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Wenying Zhang

Zhishan Yan

Mahsa Mahdavian

Mohamad Yousof

Cheng Yu

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Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures
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Tensile Strength and Serviceability of Cold-Formed Steel Clip Angles

Wenying Zhang[1], Zhishan Yan[2], Mahsa Mahdavian[3], Mohamad Yousof[4], Cheng Yu[5]

Abstract

This paper reports the recent research findings of cold-formed steel clip angles in tension. The relevant experimental program and the proposed design methods are presented. The test program involved two phases of testing: Phase I of program focused on the pull-over strength of screw connections on the anchored leg of the clip angles, and Phase II of program concentrated on the tensile strength of the anchored leg of the clip angles within the service deflection limit. Design methods for predicting the pull-over strength as well as tensile strength within the serviceability deformation limit are proposed based on the test results and analytical analysis. The Allowable Strength Design safety factors and the Load

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[1] Ph.D. Student, Tongjing University, Shanghai, China, wenyingchangan@163.com
[2] Graduate Student, University of North Texas, Denton, Texas, ZhishanYan@my.unt.edu
[3] Research Engineer, Verco Decking, Sunnyvale, California, mmahdavian@vercodeck.com
[4] Leadership Associate, Future Pipe Industries, Houston, Texas, myousof@live.com
[5] Professor, University of North Texas, Denton, Texas, cheng.yu@unt.edu

and Resistance Factor Design, Limit State Design resistance factors are also produced to support the proposed design methods.

Introduction

Cold-formed steel (CFS) clip angles are common connectors used in CFS buildings. The cantilevered leg of the clip angle may subject to shear, axial (compression or tension), bending, or a combination of those three forces. A comprehensive test program was recently conducted at the University of North Texas to investigate the clip angles' behavior under shear, tension, and compression. Shear and compression test and the recommended design methods have been reported by Yu et al. [1,2]. This paper focuses on the tensile capacities of the anchored leg of clip angle connectors. Screw pull-over failure is the typical failure mode in such connections. The screw pull-over strength has been studied experimentally and analytically [3-5]. Among those, the research findings from Pekoz [4] form the design basis for screw pull-over strength in North American Specification for the Design of Cold-formed Steel Structural Members AISI S100 [6]. However, initial confirmatory tests in this research showed that the tested pull-over strength was significantly less than the predicted values that were determined using AISI S100 (2016). It's also showed that most of the clip angles in pull-over tests reached their peak loads at relatively large deformation, which was greater than the connectors' serviceability deflection limit of 3.2 mm (1/8 in.) as specified in Acceptance Criteria For Connectors Used With Cold-Formed Steel Structural Members ICC-ES AC261 [7]. Therefore, the objective of this research is to investigate the tensile capacity and to develop appropriate design methods of the anchored leg of CFS clip angles. Two limit states are considered in this research, i.e. screw pull-over failure and the deflection limit due to serviceability.

Test program

The test program included two phases of testing: Phase I of program focused on the pull-over strength of screw connections on the anchored leg of the clip angles, and Phase II of program concentrated on the tensile strength of the anchored leg of the clip angles within the service deflection limit. All clip angle specimens were tested in the Structural Testing Laboratory at the University of North Texas, shown in Figure 1. Altogether, 49 tests were included in Phase I test program and 38 tests achieved the desired screw pull-over failure. Phase II of project encompassed a total of 26 tension tests. The nominal thickness of the test specimens ranged from 0.84 mm (33 mil) to 3.00 mm (118 mil). Table 1 lists the measured dimensions, screw configurations, and tested material properties. The yield stress, Fy, and tensile strength, Fu, were obtained from coupon tests conducted according to ASTM A370 Standard Test Method and Definitions for

Mechanical Testing of Steel Products [8]. Figure 2 illustrates the measured dimensions of the clip angles and the tension load direction. As illustrated, 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 dw' is the measured hex washer head integral washer diameter. A minimum of two tests were performed for each specimen configuration. If the difference in the maximum load between the first two tests was greater than 10% of the average result, a third test was conducted.

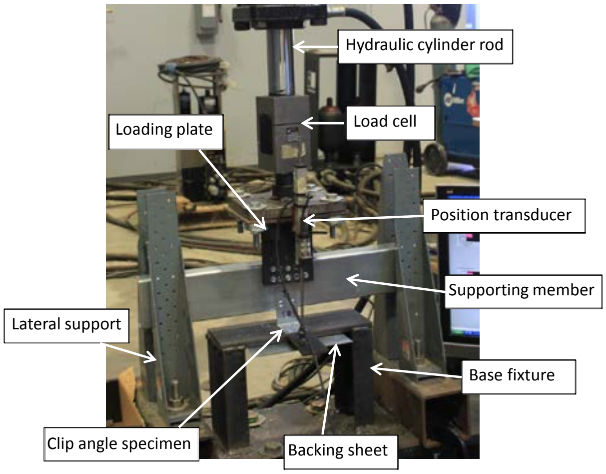

Figure 1 - Test setup for tension tests

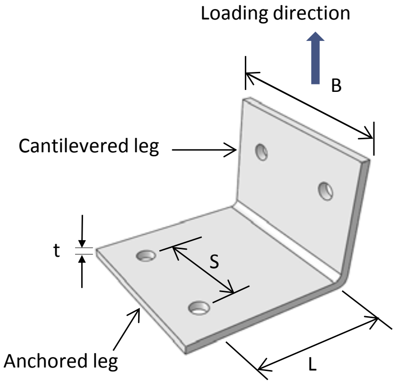

Figure 2 - Loading direction and measured dimensions

Table 1 - Properties and measured dimensions of clip angles

	Test Label	L (mm)	B (mm)	t (mm)	d_w' (mm)	No. of screws	Screw type[1]	F_y (MPa)	F_u (MPa)
Phase I	S1	22.8	76.7	1.5	8.2	4	8	315.1	345.4
	S3	22.1	132.8	1.5	8.2	3	8	315.1	345.4
	S4	23.0	190.4	0.9	8.2	4	8	344.0	384.7
	S5	23.2	191.0	1.2	8.2	4	8	319.9	353.0
	S6	22.8	76.3	1.2	8.2	4	8	319.9	353.0
	S8	22.9	133.5	1.2	8.2	3	8	319.9	353.0
	S9	22.6	191.5	0.9	8.2	4	8	344.0	384.7
	S10	22.0	190.4	1.5	8.2	4	8	315.1	345.4
	T1a	27.0	44.4	0.9	8.2	2	8	344.0	384.7
	T3a	38.7	44.5	1.5	8.2	2	8	315.1	345.4
	T4a	14.7	44.5	1.8	8.2	2	8	377.8	459.9
	T5a	23.6	44.5	0.9	8.2	2	8	344.0	384.7
	T5b	27.0	44.5	0.9	8.2	3	8	344.0	384.7
	T3b	38.7	44.5	1.5	8.2	3	8	315.1	345.4
	T4b	14.7	44.5	1.8	8.2	3	8	377.8	459.9
	T1b	16.7	44.4	0.9	12.5	2	14	344.0	384.7
	T1c	27.0	44.4	0.9	12.5	2	14	344.0	384.7
	T3c	38.7	44.5	1.5	12.5	2	14	315.1	345.4
	T5c	27.0	44.5	0.9	12.5	2	14	344.0	384.7
	T4c	14.7	44.5	1.8	12.5	2	14	377.8	459.9
	T6	21.4	44.4	3.4	12.5	2	14	342.0	366.8
Phase II	T3	38.7	44.5	1.5	8.2	2	8	315.1	345.4
	S5	22.8	190.5	1.2	8.2	4	8	319.9	353.0
	4.5D_D1a	23.4	114.3	1.5	8.2	2	8	317.8	439.2
	4.5D_D1b	23.4	114.3	1.5	8.2	4	8	317.8	439.2
	4.5D_D0.75a	17.1	114.3	1.5	8.2	2	8	317.8	439.2
	4.5D_D0.75b	17.1	114.3	1.5	8.2	4	8	317.8	439.2
	4.5D_D1.5	36.1	114.3	1.5	8.2	4	8	317.8	439.2
	4.5A_D1a	23.0	114.3	2.5	10.5	2	12	373.7	441.3
	4.5A_D1b	23.0	114.3	2.5	10.5	4	12	373.7	441.3
	4.5A_D0.75a	16.6	114.3	2.5	10.5	2	12	373.7	441.3
	4.5A_D0.75b	16.6	114.3	2.5	10.5	4	12	373.7	441.3
	4.5A_D1.5	35.7	114.3	2.5	10.5	4	12	373.7	441.3
	Note: 1-the screws refer to those used on the anchored leg.								

Phase I tests results are given in Table 2. In the table, P_{test} is the peak load per screw; Δ is the vertical deflection of the clip angle corresponding to the peak load; $P_{1/8}$ is the tension load per clip angle at the serviceability deflection limit of 3.2 mm (1/8 in.). Figure 3 shows the failure mode and load-displacement response of a 0.838mm (33 mil) clip angle; it represents the typical behavior observed in pull-over tests. Two No. 8 self-drilling screws were used to fasten the clip angle to the test bed and 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 anchored leg of the clip angle. As the cantilevered leg was continuously being pulled up, the tensile strength of two legs in a 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 pull-over failure at the screws on the anchored leg. The anchored leg of the clip angle separated from the test bed and the tension strength dropped instantly. In all the pull-over tests, excessive deformation was observed before the peak load was reached.

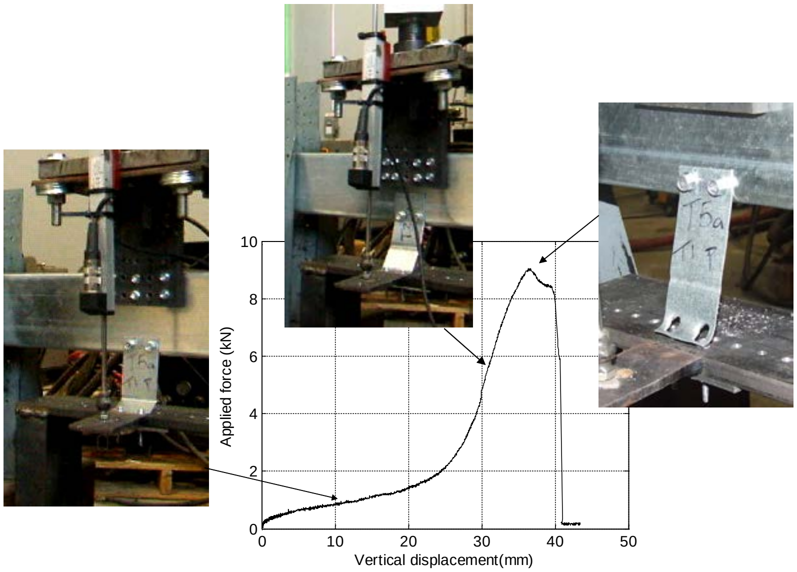

Figure 3 - Typical behavior of a clip angle in Phase I tests

Table 2 - Test and analysis results of Phase 1 specimens

Test Label	P_{test} (kN)	Δ (mm)	$P_{1/8}$ (kN)	P_{test} / P_{AISI}	P_{test} / P_{nov}
S1_1	3.301	25.58	1.290	0.526	1.051
S1_2	3.060	26.34	1.054	0.488	0.975
S3_1	3.314	26.42	2.050	0.528	1.055
S3_2	3.011	24.94	1.873	0.479	0.959
S4_1	1.641	27.08	1.195	0.411	0.821
S4_2	1.268	21.82	0.974	0.317	0.633
S4_3	1.793	25.37	1.536	0.448	0.896
S5_1	2.117	27.56	1.363	0.414	0.829
S5_2	1.779	27.58	0.990	0.348	0.696
S5_3	2.576	26.06	2.171	0.503	1.007
S5_4	2.358	26.77	1.531	0.461	0.922
S6_1	2.318	24.41	0.881	0.453	0.905
S6_2	2.398	26.37	0.948	0.469	0.938
S8 _1	2.531	26.62	1.155	0.495	0.989
S8_2	2.509	25.91	1.309	0.491	0.982
S9_1	1.312	26.49	1.068	0.328	0.657
S9_2	1.130	23.88	0.637	0.283	0.566
S9_3	1.610	23.83	1.006	0.403	0.805
S9_4	1.463	27.31	0.975	0.367	0.733
S10_1	2.326	28.30	2.394	0.370	0.741
S10_2	2.616	27.46	1.811	0.416	0.833
S10_3	2.767	28.55	2.556	0.440	0.881
T1a_1	2.237	26.26	0.351	0.534	1.068
T1a_2	2.535	23.90	0.319	0.606	1.211
T3a_1	4.515	36.37	0.519	0.719	1.438
T3a_2	4.399	34.90	0.593	0.701	1.401
T4a_1[1]	3.639	17.40	1.852	-	-
T4a_2[1]	4.310	19.43	1.987	-	-
T5a_1	2.353	22.66	0.219	0.562	1.123
T5a_2	2.086	22.20	0.222	0.498	0.997
T5b_1	2.224	24.43	0.231	0.557	1.114
T5b_2[1]	2.277	28.52	0.154	-	-
T3b_1[1]	2.400	37.74	0.374	-	-
T4b_1[1]	4.404	21.13	1.787	-	-
T4b_2[1]	4.662	21.64	1.990	-	-

Table 2 - Test and analysis results of Phase 1 specimens (continued)

Test Label	P_{test} (kN)	Δ (mm)	$P_{1/8}$ (kN)	P_{test} / P_{AISI}	P_{test} / P_{nov}
T1b_1	3.825	18.44	0.506	0.625	1.250
T1b_2	3.710	18.42	0.438	0.606	1.212
T1c_1	3.639	23.34	0.225	0.595	1.189
T1c_2	3.505	27.05	0.209	0.573	1.146
T3c_1	5.663	36.55	0.300	0.589	1.178
T3c_2	5.992	39.85	0.284	0.623	1.246
T5c_1	3.754	25.58	0.264	0.614	1.227
T5c_2	4.297	26.31	0.715	0.702	1.404
T5c_3	3.456	27.56	0.400	0.565	1.129
T4c_1[1]	4.123	15.44	1.573	-	-
T4c_2[1]	5.617	17.65	2.564	-	-
T6_1[1]	6.794	21.16	4.591	-	-
T6_2[1]	4.798	15.75	4.637	-	-
Mean				0.503	1.005
St. Dev.				0.109	0.208
C.V				0.217	0.207

Note: 1- Tests failed in screw shear failures rather than pull-over.

According to the pull-over test results, most of the CFS clip angles reached their peak loads at relatively large deformation, which was greater than the connectors' serviceability deflection limit of 3.2 mm (1/8 in.). Therefore, Phase II program focused on the tensile capacity of clip angles within the service deflection limit of 3.2 mm (1/8 in.). Figure 4 shows the deformation of a 2.464 mm (97 mil) clip angle with No. 12 self-drilling screws at the service deflection limit of 3.2 mm (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 Phase II tests are provided in Table 3.

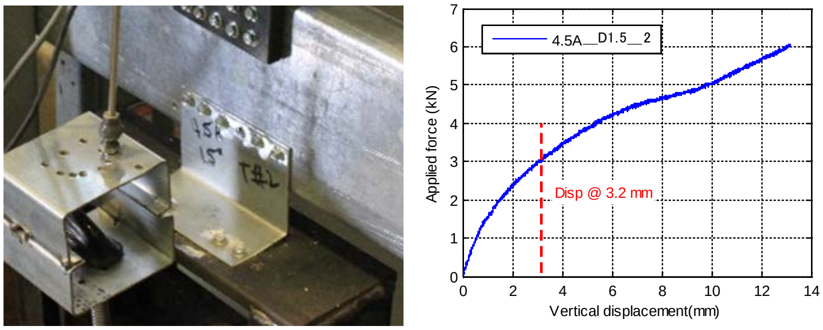

Figure 4 - Typical behavior of a clip angle in Phase II tests

Table 3 - Results of tension tests in Phase II

Test Label	$P_{1/8}$ (kN)
T3_1	0.592
S5_1	2.134
S5_2	2.292
4.5D_D1a_1	1.607
4.5D_D1a_2	1.519
4.5D_D1b_1	1.836
4.5D_D1b_2	2.018
4.5D_D0.75a_1	2.145
4.5D_D0.75a_2	2.281
4.5D_D0.75b_1	2.882
4.5D_D0.75b_2	2.733
4.5D_D1.5_1	1.013
4.5D_D1.5_2	1.001
4.5A_D1a_1	5.400
4.5A_D1a_2	5.485
4.5A_D1b_1	7.601
4.5A_D1b_2	7.306
4.5A_D0.75a_1	5.269
4.5A_D0.75a_2	7.859
4.5A_D0.75a_3	7.458
4.5A_D0.75b_1	10.588
4.5A_D0.75b_2	11.574
4.5A_D1.5_1	4.072
4.5A_D1.5_2	3.044
4.5A_D1.5_3	3.420

Proposed Pull-Over Strength for CFS Clip Angles

The pull-over strengths obtained from the tests were compared with the pull-over strength calculated according to AISI S100 [6]. It's found that the test results were on average 50.3% of the predicted pull-over strength by AISI S100 with a standard deviation of 0.109. Therefore, with simple modifications to the existing AISI design method, a design method for the pull-over strength of CFS clip angles was developed. The nominal pull-over strength of sheet per screw:

$$P_{\mathrm{nov}} = 0.75 t_1 d'_{\mathrm{w}} F_{\mathrm{u1}} \tag{2}$$

Where,

d'_{w} = effective pull-over diameter determined in accordance with Section J4.4.2 of AISI S100 [6]

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 ranges of the tested specimens are:

Clip angle design thickness: 0.84 mm to 1.37 mm (33 mil to 54 mil);

Clip angle design yield strength: 227.5 MPa to 344.7 MPa (33 ksi to 50 ksi);

Screw size: No. 8 or No. 14.

A comparison between the test results and the proposed design method is listed in Table 2. 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 J4.4.2 of AISI S100 [6] shall apply to the proposed pull-over design equations.

The LRFD and LSD resistance factors, ϕ, and the ASD safety factors, Ω, for the proposed design method were determined using the provisions in Chapter K of the AISI S100 [6].

$$\phi = C_\phi \left(M_{\mathrm{m}} F_{\mathrm{m}} P_{\mathrm{m}} \right) e^{-\beta_0 \sqrt{V_{\mathrm{M}}^2 + V_{\mathrm{F}}^2 + C_{\mathrm{P}} V_{\mathrm{P}}^2 + V_{\mathrm{Q}}^2}} \tag{3}$$

$$\Omega = 1.6 / \phi \tag{4}$$

Where,

C_{ϕ} - Calibration coefficient, 1.52 for LRFD and 1.42 for LSD;

$M_{\mathrm{m}}, F_{\mathrm{m}}, P_{\mathrm{m}}$ - Mean value of material factor, fabrication factor and professional factor;

β_0 - Target reliability index, equals to 3.5 for connections for LRFD and 4.0 for LSD;

$V_{\mathrm{M}}, V_{\mathrm{F}}, V_{\mathrm{P}}, V_{\mathrm{Q}}$ - Coefficient of variation of material factor, fabrication factor, test results and load effect;

C_{P} - Correction factor.

The type of component specified in AISI S100 [6], Screw Connections – Pull-Over, was chosen for the statistical analysis. The results are listed in Table 4. 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- 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
C.V	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

Proposed Tensile Strength of CFS Clip Angles within the Serviceability Deformation Limit

Analytical Model

The mechanical model of the clip angle can be viewed as a uniform cross-sectioned beam shown below:

$$= \qquad\qquad\qquad\qquad +$$

Figure 5 - Mechanical model of a clip angle

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:

$$\delta = \delta_{\mathrm{E}} + \delta_{\mathrm{R}} = \frac{PL^3}{3EI} + \frac{PL^2}{K} \tag{5}$$

Therefore, the applied shear force P can be expressed as:

$$P = \frac{3EIK}{KL^3 + 3EIL^2}\delta = \frac{3K}{(K + 3EI/L)} \cdot \frac{EI}{L^3} \cdot \delta = \alpha \cdot \frac{EI}{L^3} \cdot \delta \tag{6}$$

Where,

δ– Total deflection;

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 3.2 mm (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 steel;

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

B –Width of the clip angle;

t –Uncoated steel thickness of clip angle;

K – Spring stiffness;

α – A non-dimensional empirical coefficient defined as $\alpha = \dfrac{3K}{(K+3EI/L)} = \dfrac{PL^3}{EI\delta}$.

Design Equations for Nominal Strength

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.8. Regression analysis was then performed and the result is shown in Figure 6, in which S is the maximum screw spacing in the anchored leg of the clip angle. It's easy to understand that 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 $\dfrac{t}{L}\sqrt{\dfrac{S}{t}}$. Since the proposed method is essentially a deflection/serviceability check, the authors recommend the bottom bound curve to be used in design, and a LRFD resistance factor of 1.0 and a ASD factor of safety of 1.0 shall be applied to the design equation.

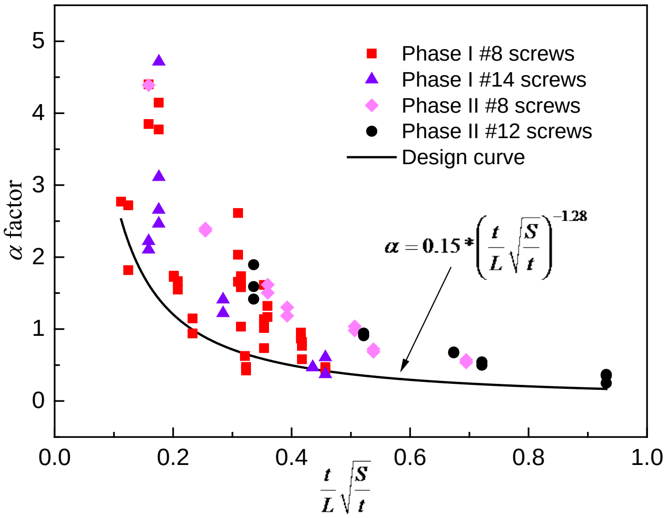

Figure 6- Result of regression analysis

According to the regression analysis, $\alpha = 0.15\left(\frac{t}{L}\sqrt{\frac{S}{t}}\right)^{-1.28}$

Therefore, the nominal tensile strength of CFS clip angles within the serviceability deformation limit is:

$$P = 0.15\left(\frac{\sqrt{St}}{L}\right)^{-1.28} \cdot \frac{EI}{L^3} \cdot \delta \tag{9}$$

Where,

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 steel (E=2.0×10^5MPa , or 29500 ksi)

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

B –Width of the clip angle

t –Uncoated steel thickness of clip angle

S –Maximum screw spacing in anchored leg of clip angle

The parameter range of the tested specimens is:

Clip angle design thickness: 0.84 mm to 3.00 mm (33 mil to 118 mil);

Clip angle design yield strength: 228 MPa to 345 MPa (33 ksi to 50 ksi);

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

It is worth mentioning that the proposed design method was developed from actual dimensions and strength of the specimens, therefore use of nominal dimensions and strength may yield conservative results from the proposed method.

Conclusions

Tensile capacities of the anchored leg of CFS clip angles were investigated experimentally and analytically. Two limit states are examined, i.e. screw pull-over failure and the deflection limit due to serviceability. The pull-over test results revealed 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. A new design equation for the tension strength at the deflection limit was proposed based on regression analysis of the test results. The Allowable Strength Design safety factors and the Load and Resistance Factor Design, Limit State Design resistance factors are also produced to support the proposed design methods.

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