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THE SHEAR PERFORMANCE COMPARISON OF A WELDED AND BOLTED COLD-FORMED STEEL CLIP-ANGLE IN A BEAM-TO-COLUMN SHEAR CONNECTION

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Keywords: CFS shear connection, welded clip-angle, bolted clip-angle, performance ratio, Reliability analysis.

Abstract. *The shear behavior of a cold-formed steel shear connection with a welded clip-angle is experimentally investigated in this paper. The paper presents a comparative study on the welded (present) and bolted clip-angle (literature) configurations. The failure modes observed in the test specimens are (i) local bucking and distortional buckling in the welded clip-angle and (ii) local buckling and tearing failure in the bolted clip-angle. The nominal shear strength equation for the welded clip-angle is formulated from the experimental data as the existing shear equation found to be conservative for the present experimental data. The relative shear performance of the bolted and welded clip-angle configurations is quantified using a performance ratio. The shift in the failure behavior of the clip-angle in the welded and bolted configurations is investigated and design recommendations are suggested for the efficient use of both configurations. The comparative study further extended by conducting a reliability check on the shear strength equations of the welded and bolted configurations.*

1 INTRODUCTION

Cold-formed steel, typically in thin gauge sheets, serves diverse purposes in steel structures. Among its applications, roll-formed C-sections and various other shapes of cold-formed steel sheets are utilized in both structural and non-structural settings. To join CFS members effectively, a frequently employed method involves the use of 90-degree clip-angles as connectors. Connecting structural steel members offers several options, including welding, riveting, screwing, and bolting. These connections can be directly between members or by incorporating connectors like plates or L-angles.

Numerous behaviour studies have been conducted on the cold-formed steel connection to understand its complex nature better and to offer helpful design guidance [1–12]. A welded clip angle connector is a suitable alternative since it is stronger than the linked structural components and more rigid than bolted and screwed connections, according to Mallepogu and Madhavan [1], who also provided an ultimate shear strength equation for welded clip angle connectors. The limit state design for the serviceability of the clip-angle connection under various loading conditions was addressed by Zhang et al. [2] and Yu et al. [3,4]. Zhang et al.'s [2] recommended a service limit state design for the pull-over strength of cold-formed clip-angle connection under tension. Yu et al.'s [3], investigated the compressive capacity of clip angle by applying a load perpendicular to the bend line of the angle connector which led to the suggestion of a novel design approach for thin-walled plate columns based on elastic deformations. Yu et al.[4] proposed a design shear equation for the screwed cold-formed steel clip angle connection.

Mills and Laboube [5] conducted experiments on self-drilling screw joints combined knee joints for CFS portal frames and observed that thes crews having less capacity than the connected member sheared out earlier. Chung and Lawson [6] investigated the structural behavior of shear connection under monotonic load where the web cleat of CFS strips is used to connect shear CFS beams and columns. Lim and Nethercot [7,8] performed experiments on the ultimate strength of bolted moment connection in eaves and apex connection of portal frames and observed that the moment capacity of the joint is fairly reduced due to web buckling of the members. Obeydi et al. [9] conducted a numerical modeling of the pull-out failures in CFS clip angles under tensile loading and proposed a new pull-out equation. Further, the experimental results from their previous study are calibrated [10].

Natesan and Madhavan [11] proposed a new shear design equation on the CFS beam-to-column two-bolted shear connection. Further, Natesan et al. [12] conducted experiments on the three bolted shear connections and observed that the ultimate shear strength results in an inverse to the aspect ratio. Mallepogu and Madhavan [16] experimentally evaluated the ultimate shear capacity of all 3-bolted clip-angle configurations through the direct shear tests.

Research Objectives

- To improvise the existing welded shear equation [1] by considering the omitted clip-angle configurations.
- To determine the relative shear performance of the bolted [16] and welded clip-angle (present) configurations is quantified using a performance ratio.
- To identify the shifts in the failure behavior of the clip-angle in the welded and bolted configurations is investigated and design recommendations are suggested for the efficient use of both configurations.

2 MATERIAL TEST

The tensile testing is conducted on the CFS clip-angle coupons following ASTM E8/E8M-13a [13] and Huang and Young [14] specifications. The outcomes of the coupon tests are given in Table. 1 and illustrated in Fig. 1. Tensile testing of CFS clip-angle coupons was performed according to ASTM E8/E8M-13a [13] and Huang and Young [14] specifications. The results of the coupon tests are provided in Table 1.

Table 1: Material properties of the coupon samples

Thickness of clip-angle (mm)	Sample number	Yield strength, f_y (N/mm^2)	Ultimate tensile strength, fu (N/mm^2)	Young's Modulus, E (N/mm^2)
1.5	1	266.476	303.783	200483
	2	274.120	299.129	201925
	3	275.221	303.029	199062
	Mean	271.939	301.980	200490
2	1	286.002	360.221	200701
	2	282.088	355.869	200664
	3	287.060	360.260	203413
	Mean	285.050	358.783	201593
2.5	1	315.192	350.869	200991
	2	301.848	366.408	199367
	3	303.410	365.165	200768
	Mean	306.816	360.814	200375

3 LABELLING OF THE TEST SPECIMENS

Table. 2. Labelling of WS test specimen

Label: **t-A-D- WS/3B- F/M-1/2**

Symbol	Description	Chosen for present study
t =	Thickness of the clip-angle	1.5 mm, 2 mm, 2.5 mm
A =	Total width of outstanding leg of the clip-angle	65 mm, 95 mm, 125 mm
D =	Depth of the clip-angle	100 mm, 150 mm, 180 mm
WS =	Welded clip-angle under shear load	Loading rate = 0.01 mm/sec
3B =	Bolted clip-angle under shear load	
F =	Four Point flexure test with CFS beam	Eccentricity = 230 mm
M =	Four Point flexure test with HRS beam	
1 or 2 or 3 =	Sample number	
Examples:	1.5-65-100-WS-F1	

4 NEW IMPROVED SHEAR STRENGTH EQUATION FOR WELDED SHEAR CLIP-ANGLE

A new shear equation was suggested by considering the previous research data [1] and present experimental data for the welded clip-angle configuration. The existing equation [1] is improved by considering the all welded clip-angles data (as shown in Figure 2 and Table 3).

$$V_{nss} = P\,(\lambda)^{Q} \times V_y \qquad \text{Eq. (1)}$$

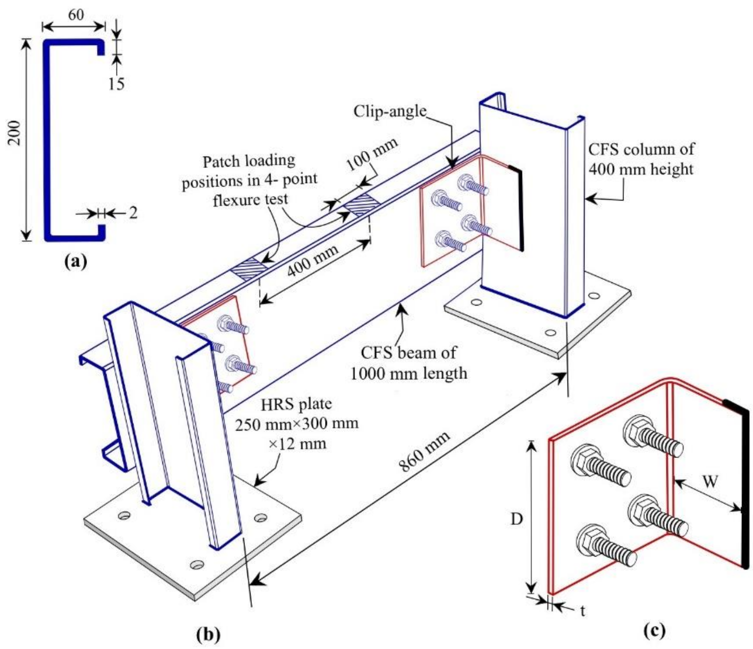

Figure 1: WS test specimen

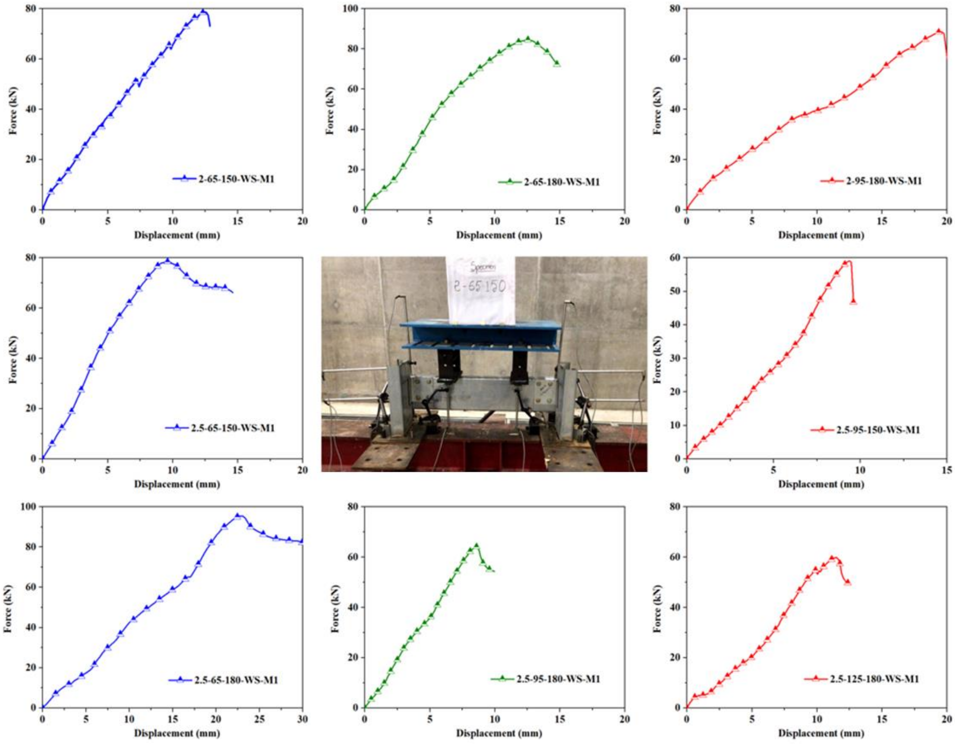

Figure 2: Shear strength and displacement curves of clip-angles.

shear equation proposed by Yu et al. for screw [4]

$$V_{nss} = 0.231\ (\lambda)^{-0.8} \times V_y$$

shear equation proposed by Natesan and Madhavan for 2 bolt [11]

$$V_{nsw} = 0.222\ (\lambda)^{-0.6} \times V_y$$

shear equation proposed by Mallepogu and Madhavan for welded clip-angle [1]

$$V_{nsw} = 0.275\ (\lambda)^{-0.8} \times V_y$$

Where,

Slenderness ratio, $\lambda = \sqrt{\dfrac{V_y}{V_{cr}}}$

Critical shear strength, $V_{cr} = f_{cr} \times t \times D$

Yield shear strength, $V_y = 0.6\ f_y \times t \times D$

Critical buckling stress $f_{cr} = \dfrac{k\pi^2 E}{12\left(1-\mu^2\right)}\left(\dfrac{t}{D}\right)^2$

The elastic buckling coefficient, $k = 2.569\left(\dfrac{W}{D}\right)^{-2.202}$

Flat width of fillet welded out-standing leg = W

Depth of the clip-angle = D

Table 3: New improved shear strength equation for welded shear clip-angle

S. No.	Clip-angle	V_{exp-WS}(kN)	λ	Vy	$V_{predict-WS}$ (kN)	V_{exp} / V_y	Vexp / Vpredict
1	1.5-65-100-WS-F1	12.76	0.72	24.47	9.99	0.52	1.28
2	1.5-95-100-WS-F1	5.10	1.12	24.47	7.05	0.21	0.72
3	1.5-125-100-WS-F1	4.31	1.54	24.47	5.48	0.18	0.79
4	1.5-65-150-WS-F1	14.39	0.69	36.71	15.50	0.39	0.93
5	1.5-95-150-WS-F1	12.80	1.08	36.71	10.88	0.35	1.18
6	1.5-95-150-WS-F2	12.45	1.08	36.71	10.88	0.34	1.14
7	1.5-125-150-WS-F1	4.76	1.47	36.71	8.53	0.13	0.56
8	1.5-125-150-WS-F2	4.41	1.47	36.71	8.53	0.12	0.52
9	1.5-65-180-WS-F1	15.87	0.68	44.05	18.82	0.36	0.84
10	1.5-95-180-WS-F1	14.35	1.06	44.05	13.25	0.33	1.08
11	1.5-125-180-WS-F1	7.12	1.45	44.05	10.35	0.16	0.69
12	2-65-100-WS-F1	16.34	0.54	34.21	17.53	0.48	0.93
13	2-95-100-WS-F1	9.2	0.85	34.21	12.25	0.27	0.75
14	2-125-100-WS-F1	8.24	1.16	34.21	9.58	0.24	0.86
15	2-95-150-WS-F1	19.36	0.81	51.31	19.09	0.38	1.01
16	2-125-150-WS-F1	13.56	1.12	51.31	14.78	0.26	0.92
17	2-125-180-WS-F1	14.6	1.1	61.57	17.99	0.24	0.81
18	2.5-65-100-WS-F1	20.33	0.44	46.02	27.73	0.44	0.73
19	2.5-65-100-WS-F2	21.3	0.44	46.02	27.73	0.46	0.77
20	2.5-95-100-WS-F1	16.38	0.69	46.02	19.44	0.36	0.84
21	2.5-125-100-WS-F1	12.2	0.96	46.02	14.97	0.27	0.81
22	2.5-125-150-WS-F1	19.63	0.92	69.03	23.23	0.28	0.85
23	2-65-150-WS-M1	39.31	0.52	49.50	26.14	0.79	1.50
24	2-65-180-WS-M1	42.25	0.51	59.40	31.85	0.71	1.33
25	2-95-180-WS-M1	35.42	0.8	59.40	22.32	0.60	1.59
26	2.5-65-150-WS-M1	39.21	0.43	61.88	37.97	0.63	1.03
27	2.5-95-150-WS-M1	29.51	0.67	61.88	26.74	0.48	1.10
28	2.5-65-180-WS-M1	47.72	0.42	74.25	46.41	0.64	1.03
29	2.5-95-180-WS-M1	32.06	0.66	74.25	32.48	0.43	0.99
30	2.5-125-180-WS-M1	29.89	0.91	74.25	25.20	0.40	1.19
						Mean	0.96
						Std. Deviation	0.25
						Coeff. Variation	0.26

As given in Table. 4, the values of 0.0094 and -1.65 are selected for the coefficient P, Q in Eq. 1 for best curve-fit the experimental data with the predicted values.

Table 4: Regression analysis

A	β	Residual mean (ε_{mean})	Parameters: P_M, σ, CoV
0.315	-0.8	0.001	0.96 0.25 0.26
0.316	-0.8	-0.060	0.95 0.25 0.26
0.315	-0.81	-0.070	0.95 0.24 0.26
0.315	-0.79	0.071	0.96 0.25 0.26

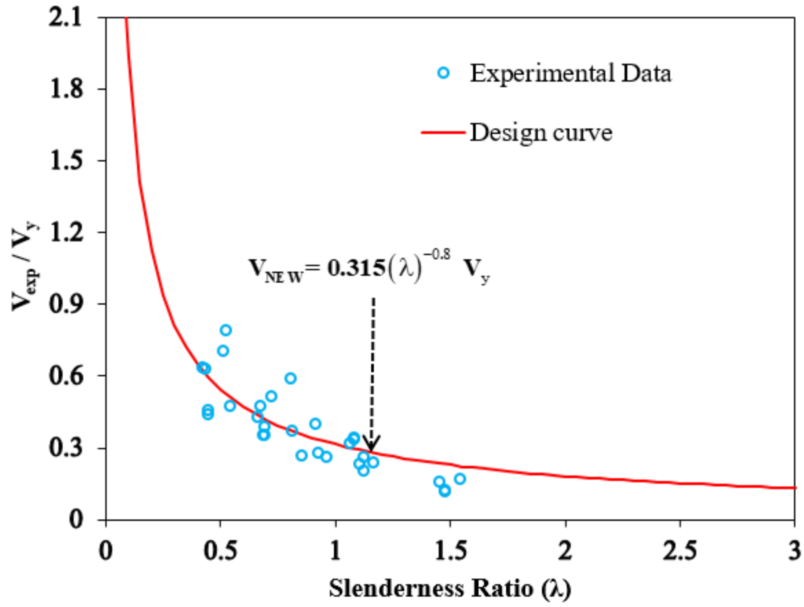

Figure 3: Design curve for Welded clip-angle

New improvised shear equation proposed for welded clip-angle (as shown in Figure 3)

$$V_{nss} = 0.315\,(\lambda)^{-0.8} \times V_y \qquad \text{Eq. (2)}$$

The application parametric range of the above equation was

Thickness of clip-angle: 1.5 mm to 2.5 mm

Aspect ratio (W/D) of clip-angle: 0.33 to 1.21

Yield strength of clip-angle, f_y: 271 MPa to 306 MPa

Clip-angle configuration: Welded clip-angle under shear load

6 PERFORMANCE RATIO OF WELDED AND 3-BOLTED CA

The performance ratio quantifies the relative shear performance between the bolted [16] and welded clip-angle (present) configurations (as shown in figure 4 and Table 5). The ultimate shear capacity of the welded clip-angle, for selected widths (A) of 65 mm, 95 mm, and 125 mm, ranges from 48 to 63%, 60% to 79% and 67% to 89% of 3-bolted clip-angle shear strength. The fillet welded clip-angles failed in distortional buckling for aspect ratio (A/D) < 0.83 and failed in shear local buckling for aspect ratio ≥ 0.83. The 3-bolted clip-angles failed in Tearing for aspect ratio (A/D) ≤ 0.43 and failed in shear local buckling for aspect ratio > 0.43.

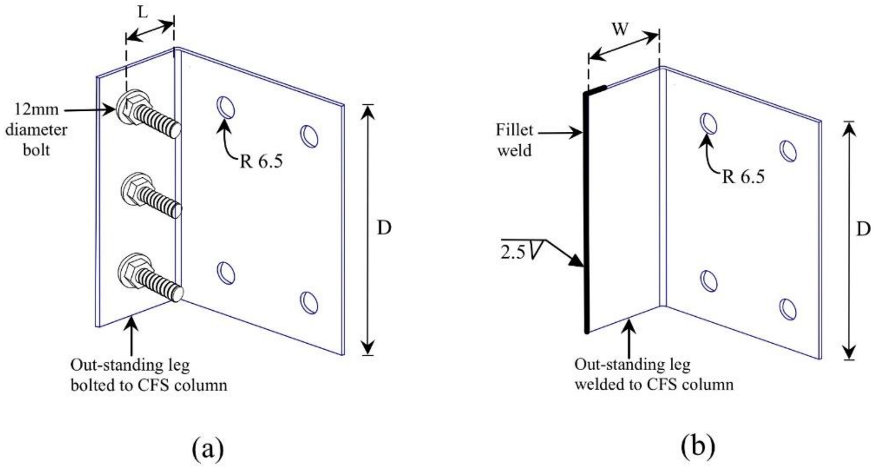

Figure 4: Clip-angle configurations: (a) 3-bolted; (b) Welded

Table 5: Performance ratio of welded and 3-bolted CA

S. No.	Clip-angle	A	D	A/D	Shear strength, Vpredict (kN)	Shear strength, V_{3B} (kN)	V_{WS} / V_{3B}	Failure Mode	
								WS	3B
1	1.5-65-150-WS/3B	65	150	0.43	15.50	26.36	0.59	DB	SLB
2	1.5-95-150-WS/3B	95	150	0.63	10.88	14.70	0.74	DB	SLB
3	1.5-125-150-WS/3B	125	150	0.83	8.53	10.23	0.83	SLB	SLB
4	1.5-65-180-WS/3B	65	180	0.36	18.82	29.96	0.63	DB	Tearing
5	1.5-95-180-WS/3B	95	180	0.53	13.25	16.70	0.79	DB	SLB
6	1.5-125-180-WS/3B	125	180	0.69	10.35	11.63	0.89	DB	SLB
7	2-65-150-WS/3B	65	150	0.43	26.14	48.29	0.54	DB	Tearing
8	2-95-150-WS/3B	95	150	0.63	19.09	26.51	0.72	DB	SLB
9	2-125-150-WS/3B	125	150	0.83	14.78	18.35	0.81	SLB	SLB
10	2-65-180-WS/3B	65	180	0.36	31.85	54.89	0.58	DB	Tearing
11	2-95-180-WS/3B	95	180	0.53	22.32	30.13	0.74	DB	SLB
12	2-125-180-WS/3B	125	180	0.69	17.99	20.86	0.86	DB	SLB
13	2.5-65-150-WS/3B	65	150	0.43	37.97	79.12	0.48	DB	Tearing
14	2.5-95-150-WS/3B	95	150	0.63	26.74	42.73	0.63	DB	SLB
15	2.5-125-150-WS/3B	125	150	0.82	23.23	29.40	0.79	DB	SLB
16	2.5-65-180-WS/3B	65	180	0.36	46.41	89.94	0.52	DB	Tearing
17	2.5-95-180-WS/3B	95	180	0.53	32.48	54.32	0.60	DB	SLB
18	2.5-125-180-WS/3B	125	180	0.69	25.20	37.39	0.67	DB	SLB

Note: DB = Distortional buckling, SLB =Shear local buckling

6 RELIABILITY ANALYSIS

To assess the design factors for the Load and Resistance Factor Design (LRFD), Limit State Design (LSD), and Allowable Strength Design (ASD) design methodologies, the reliability check is carried out on the suggested shear equations. The equation below calculates the resistance factors for the LRFD and LSD techniques for fixed reliability values of 3.5 and 4 recommended in the AISI [15] code for the CFS connections.

$$\phi = C_\phi \times M_m \times F_m \times P_m \times e^{-\beta_0 \sqrt{V_M{}^2 + V_F{}^2 + C_P V_P{}^2 + V_Q{}^2}} \quad \text{Eq. (3)}$$

Where,

C_Φ= calibration coefficient = 1.52 for LRFD method

= 1.42 for LSD method

M_m = mean of the material factor

F_m = mean of the fabrication factor

P_m = mean of the professional factor

β_0 = target reliability index value = 3.5 for connections for LRFD method

= 4 for connections for LSD method

V_M = coefficient of variation of the material factor

V_F = coefficient of variation of fabrication factor

C_P = correction factor $=\left(1+\frac{1}{n}\right)\left(\frac{m}{m-2}\right)$; if $n \geq 4$

n = number of test conducted

m = degrees of freedom = n -1

V_P = Coefficient of variation of experimental results ≤ 6.5

V_Q = Coefficient of variation of load effects

= 0.21 for LRFD and LSD methods

The design safety factor for the ASD methods is calculated from the below equation

Ω_{ASD} = safety factor = $\frac{1.6}{\phi_{LRFD}}$

Table 6. Reliability analysis

Description	WS	3B
No. of tests conducted (n)	22	60

Degrees of freedom (m)	21	59
Mean value of professional factor(P_M)	1.02	1.06
Standard deviation (σ)	0.28	0.15
Coefficient of variation of test results (V_p)	0.27	0.14
correction factor (C_p)	1.16	1.05
Mean value of material factor (M_M)	1.10	1.10
Mean value of fabrication factor (F_M)	1.00	1.00
Calibration coefficient (C_Φ): LRFD	1.52	1.52
Calibration coefficient (C_Φ): LSD	1.42	1.42
Coefficient of variation of material factor (V_M)	0.08	0.08
Coefficient of variation of fabrication factor (V_F)	0.15	0.15
Coefficient of variation of load effects (V_Q)	0.21	0.21
Target reliability index (β_o): LRFD	3.50	3.50
Target reliability index (β_o): LSD	4.00	4.00
Resistance factor (Φ): LRFD	0.43	0.61
Resistance factor (Φ): LSD	0.33	0.49
Safety factor(Ω): ASD	3.76	2.63

The values obtained for resistance and safety factors from the reliability analysis of Equation 1(WS) and 3B [16] are listed in Table 6 for the LRFD, LSD, and ASD methods as 0.43, 0.33, and 3.76; 0.61, 0.49 and 2.63 respectively. However, it is recommended to use a value of unity for all design factors to ensure a more conservative estimation of shear strength. This recommendation is especially relevant for the serviceability design, as it assumes the clip-angle is functioning within the elastic limit state.

8 CONCLUSIONS

In this study, the new improvised shear strength equation of welded clip-angle connection is suggested. The relative shear performance of the bolted and welded clip-angle configurations is quantified using a performance ratio. The ultimate shear capacity of the welded clip-angle, for selected widths (A) of 65 mm, 95 mm, and 125 mm, ranges from 48% to 63%, 60% to 79% and 67% to 89% of the 3-bolted clip-angle connection. The fillet welded clip-angles failed in distortional buckling for aspect ratio (A/D) < 0.83 and failed in shear local buckling for aspect ratio ≥ 0.83. In contrast, the 3-bolted clip-angles failed in Tearing for aspect ratio (A/D) ≤ 0.43 and failed in shear local buckling for aspect ratio > 0.43. The fillet welded clip-angle design shear strength can be determined using resistance of 0.43(LRFD), 0.33(LSD) and a safety factor of 3.76(ASD). While, the resistance (LRFD, LSD) and safety factors (ASD) of 0.48, 0.37 and 3.33 were suggested for the 3-bolted clip-angle. While, the 3-bolted clip-angle is recommended to have resistance factors of 0.61(LRFD), 0.49(LSD) and a safety factor of 2.63(ASD) for its design strength.

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