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Behavior and Design of Thin-Walled Cold-Formed Steel Clip Angles Subjected to Shear Load

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Abstract
Thin-walled cold-formed steel clip angles are commonly used in light frame steel buildings for connecting cold-formed steel members such as floor joists. The design provisions for such connectors have not been included in the AISI design specifications and standards. The paper presents a research project aimed at developing a design method for the thin-walled cold-formed steel load bearing clip angles subjected to shear forces. An extensive test program is conducted to investigate the behavior and shear capacity of clip angles with various dimensions and thicknesses. It is found that the local buckling and the lateral-torsional buckling could dominate the failure mechanism dependent upon the plate slenderness ratio. Based on the test results, a design method is developed for determining the nominal shear strength of load bearing clip angles. The analysis shows that the proposed design method has a good agreement with the test data; the ASD safety factor and the LRFD resistance factor are also produced for the development of design provisions.

1. Introduction
The shear test program is aimed at identifying the failure mechanism and determining the shear strength of the cantilevered leg of cold-formed steel (CFS) clip angles subjected to in-plane transverse shear forces. The test setup ensures the failure to occur in the clip angle, and fastener failures are prevented. The test results were initially compared with the double coped beam design procedure found in the AISC Steel Construction Manual (2011). It was found that large variations existed between the test results and those determined using the AISC methodology. A new design method is proposed that will more accurately predict the shear strength of the CFS clip angles that other previous methods. To address the deflection limit, a design method with consideration of the clip angle deformation is also developed.

2. Test Program

2.1 Test Setup and Procedure

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The shear tests were conducted 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 test setup respectively.

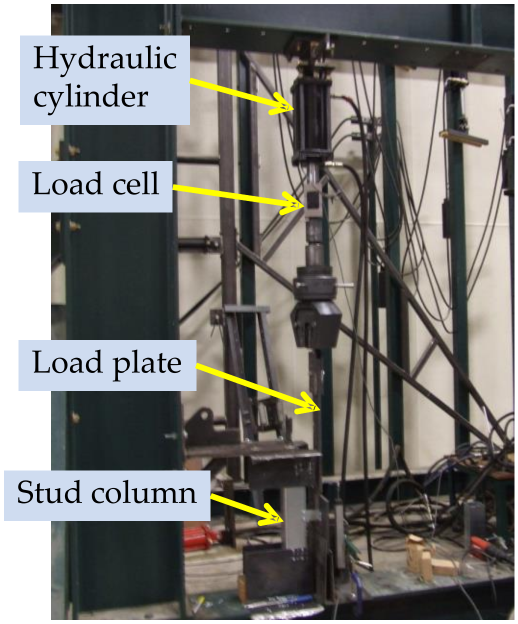

Figure 2.1: Overall view of shear test setup

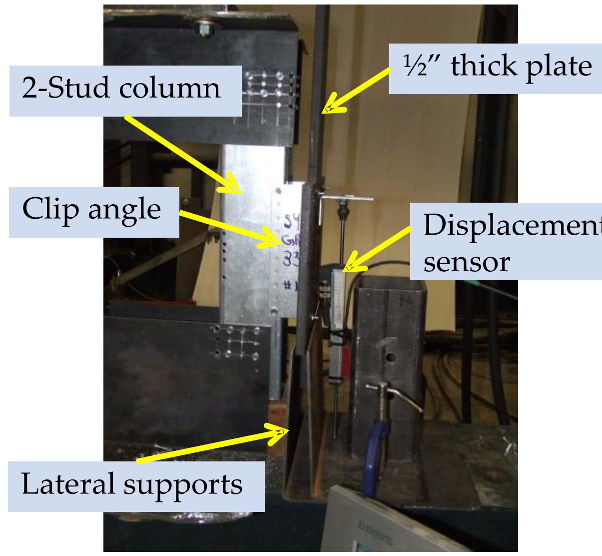

Figure 2.2: Close-up view of shear test setup

In each 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 (loaded leg) was fixed to a loading plate by No. 10-24×1 Button Head Socket Cap (BHSC) bolts. The loading plate was made of ½ in. thick structural steel which had pre-drilled holes to accommodate the BHSC bolt 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 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. During each test, the hydraulic cylinder moved the loading plate upwards at a constant speed of 0.3 in. per minute

2.2 Test Specimens and Test Results

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. 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 test program, two failure modes were observed. For thin clip angles with large aspect ratios (L/B), a lateral-torsional buckling mode dominated the behavior and failure mechanism. Figure 2.3 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, a local buckling failure could be observed. Figure 2.4 shows the test results of a 33 mil clip angle with an aspect ratio of 0.45. Local buckling failure can be observed in Figure 2.4.

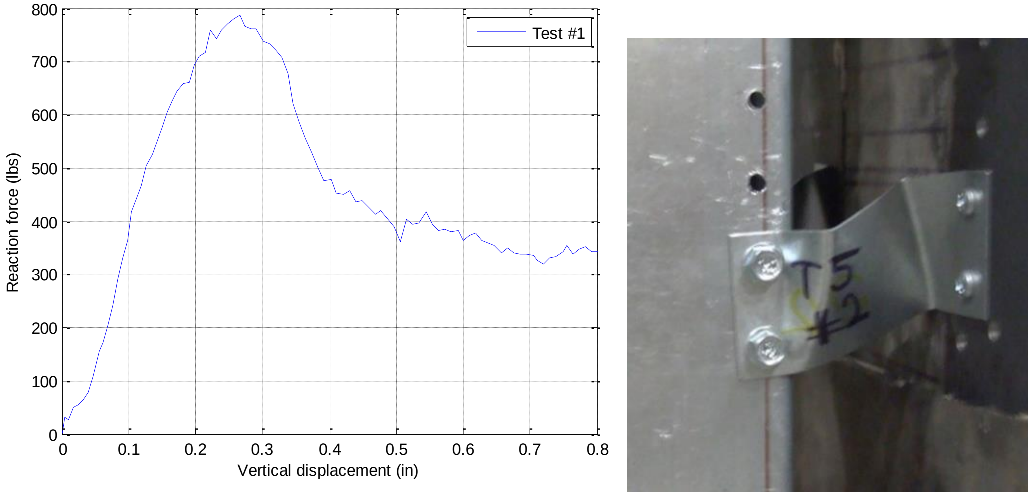

Figure 2.3: Test result of clip angle T5a#2

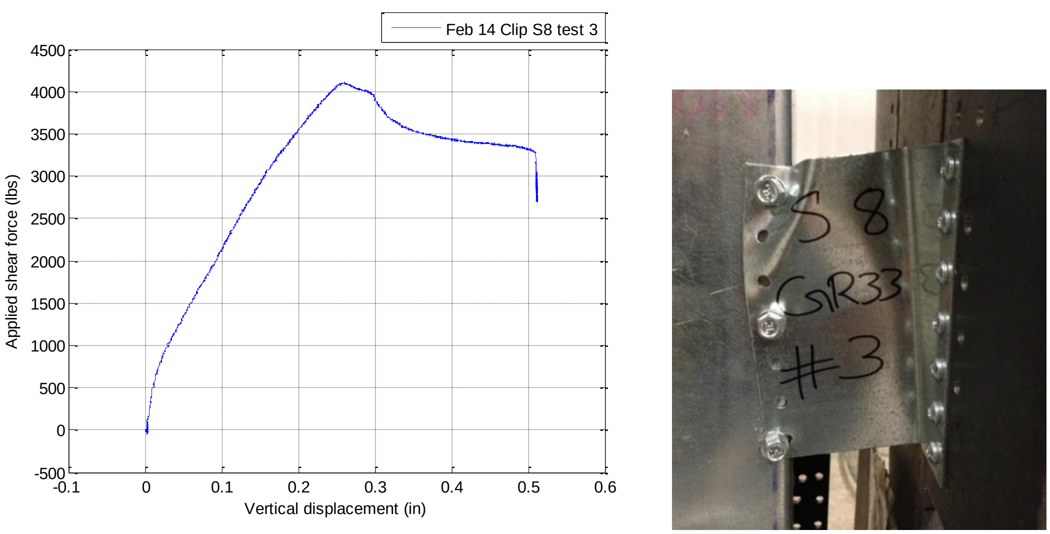

Figure 2.4: Test result of clip angle S8#4

The measured dimensions, tested material properties and shear test results are provided in Table 2.1. Figure 2.5 illustrates the measured dimensions in Table 2.1. 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 end the flat element at the corner. The thickness, t, 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). V_{test} is the peak load per clip angle. The deflection, Δ, is the displacement of the loading plate at the peak load, V_{test}. Δ can be considered as the average vertical deflection of the clip angles as two angles were used in each test.

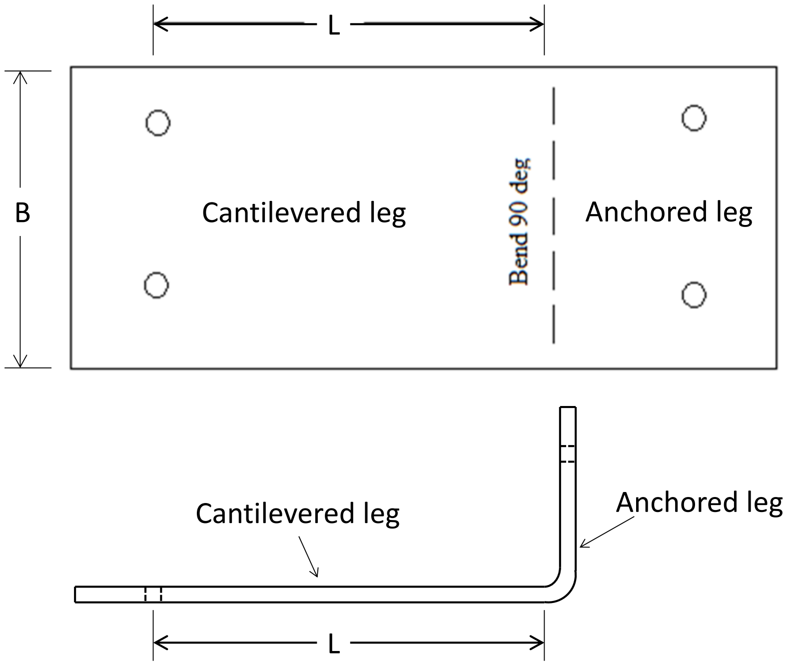

Figure 2.5: Measured dimensions in Table 2.1

Table 2.1: Results of shear tests

Test Label	L (in.)	B (in.)	t (in.)	F_y (ksi)	F_u (ksi)	V_{test} (lbs)	Δ (in.)
S1 #4	1.394	3.020	0.0584	45.7	50.1	2594	0.523
S1 #5	1.394	3.020	0.0584	45.7	50.1	2767	0.685
S3 #1	1.391	5.230	0.0584	45.7	50.1	3794	0.401
S3 #2	1.391	5.230	0.0584	45.7	50.1	3753	0.343
S4 #3	1.401	7.497	0.0349	49.9	55.8	2581	0.198
S4 #4	1.401	7.497	0.0349	49.9	55.8	2445	0.098
S5 # 3	1.415	7.520	0.0465	46.4	51.2	3534	0.294
S5 # 4	1.415	7.520	0.0465	46.4	51.2	3488	0.318
S6 #1	2.422	3.004	0.0465	46.4	51.2	1050	0.362
S6 #2	2.422	3.004	0.0465	46.4	51.2	983	0.297
S7 #1	2.362	3.021	0.1006	45.6	60.0	4339	0.608
S7 #3	2.362	3.021	0.1006	45.6	60.0	4319	0.532
S8 #3	2.387	5.254	0.0465	46.4	51.2	2054	0.259
S8 #4	2.387	5.254	0.0465	46.4	51.2	1912	0.236
S8 #5	2.387	5.254	0.0465	46.4	51.2	2048	0.286
S9 #2	2.389	7.540	0.0349	49.9	55.8	1787	0.225
S9 #3	2.389	7.540	0.0349	49.9	55.8	1670	0.197
S10 #1	2.387	7.497	0.0584	45.7	50.1	3268	0.359
S10 #2	2.387	7.497	0.0584	45.7	50.1	3421	0.256
T1a #1	2.418	1.747	0.0349	49.9	55.8	288	0.119
T1a #2	2.418	1.747	0.0349	49.9	55.8	328	0.198
T1b #1	2.038	1.747	0.0349	49.9	55.8	358	0.211
T1b #2	2.038	1.747	0.0349	49.9	55.8	315	0.198
T1b #3	2.038	1.747	0.0349	49.9	55.8	373	0.225
T3 #1	1.523	1.753	0.0584	45.7	50.1	845	1.248
T3 #2	1.523	1.753	0.0584	45.7	50.1	967	1.264
T3 #3	1.523	1.753	0.0584	45.7	50.1	932	0.831
T4 #2	2.394	1.751	0.0698	54.8	66.7	1028	1.109
T4 #3	2.394	1.751	0.0698	54.8	66.7	993	0.904
T5a #1	2.431	1.751	0.0349	49.9	55.8	319	0.109
T5a #2	2.431	1.751	0.0349	49.9	55.8	359	0.260
T5b #1	2.276	1.751	0.0349	49.9	55.8	250	0.100
T5b #2	2.276	1.751	0.0349	49.9	55.8	303	0.228

2.3 Comparison with AISC Design

The AISC Steel Construction Manual (2011) does not provide a design method for clip angles, however the double coped beam has similar loading and boundary conditions as those for the CFS clip angles. Therefore the AISC design provision for the double coped beam is 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}.

Method A:

$$F_{cr} = 0.62\,\pi\,E\,\frac{{t_w}^2}{c h_0}\,f_d \le F_y \tag{2.2}$$

where,

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

d_c = cope depth at the compression flange, in.

Method B:

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

where,

$$\begin{aligned} Q &= 1 \text{ for } \lambda \le 0.7 \\ &= (1.34 - 0.486\,\lambda) \text{ for } 0.7 < \lambda \le 1.41 \\ &= (1.30 / \lambda^2) \text{ for } \lambda > 1.41 \end{aligned} \tag{2.5}$$

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

Method B is considered as more conservative than Method A. The shear test results are compared with the AISC double coped beam design methods. In Table 2.2, 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 2.6 illustrates the comparison between the shear test results and the AISC design methods. Both AISI methods do not have good agreements with test results. Method A yields overly conservative predictions and both methods' predicted values have large variations from the test results. It can be concluded that the AISC double coped design provision is not appropriate for the shear strength of the CFS clip angles; a new design method is needed.

Table 2.2: Comparison of shear strength

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

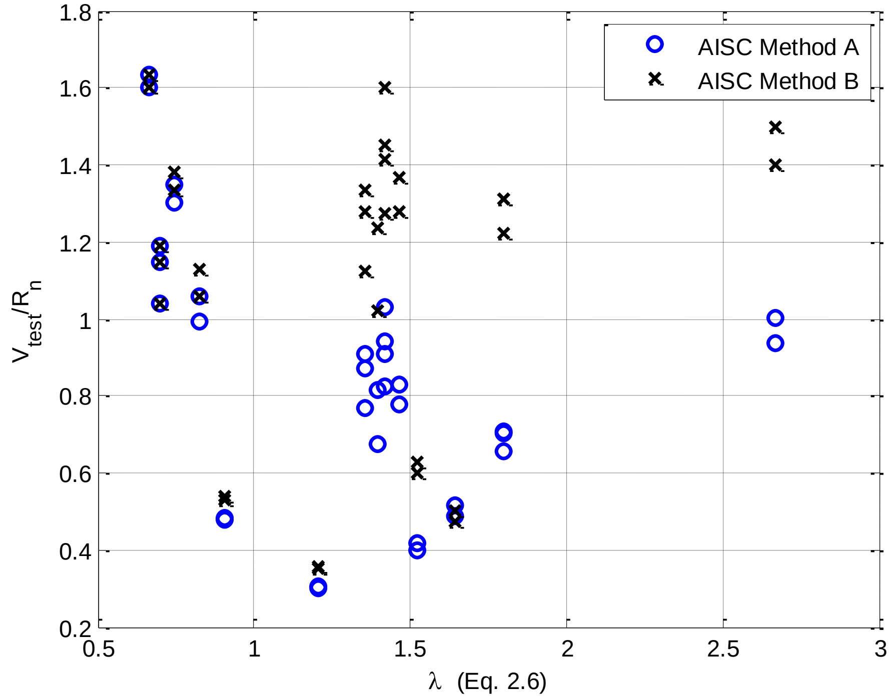

Figure 2.6: Comparison of shear test results with AISC design methods

3. Proposed Shear Design Method for CFS Clip Angles

3.1 Nominal Shear Strength

A design method for determining the nominal shear strength without consideration of deformation of CFS clip angles is developed using the peak load results from the shear test program. The design method is based on the methodology of the Direct Strength Method (Schafer and Peköz, 1998) which uses 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

$$V_n = 0.17\lambda^{-0.8}V_y \leq 0.35V_y \quad (3.1)$$

where $\lambda = \sqrt{\frac{V_y}{V_{cr}}}$ – slenderness ratio (3.2)

$V_y = F_yBt$ - yield load (3.3)

$V_{cr} = F_{cr}Bt$ - critical elastic buckling load (3.4)

$F_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)}(\frac{t}{B})^2$- critical elastic buckling stress (3.5)

$k = 2.569\left(\frac{L}{B}\right)^{-2.202}$ - buckling coefficient (3.6)

t - design thickness of clip angle

B - depth of clip angle shown in Figure 2.5

L - flat width of clip angle, distance between the first line of screws to the end of flat width as shown in Figure 2.5.

The above equations shall be valid within the following range of parameters:
Clip angle design thickness: 0.0346 in. to 0.1017 in.
Clip angle design yield strength: 33 ksi to 50 ksi
L/B ratio: 0.18 to 1.40

The comparison between the test results and the calculated nominal shear strength by the proposed design method is listed in Table 3.1 and illustrated in Figure 3.1. It can be seen that the proposed method has a good agreement with the test results, and also indicates that the concept of Direct Strength Method approach works for determining the shear strength of CFS clip angles.

Table 3.1: Comparison of shear test results with proposed design method

Test label	V_{test} (lbs)	V_n (lbs)	V_{test}/V_n
S1 #4	2594	2146	1.209
S1 #5	2767	2146	1.289
S3 #1	3794	3893	0.975
S3 #2	3753	3893	0.964
S4 #3	2581	2389	1.080
S4 #4	2445	2389	1.023
S5 # 3	3534	3801	0.930
S5 # 4	3488	3801	0.918
S6 #1	1050	878	1.196
S6 #2	983	878	1.120
S7 #1	4339	3590	1.209
S7 #3	4319	3590	1.203
S8 #3	2054	1627	1.262
S8 #4	1912	1627	1.175
S8 #5	2048	1627	1.259
S9 #2	1787	1502	1.190
S9 #3	1670	1502	1.112
S10 #1	3268	3570	0.915
S10 #2	3421	3570	0.958
T1a #1	288	306	0.941
T1a #2	328	306	1.072
T1b #1	358	356	1.006
T1b #2	315	356	0.885
T1b #3	373	356	1.048
T3 #1	845	1103	0.766
T3 #2	967	1103	0.877
T3 #3	932	1103	0.845

Table 3.1: Comparison of shear test results with proposed design method (Continued)

Test label	V_{test} (lbs)	V_n (lbs)	V_{test}/V_n
T4 #2	1028	1137	0.904
T4 #3	993	1137	0.873
T5a #1	319	305	1.046
T5a #2	359	305	1.177
T5b #1	250	324	0.772
T5b #2	303	324	0.935
Mean			1.034
St. dev			0.148
COV			0.143

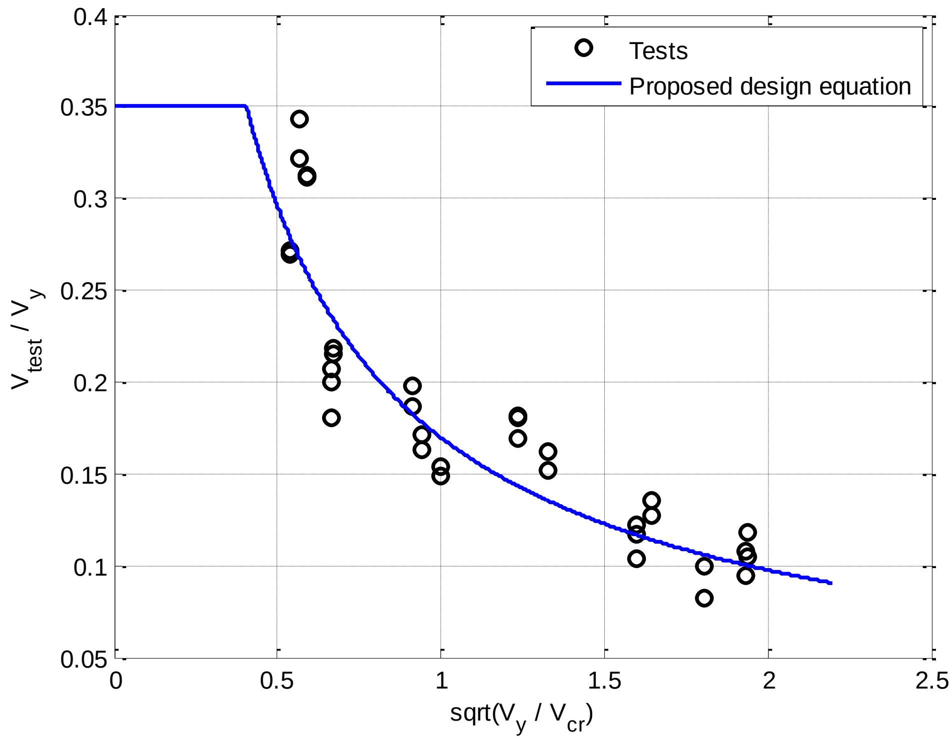

Figure 3.1: Comparison of shear test results with proposed design method

Since the clip angle's shear failure was the buckling in the plate element and the screw failures were successfully prevented in the tests, the reliability index for a flexural members in shear is recommended for the proposed shear design of CFS clip angles. The LRFD and LSD resistance factors and the ASD safety factors for the proposed shear design method are calculated following Chapter F of North American Specification for Cold-Formed Steel Design (AISI S100, 2012). Flexural Members – Shear Strength listed in Table F1 of AISI S100 (2012) were chosen as the type of component for the analysis. The results are listed in Table 3.2.

Table 3.2: Resistance factors and safety factors for shear design method

	Considered as Flexural Members – Shear Strength
Quantity	33
Mean	1.034
Std. Dev.	0.148
COV	0.143
M_m	1.10
V_m	0.10
F_m	1.00
P_m	1.034
V_f	0.05
β (LRFD)	2.5
β (LSD)	3.0
V_Q	0.21
ϕ (LRFD)	0.86
ϕ (LSD)	0.70
Ω (ASD)	1.87

3.2 Critical Elastic Buckling Solution

The development of the equation of the buckling coefficient k (Eq. 3.6) is based on the results of the elastic buckling analysis by ABAQUS (2013). Figure 3.2 shows the boundary and loading conditions adopted in the finite element models in ABAQUS. 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 3.3 shows an example of the elastic buckling analysis. Figure 3.4 and Table 3.3 present the comparison of the ABAQUS results with the Eq. 3.6. The Eq. 3.6 has a good agreement with the ABAUS results.

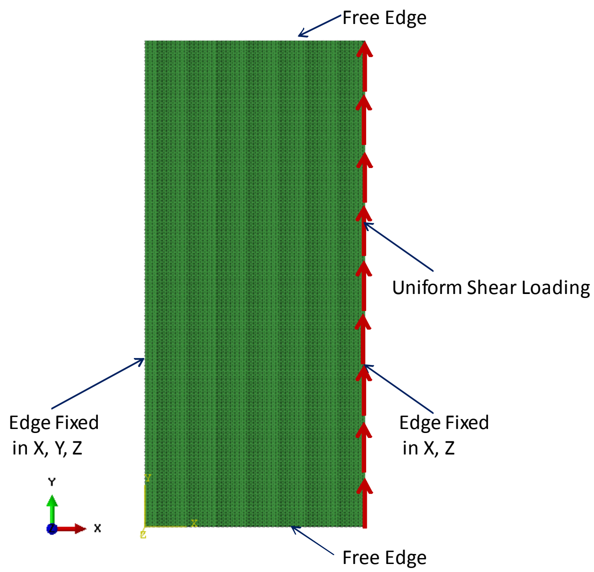

Figure3.2: ABAQUS modeling

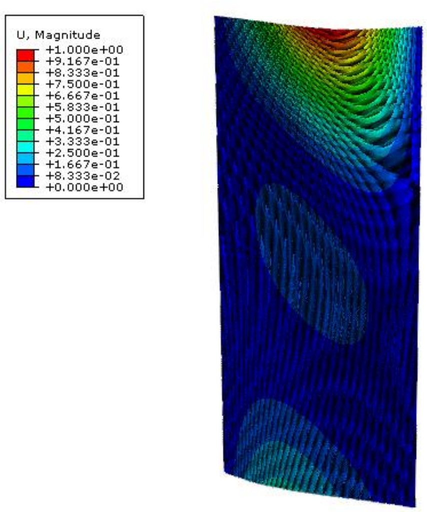

Figure 3.3: ABAQUS result

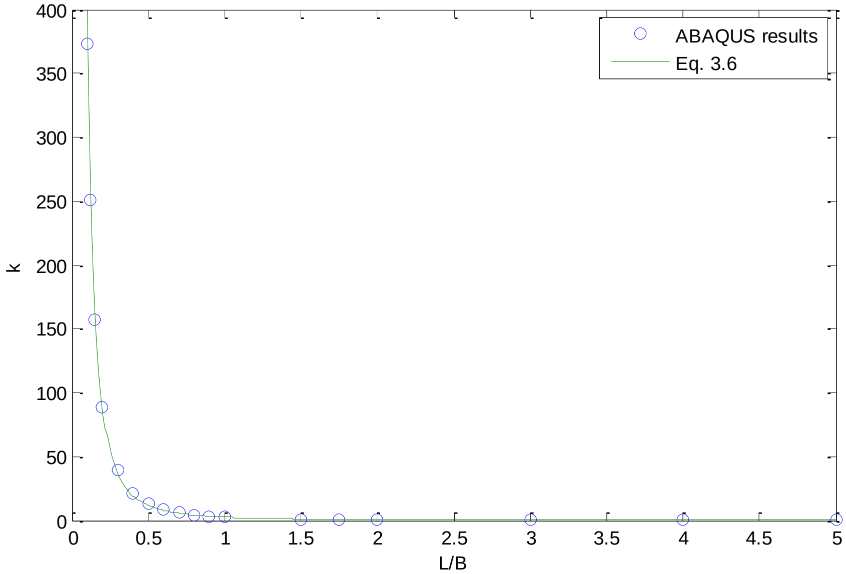

Figure 3.4: Comparison of buckling coefficient, k

Table 3.3: Comparison of k values

L/B	ABAQUS results	Eq. 2.12
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
$R^2 = 0.9992$		

4. Conclusions

A series of tests on CFS clip angles were conducted to investigate the behavior, strength, and deflection for shear. The test results were compared with the double coped beam design in AISC. It was found that the AISC method does not provide appropriate predictions for the nominal strength of clip angles in shear. A new design method for determining the nominal strength of the CFS clip angles were developed. The new method was based on the Direct Strength Method concept and was calibrated by the test results.

The LRFD, LSD resistance factors and the ASD safety factor were calculated following Chapter F of AISI S100 (2012). For the proposed shear strength of clip angles, the reliability index associated with CFS members is recommended, because the test program successfully limited the failure in the cantilevered legs of the clip angles and the screw connection failures were prevented.

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