Non-Linear Analysis of Bolted Extended End-Plate Steel Beam-To Column Connection

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Abstract. Bolted connection often use to transfer forces between steel structural members due to its practicality and speedy site erection. The actual behavior of the connection can be found by conducting laboratory test but it is time-consuming and expensive. Hence, in this study, non-linear analysis using LUSAS 14.0 is used as an alternative method to analyse the behaviour of extended end-plate connection. A model was first developed similar to the existing experimental model for validation. The results obtained from the finite element analysis were than compared with experimental results namely for the shape of moment-rotation (M-θ) curve, moment resistance and mode of failure. Also, data comparisons and validation are made between maximum capacity of the computer model and Eurocode 3. A parametric study was executed to determine the effect of plate thickness and number of bolt to behavior of the connection. The analysis shows that the shape of moment-rotation (M-θ) curve from computer model is almost similar with experimental specimen with percentage difference of 8.57%. Calculation from Eurocode 3 shows that the percentage difference of moment capacity value for the Eurocode 3 calculation and the software analysis is 7.49%. On the other hand, the thickness of end-plate slightly increased the connection behavior while number of bolts certainly increased the connection rigidity. From the moment-rotation curve, it was found that the plate thickness does not affected the rigidity and moment capacity of the connection while number of bolts had affected the rigidity and moment capacity where number of bolts increases the rigidity and moment capacity.

Introduction

Connection plays a crucial part in a steel framework as it attaches components together and transferring all relevant forces and moments between members. Failure in connections may cause the whole structure to fail. In order to understand the actual behavior of beam-to-column connection, a thorough analysis must be performed. Since experimental study is expensive and time-consuming, three dimension finite element analysis is the best method to study the connection behavior. It offers more accurate result, time-saving and cost-saving in terms of material.

In this research, the major focus is to determine the non-linear behavior of steel beam-to-column extended end plate bolted connection. To help achieve the aim, a three-dimensional finite element module was created similar to the experimental specimen, moment-rotation (M-θ) curve was obtained for the non-linear part of the extended end-plate connection, yield moment was calculated based on EN 1993-1-1: Eurocode 3 as a comparison and validation also parametric study was executed to determine the effect of thickness of plate and number of bolts towards the connection.

The scope of work includes modeling the extended end-plate bolted connection by finite element software, LUSAS 14.0 to study the non-linear analysis behavior of the connection also to perform parametric study namely number of bolts and plate thickness to the model.

Previous Studies

Study by [1] focused on moment rotation curve and deformation state of extended end-plate connection connected to column flange. Three test specimens with different in the end-plate thickness, number of bolt rows, beam and column size are chosen. Six models were generated by which three of them were using simplified bolt model and the rest using actual bolt model size. Results are then compared with experimental works to validate the data. It was found that smaller end-plate thickness will lead to lower value of moment resistance. Also, small size beam and column will have less strength to carry the moment applied by load.

For mode of failure, both experiment and LUSAS analysis showed same pattern which the failure comes from end-plate bending, column flange bending and bolt slip. However, inadequate data from experiment causes comparison other than moment resistance cannot be made with the computer analysis results from [1]. Also, data from actual tensile test that is carried out on the connection component should be obtained as it is required in defining the non-linear behavior of connection such as hardening slope and initial yield stress.

In [2], a beam to column end plate prestressed bolt connection was analyzed by ABAQUS program to simulate the behavior of end-plate bolted connection between beam and column. Six pairs of high strength bolt, M18/ 10.9 are used to connect between the beam and column. For simplification, the bolt head and nuts are modeled as circular, washer is not included in the simulation also bolt holes are equal with the bolt size.

From the analysis, the moment-rotation curve showed the ductility of connection starts after the curve reach 100 kNm. The highest stress area which is last row bolts subjected to tension is the cause of failure of both experimental specimen and numerical simulation.

The differences on nonlinear range between experiment and modeling specimen of [2] are believed come from the assumptions made earlier besides lack of information on material inelastic law and actual pretensioning force value used in experimental testing. Overall, the joint shows good behavior of semi-rigid connection type.

On the other hand, a research was conducted by [3] involving two specimens of extended end plate bolted connection trapezoidal web profiled beam with different dimensions, N3 and N4 were analyzed by LUSAS program to simulate the behavior of connection.

The study focused on the comparison of the moment rotation (M-θ) curve shape, moment resistance and mode of failure for each sample. The beam, bolts, column and end plate were assumed to behave as nonlinear material.

From the analysis of [3], it shows that the moment rotation (M-θ) curve shape and mode of failure between the finite element model and the experimental model are almost similar. From observation, both curves produced by LUSAS and experiment had similar trend. The connection behave linearly followed by nonlinear behavior when the connection progressively losing its stiffness.

The failure of both specimen N3 and N4 were due to the bending of column flange, bending of end plate and bolts deformation as shown in Figure 1 below. The failure shows the connection behavior of [3] as ductile hence act as semi-rigid connection.

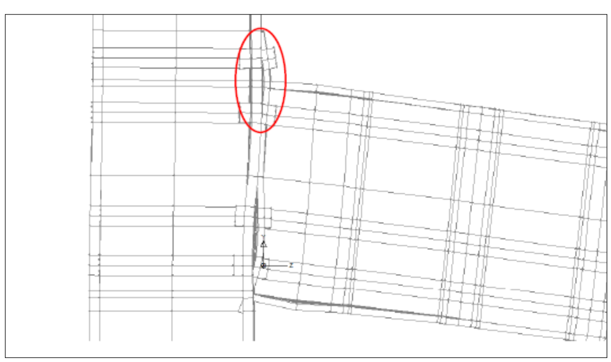

Figure 1: Failure of end-plate of [3]

Methodology

Connection dimension used throughout the modeling process are made as similar as possible with experimental model by [2]. For validation and check of modeling accuracy, moment rotation (M-θ) curve obtained from the analytical investigation was compared for validation with the full scale experimental result of the same model conducted by [2]. Theoretical value calculated from EN 1993-1-1: Eurocode 3 was also compared for validation with the LUSAS model. Besides, parametric study is executed to identify the rigidity of such connection.

Test Specimen

A total of six specimens were carried out in the full scale experiment. The experiment focused on a steel joint with end plate and prestressed bolts. The structure is designated as simply supported at beam ends as shown in Figure 2 below. Six pairs of high strength bolts M18/10.9 are used to connect between two beams with end plates assembled to a central column. A vertical force was applied on the top of column. As the full model was symmetrical on both sides, only a quarter section of the structure was considered to reduce the number of elements and analysis time.

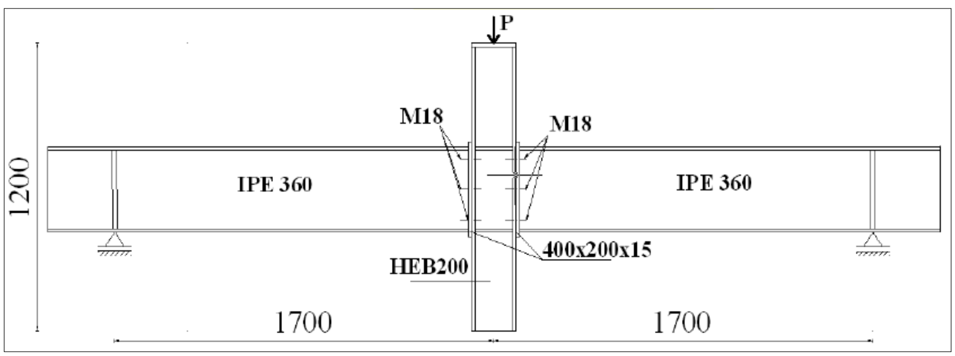

Figure 2: Geometry of the test specimen [2]

Structure Model Component

For the non-linear finite element analysis, this research focused on one specimen from previous test [2]. The components of the extended end-plate connection include beam, column, extended end-plate, stiffener, bolts and nuts.

Model Discretisation

In this research, the beam, column, end-plate, loading plate and bolt head were idealized as volume geometry with linear interpolation order to reduce complexity. The bolt shank was represented with line geometry for two dimensional bar element. Holes at the plate for installation of bolts were prepared with the same diameter. JNT4 joint element was used to model the interface between the column flange and the end-plate. The joint element was employed to provide non-linear support conditions [4]. Figure 3 shows the finite element mesh.

Non-linear Properties

In this research, non-linear material was considered in the bolts and interface between the end-plate and the column flange. For ease of analysis, the beam and steel material were set with linear properties. For elastic dataset, all elements are defined as elastic isotropic with a Young modulus value is taken as 209 x 103 N/mm2 and the value of Poisson ratio as 0.3. For plastic dataset of bolt, initial uniaxial yield stress is taken as 650 N/mm2 and 200N/m2 for column and end-plate.

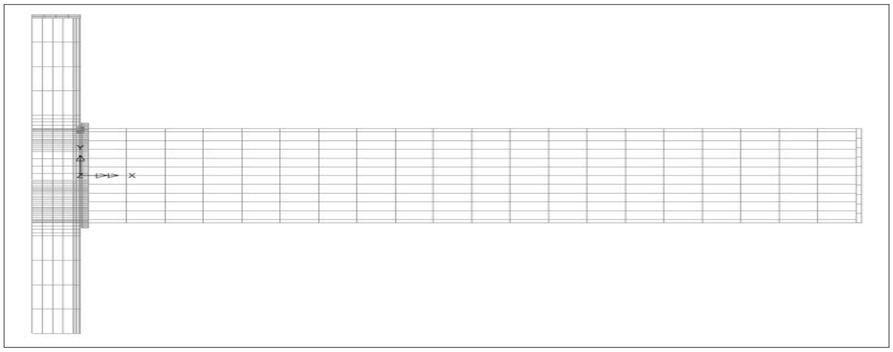

Figure 3: Finite element mesh

Boundary Condition and Loading

For boundary condition and loading, supports in all directions were restrained at all nodes for bottom end of the beam. Also, since the models developed are a quarter section of the full model, all the cutting area were restrained at X and Z axis. The loading will be applied at the top of the column in increments of 5 kN until the structure deforms.

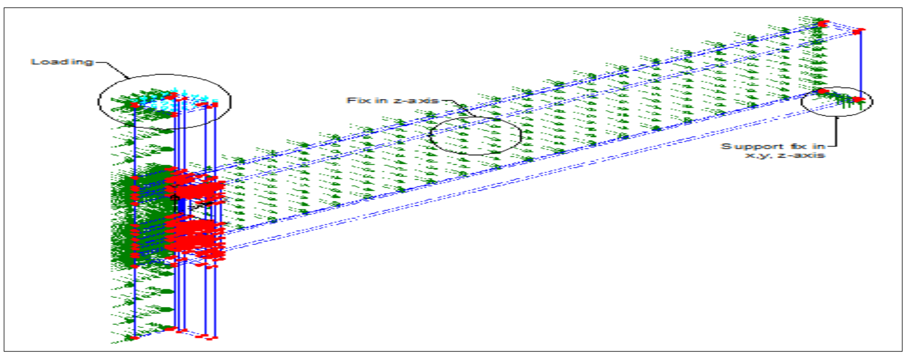

Figure 4: Boundary conditions and loading location for the LUSAS model

Theoretical Calculation

In order to obtain the maximum capacity of the structure from Eurocode 3, shear resistance and bearing resistance of bolts need to be checked. Below are the parameters that involved in the calculation of theoretical shear and moment resistance value from EN 1993-1-1: Eurocode 3:

1. Direct shear action $F_{v,Ed}$: $= \frac{P}{n}$ (1)
2. Shear action due to in-plane moment, $F_{t,Ed}$: $\frac{Per_{max}}{\sum y^2 + \sum z^2}$ where $r_{max} = \sqrt{y^2 + z^2}$ (2)
3. Shear Resistance of a single bolt, $F_{v,Rd}$: $= \frac{\propto_v f_{ub} A}{\gamma_{M2}}$ (3)
4. Bearing capacity of the connected part, $F_{b,Rd}$: $\frac{k_1 \propto_b f_{u,p}\, d t_p}{\gamma_{m2}}$ (4)
5. Vector sum of shear force, $F_{b,Rd} = \sqrt{{F_{v,Ed}}^2 + {F_{t,Ed}}^2 - 2F_{v,Ed}\, F_{t,Ed} \cos\theta}$ (5)

Parametric Study

A few parameters have been considered in the research to determine the effect of parameter on connection behavior. The parameters considered in this study are thickness of plate and number of bolt.

Three different dimension of end-plate thickness is applied to the model with size of 460x200x15, 460x200x18 and 460x200x20 mm. On the other hand, three different set of bolts number with same diameter, 18 mm is used in the analysis. The first and second set used two and three bolts while third set used four numbers of bolts.

Assumption

In this research, a few assumptions have been made to reduce complexity of the model. First, specimens are modeled to be undergoing material nonlinearity only, the beam and end-plate are modeled as one unit by welds hence will deformed as one, spring stiffness contact occurs between the interface of end-plate and column flange, nonlinearity effect is not considered in beam and column for ease of analysis and lastly expected failure occur as shear in bolt or else the structure will deformed.

Results and Discussion

From finite element analysis, both linear and non-linear part of the moment-rotation (M-θ) curve was validated with the experiment model to ascertain the model accuracy. Then, parametric study namely thickness of end plate and number of bolts parameter are taken into account. Mode of failure given by the LUSAS model was also being observed and compared with the experimental mode of failure.

Experimental Results

Figure 5 shows the moment-rotation (M-θ) curve for the experiment model. The curve is linear until about 105 kNm and connection ductility starts beyond that load.

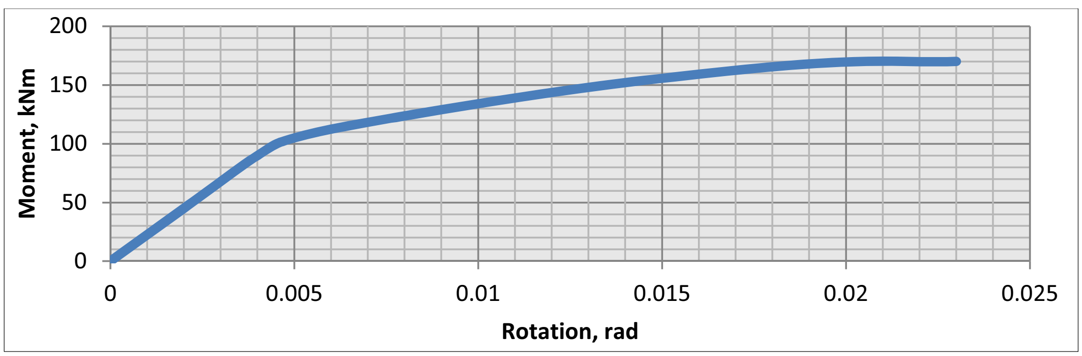

Figure 5: Moment-rotation (M-θ) curve of the experiment model

Non-linear Analysis Results

From the full experiment model, only quarter section was considered during LUSAS modeling due to symmetric arrangement. Only material nonlinearity is considered in this experiment. In this study, the position of displacement was obtained at point A as shown in Figure 6. After moment-rotation as shown in the example below was calculated, the moment-rotation (M-θ) curve for the LUSAS result was plotted as shown in Figure 7. The curve is linear up to near 114 kNm and the connection progressively losing its stiffness with increasing rotation in the nonlinear stage. Example calculation of moment:

Moment = P × L = 5 kN × 1.6 m = 8 kNm

Below is the example of calculation to obtain the value of rotation. Displacement at point A= -0.594924196 mm; Length of beam, L = 1600 mm; Calculation for rotation,

Rotation, θ = tan (displacement (dy)/length of beam(L))

= tan (-(-0.594924196)/1600)

= 0.000326067 rad

Result Comparisons

Experimental and LUSAS software. All moment-rotation (M-θ) curves show that the connection behaves linearly and followed by non-linear behavior. Comparison was made for the linear and non-linear part of the moment-rotation (M-θ) curve. The maximum load when the connection is about to fail is taken as the moment capacity of the connection.

Figure 7 below illustrates the non-linear graph of the LUSAS and experiment result. From the graph of the LUSAS results, two tangent lines were drawn and the value of yield moment was obtained. The yield moment of the connection from LUSAS is 114 kNm, which is slightly higher than the experiment value, 105 kNm. The plastic phase is slightly lower for the computer model compared to experimental specimen. The percentage difference for the LUSAS result and the experiment is 8.57% as shown in calculation below.

$$\text{Percentage Difference} = \frac{Experimental\ (\%) - Theoretical(\%)}{Experimental\ (\%)} \quad (6)$$

$$\text{Percentage Difference} = \frac{|105-114|}{105} x\ 100 = 8.57\%$$

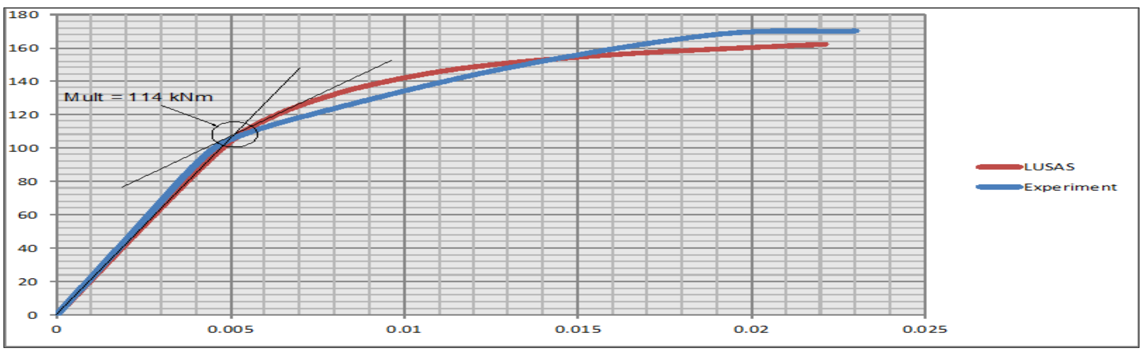

Figure 7: Moment-rotation (M-θ) curve

Experimental and Eurocode 3. By substituting equation 1 to 4 into equation 3 from paragraph 3.6, the yield moment of the connection from [5] calculation is 126.47 kNm, which is slightly higher than the experiment value, 114 kNm. The percentage difference for the [5] calculation and the software analysis is 7.49%. Shear resistance is not conservative as the difference in value is too far apart where direct shear action, Fv,Ed is 26.35 kN while the shear resistance value, Fv,Rd is 91.6 kN.

Table 1: Comparison of yielding moment

Finite Element Analysis (kNm)	Test Result (kNm)	Resistance Moment (EC 3) (kNm)
114	105	126.47

Mode of Failure

Figure 8 and Figure 9 shows the actual connection before analysis and the failure mode of the connection. The failure was occurred between the column flange and the end-plate. Figure 10 illustrates the highest value of yield stress, 400 N/mm2 was at the end-plate. By the time the bolt failed, end-plate already yielded. Failures show that the connection behave as ductile material and can be categorized as semi-rigid connection.

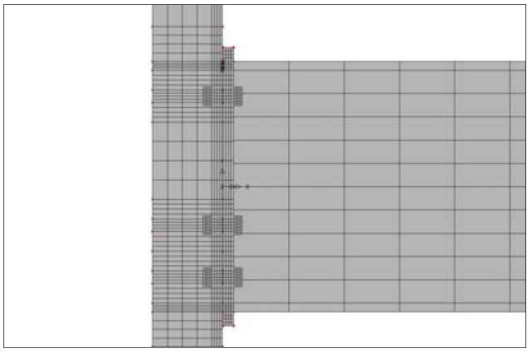

Figure 8: Finite element mesh before analysis

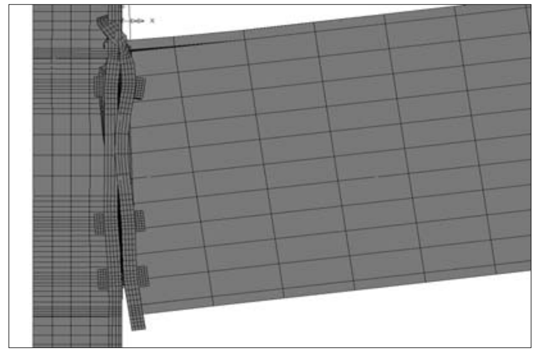

Figure 9: Finite element mesh after failure

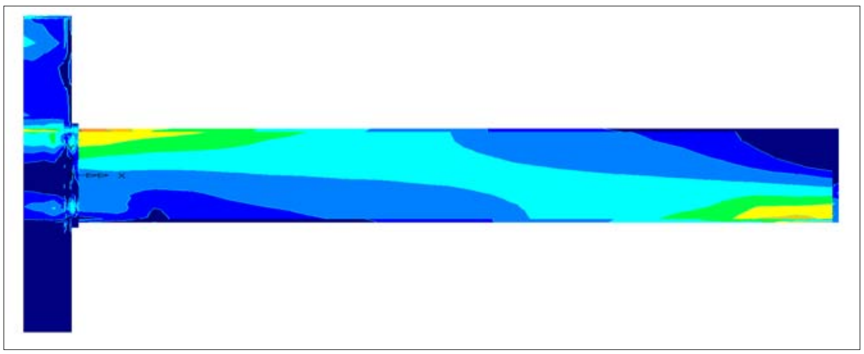

Figure 10: Stress Equivalence (SE) of the model

Parameter Study

Thickness of extended end-plate. The analysis was executed to determine the effect of different end-plate thickness towards the model behavior. Three different dimension of end-plate thickness as shown in Table 2 below was applied to the model. The result of moment-rotation (M-θ) curve obtained was presented in the Table 3 and Figure 11.

Table 2: End-plate dimension

Plate no.	Dimension
T1	460x200x15
T2	460x200x18
T3	460x200x20

Table 3: Comparison for thickness of plate

Plate no.	Dimension
T1	116.0
T2	116.4
T3	116.7

From the Figure 11, the red line represented the plate thickness of 15 mm, the blue line represented the plate thickness of 18 mm and the green line represented the plate thickness of 20 mm. From the graph, different size of plate has shown different behavior of moment-rotation (M-θ). The behavior of the connection was measured through the yield moment from the graph in Figure 10 and the yield moment was compared with theoretical value as shown in Table 3. End- plate thickness did not affect the connection strength and did not change the behavior and ultimate condition of the connection

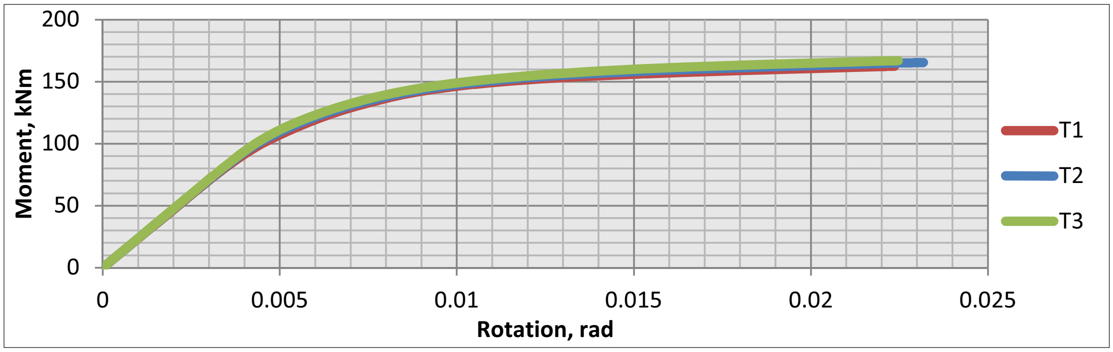

Figure 11: Moment-rotation (M-θ) curve for different plate thickness

Number of Bolt. The analysis was executed to determine the effect of different number of bolt towards the model behavior. Three different set of bolts as shown in Table 4 below was applied to the model. The result of moment-rotation (M-θ) curve obtained was presented in the graph in Table 5 and Figure 12.

Table 4: Bolt number

Bolt no.	Number of Bolt
B1	2
B2	3
B3	4

Table 5: Comparison for bolt number

Bolt no.	Finite Element Analysis
B1	116.5
B2	118.0
B3	120.0

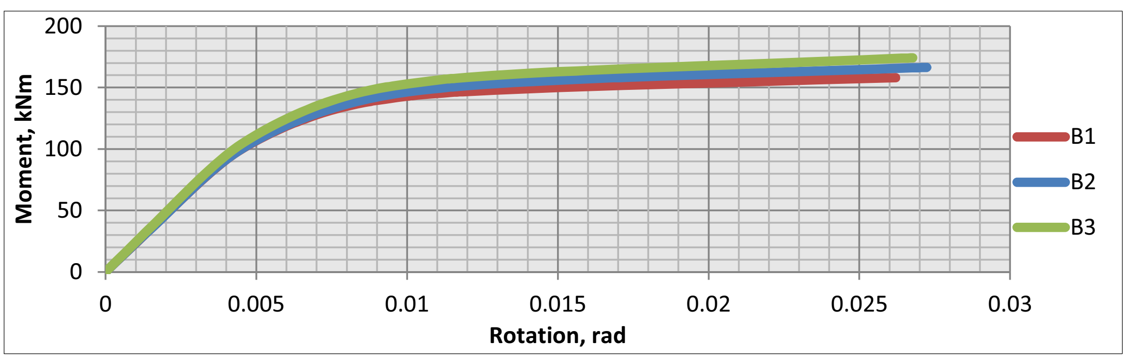

Figure 12: Moment-rotation (M-θ) curve for different number of bolt

Figure 12 illustrates the result of the different number of bolts obtained from the analysis. From the graph, the red line represented the bolt B1, the blue line represented the bolt B2 and the green line represented the bolt B3. The behavior of the connection was measured through the yield moment from the graph. From the graph, different number of bolts has shown different behavior of moment-rotation (M-θ). Higher number of bolt used resulted in higher yield moment value. Model with less number of bolt possess less strength to sustain the moment caused by applied load. Hence, specimen B1 gives the smallest yield moment compared to specimen B2 and B3. In all, number of bolts did affect the connection strength and changed the behavior and ultimate condition of the connection.

Conclusion

This paper presents the non-linear behavior of steel beam-to-column extended end plate bolted connection. The linear phase of the moment-rotation (M-θ) curve from the model have almost similar trend with experimental curve while the non-linear phase is slightly lower for the computer model. The calculation of yield moment and shear action value from EN 1993-1-1: Eurocode 3 has successfully carried out. Comparison of the moment-rotation (M-θ) curve from experimental testing and LUSAS model, the percentage different obtained was 8.57% while the percentage different between the yield moment obtained from finite element analysis and theoretical value was 7.49%. The theoretical value of the connection from Eurocode 3 shows good correlation with the yield moment from the LUSAS. Besides, the parametric study has successfully conducted to the LUSAS model. Three set of model with different extended end-plate thickness and three set of model with different number of bolts were developed. From the moment-rotation curve, it was found that the plate thickness does not affected the rigidity and moment capacity of the connection while number of bolts had affected the rigidity and moment capacity where number of bolts increased the rigidity and moment capacity of the connection.

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