Jurnal Teknologi

Full paper

Mechanical Properties Prediction for Cold-formed Steel Angle Connection with Various Flange Cleat Thickness

Yeong Huei Lee, Cher Siang Tan*, Shahrin Mohammad, Yee Ling Lee

Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author: tcsiang@utm.my

Article history

Received: 10 November 2014
Received in revised form:
23 January 2015
Accepted: 12 April 2015

Graphical abstract

Abstract

Connection is an important element in structural steelwork construction. Eurocode does not provide adequate design information for mechanical properties prediction of top-seat flange cleat connection, especially for thin-walled cold-formed steel structures. Adopting hot-rolled design with neglecting thin-walled behaviour could lead to unsafe or uneconomic design. This research aims to provide accurate mechanical properties prediction for bolted top-seat flange cleat connection in cold-formed steel structures. The scope of work focuses on the effect of various thickness of the flange cleat to the rotational stiffness and strength behaviour of a beam-to-column connection. Experimentally verified and validated finite element modelling technique is applied in the parametric investigation. Two categories of flange cleat thickness, ranged from 2 mm to 40 mm are studied. From the developed numerical models, it is observed that Eurocode has overestimated the initial rotational stiffness prediction, calculated with component method. The over-estimation would influence the overall stiffness of structures and force distribution within the components. As a conclusion, a set of newly proposed accurate predictions for initial rotational stiffness and strength of cold-formed steel top-seat flange cleat connection, with the influence of the thickness of flange cleat is presented.

Keywords: Angle connection; mechanical properties; finite element analysis; cold-formed steel; Eurocode

■1.0 INTRODUCTION

Connection is an important element in structural steelwork construction, where they can account up to 50% of the total value of a hot-rolled steel structures[1]. The significant mechanical properties of connections are strength (load capacity), stiffness (rotation rigidity) and ductility (deformation capacity). Eurocode BS EN 1993 part 1.8 (hereby addressed as EC3-1-8)[2] provides detailed calculation of mechanical properties for three common beam-to-column connection typologies, namely welded connections, bolted end-plate connections and bolted top-seat angle connections. These mechanical properties prediction of connection are based on hot-rolled steel structures using component method. The code does not provide adequate information for thin-walled cold-formed steel structures. Several recent research studied on the welded connections[3-7]. Sometimes the heat from welding may alter the galvanised coating and the strength of thin core steel for cold-formed sections[7]. In order to avoid welding process, simple configuration of bolted top-seat flange cleat connection, as shown in Figure 1 is one of the connection alternatives.

Component method was used to determine cold-formed connections characteristics for the performance of ridge and eaves joints of portal frames with pitched roof under monotonic and cyclic loading[8]. This investigation ended with fair agreement between analytical and experimental results. Furthermore, Dubina and group investigated particular bolted connection with square hollow sections (SHS) column and back-to-back beams with component method[9]. Analytical calculation was compared with the calibrated finite element model. Moreover, the stiffness of trusses joints for cold-formed steel sections has been determined using experimental investigation[10]. The buckling length of web members was obtained with proposed theoretical model and hence validated by full-scale truss tests.

Prediction of structural behaviour for a building is an important procedure in order to increase the reliability of the structural design using current design code especially in joint design. Nevertheless, cost saving[11] by optimizing its performance also can be achieved after obtaining the reliable predicted structural behaviour.

Due to thin-walled behaviour of cold-formed steel, it may vary from EC3-1-8 design specification which concentrates on hot-rolled steel design. For an instant, the elementary beam theory cannot be applied for large deflection problem of a cantilever beam since the basic assumptions are no longer valid[12]. The elementary theory ignores the square of the first curvature derivation which neglects the shortening of the moment arm, bringing inadequacy for the large deflection that may greater than the beam length[12]. Besides that, the component method is calculated based on the yield line pattern that may not occur in cold-formed connection due to buckling will occur before the formation of yield lines.

In order to answer the problem induced from the large deflection phenomena of thin-walled structures, this paper presents an investigation on connection mechanical properties prediction with variable flange cleat thickness for bolted cold-formed steel top-seat flange cleat connection.

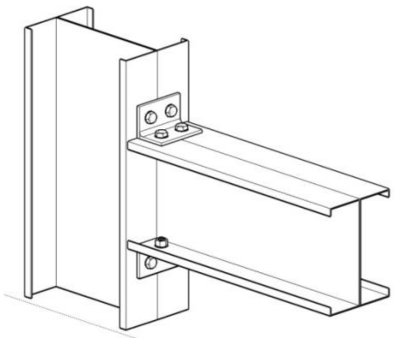

Figure 1 Top-seat flange cleat connection

2.0 INVESTIGATION MODELS

2.1 Eurocode Prediction

Top-seat flange cleat connection is analysed in accordance to the mechanical model given in EC3-1-8, which is the referred benchmark model in this investigation. The design resistance of the connection is calculated based on component method. EC3-1-8 has provided the calculation procedures to obtain the component resistances in term of strength and stiffness.

The component resistances include bolt tension resistance, bending resistance of flange cleat, bending resistance of column flange, transverse tension resistance of column web, compression resistance of beam and column flange, compression resistance of beam and column web as well as shear resistance.

For bolted connections, there are three potential failure modes, namely mode 1 complete flange yielding, mode 2 bolt failure with flange yielding and mode 3 bolt failure[2]. Since the bolt design is relatively thicker and stronger than cold-formed steel sections, mode 1 failure is most likely occurred in the cold-formed steel connection.

The failure mode of particular connection is calculated based on the yield line pattern for equivalent T-stub. The patterns divided into circular and non-circular yield lines. The resistance calculation is according to effective lengths from the yield line patterns. For cold-formed design, buckling may occur before the formation of these yield line patterns.

A moment-rotation curve is plotted with the calculated connection moment resistance. The maximum strength is achieved according to the weakest component resistance. For conservative design, Eurocode has limited the model to behave as elasto-plastic with no strain hardening characteristic.

Figure 2 shows the dimension details of built-up beam and column using channel sections. The cleats dimensions are documented[13-16]. The bended flange cleat and column flange are the failure that most likely to occur for the developed connection with respect to EC3-1-8 structural prediction.

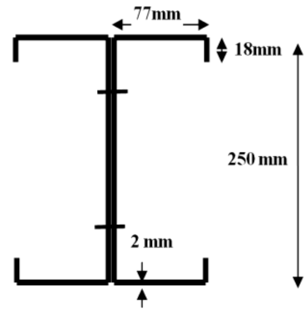

Figure 2 Dimension details for the built-up section of beam and column

2.2 Fyre-Morris Model

Several mathematical representations were developed for hot-rolled angle connections: single web cleat connection, double web cleat connection, top-seat flange cleat connection and combined web cleat and flange cleat connection. For top-seat flange cleat connection, Frye and Morris[17,18] developed a mathematical model with polynomial equations, based on Sommer's equation[19], that used the least square method for determining the polynomial constant. It was the first mathematical model for the connection.

Fyre-Morris model was developed in year 1975 which is used for the comparison in this investigation. The comparison of this model with other investigation models is to determine the suitability of developed polynomial equations in adopting in cold-formed steel design. Equation 1 and 2 shows the moment-rotation prediction by Fyre and Morris.

$$\theta_r = C_1(kM) + C_2(kM)^3 + C_3(kM)^5 \quad ...(1)$$

where,
K is the connection stiffness
M is the moment obtained
θ is the connection rotation
C is the curve-fitting constants

$$k_{Fyre} = 2.14 \times 10^{-4} t_f^{-0.5} h^{-1.5} d^{-1.1} l^{0.7} \quad ...(2)$$

where,
k_{Fyre} is the stiffness proposed by Fyre & Morris
t_f is the flange cleat thickness
h is the beam depth
d is the diameter of the bolt hole
l is the length of flange cleat

2.3 Experimental Study

The experimental study is divided into material characteristic investigation and full-scaled isolated joint test. These experimental models were developed for the validation with the finite element model.

2.3.1 Material Characteristic Study

All cold-formed steel channel sections used in the experimental investigation were 2 mm in thickness and with steel grade 350 N/mm^2. Non-preloaded bolt of M12 grade 8.8 was applied throughout the testing[13].

Tensile tests were conducted to determine the material properties of the cold-formed steel in accordance to Eurocode BS

EN 10002-1[20]. The steel coupon samples were cut into "bone" shape as shown in Figure 3.

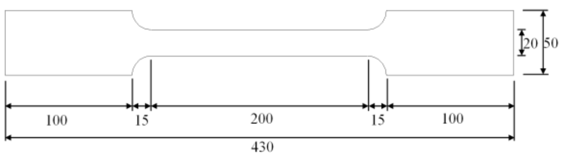

Figure 3 Specimen dimension details (in mm) of tensile test for beam and column sections[15]

2.3.2 Isolated Joint Test

A series of six isolated joint tests for top-seat flange cleat connection is carried out at Laboratory of Structures and Materials, Universiti Teknologi Malaysia. The tests aim to investigate the actual structural performance of cold-formed steel top-seat flange cleat connection under ultimate limit state. Figure 4 shows the experimental setting up.

Figure 4 Experimental setting up

The 2 mm thickness cold-formed lipped C-sections were assembled back-to-back to form I-shape beam and column. The 1.5 m I-beam was placed at 2 mm gap from column flange and the centre of 3 m length column. The column and beam were connected with flange cleats. The same length of flange cleat and same size of bolt were used to accommodate the limited space between connected members of the flange, as well as to satisfy the minimum end bearing distance.

The load was applied at the distance of 1 m from column flange onto the beam flange uniformly using hydraulic jack. The deflection was measured under the loading point and the rotations of beam and column were also placed at determined locations. The data acquisition system was shown in Figure 5.

The test was initialled with settlement of model where load was controlled to 25% of calculated design load and released to zero setting[13]. This process was completed to avoid ineffective loading-carrying characteristic which can affect the stiffness and strength of the connection. The load was applied to the model with constant rate and deflection and rotation were recorded until failure occurred.

2.4 Numerical Investigation

Experiment investigation on full-scale steel structures involves high cost. Thus FEM has become one of the alternatives to perform parametric study in order to understand the structural performance of the top-seat flange cleat connection. Moment-rotation behaviour is a good character to represent the stiffness and strength behaviour of connection and it is used for the comparison between experimental, numerical and analytical models. The dimension details for cold-formed top-seat flange cleat connection has been described earlier[13-16].

Before the parametric study was carried out, the modelling technique should be verified and validated in order to obtain a reliable model. The controlled deflection analysis also will be performed to recognize the separated component deflections which contribute to overall structural deformation.

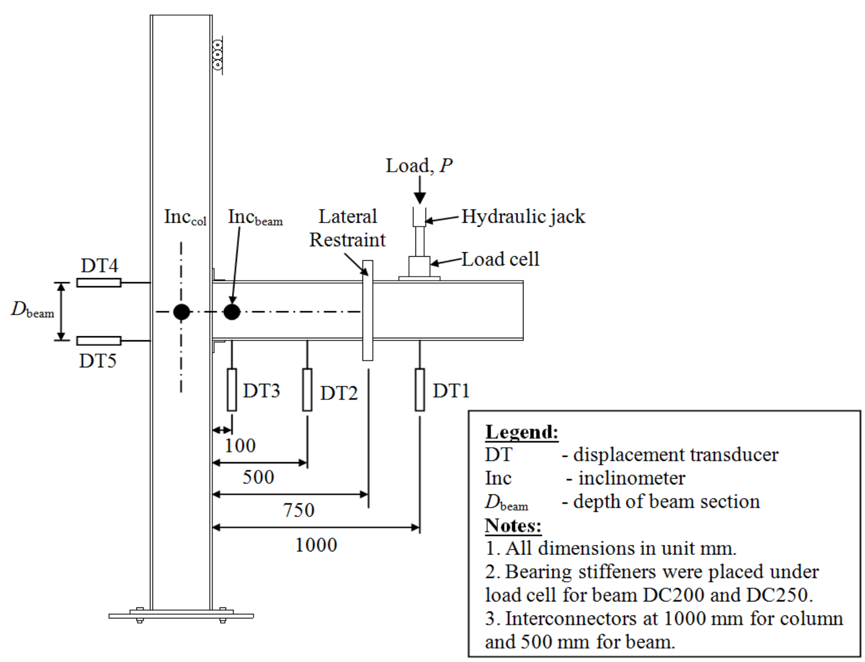

Figure 5 Locations of data acquisition system

2.4.1 Verification of FEM Model

Verification of FEM model with EC3-1-8 is carried out for solving mathematical problems. Convergence study is made from the perspectives of geometry and meshing in order to optimise the developed finite element models.

Thin-walled behaviour of cold-formed steel structures may not follow the linear geometric analysis due to lower stiffness or experience instability which may contribute the large deflection to its deformed shape. In order to fulfil the actual thin-walled behaviour, geometric quadratic analysis is applied in the finite element models which results better agreement with EC3-1-8 benchmark model.

There is a significant gap between EC3-1-8 model and FEM model at the plastic region. This is due to EC3-1-8 model assumes failure at the first component and does not associate with other component. FEM model involves other components in the resistance after the failure of the first component, thus contributes to higher plastic resistance behaviour. As the connection is developed by several components, it is essential to include the interaction between the components. The FEM model can be accepted for further validation process[13,14] as the mathematical calculation of two models have similar curve of moment-rotation behaviour.

2.4.2 Validation of FEM Model

The validation process with experimental results is done to investigate the physical uncertainties such as errors removal and uncertainties evaluation. A good agreement has been achieved between finite element model and experimental data. There was a closed comparison with differences less than 10% and similar failure observation from the two developed models[13,14].

2.4.3 Controlled Rotation Study

Since there are several components that contribute to the structural behaviour of the cold-formed top-seat flange cleat connection, the rotation of these components is investigated separately in order to understand the component resistances.

With exclusion of bolts component, there are three identified components in this study, namely beam, column and connectors. The investigated component will be assigned actual stiffness while other two components will be assigned thousand time stiffer value for each particular analysis.

In order to ensure this thousand time stiffer value was valid in the analysis, it has been tested with the failure load. The value was assigned to all components in the analysis and it was found that no deflection for this stiffer connection configuration. Therefore, the assumption of thousand time stiffer value is appropriate for the controlled rotation analysis that obtaining separated rotations from overall deformation.

■3.0 RESULTS AND DISCUSSIONS

3.1 EC3-1-8 Model

Eurocode benchmark model has shown accuracy in the failure mode prediction using component method. Hence, Eurocode component method is suitable to predict the failure mode of cold-formed steel top-seat flange cleat connection.

From the analysis, it was realized that the thickness of the components is affecting the structural performance of the top-seat flange cleat connection. From the equation 3[2], component thickness, t is one of the parameters that giving great influence to the initial rotational stiffness prediction of the connection. As the thickness increased, it will greatly affect the initial rotational stiffness of connections. Thus the flange cleat thickness is the primary investigating parameter in this study.

On the other hand, Eurocode shows inadequacy in the initial rotational stiffness and strength prediction. A corrected proposal needed to be developed in order to obtain reliable results in predicting the structural behaviour of the developed connection.

$$k = \frac{0.9 l_{eff} t_f^3}{m^3} \quad \text{... (3)}$$

where,
k is the stiffness coefficient
l_{eff} is the effective length of equivalent T-stub
t_f is the thickness of flange cleat
m is the edge distance from bolt to corner

3.2 Fyre-Morris Model

The developed models using equations 1 and 2 were not provide the detail of the failure mode. The parameters that included in the model were flange cleat thickness, beam depth, diameter of bolt hole and length of the flange cleat.

The calculated values can only represent the moment-rotation behaviour of the connection. The structural initial rotational stiffness and strength prediction by Fyre-Morris model has been tabulated in Table 1 and 2.

3.3 Experimental Model

In material characteristic study, all tested samples yielded above the design strength requirement of 350 N/mm^2. The actual yield stresses were inserted into finite element model to mimic the actual material behaviour.

For isolated joint tests, there were two identified failure modes among stated failure modes from component method that observed from the experimental study, namely bending of the flange cleat and bending of column flange. Figure 6 and 7 show the failure modes of the top-seat flange cleat connection. As the thickness of the flange cleat increases from 2 mm to 6 mm, the failure mode position changed from the flange cleat at top to column flange.

Figure 6 Failure mode for 2 mm thickness of flange cleat which is flange cleat in bending

Figure 7 Failure mode for 6 mm thickness of flange cleat which is column flange in bending

For comparison with experimental specimens, EC3-1-8 benchmarked models have shown accuracy in the failure mode prediction. However, there is a significant gap in the calculated initial rotational stiffness and strength from EC3-1-8 component method[2].

3.4 Numerical Model

Numerical analysis using finite element method with static solver, material nonlinearity, half simulation, geometric nonlinearity, well-defined boundary condition and loading are suitable for the top-seat flange cleat connection structural analysis. The mesh size can be varied to accommodate the maximum applied loads and minimize the possible occurred errors.

With the verified and validated modelling technique[14], controlled rotation analysis was done to identify the components rotation that contributed to the overall deformed shape. It was found that all components are involved in the structural performance of the top-seat flange cleat connection. From the equation 3[2], the thickness of the flange cleat has contributed one of the major effect to the performance since thickness will affect the initial rotational stiffness and strength of the connection. There was a limitation in the dimension of the flange cleat since it needs to fulfil the dimensions of interacted section.

From the controlled rotation analysis as shown in Figure 8 and Figure 9, all components (beam, column and connector) contribute rotations to the overall structure.

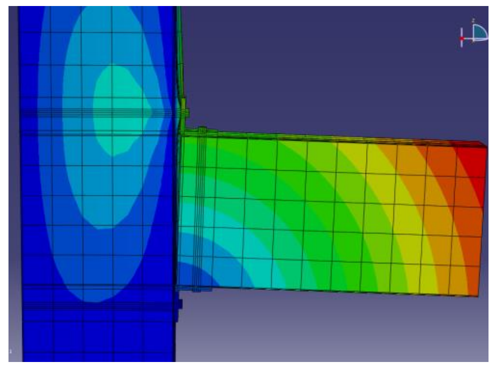

Figure 8 The deflection contour with flange cleat as reaction variable at peak load

Table 1 Initial rotational stiffness of cold-formed top-seat flange cleat connection

Thickness of flange cleat, t_f, mm	Stiffness, kNm / Rad			Ratio	
	Eurocode, $k_{e,EC}$	FEM, $k_{e,FEM}$	Frye, $k_{e,Fyre}$	$k_{e,FEM}$ / $k_{e,EC}$	$k_{e,Fyre}$ / $k_{e,EC}$
2	74	84.8	5.8	1.15	0.08
3	195	137.6	7.1	0.71	0.04
4	322	166.1	8.3	0.52	0.03
5	418	189.4	9.2	0.45	0.02
6	428	208.1	10.1	0.49	0.02
7	524	216.8	10.9	0.41	0.02
8	553	223.2	11.7	0.40	0.02
9	574	236.8	12.4	0.41	0.02
10	589	246.5	13.1	0.42	0.02
11	601	252.3	13.7	0.42	0.02
12	610	252.3	14.3	0.41	0.02

Table 2 Ultimate strength of cold-formed top-seat flange cleat connection at 0.05 Rad rotation

Thickness of flange cleat, t_f, mm	Strength, kNm			Ratio	
	Eurocode, $M_{j,EC}$	FEM, $M_{j,FEM}$	Frye, $M_{j,Fyre}$	$M_{j,FEM}$ / $M_{j,EC}$	$M_{j,Fyre}$ / $M_{j,EC}$
2	0.62	1.81	37.5	2.9	60.5
3	1.42	3.45	45.9	2.4	32.3
4	2.57	4.56	52.9	1.8	20.6
5	2.66	5.21	59.2	2.0	22.3
6	2.66	5.69	64.8	2.1	24.4
7	2.66	5.75	70.0	2.2	26.3
8	2.66	6.23	74.8	2.3	28.1
9	2.66	6.30	79.4	2.4	29.8
10	2.66	6.55	83.6	2.5	31.4
11	2.66	6.70	87.7	2.5	33.0
12	2.66	6.70	91.7	2.5	34.5

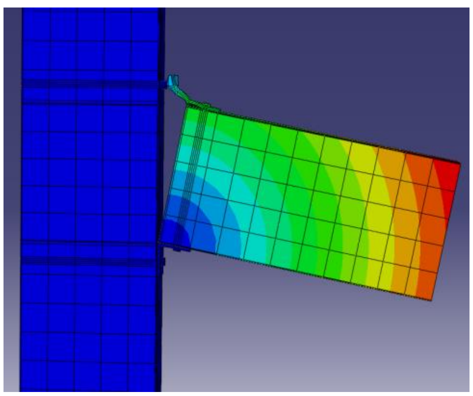

Figure 9 The deflection contour with column as reaction variable at peak load

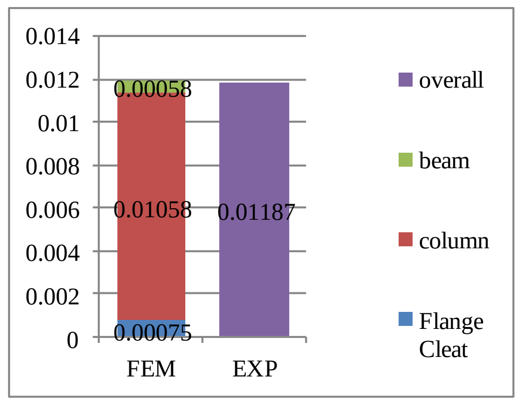

Figure 10 The component rotations (in Rad) at 4 kNm for finite element analysis and experimental investigation

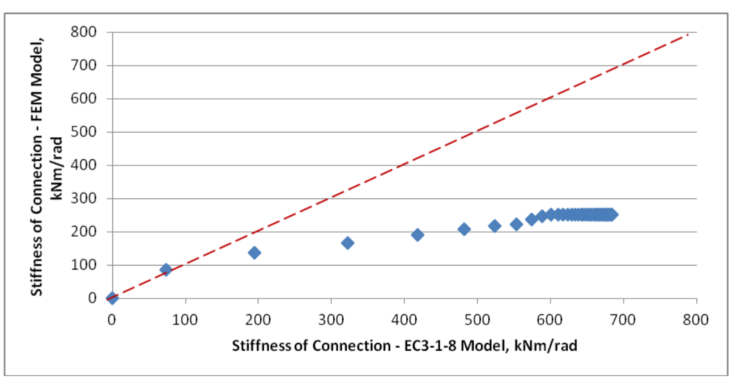

Figure 11 Graph for initial rotational stiffness prediction with flange cleat thickness ranged from 2 to 40 mm

The rotations were then compared to overall deflection from the experimental investigation as shown in Figure 10. The overall rotation from finite element model is 0.01191 Rad while the experimental rotation is 0.01187 Rad. According to the controlled rotation analysis, for 6 mm thickness flange cleat and at 4 kNm deformed shape, the rotations are 0.00075 Rad due to flange cleat, 0.01058 Rad of column deformation and 0.00058 Rad contributed by beam component.

Among the two possible failure modes (flange cleat in bending and column flange in bending), the high deflection was contributed by the component that have thinner thickness of these components. Hence, the flange cleat thickness is taken as the investigation variable to understand its structural performance.

4.0 MECHANICAL PROPERTIES

4.1 Connection Rotational Stiffness Prediction

A series of FEM model has been developed with various flange cleat thickness which can provide a comprehensive structural behaviour of cold-formed steel top-seat flange cleat connection with various flange cleat thickness as the investigation variable.

According to the Figure 11, with the reference line of unity, Eurocode initial rotational stiffness prediction has a closed comparison with the FEM model on 2 mm flange cleat thickness connection. Eurocode prediction deviated from unity line and caused the problem of overestimation for connection stiffness which may lead to inadequacy in engineering design.

Table 1 shows the initial rotational stiffness results predicted from EC3-1-8 models, Fyre-Morris models, experimental models and FEM models. For initial rotational stiffness prediction, the differences between Eurocode and FEM models are ranged from 15% to 60%. These differences are due to the thin-walled behaviour of cold-formed steel. The ratio almost become constant after 6 mm flange cleat thickness due to the reduction of thin-walled characteristic effect. Hence, the significant discrepancy has been contributed by the large deflection of thin-walled behaviour as the thickness reduced.

In addition, Fyre-Morris models[17,18] were developed for comparison. Fyre-Morris model showed almost 100% differences for flange cleat thickness from 2 mm to 11 mm which is not suitable in adopting to the cold-formed steel top-seat flange cleat connection design.

From the observation, with conservative design of Eurocode, an improvement in predicting the stiffness has been developed over decades. Depicting the development, the accuracy of structural behaviour prediction for cold-formed steel yet to be confirmed with a massive research program in order to increase the reliability of constructed model.

Throughout the analysis, for 2 mm section thickness of cold-formed beam and column, the optimum flange cleat thickness is 11 mm. Any further increment in flange cleat thickness after 11 mm will not give changes in connection initial rotational stiffness. However, Eurocode shows a different initial rotational stiffness prediction as it will increase in a slow rate after optimum design has been achieved while the initial rotational stiffness prediction from finite element analysis remains unchanged. Since there is no limitation for Eurocode stiffness prediction, the connection will behave as a phenomenon which the stiffness will increase continuously with the increment of flange cleat thickness.

For initial rotational stiffness prediction, there are two range of data can be observed throughout the investigation. The first set data was collected from the initial rotational stiffness with flange cleat thickness of 2 mm to 11 mm which finite element model will remain the same initial rotational stiffness with continuously increment of flange cleat thickness, as shown in Figure 12. The second set of data was obtained from the flange cleat thickness ranged from 12 mm to 40 mm after optimum flange cleat thickness was achieved from FEM models, as shown in Figure 13. Although 40 mm thickness is not practical, it is necessary to investigate for the behaviour after optimization. With the FEM models, the correction factor can be obtained from the Figure 12 and 13 with assumed that initial rotational stiffness from FEM model is the proposed connection initial rotational stiffness.

Moving through the two ranges of results, there are three newly defined proposals of connection initial rotational stiffness and strength prediction for the design of top-seat flange cleat connection in light steel framing. For the flange cleat thickness ranged from 2 mm to 11 mm, the proposed equation is shown in Eq 4.

$$\frac{k_{e,new}}{k_{e,EC}} = -0.0041\,t_f^3 + 0.098\,t_f^2 - 0.7502\,t_f + 2.2446 \qquad ...(4)$$

where
$k_{e,new}$ is the new proposed initial rotational stiffness
$k_{e,EC}$ is the initial rotational stiffness prediction from Eurocode
t_f is the flange cleat thickness, for $2 \le t_f \le 11$

For 12 mm to 40 mm flange cleat thickness, the connection initial rotational stiffness relation between Eurocode and proposed initial rotational stiffness can be described as Eq 5.

$$\frac{k_{e,new}}{k_{e,EC}} = 0.5073\,t_f^{-0.088} \qquad ...(5)$$

where
$k_{e,new}$ is the new proposed initial rotational stiffness
$k_{e,EC}$ is the initial rotational stiffness prediction from Eurocode
t_f is the flange cleat thickness, for $11 < t_f \le 40$

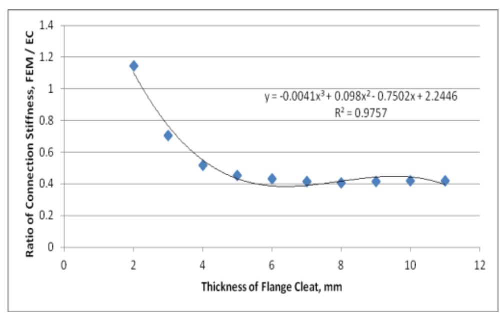

Figure 12 Initial rotational stiffness prediction with flange cleat thickness of 2 mm to 11 mm

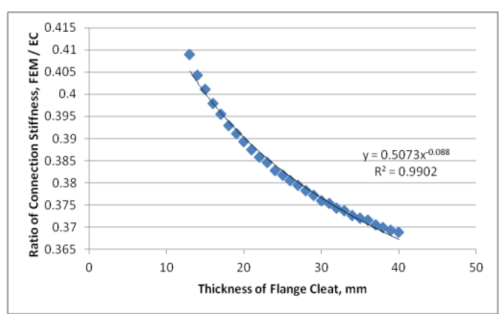

Figure 13 Initial rotational stiffness prediction with flange cleat thickness of 12 mm to 40 mm

4.2 Connection Strength Prediction

For a ductile connection, EC3-1-8 has limited the failure occurs on 0.03 Rad rotation. However, the 0.05 Rad has been recommended[21] for the finite rotation of cold-formed steel connection. The 0.05 Rad rotation is assumed to be the highest deformation and the strength at 0.05 Rad is used for the comparison between the investigation models. Any rotations after 0.05 Rad will treat as excessive deformation. Thus, the strength at 0.05 Rad rotation is the ultimate strength of the connection.

From Table 2, the percentage of difference for strength prediction at 0.05 Rad is ranged from 180% to 290% between finite element models and EC3-1-8 models. Furthermore, for the comparison between Frye-Morris models and EC3-1-8 models, the differences achieved the highest percentage according to Table 2. The ultimate strength prediction of Eurocode has shown a conservative value as the analysis is not included the strain hardening effect for cold-formed steel actual properties. Fyre-Morris equations has failed to predict the strength of the connection. Therefore, Fyre-Morris model is also not suitable for the strength prediction of the developed connection.

EC3-1-8 prediction has limited its strength to a constant after 5 mm thickness of flange cleat. Meanwhile, FEM model does indicate ultimate strength increment after 11 mm thickness of flange cleat. Since FEM and EC3-1-8 models has a constant value after 11 mm thickness of flange cleat, the investigation range is from 2 mm to 11 mm flange cleat thickness.

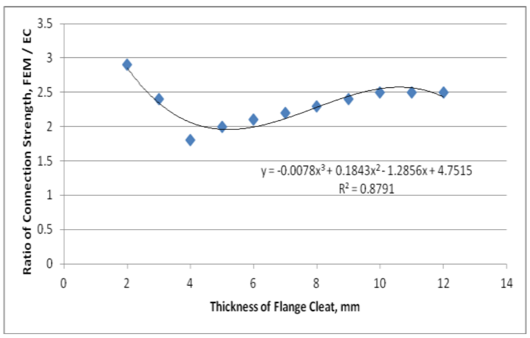

Figure 14 Ultimate strength prediction with flange cleat thickness of 2 mm to 11 mm

For ultimate strength prediction as in accordance to Figure 14, the proposed equation is given as Equation 6 for flange cleat thickness ranged from 2 mm to 11 mm.

$$\frac{M_{j,new}}{M_{j,EC}} = -0.0078\,t_f^3 + 0.1834\,t_f^2 - 1.2856\,t_f + 4.7515 \quad ...(6)$$

where
$M_{j,new}$ is the new proposed ultimate strength
$M_{j,EC}$ is the ultimate strength prediction from Eurocode
t_f is the flange cleat thickness, for $2 \leq t_f \leq 11$

For economical design of connection, Equation 4 and 6 are suggested to be applied in the design which has the ability to achieve the optimum results. The application of Equation 5 is meant for further structural behaviour investigation.

5.0 CONCLUSION

The influence of flange cleat thickness towards connection initial rotational stiffness and ultimate strength prediction is investigated. Verified and validated finite element modelling technique is applied in the development of models with various flange-cleat thicknesses. The results obtained from the analysis are compared with the mechanical properties calculated by using design specifications of Eurocode component method and Fyre-Morris polynomial equation.

Since the failure mode induced by large deflection for thin-walled structures is differed from yield line pattern of hot-rolled steel, overestimation of connection initial rotational stiffness prediction is found in the EC3-1-8 for cold-formed steel connection design. A new set of developed equations is proposed for cleat thickness range from 2 mm to 40 mm, with constant dimension for beam and column member. Nevertheless, the ultimate strength of the connection at 0.05 Rad rotation has been represented in a new polynomial equation with refer to Eurocode design.

For future study, there is a need to expand the current investigation for other variables in cold-formed steel flange-cleat connections, e.g. dimension of connected structural members, steel design strength, bolt hole location etc in order to compute a comprehensive and reliable design guides for practicing engineers in steel construction industry.

Acknowledgement

This research was funded by research grants from Universiti Teknologi Malaysia and Ministry of Eduction Malaysia (4F258 and 4F647) and Ministry of Education Malaysia (MOE). The technical and financial supports are gratefully acknowledged

References

[1] Fenster, S. M. C., Girardier, E. V. and Owens, G. W. 1992. Economic Design and the Importance of Standardized Connections. In: (Dowling PJ *et al*. Eds) *Constructional Steel Design: World Developments*. Elsevier Applied Science, U. K.
[2] British Standards Institution. 2005. Eurocode 3: Design of Steel Structures: Part 1.8: *Design of Joint*. BS EN 1993-1-8, (BSI, U. K.).
[3] Sehgal, R., Angra, S. and Sharma, V. 2007. Failure Cause Analysis of Welded Joints. *India Journal of Engineering and Materials Sciences*. 14: 24–30.
[4] Jeyakumar, M., Christopher, T., Narayanan, R. and Rao, B. N. 2011. Residual Stress Evaluation in Butt-welded Steel Plates. *India Journal of Engineering and Materials Sciences*. 18: 425–434.
[5] Teh, L. H. and Hancock, G. J. 2005. Strength of Welded Connections in G450 Sheet Steel. *ASCE Journal of Structural Engineering*. 131(10): 1561–1569.
[6] Landolfo, R., Mammana, O., Portioli, F., Di Lorenzo, G., and Guerrier M. R. 2009. Experimental Investigation on Laser Welded Connections for Built-up Cold-formed Steel Beams. *Journal of Constructional Steel Research*. 65: 196–208.
[7] Lee, Y. H., Tan, C. S., Mohammad, S., Tahir, M. M. and Shek, P. N. 2014. Review on Cold-formed Steel Connections. *The Scientific World Journal*. 11.
[8] Nagy, Z., Stratan, A. and Dubina, D. 2006. Application of Component Method for Bolted Cold-formed Steel Joints. Proceedings of the International Conference in Metal Structures-Steel-A New and Traditional Material for Building, Poiana Brasov. 207–215.
[9] Nagy, Z., Dubina, D. and Ungureanu V. 2011. Application of Component Method: Bolted Joints for Low Rise Multi Storey Cold-formed Steel Framed Structures. Eurosteel 2011-The 6th European Conference on Steel and Composite Structures, Budapest, Hungary. 273–278.
[10] Zaharia, R. and Dubina, Dan. 2006. Stiffness of Joints in Bolted Connected Cold-formed Steel Trusses. *Journal of Constructional Steel Research*. 62: 240–249.
[11] Basudhar, P. K., Dey, A. and Mondal, A. S. 2012. Optimal Cost-analysis and Design of Circular Footings. *International Journal of Engineering and Technology Innovation*. 2(4): 243–264.
[12] Bisshopp, K. E. and Drucker, D. C. 1945. Large Deflection of Cantilever Beams. *Quarterly of Applied Math*. 3(3): 272–275.
[13] Lee, Y. H., Tan, C. S., Tahir, M. M. and Mohammad, S. 2012. Numerical Modelling and Validation of Light Gauge Steel Top-seat Flange-cleat Connection. *Journal of Vibroengineering*. 14(3): 1104–1112.

[14] Tan, C. S., Lee, Y. H., Lee, Y. L., Mohammad, S., Sulaiman, A., Tahir, M. M. and Shek, P. N. 2013. Numerical Simulation of Cold-formed Steel Top-seat Flange Cleat Connection. *Jurnal Teknologi (Sciences and Engineering)*. 61(3): 63–71.

[15] Lee, Y. H., Tan, C. S., Lee, Y. L., Tahir, M. M., Mohammad, S., Shek, P. N. 2013. Numerical Modelling of Stiffness and Strength Behaviour of Top-seat Flange-cleat Connection for Cold-formed Double Channel Section. *Applied Mechanics and Materials*. 284–287: 1426–1430.

[16] Tan, C. S. 2009. Behaviour of Pin and Partial Strength Beam-to-Column Connection with Double Channel Cold-formed Steel Sections. PhD thesis, Universiti Teknologi Malaysia.

[17] Fyre, M. J. and Morris, G. A. 1975. Analysis of Flexibly Connected Steel Frames. *Canadian Journal of Civil Engineering*. 2(3): 280–291.

[18] Li, G. Q. and Li, J. J. 2007. *Advanced Analysis and Design of Steel Frames*. John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, England. 157.

[19] Sommer, W. H. 1969. Behaviour of Welded Header-plate Connection. Master Thesis, University of Toronto, Canada.

[20] British Standards Institution. 2001. *Tensile Testing of Metallic Material, Part 1*. BS EN 10002-1 (BSI, U.K.).

[21] Wong, M. F. and Chung, K. F. 2002. Structural Behaviour of Bolted Moment Connections in Cold-formed Steel Beam-column Sub-frames. *Journal of Constructional Steel Research*. 58: 253–274.