.423	3421	3387	1.010
	T1a #1	1.101	288	354	0.814
	T1a #2	1.101	328	351	0.935
	T1b #1	0.913	358	381	0.940
	T1b #2	0.913	315	381	0.827
	T1b #3	0.913	373	377	0.988
	T3 #1	0.380	845	825	1.024
	T3 #2	0.380	967	826	1.171
	T3 #3	0.380	932	828	1.126
	T4 #2	0.573	1028	1001	1.027
	T4 #3	0.573	993	1006	0.987
	T5a #1	1.110	319	353	0.903
	T5a #2	1.110	359	350	1.025
	T5b #1	1.032	250	361	0.692
	T5b #2	1.032	303	363	0.835

Table 2.7: Comparison of test results with the revised design method (Continued)

	Test Label	γ	V_{test} (lb)	V_n (lb)	V_{test}/V_n
Phase II (clips with single line screws only)	IIS3 #1	0.077	4648	4695	0.990
	IIS3 #2	0.077	5081	4654	1.092
	IIS6 #1	0.332	1416	1209	1.171
	IIS6 #2	0.332	1460	1209	1.207
	IIS8 #1	0.177	2200	2717	0.810
	IIS8 #2	0.177	2077	2717	0.765
	IIS9 #a1	0.166	3190	3234	0.986
	IIS9 #a2	0.166	3246	3234	1.004
	IIS9 #b1	0.373	2069	2337	0.885
	IIS9 #b2	0.373	2173	2337	0.930
	IIS10 #a1	0.213	4922	4455	1.105
	IIS10 #a2	0.213	4850	4455	1.089
	II4.5 #a1	1.186	1342	1356	0.990
	II4.5 #a2	1.186	1311	1356	0.967
	II4.5 #b1	0.395	1664	2104	0.791
	II4.5 #b2	0.395	1821	2104	0.865
	II8.5 #1	0.255	4525	4735	0.956
	II8.5 #2	0.255	4136	4735	0.873
	II10.5 #a1	0.078	7426	9401	0.790
	II10.5 #a2	0.078	7842	9401	0.834
	II10.5 #b1	0.145	5836	7339	0.795
	II10.5 #b2	0.145	6178	7339	0.842
	II6.5 #1	0.314	3451	3331	1.036
	II6.5 #2	0.314	3197	3331	0.960
	II8.5 #b1	0.315	4747	4351	1.091
	II8.5 #b2	0.315	4328	4351	0.995
	II10.5 #c1	0.112	7403	8137	0.910
	II10.5 #c2	0.112	7391	8137	0.908
Mean					1.003
St. Dev.					0.150
COV					0.149

The LRFD and LSD resistance factors and the ASD safety factors for the revised shear design method for clip angles with a single line of screws were calculated following the Chapter K of the North American Specification for the Design of CFS Structural Members (AISI S100, 2016). The results are listed in Table 2.8.

Table 2.8: Resistance factors and safety factors for the revised shear design method

	Considered as Members – Shear and web Crippling
Quantity	61
Mean	1.003
Std. Dev.	0.150
COV	0.149
M_m	1.10
V_m	0.10
F_m	1.00
P_m	1.003
V_f	0.05
β (LRFD)	2.5
β (LSD)	3.0
V_Q	0.21
ϕ (LRFD)	0.83
ϕ (LSD)	0.67
Ω (ASD)	1.93

2.5.3 Revised Design Method for Clip Angles with either a Single or a Double Line of Screws

In Phase II of the research project, a relatively limited number of clip angles with a double line of screws were tested that had the same 3/4 in. distance between the centers of the screw lines. Therefore, before any comprehensive design method for clip angles with a double line or multiple lines of screws can be developed it is recommended that additional tests with a range of variations of the key parameters are needed.

Based on the available experimental results in this project, the increased shear strength of the clip angle due to the double line of screws, a simple, empirical amplification factor, β, has been introduced in Eq. 2.7 and shown as Eq. 2.9. Figure 2.13 shows the strength of the tested clip angles with both a single line of screws plotted with respect to the variable γ and the limited set of tested clip angles with a double line of screws overlaid on this same plot. The correlation factor, γ, that is used is again only based on the slenderness ratio of the clip angle material and the screw spacing ratio. To account for the increased shear strength due to the double line of screws for the tested specimens a limited parametric study was carried out. Based on this study an empirical amplification factor, β, was developed that is comprised of the correlation factor γ, but does not consider any other possible key parameters. The revised shear design method is presented as follows:

Nominal shear strength

$$V_n = \beta(\gamma)^{-0.4}F_yBt \le 0.35F_yBt \quad (2.9)$$

Where $\beta = 0.12$ for clip angle with a single line of screws

$= 0.12(1+\gamma)$ for clip angles with a double line of screws (2.10)

$\gamma = \alpha\lambda$ (2.8)

$\lambda = \sqrt{\frac{F_y}{F_{cr}}}$ – Slenderness ratio (2.2)

$\alpha = \frac{S}{B}$ – Screw spacing ratio (2.6)

$F_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)}(\frac{t}{B})^2$ – Critical elastic buckling stress (2.3)

E – Modulus of elasticity of CFS, 29500 ksi

μ – Poisson's ratio for steel

$k = 2.569(\frac{L}{B})^{-2.202}$ (2.4)

t - Design thickness of clip angle

B - Depth of clip angle

S - Screw spacing on the cantilevered leg

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.

The above equations are valid within the following range of parameters and boundary conditions which are based on the specimens in both phases:

Clip angle nominal thickness: 33 mils to 97 mils

Clip angle nominal yield strength: 33 ksi to 50 ksi

L/*B* ratio: 0.18 to 1.40

The spacing between the two screw lines on the cantilevered leg is ¾ in.

The simple amplification factor, β, was developed via a regression analysis on the test results of the clip angles with a double line of screws. Table 2.9 lists the test results and the nominal shear strength by the final shear design method, Eq. 2.9. Figure 2.24 illustrate the comparison of the final shear design method with the test results of all clip angles.

Table 2.9: Comparison of the test results and the design strength for Phase II clip angles with a double line of screws

Test Label	γ	V_{test} (lb)	V_n (lb)	V_{test}/V_n
IIS9D #a1	0.498	3503	3120	1.123
IIS9D #a2	0.498	3261	3120	1.045
IIS9D #b1	0.249	4470	3431	1.303
IIS9D #b2	0.249	4471	3431	1.303
II4.5D #1	0.887	2706	2874	0.942
II4.5D #2	0.887	2650	2874	0.922
II8.5D #1	0.357	5620	5617	1.001
II8.5D #2	0.357	5272	5617	0.939
IIS6D #1	0.663	1636	1525	1.073
IIS6D #2	0.663	1526	1525	1.001
II10.5D #2	0.103	6999	9268	0.755
II10.5D #3	0.103	7579	9268	0.818
Mean				1.019
St. Dev.				0.167
COV				0.164

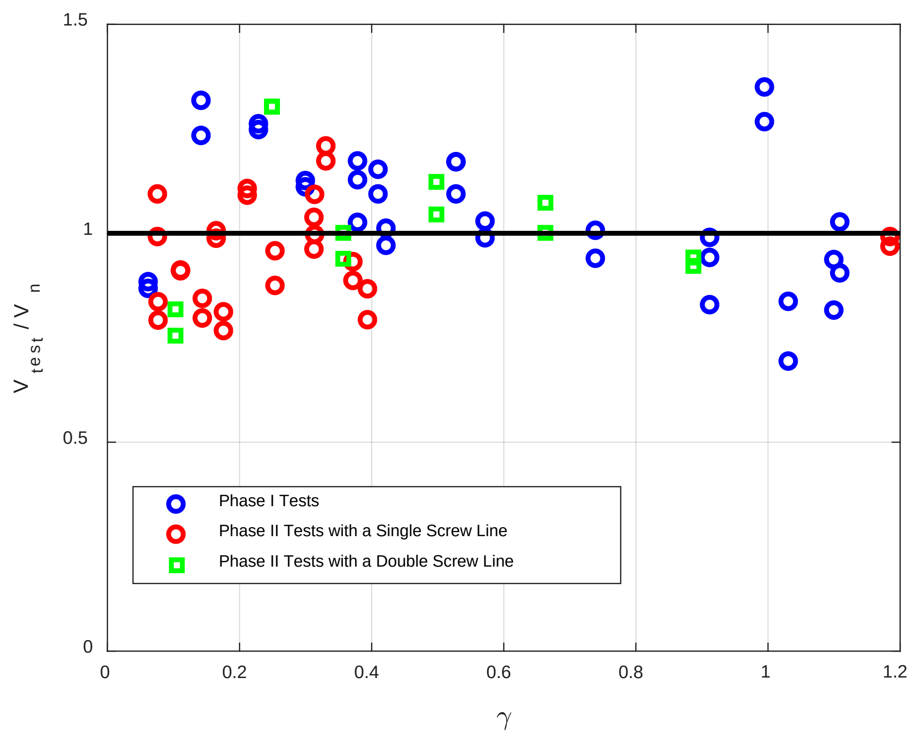


Figure 2.14: Comparison of the final shear design method with tests

The LRFD and LSD resistance factors and the ASD safety factors for the final shear design method for clip angles were calculated following the Chapter K of the North American Specification for the Design of CFS Structural Members (AISI S100, 2016). The results are listed in Table 2.10.

Table 2.10: Resistance factors and safety factors for the final shear design method

	Considered as Members – Shear and web Crippling
Quantity	73
Mean	1.005
Std. Dev.	0.151
COV	0.151
M_m	1.10
V_m	0.10
F_m	1.00
P_m	1.005
V_f	0.05
β (LRFD)	2.5
β (LSD)	3.0
V_Q	0.21
ϕ (LRFD)	0.83
ϕ (LSD)	0.67
Ω (ASD)	1.93

2.6 Shear Design Method for CFS Clip Angles with Consideration of Deformation

The shear design method for considering the deformation is essentially an assessment of the serviceability of the CFS clip angles. An alternative shear design method with consideration of deformation was developed by using the lower bound of the test results was developed in Phase I. A 1/8 in. deflection limit was used in the serviceability design. Figure 2.15 shows the comparison between the test results and the Phase I design method. It shows that the screw spacing has impact to the stiffness of the clip angle. Therefore a new design method is proposed herein to include the screw spacing effect in the serviceability check. And the average of the test results was used to develop the design method for the serviceability check.

The new design method for the nominal shear strength (lb, N) of CFS clip angles considering a 1/8 in. deformation limit is as follows:

$$V'_n = 4865\,\varepsilon\left[\frac{Bt}{L\alpha^{0.7}}\right]^{0.823} \le V_n \qquad (2.11)$$

Where

ε = 1 lb/in. for US customary units

= 0.175 N/mm for SI units

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

t – Design thickness of clip angle, in. [mm]

B – Depth of clip angle, in. [mm]

L – Flat length of clip angle, distance from the center of the first line of screws to the bend line, in. [mm]

V_n – Nominal shear strength without considering deformation, lb [N], Eq. 2.9

The same parametric ranges listed in Section 2.5.3 apply to the above equations.

The comparison between the test results and the calculated nominal strength by the new design method is shown in Figure 2.16. It was suggested that the serviceability of CFS clip angle in shear could be evaluated by the new design method without using a resistance factor or a safety factor.

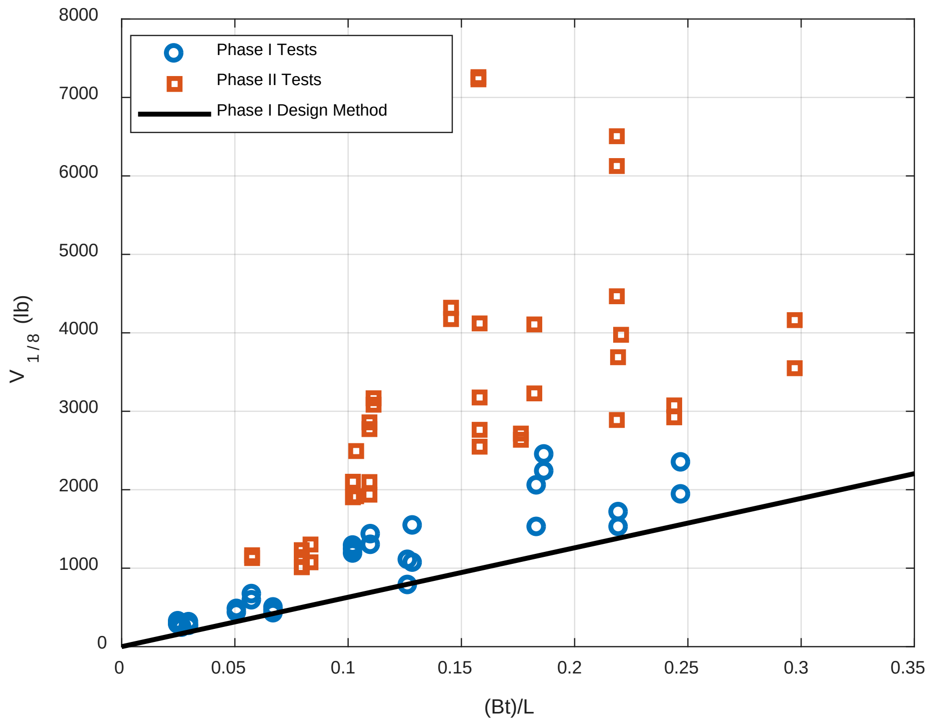


Figure 2.15: Comparison of shear test results with Phase I design method considering deformation limit

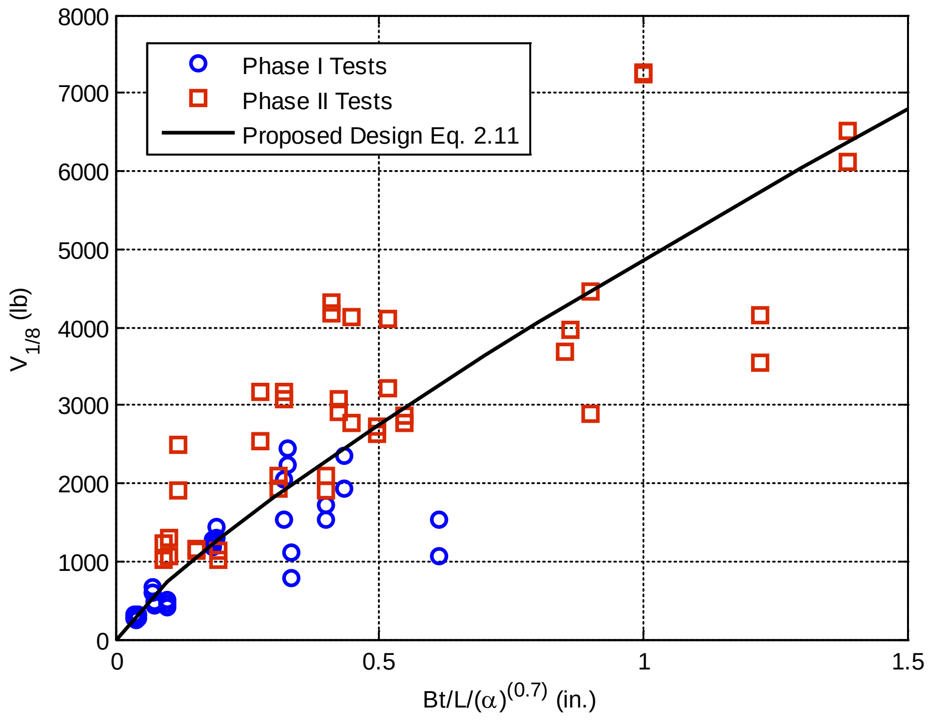


Figure 2.16: Comparison of shear test results with new design method considering deformation limit

3 COMPRESSION STRENGTH OF CLIP ANGLES

The compression test program in the Phase II project was to investigate the compression capacity and behavior of the clip angles with various screw patterns subjected to an axial load. The compression strength design method developed in Phase I was analyzed using the Phase II tests.

3.1 Test Setup and Test Procedure

The same test setup as used in Phase I was employed again in the Phase II tests. Figure 3.1 shows the setup for the compression tests. The anchored leg of the CFS 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 or 118 mil 20 in. long CFS stud member using No. 14-14×1 self-drilling self-tapping 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 was used. For clip angles with a thickness of 68 mils or greater, a 118 mil stud member was used. The CFS stud member was fixed to a steel loading plate through two lines of No. 14 screws. Four hold-downs, two on each side, were used as lateral supports to prevent the out-of-plane movement of the stud member. A position transducer was used to measure the vertical displacement of the loading plate. A universal compression/tension load cell was installed on the end of the hydraulic rod and connected to the loading plate on the other end. Figure 3.2 illustrates the loading direction and the measured dimensions listed in Table 3.1.

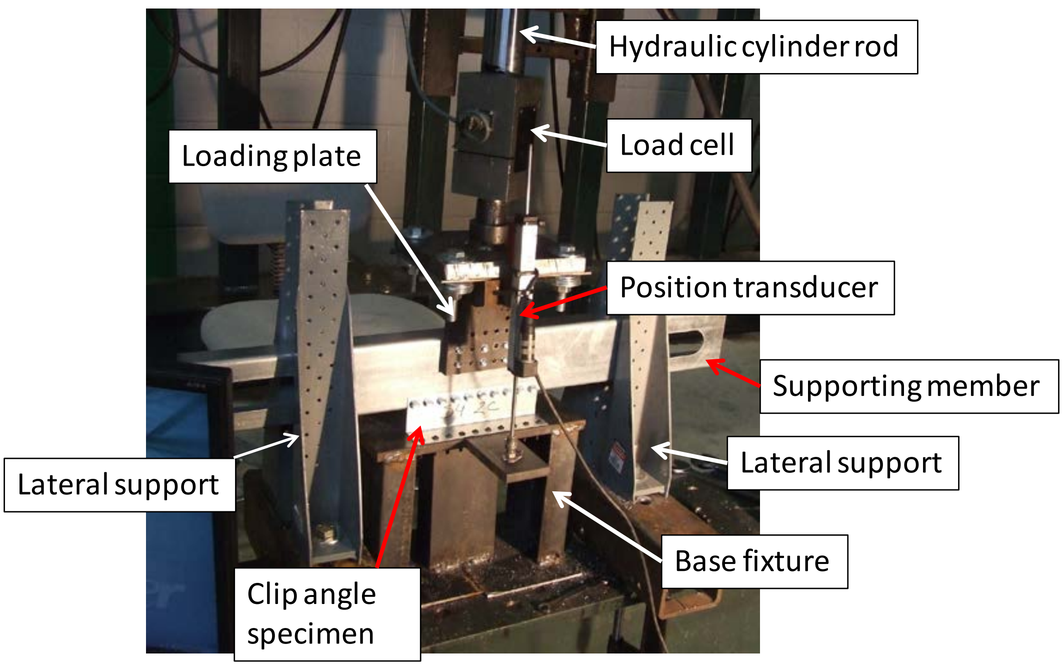


Figure 3.1: Test setup for compression tests

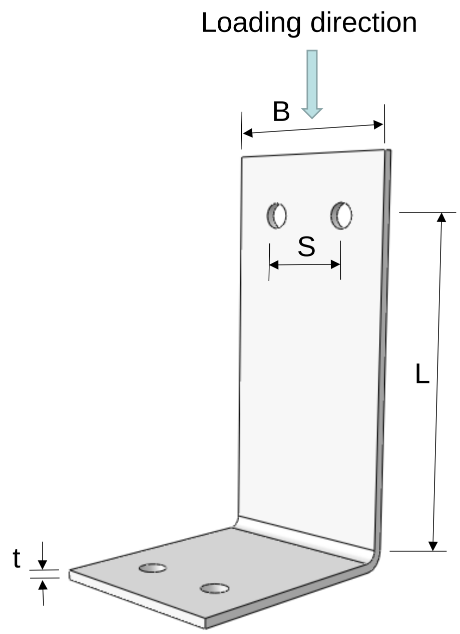


Figure 3.2: Loading direction and measured dimensions for compression tests

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 0.3 in. per minute which was the same as the load rate adopted in the Phase I tests.

3.2 Test Specimens

The clip angles used in the compression tests had the same edge distance and definition of dimensions as illustrated in Figures 2.2 and 2.3. The test specimen variations included material thickness, aspect ratio of the cantilevered leg, screw spacing on the cantilevered leg, and the number of screw lines on the cantilevered leg. The compression test program in Phase II included a total of 50 tests with the clip angle's nominal thickness range between 33 mils and 118 mils. The measured dimensions and tested material properties are provided in Tables 3.1 and 3.2, respectively for the clip angles with a single and a double line of screws on the cantilevered leg. The definitions of the measured dimensions in Tables 3.1 and 3.2 are the same as those defined in the shear test program.

Table 3.1: Properties of clip angles with a single line of screws in the compression test program

Test label	B (in.)	L (in.)	t (in.)	F_y (ksi)	F_u (ksi)	S (in.)
IIS3 #a1	5.253	1.352	0.0584	45.6	50	2.250
IIS3 #a2	5.253	1.352	0.0584	45.6	50	2.250
IIS3 #a3	5.253	1.352	0.0584	45.6	50	2.250
IIS9 #a1	7.500	2.341	0.0349	49.9	55.8	0.960
IIS9 #a2	7.500	2.358	0.0349	49.9	55.8	0.960
IIS9 #b1	7.500	2.341	0.0349	49.9	55.8	1.350
IIS9 #b2	7.500	2.358	0.0349	49.9	55.8	1.350
II4.5 #a1	4.501	3.300	0.0583	46.1	63.7	3.750
II4.5 #a2	4.501	3.300	0.0583	46.1	63.7	3.750
II4.5 #a3	4.501	3.300	0.0583	46.1	63.7	3.750
II4.5 #b1	4.501	3.300	0.0583	46.1	63.7	1.250
II4.5 #b2	4.501	3.300	0.0583	46.1	63.7	1.250
II4.5 #b3	4.501	3.300	0.0583	46.1	63.7	1.250
II4.5 #b4	4.501	3.300	0.0583	46.1	63.7	1.250
II8.5 #a1	8.499	2.811	0.0583	46.1	63.7	1.940
II8.5 #a2	8.499	2.811	0.0583	46.1	63.7	1.940
II8.5 #a3	8.499	2.811	0.0583	46.1	63.7	1.940
II8.5 #b1	8.499	2.811	0.0583	46.1	63.7	0.770
II8.5 #b2	8.499	2.811	0.0583	46.1	63.7	0.770
II8.5 #b3	8.499	2.811	0.0583	46.1	63.7	0.770
II8.5 #c1	8.499	3.53	0.0583	46.1	63.7	0.770
II8.5 #c2	8.499	3.53	0.0583	46.1	63.7	0.770
II8.5 #c3	8.499	3.53	0.0583	46.1	63.7	0.770
II10.5 #a1	10.5	2.8	0.0583	46.1	63.7	1.390
II10.5 #a2	10.5	2.8	0.0583	46.1	63.7	1.390
II10.5 #a3	10.5	2.8	0.0583	46.1	63.7	1.390
II10.5 #b1	10.5	2.8	0.0583	46.1	63.7	0.750
II10.5 #b2	10.5	2.8	0.0583	46.1	63.7	0.750
II10.5 #c1	10.5	2.14	0.0583	46.1	63.7	0.750
II10.5 #c2	10.5	2.14	0.0583	46.1	63.7	0.750
IIT6 #1	1.748	2.336	0.1352	49.6	53.2	0.500
IIT6 #2	1.748	2.336	0.1352	49.6	53.2	0.500

Table 3.2: Properties of clip angles with a double line of screws in the compression test program

Test label	B (in.)	L (in.)	t (in.)	F_y (ksi)	F_u (ksi)	S (in.)
II4.5D #a1	4.501	1.623	0.0989	54.2	63.9	1.250
II4.5D #a2	4.501	1.623	0.0989	54.2	63.9	1.250
II4.5D #b1	4.501	2.534	0.0583	46.1	63.7	3.750
II4.5D #b2	4.501	2.534	0.0583	46.1	63.7	3.750
II4.5D #b3	4.501	2.534	0.0583	46.1	63.7	3.750
II8.5D #a1	8.499	2.071	0.0583	46.1	63.7	3.870
II8.5D #a2	8.499	2.071	0.0583	46.1	63.7	3.870
II8.5D #b1	8.499	2.790	0.0583	46.1	63.7	1.940
II8.5D #b2	8.499	2.790	0.0583	46.1	63.7	1.940
II10.5D #a1	10.500	2.040	0.0583	46.1	63.7	3.250
II10.5D #a2	10.500	2.040	0.0583	46.1	63.7	3.250
II10.5D #a3	10.500	2.040	0.0583	46.1	63.7	3.250
II10.5D #b1	10.500	1.380	0.0583	46.1	63.7	1.390
II10.5D #b2	10.500	1.380	0.0583	46.1	63.7	1.390
IIS9D #a1	5.253	0.600	0.0584	49.9	55.8	2.250
IIS9D #a2	5.253	0.600	0.0584	49.9	55.8	2.250
IIT3D #1	1.753	0.754	0.0583	45.6	50.0	1.000
IIT3D #2	1.753	0.754	0.0583	45.6	50.0	1.000

3.3 Test Results

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 was performed. The test program showed that global buckling was the primary failure mode for the tested clip angles under compression. Figure 3.3 shows a comparison of a 54 mil clip angle with two different screw patterns. The two tests gave similar results. The test results are provided in Tables 3.3 and 3.4.

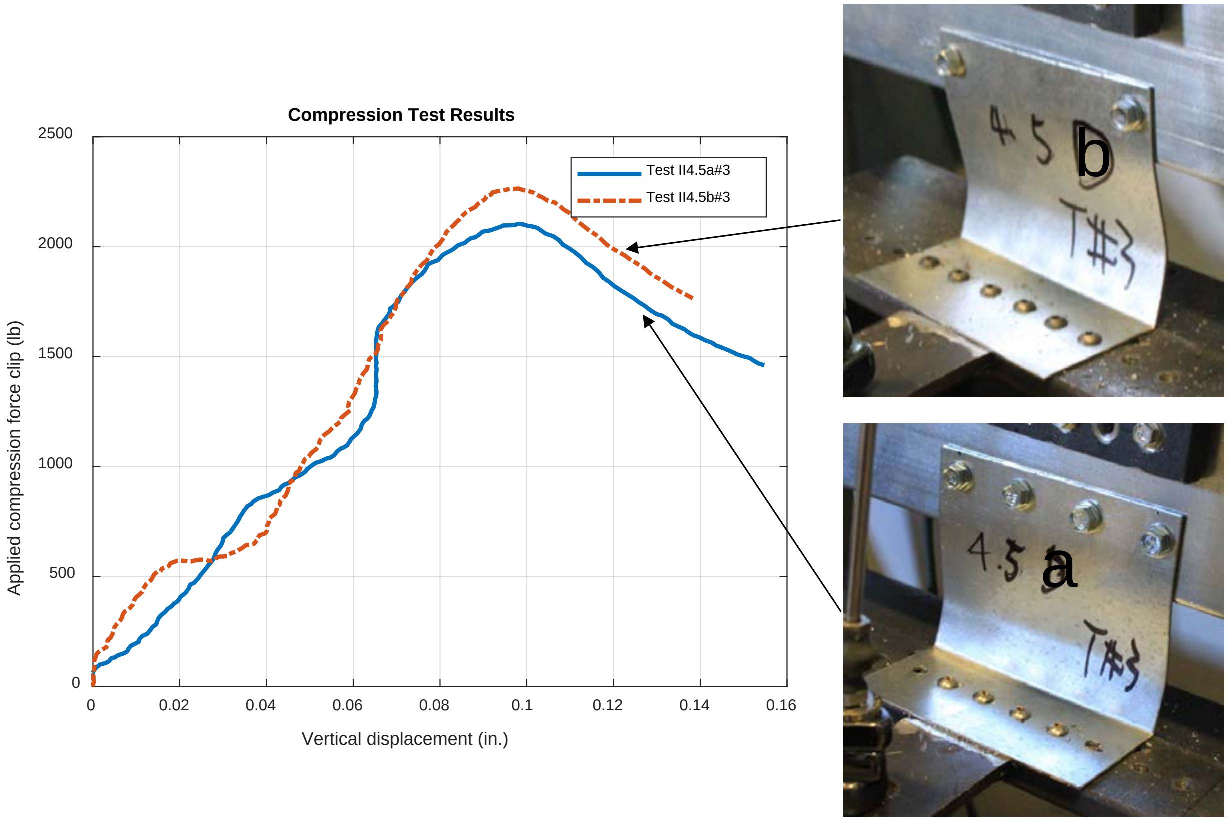


Figure 3.3: Comparison of two 54 mil clip angles with different screw patterns

Table 3.3: Results of compression tests of clip angles with a single line of screws

Test Label	P_{test} (lb)	Δ (in.)
IIS3 #a1	2355	0.136
IIS3 #a2	3216	0.187
IIS3 #a3	2964	0.194
IIS9 #a1	1238	0.196
IIS9 #a2	1118	0.099
IIS9 #b1	1388	0.054
IIS9 #b2	1549	0.084
II4.5 #a1	1970	0.160
II4.5 #a2	1682	0.112
II4.5 #a3	2142	0.099
II4.5 #b1	1956	0.120
II4.5 #b2	1665	0.083
II4.5 #b3	2300	0.095
II4.5 #b4	2322	0.071
II8.5 #a1	3819	0.161
II8.5 #a2	3114	0.123
II8.5 #a3	3886	0.156
II8.5 #b1	3758	0.088
II8.5 #b2	3070	0.077
II8.5 #b3	4141	0.102
II8.5 #c1	4197	0.080
II8.5 #c2	3576	0.084
II8.5 #c3	3996	0.089
II10.5 #a1	4337	0.172
II10.5 #a2	3856	0.131
II10.5 #a3	4169	0.079
II10.5 #b1	4737	0.142
II10.5 #b2	4392	0.182
II10.5 #c1	4106	0.024
II10.5 #c2	4001	0.087
IIT6 #1	4115	0.135
IIT6 #2	4144	0.125

Table 3.4: Results of compression tests of clip angles with a double line of screws

Test Label	P_{test} (lb)	Δ (in.)
II4.5D #a1	7056	0.136
II4.5D #a2	7390	0.154
II4.5D #b1	2015	0.118
II4.5D #b2	1615	0.239
II4.5D #b3	1988	0.091
II8.5D #a1	3902	0.117
II8.5D #a2	3948	0.138
II8.5D #b1	3574	0.110
II8.5D #b2	3323	0.147
II10.5D #a1	5260	0.148
II10.5D #a2	4243	0.183
II10.5D #a3	5586	0.191
II10.5D #b1	3993	0.044
II10.5D #b2	4158	0.117
IIS9D #a1	1475	0.113
IIS9D #a2	1418	0.075
IIT3D #1	1136	0.046
IIT3D #2	1167	0.068

3.4 Comparison with Phase I Design Method

The Phase I work developed a design method to calculate the nominal compression strength of the cantilevered leg of the clip angle as follows:

The nominal compression strength

$$P_n = A_g F_n \tag{3.1}$$

Where

$$A_g = B't \tag{3.2}$$

$$F_n = 0.0028\lambda^{1.44} F_{cr} \leq 0.4F_y \tag{3.3}$$

$$\lambda = \frac{L}{t} \tag{3.4}$$

$F_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)}\left(\frac{t}{L}\right)^2$ - critical elastic buckling stress (Houbolt and Stowell, 1950) (3.5)

E - Modulus of elasticity of CFS, 29500 ksi

μ - Poisson's ratio for steel, 0.3

k - Buckling coefficient can be found by interpolation in Table 3.5

= 0.90 as a conservative value

t - Design thickness of clip angle

B' - Lesser of the actual clip angle width or the Whitmore section width (Figure 3.4) if applicable

L - Flat width of clip angle, distance between the bend to the closest line of screws to the bend

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

Clip angle nominal thickness: 33 mils to 118 mils

Clip angle nominal yield strength: 33 ksi to 50 ksi

L/B ratio: 0.18 to 1.40

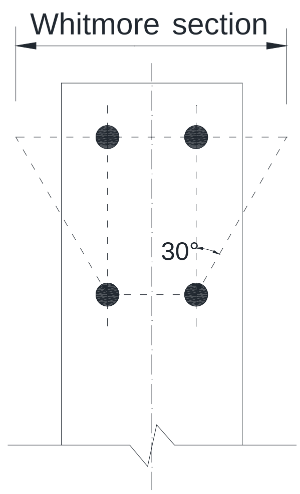


Figure 3.4: Whitmore section width

Table 3.5: 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

Figure 3.6 shows the comparison between the test results of both phases and the Phase I design method for compression. The Phase II test results have a good agreement with the Phase I design method and the screw patterns (spacing and number of lines) have limited impact to the compression strength of the clip angle. The Phase I design method can be applied to the screw

patterns investigated in this phase of the project. Tables 3.6 and 3.7 list the calculation results for Figure 3.5.

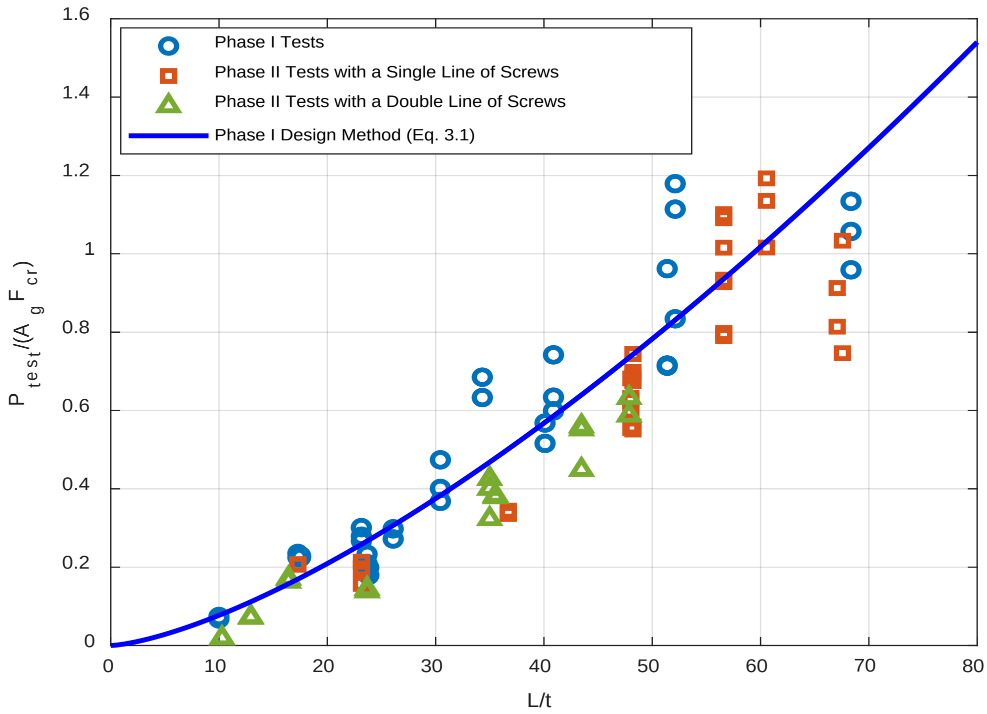


Figure 3.5: Comparison of test results with Phase I design method

Table 3.6: Results for clip angles with a single line of screws

Test Label	L/t	F_{cr} (ksi)	F_n (ksi)	P_{test} / P_n
IIS3 #a1	23.15	48.868	12.623	0.608
IIS3 #a2	23.12	49.014	12.634	0.830
IIS3 #a3	23.12	49.014	12.634	0.765
IIS9 #a1	67.08	5.810	6.944	0.681
IIS9 #a2	67.56	5.726	6.915	0.618
IIS9 #b1	67.08	5.810	6.944	0.764
IIS9 #b2	67.56	5.726	6.915	0.856
II4.5 #a1	56.60	8.037	7.523	0.998
II4.5 #a2	56.60	8.037	7.523	0.852
II4.5 #a3	56.60	8.037	7.523	1.085
II4.5 #b1	56.60	8.037	7.523	0.991
II4.5 #b2	56.60	8.037	7.523	0.843
II4.5 #b3	56.60	8.037	7.523	1.165
II4.5 #b4	56.60	8.037	7.523	1.176
II8.5 #a1	48.22	11.237	8.348	0.923
II8.5 #a2	48.22	11.237	8.348	0.753
II8.5 #a3	48.22	11.237	8.348	0.939
II8.5 #b1	48.22	11.237	8.348	0.908
II8.5 #b2	48.22	11.237	8.348	0.742
II8.5 #b3	48.22	11.237	8.348	1.001
II8.5 #c1	60.55	7.104	7.327	1.156
II8.5 #c2	60.55	7.104	7.327	0.985
II8.5 #c3	60.55	7.104	7.327	1.101
II10.5 #a1	48.03	11.351	8.386	0.845
II10.5 #a2	48.03	11.351	8.386	0.751
II10.5 #a3	48.03	11.351	8.386	0.812
II10.5 #b1	48.03	11.351	8.386	0.923
II10.5 #b2	48.03	11.351	8.386	0.856
II10.5 #c1	36.71	19.475	9.770	0.687
II10.5 #c2	36.71	19.475	9.770	0.669
IIT6 #1	17.28	84.392	14.304	1.217
IIT6 #2	17.28	84.392	14.304	1.226

Table 3.7: Results for clip angles with a double line of screws

Test Label	L/t	F_{cr} (ksi)	F_n (ksi)	P_{test} / P_n
II4.5D #a1	16.41	96.901	15.250	1.039
II4.5D #a2	16.41	96.901	15.250	1.089
II4.5D #b1	43.46	13.714	8.775	0.875
II4.5D #b2	43.46	13.714	8.775	0.701
II4.5D #b3	43.46	13.714	8.775	0.863
II8.5D #a1	35.52	20.766	9.937	0.793
II8.5D #a2	35.52	20.766	9.937	0.802
II8.5D #b1	47.86	11.408	8.384	0.860
II8.5D #b2	47.86	11.408	8.384	0.800
II10.5D #a1	34.99	21.439	10.038	0.856
II10.5D #a2	34.99	21.439	10.038	0.690
II10.5D #a3	34.99	21.439	10.038	0.909
II10.5D #b1	23.67	46.953	12.522	0.521
II10.5D #b2	23.67	46.953	12.522	0.542
IIS9D #a1	10.27	249.384	19.960	0.241
IIS9D #a2	10.27	249.384	19.960	0.232
IIT3D #1	12.93	155.631	17.382	0.639
IIT3D #2	12.93	155.631	17.382	0.657

By using the test results from both phases, the LRFD and LSD resistance factors and the ASD safety factors for the proposed compression design method can be recalculated following Chapter K of the AISI S100 (2016). The results are listed in Table 3.8.

Table 3.8: Resistance factors and safety factors for the compression design method of Phase I

	Considered as Members - Compression
Quantity	86
Mean	0.922
Std. Dev.	0.242
COV	0.262
M_m	1.10
V_m	0.10
F_m	1.00
P_m	0.922
V_f	0.05
β (LRFD)	2.5
β (LSD)	3.0
V_Q	0.21
ϕ (LRFD)	0.63
ϕ (LSD)	0.49
Ω (ASD)	2.54

4 SERVICEABILITY OF CLIP ANGLES IN TENSION

The tension test program in Phase II focused on the serviceability of CFS clip angles when the cantilevered leg was in tension. The tests investigated the tension strength of the clip angles when the deflection limit of 1/8 in. was reached. The service deflection limit of 1/8 in. was selected according to the Acceptance Criteria For Connectors Used With Cold-Formed Steel Structural Members ICC-ES AC261 (2011).

4.1 Test Setup and Test Procedure

The tension test setup in Phase II was similar to the compression test setup except that (1) the hydraulic cylinder moved the loading plate upwards to apply a tension force to the cantilevered leg of the clip angle, (2) No. 8 or No. 12 self-drilling self-tapping screws were used to anchor the clip angles to the steel base fixture, and (3) a 118 mil steel backing sheet (shown in Figure 4.1) was used at the bottom side the structural steel base to hold the screws in place. The data acquisition system and the hydraulic loading system were the same as used in the shear and compression tests. The pull-over tests were conducted in a displacement control mode at a constant speed of 0.3 in. per minute. The loading rate was the same as shear and compression tests.

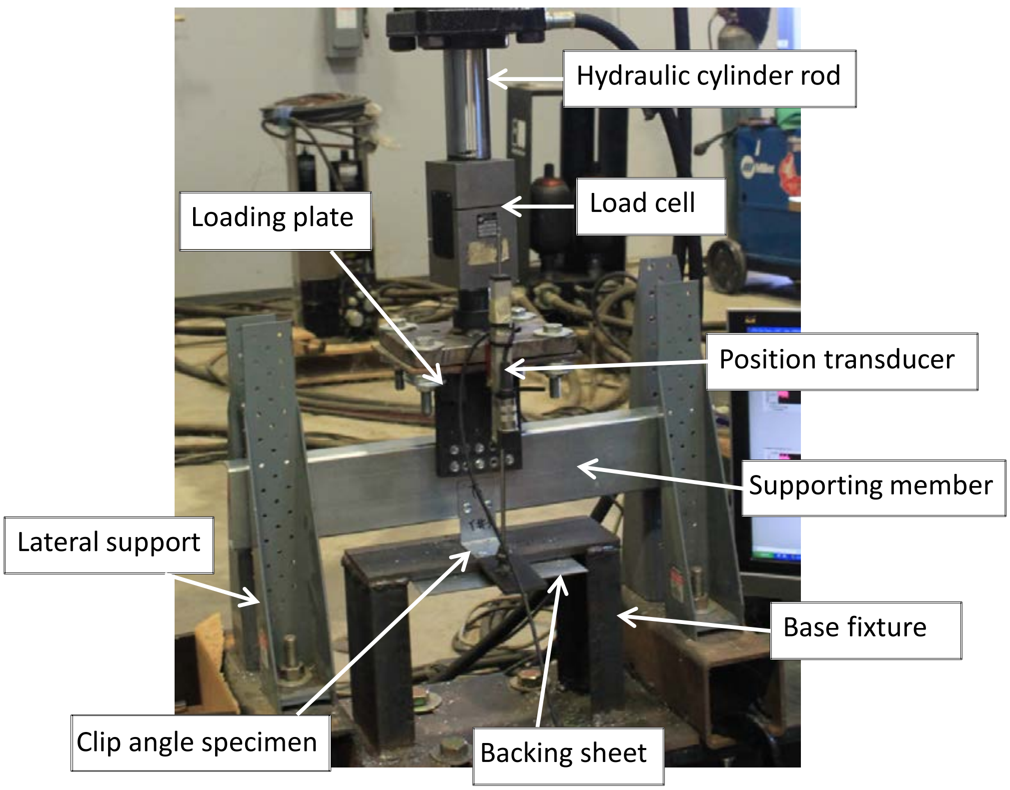


Figure 4.1: Test setup for tension tests

4.2 Test Specimens

Phase II of the project included a total of 25 tension tests. Similar to the Phase I specimens, the cantilevered leg was fully screwed to the supporting CFS channel member and the number of screws on the anchored leg varied. Both cantilevered leg and anchored leg used the same type of screws (No. 8 or No. 12 screws).

The nominal thickness of the test specimens ranged from 33 mils to 118 mils. Table 4.1 lists the measured dimensions, screw configurations, and tested material properties for the Phase II tests. As illustrated in Figure 4.2, L measures the flat length of the anchored leg between the center of the first line of screws and the bend line; B is the width of the clip angle; and t is the uncoated steel thickness. The d'_w is the measured hex washer head integral washer diameter. The yield stress, F_y, and tensile strength, F_u, were obtained from coupon tests conducted according to ASTM A370 Standard Test Method and Definitions for Mechanical Testing of Steel Products (2014). The clips had pre-punched holes for all screws. The diameter of the pre-punched holes were 0.218 in. for "S", "4.5A", "4.5D" clip angles and 0.190 in. for "T" clip angles. The edge distance from the center of the hole to its nearest edge was 0.375 in. for all specimens.

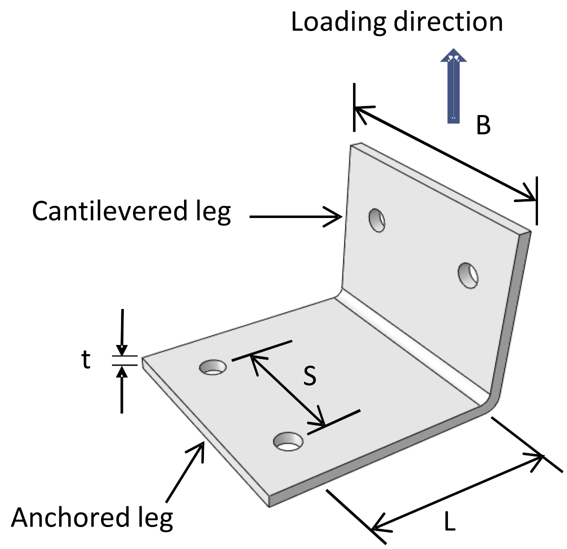


Figure 4.2: Loading direction and measured dimensions

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

Test Label	L (in.)	B (in.)	t (in.)	d'_w (in.)	No. of Screws[1]	Screw Size[1]	F_y (ksi)	F_u (ksi)
T3	1.524	1.752	0.059	0.323	2	8	45.7	50.1
S5	0.898	7.500	0.047	0.323	4	8	46.4	51.2
4.5D_D1a	0.921	4.500	0.059	0.323	2	8	46.1	63.7
4.5D_D1b	0.921	4.500	0.059	0.323	4	8	46.1	63.7
4.5D_D0.75a	0.673	4.500	0.059	0.323	2	8	46.1	63.7
4.5D_D0.75b	0.673	4.500	0.059	0.323	4	8	46.1	63.7
4.5D_D1.5	1.421	4.500	0.059	0.323	4	8	46.1	63.7
4.5A_D1a	0.906	4.500	0.098	0.413	2	12	54.2	64.0
4.5A_D1b	0.906	4.500	0.098	0.413	4	12	54.2	64.0
4.5A_D0.75a	0.654	4.500	0.098	0.413	2	12	54.2	64.0
4.5A_D0.75b	0.654	4.500	0.098	0.413	4	12	54.2	64.0
4.5A_D1.5	1.406	4.500	0.098	0.413	4	12	54.2	64.0
(1) - the screws refer to those used on the anchored leg.								

4.3 Test Results

For each specimen configuration, a minimum of two tests were performed. If the difference in the peak load between the first two tests was greater than 10% of the average result, a third test was conducted. Since Phase II's research was focused on the tensile strength of the clip angle at the service deflection limit, the tests were not performed to achieve the ultimate strength of the clip angle in tension. Figure 4.3 shows the deflection of a 97 mil clip angle with No. 12 self-drilling screws at the service deflection limit of 1/8 in. The initial stiffness was relatively small and the tension resistance was provided mainly by the bending of the angle. The results of the Phase II tests are listed in Table 4.2.

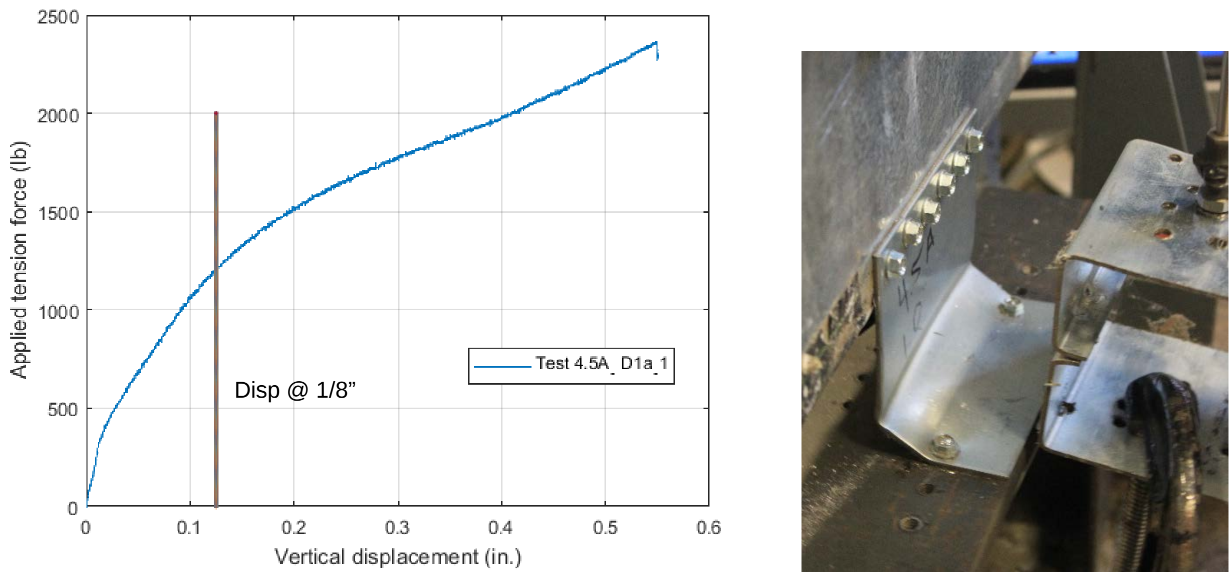


Figure 4.3: Typical behavior of a clip angle in Phase II

Table 4.2: Results of tension tests of Phase II

Test Label	$P_{1/8}$ (lb)
T3_1	133
S5_1	480
S5_2	515
4.5D_D1a_1	361
4.5D_D1a_2	342
4.5D_D1b_1	413
4.5D_D1b_2	454
4.5D_D0.75a_1	482
4.5D_D0.75a_2	513
4.5D_D0.75b_1	648
4.5D_D0.75b_2	614
4.5D_D1.5_1	228
4.5D_D1.5_2	225
4.5A_D1a_1	1214
4.5A_D1a_2	1233
4.5A_D1b_1	1709
4.5A_D1b_2	1643
4.5A_D0.75a_1	1185
4.5A_D0.75a_2	1767
4.5A_D0.75a_3	1677
4.5A_D0.75b_1	2380
4.5A_D0.75b_2	2602
4.5A_D1.5_1	915
4.5A_D1.5_2	684
4.5A_D1.5_3	769

4.4 Proposed Tensile Strength for CFS Clip Angles at the Deformation Limit of Serviceability

4.4.1 Analytical Model

Since the cantilevered leg of clip angle moved as a rigid body during the test and most of the deflection came from the deformation of the anchored leg, the mechanical model of the clip angle can be viewed as a beam element as shown in Figure 4.4.

Figure 4.4: Mechanical model of a clip angle

Therefore, the deflection of the clip angle can be obtained as the sum of the deflections of a cantilevered beam and a beam with one spring-hinged end:

$$\delta = \delta_{\mathrm{E}} + \delta_{\mathrm{R}} = \frac{PL^3}{3EI} + \frac{PL^2}{K} \tag{4.1}$$

The applied shear force P can be expressed as:

$$P = \frac{3EIK}{KL^3 + 3EIL^2}\delta = \frac{3K}{(K + 3EI/L)} \cdot \frac{EI}{L^3} \cdot \delta \tag{4.2}$$

Let $\alpha = \frac{3K}{(K + 3EI/L)}$,

The applied shear force P can be expressed as:

$$P = \alpha \cdot \frac{EI}{L^3} \cdot \delta \tag{4.3}$$

The α factor is then derived:

$$\alpha = \frac{PL^3}{EI\delta} \tag{4.4}$$

Where,

δ - Total deflection of the cantilevered beam

δ_E - Deflection of elastic cantilevered beam

δ_R - Deflection of elastic beam with a spring-hinged end

P - Load at serviceability deflection limit of 1/8 in.

L - The flat length of the anchored leg between the center of the first line of screws and the bend line

E - Modulus of elasticity of CFS, 29500 ksi

I - Moment of inertia of the cross section, $I = Bt^3/12$

B - Width of the clip angle

t - Design thickness of clip angle

K - Spring constant

4.4.2 Design Equation for Nominal Strength at Deflection Limit

The α factor is a non-dimensional empirical coefficient which reflects the constraint condition provided by the screws. For each clip angle specimen, the α factor could be obtained using Eq. 4.4. Regression analysis was then performed and the result is shown in Figure 4.5, in which S is the screw spacing in the anchored leg of the clip angle. The constraint force is getting smaller with the increase of S/t, which leads to a smaller α factor. While larger L/t indicates a more flexible clip angle and therefore a stronger screw constraint, which results in a larger α factor. Therefore, the horizontal axis in the regression analysis is selected to be $\frac{\sqrt{St}}{L}$. Since the proposed method is essentially a deflection/serviceability check, it is recommended that no LRFD, LSD resistance factor or an ASD factor of safety is used since this is a serviceability check.

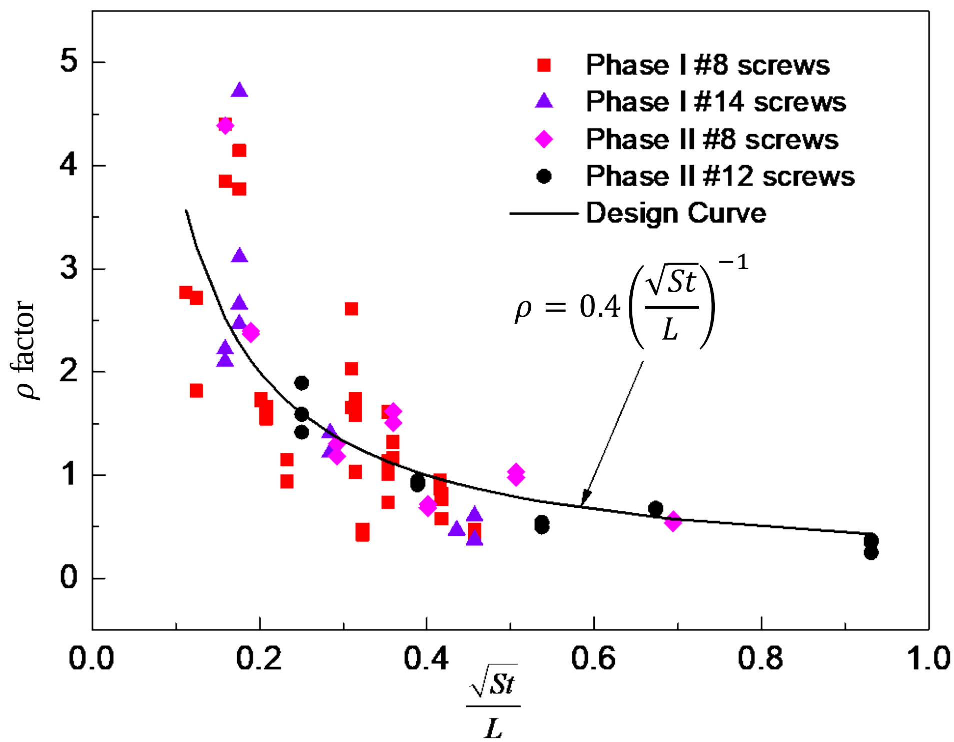


Figure 4.5: Result of regression analysis

Based on a regression analysis, the equation for α can be developed as $\rho = 0.4\left(\frac{\sqrt{St}}{L}\right)^{-1}$, which corresponds to the centerline of the test data. Therefore, the nominal tensile strength of CFS clip angles with consideration of the service deformation limit of 1/8 in. is:

$$P = \rho \frac{EI}{L^3}\delta \tag{4.5}$$

Where,

$\rho = 0.4\left(\frac{\sqrt{St}}{L}\right)^{-1}$

L - The flat length of the anchored leg between the center of the first line of screws and the bend line

E - Modulus of elasticity of CFS, 29500 ksi

I - Moment of inertia of the cross section, $I = Bt^3/12$

B - Width of the clip angle

t - Design thickness of clip angle

S - Screw spacing in anchored leg of clip angle

δ = 1/8 in.

The parameter range of the tested specimens in both phases is:

Clip angle nominal thickness: 33 mils to 118 mils

Clip angle nominal yield strength: 33 ksi to 50 ksi

Screw size: No. 8, No.12 or No. 14

5 CFS JOIST TESTS

The CFS joist tests in Phase II investigated the shear strength of clip angles subjected to loading and boundary conditions that would exist in actual CFS framing. The joist test results were directly compared with the shear test results. It was found that the cross-sectional strength of the CFS joist had significant impact to the shear strength of the clip angle connector. The actual boundary conditions of a clip angle should be considered in its strength assessment.

5.1 Test Setup and Test Procedure

The CFS joist tests used AISI S914 (2015) as a guide for the test setup as illustrated in Figures 5.1 and 5.2. In each test, two CFS joists with the same configurations were connected using one structural steel tube at the mid span, shown in Figure 5.3. Steel angles were also used to connect the flanges of the two joists. The joist assembly was anchored to two supporting members at both ends by four CFS clip angles with the same configurations. A structural steel load transfer block was used to apply a vertical force to the steel tube. Four position transducers were used to measure the vertical deflection of the clip angles. A minimum gap of 1/8 in. was provided between the end of each joist and the supporting members to avoid any contact during the test. The joist tests were performed in a displacement control mode at a constant speed of 0.3 in. per minute.

Figure 5.1: Joist test setup

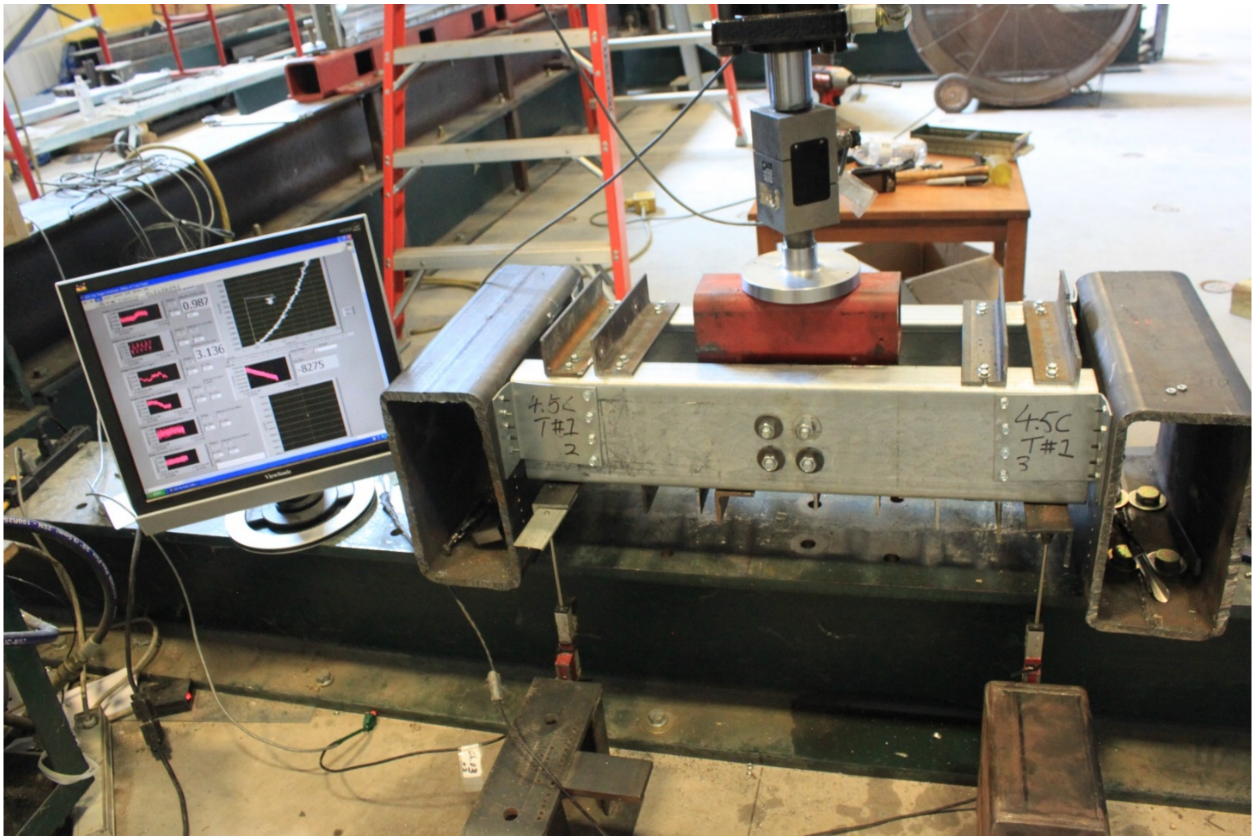


Figure 5.2: Typical joist test setup

Figure 5.3: Connection details of the two joists (photo taken after test)

5.2 Test Specimens

A total of 14 joist tests were conducted. The clip angle label was used as the joist test label. For all clip angles in this test program, a single line of No. 14-14×1 self-drilling self-tapping screws were used to attach the cantilevered leg of the clip angle to web of the joist. The anchored leg of the clip angle was attached to the supporting members by a single line of No. 10-24×1 BHSC bolts. All the clip angles were 54 mils. All the joists were 28 in. long, and the thickness was either 54 mils or 97 mils.

Table 5.1: Properties of clip angles in the joist tests

Test Label	B (in.)	L (in.)	t (in.)	F_y (ksi)	F_u (ksi)	# Screws on C-leg	S (in.)	Joist Spec.
4.5D T#1	4.492	3.157	0.0583	46.1	63.7	4	1.25	600S250-97
4.5F T#1	4.501	3.407	0.0583	46.1	63.7	4	1.25	600S250-54
4.5F T#2	4.501	3.407	0.0583	46.1	63.7	4	1.25	600S250-54
6.5A T#1	6.500	3.094	0.0583	46.1	63.7	5	1.44	800S250-54
6.5A T#2	6.500	3.094	0.0583	46.1	63.7	5	1.44	800S250-54
6.5B T #1	6.500	3.407	0.0583	46.1	63.7	5	1.44	800S250-54
6.5B T #2	6.500	3.407	0.0583	46.1	63.7	5	1.44	800S250-54
8.5B T #1	8.499	3.407	0.0583	46.1	63.7	5	1.94	1000S165-54
8.5B T #2	8.499	3.407	0.0583	46.1	63.7	5	1.94	1000S165-54
8.5B T #3	8.499	3.407	0.0583	46.1	63.7	5	1.94	1000S250-97
8.5B T #4	8.499	3.407	0.0583	46.1	63.7	5	1.94	1000S250-97
10.5B T#1	10.500	3.886	0.0583	46.1	63.7	14	0.75	1200S165-54
10.5B T#2	10.500	3.886	0.0583	46.1	63.7	14	0.75	1200S165-54
10.5B T#3	10.500	3.886	0.0583	46.1	63.7	14	0.75	1200S250-97
10.5B T#4	10.500	3.886	0.0583	46.1	63.7	14	0.75	1200S250-97

5.3 Test Results

Table 5.2 summarizes the joist test results. The P_{test} is the peak load per clip angle, it was calculated using the total force divided by 4. The deflection, Δ, is the vertical deflection of the controlling clip angle. The controlling clip angle was the one with the most significant deformation in the joist test. P_n is the predicted shear strength using Eq. 2.7.

Table 5.2: Results of joist tests

Test Label	P_{test} (lb)	Δ (in.)	P_n (lb)	P_{test} / P_n
4.5D T#1	1760	0.227	2107	0.835
4.5F T#1	1688	0.218	2046	0.825
4.5F T#2	1640	0.228	2046	0.802
6.5A T#1	3276	0.218	3404	0.962
6.5A T#2	3207	0.297	3404	0.942
6.5B T #1	2595	0.151	3268	0.794
6.5B T #2	2959	0.130	3268	0.905
8.5B T #1	3800	0.201	4269	0.890
8.5B T #2	3829	0.088	4269	0.897
8.5B T #3	4650	0.702	4269	1.089
8.5B T #4	5417	0.114	4269	1.269
10.5B T#1	4981	0.146	7857	0.634
10.5B T#2	4936	0.074	7857	0.628
10.5B T#3	8305	0.181	7857	1.057
10.5B T#4	9061	0.154	7857	1.153

Direct comparison can be made for the 4.5D clip angles which were tested in both the joist tests and the shear tests with the same screw pattern. Figure 5.4 shows the comparison of the test curves. Figures 5.5 and 5.6 show the failure mode for the 54 mil 4.5 in. clip angles in the joist and the shear test respectively. It can be seen that the 54 mil clip angle had similar peak load, deflection, and failure mode in the two test programs.

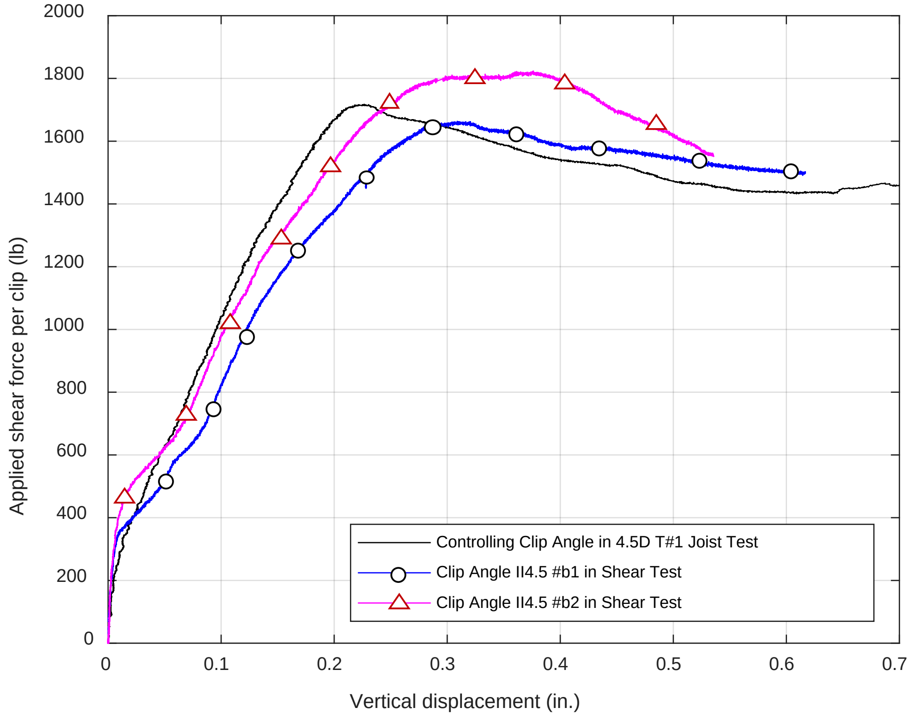


Figure 5.4: Comparison of 54 mil 4.5 in. clip angles in two test programs

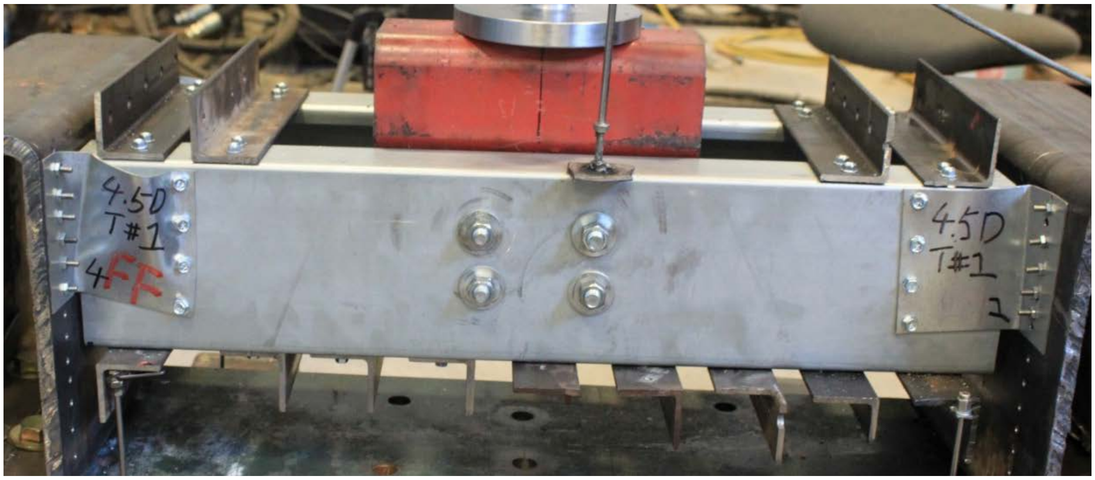


Figure 5.5: Failure mode of joist 4.5D T#1

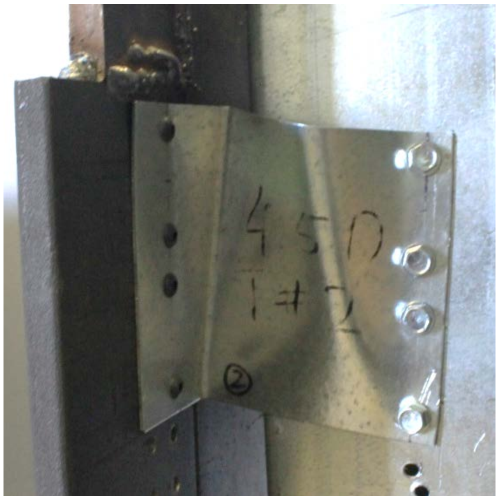


Figure 5.6: Failure mode of shear test II4.5 #b2

Direct comparison can also be made on 54 mil 6.5 in. deep clip angles with 5 screws. The test curves are shown in Figure 5.7 and the failure mode is shown in Figures 5.7 and 5.8. The clip angles in both test programs showed a similar failure mode. However the joist tests gave lower peak loads than those in the shear tests. In the joist tests, the controlling clip angle had significant deformation while the other three clip angles showed no observable deformation. It was believed that the load redistribution took place during the test and it lowered the ultimate load that the joist assembly could provide.

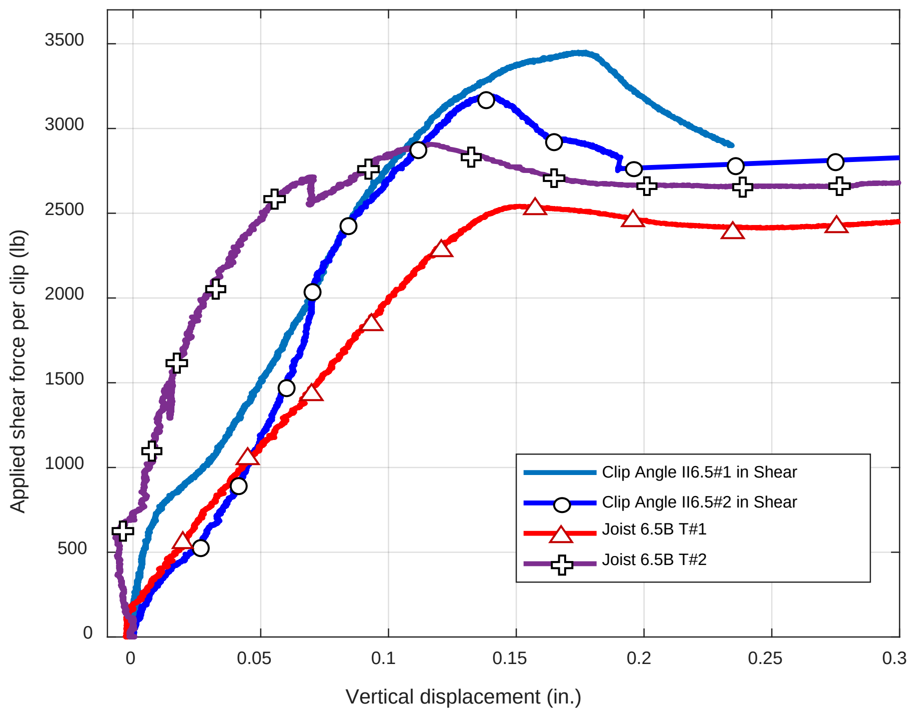


Figure 5.7: Comparison of 54 mil 6.5 in. clip angles in two test programs

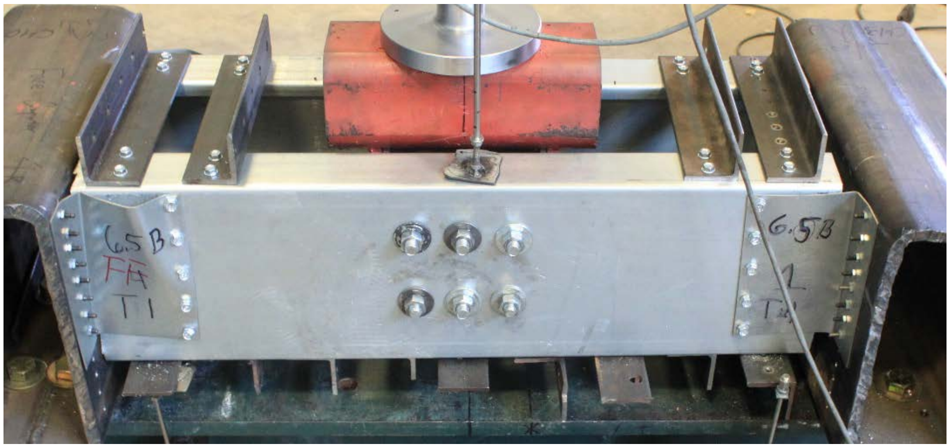


Figure 5.8: Failure mode of joist 6.5B T#1

Figure 5.9: Failure mode of shear test II6.5 #1

The joist test program discovered that for the deeper clip angles (8.5 in. and 10.5 in.) that were attached to 54 mil joists, significant deformation in the joist web occurred when the clip angle reached its capacity. Figures 5.10 and 5.11 respectively show the failure mode of 8.5B T#1 and 10.5B T#1 clip angles where 54 mil joists were used. Shear buckling occurred in the web of CFS joists. The clip angles in those two tests yielded lower strength than the predicted values mainly due to a weaker boundary condition that the joist's web provided to the cantilevered leg of clip angles. Particularly for the 10.5 in. deep clip angles, the clip angles only reached 63% of their predicted shear strength by the new design method, Eq. 2.7.

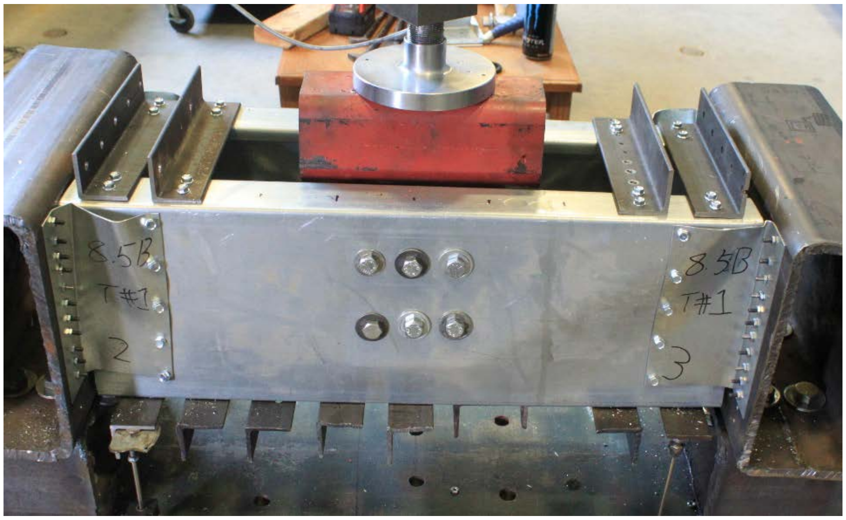


Figure 5.10: Failure mode of Test 8.5BT #1

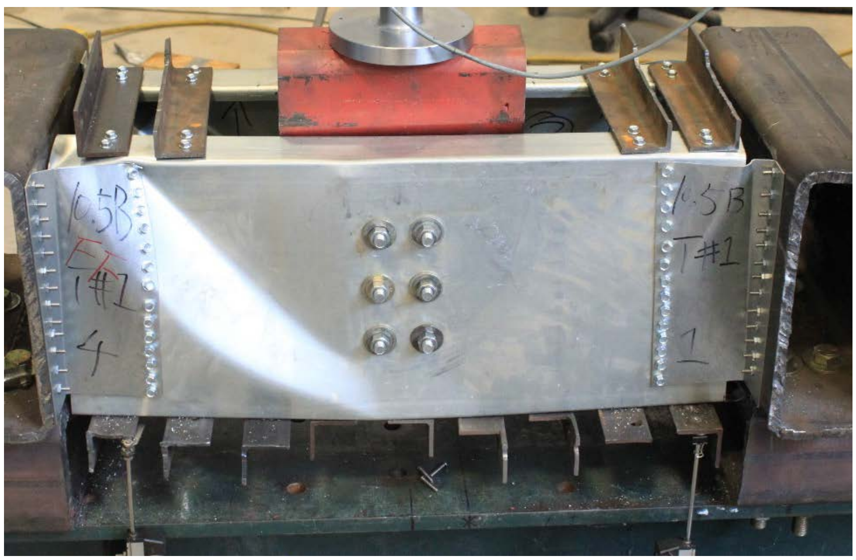


Figure 5.11: Failure mode of Test 10.5B #1

The 8.5 in. and 10.5 in. clip angles were re-tested using 97 mil joists in order to avoid buckling in the web of the joist. Figures 5.12 and 5.13 show the failures of the joist tests 8.5B T#3 and 10.5B T#3 respectively. No failure was observed in the web of the joist. The peak load was comparable with the predicted results. The joist tests discovered that the boundary conditions could have significant effect on the shear strength of the cantilevered leg of the clip angle. The new shear design method (Eq. 2.7) assumes a solid support to the cantilevered leg and the anchored leg. The CFS clip angle may not be able to provide full shear strength if the supporting members (e.g. CFS framing members) do not provide a solid support or yield significant deformation.

Figure 5.12: Failure mode of 8.5B T#3

Figure 5.13: Failure mode of 10.5B T#3

6 SUMMARY OF PROPOSED DESIGN PROVISIONS

6.1 Nominal shear strength of the cantilevered leg of clip angle without consideration of deformation

$V_n = \beta(\gamma)^{-0.4} F_y B t \leq 0.35 F_y B t$

Where $\beta = 0.12$ for clip angle with a single line of screws

$= 0.12(1 + \gamma)$ for clip angles with a double line of screws

$\gamma = \alpha\lambda$

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

$\alpha = \frac{S}{B}$ – Screw spacing 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 CFS, 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

S - Screw spacing on the cantilevered leg

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.

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

Clip angle nominal thickness: 33 mils to 97 mils

Clip angle nominal yield strength: 33 ksi to 50 ksi

L/*B* ratio: 0.18 to 1.40

For the clip angles with a double line of screws, the spacing between the two screw lines on the cantilevered leg is ¾ in.

The ϕ and Ω are as follows:

ϕ (LRFD) = 0.85

ϕ (LSD) = 0.65

Ω (ASD) = 1.95

6.2 Nominal shear strength of the cantilevered leg of a clip angle with consideration of serviceability

The new design method for the nominal shear strength of CFS clip angles considering a 1/8 in. deformation limit is as follows:

$$V'_n = 4865\,\varepsilon \left[\frac{Bt}{L\alpha^{0.7}}\right]^{0.823} \leq V_n$$

Where

ε = 1 lb/in. for US customary units

= 0.175 N/mm for SI units

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

t – Design thickness of clip angle, in. [mm]

B – Depth of clip angle, in. [mm]

L – Flat length of clip angle, distance from the center of the first line of screws to the bend line, in. [mm]

V_n – Nominal shear strength without considering deformation, lb [N]

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

Clip angle nominal thickness: 33 mils to 97 mils

Clip angle nominal yield strength: 33 ksi to 50 ksi

L/*B* ratio: 0.18 to 1.40

6.3 Nominal axial compression strength of the cantilevered leg of a clip angle

The nominal compression strength

$$P_n = A_g F_n$$

Where

$A_g = B't$

$F_n = 0.0028\lambda^{1.44} F_{cr} \leq 0.4F_y$

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

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

E - Modulus of elasticity of CFS, 29500 ksi

μ - Poisson's ratio for steel, 0.3

k - Buckling coefficient can be found by interpolation in Table 3.5

= 0.90 as a conservative value

t - Design thickness of clip angle

B' - Lesser of the actual clip angle width or the Whitmore section width (Figure 3.4) if applicable

L - Flat width of clip angle, distance between the bend to the closest line of screws to the bend

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

Clip angle nominal thickness: 33 mils to 118 mils

Clip angle nominal yield strength: 33 ksi to 50 ksi

L/B ratio: 0.18 to 1.40

The ϕ and Ω are as follows:

ϕ (LRFD) = 0.65

ϕ (LSD) = 0.50

Ω (ASD) = 2.55

6.4 Nominal pull-over strength of the anchored leg of a clip angle

The nominal pull-over strength of sheet per screw

$P_{nov} = 0.75 t_1 d'_w F_{u1}$

where

d'_w = effective pull-over diameter

t_1 = design thickness of member in contact with screw head or washer

F_{u1} = tensile strength of member in contact with screw head or washer

The parameter range of the tested specimens are:

Clip angle design thickness: 33 mils to 54 mils

Clip angle design yield strength: 33 ksi to 50 ksi

Screw size: No. 8 or No. 14

The ϕ and Ω are as follows:

ϕ (LRFD) = 0.50

ϕ (LSD) = 0.40

Ω (ASD) = 3.00

6.5 Nominal tension strength of a clip angle with consideration of serviceability

The nominal tensile strength of CFS clip angles with consideration of the service deformation limit of 1/8 in. is:

$$P = \rho \frac{EI}{L^3} \delta$$

Where,

$$\rho = 0.4 \left(\frac{\sqrt{St}}{L}\right)^{-1}$$

L - The flat length of the anchored leg between the center of the first line of screws and the bend line

E - Modulus of elasticity of CFS, 29500 ksi

I - Moment of inertia of the cross section, $I = Bt^3 / 12$

B - Width of the clip angle

t - Design thickness of clip angle

S - Screw spacing in anchored leg of clip angle

δ = 1/8 in.

The parameter range of the tested specimens is:

Clip angle nominal thickness: 33 mils to 118 mils

Clip angle nominal yield strength: 33 ksi to 50 ksi

Screw size: No. 8, No.12 or No. 14

7 CONCLUSIONS AND FUTURE RESEARCH

Three series of tests on CFS clip angles were conducted in the Phase II project to investigate the behavior, strength, and deflection for three limit states on the cantilevered leg: shear failure, compression failure, and tension at service deflection limit. The research goals were to (1) determine the effect of screw pattern to the shear and compression strength of the clip angle; (2) investigate the strength of clip angles in actual framing conditions; (3) develop a design method for checking the serviceability of clip angles in tension.

To investigate the shear strength of clip angles with various screw patterns, both tests and finite element analysis were performed. The research found that the screw pattern including the screw spacing and the number of lines of screws could have significant impact to the shear strength of the cantilevered leg of a CFS clip angle. Based on the Phase I design methods, two new design methods were proposed to include the screw pattern's effects in the nominal shear strength calculations for both the nominal strength and the strength at the service deflection limit of 1/8 in. The LRFD resistance factors and ASD factors of safety were also calculated for the new nominal shear strength methods. The shear design method for serviceability was developed using the lower bond of the test results. Therefore, a LRFD resistance factor or an ASD factor of safety are not needed for the serviceability check using the developed design equation.

For the compression strength of the cantilevered leg of a clip angle, the Phase II tests found that the screw pattern has limited impact to the nominal strength and the Phase I design method worked well for the Phase II clip angles.

Based on the tension test results from both Phase I and Phase II, an analytical model was developed to determine the nominal tension strength of a clip angle when the deflection reached the service deflection limit of 1/8 in. The design equation was calibrated using the lower bond of the test data, therefore the LRFD resistance factor and ASD factor of safety are not needed when the serviceability is evaluated using the developed design method for tension.

The CFS joist tests were conducted in the Phase II project to investigate the shear strength of the clip angles in actual CFS framing. The test results found that the web stability could have significant impact to the shear strength of the clip angle. When the joist web could not provide adequate shear resistance, it could buckle at the locations where the clip angles were installed. In order to achieve the full shear strength of a clip angle, the connecting members shall be able to provide adequate support to clip angle.

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

- The number of screw lines and the spacing effects on the clip angles
  The research found that the number of screw lines and the spacing between the lines could have significant impact to the shear strength of clip angles. However there were limited number of clip angles in both Phase I and Phase II tests that had more than one screw lines. In fact, only two lines of screws were included in the test program, and the spacing between the two screw lines was constantly 0.75 in. More comprehensive research is needed to investigate the effects of the number of screws lines and screw line spacing to the shear

strength of the cantilevered leg of clip angles. The future research shall be able to reliably determine the shear strength of a clip angle configuration as shown in Figure 6.1.

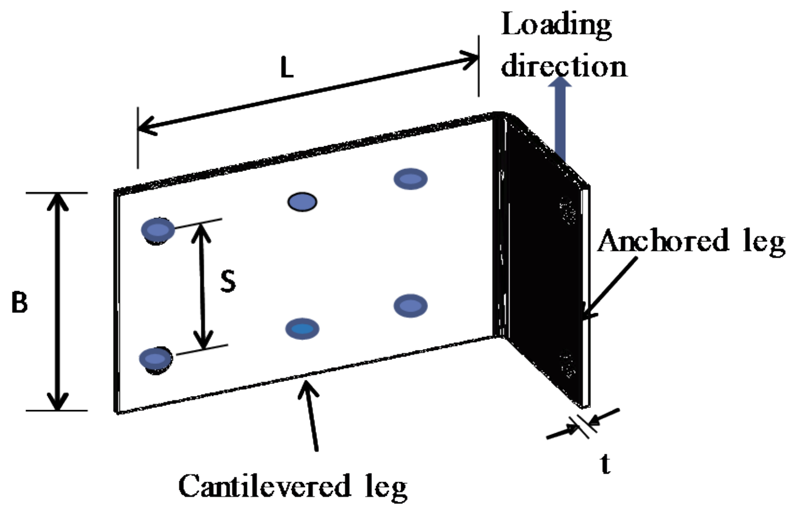


Figure 6.1: A clip angle configuration for future research

- Clip angles using other connections
  In this research, screw connections were used in all tested clip angles. The clip angles using other connection methods such as welds and pins may demonstrate different behavior and strength. Additional research is needed to verify the proposed design methods for the CFS clip angles.

ACKNOWLEDGEMENTS

The sponsorship of American Iron and Steel Institute and the test materials donation by Simpson Strong-Tie Company, Inc. and Hilti, Inc. are gratefully acknowledged. The technical advising provided by the AISI Project Monitoring Task Group is highly appreciated. The authors would also like to thank UNT graduate and undergraduate students, Nathan Derrick, Nick O'Connor, Jeremy Artman, Dawson Guerrettaz, and Rasna Baweja for their assistances in this project.

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