Non-Linear Analysis of Bolted Flush End-Plate Steel Beam-to-Column Connection

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Abstract. Moment-rotation curve is a method for representing the stiffness, strength and ductility of a connection. In order to obtain the rigidity of the moment-rotation (M-θ) curve, numerical modelling which based on finite element method (FEM) can be one of the methods besides full scale laboratory test. However, this alternative approach needs to be validated to ensure that the simulation based result gives the exact behaviour as full scale laboratory test. The purpose of this study is to develop and validate the finite element model using LUSAS 14.0 for the comparison with the experimental results and also theoretical calculation based on Eurocode 3. The moment-rotation curve obtained from finite element analysis was compared with the moment-rotation curve from a full scale laboratory results. It was found that the two curves coincide quite well with the percentage difference of only 4.76%. Furthermore, through theoretical calculation based on Eurocode 3, the moment resistance of the connection was then compared with finite element analysis which having slightly difference of 3.77%. Thus, it is proven that using numerical simulation it can give approximately same behaviour with laboratory testing. In addition, after the behaviour of finite element model had been verified with experimental and theoretical, parametric study was carried out considering a few parameter which were thickness of flush end-plate and number of bolts. All models were compared to theoretical calculation. By using variable number of bolts; 2, 3, and 4 bolts the percentage differences were 3.96%, 3.77% and 4.17% respectively as compared with theoretical while variable thickness of flush end-plates; 15 mm, 18 mm, and 20 mm were 3.77%, 1.49% and 4.26% respectively. After that, the graphs of moment-rotation curve for each parameter were plotted and examined. It can be concluded that the number of bolts does not affect the rigidity and moment capacity of the connection as there is not much difference between moment-rotation curves. Thus, rigidity of the beam-to-column connection was largely affected by the thickness of plate as the thicker the end-plate, the less rotation and higher moment can be applied to the connection.

Introduction

Connection is the most important element in structural steel construction to transfer moment and axial load between two members such as beam to beam and beam to column to avoid failure of structure. Analysis of connection to obtain the moment-rotation behaviour is important as it represents the rigidity of the connection [1]. Behaviour of the connection can be observed through laboratory testing but it is harder, tedious and costly to analyse the performance of connection [2].

In order to ease the analysis in determining the rigidity of the bolted flush end-plate, mathematical modelling is another alternative approach to simulate the same behaviour of connection. With the aim of obtaining the same connection behaviour as full scale laboratory, validation and verification of the mathematical modelling based on finite element analysis must first being approved comply with allowable having slightly difference between both experimental and numerical results. In addition, numerical simulation also can be validated with the calculation on capacity of structure based on Eurocode 3: Design of Steel Structure. Hence research based on finite element analysis will be conducted to validate the moment rotation behavior of flush end-plate beam-to-column to be compared with the experimental result and also theoretical value. The purpose of this study is to develop 3D model of bolted flush end-plate connection having the same geometry as being tested in laboratory by using LUSAS 14.0 software. Plus, theoretical calculation will be made to identify the resistance moment of the structure based on Eurocode 3 for all models.

Parametric study considers two parameters which are number of bolts and thickness of plate are carried out after verification of finite element model is made. The values for each model are also compared with theoretical value. The objective is to study the contribution of both parameters to the rigidity of the connection. Non-linear analysis will be performed on the beam-to-column connected with bolted flush end-plate. All the geometric properties are referring to the experimental model that cited in [3] to allow valid comparison of results. LUSAS 14.0 version based on finite element analysis had been selected to be used as analysis tools as it is friendly user software and able to conduct complex structure.

Previous Studies

Based on a review made in [3], the study focus on non-linear analysis of beam-to-column end-plate bolted connection. The analysis tools used in the study was ABAQUS software. Other than, a study done by [4] focus on the finite element analysis of semi-rigid connection by using LUSAS software.

The purpose of the study in [3] is to validate the ABAQUS model with laboratory result through the moment-rotation (M-θ) curve. It is found that the graph from ABAQUS model was approximately same as experimental graph. However, the result from ABAQUS does not compared with theoretical value based on Eurocode 3 to convict the finite element model as alternative approach.

Based on [4], the aim of the study is to approve the alternative meshing techniques can illustrate the behaviour of the connection. The percentage different of the results between experimental and numerical model was in a range of 0.4% to 1.11%. Parametric study does not been carried out in this study to determine the effect towards the rigidity of the connection.

Methodology

Three-dimensional finite element model was developed having exactly similar dimension to the actual experimental model using LUSAS 14.0 software so that the comparison between both modelled can be validated. The experimental structure consists of two beams connected to column flange, end plate and high strength bolts as being applied in [3] as shown in Figure 1.

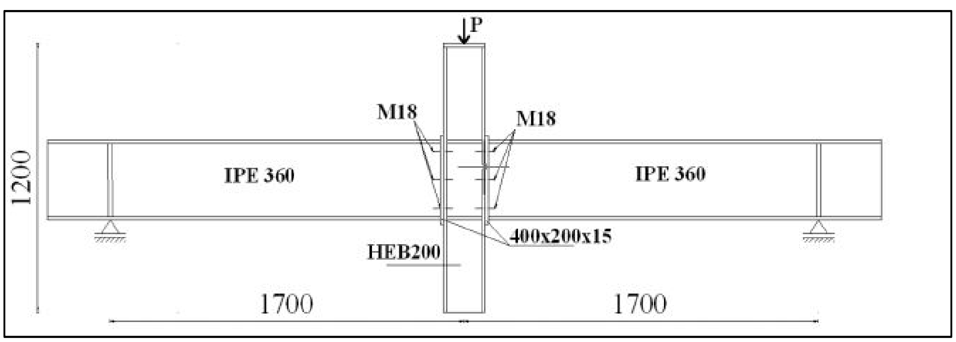

Figure 1: Geometry of test specimen [3]

Geometry of the Model

In this study, it was considered only one side of the structure to reduce the model size and complexity of analysing. The finite element model consists of a beam, column, flush end-plate and bolts. The geometry of the model was shown in Figure 1. Three high strength bolts M18/10.9 were used. The beam and column were I and H profiles respectively. In order to produce the same behaviour as a full scale laboratory model, displacement in X, Y and Z direction were restrained at all nodes at the bottom surface end of beam.

Discretisation of the Model

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. The end-plate and beam were modelled as one unit to show that both elements were welded to each other as well as column and loading plate. This is because welding is generally does not cause failure to the structure [3]. The surface of end-plate and cross-section of beam and column and loading plate were connected using tied slideline function by assuming no friction occurs between the surfaces. Holes were prepared at the plate for installation of bolts with the same diameter. Figure 2 shows the finite element mesh.

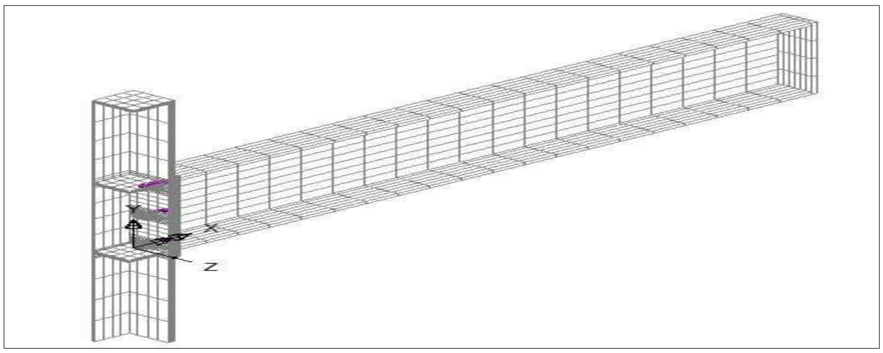

Figure 2: Finite element mesh

Non-linear Properties

In this study, the non-linear material property was assigned to part of the structure such as column, end-plate and bolt. JNT4 element was assigned to indicate interface between the end-plate and column flange having non-linear type of joint including with joint material. All values used in this model were as same as the laboratory model. For elastic dataset, all elements were defined as elastic isotropic with a Young modulus value was taken as 209 x 10^3 N/mm^2 and the value of Poisson ratio as 0.3. For plastic dataset of bolt, initial uniaxial yield stress was taken as 600 N/mm^2 and 200N/m^2 for column and end-plate. The contact spring stiffness was taken as 1000 N/mm^2 at first and by trial and error method the suitable K value was assigned to be 100 N/mm^2 after the moment-rotation curve obtained from the analysis was closed to the experimental curve.

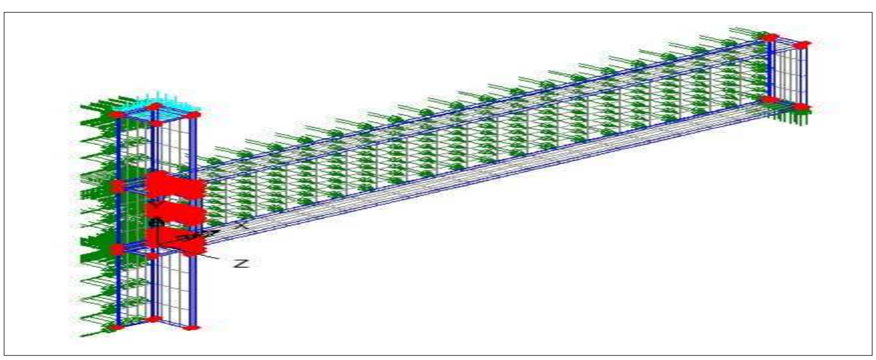

Figure 3: Location of support

Load Application and Boundary Condition

The nodes at the bottom part at the end of the beam were restrained in X, Y and Z axis from any displacement. In addition, as the structure was modelled considering the quarter section of the exact structure, the cutting plane was restrained in x and z direction. Load of 5 kN was gradually increased and applied at the plate above the column.

Theoretical Calculation

According to design steps in [5], in order to obtain the resistance moment of bolted structure, there were few factors to be checked. All calculation was based on equation from [5]. The variable that need to take into account are:

1. Shear Resistance of a single bolt, $F_{v,Rd}$: $= \frac{\propto_v f_{ub} A}{\gamma_{M2}}$ (1)
2. Bearing Resistance of the structure, $F_{b,Rd}$: $\frac{k_1 \propto_b f_{u,p}\, \mathrm{d} t_p}{\gamma_{m2}}$ (2)
3. Shear action due to In-plane moment, $F_{t,Ed}$: $\frac{\mathrm{P} e r_{max}}{\sum y^2 + \sum z^2}$ (3)

   where $r_{\max} = \sqrt{y^2 + z^2}$ (3.1)
4. Direct shear action $F_{v,Ed}$: $= \frac{\mathrm{P}}{n}$ (4)
5. Vector sum of shear force

As concern, only bearing resistance value is substituted into the vector sum of shear force as the value from shear resistance is not conservative. It also can be said that shear resistance does not control the rigidity of structure as is the implementation of higher load factor. The value of bearing capacity is being substitute in $F_{R,Ed}$as well as other variable into equation (5) to obtain the ultimate load that cause structure to yield.

$$F_{R,Ed} = \sqrt{({F_{v,Ed}}^2 + {F_{t,Ed}}^2 - 2F_{v,Ed}F_{t,Ed} \cos\theta)} \quad (5)$$

Parametric Study

Parametric study was carried out after the validation and verification of the finite element model. All the meshing shape, material properties from previous model were assigned to all specimens in parametric study. In this research, there are two parameters that being conducted namely number of bolts and thickness of plate. Each parameter was applied to three specimens.

Number of bolts. Different number of bolts was assigned to the models. Diameter of bolts was fixed to 18mm and thickness of plate was set to 15 mm. The locations of the first and last bolts were fixed to its location to maintain the distance from the top and bottom to the center of bolt. The numbers of bolt for each specimen were shown in Table 1.

Table 1: Number of bolts

Specimen	Number of bolts (diameter =18mm)
1	2
2	3
3	4

Thickness of Plate. The end plate section that was assigned is 400 x 200 x 15mm. Number of bolt was fixed to three. For conducting the parametric study, the thickness of plate was varied as shown in Table 2.

Table 2: Thickness of plate

Specimen	Thickness of plate (mm)
1	15
2	18
3	20

Results and Discussion

The result of finite element model was compared to laboratory and theoretical value based on Eurocode 3 to identify the accuracy of the numerical approach based on finite element analysis considering non-linear behaviour of the flush end-plate. For experiment and LUSAS model the comparison on the aspect of moment rotation (M-θ) was made at the specific node. The moment at yielding point was used in calculating the percentage difference between two curves. Based on theoretical, the resistance moment was obtained and was compared with value from graph. Plus, parametric study on variety number of bolts and thickness of end-plate of flush end-plate by considering non-linear behaviour were carried out. The graphs for each model were compared with each other to determine the effect toward the structure.

Experimental Result

As referred to the selected experiment in [3], the deflection or displacement of the structure was obtained from potentiometric sensors with an accuracy of 1/100 of millimetre and considering non-linear behaviour. Yielding moment for the beam-to-column connected by flush end-plate connection was approximately 105 kNm and started to have plastic property until it failed as shown in Figure 4.

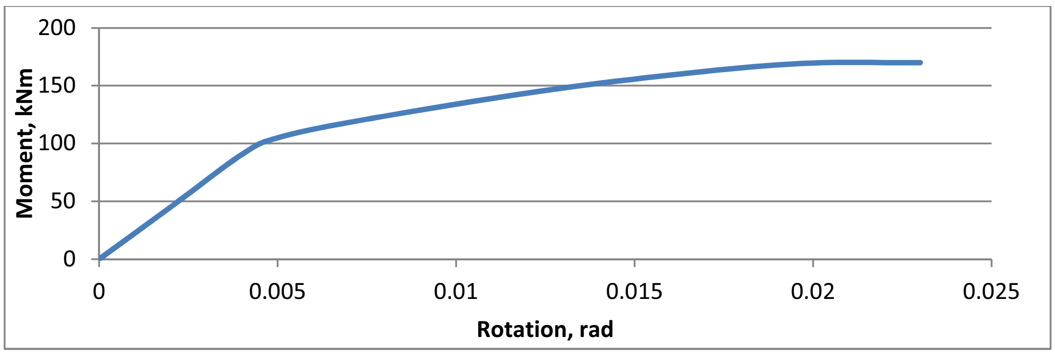

Figure 4: Moment-rotation (M-θ) curve of experiment

LUSAS Result

In this study, the position of displacement was obtained at point A as shown in Figure 5. After undergo moment-rotation calculation as refer to example calculation, the graph was plotted as shown in Figure 6.

Example calculation:

1. Calculation of moment (Length of beam, L = 1.6 m; Loading applied, P = 5 kN)
   Moment = P × L = 5 × 1.6 = 8 kNm
2. Calculation of rotation (Displacement obtain from model, dy = -0.521707×10^{-3} m; Length of span = 1.6m)
   Rotation, $\theta = \tan^{-1}(dy/\theta) = 0.000326067$ rad

The moment-rotation curve obtained after the finite element model was compared with the experimental curve. The difference of yielding moment of both graphs was found by using 0.2% offset [8] approach as it is general method to be used in obtaining yield point. The curve from finite element analysis was linear up to 110 kNm and the curve from laboratory was linear up to 105 kNm. It was found that the percentage difference between both graphs was 4.76% as shown in calculation below.

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

Percentage Difference = $\frac{|105-110|}{105} x\ 100 = 4.76\%$

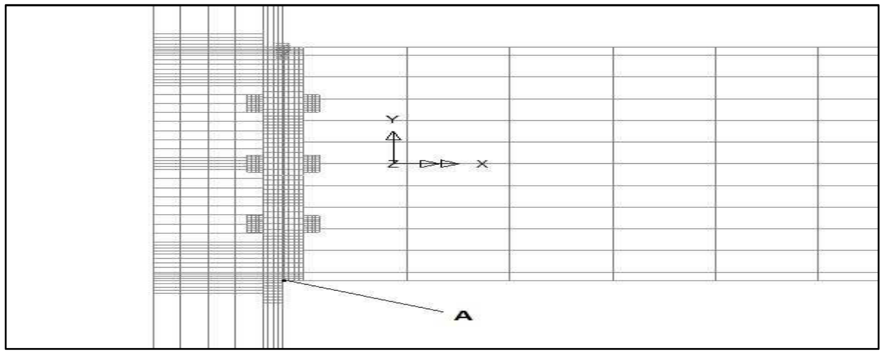

Figure 5: Location of displacement, dy

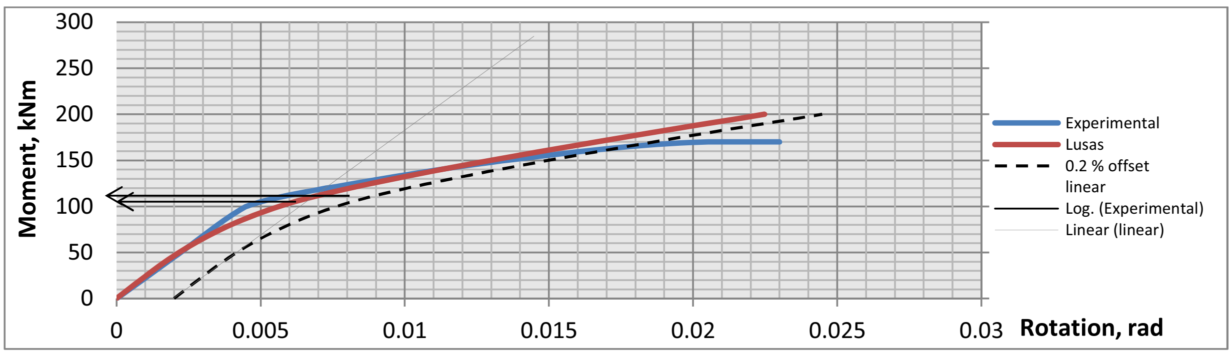

Figure 6: Moment-rotation curve for experimental and finite element model

Theoretical Result

By substitute value from equation 1 – 4 from into equation 5 from paragraph 3.5, the value of P obtained was 66.2 kN. This load was then multiply with 1.6 m to obtain moment which was 106 kNm. Thus the percentage difference between finite element analysis and theory was 3.77% as calculated using equation 6. The comparison values from finite element analysis, laboratory and theoretical were presented in Table 3. All values were approximately closed to each other. Finally, the mathematical model can be used as alternative method to analyse the behaviour of the structure.

Percentage difference = $\frac{|106-110|}{106} X\ 100 = 3.77\%$

Table 3: Comparison of yielding moment

Finite Element Analysis (kNm)	Test Result (kNm)	Resistance Moment (EC 3) (kNm)
110	105	106

Mode of Failure

Figure 7 below illustrated the mode of failure of finite element analysis. The deformation occurred between the flange of the column and flush end-plate. Based on Figure 8 the structure had highest yield stress of 691.1 N/mm^2 at the flush end-plate as supported by the parametric study that showed the thickness of plate affect the rigidity of the connection. It was found that the higher the loading, the larger the opening at the bottom of the plate. The deformed shaped of end-plate was shown in Figure 9.

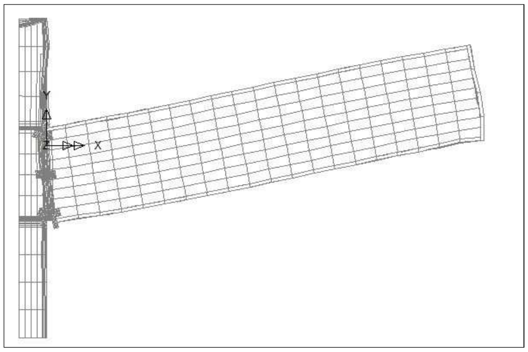

Figure 7: Mode of failure of LUSAS model

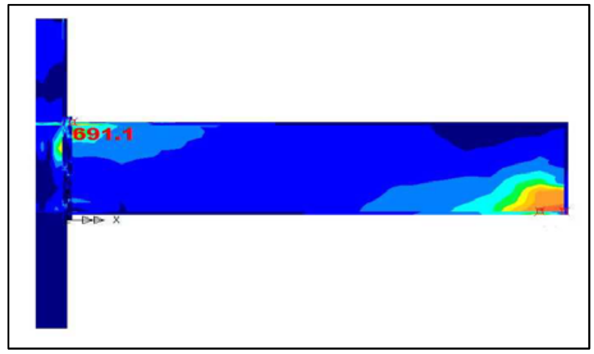

Figure 8: Stress Equivalence (SE) of the model

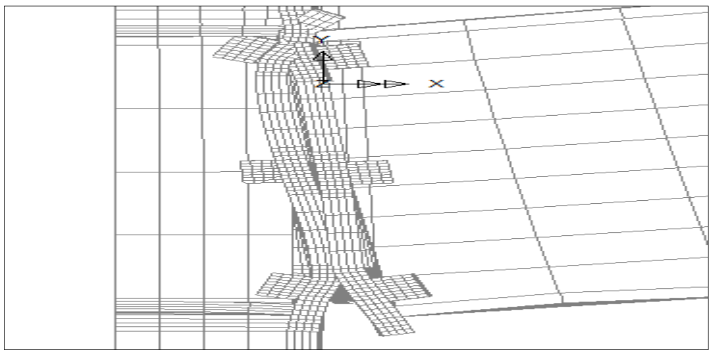

Figure 9: Close-up of the deformed shape

Parametric Study Result

As the accuracy and reliability result from finite element had been verified with the experimental result [3] and theory [5], a non-linear parametric study was then carried out to determine the behaviour of flush end-plate beam-to-column connection. There were two parameters being considered in this study to identify which parameter that affect the behaviour and moment-rotation curve of the structure. The parameters were thickness of plates and number of bolt. The thickness of flush end-plate being used was 15mm, 18mm and 20mm. A number of 4, 6 and 8 bolts were implemented to the model as the second parameter. The load, mesh and material properties were the same for each model. Theoretical value was then calculated for each models and comparison was made for each parameters.

Number of bolt. The results of variation of number of bolts used for the connection of column flange and flush end-plate were calculated same as in paragraph 4.2. The yielding moments were compared with theoretical value and percentage differences were presented in Table 4. The moment-rotation (M-θ) curves for three models were plotted in same graph to observe the behaviour of the beam-to-column connection as shown in Figure 10. Based on the graph, it showed that number of bolts do not affected the rigidity and moment capacity of the connection.

Table 4: Comparison value for number of bolts

Number of bolts (no)	Finite Element Analysis (kNm)	Resistance Moment (EC 3) (kNm)	Percentage difference (%)
2	105	101	3.96
3	110	106	3.77
4	115	120	4.17

Thickness of Plate. Different thickness of plates gives different moment-rotation (M-θ) curve. The calculation to obtained moment and rotation were the same as in paragraph 4.2. The yielding moment was compared with theoretical value and percentage difference for each model was presented in Table 5. The moment-rotation (M-θ) curve was plotted for all thickness of flush end-plate as shown in Figure 11. Based on the graph, it showed that thickness plate do affected the rigidity of the structure. The graph of moment-rotation (M-θ) for each size of plate has shown different behaviour.

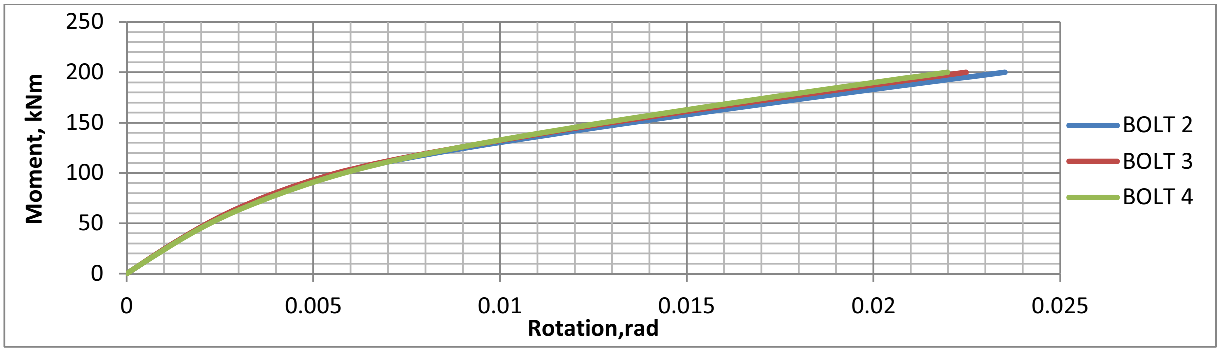

Figure 10: Moment-rotation (M-θ) curve for three number of bolt

Table 5: Comparison for thickness of plate

Thickness of Plate (mm)	Finite Element Analysis (kNm)	Resistance Moment (EC 3) (kNm)	Percentage difference (%)
15	110	106	3.77
18	124	126	1.59
20	147	141	4.26

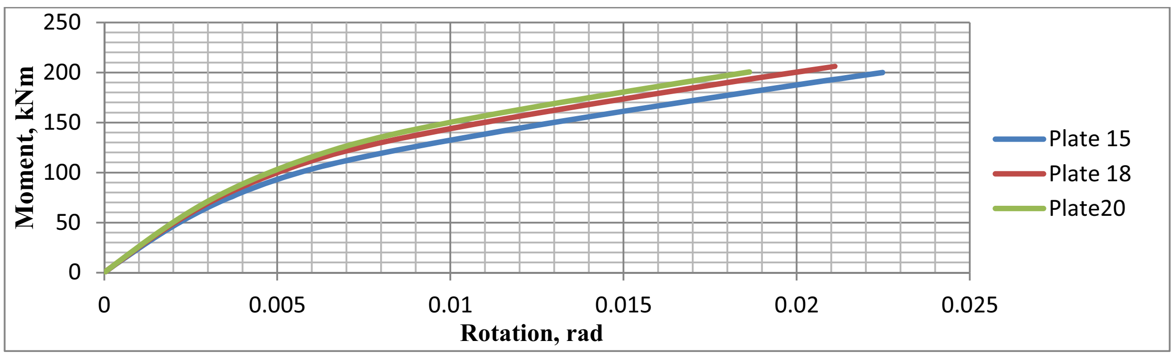

Figure 11: Moment-rotation (M-θ) curve for three thickness of end-plate

Conclusion

From the results of this study, it can be concluded that a finite element model had been successfully developed by using LUSAS 14.0 software which having approximately same to the laboratory model. By comparison the moment-rotation (M-θ) curve from laboratory testing and LUSAS model, the percentage different obtained was 4.76%. Furthermore, to support the result obtained from experimental, resistance of structure had been determined. The percentage different between the yielding moment obtained from finite element analysis and theoretical value was 3.77%. Besides that, the finite element analysis had allowed non-linear parametric study being carried out considering the thickness of plate and number of bolts. The theoretical values for the both parameter were calculated for each models. The percentage difference for number of bolts 2,3 and 4 were 3.96%, 3.77% and 4.17% respectively. For thickness of plate, the percentage difference were 3.77%, 1.49% and 4.26% for 15mm, 18mm and 20mm plates respectively. From the moment-rotation curve, it was found that the number of bolts does not affected the rigidity and moment capacity of the connection while thickness of plate had affected the rigidity and moment capacity where thicker plater increases the rigidity and moment capacity.

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