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EXPERIMENTAL STUDY ON BEHAVIOUR OF BOLTED COLD-FORMED STEEL ANGLES UNDER TENSION

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ABSTRACT

This study is focused on behaviour of bolted cold formed steel angle members under tension. L-shaped specimens with different dimensions tested by using single-line bolted connections were discussed in this study. Sixteen numbers of single plain and lipped angle specimens were tested in a Universal Testing machine using black bolts of 10mm diameter. The thickness of the steel sheet used in this study was 2 and 3mm. Various types of connection failure, Load vs deflection behaviour were studied. The comparisons are made between the test results and predictions computed based on specifications using BS 5950(Part V)-1998, AS/NZS 4600:2005.

Keywords: Cold-formed angles; Tension members; Shear lag

1. INTRODUCTION

The use of Cold- formed steel is increased nowadays in structural elements, agricultural equipments, aircrafts, etc. Angles are the most basic and widely used sections among the various forms of all rolled steel sections available. Practically angles are connected with gusset plates through one leg and due to this there will be non-uniform stress distribution due to eccentrically applied load. The reduction in load carrying capacity occurs due to a phenomenon as shear lag effect. The study of shear lag effect on single and double angles made of hot rolled sections were based on test results of 218 specimens which included different cross-sectional configurations, connection materials and fabrication methods [1]. To investigate the effect of shear lag tests on cold formed steel channel sections with different dimensions were conducted and the comparisons were made between the test results and predictions computed based on several specifications [2]. The material nonlinear effects of 20 node quadratic brick element were modeled using the Von-Mises yield criterion and the material stress-strain curve was assumed to be elastic perfectly plastic [3]. An experimental and finite element investigation on 24 specimens of single and double

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angle tension members to examine the effect of shear lag on the net section rupture capacity of the were conducted and the compared with earlier results. [4]. The resulting stress distribution justified the use of area along the gross shear plane in block shear strength prediction equation. The distribution and concentration of von Mises stresses indicated that block shear failure might occur in a two bolt connection, and net section failure might occur in three and four bolts connection [5]. The factor of safety for angles under tension in the limit state format giving due considerations to block shear failure and yielding of gross section was obtained [6]. A new expression for shear lag factor which represents the net section reduction coefficient has been suggested. [7]. An expression for net section efficiency (U) which depended on the geometrical factors such as connection eccentricity ($\overline{x}$), connection length (L), width of connected leg of the angle (b_c), net width of the angle with connected leg (b_{cn}), width of unconnected leg (b_d), nominal bolt diameter (d) and angle thickness (t) has been suggested [8].

All the above investigations were made for the hot rolled angle sections. There were only limited investigations for cold-formed steel members. The present investigation aims to study the behaviour of cold-formed steel angle members.

2. CODAL PROVISIONS

The existing Indian Standard code of practice for cold-formed steel IS 801-1975 does not elaborately deal with the design of tension members. The following codal provisions are used to predict member capacities of the cold-formed steel angle members.

Australian/NewZealand Standards: AS/NZS 4600-2005 [9].

The nominal section capacity N_t of a member in tension shall be taken as the lesser of

$$N_t = A_g f_y \text{ and} \tag{1}$$

$$Nt = 0.85\, K_t A_n f_u \tag{2}$$

where A_g = gross cross sectional area of the member

f_y = yield stress of the material

K_t = correction factor for distribution of forces.

for eccentrically connected single angles and double angles connected to opposite side of the gusset plate, the value of $K_t = 0.85$

for double angles connected to the same side of the gusset plate the value of $K_t = 1.0$

A_n = net area of the cross-section, obtained by deducting from the gross area of the cross-section, the sectional area of all penetrations and holes, including fastener holes.

f_u = tensile strength used in the design.

British Standards: BS:5950 (Part 5)-1998 [10]

The tensile capacity P_t, of a member

$$P_t = A_e * p_y \tag{3}$$

For single angles connected through one leg only, the effective area A_e is computed as

$A_e = a_1(3a_1+4a_2)/ (3a_1+a_2)$

where A_e = effective area of the section
a_1 = the net sectional area of the connected leg
a_2 = the gross sectional area of the unconnected leg
p_y = the design strength.

3. EXPERIMENTAL INVESTIGATION

A total of sixteen single plain and lipped angles of different cross sections with single line connection were tested. The cold formed steel angle specimens used in this investigation were fabricated from cold formed steel sheets of thickness 2mm and 3mm by bending and press breaking operations. The single angle specimens were connected with two mild steel gusset plates of thickness 8 mm at ends. All the members are connected with gusset plate by means ordinary block bolts of 10 mm diameter. All the specimens were fabricated for length of 500 mm and tested in an Universal Testing Machine of 400kN capacity. Standard tension tests were conducted on coupons and the modulus of elasticity was found to be $2x10^5 N/mm^2$. The yield stress of 2mm and 3mm thickness was 210 and 228 N/mm^2. Similarly the ultimate stress of 2mm thickness was $268N/mm^2$ and 3mm thickness was 292 N/mm^2. Table 1 represents the details of the single angle specimens. The length of the connection L_C is 60mm for all the single angles. The pitch and edge distance was kept as 30mm and 20mm. The shear lag distance b_s is evaluated as per Indian standards.

The gusset plates were not reused and all the members were connected to gusset plate by larger leg. The specimens were fixed vertically by gripping the gusset plate. The load was applied eccentrically through the gusset plate. Dial gauge was used for measuring the elongation. Load is gradually applied with suitable increments from control panel and for each increment of load corresponding elongation was taken.

The yield, ultimate and breaking loads were also observed. The procedure is repeated till the failure stage is reached in all specimens. During the loading process the failure pattern was recorded. Fig 1 and 2 shows the experimental setup for all single plain and lipped angle specimen.

Table 1: a) Details of single angle specimens of thickness 2mm

S.No	Size of the specimen in mm	Width of connected leg ‘a’ in mm	Width of unconnected leg ‘b’ in mm	No of bolts	Connection eccentricity x in mm	b_s = (b+a/2)-t in mm
1	50x50x2	50	50	3	13.24	73
2	60x60x2	60	60	3	15.75	88
3	50x25x2	50	25	3	4.94	48
4	60x25x2	60	25	3	4.46	53
5	50x50x15x2	50	50	3	16.5	73
6	60x60x15x2	60	60	3	18.99	88
7	50x25x15x2	50	25	3	7.91	48
8	60x25x15x2	60	25	3	7.27	53

Table 1: b) Details of single angle specimens of thickness 3mm

S.No	Size of the specimen in mm	Width of connected leg 'a' in mm	Width of unconnected leg 'b' in mm	No of bolts	Connection eccentricity x in mm	b_s= (b+a/2)-t in mm
1	50x50x3	50	50	3	13.61	72
2	60x60x3	60	60	3	16.12	87
3	50x25x3	50	25	3	5.32	47
4	60x25x3	60	25	3	4.85	52
5	50x50x15x3	50	50	3	16.12	72
6	60x60x15x3	60	60	3	18.66	87
7	50x25x15x3	50	25	3	7.43	47
8	60x25x15x3	60	25	3	6.83	52

Figure 1. Experimental setup for single plain angle specimen (t=2mm)

Figure 2. Experimental setup for single lipped angle specimen (t=3mm)

5. RESULTS AND DISCUSSION

The behaviour of cold-formed steel single and double angles when subjected to eccentric tension were studied. The ultimate-load carrying capacities of the specimens were compared with the load carrying capacities predicted using Australian/New Zealand and British standards.

1) Experimental Investigation:

a) Ultimate Load-carrying capacity:

The experimental ultimate loads for all the cold-formed steel single plain and lipped angles tested are presented in Table 2. From the table it is observed that in case of single angles the load carrying capacity of lipped angle increases by 11.2% when compared to that of plain angles. Similarly, the load carrying capacity is increased by 50% for 3mm thickness angles when compared to 2mm thickness.

Table 2: Ultimate load carrying capacity of the single angles

S. No.	Size of the specimen (mm)	Ultimate load carrying capacity in kN	
		t=2mm	t=3mm
1	50x50xt	19	50
2	60x60xt	20	55
3	50x25xt	19	50
4	60x25xt	20	52
5	50x50x15xt	23	62
6	60x60x15xt	24	53
7	50x25x15xt	22	49
8	60x25x15xt	26	55

b) Load vs Deflection:

Fig 3 and 4 show the typical load versus deflection behaviour for single angles with and without lips. From the graphs, it is observed that the ultimate load carrying capacity increases as the cross-sectional area in the connection increases. It is also observed that when the rigidity of the connection increases the stiffness of the member also increases.

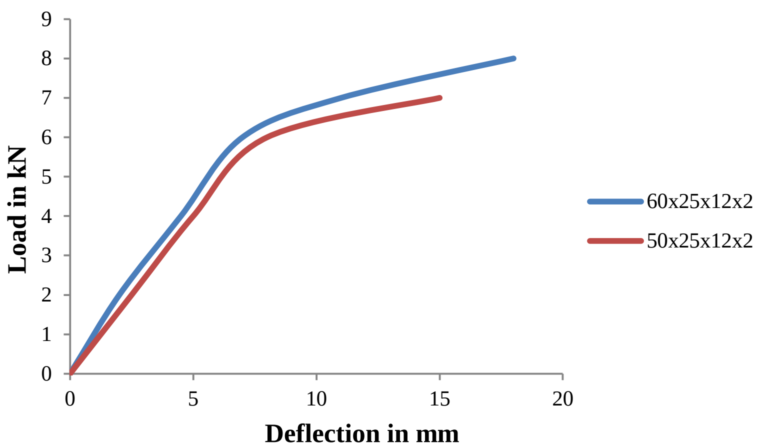

Fig.3. Load vs Deflection behaviour of single lipped angle specimen(t =2mm)

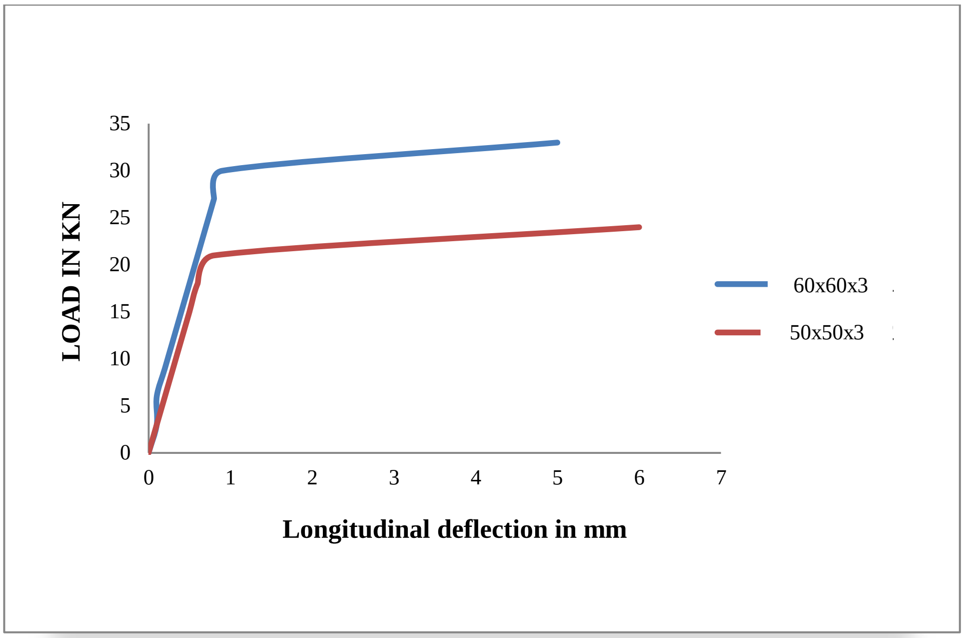

Figure 4. Load vs Deflection behaviour of single plain angle specimen (t=3mm)

c) Failure mode

The mode of failure of all single were noticed during testing. Generally block shear failure, net section fracture failure were observed as in Fig 5 and 6 . The mode of failure depends upon the cross section and rigidity of connection. Table 3 presents the mode of failure of all single angle specimens tested. From the table it is observed that for the same connection length, pitch and edge, almost all the specimens failed by net section failure irrespective of the cross sections and thickness.

Table 3: Mode of failure

S. No.	Size of the specimen (mm)	Mode of failure	
		t=2mm	t=3mm
1	50x50xt	Net section	Block shear
2	60x60xt	Net section	Net section
3	50x25xt	Net section	Net section
4	60x25xt	Net section	Net section
5	50x50x15xt	Net section	Net section
6	60x60x15xt	Block shear	Net section
7	50x25x15xt	Net section	Net section
8	60x25x15xt	Net section	Net section

The gusset plate and the angles bent during loading. This is due to eccentrically applied load. As the load was being applied, the corners of the angle at the two ends gradually separated from the gusset plates. Generally larger gaps were associated with the cases of greater eccentricity of the cross-section, smaller angle thicknesses and shorter connection lengths.

There was no major slip of the connections during the tests. All the specimens failed at the critical cross-section (inner most bolt hole) as the ultimate load was reached. After necking, the critical cross-section was torn out from the edge of the connected leg to the hole then to the corner of the angle. The specimens carried some amount of load beyond the ultimate load and until failure. It was noted that all the bolts were still tight after completion of the tests. This indicates that the bolts were not highly stressed during the tests. The outstanding leg is subjected to local bend due to shear lag.

Figure 5. Block shear failure for single plain angle specimen (t =3mm)

Figure 6. Net section failure for single lipped angle (t=2mm)

2) Comparison of Experimental and Predicted Ultimate Loads

A comparative study between the experimentally observed ultimate loads of the specimen tested with the tensile load carrying capacity of equations of the following codes AS/NZS:4600-2005, BS:5950 (Part 5)-1998 is made. Fig 7 and 8 shows the comparison of experimental and ultimate loads predicted by various codes for single plain and lipped angles. The tensile capacity equations of the international codes take it into account the effect of shear lag and incorporates the capacity reduction factor in addition to net effective area of the section.

From the tables it is observed that values predicted by AS/NZS and BS are closer and higher than experimental loads for plain angles. Similarly for lipped angles the experimental values are higher than AS/NZS and BS.

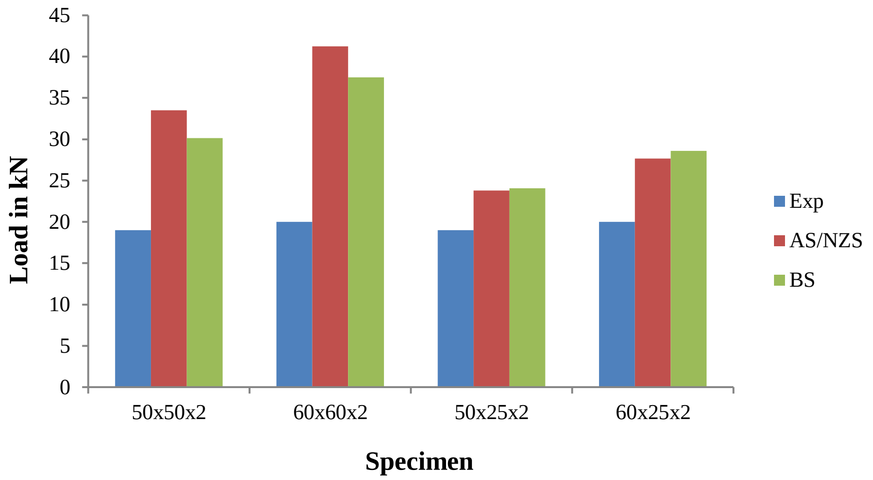

Figure 7. Comparison of ultimate loads with loads based on codal provisions for single plain angles (t =2mm)

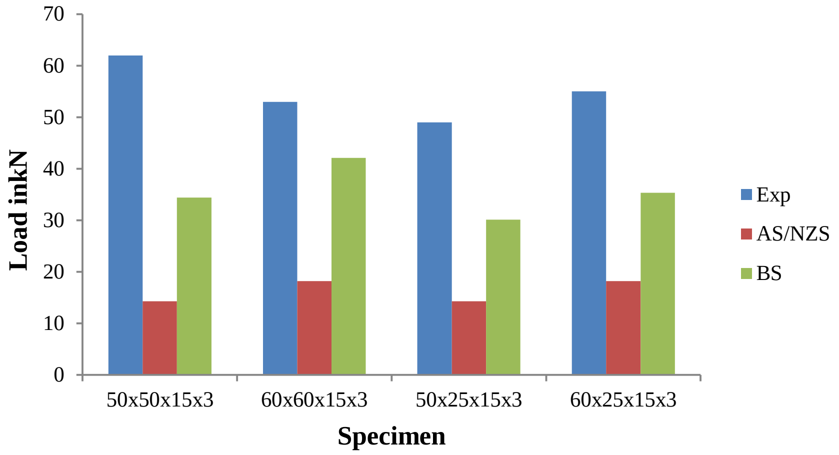

Figure 8. Comparison of ultimate loads with loads based on codal provisions for lipped angles (t=3mm)

6. CONCLUSIONS

Sixteen numbers of single plain and lipped angle specimens are subjected to tension and their ultimate load carrying capacity was found. Yielding started first at the critical section around the inner bolt holes. Fourteen specimens failed by net section failure for the same connection length, pitch and edge distance. The outstanding leg is subjected to local bend due to shear lag. From the table it is observed that the ultimate load carrying capacity increases as the cross – sectional area increases. Based on the test results, it is concluded that the net section capacity of tension member is affected by connection eccentricity, cross sectional area and thickness of the member.

Also when the experimental loads are compared with the ultimate loads predicted by various codes, it is observed that values predicted by AS/NZS and BS are closer and higher than experimental loads for plain angles. Similarly for lipped angles the experimental values are higher than AS/NZS and BS.

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