Load Bearing Clip Angle Design

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research report

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ABSTRACT

The report presents a comprehensive research project aimed at developing design methods for three limit states of cold-formed steel clip angles: shear, compression, and pull-over of the screw connections. 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.

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1 OBJECTIVES

The objective of this project was to investigate the behavior of load-bearing cold-formed steel (CFS) clip angles and then develop appropriate design methods for their use when subjected to three different loading conditions. Three limit states were considered in the research: (1) transverse shear capacity of the cantilevered leg; (2) axial compression capacity of the cantilevered leg; and (3) pull-over strength of fasteners on the anchored leg.

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. 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 double coped beam design procedure found in the AISC Steel Construction Manual (AISC, 2011). It was found that large variations existed between the test results and those determined using the AISC methodology. A new design method was proposed that would more accurately predict the shear strength of the CFS clip angles than other previous methods. To address the deflection limit, a design method with consideration of the deformation limit was also developed.

2.1 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. Figures 2.1 and 2.2 show the overall view and close-up view of the shear test setup respectively.
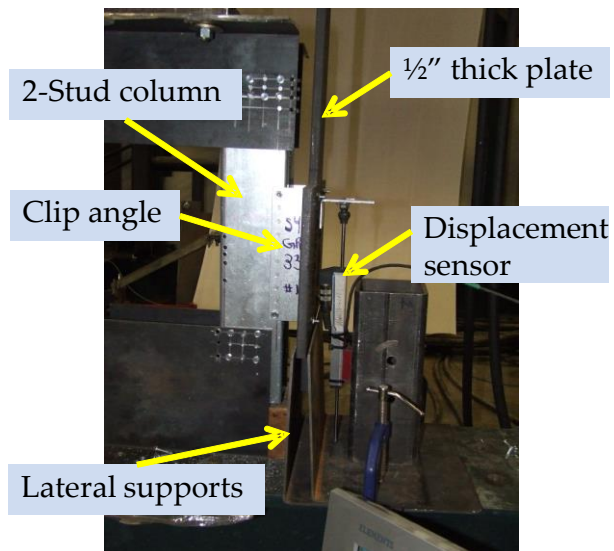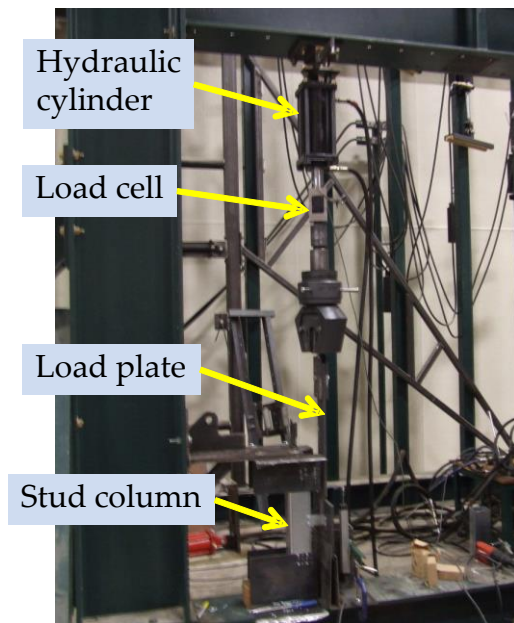

Figure 2.1: Overall view of shear test setup   Figure 2.2: Close-up view of shear test setup

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 Figures 2.1 and 2.2. 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 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 2.2, 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.

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 33 valid shear tests with the thickness range of the clip angles between 33 mil and 97 mil. The failure modes of invalid tests are provided in Appendix 1. 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 2.1 lists the measured dimensions related to the proposed shear design method, tested material properties, and the number of screws used in each clip angle. The detailed dimensions of the clip angles are provided in Appendix 2. The test specimens were manufactured by Simpson Strong-Tie Company. The test specimen designations used in this test program were the same as the original product labels from the manufacturer. 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. The thickness, t, is the uncoated thickness of materials. The yield stress F_y, and tensile strength, F_u, were obtained from coupon tests following

ASTM A370 Standard Test Method and Definitions for Mechanical Testing of Steel Products (2014). Figure 2.3 illustrates the measured dimensions.

Table 2.1: Properties of clip angles in the shear test program

| Test Label	L (in.)	B (in.)	t (in.)	F_y (ksi)	F_u (ksi)	No. of Screws C-leg[1]	No. of Screws on A-leg[2]
S1 #4	1.394	3.020	0.0584	45.7	50.1	4	4
S1 #5	1.394	3.020	0.0584	45.7	50.1	4	4
S3 #1	1.391	5.230	0.0584	45.7	50.1	3	7
S3 #2	1.391	5.230	0.0584	45.7	50.1	3	7
S4 #3	1.401	7.497	0.0349	49.9	55.8	3	10
S4 #4	1.401	7.497	0.0349	49.9	55.8	3	10
S5 # 3	1.415	7.520	0.0465	46.4	51.2	3	5
S5 # 4	1.415	7.520	0.0465	46.4	51.2	3	5
S6 #1	2.422	3.004	0.0465	46.4	51.2	2	4
S6 #2	2.422	3.004	0.0465	46.4	51.2	2	4
S7 #1	2.362	3.021	0.1006	45.6	60.0	8	8
S7 #3	2.362	3.021	0.1006	45.6	60.0	8	8
S8 #3	2.387	5.254	0.0465	46.4	51.2	3	7
S8 #4	2.387	5.254	0.0465	46.4	51.2	3	7
S8 #5	2.387	5.254	0.0465	46.4	51.2	3	3
S9 #2	2.389	7.540	0.0349	49.9	55.8	3	10
S9 #3	2.389	7.540	0.0349	49.9	55.8	3	10
S10 #1	2.387	7.497	0.0584	45.7	50.1	3	10
S10 #2	2.387	7.497	0.0584	45.7	50.1	3	10
T1a #1	2.418	1.747	0.0349	49.9	55.8	2	2
T1a #2	2.418	1.747	0.0349	49.9	55.8	2	2
T1b #1	2.038	1.747	0.0349	49.9	55.8	2	2
T1b #2	2.038	1.747	0.0349	49.9	55.8	2	2
T1b #3	2.038	1.747	0.0349	49.9	55.8	2	2
T3 #1	1.523	1.753	0.0584	45.7	50.1	2	2
T3 #2	1.523	1.753	0.0584	45.7	50.1	2	2
T3 #3	1.523	1.753	0.0584	45.7	50.1	2	2
T4 #2	2.394	1.751	0.0698	54.8	66.7	2	4
T4 #3	2.394	1.751	0.0698	54.8	66.7	2	4
T5a #1	2.431	1.751	0.0349	49.9	55.8	2	2
T5a #2	2.431	1.751	0.0349	49.9	55.8	2	2
T5b #1	2.276	1.751	0.0349	49.9	55.8	2	2
T5b #2	2.276	1.751	0.0349	49.9	55.8	2	2
Note: 1- the cantilevered leg; 2- the anchored leg							
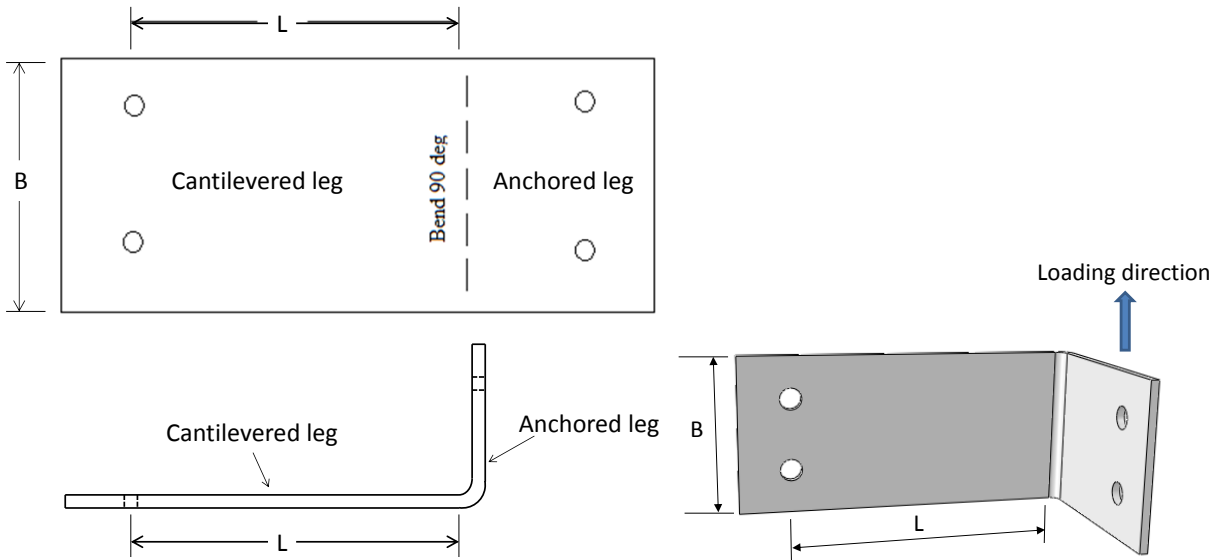
Figure 2.3: Measured dimensions

2.3 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 would be performed. In the shear test program, two failure modes were observed. For thin clip angles with large aspect ratios (L/B > 0.8), a lateral-torsional buckling mode dominated the behavior and failure mechanism. Figure 2.4 shows the test curve and the lateral-torsional failure mode of a 33 mil clip angle (T5a#2). For thick clip angles with small aspect ratios (L/B < 0.8), a local buckling failure could be observed. The observed failure mode for each test is provided in Table 2.2. Figure 2.5 shows the test results of a 33 mil clip angle with an aspect ratio of 0.45. Figure 2.6 shows the test results of a 97 mil clip angle. Local buckling failure can be observed in Figures 2.5 and 2.6. In Figure 2.4, the test label was later revised from T5#2 to T5a#2.
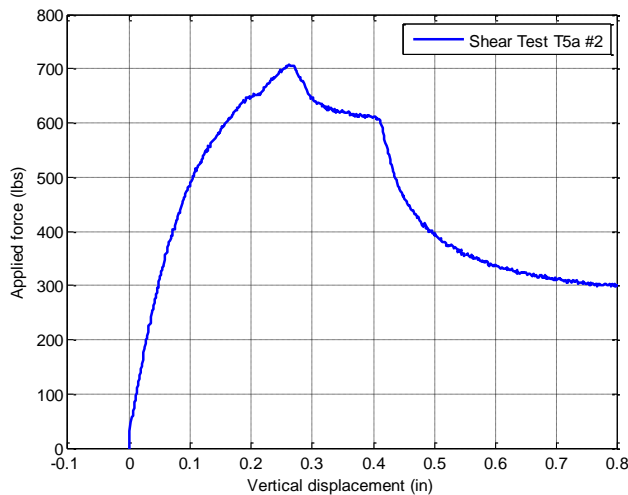
Figure 2.4: Test result of clip angle T5a #2

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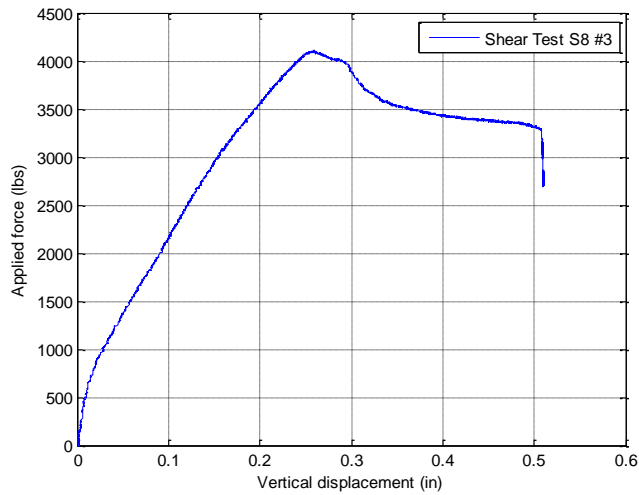
Figure 2.5: Test result of clip angle S8 #3
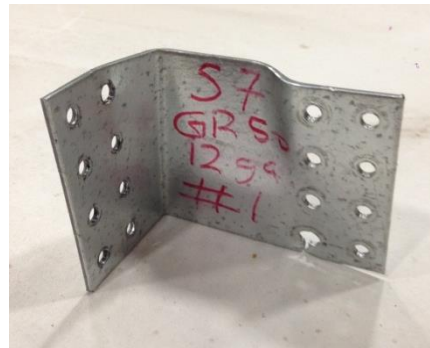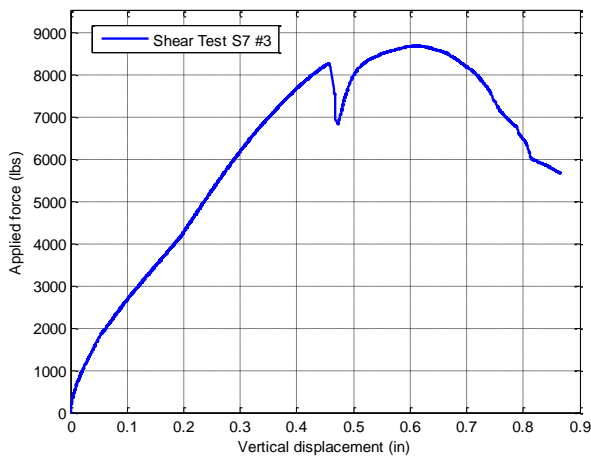
Figure 2.6: Test result of clip angle S7 #1

The test results are provided in Table 2.2 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 clip angles as two identical angles were used in each test.

Table 2.2: Results of shear tests

Test Label	V_{test} (lbs)	Δ (in.)	$V_{1/8}$ (lbs)	Failure Mode
S1 #4	2594	0.523	1102	L
S1 #5	2767	0.685	781	L
S3 #1	3794	0.401	1521	L
S3 #2	3753	0.343	1710	L
S4 #3	2581	0.198	2230	L
S4 #4	2445	0.098	2445	L
S5 # 3	3534	0.294	2344	L
S5 # 4	3488	0.318	1936	L
S6 #1	1050	0.362	586	L
S6 #2	983	0.297	665	L
S7 #1	4339	0.608	1540	L
S7 #3	4319	0.532	1066	L
S8 #3	2054	0.259	1284	L
S8 #4	1912	0.236	1236	L
S8 #5	2048	0.286	1182	L
S9 #2	1787	0.225	1429	L
S9 #3	1670	0.197	1293	L
S10 #1	3268	0.359	1521	L
S10 #2	3421	0.256	2051	L
T1a #1	288	0.119	288	LTB
T1a #2	328	0.198	280	LTB
T1b #1	358	0.211	307	LTB
T1b #2	315	0.198	261	LTB
T1b #3	373	0.225	261	LTB
T3 #1	845	1.248	421	LTB
T3 #2	967	1.264	495	LTB
T3 #3	932	0.831	462	LTB
T4 #2	1028	1.109	429	LTB
T4 #3	993	0.904	476	LTB
T5a #1	319	0.109	319	LTB
T5a #2	359	0.260	279	LTB
T5b #1	250	0.100	250	LTB
T5b #2	303	0.228	237	LTB
Note: L – local buckling failure; LTB – lateral-torsional buckling failure				

2.4 Comparison with AISC Design Method

The AISC Steel Construction Manual (AISC, 2011) does not provide a design method for clip angles, however the double coped beam, shown in Figure 2.7 has similar loading and boundary conditions as those for the CFS clip angles. Therefore the AISC design provision for the double coped beam was adopted as a reference design method in this research. The nominal shear strength of a double coped beam, R, can be expressed as the following:

$$R = (F_{cr}S_{net})/e \tag{2.1}$$

where F_{cr} is the elastic buckling stress, S_{net} is the net section modulus, e is the width of the coped flange. The AISC design manual lists two methods for calculating F_{cr}.
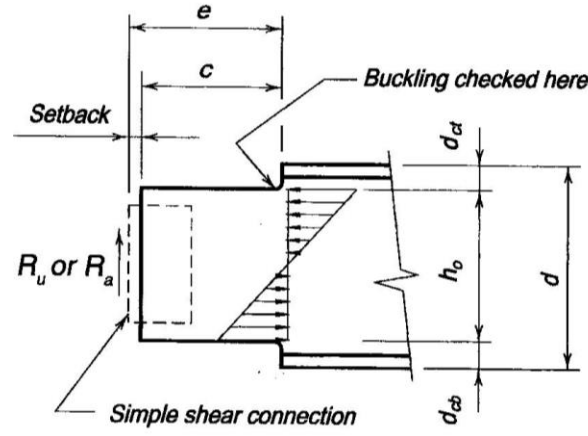
Figure 2.7: Loading and boundary conditions for a double coped beam (AISC Design Manual, Figure 9-3)

Method A:

$$F_{cr} = 0.62 \, \pi \, E \, \frac{t_w{}^2}{ch_0} \, f_d \le F_y \tag{2.2}$$

where,

$$f_d = 3.5 - 7.5 \left(\frac{d_c}{d} \right) \tag{2.3}$$

d_c = cope depth at the compression flange

Method B:

$$F_{cr} = F_y \, Q \tag{2.4}$$

where,

$Q = 1$ for $\lambda \le 0.7$
$= (1.34 - 0.486 \, \lambda)$ for $0.7 < \lambda \le 1.41$
$= (1.30 \, / \, \lambda^2)$ for $\lambda > 1.41$ $\qquad$ (2.5)

$$\lambda = \frac{h_0\sqrt{F_y}}{10\,t_w\sqrt{475+280\left(\frac{h_0}{c}\right)^2}} \qquad (2.6)$$

The definitions of the notations used in above equations can be found in AISC (2011).

Method B was considered as more conservative than Method A. The shear test results were compared with the AISC double coped beam design methods. In Table 2.3, R_a is the AISC predicted shear strength using Method A for F_{cr}, R_b is the predicted strength using Method B for F_{cr}. Figure 2.8 illustrates the comparison between the shear test results and the AISC design methods. Both AISC methods do not provide good agreements with test results. On average, Method A yields unconservative predictions and both methods' predicted values have large variations from the test results. It can be concluded that the AISC double coped design provision was not appropriate for the shear strength of the CFS clip angles; a new design method was needed.

Table 2.3: Comparison of test results with AISC design methods

| Test Label	V_{test}/R_a	V_{test}/R_b
S1 #4	0.992	1.057
S1 #5	1.058	1.127
S3 #1	0.483	0.537
S3 #2	0.478	0.532
S4 #3	0.515	0.502
S4 #4	0.488	0.476
S5 #3	0.304	0.355
S5 #4	0.300	0.350
S6 #1	0.829	1.367
S6 #2	0.776	1.279
S7 #1	1.602	1.602
S7 #3	1.635	1.635
S8 #3	0.706	1.312
S8 #4	0.657	1.222
S8 #5	0.704	1.309
S9 #2	1.002	1.498
S9 #3	0.936	1.400
S10 #1	0.399	0.599
S10 #2	0.418	0.627
T1a #1	0.825	1.275
T1a #2	0.941	1.453
T1b #1	0.873	1.280
T1b #2	0.768	1.126
T1b #3	0.911	1.335
T3 #1	1.039	1.039
T3 #2	1.189	1.189
T3 #3	1.146	1.146
T4 #2	1.350	1.380
T4 #3	1.304	1.333
T5a #1	0.911	1.416
T5a #2	1.030	1.601
T5b #1	0.674	1.021
T5b #2	0.817	1.238
Mean	0.550	1.110
St. Dev.	0.491	0.385
COV	0.893	0.346
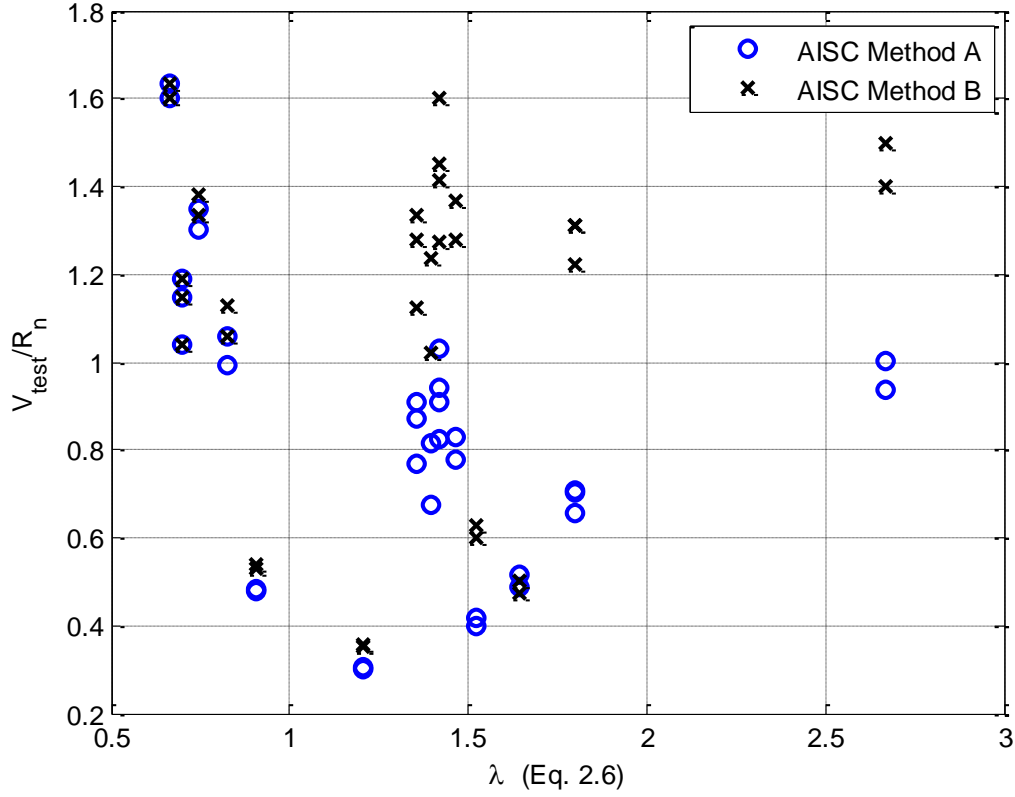
Figure 2.8: Comparison of shear test results with AISC design methods

2.5 Proposed Shear Design Method for CFS Clip Angles 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 the shear test program. The design method was based on the methodology of the Direct Strength Method (Schafer and Peköz, 1998) which used the yield strength and the critical elastic buckling solution of the entire CFS member to predict the ultimate strength. The proposed shear strength method without consideration of deformation is listed as follows:

Nominal shear strength

$$V_n = 0.17\lambda^{-0.8}F_y Bt \leq 0.35F_y Bt \tag{2.7}$$

where $\lambda = \sqrt{\dfrac{F_y}{F_{cr}}}$ - slenderness ratio $\tag{2.8}$

$F_{cr} = \dfrac{k\pi^2 E}{12(1-\mu^2)}\left(\dfrac{t}{B}\right)^2$ - critical elastic buckling stress $\tag{2.9}$

E - modulus of elasticity of steel, 29500 ksi

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μ - Poisson's ratio for steel, 0.3

$$k = 2.569 \left(\frac{L}{B}\right)^{-2.202} \text{ - buckling coefficient} \tag{2.10}$$

t - design thickness of clip angle

B - depth of clip angle as shown in Figure 2.3

L - flat width of clip angle, distance between the center of first line of screws to the bend line as shown in Figure 2.3.

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 results and the calculated nominal shear strength by the proposed design method is listed in Table 2.4 and illustrated in Figure 2.9. It can be seen that the proposed method has a good agreement with the test results, and it indicates that the concept of Direct Strength Method approach works for determining the shear strength of CFS clip angles.

The LRFD and LSD resistance factors and the ASD safety factors for the proposed shear design method were calculated following Chapter F of the North American Specification for the Design of Cold-Formed Steel Structural Members (AISI S100, 2012). Two types of components listed in Table F1 of AISI S100, Flexural Members – Shear Strength and Connections Not Listed Above, were chosen for the statistical analysis. The results are listed in Table 2.5.

Table 2.4: Comparison of shear test results with the proposed design method

| Test Label	λ	V_{test} (lbs)	V_n (lbs)	V_{test}/V_y	V_{test}/V_n
S1 #4	0.570	2594	2146	0.322	1.209
S1 #5	0.570	2767	2146	0.344	1.289
S3 #1	0.538	3794	3893	0.272	0.975
S3 #2	0.538	3753	3893	0.269	0.964
S4 #3	0.914	2581	2389	0.197	1.080
S4 #4	0.914	2445	2389	0.187	1.023
S5 # 3	0.669	3534	3801	0.218	0.930
S5 # 4	0.669	3488	3801	0.215	0.918
S6 #1	1.328	1050	878	0.162	1.196
S6 #2	1.328	983	878	0.152	1.120
S7 #1	0.591	4339	3590	0.313	1.209
S7 #3	0.591	4319	3590	0.319	1.203
S8 #3	1.235	2054	1627	0.181	1.262
S8 #4	1.235	1912	1627	0.169	1.175
S8 #5	1.235	2048	1627	0.181	1.259
S9 #2	1.643	1787	1502	0.136	1.190
S9 #3	1.643	1670	1502	0.127	1.112
S10 #1	0.940	3268	3570	0.164	0.915
S10 #2	0.940	3421	3570	0.171	0.958
T1a #1	1.930	288	306	0.094	0.941
T1a #2	1.930	328	306	0.108	1.072
T1b #1	1.599	358	356	0.117	1.006
T1b #2	1.599	315	356	0.103	0.885
T1b #3	1.599	373	356	0.123	1.048
T3 #1	0.664	845	1103	0.181	0.766
T3 #2	0.664	967	1103	0.207	0.877
T3 #3	0.664	932	1103	0.199	0.845
T4 #2	1.002	1028	1137	0.154	0.904
T4 #3	1.002	993	1137	0.148	0.873
T5a #1	1.941	319	305	0.104	1.046
T5a #2	1.941	359	305	0.118	1.177
T5b #1	1.805	250	324	0.082	0.772
T5b #2	1.805	303	324	0.099	0.935
Mean					1.034
St. Dev.					0.148
COV					0.143
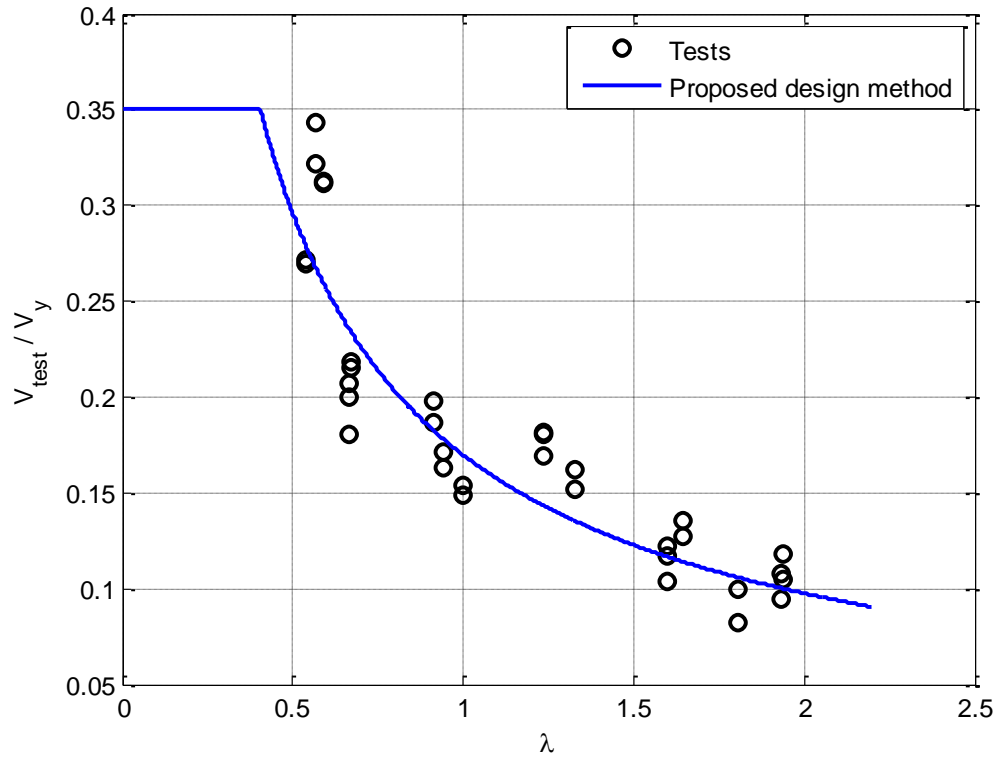
Figure 2.9: Comparison of shear test results with proposed design method

Table 2.5: Resistance factors and safety factors for the proposed shear design method

	Considered as Flexural Members – Shear Strength	Considered as Connections Not Listed Above
Quantity	33	33
Mean	1.034	1.034
Std. Dev.	0.148	0.148
COV	0.143	0.143
M_m	1.10	1.10
V_m	0.10	0.10
F_m	1.00	1.00
P_m	1.034	1.034
V_f	0.05	0.15
β (LRFD)	2.5	3.5
β (LSD)	3.0	4.0
V_Q	0.21	0.21
ϕ (LRFD)	0.86	0.57
ϕ (LSD)	0.70	0.46
Ω (ASD)	1.87	2.78

2.6 Critical Elastic Buckling Solution

The development of the equation of the buckling coefficient k (Eq. 2.10) is based on the results of an elastic buckling analysis carried out using the commercially available software ABAQUS (2013). Figure 2.10 shows the boundary conditions and loading prescribed in the finite element models. The two loaded edges are simply supported, and the other two unloaded edges are free. Uniform shear loading is applied to one loaded edge. Figure 2.11 shows an example of the elastic buckling analysis. Figure 2.12 and Table 2.6 present the comparison of the ABAQUS results with Eq. 2.10.
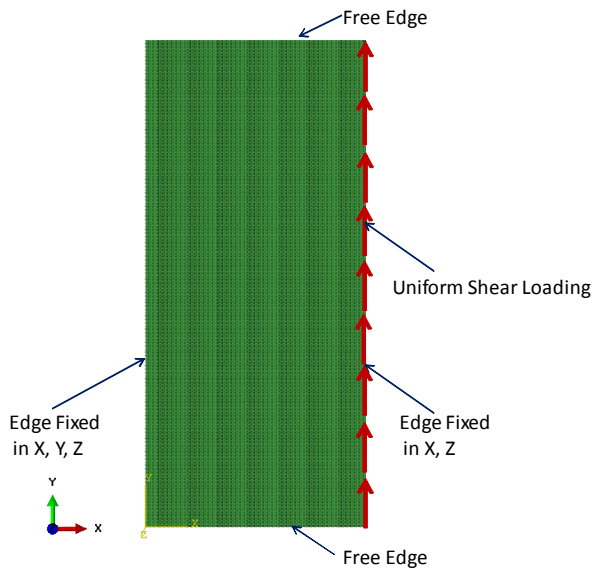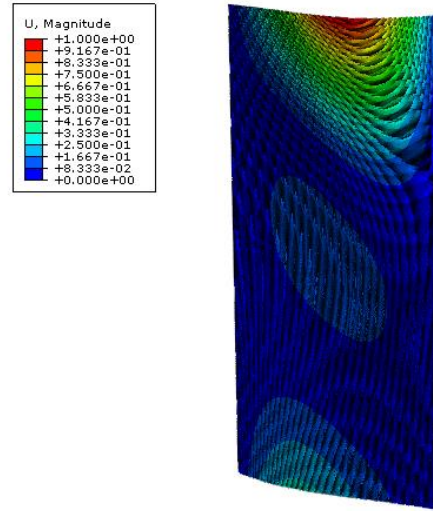

Figure 2.10: ABAQUS model
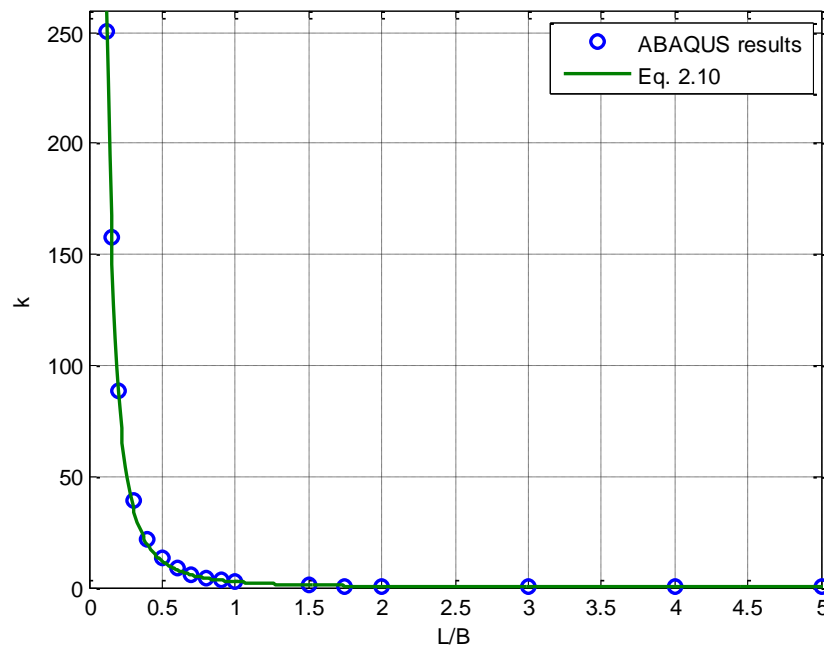

Figure 2.11: ABAQUS result

Figure 2.12: Comparison of buckling coefficient, k

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Table 2.6: Comparison of k values

L/B	ABAQUS Results	Eq. 2.10
0.1	373	409
0.12	250	274
0.15	158	167
0.2	88.8	88.9
0.3	39.0	36.4
0.4	21.5	19.3
0.5	13.5	11.8
0.6	8.82	7.91
0.7	6.03	5.63
0.8	4.33	4.20
0.9	3.25	3.24
1	2.52	2.57
1.5	0.984	1.05
1.75	0.698	0.749
2	0.521	0.558
3	0.218	0.229
4	0.120	0.121
5	0.0756	0.0742
$R^2 = 0.9992$		

2.7 Proposed Shear Design Method for CFS Clip Angles with Consideration of Deformation

The shear test results indicated that most of the CFS clip angles reached their peak loads at relatively excessive deformation, i.e., greater than the serviceability deflection limit of 1/8 in. specified in ICC-ES AC261 (2011). Therefore a design method for determining the nominal shear strength of CFS clip angles with consideration of the deformation limit needed to be developed. The proposed design method for deformation limit was based on the concept of elastic shear deformation of a plate element. If one assumed a plate deformed in its elastic stage under a shear force, then the shear force could be given in terms of the plate's (cantilevered leg of a clip angle) geometric factor, Bt/L. The proposed design method for the nominal shear strength (lb, N) of CFS clip angles considering a 1/8 in. deformation limit is as follows:

$$V'_n = 9000 \, \alpha \left(\frac{Bt}{L} \right) \leq V_n \tag{2.11}$$

where

α = 1 lb/in. for US customary units

= 0.175 N/mm for SI units

t - design thickness of clip angle, in. [mm]

B - depth of clip angle, in. [mm], as shown in Figure 2.3

L - flat length of clip angle, in. [mm], distance between the center of the first line of screws to the bend line as shown in Figure 2.3.

V_n - nominal shear strength without considering deformation, lb [N], Eq. 2.7

The same parametric ranges in Section 2.4 apply to the above equations.

The comparison between the test results and the calculated nominal strength by the proposed design method is listed in Table 2.7 and shown in Figure 2.13. It can be seen that the proposed method has a good agreement with the test results.

The LRFD and LSD resistance factors and the ASD safety factors for the proposed shear design method considering deformation were calculated following Chapter F of AISI S100 (2012). Two types of components listed in Table F1, Flexural Members – Shear Strength and Connections Not Listed Above, were chosen for the statistical analysis. The results are listed in Table 2.8.

Table 2.7: Comparison of shear test results with the proposed design method considering deformation limit

| Test Label	Bt/L	$V_{1/8}$ (lbs)	V'_n (lbs)	$V_{1/8}/V'_n$
S1 #4	0.1265	1102	1139	0.968
S1 #5	0.1265	781	1139	0.685
S3 #1	0.2196	1521	1976	0.770
S3 #2	0.2196	1710	1976	0.865
S4 #3	0.1869	2230	1683	1.325
S4 #4	0.1869	2445	1683	1.453
S5 #3	0.2470	2344	2223	1.054
S5 #4	0.2470	1936	2223	0.871
S6 #1	0.0576	586	519	1.130
S6 #2	0.0576	665	519	1.282
S7 #1	0.1287	1540	1158	1.330
S7 #3	0.1287	1066	1158	0.920
S8 #3	0.1023	1284	920	1.395
S8 #4	0.1023	1236	920	1.343
S8 #5	0.1023	1182	920	1.285
S9 #2	0.1103	1429	992	1.440
S9 #3	0.1103	1293	992	1.302
S10 #1	0.1834	1521	1650	0.921
S10 #2	0.1834	2051	1650	1.243
T1a #1	0.0252	288	227	1.267
T1a #2	0.0252	280	227	1.233
T1b #1	0.0299	307	270	1.140
T1b #2	0.0299	261	270	0.967
T1b #3	0.0299	261	270	0.967
T3 #1	0.0672	421	605	0.697
T3 #2	0.0672	495	605	0.819
T3 #3	0.0672	462	605	0.763
T4 #2	0.0510	429	459	0.934
T4 #3	0.0510	476	459	1.036
T5a #1	0.0252	319	227	1.402
T5a #2	0.0252	279	227	1.230
T5b #1	0.0269	250	242	1.034
T5b #2	0.0269	237	242	0.981
Mean				1.092
St. Dev.				0.230
COV				0.210
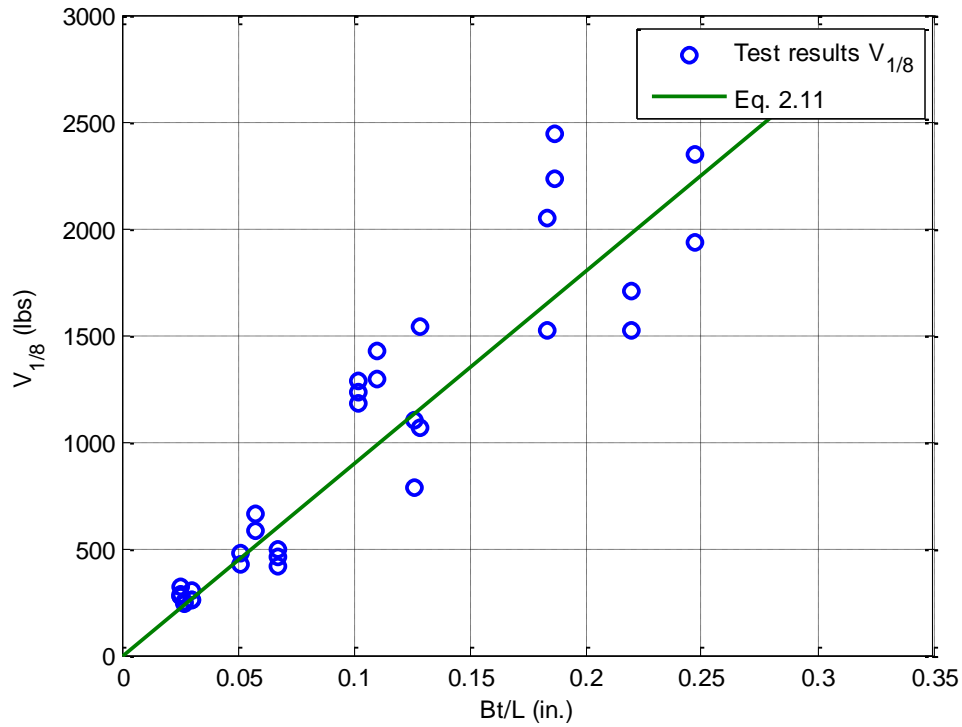
Figure 2.13: Comparison of shear test results with the proposed design method considering deformation limit

Table 2.8: Resistance factors and safety factors for shear design with consideration of deformation

	Considered as Flexural Members – Shear Strength	Considered as Connections Not Listed Above
Quantity	33	33
Mean	1.092	1.092
Std. Dev.	0.230	0.230
COV	0.210	0.210
M_m	1.10	1.10
V_m	0.10	0.10
F_m	1.00	1.00
P_m	1.092	1.092
V_f	0.05	0.15
β (LRFD)	2.5	3.5
β (LSD)	3.0	4.0
V_Q	0.21	0.21
ϕ (LRFD)	0.81	0.53
ϕ (LSD)	0.65	0.41
Ω (ASD)	1.97	3.02

2.8 Alternative 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 shown in Figure 2.13.

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

$$V'_n = 6300 \, \alpha \left(\frac{Bt}{L}\right) \leq V_n \tag{2.12}$$

where

α = 1 lb/in. for US customary units

= 0.175 N/mm for SI units

t - design thickness of clip angle, in. [mm]

B - depth of clip angle, in. [mm], as shown in Figure 2.3

L - flat length of clip angle, in. [mm], distance between the center of the first line of screws to the bend line as shown in Figure 2.3.

V_n - nominal shear strength without considering deformation, lb [N], Eq. 2.7

The same parametric ranges in Section 2.4 apply to the above equations.

The comparison between the test results and the calculated nominal strength by the proposed alternative design method shown in Figure 2.14. It was suggested that the serviceability could be checked using the alternative design equation (Eq. 2.12) without a resistance factor or a safety factor.
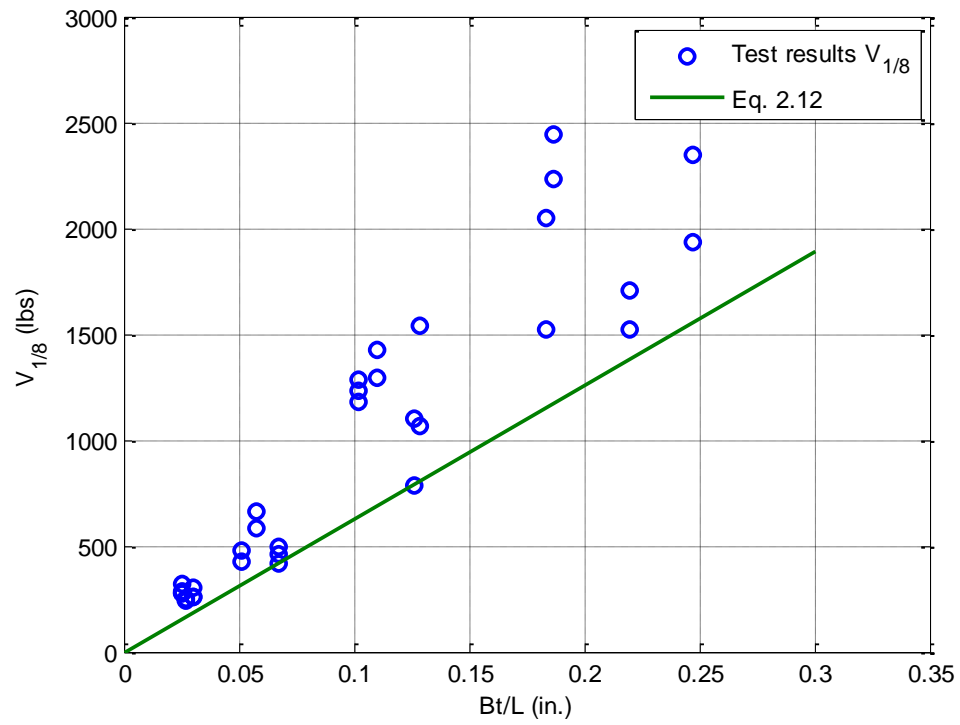
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Figure 2.14: Comparison of shear test results with the proposed alternative design method considering deformation limit

3 COMPRESSION STRENGTH OF CLIP ANGLES

The compression test program was to investigate the compression capacity of the clip angle fastened to CFS members. The test results were compared with (1) the AISI gusset plate design method found in the North American Steel Framing Standards – Truss Design (AISI S214, 2012), (2) the axial compression member design method found in the North American Specification for the Design of Cold-Formed Steel Structural Members (AISI S100, 2012), and (3) the web crippling design method also found in AISI S100 (2012). There was no good agreement with any of the three existing AISI design methods when the test results were compared, therefore a new design method was developed to determine the nominal compression strength of CFS clip angles.

3.1 Test Setup and Test Procedure

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 54 mil or less, a 54 mil stud member was used. For clip angles with a thickness 68 mil 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.
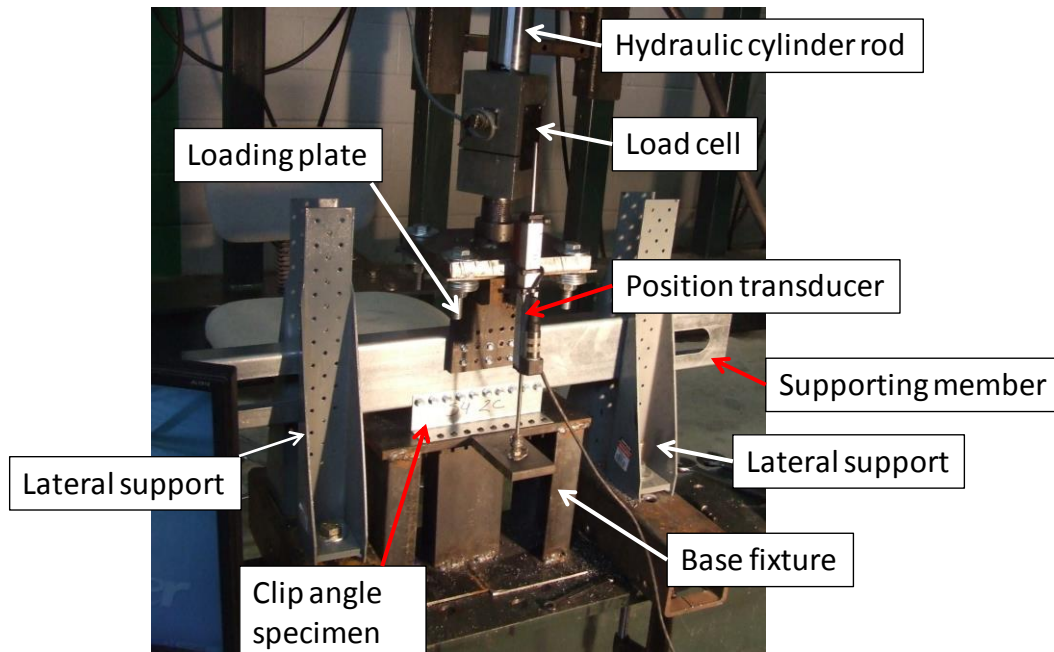

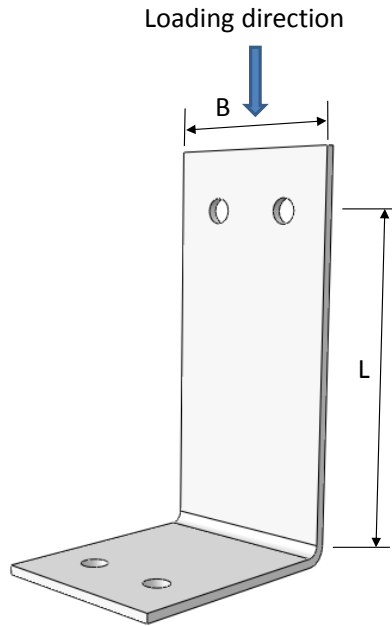Figure 3.1: Test setup for compression tests

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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. The loading rate was the same as used in shear tests since it was found that the selected loading rate worked well for the clip angle specimens. The strength and deformation of clip angles under static compression loads were successfully captured by the apparatus, and the testing speed was slow enough to have no impact to the test results.

3.2 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 3.1. The definitions of the measured dimensions in Table 3.1 are the same as those defined in the shear test program, Section 2.2. Additional dimensions of the clip angles can be found in Appendix 2. All the pre-punched holes in each clip angle were used for screw connections.

Table 3.1: Properties of clip angles in the compression test program

Test Label	L (in.)	B (in.)	t (in.)	F_y (ksi)	F_u (ksi)
S1 #1 C	1.382	3.020	0.0584	45.7	50.1
S1 #2 C	1.382	3.020	0.0584	45.7	50.1
S1 #3 C	1.382	3.020	0.0584	45.7	50.1
S2 #1 C	1.351	3.001	0.1352	49.6	53.2
S2 #2 C	1.351	3.001	0.1352	49.6	53.2
S3 #1 C	1.391	5.230	0.0584	45.7	50.1
S3 #2 C	1.391	5.230	0.0584	45.7	50.1
S3 #3 C	1.391	5.230	0.0584	45.7	50.1
S4 #1 C	1.401	7.497	0.0349	49.9	55.8
S4 #2 C	1.401	7.497	0.0349	49.9	55.8
S5 #1 C	1.415	7.520	0.0465	46.4	51.2
S5 #2 C	1.415	7.520	0.0465	46.4	51.2
S5 #3 C	1.415	7.520	0.0465	46.4	51.2
S6 #1 C	2.422	3.004	0.0465	46.4	51.2
S6 #2 C	2.422	3.004	0.0465	46.4	51.2
S6 #3 C	2.422	3.004	0.0465	46.4	51.2
S7 #1 C	2.328	3.021	0.1006	45.6	60.0
S7 #2 C	2.328	3.021	0.1006	45.6	60.0
S7 #3 C	2.328	3.021	0.1006	45.6	60.0
S8 #1 C	2.387	5.254	0.0465	46.4	51.2
S8 #2 C	2.387	5.254	0.0465	46.4	51.2
S8 #3 C	2.387	5.254	0.0465	46.4	51.2
S9 #1 C	2.388	7.540	0.0349	49.9	55.8
S9 #2 C	2.388	7.540	0.0349	49.9	55.8
S9 #3 C	2.388	7.540	0.0349	49.9	55.8
S10 #1 C	2.387	7.497	0.0584	45.7	50.1
S10 #2 C	2.387	7.497	0.0584	45.7	50.1
S10 #3 C	2.387	7.497	0.0584	45.7	50.1
T2 #1 C	2.370	1.749	0.1352	49.6	53.2
T2 #2 C	2.370	1.749	0.1352	49.6	53.2
T3 #1 C	1.523	1.753	0.0584	45.7	50.1
T3 #2 C	1.523	1.753	0.0584	45.7	50.1
T4 #1 C	2.394	1.751	0.0698	54.8	66.7
T4 #2 C	2.394	1.751	0.0698	54.8	66.7
T6 #1 C	2.336	1.748	0.1352	49.6	53.2
T6 #2 C	2.336	1.748	0.1352	49.6	53.2

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 would be performed. The test program showed that the flexural buckling was the primary failure mode for the tested clip angles under compression. Figure 3.3 shows the results of a 97 mil clip angle. Figure 3.4 shows the results of a 33 mil clip angle. The tests results are provided in Table 3.2.
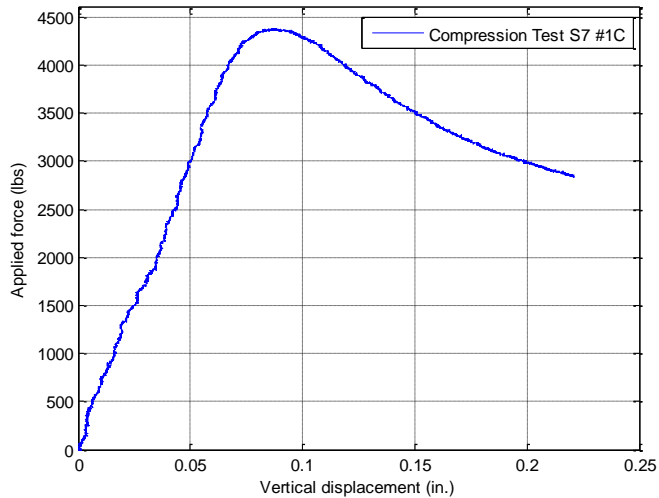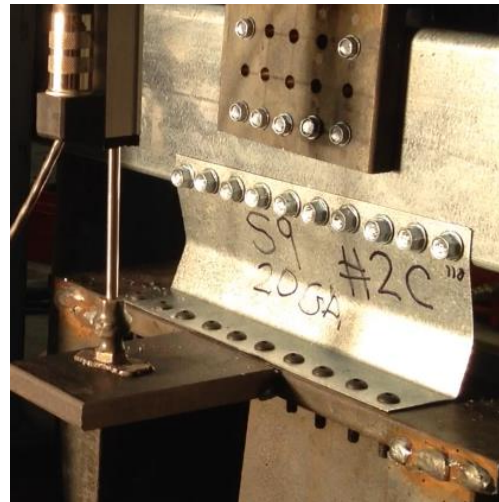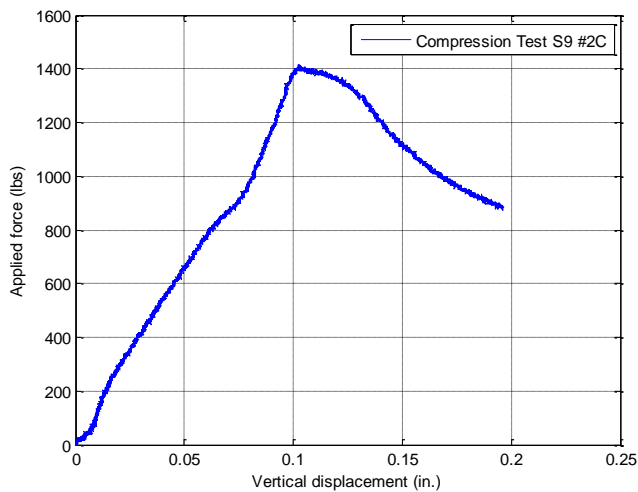

Figure 3.3: Test results of S7 #1C

Figure 3.4: Test results of S9 #2C

Table 3.2: Results of compression tests

Test Label	P_{test} (lbs)	Δ (in.)
S1 #1 C	1906	0.049
S1 #2 C	1556	0.074
S1 #3 C	1714	0.068
S2 #1 C	7219	0.206
S2 #2 C	7870	0.213
S3 #1 C	2537	0.052
S3 #2 C	2819	0.150
S3 #3 C	2533	0.076
S4 #1 C	2437	0.059
S4 #2 C	2214	0.078
S5 #1 C	4714	0.118
S5 #2 C	3656	0.090
S5 #3 C	3983	0.235
S6 #1 C	1097	0.037
S6 #2 C	1465	0.053
S6 #3 C	1551	0.053
S7 #1 C	4380	0.088
S7 #2 C	3877	0.129
S7 #3 C	4058	0.077
S8 #1 C	2313	0.059
S8 #2 C	1722	0.051
S8 #3 C	1714	0.055
S9 #1 C	1675	0.054
S9 #2 C	1416	0.102
S9 #3 C	1561	0.039
S10 #1 C	5087	0.115
S10 #2 C	4348	0.120
S10 #3 C	4105	0.095
T2 #1 C	4426	0.164
T2 #2 C	4354	0.173
T3 #1 C	1042	0.072
T3 #2 C	1144	0.068
T4 #1 C	1784	0.080
T4 #2 C	1649	0.076
T6 #1 C	4680	0.178
T6 #2 C	4470	0.171

3.4 Comparison with AISI Design Methods

The peak loads from the compression tests were compared with the predicted nominal strength by (1) the gusset plate design in AISI S214 (2012), (2) the axial compression member design in AISI S100 (2012), and (3) the web crippling design in AISI S100 (2012). The test-to-predicted ratios are listed in Table 3.3 and illustrated in Figure 3.5. In Table 3.3, P_{AISI-G} is the predicted strength by the gusset plate design, P_{AISI-C} is the predicted strength by the compression member design, and P_{AISI-W} is the predicted web crippling strength assuming a C section subjected to Interior Two-Flange Loading with flanges fastened to the support.

It can be seen in Figure 3.5 that the predicted strengths are not in agreement with the test results. For clip angles with an aspect ratio, L/B, greater than 0.3, the three design methods yielded consistently higher strength than the test results. A new design method for the compression strength of CFS clip angles was needed. The analysis also showed that the gusset plate design and the compression member design yielded similar results, particularly for clip angles with an aspect ratio (L/B) less than 0.8. For clip angles with an aspect ratio greater than 0.8, the compression member design yielded consistently higher results than the gusset plate design, and the difference increased as the L/B ratio got larger.

Table 3.3: Comparison of test results with AISI design methods

| Test Label	P_{test} / P_{AISI-G}	P_{test} / P_{AISI-C}	P_{test} / P_{AISI-W}
S1 #1 C	0.321	0.322	1.029
S1 #2 C	0.262	0.263	0.869
S1 #3 C	0.289	0.290	0.958
S2 #1 C	0.365	0.359	0.525
S2 #2 C	0.398	0.391	0.429
S3 #1 C	0.385	0.386	0.472
S3 #2 C	0.428	0.429	0.442
S3 #3 C	0.385	0.385	0.391
S4 #1 C	0.918	0.923	0.409
S4 #2 C	0.834	0.838	1.365
S5 #1 C	1.059	1.061	1.240
S5 #2 C	0.821	0.823	1.617
S5 #3 C	0.894	0.897	1.254
S6 #1 C	0.309	0.277	0.500
S6 #2 C	0.412	0.371	0.668
S6 #3 C	0.436	0.392	0.707
S7 #1 C	0.417	0.320	1.241
S7 #2 C	0.369	0.283	0.948
S7 #3 C	0.386	0.296	0.705
S8 #1 C	0.535	0.540	0.702
S8 #2 C	0.398	0.402	0.317
S8 #3 C	0.397	0.400	0.348
S9 #1 C	0.629	0.639	0.332
S9 #2 C	0.532	0.540	0.307
S9 #3 C	0.586	0.595	1.061
S10 #1 C	0.743	0.746	1.001
S10 #2 C	0.635	0.638	0.353
S10 #3 C	0.599	0.602	0.385
T2 #1 C	0.578	0.378	0.240
T2 #2 C	0.568	0.371	0.236
T3 #1 C	0.263	0.224	0.253
T3 #2 C	0.289	0.246	0.242
T4 #1 C	0.411	0.269	0.627
T4 #2 C	0.380	0.248	0.697
T6 #1 C	0.606	0.399	0.626
T6 #2 C	0.579	0.381	1.366
Mean	0.512	0.470	0.691
St. Dev.	0.201	0.220	0.384
COV	0.393	0.467	0.557
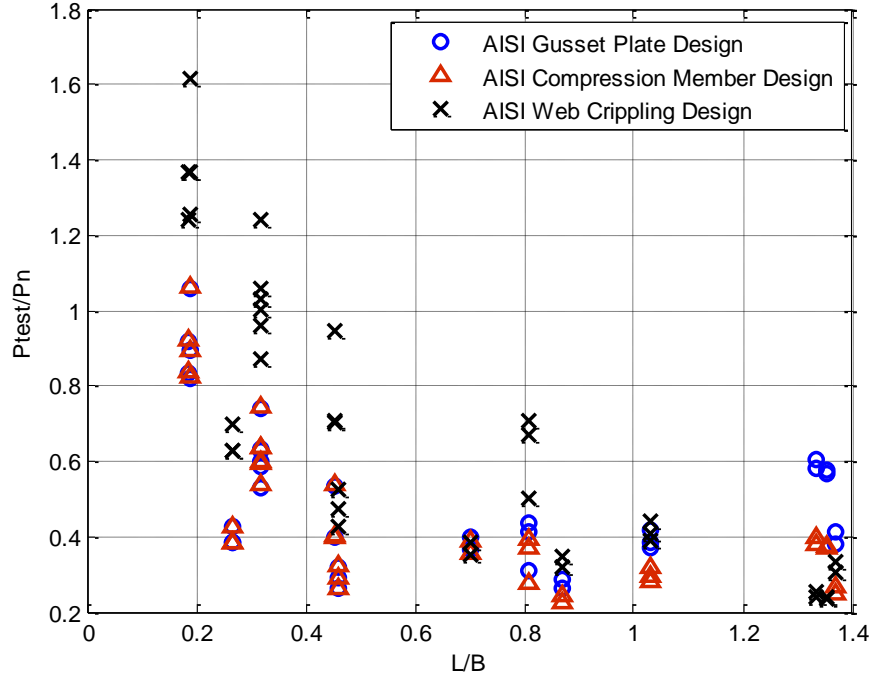
Figure 3.5: Comparison of test results to existing AISI design methods

3.5 Proposed Comparison Design Method for CFS Clip Angles

The compression tests showed that the CFS clip angles behaved in a similar manner as a plate columns, where the global/flexural buckling dominated the failure mechanism. The proposed design method for the compression strength of CFS clip angles was developed considering the column theory of the AISI design which expresses the column strength as a function of slenderness (KL/r). For a pin-pin supported plate column, $\frac{KL}{r} = \frac{\sqrt{12}L}{t}$. The proposed compression design is listed as follows:

The nominal compression strength

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

where

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

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

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

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

E - modulus of elasticity of steel, 29500 ksi

μ - Poisson's ratio for steel, 0.3

k - buckling coefficient can be found by interpolation in Table 3.4

    = 0.90 as a conservative value

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t - design thickness of clip angle

B' - shall be taken as the lesser of the actual clip angle width (Figure 2.3) or the Whitmore section width (Figure 3.6)

L - flat width of clip angle, distance between the first line of screws to the bend line as shown in Figure 2.3

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

Clip angle design thickness: 33 mils to 118 mils

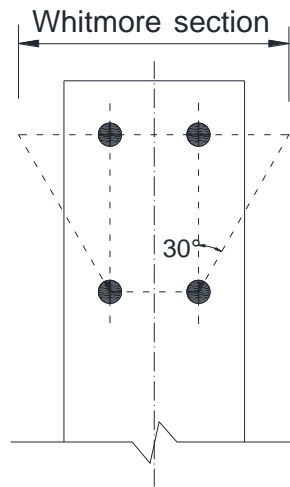Clip angle design yield strength: 33 ksi to 50 ksi

L/B ratio: 0.18 to 1.40

Figure 3.6: Whitmore section width

Table 3.4: 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 3.5 lists the comparison between the test results (P_{test}) and the predicted strength by the proposed design method (P_n). In Table 3.5, F_{test} is the applied stress, $F_{test} = P_{test} / (Bt)$. Figure 3.7 shows the comparison

Table 3.5: Comparison of test results with the proposed design method

| Test label	L/t	F_{cr} (ksi)	F_{test} / F_{cr}	P_{test} / P_n
S1 #1 C	23.67	46.40	0.233	0.873
S1 #2 C	23.67	46.40	0.190	0.713
S1 #3 C	23.67	46.40	0.209	0.786
S2 #1 C	9.99	260.78	0.068	0.887
S2 #2 C	9.99	260.40	0.074	0.967
S3 #1 C	23.82	46.27	0.180	0.667
S3 #2 C	23.82	46.27	0.199	0.741
S3 #3 C	23.82	46.27	0.179	0.666
S4 #1 C	40.10	16.39	0.568	0.996
S4 #2 C	40.10	16.39	0.516	0.905
S5 #1 C	30.44	28.44	0.474	1.238
S5 #2 C	30.44	28.44	0.368	0.960
S5 #3 C	30.44	28.44	0.401	1.046
S6 #1 C	52.12	9.42	0.834	1.004
S6 #2 C	52.12	9.42	1.114	1.341
S6 #3 C	52.12	9.42	1.179	1.419
S7 #1 C	23.14	47.85	0.301	1.167
S7 #2 C	23.14	47.85	0.267	1.033
S7 #3 C	23.14	47.85	0.279	1.081
S8 #1 C	51.38	9.85	0.962	1.182
S8 #2 C	51.38	9.85	0.716	0.880
S8 #3 C	51.38	9.85	0.713	0.876
S9 #1 C	68.35	5.60	1.134	0.924
S9 #2 C	68.35	5.60	0.959	0.781
S9 #3 C	68.35	5.60	1.057	0.861
S10 #1 C	40.88	15.66	0.742	1.267
S10 #2 C	40.88	15.66	0.634	1.083
S10 #3 C	40.88	15.66	0.599	1.022
T2 #1 C	17.53	81.68	0.229	1.324
T2 #2 C	17.53	81.68	0.225	1.302
T3 #1 C	26.08	37.50	0.272	0.886
T3 #2 C	26.08	37.50	0.298	0.971
T4 #1 C	34.31	21.31	0.685	1.505
T4 #2 C	34.31	21.31	0.633	1.392
T6 #1 C	17.28	84.12	0.235	1.389
T6 #2 C	17.28	84.12	0.225	1.327
Mean				1.041
St. Dev.				0.232
COV				0.223
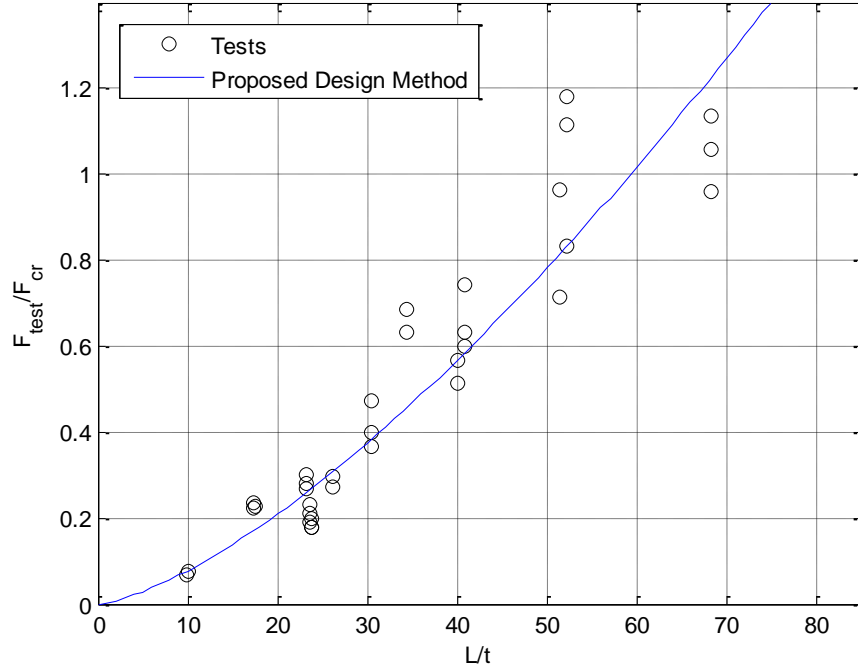
Figure 3.7: Comparison of test results with the proposed design method

The LRFD and LSD resistance factors and the ASD safety factors for the proposed compression design method were calculated following Chapter F of the AISI S100 (2012). Two types of components: Concentrically Loaded Compression Members and Connections Not Listed Above, listed in Table F1 were chosen for the analyses. The results are listed in Table 3.6.

Table 3.6: Resistance factors and safety factors for the proposed compression design method

	Considered as Concentrically Loaded Members	Considered as Connections Not Listed Above
Quantity	36	36
Mean	1.041	1.041
Std. Dev.	0.232	0.232
COV	0.223	0.223
M_m	1.10	1.10
V_m	0.10	0.10
F_m	1.00	1.00
P_m	1.0241	1.027
V_f	0.05	0.15
β (LRFD)	2.5	3.5
β (LSD)	3.0	4.0
V_Q	0.21	0.21
ϕ (LRFD)	0.76	0.49
ϕ (LSD)	0.60	0.38
Ω (ASD)	2.11	3.26

3.6 Critical Elastic Buckling Solution for Plate Column

The proposed compression design method required the elastic buckling solution of a plate column which has been solved analytically by Houbolt, J. C. and Stowell, E. Z. (1950), Eq. 3.5. However a closed-form equation was not available for the buckling coefficient, k. Table 3.4 lists the theoretical values for k, and Figure 3.8 shows the theoretical solution of k. It is recommended to determine the buckling coefficient, k, using Table 3.4 by interpolation. However the k value can be conservatively chosen to be 0.9.
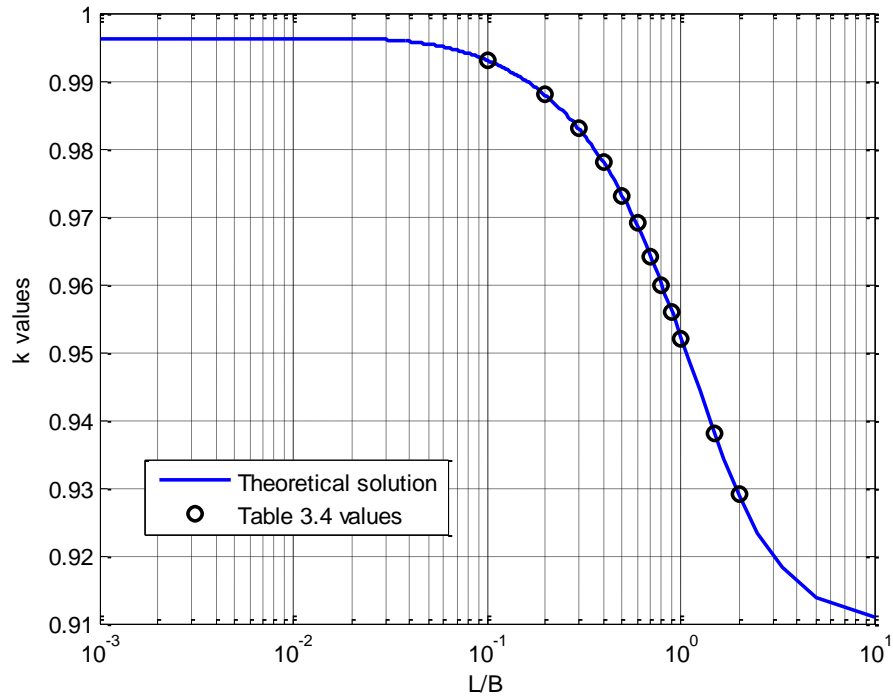
Figure 3.8: Theoretical solution for the buckling coefficient, k

4 PULL-OVER STRENGTH OF SCREW CONNECTIONS

The pull-over test program investigated the pull-over strength of fasteners on the anchored leg of the clip angle. Initial confirmatory tests showed that the tested pull-over strength was significantly less than the predicted values that were determined using AISI S100 (2012). Therefore additional specimens were tested in order to develop an appropriate design method for the pull-over strength of screws used in CFS clip angles.

4.1 Test Setup and Test Procedure

The test setup for the pull-over strength was identical 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. 14 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 to ensure the occurrence of the pull-over failure mode.
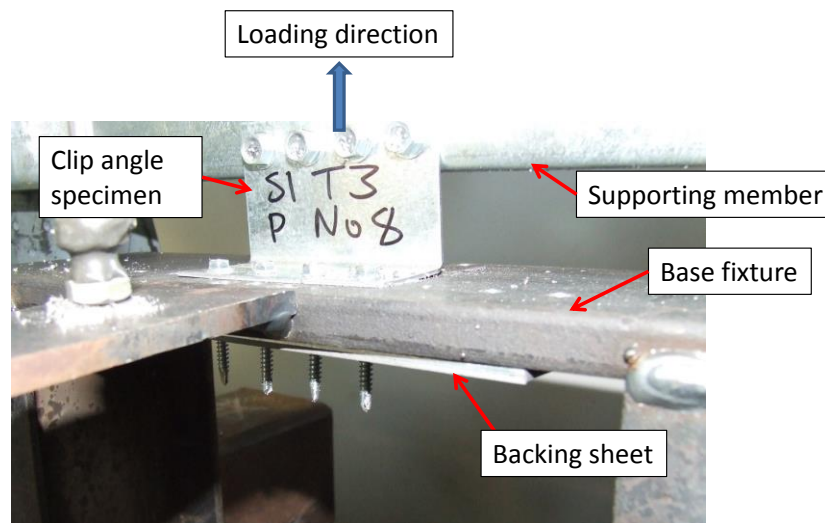

Figure 4.1: Close-up view of the pull-over test setup

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.

4.2 Test Specimens

The test program focused on the pull-over failure of the screws on the anchored leg of the clip angles. Tests that failed in other modes such as screw pull-out failures, screw shear failures, etc. were not included in the analyses. The failure modes of invalid tests can be found in Appendix 1. All the pre-punched holes in the cantilevered leg of the tested clip angles were used by No. 14 screws to prevent undesired failures. The number of screws used in the anchored leg varied. A total of 38 valid pull-over tests were conducted. Table 4.1 lists the measured dimensions, screw configurations, and tested material properties. The definitions of L, B, and t in Table 4.1 are same as those defined in the shear and compression test programs. The d'_w is the measured hex washer head integral washer diameter.

Table 4.1: Properties of clip angles in the pull-over test program

Test Label	L (in.)	B (in.)	t (in.)	d'_w (in.)	No. of Screws[1]	Screw Type	F_y (ksi)	F_u (ksi)
S1 #2 P No 8	1.394	3.020	0.0584	0.322	4	8-22x1 1/4	45.7	50.1
S1 #3 P No 8	1.394	3.020	0.0584	0.322	4	8-22x1 1/4	45.7	50.1
S3 #1 P No 8	1.391	5.230	0.0584	0.322	3	8-22x1 1/4	45.7	50.1
S3 #2 P No 8	1.391	5.230	0.0584	0.322	3	8-22x1 1/4	45.7	50.1
S4 #1 P No 8	1.401	7.497	0.0349	0.322	4	8-22x1 1/4	49.6	53.2
S4 #2 P No 8	1.401	7.497	0.0349	0.322	4	8-22x1 1/4	49.6	53.2
S4 #3 P No 8	1.401	7.497	0.0349	0.322	4	8-22x1 1/4	49.6	53.2
S5 #1 P No 8	1.415	7.520	0.0465	0.322	4	8-22x1 1/4	46.4	51.2
S5 #2 P No 8	1.415	7.520	0.0465	0.322	4	8-22x1 1/4	46.4	51.2
S5 #3 P No 8	1.415	7.520	0.0465	0.322	4	8-22x1 1/4	46.4	51.2
S5 #4 P No 8	1.415	7.520	0.0465	0.322	4	8-22x1 1/4	46.4	51.2
S6 #1 P No 8	2.422	3.004	0.0465	0.322	4	8-22x1 1/4	46.4	51.2
S6 #2 P No 8	2.422	3.004	0.0465	0.322	4	8-22x1 1/4	46.4	51.2
S8 #1 P No 8	2.387	5.254	0.0465	0.322	3	8-22x1 1/4	46.4	51.2
S8 #2 P No 8	2.387	5.254	0.0465	0.322	3	8-22x1 1/4	46.4	51.2
S9 #1 P No 8	2.389	7.540	0.0349	0.322	4	8-22x1 1/4	49.6	53.2
S9 #2 P No 8	2.389	7.540	0.0349	0.322	4	8-22x1 1/4	49.6	53.2
S9 #3 P No 8	2.389	7.540	0.0349	0.322	4	8-22x1 1/4	49.6	53.2
S9 #4 P No 8	2.389	7.540	0.0349	0.322	4	8-22x1 1/4	49.6	53.2
S10 #1 P No 8	2.387	7.497	0.0584	0.322	4	8-22x1 1/4	45.7	50.1
S10 #2 P No 8	2.387	7.497	0.0584	0.322	4	8-22x1 1/4	45.7	50.1
S10 #3 P No 8	2.387	7.497	0.0584	0.322	4	8-22x1 1/4	45.7	50.1
T1b #2 P No 8	2.038	1.747	0.0349	0.322	2	8-22x1 1/4	49.6	55.8
T1b #3 P No 8	2.038	1.747	0.0349	0.322	2	8-22x1 1/4	49.6	55.8
T3 #1 P No 8	1.523	1.753	0.0584	0.322	2	8-22x1 1/4	45.7	50.1
T3 #2 P No 8	1.523	1.753	0.0584	0.322	2	8-22x1 1/4	45.7	50.1
T5a #1 P No 8	2.431	1.751	0.0349	0.322	2	8-22x1 1/4	49.6	55.8
T5a #2 P No 8	2.431	1.751	0.0349	0.322	2	8-22x1 1/4	49.6	55.8
T5b #1 P No 8	2.276	1.751	0.0349	0.322	3	8-22x1 1/4	49.6	53.2
T1a #1 P No 14	2.418	1.747	0.0349	0.493	2	14-15x1 1/4	49.6	53.2
T1a #2 P No 14	2.418	1.747	0.0349	0.493	2	14-15x1 1/4	49.6	53.2
T1b #1 P No 14	2.038	1.747	0.0349	0.493	2	14-15x1 1/4	49.6	53.2
T1b #2 P No 14	2.038	1.747	0.0349	0.493	2	14-15x1 1/4	49.6	53.2
T3 #1 P No 14	1.523	1.753	0.0584	0.493	2	14-15x1 1/4	45.7	50.1
T3 #2 P No 14	1.523	1.753	0.0584	0.493	2	14-15x1 1/4	45.7	50.1
T5b #1 P No 14	2.276	1.751	0.0349	0.493	2	14-15x1 1/4	49.6	53.2
T5b #2 P No 14	2.276	1.751	0.0349	0.493	2	14-15x1 1/4	49.6	53.2
T5b #3 P No 14	2.276	1.751	0.0349	0.493	2	14-15x1 1/4	49.6	53.2

Note: 1 – the screws refer to the 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 would be conducted. Figure 4.2 shows a pull-over test on a 33 mil clip angle; it represents the typical behavior observed in this test program for a CFS clip angle subjected to a tension force. Two No. 8 self-drilling screws were used to fasten the clip angle to the test bed while two No. 14 self-drilling screws were used to fasten the cantilevered leg of the clip angle to the loading stud member. In the pull-over test, the clip angle demonstrated three different stages of behavior. The initial stage had relatively small stiffness, the tension resistance was provided by the bending capacity of the angle. As the cantilevered leg was continuously being pulled up, the tensile strength of the clip angle began to contribute to the resistance of the applied force and later became the primary load bearing mechanism. At this stage, the stiffness of the clip angle increased significantly. The clip angle finally failed by the pull-over failure at the No. 8 screws; the anchored leg of the clip angle separated from the test bed and the tension strength dropped instantly after the pull-over failure occurred. In all the pull-over tests, excessive deformation was observed before the clip angle reached its tension capacity.
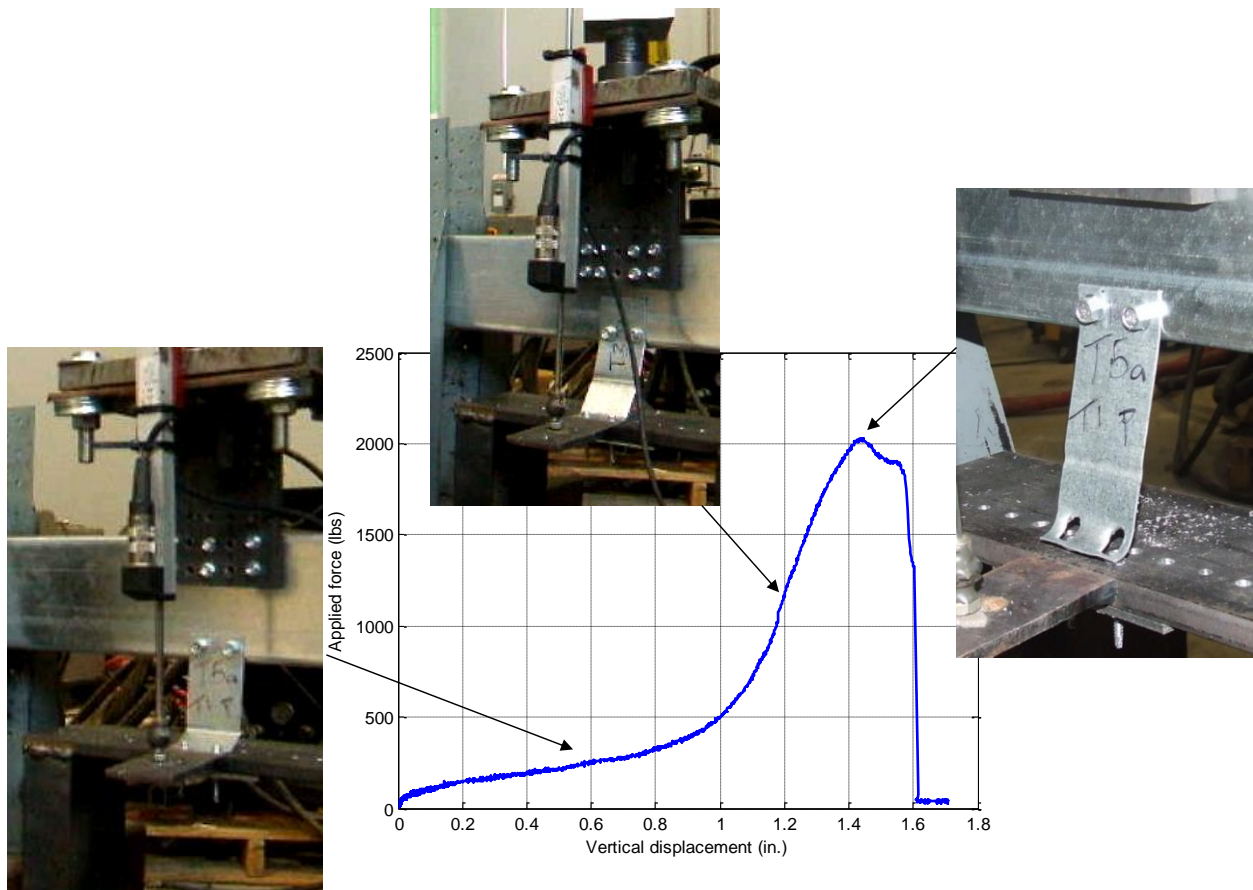
Figure 4.2: Typical behavior of a clip angle under tension

The test results are listed in Table 4.2 in which the P_{test} is the peak load per screw, Δ is the vertical deflection of the cantilevered leg corresponding to the peak load.

Table 4.2: Results of the pull-over tests

Test Label	P_{test} (lbs)	Δ (in.)
S1 #2 P No 8	1485	1.007
S1 #3 P No 8	1377	1.037
S3 #1 P No 8	1118	1.040
S3 #2 P No 8	1015	0.982
S4 #1 P No 8	738	1.066
S4 #2 P No 8	569	0.859
S4 #3 P No 8	805	0.999
S5 #1 P No 8	953	1.085
S5 #2 P No 8	800	1.086
S5 #3 P No 8	1158	1.026
S5 #4 P No 8	1061	1.054
S6 #1 P No 8	1041	0.961
S6 #2 P No 8	1079	1.038
S8 #1 P No 8	853	1.048
S8 #2 P No 8	847	1.020
S9 #1 P No 8	590	1.043
S9 #2 P No 8	508	0.940
S9 #3 P No 8	723	0.938
S9 #4 P No 8	659	1.075
S10 #1 P No 8	1046	1.114
S10 #2 P No 8	1176	1.081
S10 #3 P No 8	1243	1.124
T1b #2 P No 8	503	1.034
T1b #3 P No 8	570	0.941
T3 #1 P No 8	1015	1.432
T3 #2 P No 8	989	1.374
T5a #1 P No 8	529	0.892
T5a #2 P No 8	469	0.874
T5b #1 P No 8	751	0.962
T1a #1 P No 14	860	0.726
T1a #2 P No 14	834	0.725
T1b #1 P No 14	818	0.919
T1b #2 P No 14	788	1.065
T3 #1 P No 14	1273	1.439
T3 #2 P No 14	1347	1.569
T5b #1 P No 14	844	1.007
T5b #2 P No 14	966	1.036
T5b #3 P No 14	777	1.085

4.4 Comparison with AISI Design Method

The pull-over strengths obtained from the tests were compared with the pull-over strength calculated in Section E4.4.2 of AISI S100 (2012). The results are listed in Table 4.3. The test results are on average 50.3% of the predicted pull-over strength by AISI S100 with small standard deviation.

Table 4.3: Comparison of test results with AISI design method

Test label	P_{test} / P_{AISI}
S1 #2 P No 8	0.526
S1 #3 P No 8	0.488
S3 #1 P No 8	0.528
S3 #2 P No 8	0.479
S4 #1 P No 8	0.411
S4 #2 P No 8	0.317
S4 #3 P No 8	0.448
S5 #1 P No 8	0.414
S5 #2 P No 8	0.348
S5 #3 P No 8	0.503
S5 #4 P No 8	0.461
S6 #1 P No 8	0.453
S6 #2 P No 8	0.469
S8 #1 P No 8	0.495
S8 #2 P No 8	0.491
S9 #1 P No 8	0.328
S9 #2 P No 8	0.283
S9 #3 P No 8	0.403
S9 #4 P No 8	0.367
S10 #1 P No 8	0.370
S10 #2 P No 8	0.416
S10 #3 P No 8	0.440
T1b #2 P No 8	0.534
T1b #3 P No 8	0.606
T3 #1 P No 8	0.719
T3 #2 P No 8	0.701
T5a #1 P No 8	0.562
T5a #2 P No 8	0.498
T5b #1 P No 8	0.557
T1a #1 P No 14	0.625
T1a #2 P No 14	0.606
T1b #1 P No 14	0.595
T1b #2 P No 14	0.573
T3 #1 P No 14	0.589
T3 #2 P No 14	0.623
T5b #1 P No 14	0.614
T5b #2 P No 14	0.702
T5b #3 P No 14	0.565
Mean	0.503
St. Dev.	0.109
COV	0.217

4.5 Proposed Pull-Over Strength for CFS Clip Angles

With simple modifications to the existing AISI design method, a design method for the pull-over strength of CFS clip angles can be developed. The new design method is listed as follows.

The nominal pull-over strength of sheet per screw

$$P_{nov} = 0.75 t_1 d'_w F_{u1} \tag{4.1}$$

where

d'_w = effective pull-over diameter determined in accordance with Section E4.4.2 of AISI S100 (2012)

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

Since the limit state is the pull-over failure of the screw connections, the parameter limits of the clip angles in this test program do not apply to the pull-over strength of screw connections. Therefore, it is recommended that the existing limits specified in Section E4.4.2 of AISI S100 (2012) shall apply to the proposed pull-over design equations.

A comparison between the test results and the proposed design method is listed in Table 4.4. The LRFD and LSD resistance factors and the ASD safety factors for the proposed pull-over design method were calculated following Chapter F of AISI S100 (2012). The type of component listed in Table F1, Screw Connections – Pull-Over, was chosen for the statistical analysis. The results are listed in Table 4.5. The calculated resistance factors are close to the AISI values: 0.52 vs. 0.50 for the LRFD resistance factor and 0.42 vs. 0.40 for the LSD resistance factor.

Table 4.4: Comparison of test results with the proposed design method

Test label	P_{test} / P_{nov}
S1 #2 P No 8	1.051
S1 #3 P No 8	0.975
S3 #1 P No 8	1.055
S3 #2 P No 8	0.959
S4 #1 P No 8	0.821
S4 #2 P No 8	0.633
S4 #3 P No 8	0.896
S5 #1 P No 8	0.829
S5 #2 P No 8	0.696
S5 #3 P No 8	1.007
S5 #4 P No 8	0.922
S6 #1 P No 8	0.905
S6 #2 P No 8	0.938
S8 #1 P No 8	0.989
S8 #2 P No 8	0.982
S9 #1 P No 8	0.657
S9 #2 P No 8	0.566
S9 #3 P No 8	0.805
S9 #4 P No 8	0.733
S10 #1 P No 8	0.741
S10 #2 P No 8	0.833
S10 #3 P No 8	0.881
T1 b #2 P No 8	1.068
T1 b #3 P No 8	1.211
T3 #1 P No 8	1.438
T3 #2 P No 8	1.401
T5a #1 P No 8	1.123
T5a #2 P No 8	0.997
T5b #1 P No 8	1.114
T1a #1 P No 14	1.250
T1a #2 P No 14	1.212
T1b #1 P No 14	1.189
T1b #2 P No 14	1.146
T3 #1 P No 14	1.178
T3 #2 P No 14	1.246
T5b #1 P No 14	1.227
T5b #2 P No 14	1.404
T5b #3 P No 14	1.129
Mean	1.005
St. Dev.	0.208
COV	0.207

Table 4.5: Resistance factors and safety factor for the proposed pull-over design method

	Considered as Screw Connections – Pull-Over
Quantity	38
Mean	1.005
Std. Dev.	0.208
COV	0.207
M_m	1.10
V_m	0.10
F_m	1.00
P_m	1.005
V_f	0.10
β (LRFD)	3.5
β (LSD)	4.0
V_Q	0.21
ϕ (LRFD)	0.52
ϕ (LSD)	0.42
Ω (ASD)	3.05

5 CONCLUSIONS AND FUTURE RESEARCH

Three series of tests on CFS clip angles were conducted to investigate the behavior, strength, and deflection for three limit states: shear of clip angle, compression of clip angle, and pull-over of clip angle screw connection. The test results were compared with existing design methods in AISI and AISC documents for members similar, but not same as the clip angles. It was found that none 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 the shear strength, two design methods were proposed: nominal shear strength without consideration of deformation, and nominal shear strength with consideration of deformation. For the compression design, since a majority of the specimens reached their peak loads at a deflection less than the deflection limit of 1/8 in., a single design method was proposed. For the pull-over of screw connections, it was found that the existing pull-over design method in AISI S100 (2012) could be applied to clip angle applications with a reduction factor of 0.5.

The LRFD, LSD resistance factors and the ASD safety factors for the proposed design methods were calculated using Chapter F of AISI S100 (2012).

Draft specification language for the three proposed design methods are provided in Appendix 3 of this report.

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

- Clip angles using welded connections
  In this research, screw connections were used in all tested clip angles. The clip angles using welded connections may demonstrate different behavior and strength. Additional tests on clip angles with welds can be conducted to verify the proposed design methods.

- The fastener pattern effects on the clip angles
  The specimens used in this research had predrilled holes for screws, and the holes were uniformly distributed along the width of the clip angle in one line or two. The screw pattern may have effects on the behavior and strength of clip angles, additional research is needed to study the screw pattern's impact.

- Serviceability of clip angles subjected to tension
  In the pull-over test program of this research, the ultimate strength of screw's pull-over failure was focused on. It was found that the clip angles yielded significant amount of deflection before their ultimate strength was reached. The stiffness and strength of the clip angles under tension within the service deflection limit can be included in the future research.

- Reliability of proposed design equations for clip angles
  In the shear and compression test programs of this research, fastener's failures were prevented, and the clip angles failed in the cantilevered legs. Members' failures were achieved. The proposed design equations for shear and compression might be appropriate

to use a reliability index for members when the resistance factors and safety factors were determined. However if one considered the clip angle as a connector that shall have higher reliability than a structural member, a reliability index for connections shall be used. Furthermore, when the clip angles were used in the secondary structural components of a building such as curtain walls, a reliability index smaller than that for the primary structural components might be reasonable. A comprehensive study on the reliability issue of the design methods is needed to ensure safe and efficient use of CFS clip angles.

6 ACKNOWLEDGEMENTS

7 REFERENCES

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APPENDIX 1 – FAILURE MODES OF INVALID TESTS

Table A1-1 Failure modes of invalid shear tests

Test Label	Failure Mode
S1 #1	Screw shear failure
S1 #2	Screw shear failure
S1 #3	Screw shear failure
S4 #1	Hydraulic servo not ON
S4 #2	Screw shear failure
S4 #4	Buckling on anchored leg, only 2 screws used
S5 # 1	Screw shear failure
S5 # 2	Screw shear failure
S7 #2	Screw shear failure
S8 #1	Only 2 screws used, C leg not fully constrained
S8 #2	Only 2 screws used, C leg not fully constrained
S9 #1	Hydraulic servo not ON
T4 #1	Screw shear failure

Table A1-2 Failure modes of invalid pull-over tests

Test Label	Failure Mode
S1 #1 P No 8	One screw not installed properly
T1 b #1 P No 8	Hydraulic problem

APPENDIX 2 – DETAILED DIMENSIONS OF CLIP ANGLES

Table A2-1 Measured outside corner radii

Specimen Label	r (in.)
S1	0.156
S2	0.250
S3	0.156
S4	0.125
S5	0.125
S6	0.141
S7	0.250
S8	0.156
S9	0.141
S10	0.172
T1a	0.125
T1b	0.125
T2	0.250
T3	0.156
T4	0.172
T5a	0.125
T5b	0.125
T6	0.141

The following figures present the nominal dimensions of the clip angles. Note that the cantilevered leg is on the left side of the bend line.

Type S1
16 ga., GR50
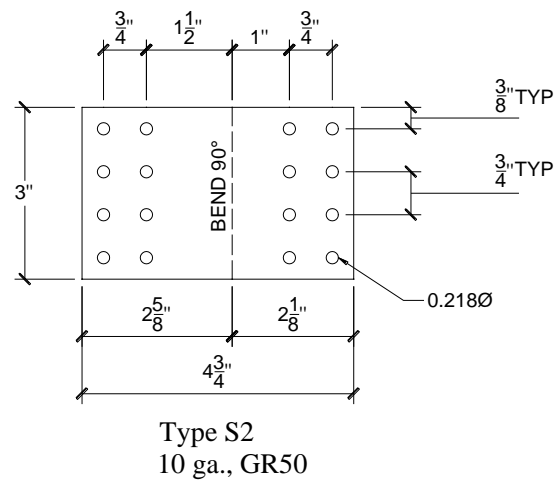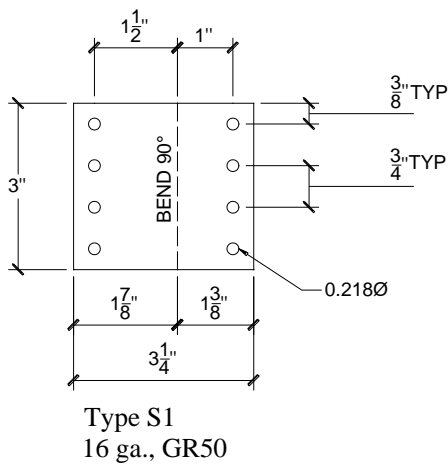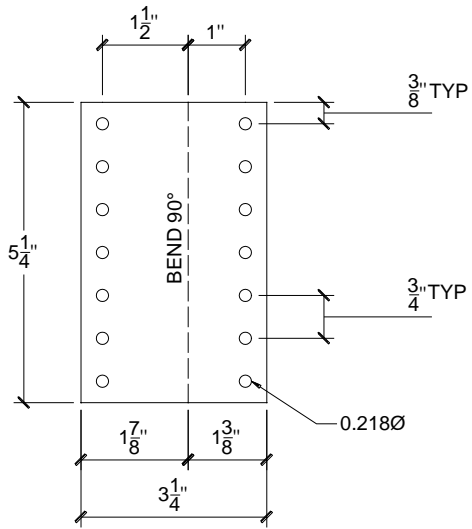
Type S2
10 ga., GR50
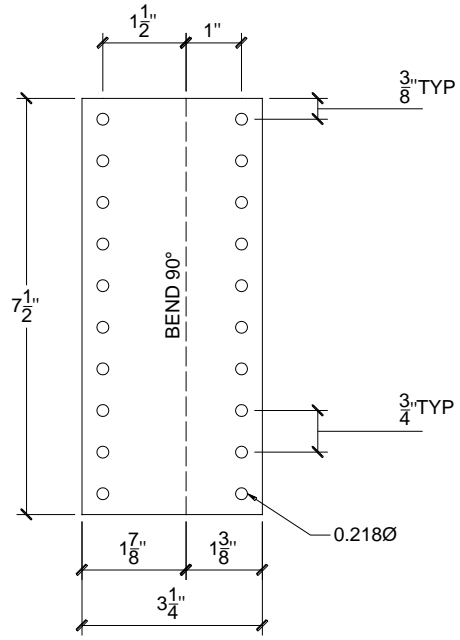
Type S3
16 ga., GR50

Type S4
20 ga., GR33
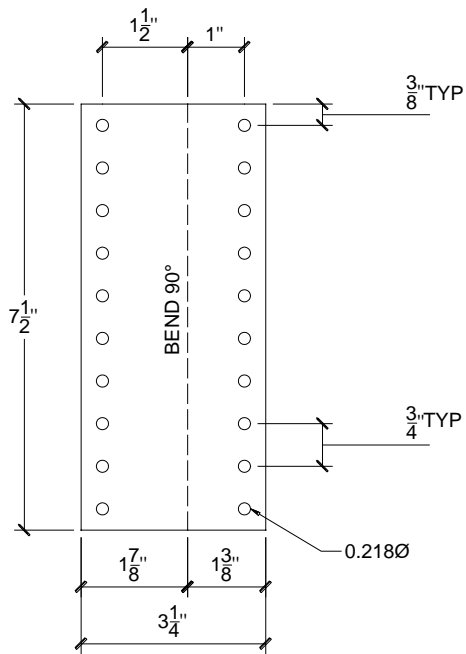
Type S5
18 ga., GR33

Type S6
18 ga., GR33

45
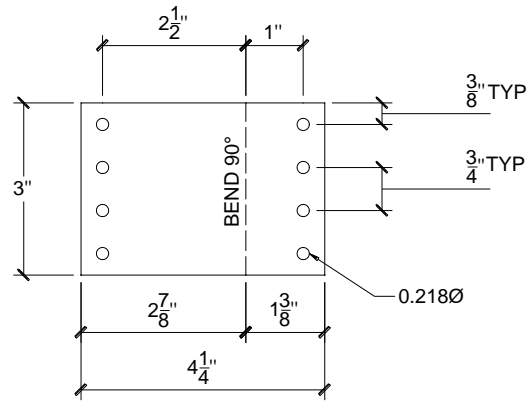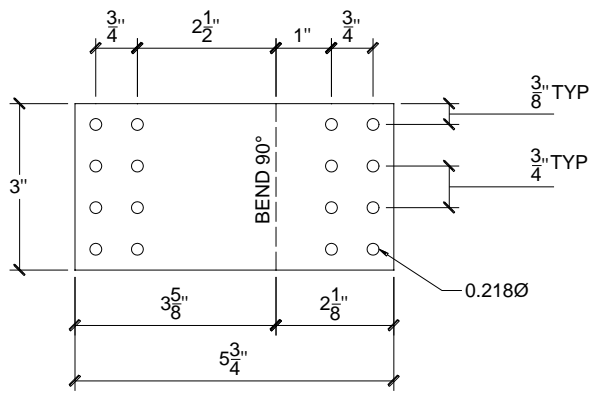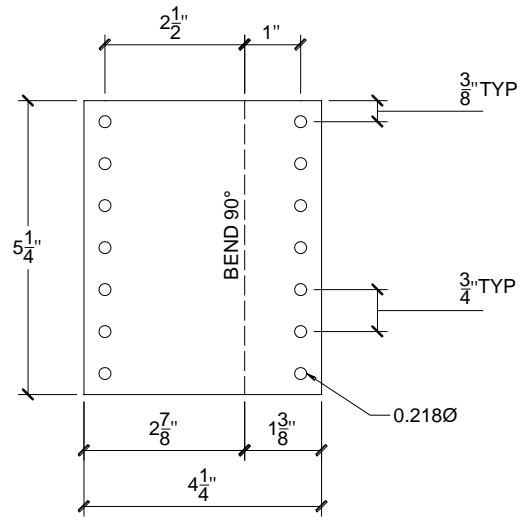
Type S7
12 ga., GR50
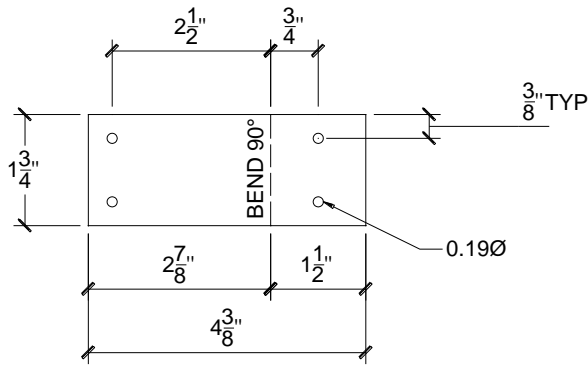

Type S8
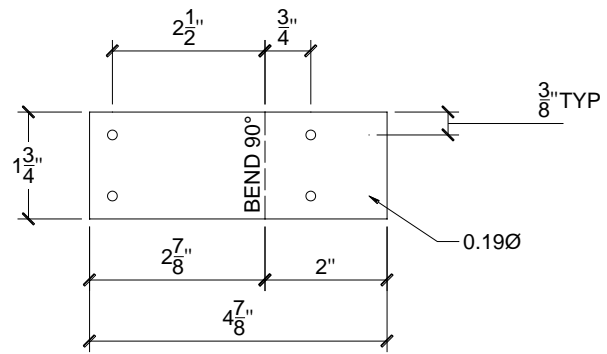18 ga., GR33
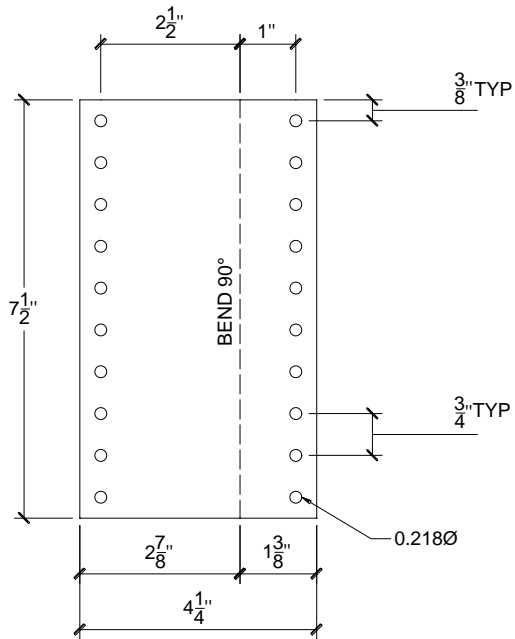
Type S9
20 ga., GR33

Type S10
20 ga., GR50
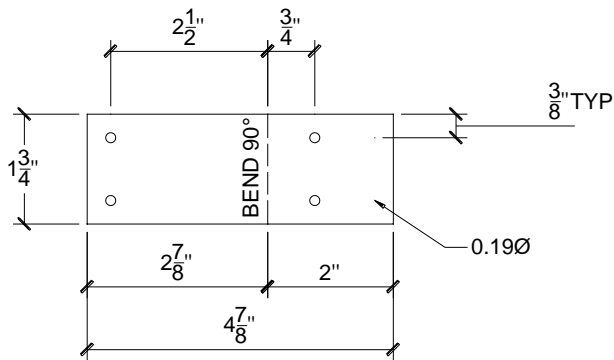
46
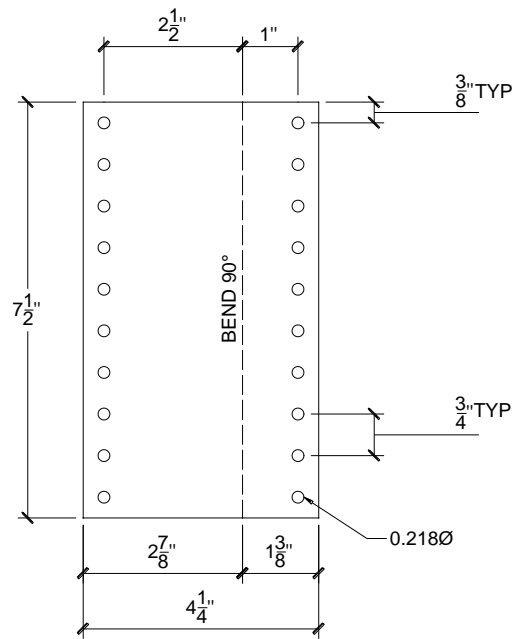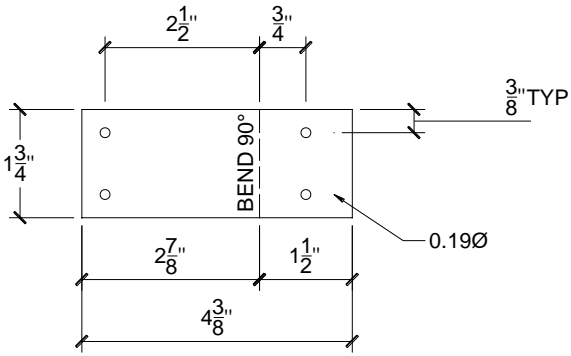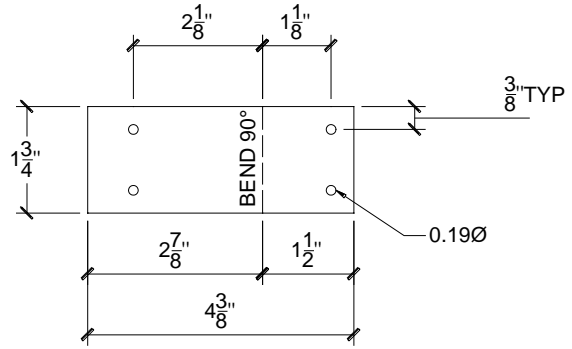
Type T1a
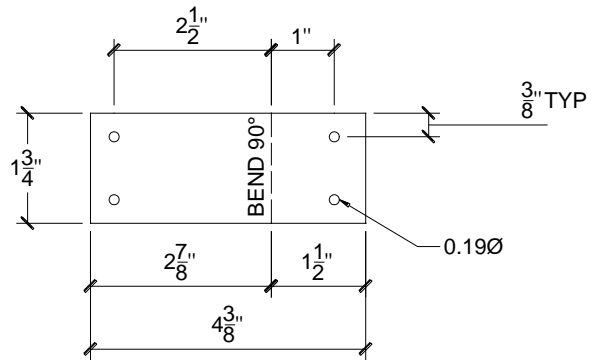20ga., GR33
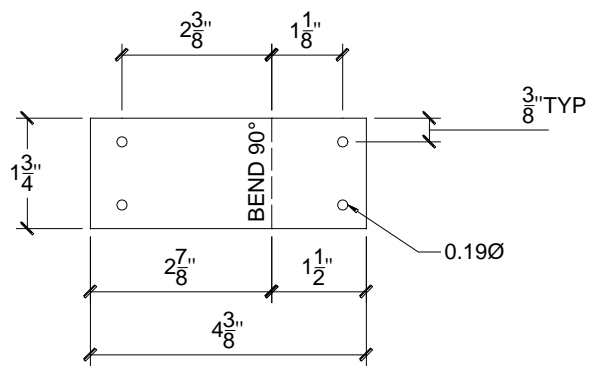
Type T1b
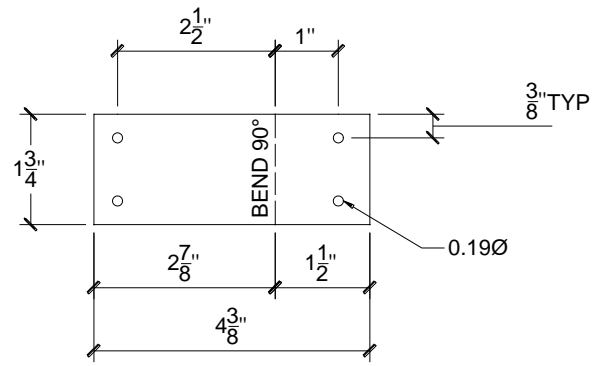20ga., GR33

Type T2
10 ga., GR50

Type T3
16 ga., GR50

Type T4
14 ga., GR50

Type T5a
20 ga., GR33

47

Type T5b
20 ga., GR33

Type T6
10 ga., GR50

APPENDIX 3 – DRAFT DESIGN PROVISIONS

(1) Shear Strength without Consideration of Clip Angle Deformation

When deformation of the clip angle is not a design consideration, the nominal shear strength [resistance], V_n, of clip angles shall be calculated as follows:

$$V_n = 0.17\lambda^{-0.8}F_yBt \leq 0.35F_yBt \qquad \text{(Eq. A3-1)}$$

where

$$\lambda = \sqrt{\frac{F_y}{F_{cr}}} \qquad \text{(Eq. A3-2)}$$

$$F_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)}\left(\frac{t}{B}\right)^2 \qquad \text{(Eq. A3-3)}$$

E - modulus of elasticity of steel, 29500 ksi

μ - Poisson's ratio for steel, 0.3

$$k = 2.569\left(\frac{L}{B}\right)^{-2.202} \qquad \text{(Eq. A3-4)}$$

F_y = specified minimum yield strength

$t =$ design thickness of clip angle

B = width of cantilevered leg measured parallel to the applied shear force

L - flat length of cantilevered leg measured from the center of the first line of fasteners to the bend line.

Ω = 2.80 for ASD

ϕ = 0.55 for LRFD

    = 0.45 for LSD

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.

(2) Shear Strength with Consideration of Clip Angle Deformation

When deformation of the clip angle is a design consideration, the nominal shear strength [resistance], V_n, of clip angles shall be calculated in accordance with this section. In addition, the available strength shall not exceed the nominal shear strength obtained in accordance with Section (1).

$$V_n = 9000\,\alpha \left(\frac{Bt}{L}\right) \qquad \text{(Eq. A3-5)}$$

where

$\alpha = 1$ lb/in. for US customary units

$\quad = 0.175$ N/mm for SI units

$\Omega = 3.00$ for ASD

$\phi = 0.55$ for LRFD

$\quad = 0.40$ for LSD

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.

(3) Compression Strength

The nominal compression strength [resistance], P_n, of the clip angle shall be calculated as follows:

$$P_n = F_n A_g \qquad \text{(Eq. A3-6)}$$

where

$$A_g = B't \qquad \text{(Eq. A3-7)}$$

$$F_n = 0.0028\lambda^{1.44}F_{cr} \le 0.4F_y \qquad \text{(Eq. A3-8)}$$

$$\lambda = \frac{L}{t} \qquad \text{(Eq. A3-9)}$$

$$F_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)} \left(\frac{t}{L}\right)^2 \qquad\qquad \text{(Eq. A3-10)}$$

E - modulus of elasticity of steel, 29500 ksi

μ - Poisson's ratio for steel, 0.3

k = buckling coefficient can be determined by interpolation in Table A3-1

= 0.90 as a conservative value

B' = shall be taken as the lesser of the actual clip angle width or the Whitmore section width, which shall be determined using a spread-out angle of 30 degrees along both sides of the connection, beginning at the first row of fasteners in the cantilevered leg of the clip angle

Ω = 3.25 for ASD

ϕ = 0.50 for LRFD

= 0.40 for LSD

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

Clip angle design thickness: 33 mils to 118 mils

Clip angle design yield strength: 33 ksi to 50 ksi

L/B ratio: 0.18 to 1.40

Table A3-1: 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

(4) Pull-Over

The nominal pull-over strength [resistance], P_{nov}, shall be calculated as follows:

$$P_{nov} = 0.75t_1 d'_w F_{u1}$$
(Eq. A3-11)

where

d'_w = effective pull-over diameter determined in accordance with Section E4.4.2 of AISI S100 (2012)

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

Ω = 3.00 for ASD

ϕ = 0.50 for LRFD

= 0.40 for LSD

All the requirements for screws in Section E4 of AISI S100 shall apply to the above equations.

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