Scientia Iranica B (2015) 22(4), 1554–1566

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions B: Mechanical Engineering
www.scientiairanica.com

Numerical study of joint behaviour for top-seat flange cleat connection in cold-formed steel structures

Y.H. Lee[a,*], C.S. Tan[a], S. Mohammad[a], J.B.P. Lim[b] and R. Johnston[c]

a. *Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.*
b. *Department of Civil and Environmental Engineering, The University of Auckland, New Zealand.*
c. *School of Planning, Architecture and Civil Engineering, Queen's University Belfast, United Kingdom.*

Received 22 May 2014; received in revised form 12 November 2014; accepted 5 January 2015

KEYWORDS
Bolted connection;
Joint behaviour;
Cold-formed steel;
Light steel frame;
Stiffness;
Strength.

Abstract. The use of cold-formed steel for primary load bearing members in low and medium rise buildings has become an increasingly popular form of construction. The design of connections between these members is crucial to the overall structural integrity of such buildings. However, for beam-to-column joint design, recent codes of practice show ambiguity in the mechanical behaviour. Further research is required to investigate the strength, stiffness and ductility prediction of such connections. This paper addresses these concerns by proposing simplified formulas for the moment-rotation behaviour of light steel frames with bolted top-seat flange cleat joints. A finite element study is presented which is validated against laboratory experimental tests on cold-formed steel arrangements. The validated model is used within a parametrical study to investigate several additional geometrical parameters that are not included in the experimental works. An exponential equation has been proposed for large deformation of top-seat flange cleat joint under monotonic vertical load. The predictions using the equations are compared to the design codes (BS EN1993-1-8) and experimental data. From the comparison, the proposed equation can improve the BS EN1993-1-8 prediction from 168.08% difference, compared to experimental results, to 7.09% difference. The new proposed model gives a safe design for top-seat flange cleat joint in cold-formed steel light frame construction.

1. Introduction

Light steel frame system utilising cold-formed steel sections has become a popular form of construction in recent years. This is due to the economic and sustainability benefits. The cold-formed steel members can satisfy load bearing requirements, yet they are light weight as compared to hot-rolled steel. This saving in material weight and ease of construction means this form of construction is able to compete with traditional masonry and timber construction. Other benefits of cold-formed steel construction include durability, quality and speed of construction, design flexibility and cost savings. In addition, it is a sustainable form of construction, requiring smaller manufacturing plant, machinery and material resources. Cold-formed steel is also a recyclable material which can be reused or recycled after demolition of an obsolete building. Light steel frames are often used for medium-rise or low-rise residential buildings that have modest span. The frames of cold-formed steel buildings are suitable for off-site constructions, leading to reduced labour costs and time for site construction. Cold-formed steel structures also have simple bolts connections, compared to hot-rolled steel connections which can require larger connection costs due to welding. This

*. *Corresponding author.*
E-mail addresses: yhlee7@live.utm.my (Y.H. Lee); tcsiang@utm.my (C.S. Tan); shahrin@utm.my (S. Mohammad); james.lim@auckland.ac.nz (J.B.P. Lim); rjohnston29@qub.ac.uk (R. Johnston)

is an important factor when considering the benefits of cold-formed steel structures, as the cost of fabricating connections can account for approximately 50% of the total costs in steelwork construction [1].

Most of the codes and standards use the single fastener capacity method in the prediction of cold-formed steel joint structural behaviour. The component method in the Eurocodes considers the adjacent member capacity. This is more accurate for cold-formed steel design since failure may occur on the member (through buckling), rather than failure of the connection itself - this is due to the thin-walled nature of cold-formed steel sections. Therefore, the Eurocode is used in this investigation for joint design. For beam-to-column connections, there are three common types of connections that are suitable, namely, welded connection, bolted connection and screw connection. However, according to Wong (2002) [2], cold-formed steel sections with thickness less than 3.2 mm are not suitable for welding as the heat from the welding process will burn through the section. There is also a limitation on screw connections, where the thickness of thicker part should not exceed 12.7 mm (0.5 inch) [3] and the difficulty increases with higher steel grade of cold-formed steel. This is due to practical limitations and screw tapping characteristics. Bolted connection is another alternative for cold-formed steel beam-to-column connections in light steel frame. In BS EN1993 Part 1.8 (hereby addressed as BS EN1993-1-8) [4], there are two typical bolted joints that have been codified: end-plate connection and top-seat angle connection. Since the end-plate connection also needs welding process, it is therefore advisable to use top-seat angle connections in light steel frame design.

The top-seat flange cleat connection has a simple joint configuration and requires no welding, recommended by BS EN1993-1-8 [4]. The behaviour of top-seat flange cleat connections using hot-rolled steel has been investigated by a number of researchers [5-10] in which they have classified it as a semi-rigid joint. For Eurocode design specifications, the effective width method is applied to distinguish between compact hot-rolled steel and slender cold-formed steel when considering instability problems of large deflection analysis. However, for the component method used in connection design, the Eurocodes do not provide the joint analysis for large deflection that is experienced by cold-formed steel structures in light steel frame.

For hot-rolled steel sections, several mathematical models have been developed to idealise the moment-rotation curve of several structural joints [11-22]. These are outlined in more details. The first model was developed for the prediction of the initial rotational stiffness for riveted connections [11]. An improved bilinear model [12-14] was proposed to represent both the initial rotational stiffness as well as the plastic behaviour. A multi-linear mathematical model was preached by Razzaq to further increase the accuracy in the moment-rotation behaviour [15].

Frye and Morris [16] developed a mathematical model with polynomial equations, based on Sommer's equation [17] that used the least square method for determining the polynomial constant for top-seat flange cleat connections [16]. Kishi and Chen [18] refined Lui and Chen's model [14] to show critical changes in the rotational stiffness of the moment-rotational curve. Kishi and Chen adopted Heaviside's step function for the exponential model which solves the full range of relative rotation with secant connection stiffness in a second order analysis. A four-parameter exponential mathematical model was proposed in [19-22]. Kishi and Chen presented two-parameter [20], three-parameter [21] and power models [22].

Existing studies for the moment-rotation behaviour of bolted moment connections under monotonic loading are therefore well-established for hot-rolled steel. Despite this, there is little information available for the design light steel frames with bolted top-seat flange cleat connections. Some work on cold-formed steel top seat flange cleat connections was presented by Tan [23] in which a series of experimental studies were performed. However, a comprehensive mathematical equation that accommodates the large deflection analysis to represent the moment-rotation behaviour of such connections has not yet been developed. Since the mechanical behaviour of cold-formed steel varies significantly from that of hot-rolled steel, adapting hot-rolled connection design may not be safe.

This paper addresses the mentioned concerns and presents the design of bolted top-seat flange cleat connections in light steel frame. It includes a study to investigate parameters that influence the moment-rotation behaviour of cold-formed steel top-seat flange cleat connections. The investigated parameters include the elastic rotational stiffness, k_e, plastic rotational stiffness, k_p, and plastic moment resistance of the connection, M_{pl}. An empirical model is proposed which represents the large deformation moment-rotation behaviour for top-seat flange cleat connections. The influences of the thickness of the flange cleat and column flange, as well as the depth of the beam were also investigated. The elastic rotational stiffness is represented by an equation developed on the least squares method using finite element models, which was then applied to the proposed moment-rotation curve approximation.

2. Investigation models for bolted joint

There are three developed investigation models, namely, BS EN1993-1-8, experimental and finite element models. The unit for rotational stiffness and moment resistance are kNm/Rad and kNm, respectively, throughout the study.

2.1. BS EN1993-1-8 model

The top-seat flange cleat connection has been codified in BS EN1993-1-8. The design resistance of the joint is calculated with component method. BS EN1993-1-8 has provided the procedures to obtain the component resistances for design purpose. The component resistance includes 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, shear resistance of column web panel and shear resistance of bolts. The investigation has been discussed in [24-26].

The moment-rotation curve is plotted with the calculated joint moment resistance. For conservative design, Eurocode has limited the model behaviours as elasto-plastic with no plastic rotational stiffness and fails at the lowest stiffness component. This characteristic is suitable for hot-rolled steel. The calculation is based on the yield line pattern for component failure mode and the joint resistance. There are two identified yield line patterns: circular and non-circular patterns. According to BS EN1993-1-8, there are three structural properties in the moment-rotation behaviour, namely moment resistance (strength), rotational stiffness and rotation capacity (ductility), which are discussed in the following section.

2.2. Experimental investigation

Three tests were carried out in the Laboratory of Structures and Materials, Universiti Teknologi Malaysia. Figure 1 shows details of the experimental test setup. The thickness of the flange cleat used depended on the beam depth. The beam depths used were: 150 mm, 200 mm, and 250 mm. These beams are referred to as DC150, DC200 and DC250, respectively. For all beam sizes, 6 mm flange cleats were used as connectors. Back-to-back channel sections were used for the beams and columns. Further details of the experimental studies are found in [23,25,26]. The experimental results were applied for the model validation of developed numerical models and compared to the newly developed formulation at later stage.

With reference to Yu et al. (2005) [27], the same test configuration was set for the experimental study. The data transducer was placed at 1000 mm from column surface for taking the deflection of beam bending parallel to loading point. Inclinometers were located, as shown in Figure 1, for the record of the rotations of beam and column.

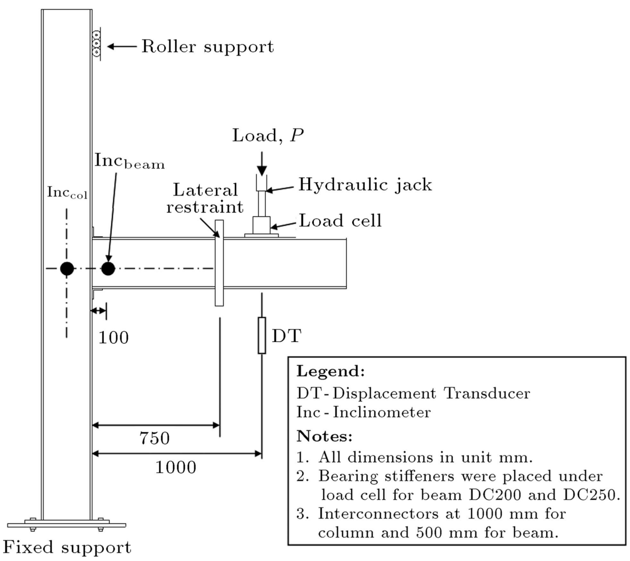


Figure 1. Experimental set up of full-scale isolated joint test.

2.3. Numerical investigation

2.3.1. Verification and validation

From the process of verification and validation, the expected outcome is the quantified level of agreement between experimental results and model prediction [28]. The factor of high accuracy of the developed predictive model is the driven force to execute the verification and validation process. The finite element program ABAQUS version 6.9 was used to model the top-seat flange cleat joint. The details of modelling technique on cold-formed steel with top-seat flange cleat connections have been proposed [24-26]. Figure 2 shows the details of the finite element model.

The important activity of calculation verification is performing grid or time convergence study by successively refining the mesh or time step until a sufficient level accuracy is obtained [28]. The results

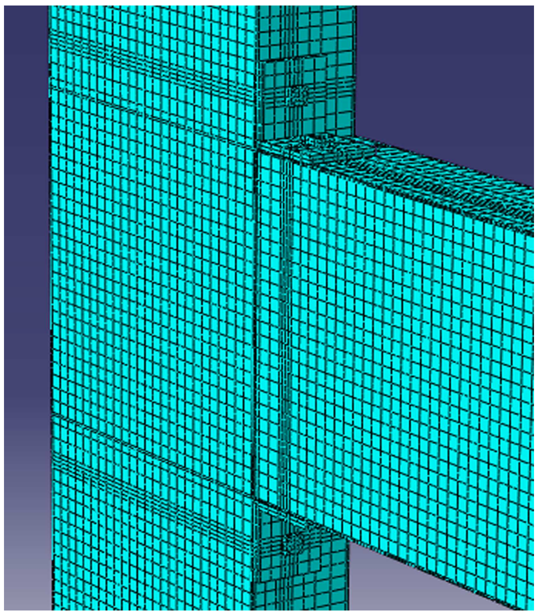


Figure 2. Mesh of developed finite element model.

Table 1. Summary of validation results.

Specimen	Predictive parameter	EXP	FEM	%Difference
DC150FC6	k_e	97.6	93.4	4.3
	M_{j30}	2.00	2.17	8.5
	M_{j50}	2.98	3.01	1.0
	$k_{\text{sec}30}$	66.7	72.3	8.4
	$k_{\text{sec}50}$	59.6	60.2	1.0
DC200FC6	k_e	147.6	137.9	6.6
	M_{j30}	3.02	2.90	4.0
	M_{j50}	4.42	4.08	7.7
	$k_{\text{sec}30}$	100.7	96.7	4.0
	$k_{\text{sec}50}$	88.4	81.6	7.7
DC250FC6	k_e	179.8	190.7	6.1
	M_{j30}	3.83	4.11	7.3
	M_{j50}	5.78	5.64	2.4
	$k_{\text{sec}30}$	127.7	137.0	7.3
	$k_{\text{sec}50}$	115.6	112.8	2.4

were documented in [24]. High von Mises stress was found at the component with low stiffness. Meshing, geometrical properties and boundary conditions were checked to eliminate the errors. Therefore, BS EN1993-1-8 achieved good agreement with numerical model for model verification.

The assessment of model validation determines the degree of accuracy in representing the real behaviour from the perspective of the intended uses of the model [24]. For model validation, the results were summarized in Table 1 and compared to the experimental data. Comparison was made on elastic rotational stiffness, secant rotational stiffness and resistance at desired rotations. In order to fulfill the minimum requirement of connection ductility, the rotation capacity of ductile connection has been ranged between 0.02 Rad to 0.03 Rad rotations [29]. Cold-formed steel exhibits large plasticity performance and the connection have the possibility to fail at large deflection that exceeds 0.05 Rad. The limitation has been made at 0.05 Rad to avoid excessive deformation of the connected members for flexible connection specimens [30]. Therefore, the rotation limitations are set at 0.03 Rad and 0.05 Rad. The secant rotational stiffness and strength comparisons are made on the point of 0.03 Rad and 0.05 Rad rotations, respectively.

Statistical T-test analysis is performed to correlate the developed finite element models with experimental data. The analysis covers 99% level of confidence. There are two evidences that the null hypothesis should not be rejected at the 99% confidence interval of the difference, as shown in Table 2. The lower boundary of confidence level is below zero, -4.12349, and the upper boundary of the confidence level is a positive number, 4.28615. Hence, there is a possibility that the population means of the differences is zero and it fails to reject the null hypothesis. In addition, the Sig (2-tailed) value is 0.955, and it is greater than 0.05, which indicates that there is no statistically significant difference between experimental results and FEM models. Therefore, it fails to reject the null hypothesis. At the 99% of confidence level, there exists enough evidence to conclude that there is no statistically significant difference between two investigated models.

Therefore, the developed modelling technique can be used for further parametric study. ABAQUS/Standard analysis with static solver, material nonlinearity, half simulation, geometric nonlinearity, 10 mm mesh size, well-defined boundary condition and loading are used for the top-seat flange-cleat connection, as these conditions passed verification and validation processes [24,26].

3. Bolted joint design

3.1. Moment-rotation characteristic

The moment-rotation characteristic of a joint can be idealised as shown in Figure 3. It also can be described as Eqs. (1) and (2). The elastic rotational stiffness is defined as:

$$\frac{dM}{d\phi} = k_e, \qquad \text{when} \quad 0 < M < M_p. \tag{1}$$

In the elasto-plastic region, the plastic moment resistance of the connection, M_p, becomes the boundary value and the initial point for non-linear behaviour of

Table 2. Paired samples test at 99% of confidence level.

	Paired differences							
	Mean	Std. deviation	Std. error mean	99% confidence interval of the difference		t	df	Sig. (2-tailed)
				Lower	Upper			
EXP-FEM	0.0813	5.4706	1.4125	-4.1235	4.2862	0.058	14	0.955

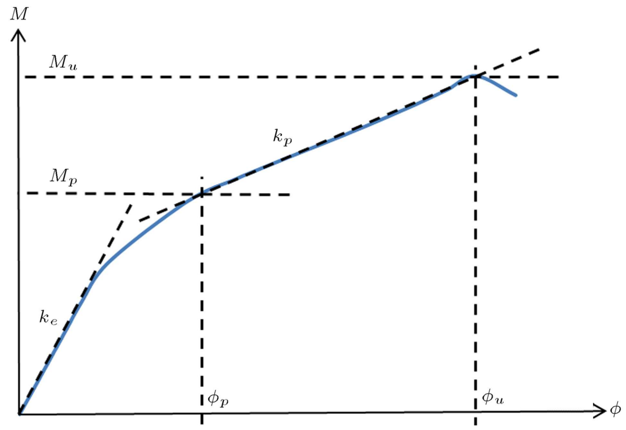


Figure 3. Moment-rotation curve of cold-formed steel with top-seat flange-cleat connection.

the connection. The rotational stiffness of the plastic region is defined as follows:

$$\frac{dM}{d\phi} = k_p, \qquad \text{when} \quad M > M_p \quad \text{and} \quad k_p < k_e. \qquad (2)$$

The steel section stops exhibiting plastic behaviour once the connection collapses completely. The moment-rotation behaviour of hot-rolled steel end-plate connection as Eq. (3) [19] which exhibits the similar moment-rotation behaviour as top-seat flange cleat connection with consideration of plastic rotational stiffness.

$$M = M_p \left[1 - e^{-\frac{-(k_e - k_p + C\phi)}{M_p}\phi} \right] + k_p\phi. \qquad (3)$$

From BS EN1993-1-8, with strain hardening, at intervals of 2/3 M_p and M_p, there is a gradual decrease in the rotational stiffness in order for the connection to achieve k_p. With respect to the non-linear properties of BS EN1993-1-8 model, another simplified exponential equation for the moment-rotation behaviour to the exponential model is proposed. The proposed equation is developed on the basis shown in Figure 3.

From Figure 3, the rotational stiffness is linear from the unloading condition until 2/3 of M_p, and then becomes nonlinear until M_p. Beyond M_p, any further loading combined with strain hardening will result in reduced rotational stiffness that propagates until the connection collapses.

3.2. Preliminary study of BS EN1993-1-8 prediction

Finite element models were developed using the verified and validated modelling technique in order to make a comparison with the BS EN1993-1-8 model. The adequacy of BS EN1993-1-8 is checked with finite element models as the small deflection principle of the code may not be able to convey the problems induced by large deformation.

The obtained values for comparison were documented in [31]. The thickness of flange cleat was varied from 2 mm to 14 mm. All sections are assigned actual material behaviour from the data of experimental tensile test. From the finite element models, any increment after 12 mm gave a neglected change for structural behaviour. Therefore, the comparison was made on the thickness of flange cleat which ranged from 2 mm to 12 mm.

The differences between BS EN1993-1-8 and finite element models range from 15% to 60% for initial stiffness prediction, 1.3 to 2.3 time lower than FEM at 0.03 Rad rotation and 1.8 to 2.9 time lower than FEM for secant stiffness at 0.05 Rad. The overestimation of initial rotational stiffness in BS EN1993-1-8 may cause safety issue in design, whereas the conservative design of secant stiffness can be accepted for safety reason but induced economic design issue. The BS EN1993-1-8 prediction has low accuracy in moment-rotation prediction of cold-formed steel bolted top-seat flange cleat joint. It is recommended to do revision in adapting BS EN1993-1-8 in large deflection analysis of joint design.

4. Component rotation analysis

Since there are several components that contribute to the structural behaviour of the cold-formed steel top-seat flange cleat connection, the rotation of these components is investigated separately in order to understand the components resistance. With exclusion of bolts component, there are three identified components in this study, namely, beam, column and flange cleats. The investigated component will be assigned actual stiffness while other two components will be assigned a thousand times stiffer value of Young's Modulus for each particular analysis.

In order to ensure this thousand time stiffer value is valid in the analysis, a study has been carried out with the failure load for all components assigned with this value. It was found that there was no deflection for this stiffer connection configuration. Therefore, the assumption of the thousand time stiffer value is appropriate for the component rotation analysis that obtains separated deflections from overall deformation.

The deflections were recorded from one of the developed FEM models, as shown in Figure 4 for the specimen of DC250FC6 [26]. The overall rotation from finite element model was 11.91 mRad. According to the controlled rotation analysis, for 6 mm thickness flange cleat and at 4 kNm deformed shape, the rotations were 0.75 mRad due to flange cleat, 10.58 mRad of column deformation and 0.58 mRad contributed by beam component.

Among the two possible failure modes (flange cleat in bending and column flange in bending), the

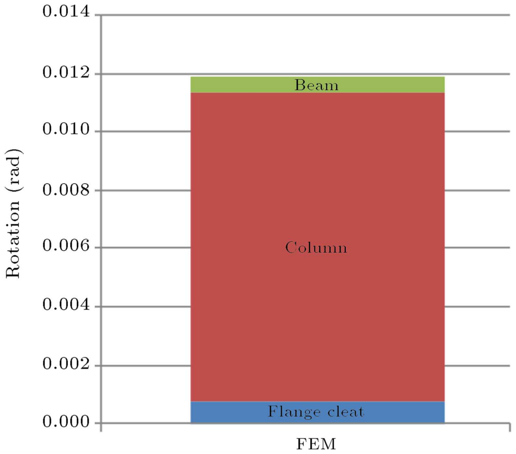


Figure 4. The component rotations at 4 kNm in finite element analysis.

high rotation was contributed by the component that has thinner thickness of these components. Hence, the flange cleat and column flange are taken as the primary investigation variables to understand its structural performance. However, the beam depth and the flange cleat end bolt distance are also included in the study.

4.1. Flange cleat component analysis

4.1.1. Thickness of flange cleat

The component of flange cleat acts as a connector in joining the two other structural components. In a beam-to-column joint, flange cleats connect the beam to column and transform the forces and moments. The top flange cleat is in tension and the bottom flange cleat is in compression.

The thickness of the flange cleat has been identified as one of the significant parameters in the flexural condition. The parametric study is carried out to investigate the structural performance for various thickness of flange cleat with neglected deformations of beam and column components. The increment of 1 mm has been assigned to the investigation range from 2 to 14 mm.

Figure 5 shows the deflection contour with flange cleat component as the investigation variable. From the failure of the flange cleat, it can be realised that the deformation of the flange cleat has dominantly contributed to the overall deflection at lower thickness of the flange cleat. The 2 mm top tension flange cleat buckled at peak load. As the flange cleat thickness increases to 14 mm, the deflection has significantly reduced at peak load as compared to 2 mm thickness flange cleat connection. The buckling effect also reduced for 14 mm thickness flange cleat. The stiffness and the moment resistance of the developed joints have shown a gradual increment trend according to the recorded results, as shown in Figure 6. There is a nonlinear increment which is preliminary similar to the BS EN1993-1-8 structural prediction.

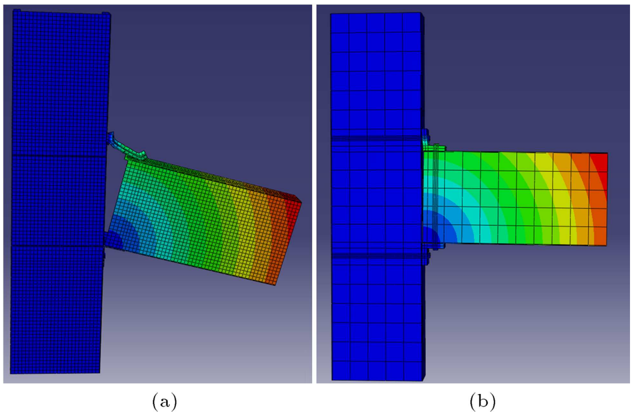


Figure 5. Deflection contour for connection with flange cleat as dependent variable for (a) 2 mm thickness, and (b) 14 mm thickness of flange cleat.

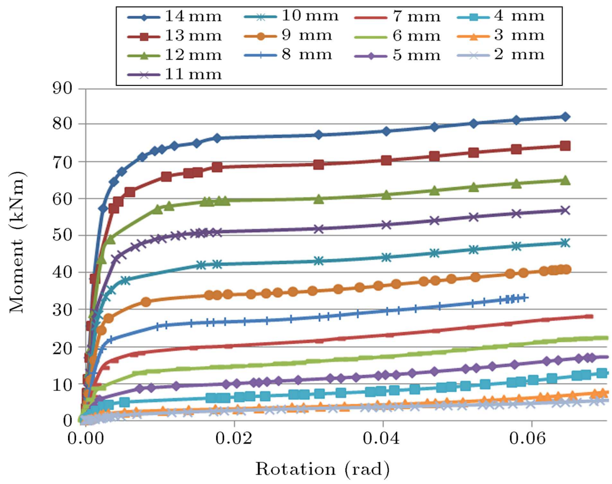


Figure 6. Moment-rotation curves for component deformation of flange cleat with 2 mm to 14 mm flange cleat thickness.

4.1.2. Distance of end bolts

Distance of end bolts is one of the critical factors in the determination of structural failure. In BS EN1993-1-8 [4], the distance is described as m which is shown in Figure 7. The m greatly influences the structural performance for a developed bolted connection. The investigated end bolts distance, e, ranges from 12 to 37 mm. The 12 mm end bolt distance is applied as it is slightly lower than minimum requirement of 1.2 d_o which is equivalent to 14.4 mm according to BS EN1993-1-8.

At peak loads, the deformation of the flange cleat has been studied with different end bolt distances as shown in Figure 8. From the flange cleat failure observation, the deformation effect was less experienced by the bolt near to the angle corner of the top tension flange cleat. The deflection become less and the stiffness is increased as the bolt distance approaches the corner of the flange cleat. The moment-rotation behaviour was recorded in Figure 9.

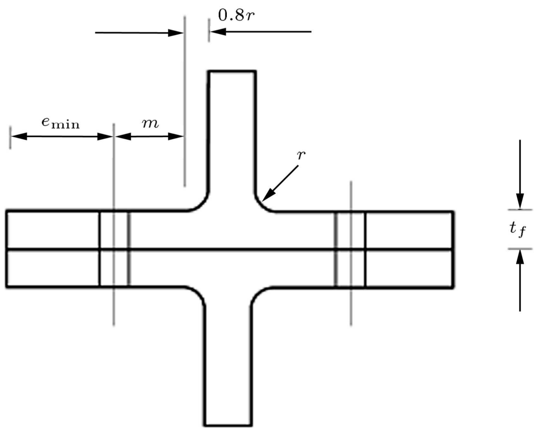


Figure 7. The m distance in BS EN1993-1-8 [4].

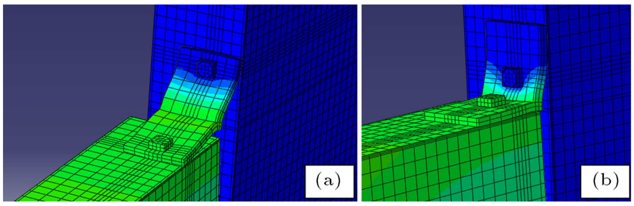


Figure 8. Deformation contour of flange cleat with end distance of (a) 12 mm, and (b) 37 mm.

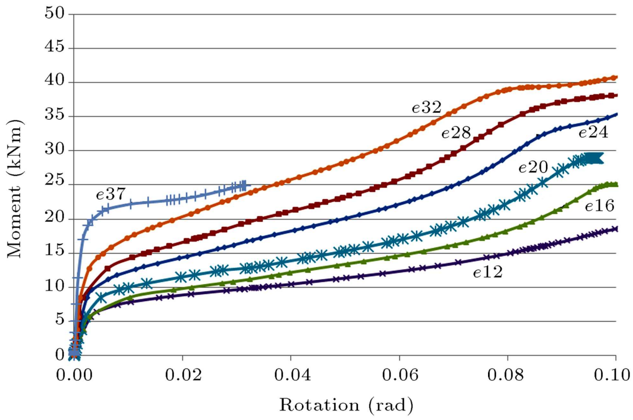


Figure 9. Moment-rotation curves for component deformation of flange cleat with different end bolt distances (e indicates the end bolt distance).

There is an inconsistence trend of value prediction at the plastic behaviour for different end bolt distances analysis. For the end distance ranges from 12 to 32 mm, at limitation of 0.1 Rad rotation, there is a clear and acceptable trend, without overlapping each other, for the moment-rotation characteristic. However, for 37 mm end bolt distance of the flange cleat, the analysis was terminated due to suspicious convergence problem, but it was able to give the results before 0.03 Rad rotation.

4.2. Column component analysis

The component of column is a structural member to transfer loading from the top building to the foundation or footing. For a beam-to-column joint, column component transmits the flexural loads from the beam to the sub-structure. The column should be stiff enough to take the loads and moments from other structural members. For open I-section of column, the column flange is in tension and the column web located at bottom flange cleat is in compression mode.

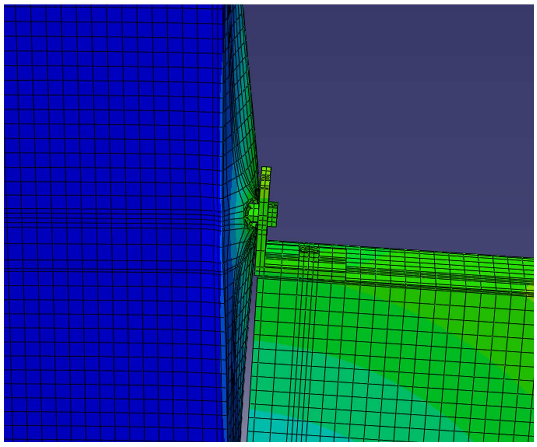


Figure 10. Bolt pull-out from column flange.

The effective length from BS EN1993-1-8 stiffness prediction has less effect on the structural performance. With stiffer value assigned to the material properties of bolt, beam and flange cleats, the failure mode will concentrate on column flange. In addition, since there is a limitation of the length for column flange by manufacturer, the end bolt distance is excluded from this investigation.

A desired failure on column flange is achieved in all investigated FEM models. Figure 10 shows the deformed shape of column flange. The investigated column flange thicknesses ranged from 2 mm to 14 mm as studied by flange cleat thickness. The bolt was pulled out from the column flange at peak load as it exceeded the column moment resistance. The moment-rotation behaviour has been recorded in Figure 11.

4.3. Beam component analysis

The beam component takes the dead and live loads from the slab and transfers to column through connectors. Beam dominantly resists the flexural loads of the overall structure. The flexural behaviour become significant as the slender cold-formed steel sections are applied in the joint design.

According to BS EN1993-1-8 design, beam normally plays a role in joint classification. In order to resist the flexural loads, the beam depth is the key parameter in the joint design. The beam depth can affect the moment resistance of a joint as the distance between tension zone and compression zone varies according to the beam depth. The investigated beam depth ranged from 150 to 400 mm. Web crushing was prevented by restricting the beam depth.

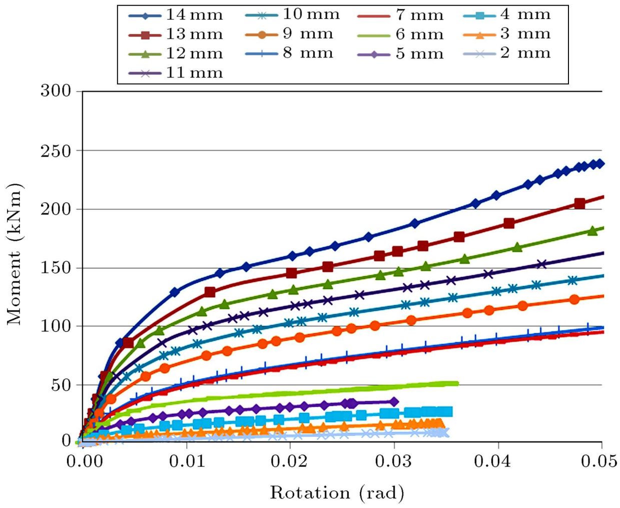
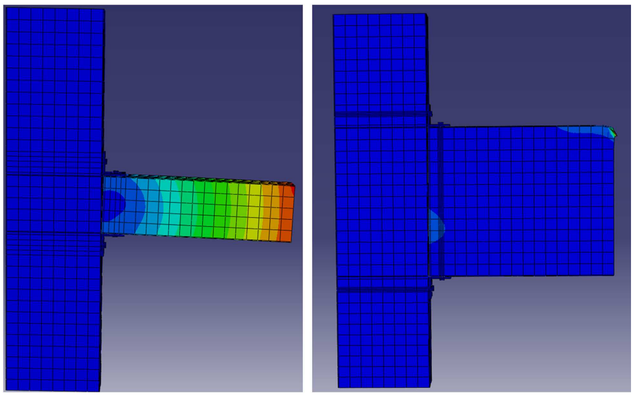


Figure 11. Moment-rotation curves for component deformation of column with 2 mm to 14 mm column flange thickness.



(a) (b)

Figure 12. The deflection contour for beam depth of (a) 150 mm, and (b) 400 mm.

From Figure 12, the deformation has been depicted in the finite element analysis. There is a small rotation observed for beam depth of 150 mm. The failure mode of crushing at load point and the buckling effect at the beam web have decreased the rotational stiffness of the beam component. For moment-rotation curve, as shown in Figure 13, there is no significant trend of the curves due to buckling on the beam web. The beam experiences web buckling as the beam depth increases. The stiffness and moment resistance are affected by the slenderness of the beam web. Since the obtained curves have less rotation capacity, the comparison is made on 0.01 Rad rotation.

4.4. Discussion on component analysis

The component rotation analysis for flange cleat, column flange and beam was carried out to investigate the component behaviour at peak load. Basically, all studied geometrical parameters: flange cleat thickness, distance of end bolts at flange cleat, column

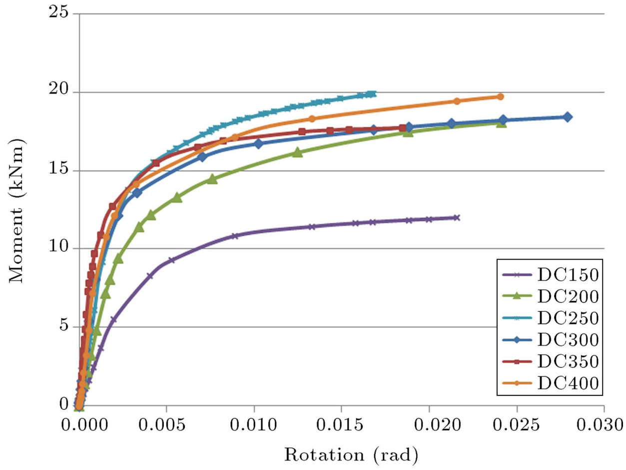


Figure 13. Moment-rotation curves for different beam depths as investigation variables.

flange thickness and beam depth have obtained desired moment-rotation behaviour for structural prediction.

The increment of flange cleat thickness and column flange thickness led to stiffer joint configuration. The thicknesses of structural members were proved in the structural performance under flexural loads. The end bolt distance also affected the rotational stiffness of a joint. The stiffness become greater when getting closer to the corner of the flange cleat. Moreover, as the beam depth increased, the rotational stiffness was enhanced. However, web buckling between the flange cleats and crushing at loading point has altered the moment-rotation behaviour of joint.

In order to achieve ductile connection with no sudden collapse upon failure, BS EN1993-1-8 stated the failure should be controlled at flange cleat or column flange. This is proven by component deflection analysis where the failure in beam depth was not able to achieve 0.02 Rad and 0.03 Rad rotation. Hence, it is recommended to use the beam with a depth not exceeding 250 mm to avoid the web crushing.

The obtained stiffness of these components: flange cleat, column and beam are not suitable for combining in forming overall stiffness. This is due to the fact that these components are associated with each other on the deformation. Therefore, it can be concluded that the geometrical parameters have affected the initial or secant rotational stiffness significantly and modelling is continued with the actual material behaviour assigned to all components in order to form a reliable formulation.

5. Formulation development

5.1. Investigated parameters

The parameters for the moment-rotation curve include the plastic moment of connection, M_p, the elastic rotational stiffness, k_e, and the plastic rotational stiffness,

k_p. The plastic moment resistance, M_p, is the limiting point of the connection and can be calculated using the component method of BS EN1993-1-8.

The equations proposed by Fyre and Morris [16] are shown in Eq. (4):

$$k_{e,\text{Fyre}} = 2.14 \times 10^{-4} t_1^{-0.5} h^{-1.5} d^{-1.1} l^{0.7}. \quad (4)$$

Ang and Morris [32] also proposed a power equation for semi-rigid beam-to-column connections. In this equation, the least square of parameter has reduced the effect of beam depth towards the initial stiffness of the connection. The equation by Ang and Morris [32] is described in Eq. (5):

$$k_{e,\text{Ang}} = 2.14 \times 10^{-4} t_1^{-0.54} h^{-1.06} d^{-1.28} l^{0.85}. \quad (5)$$

The above parameters are limited to the same type of bolt size and steel grade. The geometry of the connection is therefore the most important parameter for the rotational stiffness. According to the component method of BS EN1993-1-8, the tension failure of the top-seat flange cleat connection is considered in terms of bending of the flange cleat, bending of the column flange, and development of transverse tension in the column web. In the case of cold-formed steel, since the thickness of the web is always twice the thickness of flange, the mode of failure can be expected to be in the flange.

In accordance with BS EN1993-1-8, the effective length of an equivalent T-stub involves the length of the flange cleat and column flange. In industry, the length of the connected flange cleat is often limited by the manufacturer's specification on the dimension of the C-channel section. By ignoring the material strength, the influencing factor is the thickness of the cleat or column flange.

The beam depth is another factor that will also affect the connection's resistance. This contribution to the connection's flexural behaviour has also been included in this paper. The investigated parameters are now extended to include the thickness of flange cleat, t_{fc}, thickness of column flange, t_{cf}, and beam depth, D_{beam}.

5.1.1. Elastic rotational stiffness, k_e

From the component rotation analysis, the thickness of column flange or flange cleat affects the moment-rotation of a joint. The stiffness will keep increase as the thickness is increased. For practice, the thickness of 6 mm that is covered by hot-rolled steel is carrying less effect of thin-walled properties. Therefore, the ranges of the parameters are: 2 to 6 mm of column flange or flange cleat thickness and 150 to 250 mm of beam depth. A total of 75 finite element models were set-up in these combinations. From these models, the elastic rotational stiffness was extracted from the moment-rotational behaviour of the models. The proposed elastic stiffness equation, $k_{e,pr}$, is as follows:

$$k_{e,pr} = 1.1 \times 10^{-3} x, \quad (6)$$

$$x = \left\lfloor t_{cf}^{1.15} \times t_{fc}^{1.17} \times D_{\text{beam}}^{1.62} \right\rfloor. \quad (7)$$

All units are in mm for geometrical dimension and kNm/Rad for rotational stiffness. These equations were developed using least square method to obtain the power of the geometrical effects and linear regression method for elastic rotational stiffness.

Figure 14 shows the least square graph. As can be seen, it was shifted to the conservative linear behaviour in order to obtain a reliable design. All depicted values are conservative to the experimental values and are safe to be used in the construction industry.

5.1.2. Plastic rotational stiffness, k_p

Table 3 shows the ratio of k_e/k_p as the steel propagates from the elastic to plastic region in the moment-rotation curve.

From the experimental results, the ratio of elastic to plastic rotational stiffness ranged from 1.88 to 2.24

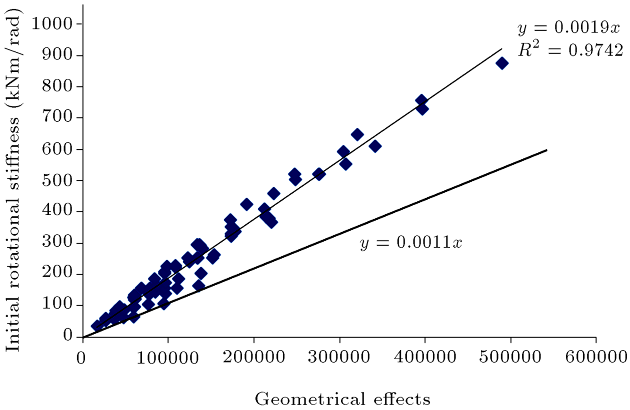


Figure 14. Least square graph of elastic rotational stiffness.

Table 3. Ratio of elastic and plastic rotational stiffness.

Model	$k_{e,\text{exp}}$	$k_{p,\text{exp}}$	Ratio$_{\text{exp}}$, $k_{e,\text{exp}}/k_{p,\text{exp}}$	$k_{e,\text{FEM}}$	$k_{p,\text{FEM}}$	Ratio$_{\text{FEM}}$, $k_{e,\text{FEM}}/k_{p,\text{FEM}}$	Coefficient, Ratio$_{\text{FEM}}$/Ratio$_{\text{exp}}$
DC150FC6	97.6	43.5	2.24	93.4	41.7	2.24	1
DC200FC6	147.6	68.4	2.16	137.9	60.0	2.30	1.06
DC250FC6	179.8	95.5	1.88	190.7	80.8	2.36	1.26

after the joint behaviour passed the transition point (M_p). For the numerical models, the ratio can be controlled within 2.24 to 2.36. It can be assumed in the equations that a conservative cold-formed steel with top-seat flange cleat connection has a ratio of k_p/k_e= 0.4 where 10% of safety factor was added to the ratio of 2.36 and it became approximately 2.50.

5.1.3. *Plastic moment resistance, M_p, and slope fitting coefficient, C*

From the preliminary study of BS EN1993-1-8, it was found that Eurocode gives less accurate prediction on elastic rotational stiffness, but safe values were obtained for the plastic moment. Therefore, the transition point at which the steel characteristic changes from elastic to plastic can be determined through the BS EN1993-1-8 component method. The procedures to obtain the moment resistance of top-seat flange cleat joint have been documented in BS EN1993-1-8.

The slope fitting coefficient, C, is applied to the exponential equation to determine the curve of the moment-rotation behaviour. It was found that the small value of C will give a gradual slope change, whereas greater value of C gives slow rate of slope change. The proposed equation is as Eq. (8). The C is fixed as 0.1 where the rate is moderate to record the slope fitting at plastic behaviour.

$$M = M_p\left[1 - e^{-\frac{-(0.6k_e+0.1\phi)}{M_p}\phi}\right] + 0.4k_e\phi. \qquad (8)$$

5.2. *Application of the proposed moment-rotation curve*

Figures 15 to 17 show the experimental test results, Eurocode curves, and proposed modified exponential curves, respectively, for the moment-rotation behaviour of the top-seat flange cleat connection. The trend line of the proposed equation is always lower than that of the experimental test results.

The proposed equation in Eq. (8) has shown a closed comparison with experimental results and improved the BS EN1993-1-8 structural prediction. For safety purpose, all predicted structural moment-rotation behaviour by the proposed equations is below the experimental results. Therefore, the proposed equations can be applied safely into the design stage in cold-formed steel top-seat flange cleat joint in light steel frame.

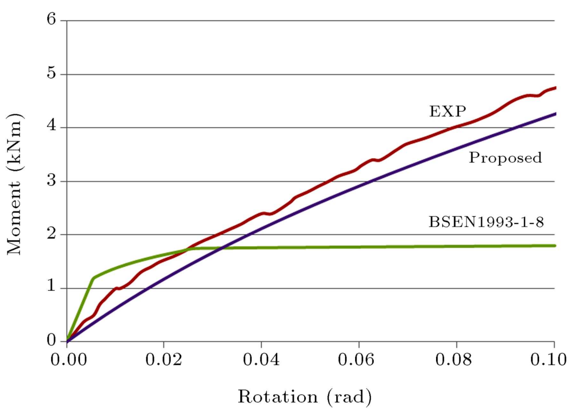


Figure 15. Comparison of moment-rotation curves between proposed, experimental and BS EN1993-1-8 models for DC150FC6.

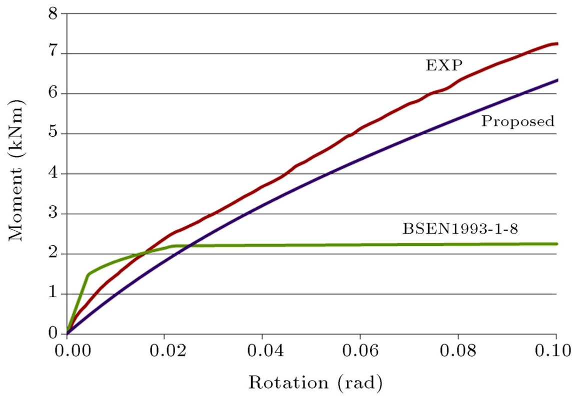


Figure 16. Comparison of moment-rotation curves between proposed, experimental and BS EN1993-1-8 models for DC200FC6.

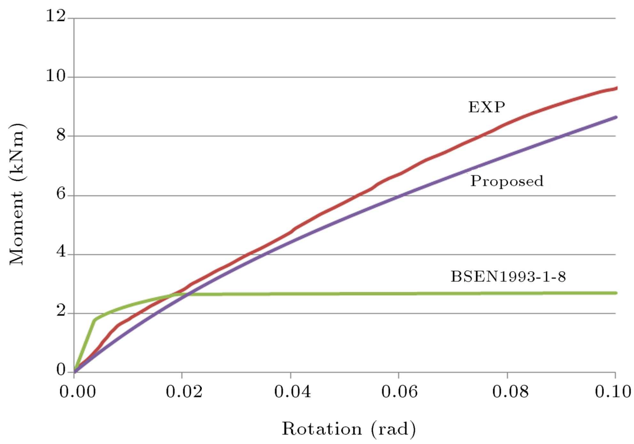


Figure 17. Comparison of moment-rotation curves between proposed, experimental and BS EN1993-1-8 models for DC250FC6.

From Table 4, the percentage of difference between experimental results and BS EN1993-1-8 ranges from 168.08% to 124.39%, 11.00% to 30.18% and 37.54% to 53.98% for elastic rotational stiffness, moment resistance at 30 mRad and 50 mRad rotations, respectively. The differences were closer between experimental results and the proposed equation with a difference not more than 33% for the structural prediction.

6. Conclusions

This paper has presented three investigation models to determine the structural performance of top-seat flange cleat joints for light steel frame under flexural loads.

Table 4. Summary of validation results.

Specimen	Parameter	Experimental results, EXP	BS EN1993-1-8, EC	Proposed	%Difference	
					EXP-EC	EXP-proposed
DC150FC6	k_e	97.6	219.0	66.6	124.39	32.76
	M_{j30}	2.00	1.78	1.67	11.00	16.50
	M_{j50}	2.85	1.78	2.53	37.54	11.23
DC200FC	k_e	147.6	338.0	106.1	129.00	28.11
	M_{j30}	3.02	2.22	2.55	26.49	15.56
	M_{j50}	4.42	2.22	3.81	49.77	26.25
DC250FC6	k_e	179.8	482.0	152.3	168.08	15.29
	M_{j30}	3.81	2.66	3.54	30.18	7.09
	M_{j50}	5.78	2.66	5.23	53.98	9.52

From the numerical, codified and experimental models, the following conclusions are presented:

i. Preliminary study was conducted to get the evidence of the suitability in adopting BS EN1993-1-8 to joint behaviour with thin-walled behaviour of cold-formed steel top-seat flange cleat joint. There is a significant difference in the structural prediction of BS EN1993-1-8 for structural prediction of mechanical properties.

ii. Component rotation analysis was performed to investigate the component behaviour under peak flexural load. The increment in thickness of flange cleat, end bolt distances, thickness of column flange and beam depth led to the growth of the stiffness.

iii. A modified exponential equation has been proposed to represent the moment-rotation curve for cold-formed steel with top-seat flange cleat connections as shown in Eq. (8). The proposed equation can improve the BS EN1993-1-8 prediction from 168.08% difference compared to experimental results, to 7.09% difference.

Acknowledgments

This research was funded by research grants (03H76, 4F258, 4F647 and 02G88) from the Research Management Centre, Universiti Teknologi Malaysia and the Ministry Of Higher Education (Malaysia) (MOHE). The financial support provided is gratefully acknowledged. The technical support from the Laboratory of Structures and Materials of UTM is also appreciated.

Nomenclature

B_{beam}	Width of beam section
B_{col}	Width of column section
C	Curve-fitting coefficient
D_{beam}	Depth of beam section
D_{col}	Depth of column section
$F_{T,1,Rd}$	Design strength of mechanism type 1
$F_{T,2,Rd}$	Design strength of mechanism type 2
f_y	Component design strength
k_e	Elastic rotational stiffness
k_p	Plastic rotational stiffness
$k_{e,EC}$	Elastic rotational stiffness from BS EN1993-1-8
$k_{e,\text{exp}}$	Elastic rotational stiffness of experimental model
$k_{e,\text{FEM}}$	Elastic rotational stiffness of finite element model
$k_{e,pr}$	Proposed initial rotational stiffness
$k_{p,pr}$	Proposed plastic rotational stiffness
k_{sec30}	Secant rotational stiffness at 30 mRad rotation
k_{sec50}	Secant rotational stiffness at 50 mRad rotation
k_{Fyre}	Stiffness developed by Fyre and Morris
k_{Ang}	Stiffness developed by Ang and Morris
M	Applied moment
M_{j30}	Moment resistance at 30 mRad rotation
M_{j50}	Moment resistance at 50 mRad rotation
$M_{j30,EC}$	Moment resistance at 30 mRad rotation from BS EN1993-1-8
$M_{j50,EC}$	Moment resistance at 50 mRad rotation from BS EN1993-1-8
$M_{j30,\text{exp}}$	Moment resistance at 30 mRad rotation of experimental model
$M_{j50,\text{exp}}$	Moment resistance at 50 mRad rotation of experimental model
$M_{j30,pr}$	Proposed moment resistance at 30 mRad rotation

$M_{j50,pr}$	Proposed moment resistance at 50 mRad rotation
M_p	Plastic moment resistance of connection
t_{beam}	Thickness of beam section
t_{cf}	Thickness of column flange
t_{col}	Thickness of column section
t_{fc}	Thickness of flange-cleat
x	Geometrical parameters for least square equation
ϕ	Connection rotation

References

1. Bijlaard, F. "Eurocode 3, a basis for further development in joint design", *J. Constr. Steel Res.*, **62**, pp. 1060-1067 (2006).
2. Wong, M.F. "Bolted moment connections in cold-formed steel beam-column sub-frames" Master thesis, The Hong Kong Polytechnic University, Hong Kong (2002).
3. Mujagic, J.R.U. and Easterling, W.S. "Connections in cold-formed steel framing - Designing with AISI 2007: Specification and application overview", *STRUCTURE Magazine*, pp. 9-11 (August 2009).
4. British Standards Institution. Eurocode 3 "Design of steel structures. Part 1.8: Design of Joint", BS EN 1993-1-8. U.K. BSI (2005).
5. Abdalla, K.M. and Chen, W.F. "Expanded database of semi-rigid steel connections", *Comput. Struct.*, **56**(4), pp. 553-564 (1995).
6. Kameshki, E.S. and Saka, M.P. "Genetic algorithm based optimum design of nonlinear planar steel frames with various semi-rigid connections", *J. Constr. Steel Res.*, **59**, pp. 109-134 (2003).
7. Daryan, A.S. and Yahyai, M. "Behavior of bolted top-seat angle connections in fire", *J. Constr. Steel Res.*, **65**(7), pp. 531-541 (2009).
8. Kishi, N. and Chen, W.F. "Moment-rotation relations of semirigid connections with angles", *J. Struct. Eng.*, **116**, pp. 1813-1834 (1990).
9. Faella, C., Piluso, V. and Rizzano, G., *Structural Steel Semirigid Connections - Theory, Design and Software*, CRC Press (2000).
10. Loureiro, A., Reinosa, J.M., Gutiérrez, R. and Moreno, A. "New proposals on the calculation of the flexural resistance in angle connections", *J. Constr. Steel Res.*, **67**, pp. 613-622 (2011).
11. Rathbun, J.C. "Elastic properties of riveted connection", *Transaction of the ASCE*, **101**, pp. 524-563 (1936).
12. Tarpy, T.S. and Cardinal, J.W. "Behavior of semi-rigid beam-to-column end plate connection", *Proceedings of the International Conference: Joints in Structural Steelwork*, Teesside Polytechnic, Middlesbrough, Cleveland, U.K. 2.3-2.25 (1981).
13. Melchers, R.E. and Kaur, D. "Behaviour of frames with flexible joints", *Proceedings of 8th Australia Conference Mechanical of Structural Materials*, Newcastle, Australia, pp. 271-275 (1982).
14. Lui, E.M. and Chen, W.F. "Analysis and behavior of flexibly-jointed frames", *Eng. Struct.*, **8**(2), pp. 107-118 (1986).
15. Razzaq, Z. "End restraint effect on steel column strength", *J. Struct. Eng.*, **109**(2), pp. 314-334 (1983).
16. Frye, M.J. and Morris, G.A. "Analysis of flexibly connected steel frames", *Can. J. Civil Eng.*, **2**(3), pp. 280-291 (1975).
17. Sommer, W.H. "Behaviour of welded header-plate connection", Master Thesis, University of Toronto, Canada (1969).
18. Kishi, N. and Chen, W.F. "Database of steel beam-to-column connections", Structural Engineering Report No. CE-STR-86-26, School of Civil Engineering, Purdue University, West Lafayette, IN (1986).
19. Yee, Y.L. and Melchers, R.E. "Moment-rotation curves for bolted connections", *J. Struct. Eng.*, **112**(3), pp. 615-635 (1986).
20. Batho, C. and Lash, S.D. "Further investigations on beam and stanchions connection, including connections encased in concrete; together with laboratory investigations on a full-scale steel frames", Final Report of the Steel Structures Research Committee, Department of Scientific and Industrial Research. His Majesty's Stationery Office, London (1936).
21. Colson, A. and Louveau, J.M. "Connections incidence on the inelastic behavior of steel structures", *Proceedings of the Euromech Colloquium*, No. 174 (1983).
22. Kishi, N., Chen, W.F., Matsuoka, K.G. and Nomachi, S.G. "Moment-rotation relation of top- and seat-angle with double web-angle connections", *Proceedings of the State-of-the-Art Workshop on Connections and the Behavior, Strength and Design of Steel Structures*, R. Bjorhovde, J. Brozzetti and A. Colson, Eds., Superieure de Cachan, France (May 25-27, 1987).
23. Tan, C.S., Tahir, M.M. and Shek, P.N. "Experimental investigation on angle cleat connections for cold-formed steel sections", *Advanced in Steel and Aluminium Structures*, Research Publishing, Singapore, pp. 186-192 (2011).
24. Tan, C.S., Lee, Y.H., Lee, Y.L., Mohammad, S., Sulaiman, A., Tahir, M.M. and Shek, P.N. "Numerical simulation of cold-formed steel top-seat flange cleat connection", *Jurnal Teknologi, Sciences & Engineering*, **61**(3), pp. 63-71 (2013).
25. Lee, Y.H., Tan, C.S., Lee, Y.L., Tahir, M.M., Mohammad, S. and Shek, P.N. "Numerical modelling of stiffness and strength behaviour of top-seat flange-cleat connection for cold-formed double channel sections", *Applied Mechanics and Materials*, **284-287**, pp. 1426-1430 (2013).

26. Lee, Y.H., Tan, C.S., Mahmood, T. and Shahrin, M. "Numerical modelling and validation of light gauge steel top-seat flange-cleat connection", *J. Vibroeng.*, **14**(3), pp. 1104-1112 (2012).
27. Yu, W.K., Chung, K.F. and Wong, M.F. "Analysis of bolted moment connections in cold-formed steel beam-column sub-frames", *J. Constr. Steel Res.*, **61**, pp. 1332-1352 (2005).
28. Thacker, B.H., Doebling, S.W., Hemez, F.M., Anderson, M.C., Pepin, J.E. and Rodriguez, E.A. "Concepts of model verification and validation", Los Alamos National Laboratory, United State of America (October 2004).
29. Chen, W.F., *Practical Analysis for Semi-rigid Frame Design*, World Scientific, Singapore (2000).
30. Wong, M.F. "Bolted moment connections in cold-formed steel beam-column sub-frames", Master thesis. The Hong Kong Polytechnic University, Hong Kong (2002).
31. Lee, Y.H., Tan, C.S., Tahir, M.M., Mohammad, S., Shek, P.N. and Lee, Y.L. "Influence of angle thickness towards stiffness and strength prediction for cold-formed steel top-seat flange cleat connection", *Applied Mechanics and Materials*, **479-480**, pp. 1144-1148 (2014).
32. Ang, K.M. and Morris, G.A. "Analysis of three-dimensional frames with flexible beam-column connections", *Can. J. Civil Eng.*, **11**, pp. 245-254 (1984).

Biographies

Yeong Huei Lee obtained his PhD from Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM) in 2015. His research interests include, but not limited to, light steel framing, cold-formed steel, connection design, structural stability, rapid construction system and finite element analysis.

Cher Siang Tan is a senior lecturer in the Department of Structures and Materials, Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM). He has strong research interest in the field of structural steelwork, especially cold-formed steel, thin-walled structures and lightweight construction. He was also post-doctorate at École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland.

Shahrin Mohammad is a Professor in Department of Structures and Materials, Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM). He jointly published 10 books, monograph and standards. To date, he had jointly written more than 70 journals, seminar and conference papers both at the national and international levels. These papers addressed research findings as well as sharing experiences on the teaching and learning activities. Apart from this, 12 technical and academic administrative papers had also been written.

James B.P. Lim is currently a senior lecturer in The University of Auckland, New Zealand. His research interests lie in the field of steel-framed structures. With particular reference to portal frames and cold-formed steel. His research is dominated in trying to understand fundamental structural behaviour for which he employ a combination of numerical modelling and full-scale testing.

Ross Johnston is a PhD candidate in School of Architecture, Planning and Civil Engineering, Queen's University Belfast, United Kingdom. His research interests lie within Building Information Modelling (BIM) and Finite Element Analysis (FEA). He also has experience within sustainable construction and design/analysis compatibility.