Grenze Int. J. of Engineering and Technology, Vol. 1, No. 1, January 2015

A Critical Review on the Shear Lag Effect of Steel Channel Sections Subject to Tensile Loading

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***Abstract*— The net section capacity of channel sections under tension are affected by shear lag effect. In India the strength of channel sections are evaluated by using the equations available for angle sections. Hence, an attempt has been made to check the validity of these equations for channel sections. For this purpose, guidelines available in various codes of practices and literature are revisited. This paper examines the factors affecting the net section capacity of tension members and the various empirical equations from the literature. Different codal equations related to the net section capacity of channel sections are studied and compared with the corresponding experimental results reported in literature. Effect of the gauge, length of connection and the number of row of bolts are studied.**

***Index Terms*— Tension capacity, Shear lag effect, Channel sections, Angle sections.**

I. Introduction

The net section failure capacities of channel sections under tension are influenced by shear lag effect, which arises due to uneven stress distribution due to the presence of bolt holes and eccentricity of the loading. This creates a lag in stress transfer across the cross-section, which leads to reduction in the cross section strength. The consequence of this shear lag can be observed when the member fails through net tensile area at a load lesser than the tensile capacity of the member. For plates under tension having bolts, the tensile stress is usually not uniformly distributed, having stress concentration adjacent to the hole and decreases in transverse direction. Due to this only the portion around the hole reaches ultimate and the stress in the other regions are less.

The criterion for the design of angles and channel tension members is governed by eccentricity unlike plate sections which is loaded axially and the reduction in the effective area is due to stress concentration around the bolt hole. Whereas in angle and channel sections, shear lag effect is more pronounced than plate elements due to various factors like eccentricity, ratio of unconnected leg to that of connected leg length, length of the connection, thickness of the section etc. Stress distribution on angle section under tension is shown in Fig.1. It shows the stress lag in the unconnected leg. Similarly, the stress distribution of channel sections is also affected by shear lag. However, there are no design guidelines for channel tension members. This paper presents the critical review of literature of channel sections under tension and compares the strength predicated by the codal provisions.

Grenze ID: 01.GIJET.1.1.18

II. REVIEW OF EMPIRICAL EQUATIONS

A. McKibben et al. (1906) [15] tested 18 specimens for tensile tests and studied the net section efficiencies of each member and on the bases of the findings and results, the following equation was formulated.

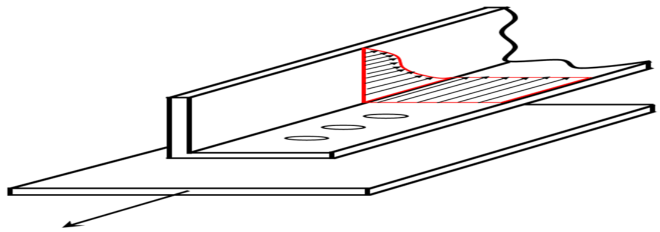

Fig.1 Stress Distribution in unconnected leg due to Shear Lag

$$\text{Capacity} = f_u \times A_n \times U \quad (1)$$

$$U = 1.0 - 0.18\frac{L_0}{L_c} \quad (2)$$

where, L_C = width of the connected leg, L_0 = width of the unconnected leg, A_n is the net cross sectional area, f_u is the ultimate tensile strength of steel.

B. Nelson et al. (1953) [17] observed that the capacity is a function of no of bolt hole per line and the ratio of outstanding leg area to that of connected leg area. It was observed that there was no change in the capacity of the connection on increasing the connection length or by changing the connection type. Based on the results obtained from 18 single angles connected at their ends, the following equation was proposed

$$\text{Capacity} = f_u \times A_n \times U \quad (3)$$

$$U = \frac{1}{1+\frac{r}{n}} \quad (4)$$

where, n is the number of bolts per line and $r = \frac{A_0}{A_{cn}}$, where A_o is the gross cross sectional area of outstanding leg and A_{cn} is the net cross sectional area of connected leg.

C. Munse et al. (1963) [16] proposed an empirical equation based on tests of 218 tension specimens out of which 56 are single angles and 33 are double angles. The empirical equation includes a factor for the ductility of the material, the effect of punching the holes, the effect of holes spacing on the connection and a factor to take account for both eccentricity in the connected parts and the connection length.

$$\text{capacity}=f_u \times A_{ne} \quad (5)$$

$$A_{ne} = K_1 \times K_2 \times K_3 \times K_4 \times A_n \quad (6)$$

where, K_1 is the ductility factor given by (0.82+0.0032Q), Q is the percentage reduction in the area of a standard tensile coupon test.

K_2 is the fabrication factor = 0.85 for punching effect

= 1.0 for drilling effect

$$K_3 = 1.6 - 0.7\left(\frac{A_{ne}}{A_g}\right)$$

K_4 is the shear lag factor given by 1.0 – (X/L)

where X refers to the distance from face of the plate to the center of gravity of the member. L is the length of the connection (distance between the first and the last bolt).

D. Marsh et al. (1969) [14] conducted a series of tests on single angle members in tension and compression to study the effects of plastic behavior during ultimate loading of the sections. Marsh stated that as the extreme fibers of the section yield, the line of action of the load would move, as well as the eccentricity. Based on these observations, it was proposed that the net effective area **(**A_{ne}**)** could be calculated as follows

$$A_{ne} = \frac{(L_c^2 + L_o.t)t}{L_c - 0.04L'} \quad (7)$$

where L_c = width of the connected leg, L_0 = width of the unconnected leg, t = thickness of the section, L' = distance from the point of loading to the innermost bolt and d = diameter of the bolt hole.

E. Gaylord (1992) [8] gave an equation for the net section capacity accounting for the shear lag effects. He assumed it depends on four factors: steel ductility, fabrication methods, connection efficiency, and shear lag effects. They gave an expression as follows

$A_{eff} = K_1.K_2.K_3.K_4.A_n$

where, K1 = ductility factor = 0.82 + 0.0032 R ≤ 1.0

K2 = fabrication factor = 0.85 for punching effects

= 1.0 for drilling effects.

K3 = efficiency coefficient

K4 = shear lag factor.

R = percent reduction in the cross sectional area of a tensile coupon at failure.

F. Kulak et al. (1993) [10] conducted experiments on single and double angle tension members. Based on test results the following equation was proposed

$$P_p = 0.85\varphi(F_u.A_c + \beta.A_u.F_y) \quad (8)$$

P_p is the factored resistance of the member

φ = 0.90

F_u = ultimate tensile strength of the material, F_y = yield strength of the material

A_C = net area of the connected leg, A_u = gross area of the connected leg

β = 1 .0 for members with four or more transverse lines of fasteners

= 0.5 for members with fewer than four transverse lines of fasteners

G. Usha et al. (2003) [18] developed a finite element model considering both material and geometrical non-linearity. Various parameters were studied and then compared with the respective experimental results. It was observed that the net section efficiency depends on connection length (*b/L*), the slenderness of outstanding leg (*w/t*), ratio of material yield strength to ultimate strength (f_y/f_u) and hence the following equation was proposed

$$P_u = f_u \times A_{cn} + \beta \times f_y \times A_0 \quad (9)$$

$$\beta = 1.38 - 0.076\left(\frac{b}{L} \times \frac{w}{t} \times \frac{f_y}{f_u}\right) \quad (10)$$

where A_{cn} = net area of connected leg, A_o = area of the outstanding leg

H. Lip Teh et al. (2013) [12] studied net tension of cold reduced steel channel brace and proposed an equation for net section strength. It was observed to be influenced by stress concentration around the bolt hole, which is referred as in-plane shear lag, the out-of-plane shear lag, and the bending moment arising from the connection eccentricity with respect to the neutral axis. Based on the results presented in the paper of Pan (2004) and the results from Lip Teh et al. (2012)[13], a net section capacity for channel braces in tension is developed as given below

$$P_P = A_n.F_u.\left[\frac{1}{1.1 + \frac{wf}{wc + 2wf} + \frac{x}{l}}\right] \quad (11)$$

where, w_f = flange width, w_c = web depth, x = connection eccentricity, and l = length of connection.

From the review, it is found that the empirical equations reported in the literature are for angle sections only. All the equations addressed the shear lag effect of unconnected leg adequately f or angle sections. Its adequacy for channel sections will be discussed in the later sections. Further, the review of design guidelines reported in the codes has been conducted.

III. REVIEW OF INTERNATIONAL CODAL PROVISIONS

A. *IS 800:2007* [9]

Indian standard considers three modes of failure for the design of tension members namely gross yielding, net section rupture, block shear and the least among these is considered as design strength. In angle and channel sections, for the design of net section rupture additional reduction factor beta (β) is incorporated, which varies with connection length, slenderness of outstanding leg, and ratio of yield strength to ultimate strength and hence strength varies accordingly. Net section rupture is given by

$$P_u = f_u \times A_{cn} + \beta \times f_y \times A_0 \tag{12}$$

$$\beta = 1.38 - 0.076\left(\frac{b}{L} \times \frac{w}{t} \times \frac{f_y}{f_u}\right) \tag{13}$$

where, A_{cn} = net area of the connected leg, A_o= gross area of outstanding leg

B. *AISC 360: 2010* [1]

American standard considers the limit states of tensile yielding in the gross section and tensile rupture in the net section as the governing factors for the design of tension members. For tensile rupture in the net section, the equation is given by

$$P_p A_e = F_u . A_e . \emptyset_t \tag{14}$$

where, A_e = effective net area, A_g = gross area of the member, F_y = yield stress, Fu = ultimate stress, $\emptyset_t$ = 0.75.

C. *Euro Code – 1993* [7]

Euro code takes into account the effect of spacing and edge distances of the bolts, number of bolts and pitch for the design of net section strength. Based on these parameters, euro code gives net section strength.

$$For\ 1\ Bolt\ \ N_{u,rd} = \frac{2(e_2 - 0.5d_o)tf_u}{\gamma_{m2}} \tag{15}$$

$$For\ 2\ bolts\ \ N_{u,rd} = \frac{\beta_2 . A_{net.}f_u}{\gamma_{m2}} \tag{16}$$

$$For\ 3\ or\ more\ bolts\ N_{u,rd} = \frac{\beta_3 . A_{net.}f_u}{\gamma_{m2}} \tag{17}$$

β_2 and β_3 are the reduction factors dependent on pitch p_1 as given in Table I. For intermediate values of p_1, the intermediate values of β may be determined by linear interpolation. A_{net} is the net area of the section.

TABLE I. REDUCTION FACTORS BASED ON VARIATION OF PITCH

Pitch	p_1	$\le 2.5d_0$	$\ge 5.0\ d_0$
2 Bolts	β_2	0.4	0.7
3 Bolts	β_3	0.5	0.7

D. *British Standard – 5950* [4]

British code states that for angles, channels, T-sections with eccentric end connection can be treated as axially loaded section with reduced net section area and hence reduced strength. The equation for net section tension capacity is given as

$$P_t = P_y(A_e - 0.5a_2) \tag{18}$$

Where P_y is the ultimate tensile strength, $a_2 = A_g - a_1$, A_g = gross sectional area of the section, a_1 = gross area of the connected element, A_e = sum of effective net areas given as, $A_e = K_e a_n$ but $a_e < a_g$

K_e depends on grade of steel, where S 275 represents the specified minimum yield strength of the material (which is 275) and the yield strength of the material increases with increase in thickness of the member.

For grade

S 275,	K_e	=	1.2	S460, K_e = 1.0
S 355,	K_e	=	1.1	For other steel grades $K_e = (u_s/1.2)/p_y$

E. Australian- 4100 [2]

Australian code provides two criteria for tension member design which are yield and ultimate strength. The yield criterion is given by ($A_g .f_y$) and the ultimate strength through the net section is given by

$$N_t = 0.85 K_t A_n f_u \tag{19}$$

K_t is the correction factor for the distribution of forces determined in accordance with clause 7.3 of AS 4100 given as below

K_t = 0.75 for unequal angles connected by short leg, 0.85 otherwise

K_t = 0.85 for channels sections

K_t = 0.90 for T section

For sections on both sides of gusset plate, $K_t = 1$.

From the review of codal provisions, it is found that most of the codes suggest the adoption of the provisions given for angle sections to channel sections also. However, Australian-code adopts the shear lag of channel section through empirical factor. Hence, in order to check the validity of design guidelines given for angle sections, the experimental results available in the literature are collected and used for comparative study

IV. Details of experimental work from literature

Udagawa et al. (2004) [11] conducted experiments on 42 channel sections in order to investigate the effect of bolt hole arrangements and edge distances of bolted joints on the ultimate tensile strength and failure modes. The setup is kept such that two channels are placed opposite to each other and a gusset plate is placed in between them and tension load is applied.

A. Specimen details

Fig. 2 shows the specimen details of Udagawa et al. (2004) [11]. Channels of three different dimensions were considered which are (75x40x5x7), (100x50x5x7.5), (125x65x6x8). The arrangements of bolts were made in single rows and two rows and in each case the number of bolts are varied from 2 bolts to 5 bolts. The bolt arrangements of one line and high strength bolts of M16 or M20 of channel (75x40x5x7) are referred to as A series. A two line bolt hole arrangements and high strength bolts of M16 of channel (100x50x5x7.5) were referred to as B series. A two line bolt hole arrangements of high strength bolts of M16 or M20 were used for channels of (125x65x6x8) are referred to as C series.
The pitch of different specimens were varied as 2.5d or 3.0d respectively, where d represents bolt diameters as 16mm or 20mm.

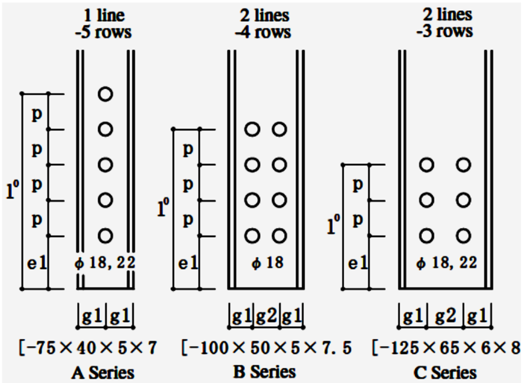

Fig.2: Test specimen (Kuniaki Udagawa et al)

The different channel specimens were represented as xyz*, where x refers the number of bolt lines, y refers the number of bolts per row and z refers the variation of the configuration of bolts such as pitch and the end distance, * refers for 20 mm bolt diameter. Table II presents the specimen details

TABLE II. DETAILS ABOUT THE EXPERIMENTAL SECTIONS

Specimen	Section	f_y (N/mm^2)	f_u (N/mm^2)	g_1/d	e_1/d
A122	75 x 40 x 5x7	304.11	459.108	2.36	4.5
A132	75 x 40 x 5x7	304.11	459.108	2.36	4.5
A142	75 x 40 x 5x7	304.11	459.108	2.36	4.5
A143*	75 x 40 x 5x7	308.034	464.994	1.87	2.51
A151	75 x 40 x 5x7	317.844	482.652	2.35	2.51
A152	75 x 40 x 5x7	304.11	459.108	2.36	4.5
A153*	75 x 40 x 5x7	308.034	464.994	1.88	2.5
B222	100 X 50 X 5 X 7.5	300.186	455.184	1.97	4.5
B232	100 X 50 X 5 X 7.5	300.186	455.184	1.97	4.5
B242	100 X 50 X 5 X 7.5	300.186	455.184	1.97	4.5
B251	100 X 50 X 5 X 7.5	300.186	455.184	1.97	4.5
C224	125 X 65 X 6 X8	300.186	464.013	1.99	4.5
C225	125 X 65 X 6 X8	299.205	456.165	2.33	4.5
C234	125 X 65 X 6 X8	300.186	464.013	1.99	4.5
C235	125 X 65 X 6 X8	299.205	456.165	2.33	4.5
C237*	125 X 65 X 6 X8	300.186	442.431	2.03	4.49
C244	125 X 65 X 6 X8	300.186	464.013	1.99	4.5
C245	125 X 65 X 6 X8	299.205	456.165	2.33	4.5
C247*	125 X 65 X 6 X8	300.186	442.431	2.03	4.49
C251	125 X 65 X 6 X8	299.205	456.165	2.33	4.5
C252*	125 X 65 X 6 X8	309.996	457.146	2.03	4.5

V. COMPARISION OF DIFFERENT EQUATIONS

With the results of Udagawa et al.(2004)[11],a comparative study has been conducted by using different code equations and empirical equations reported in the literature .The above empirical equations and different codal equations are studied and their failure capacities for the different experimental specimens are evaluated and compared with corresponding experimental value and their error is given in Table III and Table IV.

VI. RESULTS AND DISCUSSIONS

- For BS code if only two number of bolts are used in single row, the error in prediction is high. But on increasing the number of bolts it predicts with reasonable accuracy. This concludes that as we increase the length of connection, the shear lag effect reduces, hence the prediction value is closer to actual value.

TABLE III. PERCENTAGE ERROR IN PREDICTION OF STRENGTH AS PER DIFFERENT INTERNATIONAL CODES

Specimen	Experimental Udagawa et al. (2004)	IS Code	AISC	AUS	Euro code	Canadian	BS Code
	(KN)	(%)	(%)	(%)	(%)	(%)	(%)
A122	212.58	-18.85	-19.21	-56.95	29.70	-6.70	-74.39
A132	296.90	2.45	-2.54	-12.38	50.47	13.41	-24.87
A142	331.92	9.01	3.12	-0.52	55.70	22.55	-11.69
A143*	337.51	11.51	5.59	-0.12	47.99	24.85	-6.84
A151	344.38	7.32	0.75	-1.85	45.69	21.52	-13.17
A152	335.75	8.20	1.67	0.62	56.20	23.43	-10.42
A153*	337.37	9.71	3.15	-0.17	47.97	24.82	-6.89
B222	265.56	-10.63	-0.78	-44.97	57.43	35.39	-2.32
B232	340.65	-4.06	-5.65	-13.01	57.43	26.77	-2.32
B242	385.93	2.91	-1.29	0.25	57.43	26.77	-2.32
B251	401.18	4.08	-1.35	4.04	57.43	26.77	-2.32
C224	435.51	12.78	1.50	-33.85	56.27	33.62	-6.92
C225	380.92	5.78	-10.71	-50.45	56.27	33.62	-6.92
C234	526.50	5.06	-5.77	-10.72	56.27	24.77	-6.92
C235	472.84	-2.99	-15.78	-21.20	56.27	24.77	-6.92
C237*	473.33	-1.73	-8.54	-13.61	57.69	27.22	-1.51
C244	599.29	9.92	-0.09	2.73	56.27	24.77	-6.92
C245	559.42	1.50	-5.42	-2.44	56.27	24.77	-6.92
C247*	539.35	3.94	-2.60	0.29	57.69	35.78	-1.51
C251	602.82	8.59	-1.37	4.93	56.27	24.77	-6.92
C252*	566.87	2.26	-4.52	1.98	57.69	27.22	-1.51

- For two numbers of bolts, error in prediction by using Euro Code equations is high. Error as high as about 58% is observed. Hence these equations are too economical to be considered for designs.

- All the predictions with respect to AISC and IS CODE are with an accuracy of about 90%. Also AISC has better prediction than all the codes, because it considers the effect of eccentricity of the connection to account for the effect of shear lag.

It can be observed that on specimens (C224, C225), (C234, C235) and (C244, C245) only parameter that change is the gauge and their experimental strength changes significantly, whereas the codal predictions do not show a significant change. This is because gauge distance is not considered in any of the equations. It has to be considered as a parameter.

TABLE IV. PREDICTED STRENGTH FOR DIFFERENT EMPIRICAL EQUATIONS

Specimen	Experimental Udagawa et al. (2004)	Nelson et al. (1953)	Teh et al. (2013)	Pan (2004)	Munse and Chesson (1963)
	(kN)	(kN)	(kN)	(kN)	(kN)
75 x 40 x 5x7	212.58	191.48	238.50	295.65	208.27
75 x 40 x 5x7	296.90	230.90	287.33	390.06	290.05
75 x 40 x 5x7	331.92	257.40	287.90	390.97	290.84
75 x 40 x 5x7	337.51	253.12	291.59	395.99	294.57
75 x 40 x 5x7	344.38	290.61	302.96	411.50	306.17
75 x 40 x 5x7	335.75	276.43	288.18	391.43	291.24
75 x 40 x 5x7	337.37	272.96	291.88	396.45	294.97
100 X 50 X 5 X7.5	265.56	200.31	267.63	324.11	246.14
100 X 50 X 5 X7.5	340.65	246.05	297.74	390.78	310.18
100 X 50 X 5 X7.5	385.93	277.77	309.34	413.00	331.53
100 X 50 X 5 X7.5	401.18	301.05	315.49	424.11	342.21
125 X 65 X 6 X8	435.51	339.41	411.10	504.03	382.17
125 X 65 X 6 X8	380.92	333.67	404.15	495.50	375.71
125 X 65 X 6 X8	526.50	408.13	453.71	596.43	469.37
125 X 65 X 6 X8	472.84	401.22	446.03	586.34	461.43
125 X 65 X 6 X8	473.33	360.51	427.42	567.27	458.09
125 X 65 X 6 X8	599.29	454.09	469.94	627.23	498.43
125 X 65 X 6 X8	559.42	446.41	470.41	631.76	504.29
125 X 65 X 6 X8	539.35	403.95	439.83	590.00	479.97
125 X 65 X 6 X8	602.82	478.77	470.41	631.76	504.29
125 X 65 X 6 X8	566.87	449.92	461.15	621.36	507.24

VII. SUMMARY AND CONCLUSIONS

An attempt has been made to check the validity of these equations for channel sections. For this purpose, guidelines available in various codes of practices and literature are revisited. Several International Codal provisions and equation available in literature, on shear lag effect have been reviewed. The capacity predicted by these equations are compared with the experimental results available in literature. Gauge distance is found to influence the net-section capacity significantly and has been not considered adequately. Hence it should be considered.

ACKNOWLEDGEMENTS

This paper is being published with the kind permission of Director, CSIR-SERC.

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