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Numerical Studies on Channel Sections Subject to Tension

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***Abstract*—The various codal provisions for predicting the net section capacity of channels are compared with experimental results available in literature. Based on the experimental results and finite element simulations some key parameters have been identified and parametric studies are conducted. Using the above results two forms of equations for prediction of net section capacity of channel sections have been proposed and it is found to predict the capacity with very good accuracy.**

***Index Terms*— Channels, Net section capacity, Finite element simulations, Stress concentration.**

I. INTRODUCTION

The tensile net section capacity of channel sections is influenced by the stress distribution across the section. This stress distribution across the section is not uniform due to the eccentricity in loading, stress concentration around the bolt holes etc. This uneven stress distribution across the section leads to shear lag, which reduces the tensile capacity of the section.

McKibben et al. (1906,1907), *Nelson et al.* (1953), *Munse et al.*(1963), *Marsh et al*. (1969), *Kulak et al.* (1993), *Usha et al.* (2003), *Lip H. Teh et al.* (2013) have conducted studies on net section capacity. Several international codal provisions are available. These codal provisions are compared with experimental results present in the literature. The results are presented in Table 1 .In the table * refers to 20mm bolt diameter.

II. MODELLING OF CHANNEL SECTION

Channel sections consisting of varying number of bolts have been modeled using FEM software and compared with the experimental results. This is done to validate the model for further parametric studies. The sections modeled are A122,A132,A143*,A153*,B222,B232,B242,C224, C234,C244 and their configurations are as described above. Only a quarter of the experimental setup is modeled because of symmetry conditions. Hence a half channel and a gusset plate with bolts is modeled and load is applied with boundary conditions as given below. The finite element analysis is carried out using abacus software which can handle large deformations, loads, boundary conditions, and more importantly material and geometric non linearity. Details of the modeling are given below.

A. Element type

An 8-node linear brick element (C3D8R) is used to model channel tension members.

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TABLE I. PERCENTAGE ERROR IN PREDICTION OF STRENGTH IN DIFFERENT INTERNATIONAL CODES

SPECIMEN	EXP. strength (KN)	IS CODE (2007)	AISC (1999)	AUS (1998)	EURO (1992)	CANADIAN (1994)	BS (1990)
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

B. Material proprieties

The elastic properties of the material are taken as per the material used for the experimental setup and to account for the material non linearity plastic properties of the material and also true stress strain curve is also used for exact non linear effects of the material.

The true stress true strain input parameters were found from the equation used in *Taesoo kim et al.*[17] and true stress equation is derived in the following way and then similarly true strain is also found as shown below.

Engineering strain can be defined as (Eq.1)

$$\epsilon_{eng} = \frac{L-L_0}{L_0} = \frac{L}{L_0} - 1 \qquad (1)$$

and true strain can be expressed as an integral of the strain increments (Eq.2)

$$\epsilon_{true} = \int \frac{dL}{L} = \ln \frac{L}{L_0} \tag{2}$$

Substituting Eq.1 in Eq.2, we get the following equation (Eq.3)

$$\epsilon_{true} = \ln(1 + \epsilon_{eng}) \tag{3}$$

L_o is the original length of the member and L is the instantaneous length of the member

Engineering stress can be expressed as (Eq.4)

$$\sigma_{true} = \sigma_{engg}(1 + \epsilon_{engg}) \tag{4}$$

where

σ_{true} is true stress

σ_{engg} is engineering stress

ε_{engg} is engineering strain

P is axial tension,

A_o is the original area of cross section,

A_i is the instantaneous area of cross section.

Hence on the true stress true strain values as input parameters we get the exact behavior of the material in practical situation. Typical graph representing true stress and true strain and engineering stress and engineering strain is given below in Fig.1.

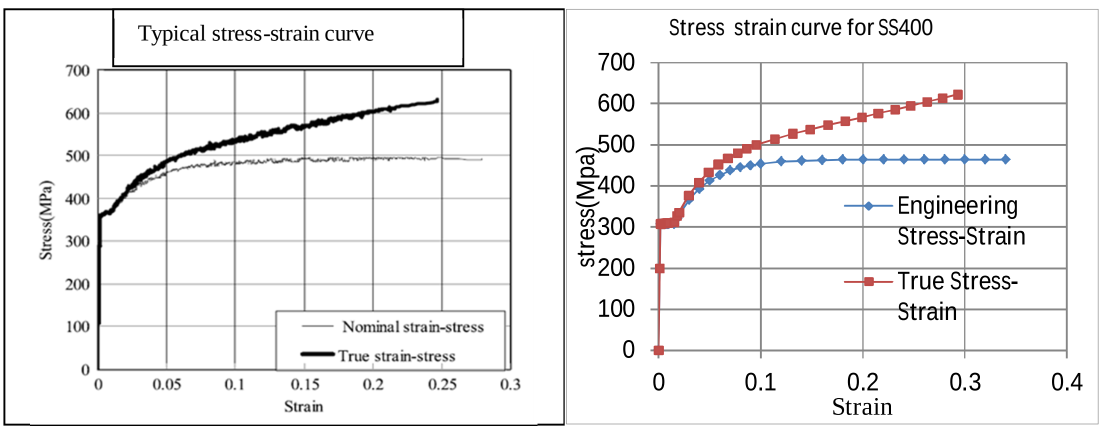

Fig. 1 (a) A typical stress-strain curve for SS400 grade steel [Tae Soo Kim (2011)],(b) Stress strain curve for the used SS400 grade steel

The material properties of ss400 which is used in experiment is taken and true stress and true strain values are formulated for each specimen and given as material properties in ABACUS.

C. Interaction

In the present model we have used contact pairs method, to exactly simulate the experimental conditions.

D. Meshing

The process of messing of a model with varying cross sections and curvatures in between requires additional work of creating portions and then selecting the required algorithms to help the pre-processer to generate an adequate mesh for the model, if not the pre-processor generates a non uniform mesh.

For this model we have used Bottom up algorithm for messing simple rectangular sections and whenever there is a curvature we have used sweep-up algorithm to mesh the part. For better results we have also used meshing along the edges using seed through edges option and meshed the curve to the required size. Meshing of the model is shown below.

E. Effect of bearing of bolts on channel

In experimental situation, when the load is applied on the channel section, the bolts bears on the channel section and hence an additional stress is created on the channel section and this is accounted in the modeling by moving the gusset plate in the opposite direction to loading and hence making the bolt bear on the channel section, then load is applied to this assembly. This is depicted in the following figure.

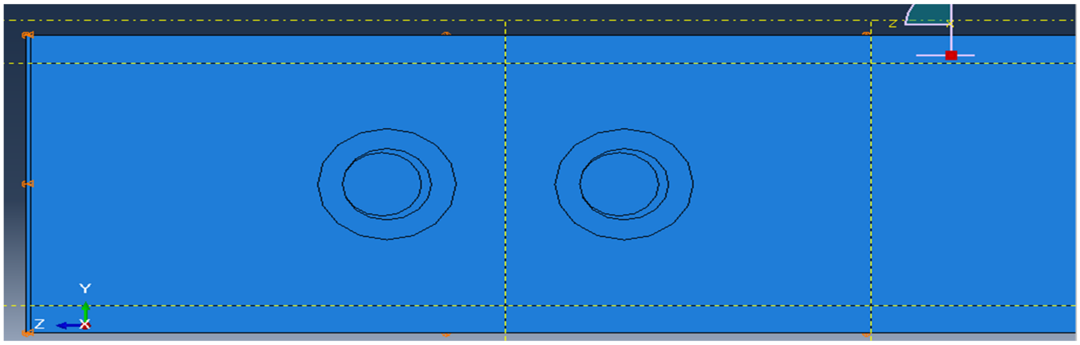

Fig.2 Bearing effect of bolt on the channel section in ABAQUS model

III. Validation Of The Model Using Experimental Values

Ten models of varying number of bolts is modeled, and the specimen details, configuration, ultimate load is taken from the paper by *Udagawa et al.* (2003). The Von miss stress distribution on one of the modeled channel sections are shown in section 3.1 and the comparison of the finite element results with the experimental results along with the IS codal prediction is also tabulated in section 3.2.

A. Von miss stress distribution of different configurations of channel sections:

1. A122 : Fig 4(a) shows that there is a significant decrease in the variation of the stress along the web and Fig 3(b),Fig 3(c) shows the Von-Miss stress distribution on the channel section 75x40x5x7,and it has two bolts of single row. It is clear from the Fig 3(c) that the flange portion has just yielded, while the web has failed. This proves that the effect of shear lag is predominant in case of two bolts of single row.

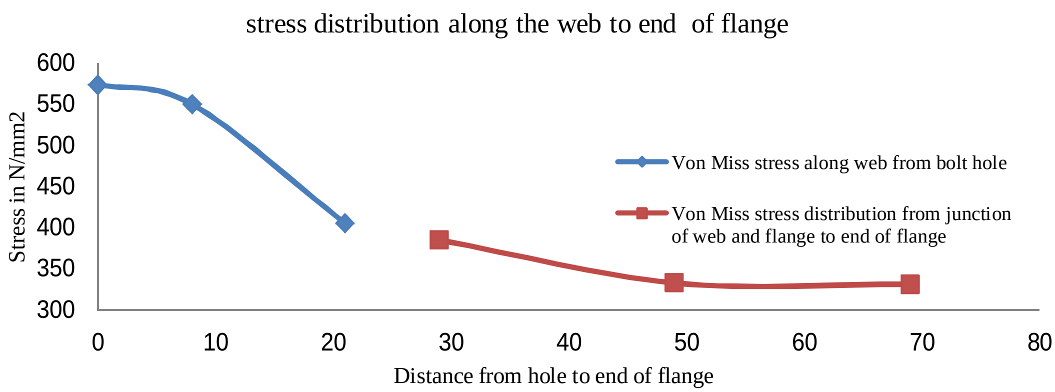

Fig. 3(a) Stress distribution along the web to end of the flange

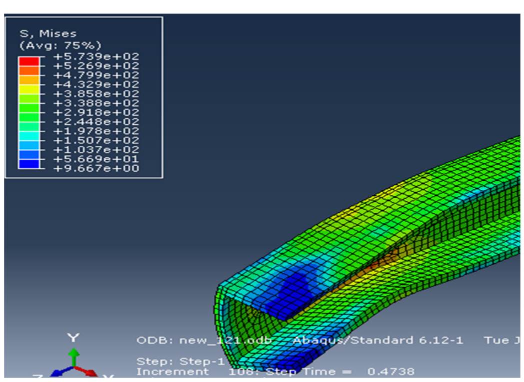

Fig.3(b) Bending deformation of the Section

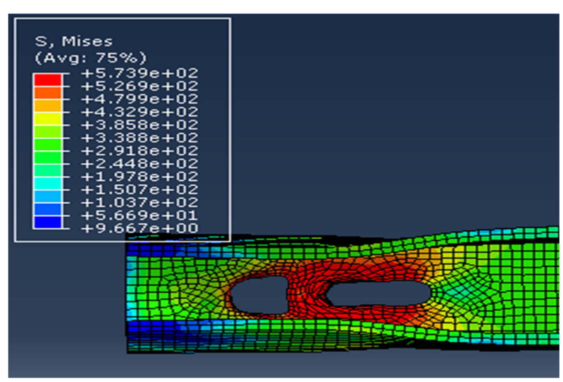

Fig3(c) Showing the stress along the Net section due to eccentricity

B. Validation of FEM Models

TABLE II. STRENGTH PREDICTION USING FEM ANALYSIS AND ITS PERCENTAGE ERROR

SPECIMEN	EXP. (kN)	FEM MODELLING (kN)	CODAL PREDICTION (kN)	DIFFERENCE WITH FEM MODEL(in%)	DIFFERENCE WITH IS CODE(in %)
A122	212.58	202	252.66	-4.97	18.85
A132	297	325	289.61	9.42	-2.48
A143*	337.51	322	298.65	-4.59	-11.51
A153*	337.36	340.497	304.60	0.92	-9.71
B222	265.55	250.025	293.79	-5.84	10.63
B232	340.65	322.36	293.79	-5.36	13.75
B242	385.92	408.29	374.70	5.79	-2.90
C234	526.50	493	499.85	-6.36	-5.06
C224	435.51	414.6	379.85	-4.80	-12.77
C244	599.29	565.5	539.85	-5.63	-9.91

From the Table II we can see that the average error in FEM models is 5.3% only. Hence we can conclude that the modeled section is valid for further parametric studies on the channel sections.

IV. PARAMETRIC STUDIES

A. Length of connection

The effect of increasing the number of bolts in single row sections on100mm sections and 125 mm sections are studied keeping the end and pitch as constant. The numerical strength prediction along with IS codal prediction and AISC code prediction for the increase in the number of bolts is given in Table III.

TABLE III. CODAL PREDICTIONS AND FEM PREDICTION ON INCREASING THE LENGTH OF CONNECTION

SPECIMEN	SECTION	NUMBER OF BOLTS	FEM PREDICTION (kN)	IS CODAL PREDICTION (kN)	AISC CODAL PREDICTION (kN)
B121	100x50x 5x7.5	2	265.44	326.319	253.0053
B131	100x50x5x7.5	3	315.48	398.54	312.1946
B141	100x50x 5x7.5	4	326.00	422.622	331.9243
C121	125 x 65 x 6 x 8	2	297.65	468.394	341.7892
C131	125 x 65 x 6 x 8	3	337.26	530.867	347.7082
C141	125 x 65 x 6 x 8	4	445.00	581.56	351.6541

It can be seen that on increasing the number of bolts from two to four (A122 to A142) the strength increases significantly and on further increasing the length of connection the strength of the section saturates. This is due to the increase in stress on the flange on increasing the length of connection, and this can be seen from stress distribution along the flange on (75x40x5x7) channel sections as shown in Fig. 4.

B. Effect of change in gauge

The 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. When the gauge of the section is increased, it is found that from FEM modeling that there is significant increase in the strength of the member but this aspect is not considered effectively in the IS code, as it only shows small increase in the prediction, where as in AISC code there is no change in the predicted strength with change in gauge.

This can be attributed to the increase in stress distribution in the flange part on increasing the gauge due to the reduction in eccentricity. Hence in this case flange is more stressed than with reduced gauge. This can also be seen in the following graph (Fig. 5).

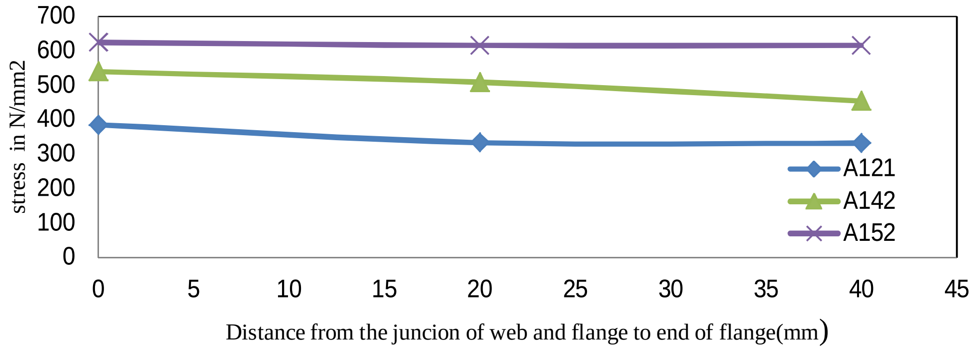

Fig.4 Stress distribution on the flange with increase in length of connection

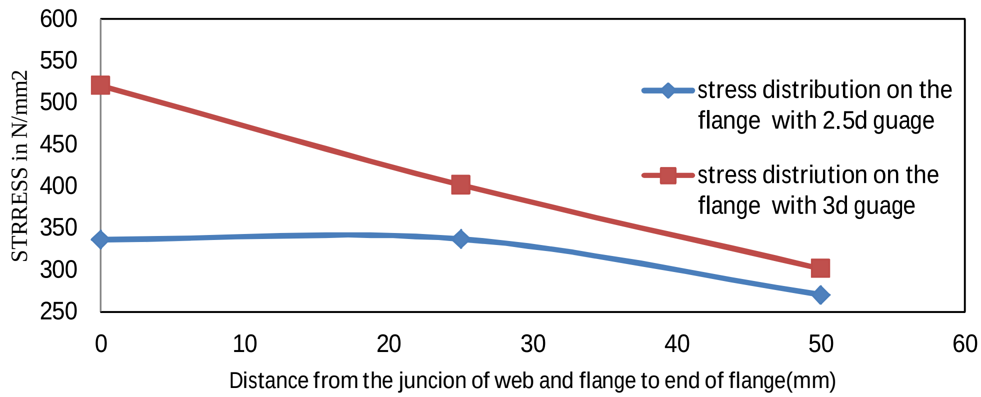

Fig. 5 Effect of change in gauge on the stress distribution of the flange

Considering the change in gauge as the influencing parameter on the strength, four sections of B232,B242,C235,C245 have been modeled but with only change in the gauge length and keeping all other parameters and material properties as constant. The predicted values along with the IS codal and AISC code prediction are shown in the Table 4.In the table #refers to 20 mm diameter bolt.

TABLE IV. CODAL PREDICTIONS AND FEM PREDICTION ON CHANGING THE GAUGE LENGTH

SECTION	PITCH	GAUGE	CODAL PREDICTION(kN)	FEM PREDICTION(kN)	AISC(kN)
B232	3	2.3	360.06	336.78	340.6523
B232#	3	3	364.171	357	340.6523
B242	3	2.3	378.43	408.29	385.9254
B242#	3	3	381.16	396.706	385.9254
C235	3	3	496.674	472	472.842
C235#	3	2.5	490.46	416.78	472.842
C245	3	3	536	555	559.4153
C245#	3	2.5	532	511	559.4153

V. EQUATION FOR THE PREDICTION OF STRENGTH OF THE CHANNEL SECTION

Apart from the above parameters, various other parameters are considered to be affecting the strength of the section they are given as follows

a) Ratio of unconnected area to that of connected area of the section$\left(\frac{A_f}{A_{nc}}\right)$
b) Effect of eccentricity of the section in the form of (x/l)
c) Ratio of edge distance to that of width of the flange (e/w)
d) Ratio of moment of inertia of the total section to that of moment of inertia of the flanges about minor axis (I_t/I_f)

e) Effect of gauge in the form of (1+g/w) where g represents the gauge length and w represents the depth of the web.

Considering all the parameters given above, an equation for strength is obtained using regression analysis as shown below (Eq.5)

$$P_u = 0.9 \times f_u \times A_{nc} + \beta \times A_{go} \times \left(\frac{f_u + f_y}{2}\right) \quad (5)$$

Where the predicted beta (β) is a function of alpha (α) (Eq.6)

$$\beta = 1.383 - 0.739 \times \alpha \quad (6)$$

Where

$$\alpha = \sqrt{\frac{e}{w} \times \frac{X}{L} \times \frac{I_t}{I_f}} \times \left(1 + \frac{A_f}{A_{nc}}\right) \times \left(1 + \frac{g}{w}\right) \quad (7)$$

This predicted beta (β) is obtained through a correlation between the alpha(α) obtained using Eq.7 and the experimental beta (B_{exp}) given as below (Eq.9)

$$P_{0(\exp)} = P_{u(\exp)} - (0.9 \times A_{nc} \times f_u) \quad (8)$$

$$\beta_{exp} = P_{o(\exp)} / \left(A_{go} \times \left(\frac{f_u + f_y}{2}\right)\right) \quad (9)$$

Where $P_{u(exp)}$ = Experimental capacity of the section
$P_{o(exp)}$ = Experimental capacity of the outstanding leg
β_{exp} = experimental value of beta
A_{nc} = net area of connected leg
A_{go} = gross area of outstanding leg
f_u, f_y = ultimate strength ,yield strength of the section

The correlation between β_{exp} and α is obtained as 88.5%, and hence the equation for β is calculated using Eq-6.

With this equation of $\beta_{predicted}$, the ultimate load taken by the section is calculated using Eq-5, and the comparisons of predicted value is made with the experimental values and plotted as shown below (Fig. 6).

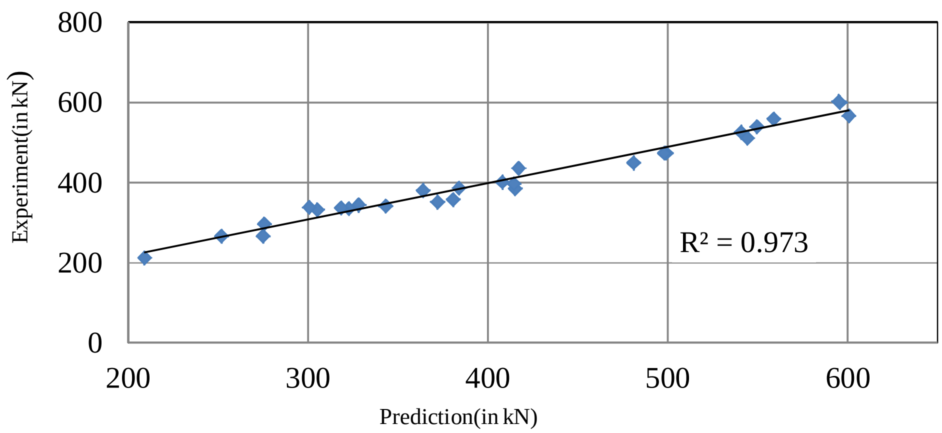

Fig.6 Comparison of predicted strength based on form 1 (Eq. 6.4) with experimental strength

As we can see from Fig .6 that the correlation between strength to that of experimental strength is 97.3%, and hence the prediction is good enough.

Alternatively another equation is also found to be predicting accurately which is given by (Eq.10)

$$P_u = 0.9 \times f_u \times A_{nc} + \beta \times A_{go} \times (f_u + f_y)/2 \quad (10)$$

And β is obtained as (Eq-11)

$$\beta = 1.588 - 2.754\,\alpha \quad (11)$$

where $$\alpha = \sqrt{\frac{e}{w} \times \frac{X}{L} \times \frac{I_t}{I_f}} \times \frac{f_y}{f_u} \times \left(1 + \frac{g}{w}\right) \quad (12)$$

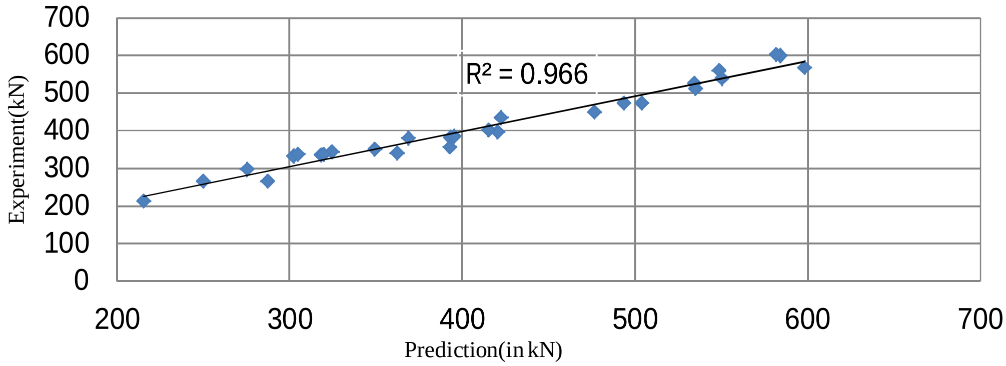

Fig.7 Comparison of predicted strength based on form 2 (Eq-10) with experimental strength

TABLE V. COMPARISON OF PREDICTED STRENGTH OF DIFFERENT CHANNEL SPECIMENS WITH IS CODE AND AISC CODE

Specimen ID	Exp. (kN)	Prediction (Eq.5) (kN)	% Error (in prediction)	IS code (kN)	IS code % error	AISC code (kN)	AISC code % error
A122	212.58	207.18	-2.54	261.49	23.01	258.87	21.77
A132	296.90	274.05	-7.70	294.05	-0.96	307.18	3.46
A142	331.92	303.84	-8.46	304.97	-8.12	323.39	-2.57
A143*	337.51	299.31	-11.32	302.03	-10.51	320.36	-5.08
A151	344.38	326.84	-5.09	321.86	-6.54	343.50	-0.26
A152	335.75	321.60	-4.21	310.43	-7.54	331.49	-1.27
A153*	337.37	317.30	-5.95	307.19	-8.94	328.04	-2.76
B121	265.44	275.30	3.71	322.91	21.65	330.59	24.55
B131	352.00	372.15	5.73	393.10	11.68	414.36	17.72
B141	385.00	415.06	7.81	416.50	8.18	442.29	14.88
B222	265.56	252.14	-5.05	320.59	20.72	300.58	13.19
B232	340.65	343.47	0.83	367.88	7.99	376.75	10.60
B232#	357.00	380.67	6.63	364.17	2.01	376.74	5.53
B242	385.93	383.92	-0.52	383.64	-0.59	402.13	4.20
B242#	396.71	414.30	4.44	386.38	-2.60	402.13	1.37
B251	401.18	408.04	1.71	391.52	-2.41	414.83	3.40
C224	435.51	419.35	-3.71	424.02	-2.64	396.13	-9.04
C225	380.92	366.67	-3.74	403.33	5.88	389.43	2.23
C234	526.50	542.29	3.00	521.94	-0.87	540.97	2.75
C235	472.84	500.88	5.93	509.20	7.69	531.82	12.47
C235#	450.00	482.66	7.26	502.99	11.77	531.82	18.18
C237*	473.33	499.47	5.52	505.01	6.69	525.78	11.08
C244	599.29	596.75	-0.42	554.58	-7.46	589.25	-1.68
C245	559.42	560.34	0.17	544.49	-2.67	579.28	3.55
C245#	511.00	545.46	6.74	540.34	5.74	579.28	13.36
C247*	539.35	550.76	2.11	533.71	-1.05	561.41	4.09
C251	602.82	596.05	-1.12	562.18	-6.74	603.02	0.03
C252*	566.87	601.60	6.13	566.25	-0.11	598.49	5.58
RMS Error (%)			5.30		9.44		10.27

Hence the predicted equation gives better results than AISC and IS code as it has an error of only about 5.3% where as IS code has an error of 9.44% and AISC code has an error of 10.27%.

The comparison of predicted equation with IS code and AISC code with varying length of connection is given below (Fig.8).It can be seen from the graphs that as we increase the length of connection, strength of the section increases initially and as we further increase the length of connection, strength of the section almost saturates.

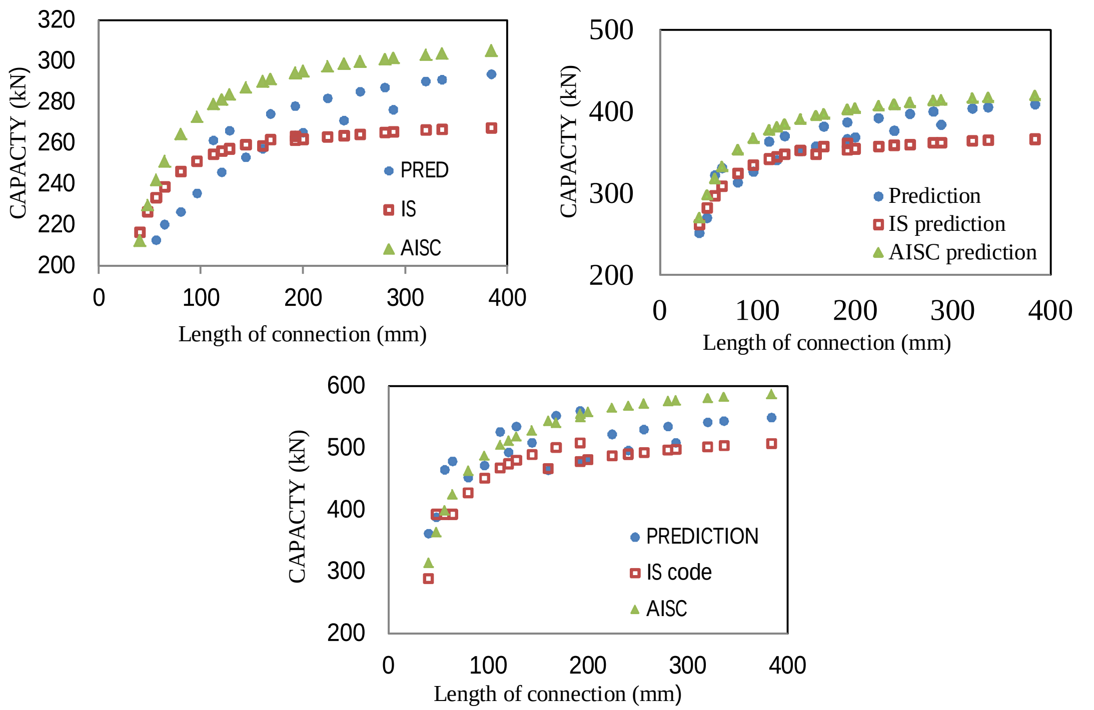

Fig. 8 a) Variation of prediction on increasing the length of connection for ISMC 75, b)Variation of prediction on increasing the length of connection for ISMC100, c) Variation of prediction on increasing the length of connection for ISMC125

VI. Conclusions

Experimental values on the strength of channel sections are taken from the literature and different International codal predictions for these sections are compared and it was found that IS code prediction is having an error of about 9 % and as AISC code is having an error of 8% where as EURO CODE has having an error of about 55% which is too economical in its prediction.

All the models have been validated using ABAQUS software on comparing with the experimental results from literature. Hence parametric studies are conducted using FEA. Based on the experimental results and results from validated models, and considering the factors affecting the strength, two forms of equations have been proposed.

This predicted equation is compared with the experimental results and it was found that it has an error of only 5% as compared to IS code which has an error of 9% and AISC has an error of 10%.

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