Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 4, No. 11, November, 2018

Design Methodology of Base Plates with Column Eccentricity in Two Directions under Bidirectional Moment

Parviz Ebadi [a*], Mohammad Soleimani [b], Mohsen Beheshti [c]

[a] *Assistant Professor, Sadra Institute of Higher Education, Tehran, Iran.*

[b] *M.Sc. Student, Sadra Institute of Higher Education, Tehran, Iran.*

[c] *M.Sc. of Structural Engineering, Sadra Institute of Higher Education, Tehran, Iran.*

Received 04 April 2018; Accepted 27 September 2018

Abstract

Base plate is a critical structural component responsible for transferring loads from the structure to the foundation. By increasing the contact surface between the column foot and the foundation, base plates contribute to more manageable distribution of column forces and the resulting stresses in the substructure. The off-center positioning of column on the base plate, which is sometimes unavoidable because of the limitations imposed by elevator shaft, adjacent buildings, etc. could be a major design issue. This paper investigates the effects of column eccentricity on the design and stress distribution of base plates and the impact of stiffeners on the thickness of these plates. In this investigation, a comparison is made between the superposition method and the finite element method in terms of their evaluation of stress levels under the base plate with column eccentricity. The study also aims to determine the magnitude and distribution of maximum stresses with plate's thickness and dimensions and column's position on the plate taken into account. The results show that the superposition method can be confidently used in the force analysis and design of base plates with column eccentricity under bidirectional moments.

Keywords: Base Plate; Bearing Stress; Stiffener; Finite Element; Foundation; Cracking.

1. Introduction

Base plates are the structural components responsible for the transfer of loads from columns to the foundation. Basically, a base plate increases the area of contact between a column and its underlying foundation, thus allowing the designer to control the distribution of column forces over the concrete surface. It is typical to use anchor bolts on base plates for transferring lateral forces and employ stiffeners to reduce the thickness of the plate. The majority of studies in this field utilize either software models or laboratory models in their investigations. What seems to be lacking in these studies is an effort to derive a formula or coefficient for more consistency between the numerical and experimental models. The divergent behavior of the components of column-base plate connections (i.e. column, base plate, anchor bolts, and concrete foundation) can complicate the structural analysis of these connections. Past studies on base plates have utilized both experimental and numerical approaches. In 1970, Fling used the yield line theory for the analysis of base plates. He obtained some limits for the displacement between the plate and the foundation provided that the plate bending remains in the elastic region. Ultimately, he concluded that the method requirement (that the plate bending should remain in the elastic region) make this a conservative method [1]. In 1975, Stockwell investigated the replacement of a rigid base plate with a flexible one and concluded that the uniform bearing pressure below the base plate is not a

* Corresponding author: Parviz.Ebadi@gmail.com

http://dx.doi.org/10.28991/cej-03091197

suitable design criterion as the maximum pressure follows the profile shape [2]. In 1985, Pickard and Beaulieu studied the impact of axial load of columns on base plates with the help of experimental specimens [3].

In 1986, Thambiratnam and Paramasivam built a laboratory connection model consisting of a column, a base plate, anchor bolts, and foundation, and used that to investigate the maximum axial load capacity and bending moment capacity of base plate connections. This study showed that in lower eccentricities, the failure is controlled by the concrete strength whereas in high eccentricities, it is the base plate and anchor bolt that control failure [4]. In 1989, Thambiratnam and Krishnamurthy used a finite element method to analyze base plates and obtained the distribution of compressive stress over the support surface below the base plate [5]. In 1997, Stamapolos and Ermupolos investigated the numerical models of base plates under cyclic and seismic loads and presented a nonlinear relationship for moment-rotation curves of these plates [6]. In 1998, Jaspart and Vandegans used a series of experimental models to investigate the behavior of anchor bolts with end-hooks in the base plate connections. They observed that the contact and bond between the anchor bolt and the foundation concrete can easily disappear, particularly in large or earthquake-induced displacements and deformations. They argued that in a sense, one can assume that anchor bolt loses its contact and bond with concrete as soon as loading begins [7]. In 2000, Kontoleon et al. performed a numerical study on the base plate connections with thickness variations. In this study, a two-dimensional model of a three-dimensional connection was developed, and then moment-angle diagrams were obtained accordingly [8]. Adany, Donay, and Calado (2000) studied the behavior of base plates under cyclic loading and the effect of different variables on this behavior. This study concluded that semi-rigid plates have the best behavior among the studied plates [9].

In another study, Kontoleon et al. (2000) investigated the effects of various factors, such as steel reinforcement, base plate thickness, and eccentricity in 16 specimens. Parametric analysis of the specimens showed the importance of base plate rigidity as a determinant of the generation of uplift force in the contact area between the concrete and the base plate [10]. In 2009, Stamapolos and Ermupolos examined the stress distribution of different baseplates and tried to obtain the moment-angle curve of these connections by deriving statics based relations. This study showed that moment-angle curve is influenced by many variables, and preliminary experiments demonstrated the good accuracy of the derived theory and equations [11]. In 2012, Khodaie et al. performed a parametric analysis on the initial stiffness of the base plates of Square Hollow Section (SHS) columns with the help of a finite element model. In this model, connection characteristics and details such as concrete and steel behavior, geometry, concrete-steel contact, and the contact of other components were considered. Using the regression analysis approach, they derived a function for the initial stiffness of the base plate connection. The results showed a good agreement between the initial stiffness obtained from FEM and those measured in experimental models [12].

In 2015, Yao et al. examined the shear behavior of the exposed column base plate connections, and reported that when axial force switches from compressive to tensile state, ultimate strength and energy absorption decrease. The results showed severely reduced strength under tensile axial forces, which was attributed to the separation of the base plate from the grout layer. They also suggested that the base of columns should be designed in a way that uplift force is prevented. Increasing the number of anchor bolts improved the ultimate strength but not the energy dissipation because bolts did not yield as much as needed for that to happen [13]. In 2015, Gunnur et al. designed the base plates of a steel industrial building using the AISC-LRFD Method. After calculating the dimensions of the base plates under loading, the minimum thickness of the plate was found to be about 2 inches (8.50 cm). Six base plate specimens were tested in ASDIP software and the parameters related to plate thickness, ultimate stress, and flexural strength were calculated and controlled [14]. In a study by Silviu et al. (2015) on the behavior of steel base plate connections under cyclic loading, they reported an agreement between ultimate strength values obtained from numerical and experimental models and observed that reducing the plate stiffness causes the base plate connection to exhibit a semi-rigid behavior and this behavior makes the base plate more ductile [15].

Gholizadeh et al. (2015) studied the impact of details of column-base plate connections, including the number and layout of anchor bolts, stiffener dimensions, and plate thickness, on the behavior of foundation-base plate-column system. This study reported that using a greater number of bolts results in more uniform stress distribution and reduced plate rotation, and using thicker stiffeners and plates significantly improves the performance of the system as a whole [16]. In 2017, Scudlari et al. investigated the distribution of tensile forces over anchor bolts and found that the distribution of load on anchor bolts largely depends on the shape of the base plate. They also reported that adding a stiffener plate increases the local stiffness of the base plate and makes the stress distribution more uniform [17]. In 2017, Ebadi et al. examined the effect of stiffeners on the stress distribution of base plates under small biaxial moments. In this study, a comparison was made between the base plate stresses obtained by numerical modeling with ANSYS and design theory and the results of the superposition method [18]. In another study, Ebadi et al. (2017) used the finite element software to investigate the effect of stiffeners on the cracking and stress level under the base plate [19]. In 2018, Trutner et al. developed a parametric finite element model for steel base plate connections of moment frames under lateral loads. This study provided a fast parametric numerical modeling technique for the analysis of base plate connections in moment frames [20]. In a study by Fasayi et al. (2018) on the capacity of base plate connections under uniaxial and biaxial bending moments, they first created a 3-D model in software and then used the results to develop a simple analysis method for more accurate prediction of the capacity of ductile, rigid, and semi-rigid base plates [21].

In the present study, eight base plate specimens with and without stiffener and subjected to axial moment load were analyzed in the structural analysis software ANSYS. Four of the specimens had column eccentricity (relative to the plate's center) in one direction and the other four had column eccentricity in two directions. The specimens were examined using the limit state design method and the finite element method. The effects of stiffeners on the stress magnitude and distribution, cracking, uplift, and behavior of these base plates were also examined.

2. Design of Column Base Plate with Column Eccentricity

2.1. Base Plate with Small Column Eccentricity under Uniaxial Moment

In this mode, it is assumed that the column is subjected to a moment applied in the counterclockwise direction and an axial load applied at its center (see Figure1). The distance between the column's center and the plate's center is considered as the measure of base plate eccentricity. The stress under the base plate is assumed to have a trapezoidal distribution. In this case, eccentricity is small if Equation 1 is satisfied. As shown in Figure1-a, with the stress distribution assumed to be trapezoidal, the critical moment should be calculated on both sides of the column, and the highest moment applied to the column side should be used in the design.

The relationships obtained from the mentioned equations provide some limits for the extent of eccentricity and the size of the base plate based on the axial load applied to the column and the bearing stress of the concrete. These limits need to be considered in the design of column.

The maximum and minimum stresses of the base plate with small eccentricity are obtained from Equation 2.

$$\begin{cases} e_{px}+e_x \le \dfrac{B_x}{6} \\ e_{px}+e_x \le \dfrac{q_{all}.B_y.B_x^2}{6p} - \dfrac{B_x}{6} \end{cases} \quad (1)$$

$$\begin{cases} q_{min} = \dfrac{p_u}{B_y.B_x} - \dfrac{6p_u}{B_y.B_x^2}(e_x+e_{px}) \\ q_{max} = \dfrac{p_u}{B_y.B_x} + \dfrac{6p_u}{B_y.B_x^2}(e_x+e_{px}) \end{cases} \quad (2)$$

Where q_{max} and q_{min} are the maximum and minimum stresses, respectively.

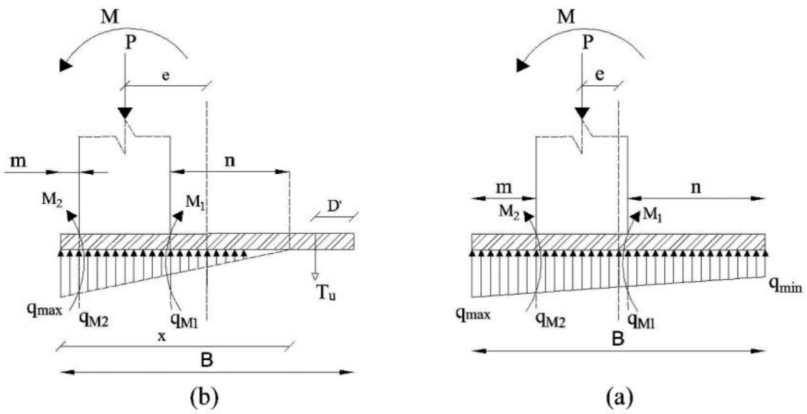

Figure1. a) Base plate with small eccentricity, b) Base plate with large eccentricity

The stress and moment in the critical section of the base plate with small eccentricity are given by Equations 3, 4, 5 and 6.

$$q_{M2} = \frac{q_{max}+q_{min}}{2} + (q_{max}-q_{min}) \times \frac{2e_{px}+d}{3B_x} \quad (3)$$

$$M_2 = q_{M2} \times \frac{m^2}{2} + (q_{max}-q_{M2}) \times \frac{m^2}{3} \quad (4)$$

$$q_{M1} = q_{min} + \frac{n}{B}(q_{max}-q_{min}) \quad (5)$$

$$M_1 = q_{min} \times \frac{n^2}{2} + (q_{M1}-q_{min}) \times \frac{n^2}{6} \quad (6)$$

Where m and n are distances shown in Figure1, q_{min} and q_{max} are the minimum and maximum stresses, q_{M1} and q_{M2} are the stresses in the critical sections on the right side and left side of the column (as shown in Figure1-a). q_{all} is the allowable bearing strength of the concrete, and M_1 and M_2 are the critical moments on the right and left sides of the column, respectively.

2.2. Base Plate with Large Column Eccentricity under Uniaxial Moment

In this mode, the stress under the base plate is assumed to have a triangular distribution. The stress distribution length, the moment applied to the column, and the tensile force applied to the anchor bolt are illustrated in Figure 1-b. With these assumptions, stress under the base plate will have a triangular distribution if eccentricity satisfies Equation 7. If the stress distribution under the base plate is triangular, then the tensile force generated in the anchor bolt needs to be calculated. This necessity arises from the fact that the thickness of the base plate should be determined with the moment of this tensile force on the column side taken into account. Having the length of the stress distribution and the applied load, the tensile force can be obtained. As mentioned, this tensile force is sustained by anchor bolts. The design moments are determined using the laws of statics, according to which we can write one inequality based on the relationship between the stress force under the base plate and the vertical force applied to the column and another one based on the moment of forces about the extreme ends of the column.

$$\begin{cases} e_x+e_{px}\geq\frac{B_x}{6} \\ \frac{q_{max}\cdot\frac{B_y}{4}\cdot(B_x-D')^2-\frac{2}{3}\cdot p_u\cdot\left(\frac{B_x}{2}-D'\right)}{\frac{2}{3}\cdot p_u}\geq e+e_{px} \end{cases} \tag{7}$$

In the above relations, e_{px} is the load eccentricity relative to the column's center along axis X, e_x is the column eccentricity relative to the plate's center along axis X, B_x and B_y are the length and width of the base plate, p_u is the force applied to the column, q_{all} is the allowable bearing stresses of the concrete, and D' is the distance of the center of the anchor bolt from the plate's edge.

To design a base plate with large eccentricity, the length of the stress distribution (x) must be determined by calculating the moments about the force of anchor bolts. Then, the force of anchor bolts is obtained by Equation 8.

$$T_u=q_{max}\cdot\frac{x}{2}.B_y-P_u \tag{8}$$

Where q_{max} is equal to the allowable bearing stress of concrete (q_{all}).

The stress and moment in the critical section of the base plate with large eccentricity are obtained from Equations 9, 10, 11 and 12.

$$q_{M2}=q_{max}\cdot\frac{x-m}{x} \tag{9}$$

$$M_2=q_{M2}\cdot\frac{m^2}{2}+\left(q_{max}-q_{M2}\right)\cdot\frac{2m^2}{6} \tag{10}$$

$$q_{M1}=q_{max}\cdot\frac{x-n}{x} \tag{11}$$

$$M_1=q_{M1}\cdot\frac{n^2}{6}.B_y-T_u\left(\frac{B}{2}-D'+e_x-\frac{d}{2}\right) \tag{12}$$

As before, m and n are distances shown in Figure1-b, q_{min} and q_{max} are the minimum and maximum stresses, q_{M1} and q_{M2} are the stresses in the critical sections on the right side and left side of the column (as shown in Figure1-b), and M_1 and M_2 are the critical moments on the right side and left side of the column, respectively.

For the base plates with large eccentricities, if the moment due to the force of anchor bolt exceeds the column side moment due to the stress under the base plate, then the base plate thickness should be designed according to the former moment.

2.3. Base Plate with Small Column Eccentricity under Biaxial Moment

In this mode, the stress under the base plate is assumed to be trapezoidal along both axes X and Y. Accordingly, the base plate has small eccentricity in both directions if Equation 13 is satisfied. Therefore, all points of the base plate are subject to stress. To design the thickness and dimensions of such base plate, the stress in the four corners of the base plate and column should be calculated according to Equation 14. This equation assumes an XY coordinate system where the origin is positioned at the center of the plate. Thus, stress values at different points of the base plate are calculated according to this origin. As shown in Figure 2-a, stress is obtained by punctuation at different points.

$$e_x+e_{px}<\frac{B_x}{6} \quad , \quad e_y+e_{py}<\frac{B_y}{6} \tag{13}$$

$$q_{(X,Y)}=\frac{P_u}{B_y.B_x}+\frac{12P_u.X}{B_y.B_x^3}\left(e_x+e_{px}\right)+\frac{12P_u.Y}{B_y^3.B_x}\left(e_y+e_{py}\right)\leq q_{all} \tag{14}$$

Where e_{py} is the load eccentricity relative to the column's center along axis Y, and e_y is the column eccentricity relative to the plate's center along axis Y.

As an example, two points of the base plate that experience stress are marked in Figure 2-b. To design the plate thickness, we have to calculate the moment per unit width that results from the stress between these two points and repeat these calculations for every corner of the base plate and the column. Ultimately, the highest plate thickness obtained in these calculations should be used as design thickness.

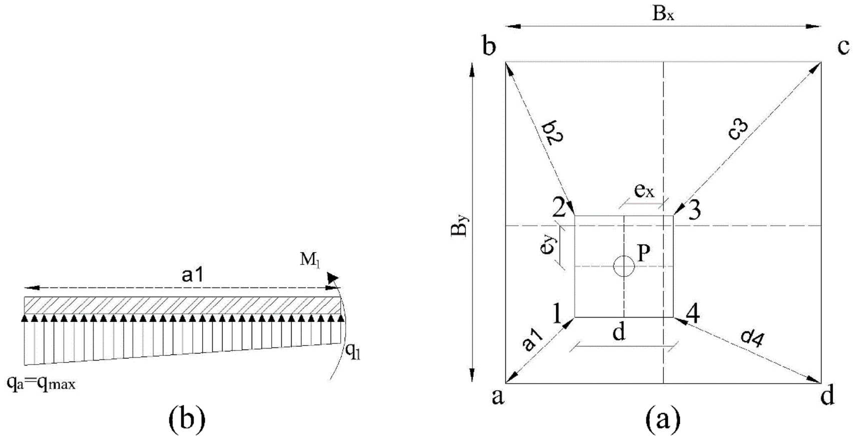

Figure 2. a) Plan of the base plate with small eccentricity under bidirectional moment, b) Stress at points 1 and a

2.4. Base Plate with Large Column Eccentricity under Biaxial Moment

In this mode, stress is assumed to be triangular along both directions. As in uniaxial state, the stress under this base plate is triangular along both directions if Equation 15 is satisfied.

$$e_x+e_{px}>\frac{B_x}{6} \quad , \quad e_y+e_{py}>\frac{B_y}{6} \tag{15}$$

In this case, each side of the base plate should be designed separately. But the design process for individual directions should proceed in parallel to each other. For this purpose, the force applied to the base plate is divided by the eccentricity along each direction. Equation (16) shows how the load is decomposed into two axes.

$$\begin{cases} \frac{P_x}{P_y}=\frac{e_x+e_{px}}{e_y+e_{py}} \rightarrow P_x=\alpha.P_u \ , \ P_y=\beta.P_u \\ P_x+P_y=P_u \end{cases} \tag{16}$$

In the above equations, α and β are load factors for the directions X and Y respectively. Basically, these factors reflect the contribution of the load in each direction to the total load applied to the column.

The maximum stress in each direction is obtained from Equation 17. The sum of the stresses in each direction should not exceed the allowable bearing stress of the concrete (q_{all}).

$$\begin{cases} q_1=\frac{P_y}{B_y.B_x}+\frac{6P_y}{B_y^2.B_x}\left(e_y+e_{yp}\right) \\ q_2=\frac{P_x}{B_y.B_x}+\frac{6P_x}{B_y.B_x^2}\left(e_x+e_{xp}\right) \\ q_1+q_2\leq q_{all} \end{cases} \tag{17}$$

In the above equations, q_1 and q_2 are the maximum stresses in the directions Y and X, respectively.

Having the maximum stress and the load applied in each direction, the stress distribution length can be obtained. The tensile force inside the anchor bolts must then be calculated accordingly. It should be noted that the corner anchor bolts receive tensile force from both directions X and Y. In Figure 3, Area 1 marks the effective width of the corner anchor bolt, and Area 2 is the unit width area between the corner of the base plate and that of the column. To obtain the design thickness, the moment of Area 2 must be calculated and the thickness needed to control this moment should be determined. Simultaneously, the moment of the force of the corner anchor bolt in Area 1 must be calculated and then the thickness needed for Area 1 should be calculated according to the effective width of this anchor bolt. The highest thickness obtained from these two calculations should be used in the base plate design.

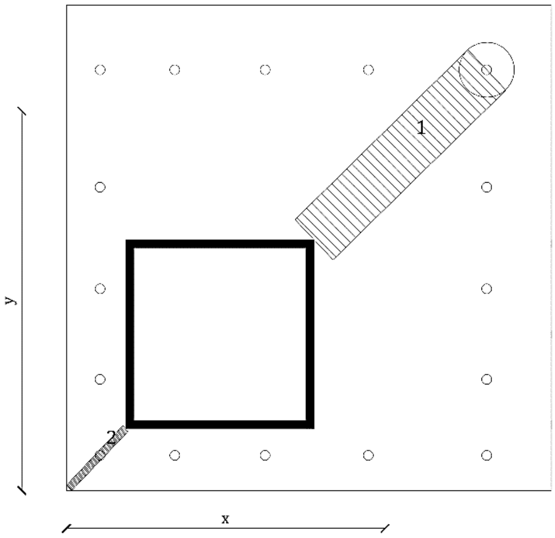

Figure 3. Design plan of the base plates with large eccentricity

3. Design of Specimens

The validity of the proposed theory for the design of base plates with column eccentricity relative to the plate's center under compressive axial loads was investigated with the help of ANSYS. All analyses were performed on columns of equal dimensions to allow comparison between base plates with different extents of eccentricity.

The first analysis was performed on a box-shaped column of dimensions 500 × 500 × 30 mm under an 11720 kN axial load applied at its center. Using the limit state method, the dimensions of the base plate was calculated to 1000 × 800 × 92 mm. The stresses and moments of the base plate were calculated using the superposition method. The column eccentricity relative to the plate's center was 130 mm (along axis X). The maximum and minimum stresses were 26.07 and 3.22 MPa, respectively. The maximum stress was lower than the allowable bearing stress of the concrete (27.63 MPa). The critical widths m and n were 120 and 380 mm, respectively. The stress at the critical distance n from the column edge was 11.9 MPa and the stress at the critical distance m from the column edge was 23.33 MPa. The critical moment at the critical distances m and n was 181.51 and 441.7 Nm, respectively. The base plate specimens used for the first analysis are displayed in Figure 4. The details of these base plates are provided in Table 1.

In the second analysis, the column had the same dimensions as before, but had 200 mm eccentricity relative to the plate's center (along axis X). In this mode, it was assumed that a 6215 kN load is applied at the 150 mm distance from the center of the column. Accordingly, the dimensions of the base plate were calculated to 1000 × 750 × 78 mm. The maximum stress was assumed equal to the allowable bearing stress of the concrete (27.63 MPa). The critical widths m and n were 50 and 450 mm, respectively. Using the superposition method, the stress at the critical distance m was calculated to 25.50 Mpa. The critical moment at critical width m was 33.62 Nm. The length of the stress distribution in this mode was 659.5 mm. The tensile force applied to the anchor bolts was 611.28 kN. The base plates used for this analysis are shown in Figure 4.

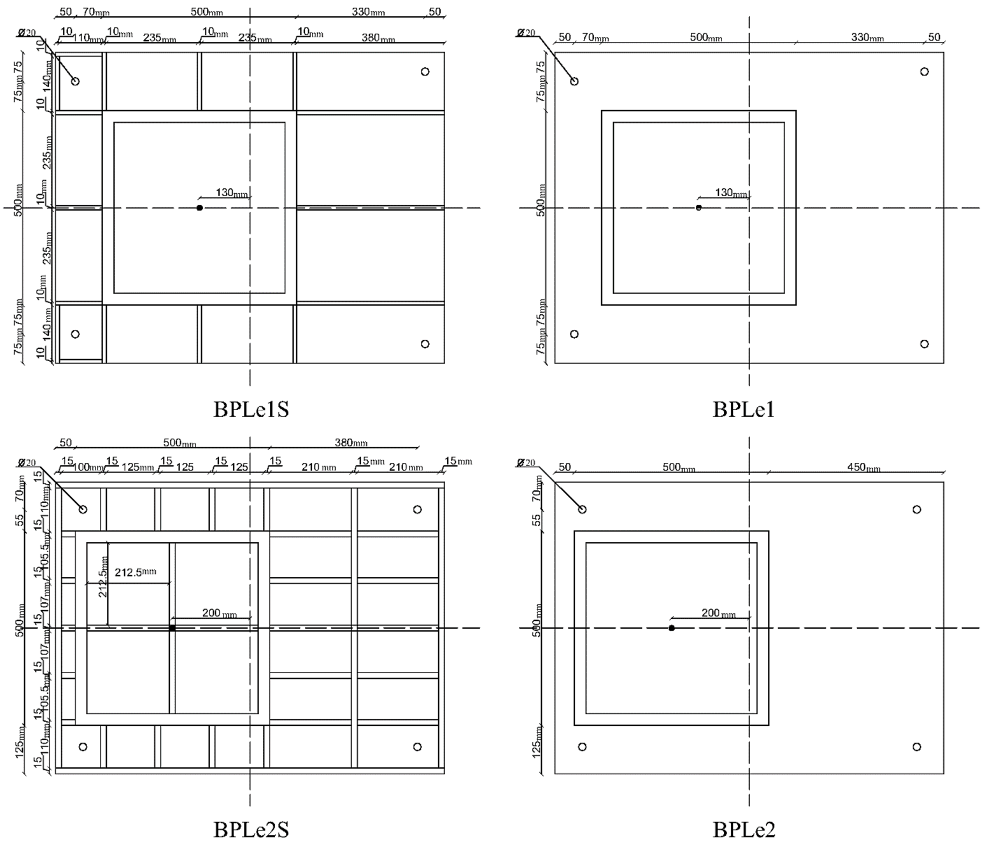

Figure 4. Plan of the base plate designed in the first mode

Table 1. Base plate specimen nomenclature

Name	Description
BPLe1	Base plate with small unidirectional column eccentricity relative to the plate's center
BPLe1S	Base plate with small unidirectional column eccentricity relative to the plate's center with stiffener
BPLe2	Base plate with large unidirectional column eccentricity relative to the plate's center
BPLe2S	Base plate with large unidirectional column eccentricity relative to the plate's center with stiffener
BPLe3	Base plate with small bidirectional column eccentricity relative to the plate's center
BPLe3S	Base plate with small bidirectional column eccentricity relative to the plate's center with stiffener
BPLe4	Base plate with large bidirectional column eccentricity relative to the plate's center
BPLe4S	Base plate with large bidirectional column eccentricity relative to the plate's center with stiffener

The third analysis was performed on the column with the same dimensions as before, but with 100 mm eccentricity relative to the plate's center along the X-axis and 60 mm eccentricity relative to the plate's center along the Y-axis. It was assumed that column is subjected to an 11720 kN load applied at the center of the column. Accordingly, the dimensions of the base plate were calculated to 1000 × 1000 × 130 mm. The maximum and minimum stresses were 23.00 and 0.5 Mpa, respectively. Thus, the maximum stress was lower than the allowable bearing stress of the concrete (27.63 MPa). The stress in the corner of the column and its corresponding point on the base plate was 15 and 14.5 MPa, respectively. The bending moment at this distance was 872 Nm. The specimen used in the third analysis is shown in Figure 5.

The fourth analysis was carried out on the column with the same dimensions as before, but with 180 mm eccentricity relative to the plate's center along the X-axis and 190 mm eccentricity relative to the plate's center along the Y-axis. In this mode, 3800 kN load was applied with 200 mm eccentricity relative to the column's center along the X-axis and 150 mm eccentricity relative to the column's center along the Y-axis. Accordingly, the size of the base plate was calculated to 1100 × 1100 × 80 mm. The maximum stress was 9.32 MPa, which was lower than the allowable bearing stress of the concrete (27.63 MPa). The stress in the corner of the column and the corresponding corner in the base plate was 8 and 9.32 Mpa respectively. The moment due to the stress under the base plate at the distance between the base plate corner and the column corner was 117.83 Nm. The stress distribution length in the X and Y directions was 814.3 and 848.4

mm, respectively. The tensile force applied to the anchor bolt at the farthest corner from the column edge was 65.18 kN. The moment of this anchor bolt was 36186 Nm. The details of the base plate in this analysis are shown in Figure 5.

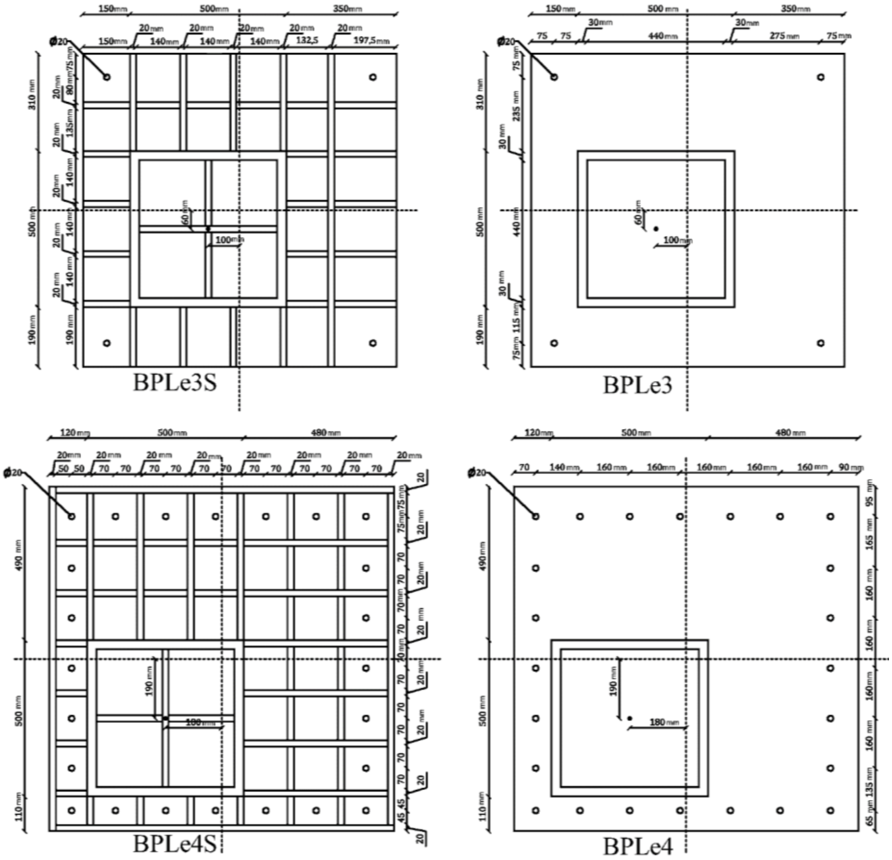

Figure 5. Plan of the designed specimens under a bi-directional eccentricities

4. Finite Element Model

A nonlinear static analysis was performed on the models of specimens. It was assumed that steel components are made of St37 steel with a yield strength of 235 MPa. The properties of materials were introduced by a bilinear hardening diagram with the slope set to 2% of the elastic modulus. The Poisson's ratio and the elastic modulus of steel were set to 0.3 and 200 GPa, respectively. The characteristic strength of the foundation concrete was assumed to be 25 MPa.

In ANSYS, steel sections were modeled by SOLID187 element with 10 nodes and concrete was modeled by SOLID65 element.

SOLID187 element is a typical choice for three-dimensional modeling of solids. Defined with ten nodes, each with three degrees of freedom, this element enjoys plasticity, hyperelasticity, stress stiffening, creep, large flexural deformations (deflection), and large strain capabilities as well as mixed formulation capability for simulating deformations of nearly incompressible (elastoplastic) and completely incompressible (hyperelastic) materials. This element supports various modeling technologies such as B-bar, uniformly reduced integration, and enhanced strains.

SOLID65 is a typical element for 3D modeling of reinforced and non-reinforced concrete. This element can model cracking under tensile stress and crushing under compression. SOLID65 is defined with eight nodes, each with three translational degrees of freedom Ux, Uy, Uz. In terms of features, this element is similar to a typical SOLID element, except that it can represent nonlinear characteristics, cracking and crushing in three orthogonal directions as well as plastic deformation and creep.

The interface between the base plate and concrete was modeled with the help of contact elements Conta74 and Target 170. In the developed models, a stiffener was used to reduce the plate thickness, decrease the cracking, and increase the stress uniformity under the base plate. The finite element models of the base plates with and without stiffener are displayed in Figure 6.

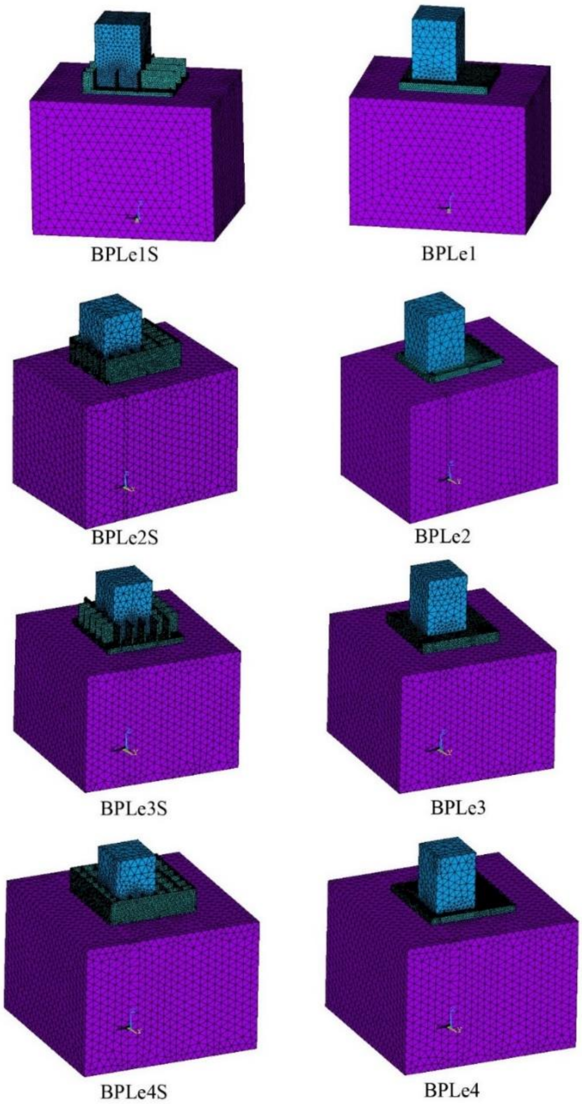

Figure 6. Meshing of column base plates with and without stiffeners

5. Analysis of Base Plate Behavior

5.1. Bearing Stress

In the specimen BPLe1, the mean stress in the 120mm and 380mm critical region is 20.00 and 6.09 Mpa, respectively. None of the stresses exceed the allowable bearing stress of the concrete (27.6 Mpa). The moment in the critical regions n and m of this model is 433.2 and 144.00 Nm respectively. Figure 7 shows the magnitude and distribution of stress in the specimens. The stresses in this model range from about 2 to 24 Mpa, indicating that the stress distribution under the base plate is trapezoidal. The use of a stiffener, which leads to increased rigidity, increases the stress and reduces the plate thickness.

In the specimen BPLeS1, the mean stress in the 120 and 380 mm critical sections was 21.86 and 6.12 Mpa, respectively. As before, none of the stresses exceeds the allowable bearing stress of the concrete (27.6 Mpa). The moment in the 120 and 380 mm critical sections is 157.39 and 441.8 Nm respectively

In the specimen BPLe2, the mean stress in the 50 mm critical region is 23.90 Mpa and never exceeds the allowable bearing stress of the concrete. The moment in the critical region of the model is 29.87 Nm. As shown in Figure 7, the stress starts at 25.6 Mpa on one side of the base plate and reaches zero at 590 mm distance. This indicates that the stress below the base plate has a triangular distribution. In this model, the tensile force of anchor bolts is 575 kN.

In the specimen BPLe2S, the presence of stiffener has led to not only reduced plate thickness but also better distribution of stress over the plate surface. As Figure 7 shows, in this specimen, the stress has a mean value of 24.5 MPa in the critical section and reaches to 25.6 MPa at the edge of the base plate. Because of the better distribution of stress over a wider area of the plate surface, in this specimen, the tensile force of anchor bolts is 490 kN.

In the specimen BPLe3, the stress in the critical section is 12.5 Mpa, which is lower than the allowable bearing stress of the concrete. The moment in this section is 741.23 Nm. Since the entire surface of the base plate experience some amount of stress, it can be concluded that the stress under the base plate has a trapezoidal distribution. According to Figure 7, the critical section of the specimen BPLe3S has a mean stress of 13.4 Mpa and a moment of 794.60 Nm. The presence of stiffener in this specimen has increased the stress at a local level but has decreased the total stress across the plate.

In the specimen BPLe4, the stress in the critical section is 7.72 Mpa, and the moment of this section is 102.30 Nm. As shown in Figure 7, in this specimen, the stress distribution has a length of 720 mm along the X-axis and 760 mm along the Y-axis. The force of the corner anchor bolt of this specimen is 62 kN. As Figure 7 shows, the stress has reached zero at some point, indicating that it has a triangular distribution in both directions. The distribution of this stress is linear as well.

In the specimen BPLe4S, the critical section has a stress of 3.8 Mpa and a moment of 109.96 Nm. Again, because of the better distribution of stress over a wider area, there is an increase in the length of the stress distribution. According to Figure 7, in this specimen, the length of the stress distribution along X and Y directions is 770 and 800 mm respectively. In this specimen, the force in the anchor bolt positioned at the farthest corner from the column is 50 kN, and the stress under the base plate has a triangular distribution in both directions.

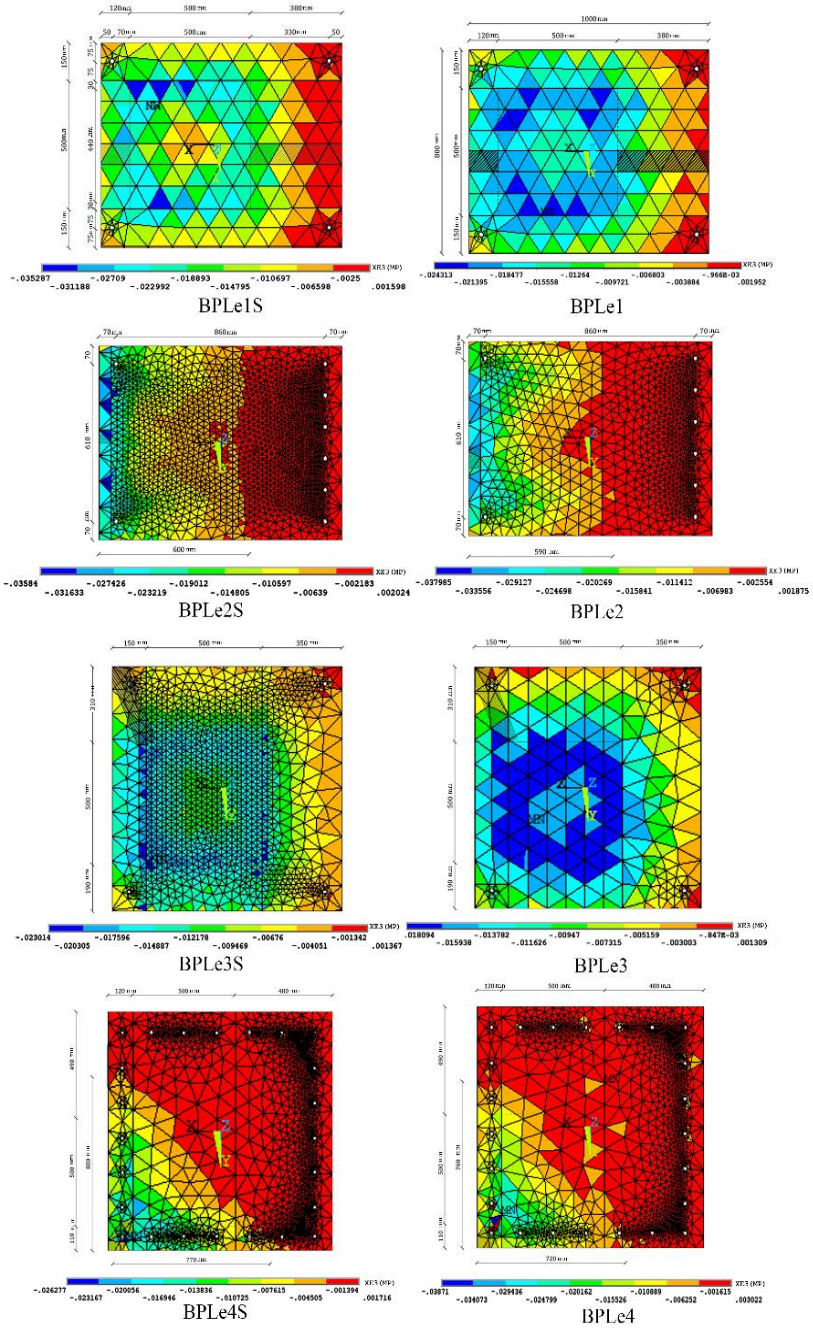

Figure 7. Bearing stress under the designed base plates

5.2. The Von - Misses Stress

The Von-Mises stress is a yield parameter based on the determination of the distortion energy of the material, that is, the energy required for a material to change shape. Von-Mises stress is a reliable failure analysis measure preferred by many design engineers. According to the deformation theory, the main cause of the failure is the shear or angular deformation caused by inter-molecular sliding. The distortion energy theory argues that the main condition for failure is the emergence of a Von-Mises stress that surpasses the yield stress. To determine whether a structure fails under a certain load, design engineers compare the greatest Von-Mises stress in the structure with the yield stresses of the corresponding points.

The distribution of Von-Mises stress under the designed base plates is shown in Figure 8. The highest Von-Mises stress in the specimens BPLe1 and BPLe1S (base plate with small unidirectional column eccentricity with and without stiffener) are 16.85 and 19.76 Mpa, respectively. As shown in Figure 8, this stress is distributed uniformly and is highest at the corners of the base plate. Also, stress concentration is prevented and thus local failure is averted. In the specimens BPLe2 and BPLeS2, the maximum stress is 19.47 and 17.95 MPa, respectively. As Figure 8 illustrates, because of left-leaning eccentricity of the column relative to the base plate, the stresses below the plate are larger on the left side than on the right side. In all modes, stress distributions remain lower than the levels allowed in the building codes; a result that demonstrates the validity of the design approach.

According to Figure 8, the maximum stresses in the specimens BPLe3 and BPLe3S are 14.21 and 16.60 MPa, respectively. It can be seen that the presence of stiffener broadens the area over which stress is distributed and makes it more uniform as well. In the specimens BPLe4 and BPLe4S, the highest stress levels are 16.17 and 14.44 MPa, respectively. These two specimens also clearly demonstrate the effect of stiffener on the uniformity of stress distribution.

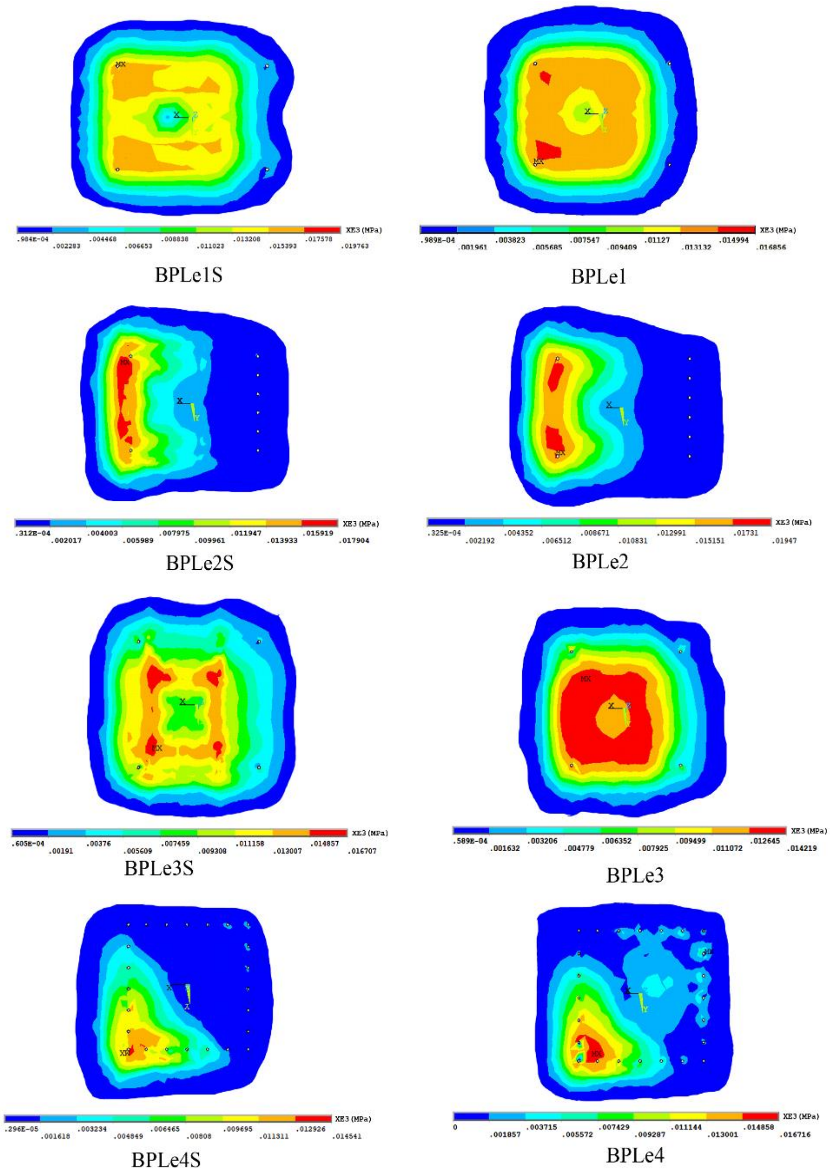

Figure 8. The Von - Misses stress

5.3. Separation of the base Plate from the Foundation

The extent of base plate separation from the foundation in each specimen is shown in Figure 9. Because of the column displacement and the eccentricity due to the load displacement, there is some uplift in the corners of the base plates. In the examined specimens, the presence of stiffener has made the base plate uplift more uniform and has reduced the thickness. For example, in the specimen BPLe4, the uplift passes through the middle of the column and has a non-uniform distribution. But in the specimen BPLe4S, the presence of stiffener, in addition to reducing the thickness, has stopped the progress of uplift and made it distributed over a larger area of the base plate. The greater the load eccentricity and the column eccentricity relative to the plate's center, the greater is the uplift.

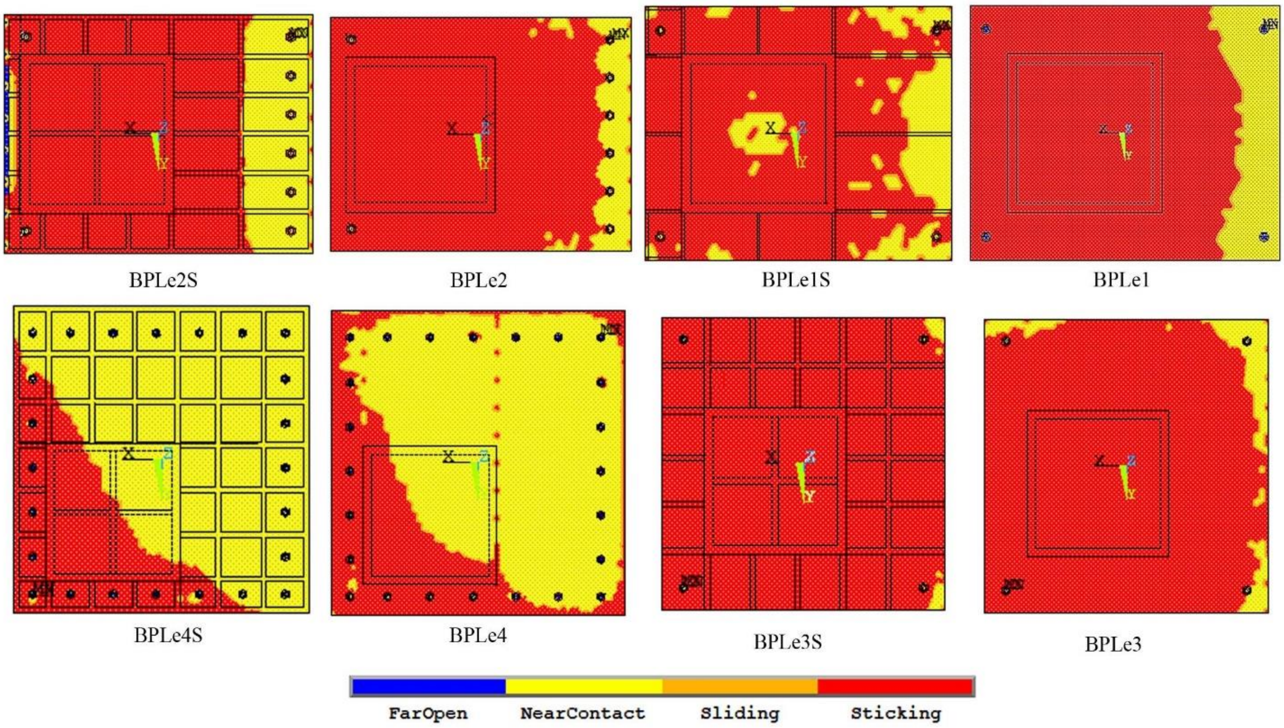

Figure 9. Separation of the base plate from the foundation

5.4. Cracking in Concrete

Figure 10 shows the patterns of crackling in the concrete foundation under the base plate. In all specimens, there are some cracks in the peripheries of base plate platform. As eccentricity increases, these cracks become more concentrated on the side to which the column is positioned. There are two groups of cracks in these specimens: primary cracks and secondary cracks. Primary cracks appear when the applied load is slightly larger than the concrete capacity. In the case of persistence or increase of this excess load, it gradually causes secondary cracking. Eccentricity can accelerate and exacerbate secondary cracking. As shown in Figure 10, the specimen BPLe1 exhibited 26% primary cracking and 4% secondary cracking, which amount to 30% cracking in total. This figure also shows that in the specimen BPLeS1, the primary cracking and secondary cracking were 28% and 6%, respectively (34% in total). The primary cracking and secondary cracking observed in other specimens were respectively: 30 and 5% (35% overall) in the specimen BPLe2, 33% and 3% (36% overall) in the specimen BPLe2S, 28% and 5% (33% overall) in the specimen BPLe3, 35% and 5% (40% overall) in the specimen BPLe3S, 40% and 10% (50% overall) in the specimen BPLe4, and 20% and 5% (25% overall) in the specimen BPLe4S. It can be observed that in the presence of stiffener, the cracks become more evenly distributed across the base plate. As indicated in Figure 6, while higher eccentricity increases the cracking, the presence of stiffener reduces it to a great extent. This is because stiffener prevents local cracking and makes the cracks more widely distributed, which in turn prevents concrete from being crushed.

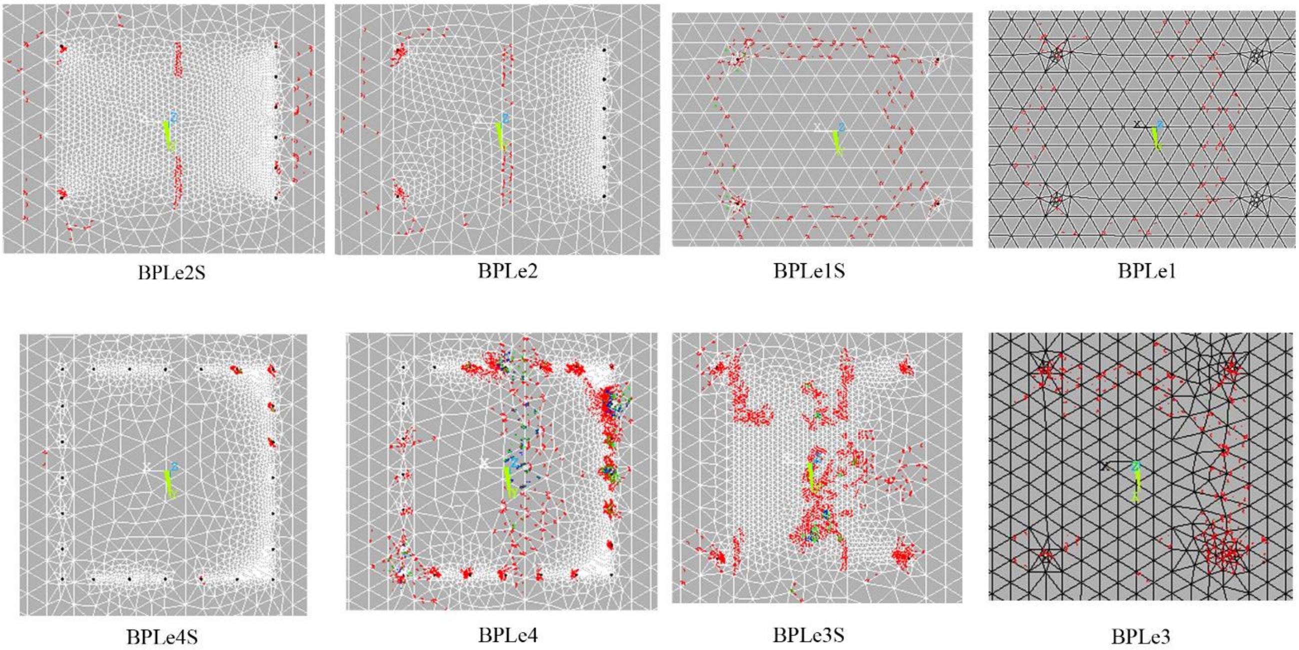

Figure 10. Foundation surface cracking

6. Conclusion

The positioning of columns on the edges of a plan or elevator shaft may impose column eccentricity relative to the center of the base plate, which necessitates extra caution in the design process. This paper presented a method based on the superposition theory for the design of columns with (small and large) eccentricity relative to the plate's center under bidirectional moments. After numerical modeling in ANSYS, the resulting stresses, base plate separation from the foundation, design moments, and foundation cracking with and without stiffener were investigated and compared with the presented theory. The results indicate that higher column eccentricity relative to the base plate leads to increased cracking. The presence of stiffener not only reduces the plate thickness but also inhibits the uplift and decreases the cracking. The extent of eccentricity has a significant impact on the base plate behavior as well as cracking under the plate. According to the results obtained from finite element models with and without stiffener, the proposed method for the design of base plates with column eccentricity relative to the plate's center has acceptable consistency with the finite element analysis and can be used in the design of these connections.

7. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] Fling, R. S. "Design of steel bearing plates." Engineering J, Am Inst Steel Constr (1970).

[2] Stockwell, F. W. "Preliminary base plate selection." Engineering Journal-American Institute of Steel Construction INC 12, no. 3 (1975): 92-99.

[3] Picard, A., and D. Beaulieu. "Behaviour of a simple column base connection." Canadian Journal of Civil Engineering12.1 (1985): 126-136. doi:10.1139/l85-013.

[4] Thambiratnam, David P., and P. Paramasivam. "Base plates under axial loads and moments." Journal of Structural Engineering 112.5 (1986): 1166-1181. doi:10.1061/(ASCE)0733-9445(1986)112:5(1166).

[5] Thambiratnam, David P., and N. Krishnamurthy. "Computer analysis of column base plates." Computers & structures33.3 (1989): 839-850. doi:0.1016/0045-7949(89)90258-7.

[6] Ermopoulos, John Ch, and George N. Stamatopoulos. "Mathematical modelling of column base plate connections." Journal of constructional steel research 36.2 (1996): 79-100. doi:10.1016/0143-974X(95)00011-J.

[7] Jaspart, Jean-Pierre, and D. Vandegans. "-Application of the Component Method to Column Bases." Advances in Steel Structures (ICASS'96). 1996. 139-144. doi:10.1016/S0143-974X(98)90196-1.

[8] Kontoleon, M. J., et al. "Parametric analysis of the structural response of steel base plate connections." Computers & structures 71.1 (1999): 87-103. doi:10.1016/S0045-7949(98)00232-6.

[9] Adany, S., L. Calado, and K. Dunai. "Experimental studies on cyclic behavior modes of base-plate connections." Proceedings of the Third International Conference on the Behavior of Steel Structures in Seismic Areas (STESSA 2000), Montreal, Canada. 2000.

[10] Kontoleon, M. J., and C. C. Baniotopoulos. "Computational aspects on the frictional unilateral contact problem arising on steel base plate connections." Computers & Structures78.1-3 (2000): 303-309. doi:10.1016/S0045-7949(00)00082-1.

[11] Ermopoulos, J. Ch, and G. N. Stamatopoulos. "Analytical modelling of column-base plates under cyclic loading." Journal of constructional steel research 40.3 (1996): 225-238. doi:10.1016/S0143-974X(96)00043-0.

[12] Khodaie, Sina, Mohammaed R. Mohamadi-shooreh, and Masood Mofid. "Parametric analyses on the initial stiffness of the SHS column base plate connections using FEM." Engineering structures 34 (2012): 363-370. doi:10.1016/j.engstruct.2011.09.026.

[13] Yao, C. U. I., Hao Liu, and Hao Li. "Shear Behavior of Exposed Column Base Plate Connections." 6th International Conference on Advances in Experimental Structural Engineering 11 th International Workshop on Advanced Smart Materials and Smart Structures Technology, August 1-2, 2015, University of Illinois, Urbana-Champaign, United States.

[14] YAVUZ, Gunnur, Hussein HUSSEIN, and Pinar Salahaldin. "Designing the Column Base Plate of a Steel Industrial Building according to AISC-LRFD Method." International Journal of Natural & Engineering Sciences 9.2 (2015).

[15] Melenciuc, Silviu Cristian, et al. "Behaviour of Steel Column Base Connections Under Cycling Loading Conditions." Buletinul Institutului Politehnic din lasi. Sectia Constructii, Arhitectura 61.2 (2015): 53.

[16] Amin, Gholizade, Vahid Shamsi and Javad Shamsi, 1394, Assessment of base plates connections characteristics on foundation,base plate and column behavior, 10th international congress of civil engineering,Tabriz faculty of civil engineering,Tabriz.

[17] de Macedo, Rafael Scudelari, and Luiz Francisco Scudelari de Macedo. "03.18: Anchor bolt tensile load distribution: Effects of the column base ‐ plate design: Wide flange column bases–loading on additional line of bolts." ce/papers 1.2-3 (2017): 649-658. doi:10.1002/cepa.103.

[18] Ebadi, Parviz, Mohsen Beheshti and Saeedeh Hasani, 1396, The effect of hardeners on the distribution of sub-column stresses under two-directional bending anchors using nonlinear static analysis, Second International Conference on Civil Engineering, Architecture and Crisis Management, Tehran, Allameh Majlesi University.

[19] Ebadi, Parviz; BEHESHTI, Mohsen; HASSANI, Saeedeh. Effects of stiffeners on stress distribution and crack control below base plates under small bidirectional moments using nonlinear static analyses. QUID: Investigación, Ciencia y Tecnología, 2017, 1: 1128-1136.

[20] Trautner, Christopher A., and Tara C. Hutchinson. "Parametric Finite-Element Modeling for Exposed Steel Moment Frame Column Baseplate Connections Subjected to Lateral Loads." Journal of Structural Engineering 144.6 (2018): 04018049. doi:10.1061/(ASCE)ST.1943-541X.0001990.

[21] Fasaee, Mohammad Ali Khaksar, Mohammad Reza Banan, and Sina Ghazizadeh. "Capacity of exposed column base connections subjected to uniaxial and biaxial bending moments." Journal of Constructional Steel Research 148 (2018): 361-370. doi:10.1016/j.jcsr.2018.05.025.