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Shear strength of cold-formed steel flexural members connected using clip angles

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Abstract
In building construction, cold-formed steel flexural members are commonly connected to other cold-formed steel members or the main building structures using clip angles with screws. A series of flexural tests were recently conducted at University of North Texas to study the shear strength of cold-formed steel clip angles used in cold-formed steel framing. The tests showed that the shear strength of the connected cold-formed steel floor joists can be significantly increased when a clip angle is installed on the web. This paper presents a design guide to consider the shear strength improvement in the cold-formed steel joists due to the presence of a clip angle. The paper also reports the results of the flexural tests on floor joists recently conducted at the University of North Texas.

1. Introduction
A cold-formed steel (CFS) clip angle is an L-shaped piece of steel member (normally with a 90-degree bend) which is typically used as connectors in CFS buildings. Fig. 1 shows an application of a clip angle in steel framing. The cantilevered leg of the clip angle could be subjected to shear, compression, tension, bending, and combined loading.

A research project by Fox (2005) investigated the behavior and strength of the CFS clip angles used in steel framing assemblies. The research focused in Fox (2005) was on the compression strength of the clip angles when the axial force was applied to the cross section parallel to the fold line of the clip angle. A series of tests was recently conducted by in University of North Texas (UNT) to study the mechanics behavior of the clip angle under shear, tension and compression load. Yu et al. (2016) provided detailed research results and design provisions for the cantilevered leg of clip angles under shear loading. Yu et al. (2017) focused on the compression strength of the cantilevered leg of clip-angle connectors and presented a new design method. Zhang et al. (2018) studied the capacities of the anchored leg of clip angle connectors in two limit states: screw pull-over failure and the deflection limit due to serviceability. Yu et al. (2018) conducted the shear tests of clip angles with different patterns of screws for revising the design method presented by Yu et al. (2016). Yu et al. (2018) also investigated the shear strength of clip angles subjected to various

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loading and boundary conditions that would exist in actual CFS framing. It was found that the cross-sectional strength of the CFS joist had significant impact to the shear strength of the clip angle connector. The actual boundary conditions of a clip angle should be considered in its strength assessment.

This paper presents the results of the flexural tests on floor joists recently conducted at the UNT and a new calculate method to determine the shear strength of the flexural members connected with clip angles.

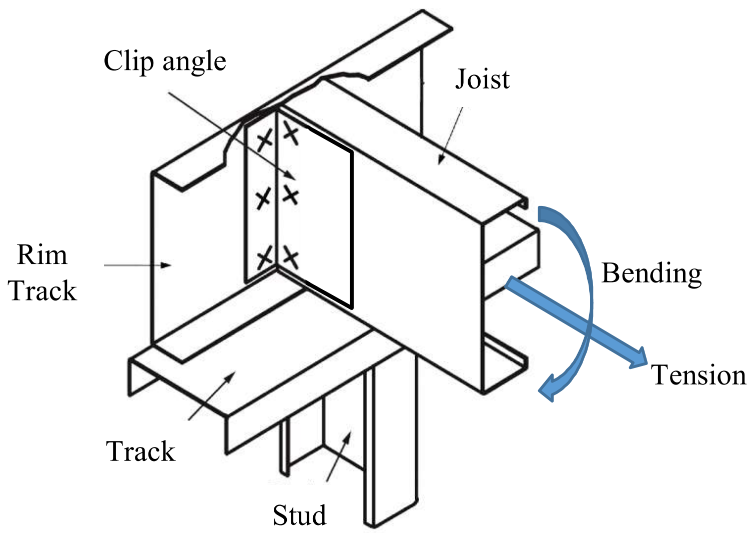

Figure 1 : Typical use of clip angle

2. CFS joist tests

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

2.1 Test setup and test procedure

The CFS joist tests used AISI S914 (2015) as a guide for the test setup as illustrated in Fig. 2 and Fig. 3. In each test, two CFS joists with the same configurations were connected using one structural steel tube at the mid span, shown in Fig. 4. Steel angles were also used to connect the flanges of the two joists. The joist assembly was anchored to two supporting members at both ends by four CFS clip angles with the same configurations. A structural steel load transfer block was used to apply a vertical force to the steel tube. Four position transducers were used to measure the vertical deflection of the clip angles. A minimum gap of 1/8 in. was provided between the end of each joist and the supporting members to avoid any contact during the test. The joist tests were performed in a displacement control mode at a constant speed of 0.3 in. per minute.

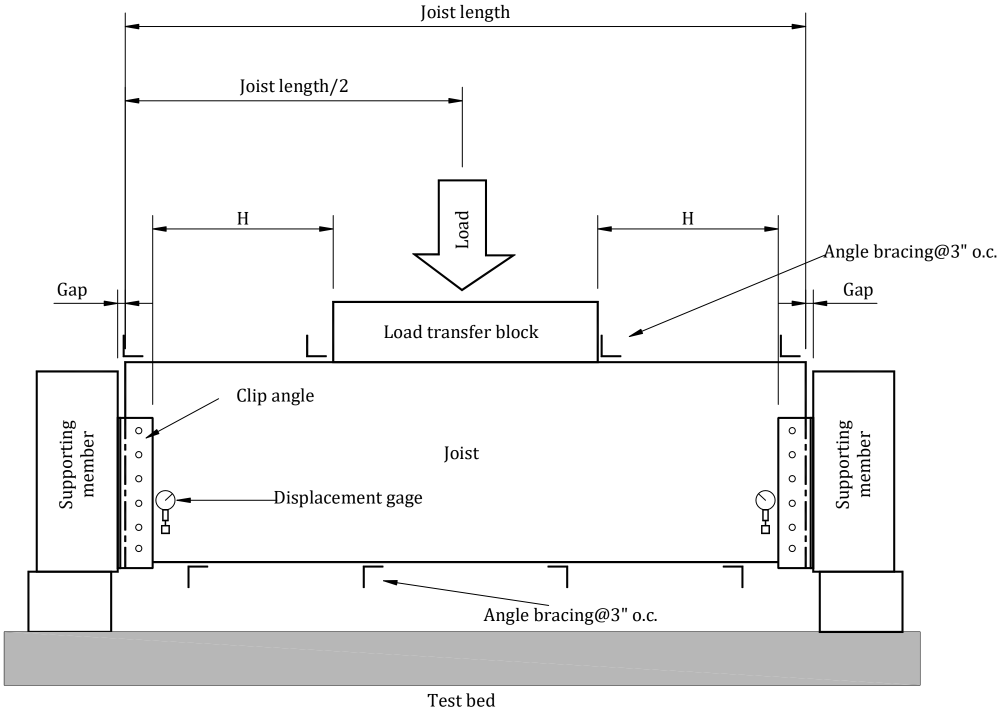

Figure 2: Joist Test Setup

2.2 Test specimens

A total of 14 joist tests were conducted. The clip angle label was used as the joist test label. Fig. 5 illustrates the measured dimensions of clip angles. For all clip angles in this test program, a single line of No. 14-14×1 self-drilling self-tapping screws were used to attach the cantilevered leg of the clip angle to web of the joist. The anchored leg of the clip angle was attached to the supporting members by a single line of No. 10-24×1 BHSC bolts. All the clip angles were 54 mils. All the joists were 28 in. long, and the thickness was either 54 mils or 97 mils. The test matrix is shown in Table 1.

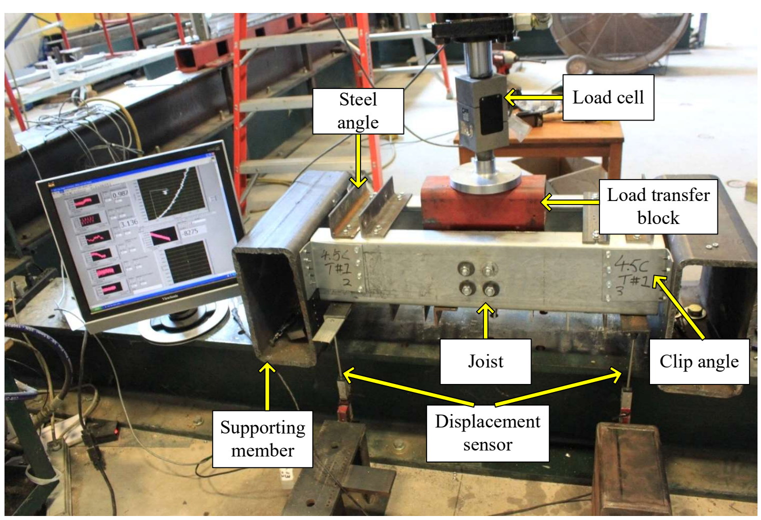

Figure 3: Typical joist test setup

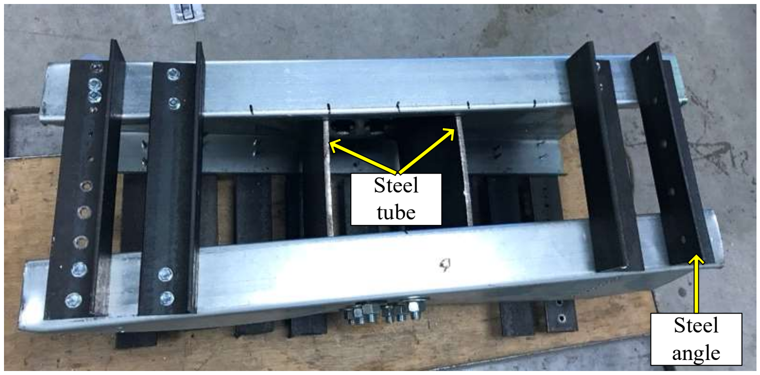

Figure 4: Connection details of the two joists (photo taken after test)

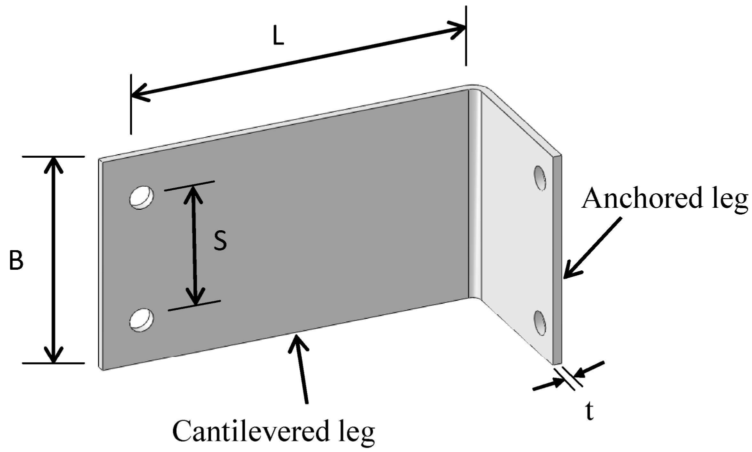

Figure 5: Measured dimensions for clip angles in joist tests

Table 1: Properties of clip angles in the joist tests

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

2.3 Tests results

Table 2 summarizes the joist test results. The P_{test} is the peak load per clip angle, it was calculated using the total force divided by 4. The deflection, Δ, is the vertical deflection of the controlling clip angle. The controlling clip angle was the one with the most significant deformation in the joist test. P_n is the predicted shear strength using Eq. 1 present by Yu et al. (2018)

$$V_n = 0.12(\gamma)^{-0.4} F_y B t \leq 0.35 F_y B t \tag{1}$$

$$\gamma = \alpha\lambda \tag{2}$$

$$\lambda = \sqrt{\frac{F_y}{F_{cr}}} \tag{3}$$

$$\alpha = S/B \tag{4}$$

$$F_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)}\left(\frac{t}{B}\right)^2 \tag{5}$$

$$k = 2.569\left(\frac{L}{B}\right)^{-2.202} \tag{6}$$

where λ is the slenderness ratio, α is the screw spacing ratio, F_y is the yield strength of CFS, F_{cr} is the critical elastic buckling stress, E is the modulus of elasticity of CFS, μ is the Poisson's ratio for steel, t is the design thickness of clip angle, B is the depth of clip angle, S is the screw spacing on the cantilevered leg, L is the flat width of clip angle, distance between the center of first line (or the line closest to the corner of the clip angle) of screws to the bend line.

Table 2: Results of joist tests

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

1.Failure mode A is buckling of clip angle; Failure mode B is buckling of web of joist.

The test results shown that the 54 mil 4.5 in. deep clip angles and 54mil 6.5 in. deep clip angles had similar peak load, deflection, and failure mode between joist tests and shear tests. As shown in Fig. 6, the failure mode is the local buckling of the clip angle.

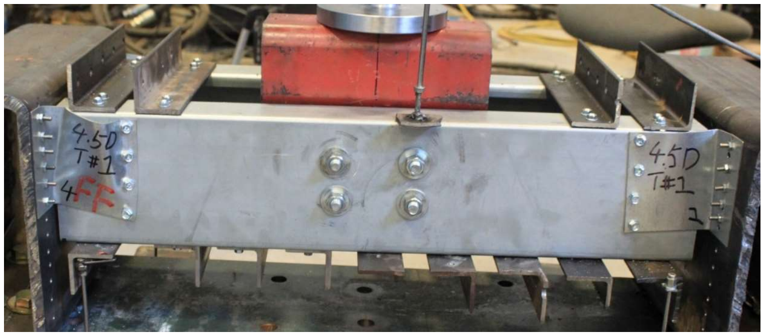

Figure 6 : Failure mode of joist 4.5D T#1

The joist test program discovered that for the deeper clip angles (8.5 in. and 10.5 in.) that were attached to 54 mil joists, significant deformation in the joist web occurred when the clip angle reached its capacity. Fig. 7 and Fig. 8 respectively show the failure mode of 8.5B T#1 and 10.5B T#1 clip angles where 54 mil joists were used. Shear buckling occurred in the web of CFS joists. The clip angles in those two tests yielded lower strength than the predicted values mainly due to a weaker boundary condition that the joist's web provided to the cantilevered leg of clip angles. Particularly for the 10.5 in. deep clip angles, the clip angles only reached 63% of their predicted shear strength by the design method, Eq. 1.

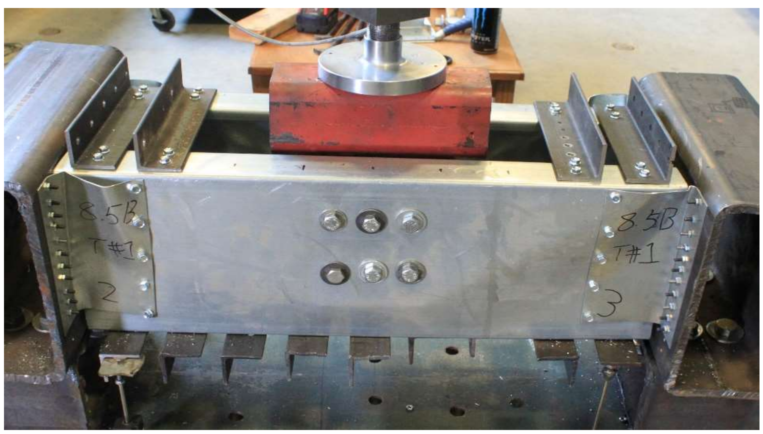

Figure 7 : Failure mode of Test 8.5BT #1

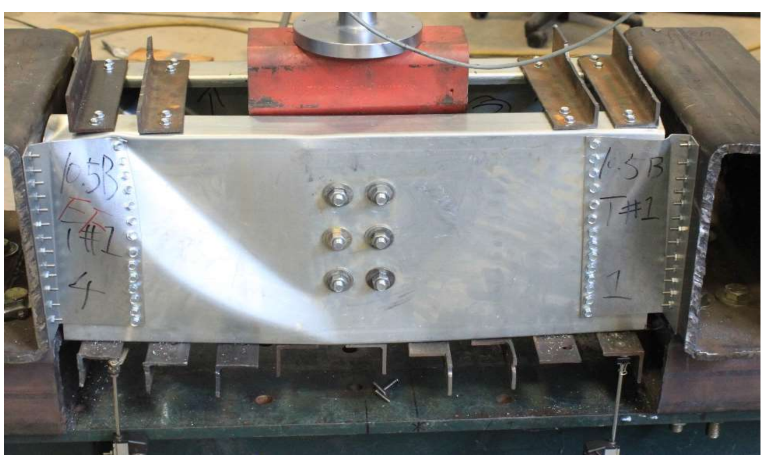

Figure 8 : Failure mode of Test 10.5B #1

The joist tests discovered that the boundary conditions could have significant effect on the shear strength of the cantilevered leg of the clip angle. The shear design method (Eq. 1) assumes a solid support to the cantilevered leg and the anchored leg. The CFS clip angle may not be able to provide full shear strength if the supporting members (e.g. CFS framing members) do not provide a solid support or yield significant deformation.

3. Proposed design method

The failure mode of the deeper clip angles (8.5 in. and 10.5 in.) that were attached to 54 mil joists is the buckling of the joist web. So the shear strength of the connection can be considered as the minimum value between the shear strength of the clip angles and that of web with clip angles. The shear strength of clip angles can be determined by the existing method developed by Yu et al. (2018) (Eq. 1). This paper focuses on developing a method that can calculate the shear strength of joist web with clip angles. The current provision of shear strength in AISI S100 (2016) was used as the primary methodology in this research. The AISI shear design provision is summarized as follows.

For $\lambda_v \leq 0.815$

$$V_n = V_y \tag{7}$$

For $0.815 \leq \lambda_v \leq 1.227$

$$V_n = 0.815\sqrt{V_{cr}V_y} \tag{8}$$

For $\lambda_v > 1.227$

$$V_n = V_{cr} \tag{9}$$

$$\lambda_v = \sqrt{V_y/V_{cr}} \tag{10}$$

$$V_y = 0.6A_wF_y \tag{11}$$

$$V_{cr} = A_wF_{cr} \tag{12}$$

Where λ_v is the slenderness ratio; V_n is the nominal shear strength of the flexural member; V_y is the yield shear force of cross-section; A_w is the area of web element; V_{cr} is the elastic shear buckling force; F_y is the yield stress of CFS; F_{cr} is the elastic shear buckling stress.

3.1 Finite element modeling

The AISI S100 shear method requires the calculation of elastic shear buckling stress in the web. This research used the finite element method for the elastic buckling analysis. The commercially available finite element software ABAQUS (2018) was used in this research. The structure model was half of the actual specimens because the load, test specimen assembly, and boundary conditions were symmetrical. The clip angles and joists were modeled using 4-node linear shell elements with reduced integration and hourglass control (S4R). The support members and angle bracing were modeled using 8-node linear brick solid elements with reduced integration and hourglass control (C3D8R). The connection of bolts and screw were simulated by tying constraint. The section of mid-span was coupled to a reference point to which the shear load (y axis direction) was applied. Surface-to-surface contact was set between the joists and the clip angles, the angle bracing and the supporting members. The supporting members were simplified to the thick steel plates which have been fixed. The analysis result shows the buckling eigenvalues of the structure.

Fig. 9 shows the buckling mode of the web connected with clip angle. The buckling mode of 10.5B T#1 is similar with the failure mode in tests.

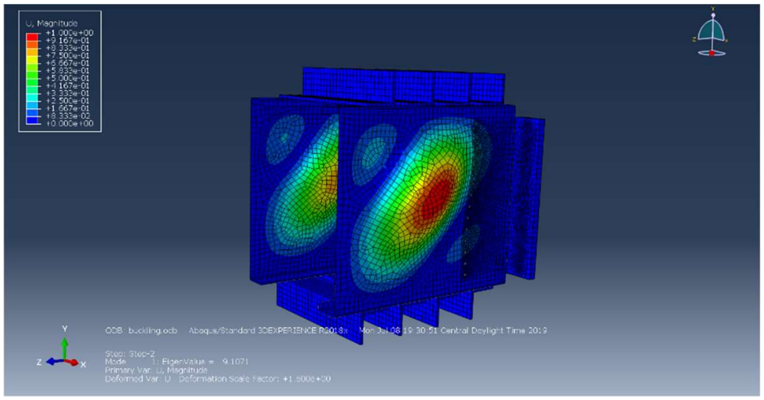

Figure 9: The buckling mode of 10.5B T#1

3.2 Shear strength of web

The $\overline{V_{cr}}$ is the elastic critical shear buckling force of each web with clip angle, it was calculated using the first positive eigenvalue from the ABAQUS model. Follow the provisions in of AISI S100 (2016), the shear strength of web is shown in Table 3. The tests listed in Table 3 are those having web shear buckling as the primary failure mode. V_{aisi} is the shear strength calculated by AISI S100 using the elastic shear buckling results from ABAQUS analyses. V_{web} is the shear strength of web without clip angle. $\overline{\lambda_v}$is the slenderness ratio of web. λ_{n} is the slenderness ratio of connection.

$$\overline{\lambda_v} = \sqrt{V_y/\overline{V_{cr}}} \tag{13}$$

$$\lambda_n = \sqrt{P_n/\overline{V_{cr}}} \tag{14}$$

Where V_{y} is the yield shear force of cross-section of joist without clip angle.

Table 3: The shear strength of the web of joist

Test Label	$\overline{V_{cr}}$ (lb)	P_{test} (lb)	V_{aisi} (lb)	V_{web} (lb)	$P_{\mathrm{test}}/ V_{\mathrm{aisi}}$	$V_{\mathrm{aisi}}/ V_{\mathrm{web}}$	$\overline{\lambda_v}$	λ_{n}
6.5A T #1	4911	3242	4911	2903	0.660	1.692	1.596	0.833
6.5B T #1	5003	2595	5003	2903	0.519	1.723	1.581	0.653
8.5B T #1	4397	3800	4397	2306	0.868	1.907	1.892	0.985
10.5B T#1	4553	4959	4553	1913	1.089	2.380	2.042	1.313

As the web depth goes larger, the shear buckling of web becomes more dominating failure mechanism. The test results therefore are more close to the predicted shear strength of the web. The AISI method using elastic buckling results from ABAQUS has good agreement with the test results of 10.5B T#1 and 8.5B T #1. That indicate the $\overline{V_{cr}}$ obtained from ABAQUS is appropriate in order to determine the shear strength of joist web with clip angle using the current shear provision in AISI S100. The results also indicate that shear strength of the connected cold-formed steel floor joists can be significantly increased when a clip angle is installed on the web. The strength of connection depends on the shear strength of clip angles when $\lambda_n < 0.985$; the strength of connection is controlled by the shear stability of the joist web connected using clip angles when $\lambda_n > 0.985$.

4. Conclusions

This paper presents the experimental and analytical study of CFS floor joists when clip angles are installed on the web. Test results show that the shear strength of connection was controlled by the minimum value of the shear strength of clip angles and the joist web with clip angles. The shear strength of the connected cold-formed steel floor joists can be significantly increased when a clip angle is installed on the web. The shear strength of cold-formed steel floor joists can be calculated by the current shear provisions in AISI S100 using the accurate shear buckling force of the web-clip angle assembly. In this research, finite element software ABAQUIS was used to obtain the elastic buckling results. Future research is needed to develop a simplified method for the elastic buckling analysis.

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