Paper 5

Numerical Evaluation of Column Base Rigidity

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Abstract

Fixity and behaviour of the steel column base connection have been studied in the current investigation. The effects of components such as base plate, anchor bolts and stiffeners have been considered through a numerical study. A non-linear three dimensional finite element model has been utilized to simulate the column base connection. It is shown that the connection behaviour such as its moment-rotation property and stress distribution can be significantly influenced by altering each of the mentioned component properties. Besides, the upper and lower bounds for rotational stiffness and ultimate strength of column base connections were obtained and categorized and appropriate recommendations were made for use for analytical modelling of steel structures in order to have more realistic and accurate design.

Keywords: base connection, rigidity, rotational stiffness, steel structures, numerical analysis, finite element.

1   Introduction

One of the most important components in steel structures is the base connection. Determination of column base rigidity has been a major challenge for civil engineers. In reality, the majority of column base connections show relatively semi rigid behaviour. Nonetheless, due to difficulties in assessment of the degree of rigidity, it is a common practice to assume a fully rigid or fully pinned behaviour when a column base is being designed. It is worth to mention that any difference between the actual behaviour of the column base and the presumed rigidity of the connection may affect overall behaviour of the whole frame. Hence structural engineers use a wide range of detailing to assure the degrees of rigidity assumed in the design of structure.

Some theoretical and experimental studies have been conducted on the column base connection. Jaspart and Vandegans carried out several experimental tests and

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observed that the main failure modes of column base connection are failure of the anchor bolts, yielding of the base plate and crushing of the concrete [1]. They also found out that the bond between the anchor bolts and the concrete is negligible, hence the anchor bolts can be assumed to be free to extend in tension from the beginning of loading. Hon and Melchers considered the so-called "pinned" column base connection and assessed the effects of some parameters such as base plate thickness and anchor bolt size [2]. The experimental test results indicate that the connection stiffness clearly increases with the increase of the plate thickness and the anchor size. Ermopoulos and Stamatopoulos have performed an analytical study on the base connection [3]. They considered parameters such as size and thickness of base plate, size and location of anchor bolts and the amount of axial load, they proposed an analytical procedure which led to moment-rotation curves of the connection according to various amounts of the considered parameters. Besides, a simple formula was presented which described the non-linear relation between moment and rotation of the connection that was in good agreement with those obtained from analytical study.

However, statistical studies of the damages in steel structures, such as reports by the Technical Council on Lifeline Earthquake Engineering and the Northridge Reconnaissance Team [4], indicate that during earthquake excitations column base connections have not performed properly. It apparently reveals the need for more comprehensive studies in order to have more realistic understanding of the real behaviour of the column base connection.

The current investigation evaluates the effects of some the most commonly used components of the base connections, among them base plate, anchor bolts and stiffeners can be mentioned. A nonlinear three dimensional finite element model has been utilized to simulate the column base connection. The thickness of base plate and stiffeners and also the size and configuration of anchor bolts were changed in a number of models in order to assess their influence on moment-rotation properties and stress distribution of the connection. Furthermore, a series of tests were carried out to define the upper and lower bounds for rotational stiffness and ultimate strength of the base connection. Therefore, several base connection details which represent nominally "pinned" and "fixed" connections were considered and their rotational stiffness and ultimate strength were obtained from their moment-rotation curves.

2   Finite element modelling

In the current study, a three-dimensional finite element analysis (FEA) has been performed in order to assess the nonlinear behaviour of column base connection. The numerical simulation was performed with the ABAQUS software [5]. Due to the symmetry of the model, only half of the connection was modelled as shown in Figure 1. The connection main components like concrete block, anchor bolts, base plate and column, were modelled as separate parts and then the parts were assembled and located depending on their true configuration. The symmetric boundary condition was applied to the surfaces at the symmetric plane of the

specimen. As it is shown in Figure 1, all degrees of freedom at the bottom surface of the concrete block were constrained, whereas all degrees of freedom on the lateral sides of it were released. All components were modelled with 8-node brick elements with three translational degrees of freedom at each node and reduced integration stiffness as shown in Figure 2. This element can be used for nonlinear analysis including contact, large deformation, plasticity and failure.
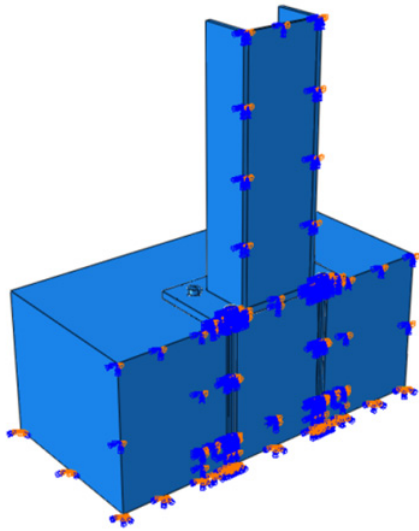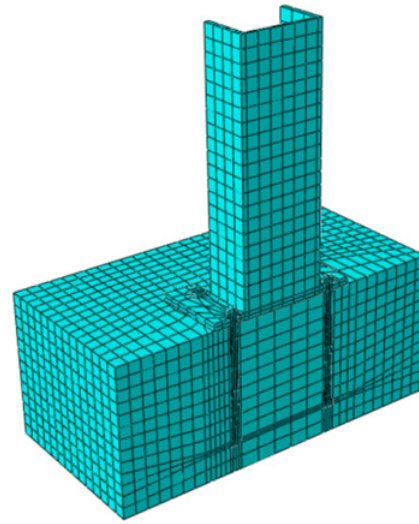

Figure 1: Boundary conditions of the model   Figure 2: The meshed model

Appropriate constrains were imposed to describe the interaction between components. Friction coefficient equal to 0.55 was assumed for the interfaces. No bond was considered for the interface between the anchor rod and the concrete block as it was suggested by previous study conducted by Jaspart and Vandegans [1]. In order to apply bending moment to the connection, an incremental lateral load was applied to the top of the column. Both geometric and material nonlinearity were included in the finite element analyses.

Steel yielding and ultimate stress for column and base plate were considered to be 2400 and 3800 kg/cm^2 respectively, those values were 3000 and 5000 kg/cm^2 for anchor bolts. Von Misses yield criterion and isotropic hardening were employed for non-linear modelling. Poisson's ratio and the young's modulus of steel were taken as 0.3 and 2.1e6 kg/cm^2, respectively.

The Concrete Damage Plasticity model available in the software material library was used to model the concrete in this study [5]. The behaviour of the concrete material consists of two main parts. The first part is initially assumed to be in the elastic range until the proportional limit stress. The value of the proportional limit stress was taken as $0.45f'_c$, as mentioned in ACI 318-08 [6]. The young's modulus was taken as 2.2e5 kg/cm^2. The second part of the curve is the non-linear portion starting from the proportional limit stress ($0.45f'_c$) and going to the concrete specified compressive strength (f'_c). The Poisson's ratio of concrete was assumed to be 0.15. In the current study, the concrete specified compressive strength was considered to be 210 kg/cm^2.

3 Verification of numerical models

In order to calibrate the numerical analyses, the experimental model created by Jaspart and Vandegans [1] was modelled numerically. The test model consisted of a 60x60 cm concrete block, a HE160B steel column, a 34x22 cm base plate with 15 mm thickness and four M20-10.9 anchor bolts. The column and base plate steel grades were S355 and S235, respectively. Loading was applied in two steps: preliminary application of 100 KN compressive force on the column which remains constant, following by a progressive application of lateral force until the collapse. Figure 3 shows a comparison between the moment-rotation curves obtained from experimental and numerical models.
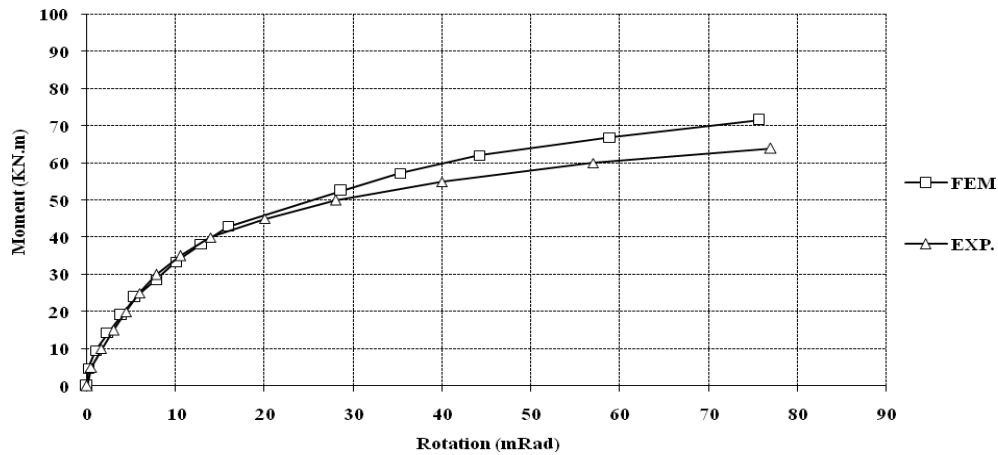

Figure 3: Moment-Rotation curves of the experimental and numerical models

Despite lack of enough information about some parameters such as the ultimate strain of steel materials and precise stress-strain behaviour of anchor bolts, Figure 3 reveals an acceptable agreement between the numerical and experimental models, especially in the elastic and elasto-plastic phases. Besides, the collapse mode of the connection, in the experimental model, was the yielding of the base plate which is confirmed through the numerical modelling.

4 Parametric study

Several parameters influence the real behaviour of column base connection. In the current study the effects of base plate thickness, anchor bolts size and configuration and stiffeners dimension is studied. In each case, corresponding changes were applied to a reference column base connection model (Ref.). The reference model consists of a 60x60 cm base plate with 3 cm thickness, six M28 anchor bolts and a 140x140 cm concrete block. The attached column flange and web dimension are 40x2 cm and 30x2 cm, respectively. The connection configuration is presented in figure 4. The material properties of the connection components are mentioned in part 2.
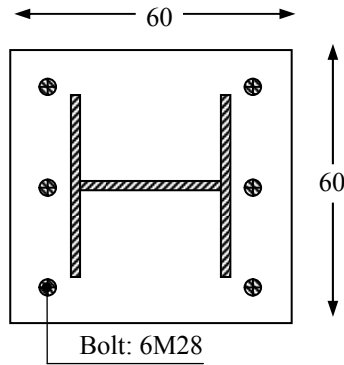
Figure 4: Reference model configuration

4.1 Base plate thickness

In order to investigate the effect of base plate thickness on the behaviour of column base connection, five different thicknesses including 2, 2.5, 3, 3.5 and 4 cm were considered for the base plate whereas all the other connection properties were the same as the reference model (Ref.). After analyzing the models, the moment-rotation curves are obtained and presented in Figure 5.
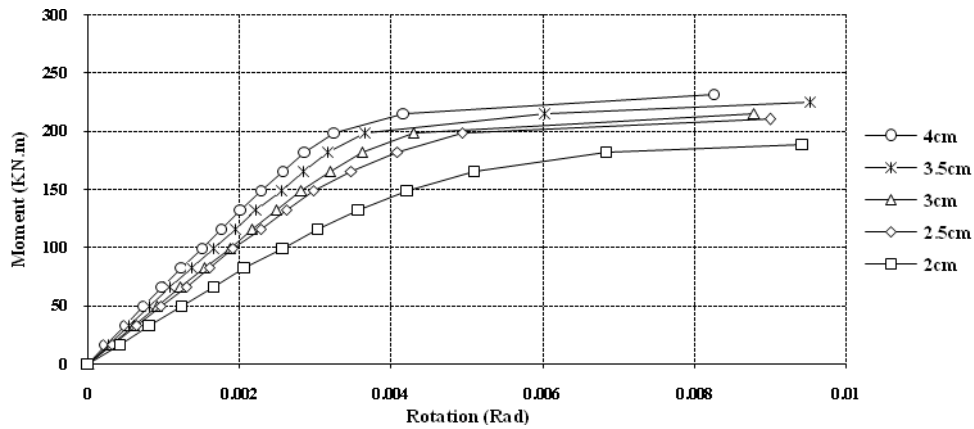

Figure 5: Moment-rotation curves for different base plate thicknesses

As it is obvious in Figure 5, increase of the base plate thickness causes an apparent increase in the connection stiffness and moment capacity. The connection main properties for each case have been listed in table 1.

Property	2 cm	2.5 cm	3 cm	3.5 cm	4 cm
Rotational Stiffness (KN.m/rad)	38280	50640	53270	58670	64900
Moment Capacity (KN.m)	190	210	215	225	230

Table 1: column base connection properties for different base plate thicknesses

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Table 1 shows that increasing of the base plate thickness from 2 to 2.5 cm causes an intense increase in rotational stiffness of the connection, more than 32%, whereas increase of the thickness from 2.5 to 4 cm lead to a lower increase, about 28%. Assessing the base plate deformation and stress distribution illustrates that in the case of 2 cm base plate thickness, as the base plate edge comes to contact with the concrete surface in the tensile side of the connection, prying forces develop in this zone. As this phenomenon does not occur in cases with thicker base plates, a sudden increase of connection stiffness occurs. The magnified deformation of base plate for different thicknesses when the connection is subjected to 100 KN.m bending moment is presented in Figure 6. Besides, the stress distribution along the marked zone of the connection in Figure 6, is presented in Figure 7.
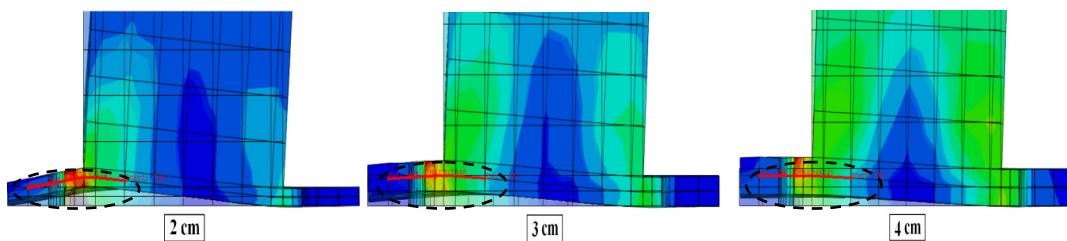

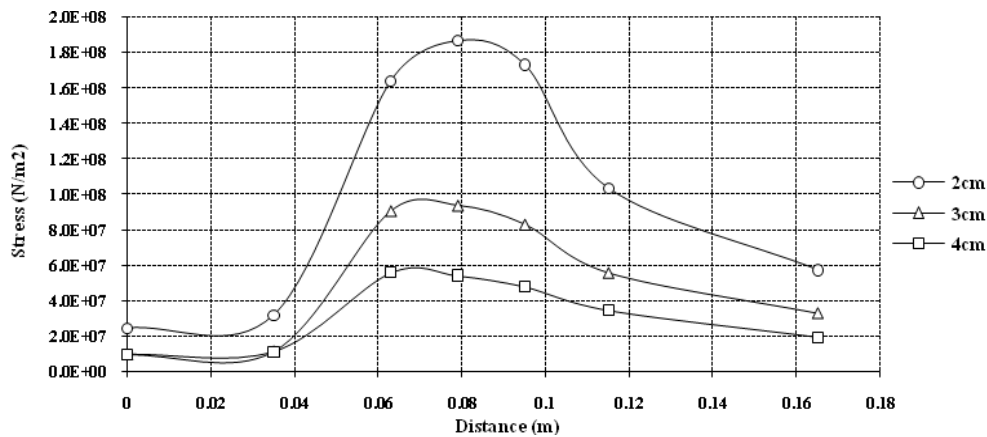Figure 6: Column base connection deformation for different base plate thicknesses

Figure 7: Stress distribution for different base plate thicknesses

Figure 7 indicates an intense stress concentration where the column meets the base plate in case of 2 cm base plate thickness. It leads to sooner failure of the connection and subsequently, lower stiffness and moment capacity.

4.2 Anchor bolts size and configuration

Four different anchor bolt diameters, including 25, 28, 32 and 40 mm, were considered for the base connection in order to evaluate the effect of anchor bolt size

on the behaviour of the connection. All other connection components are like the reference model (Ref.). The corresponding moment-rotation curve for each case is shown in Figure 8.
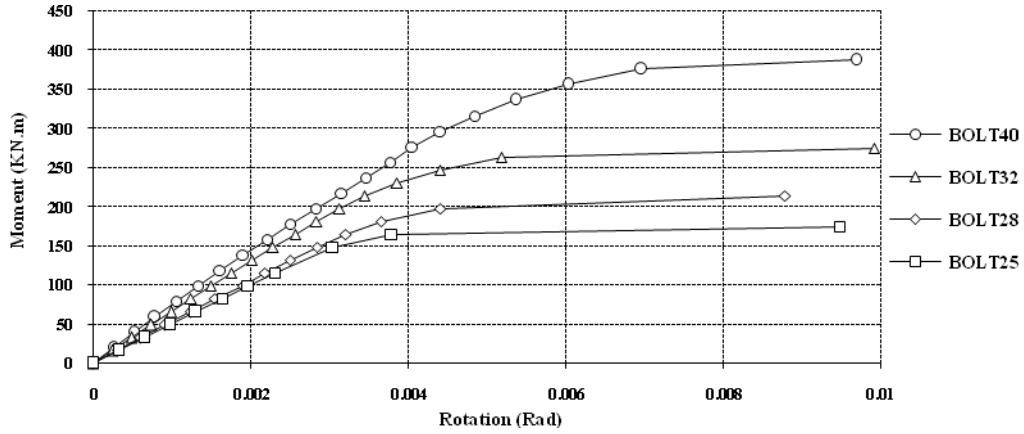

Figure 8: Moment-rotation curves for different anchor bolt sizes

The connection rotational stiffness and moment capacity are presented in Table 2.

Property	Bolt 25	Bolt 28	Bolt 32	Bolt 40
Rotational Stiffness (KN.m/rad)	49340	53270	64980	80430
Moment Capacity (KN.m)	175	215	275	390

Table 2: column base connection properties for different anchor bolt sizes

Figure 8 and Table 2 show that the connection properties can significantly be affected by increasing the anchor bolts size. For instance, increasing the anchor bolts diameter from 25 mm to 40 mm increases the connection rotational stiffness and moment capacity about 63% and 123%, respectively.

Furthermore, the effect of anchor bolts configuration has been studied. Therefore, two column base connections with almost the same anchor bolt cross-sectional area but different configuration, as shown in Figure 9, were considered and their behaviour was studied.
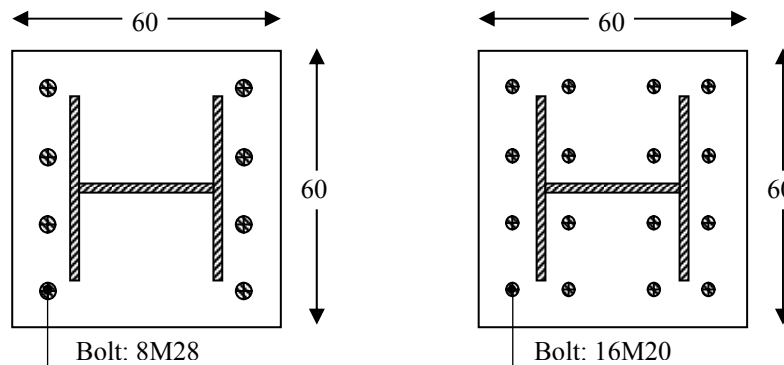

Figure 9: Column base connections with different anchor bolt configuration

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The moment-rotation curve and the main connection properties are presented in Figure 10 and Table 3, respectively.
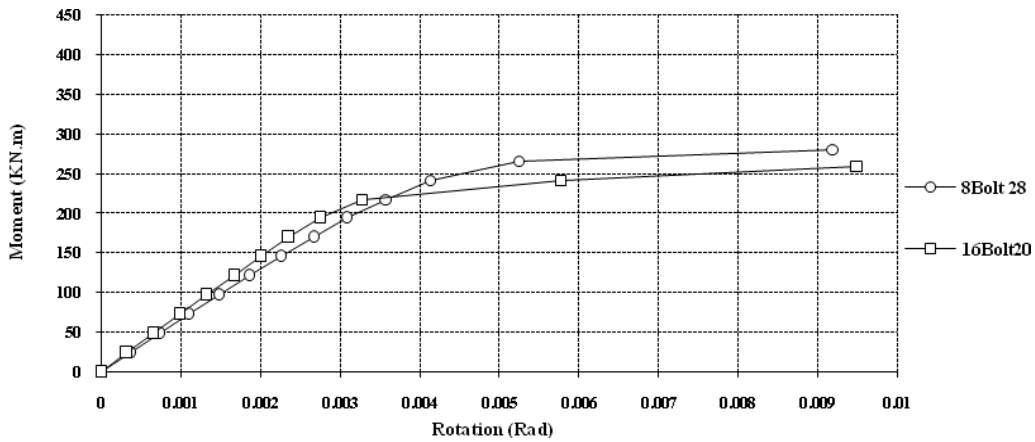

Figure 10: Moment-rotation curves for different anchor bolt configuration

Property	8 Bolt28	16 Bolt20
Rotational Stiffness (KN.m/rad)	64450	71800
Moment Capacity (KN.m)	280	260

Table 3: column base connection properties for different anchor bolt configuration

Results reveal that in the "16Bolt20" case, in which the anchor bolts are placed in two rows, more rotational stiffness and less moment capacity than the other case is obtained. This is mainly due to non-uniform stress distribution between anchor bolts in the tensile side of the connection. Figure 11 shows the magnified deformation of column base connection for the two cases when the connection is subjected to 170 KN.m bending moment. As it is apparent in Figure 11, in the "16Bolt20" case, the anchor bolts in the inner row receive less tensile force as they have shorter moment arm. So, these anchor bolts experience less elongation and consequently, they restrict the rotation of the connection that leads to more rotational stiffness. On the other hand, as the anchor bolts in the cantilever zone of the base plate tolerate excessive tensile stress, they yield sooner in comparison with the tensile anchor bolts of the "8Bolt28" case and it results in lower moment capacity of the connection.
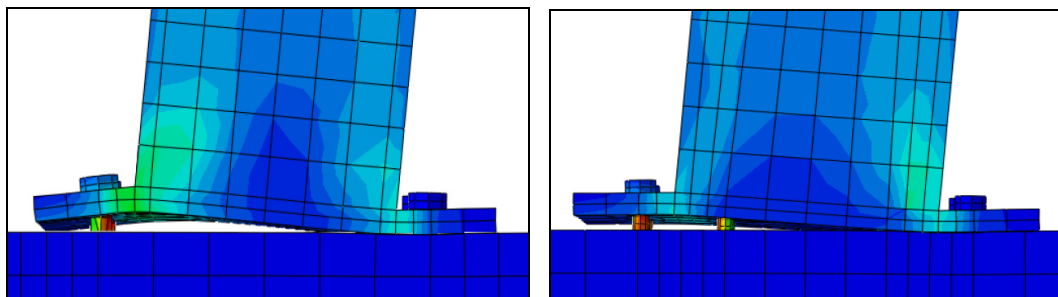

Figure 11: Base connection deformation for different anchor bolt configuration

4.3 Stiffener dimension

In order to investigate the effect of stiffeners on the behaviour of column base connection, four stiffeners as shown in Figure 12 were considered in the reference base connection model (Ref.).
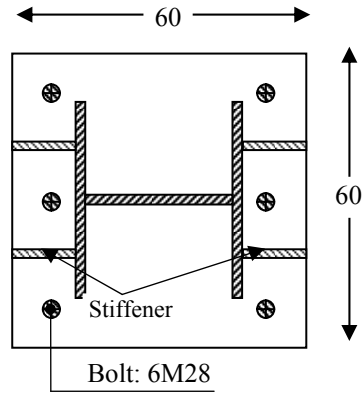

Figure 12: Stiffeners arrangement in column base connection

The thickness and height of the stiffeners were variable. In the moment-rotation curves that are presented in Figure 13, the first number in each model name shows the stiffener thickness and the second one represents the height of the stiffener.
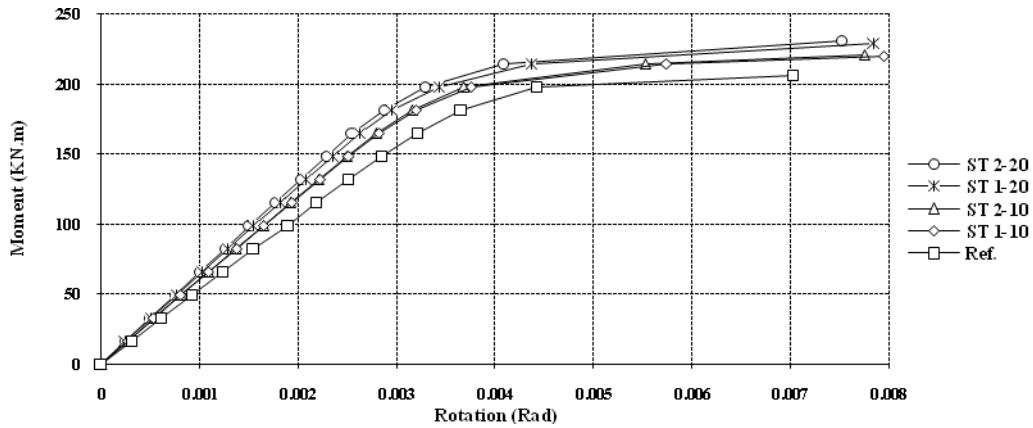

Figure 13: Moment-rotation curves for different stiffeners dimension

The connection properties are also presented in Table 4.

Property	Ref.	ST1-10	ST2-10	ST1-20	ST2-20
Rotational Stiffness (KN.m/rad)	53270	59370	60030	62970	64760
Moment Capacity (KN.m)	215	220	222	230	233

Table 4: column base connection properties for different stiffeners dimension

According to the analyses results, utilising stiffeners in base connection increases both the rotational stiffness and moment capacity of the connection. However, as it was expected, the thickness of stiffeners has much less effect on the mentioned properties than their height. Regarding Table 1 and Table 4 reveals that using four stiffeners with 2 cm thickness and 20 cm height in the reference base connection model (Ref.) and enhancing the base plate thickness from 3 to 4 cm, have almost the same effect on the connection properties.

5   Column base connection stiffness and moment capacity

In this part, the upper and lower bounds for rotational stiffness and moment capacity of column base connection have been studied. The column base connections were classified into four groups according to their base plate dimension. The groups were 50x50 cm, 60x60 cm, 70x70 cm and 80x80 cm. In each case, in order to obtain the upper and lower bounds of rotational stiffness and moment capacity, appropriate connection detail was regarded to represent either fully pinned or fully rigid connections.

The base connection details for obtaining the lower bounds are presented in Figure 14. The connections details are so that they represent so-called "pinned" connections.
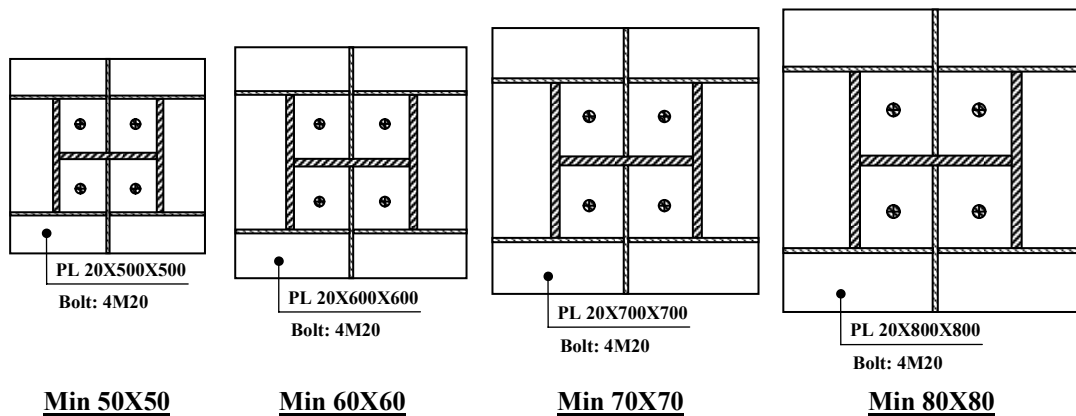

Figure 14: So-called "pinned" column base connection details

In Figure 15, the moment-rotation curves of the connections are shown. The connections properties are also gathered in Table 5.
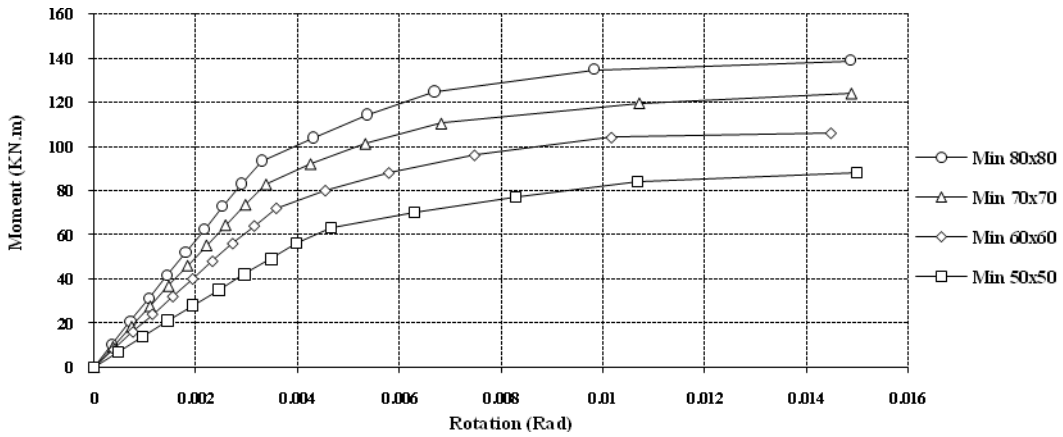
Figure 15: Moment-rotation curves for so-called "pinned" connections

Property	Min50x50	Min60x60	Min70x70	Min80x80
Rotational Stiffness (KN.m/rad)	14230	20720	24900	28730
Moment Capacity (KN.m)	85	105	125	140

Table 5: column base connection properties for so-called "pinned" connections

As it is evident from Table 5, initially fully pinned base connections exhibit considerable rotational stiffness which can shed doubt over the accuracy of the design assumptions. So, it is recommended to consider the rotational stiffnesses expressed in Table 5 as the minimum fixity of column bases in the analytical model of pin-ended frames in order to have more realistic designs.

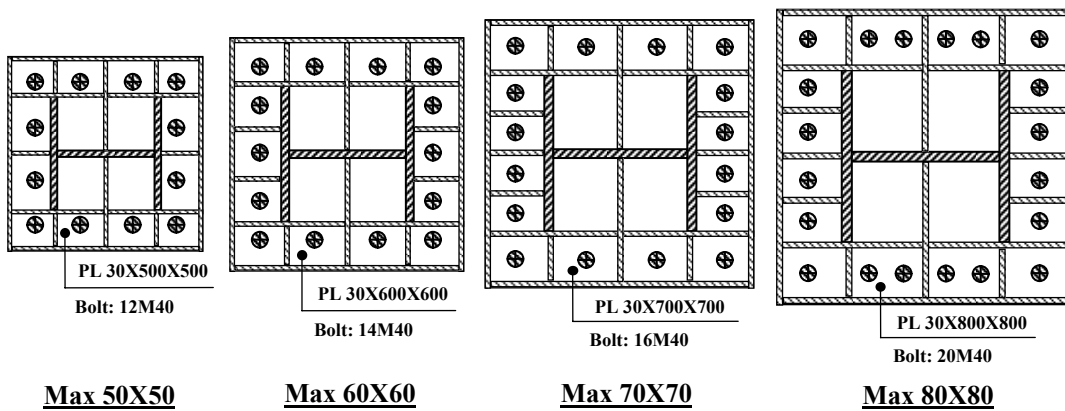The nominally "fixed" column base connections details are presented in Figure 16.

Figure 16: So-called "fixed" column base connection details

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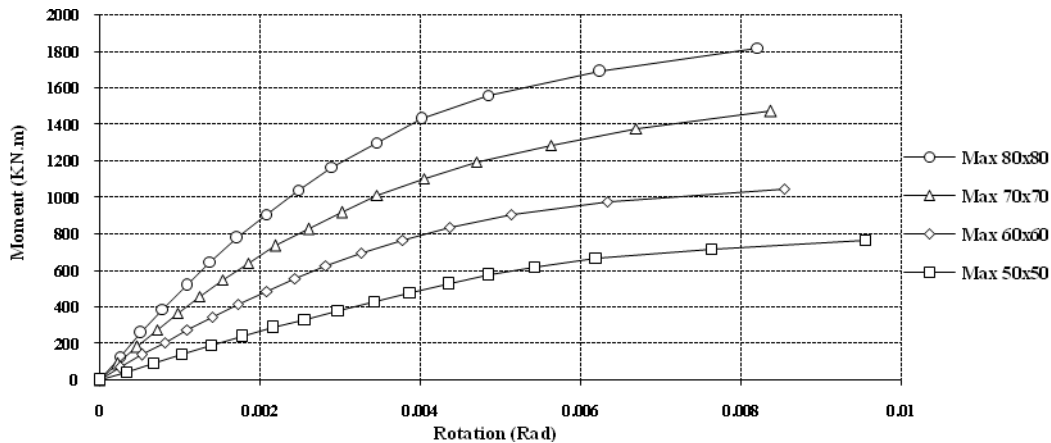The moment-rotation curves and the connections properties are presented in Figure 17 and Table 6, respectively.

Figure 17: Moment-rotation curves for so-called "fixed" connections

Property	Max50x50	Max60x60	Max70x70	Max80x80
Rotational Stiffness (KN.m/rad)	130250	238790	351420	443210
Moment Capacity (KN.m)	770	1050	1470	1820

Table 6: column base connection properties for so-called "fixed" connections

It was observed that relatively high amount of rotations were obtained from the connections which were initially designed to be fully rigid. For instance, in the "Max 60x60" case, the connection experiences a rotation about 5 mrad until yielding of one of the connection components. It can affect overall behaviour of the steel structure specially its lateral displacement and moment distribution. Therefore, it seems logical to consider column bases as semi-rigid connections.

Besides, assessing the stress distribution in the connection components indicates that yielding occurs almost simultaneously in the column and the tensile anchor bolts. Figure 18 shows the connection stress contour for 700 KN.m bending moment. It reveals the need for utilizing high-strength steel for the anchor bolts in order to increase the moment capacity of nominally "fixed" connections and consequently, to prevent occurring strong column-weak connection mechanism.
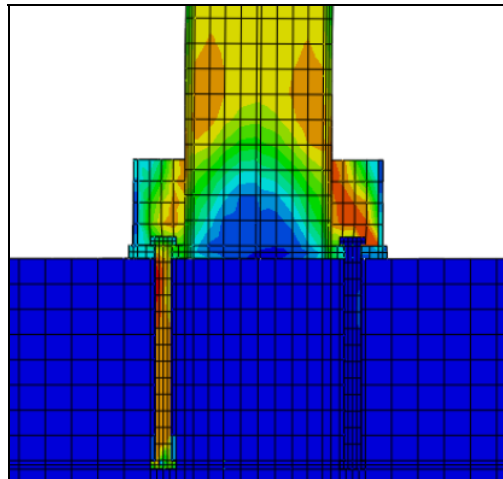
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Figure 18: The "Max 60x60" stress distribution

6   Conclusion

In this paper, the non-linear behaviour of column base connections has been evaluated through a parametric study. Besides, an investigation has been conducted on the rate of fixity of regular column bases. The following conclusions have been obtained on the basis of the analyses results.

The thickness of base plate is an important parameter in the behaviour of column base connections. The rotational stiffness and moment capacity of the connection can be significantly affected by changing the base plate thickness, especially in the cases that the base plates are thin enough to let prying forces develop, increasing the base plate thickness can have an intense effect on the connection properties.

Increasing the anchor bolts size causes considerable increase in the connection properties. It was also observed that placing the anchor bolts in two rows in the base connection causes an increase in the connection rotational stiffness whereas the moment capacity decreases. This phenomenon is mainly due to non-uniform stress distribution between anchor bolts in the tensile side of the connection.

Stiffeners play a major role in increasing the stiffness of column base connections. The stiffeners effects increase by increasing their height meanwhile the effects of increasing the stiffeners thickness are negligible.

It was observed that nominally "pinned" base connections exhibit considerable rotational stiffness. So, it is recommended to regard the observes partial fixity offered by the connections in the analytical models as it may lead to considerable changes in lateral displacement and moment distribution in initially pin-ended steel frames. It may also reduce the P-Δ effects in the structures. In the other hand, relatively high amount of rotations were obtained from the connections which were initially designed to be fully rigid. Therefore, taking these semi-rigidity effects into account in modelling of steel structures seems to results in more reliable designs. Furthermore, analyses results show that high-strength steel must be used for the anchor bolts in order to increase the moment capacity of nominally "fixed"

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connections and consequently to prevent occurring strong column-weak connection mechanism.

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