

EFFECTS OF STIFFENERS ON STRESS DISTRIBUTION AND CRACK CONTROL BELOW BASE PLATES UNDER SMALL BIDIRECTIONAL MOMENTS USING NONLINEAR STATIC ANALYSES

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Resumen: Las conexiones de base de columna son componentes críticos en las estructuras de acero y transfieren todas las fuerzas y momentos a la fundación. Los códigos de construcción y manuales de diseño ilustran en general la carga axial junto con pequeños momentos unidireccionales para el diseño de conexiones de base de columna. Mientras que el único método exacto para el diseño de estas conexiones críticas es el modelado de elementos finitos. Este método es altamente complicado debido a la multiplicidad y variaciones de los tipos de placas base en los edificios. En realidad, existen muchos problemas para el modelado y análisis de las diversas combinaciones de cargas de las estructuras. Por lo tanto, la mayoría de los diseñadores prefieren no utilizar este método. En este artículo, el método de superposición utilizado para el diseño de placas base bajo pequeños momentos biaxiales y los resultados se comparan con los resultados obtenidos de los análisis de pushover en el software ANSYS. Los resultados muestran que el método de superposición puede ser utilizado para el análisis de placas base bajo pequeños momentos biaxiales. Además, el uso de refuerzos aumenta la tensión bajo las placas de base hasta un 5 por ciento en el método de elementos finitos en comparación con las placas de base sin refuerzos. Además, la diferencia entre los métodos de superposición y de elementos finitos para placas base con y sin refuerzos difiere hasta 6 y 13 por ciento, respectivamente.

Palabras clave: Placa base, Pequeña excentricidad, Momento biaxial, Análisis no lineal, Diseño, Conexión.

Abstract: Column base connections are critical components in the steel structures and transfer all forces and moments to the foundation. The building codes and design handbooks generally illustrate the axial loading along with one-way small moments for the design of column base connections. while the only accurate method for design of these critical connections is finite element modeling. This method is highly complicated because of multiplicity and variations of the base plate types in the buildings. Actually, there are many problems for the modeling and analysis for the various plate loads combinations of the structures. Therefore, most of the designers prefer not to use this method. In this paper, the superposition method used for the design of base plates under small biaxial moments and the results are compared with the results obtained from pushover analyses in ANSYS software.

The results show that superposition method can be used for the analysis of base plates under small biaxial moments. In addition, using stiffeners increases the stress under the base plates up to 5 percent in finite element method in compare with base plates without stiffeners. Also, the difference between superposition and finite element methods for base plates with and without stiffeners differs up to 6 and 13 percent, respectively.

Keywords: Base plate, Small eccentricity, Biaxial moment, Nonlinear analysis, Design, Connection.

1. INTRODUCTION

The base plate connections are crucial components of the steel structures for their rules to transfer loads from the columns to the foundation. They increase the interface area between the column and foundation to decline the stress under the column and prevent failure of foundation material.

According to the results have been reported by Technical Council on Lifetime Earthquake Engineering and Northridge Reconnaissance Team, most of the base plate connections which had been designed according to the usual methods, worked incorrectly under severe earthquake excitations. In addition, the studies on damaged steel structures after the Kobe earthquake state that the majority of damages are relevant to the improper functioning of the base plates.

These researchers focused on the necessity of design of the base plate connections for higher ductility and providing more reliable design methods.

Fling (1970) proposed the use of yield line theory for the design of column bases. He assumed that the plate bending is elastic and stated that the deflection between the plate and the concrete foundation should be limited to a prescribed value. He conceded that his method was conservative because of his assumptions.

Stockwell (1975) need some discussions for the design of base plates for lightly loaded columns and concluded that the flexibility of the plate and the subsequent redistribution of bearing stress is not consistent with the uniform distribution of stresses assumption below the plate. He found that the stress distribution under base plate depends on the shape of steel column section. Murray (1983) conducted an analytical and experimental study. He used an elastic finite element analysis to model the base plate. Springs were used for connecting the plate to a rigid foundation. They were disconnected under uplift condition. Based on his analytical study and test results, he proposed that Stockwell's approach

may be used. He defined the effective bearing portion of the plate and developed a design approach for plates subjected to uplift, based on a yield line analysis. Picard and Beaulieu (1985) looked at the effects of axial loads on the rigidity of base plates. They found that the axial compression force increases the rigidity at the base. Thambiratnam and Paramasivam (1986) constructed connection base plate with bolts in the laboratory and determined the maximum capacity under axial and bending loads. The test results show that flexible base plates when loaded at high eccentricities, controlled by the failure of the base plate and anchor bolts. While the crack of concrete governs the failure of connection under small load eccentricities. Thambiratnam and Krishnamurthy (1989) analyzed the base plate using finite element method and found the real bearing stress distribution under the base plates. Stamapolos and Ermupolos (1997) studied the mathematical model of the base plates under cycling and seismic loading and suggested the nonlinear relation for the moment –rotation diagram. Jaspert and Vandegans (1998) conducted a survey about the behavior of anchor bolts with end anchorages and found that the bond between anchorage and concrete have been broken easily, especially under large deflections or heavy earthquake excitations. So that the bond between anchor bolts and foundation may be ignored from the beginning of the loading. Kontoleon et. al. (1999) studied the structural response of column base plate connections by means of two-dimensional models and moment-rotation diagrams extracted for base plates with different thicknesses. The parametric analysis of their model shows that the stiffness of the base plate is a significant parameter, affecting the development of prying action at the active contact areas of the plate. Adany et. al. (2000) studied the behavior of the column base plate connections under cyclic loading. They investigated the effects of various parameters on the behavior of the base plate connections and found that semi-rigid base plate connections work correctly in compare with others connection types. Khodaie et. al. (2012) presented a paper which conducts a parametric study on the initial stiffness of bolted base plate with Square Hollow Section (SHS) column connection, through an

extended 3-D Finite Element Modeling (FEM). Different features of the connection such as material behavior, geometric details, typical contact phenomena and large displacements considered in the modeling. A comparison between experimental test and FEM carried out to illustrate the ability of the numerical method to simulate the connection behavior. In addition, an analytical explanation on the initial stiffness of the connection introduced. The parameters for the numerical study were appointed and finally, using regression analysis, a function obtained to evaluate the initial stiffness of the connection. Heristchian et. al. (2014) studied the tensile behavior of embedded base plates and presented three methods for the design of embedded base plates considering the effects of boundary conditions, the size of the concrete block, the tapering angle, and the coefficient of friction. They found that the restrained boundary conditions prevent the splitting of the concrete block, which is the most common type of failure in embedded tapered sections and could double its pull-out strength. Under proper confinement, the embedded tapered sections could have very large post-failure pull-out strength. Kavoura (2015) evaluated the influence of base plate rotational stiffness on the design of low-rise steel buildings. His study stated that consideration of the rotational stiffness of the pinned connections reduces frame deflections between 11 and 67 percent and has the potential to make steel building systems more economical by decreasing the frame weight between 0 and 12 percent, which is considered a substantial cost saving for the steel building industry where profit margins are relatively low. One of the main references for the design of the base plates is AISC Design Guide-1, which do not consider the biaxial bending loads. Ebadi et. al. (2017) studied the design of base plates under small and large biaxial eccentricities and found that superposition method can be used for the design of base plates under biaxial moments. They also found that using stiffeners can decrease the maximum induced stresses under base plates up to five percent.

In this paper, six base plate specimens with and without stiffeners investigated under different loading scenarios of pure axial loading, axial loading with the small eccentricity and biaxial loading with small eccentricity. They designed and analyzed using ultimate limit state and finite element methods. In addition, the effects of using the stiffeners on the stress distribution pattern, a number of cracks in concrete and the behavior of the base plate connection studied. It was found that superposition method can be used for the analysis of base plates under small biaxial moments. Providing stiffeners on base plates

increases the stress under the base plates. Also, there are some differences between superposition and finite element method that may be considered in the design.

2. DESIGN PHILOSOPHY OF BASE PLATES

Six base plate specimens, with and without stiffeners, designed and analyzed under three loading conditions for pure axial loading, axial loading with small eccentricity and biaxial loading with small eccentricity. The design of base plates based on ultimate limit state and finite element method. In subsequent sections, the design assumptions and considerations for the design of specimens illustrated for different loading conditions.

2.1 Design of base plates under pure axial loading

The stress distribution under base plate subjected to axial load with no eccentricity assumed to be uniform (see Figure 1(a)). The stress under the base plate may be calculated using Equation Figure (1). In addition, the critical moment adjacent to column edge, M_{pl} , calculated using Equation (2).

$$q = \frac{P}{A} \quad (1)$$

$$M_{pl} = q\left(\frac{l^2}{2}\right) \quad (2)$$

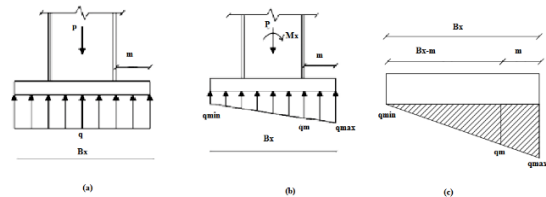


Figure 1. The Distribution of stress under the base plate; a) The Pure axial load, b) the axial load with small one-way eccentricity, c) moment adjacent column.

where, m is the length of the critical bending section, P is axial load, A is the area of the base plate, and q is stress under the base plate.

2.2 Design of base plates under axial loading with one-way small eccentricity

For the small moment case, the eccentricity is small ($e_x < B_x/6$). Based on the elastic behavior assumption, the compression distribution of stress is not uniform and it distributes as a trapezium

form. For the small eccentricity, the axial loading just transferred by the compression strength under the base plate. Therefore, the distributed stress is linear(see Figure 1(b)). In this case, there is no tension between the base plate and foundation and the anchor bolts are not effective. The maximum stress that occurs under the base plate is limited to the maximum bearing stress of concrete, as described by Equation (3).

$$q_m = \left(1 - \frac{m}{B_x}\right)q_{\max} + \frac{m}{B_x}q_{\min} . \quad (3)$$

where, q_m denotes the stress in the critical section (adjacent to column) and m is defined in Figure 2. q_{\min} and q_{\max} are the minimum and maximum stress's under the plate, respectively. B_x is the dimension of base plate parallel to eccentricity direction.

The critical moment that occurs at the edge of the column can be obtained by the static balance similar to the cantilever beam that is loaded from bottom, as described by Equation (4).

$$M_{bp} = \frac{m^2}{6} (2q_{\max} + q_m) \quad (4)$$

Where, M_{pl} is the critical moment in the critical section, as defined in Figure 1.

2.3 Design of base plates under axial loading with two-way small eccentricity

For the biaxial small bending, M_x and M_y , that occur along two orthogonal directions, the evaluation of the exact distribution of stress is essential to obtain the critical bending. The effect of this bending and the stress due to them have obtained in any of directions separately with the considering the effect of the bending along both orthogonal directions.

with the bendings in the direction of x-direction or y-direction, the distributed stress under the base plate is not uniform. In this situation, the stress under one of the corners is maximum. At each direction, it is possible to calculate the stresses and moments similar to one-way moment condition and superpose the effects of two directions together. Because of the small eccentricity, the tensile stress does not occur in the foundation and no need to design anchor bolts. The distributed stress is as a trapezium form in two directions. Therefore, this trapezium is divided into the rectangle and triangle for calculating the quantity of stress (The principle of superposition of forces). The distributed stress with the small biaxial eccentricity is shown in Figure 2.

Figure 2(a) shows the distribution of stresses under axial loading with no eccentricity. The distribution of stresses along x and y directions under biaxial moments is shown in Figure 2(b,c).

Because of using the principle of superposition of forces, three figures (in Figure 2(a,b, c)) added together and the total distributed stress is shown in Figure 2(d).

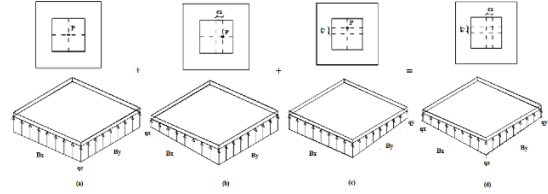


Figure 2. The Distribution of stresses under the base plate; a) The Pure axial loading, b) The axial loading with small uniaxial eccentricity in the x-direction, c) The axial loading with small uniaxial eccentricity in the y-direction, d) The axial loading with small biaxial eccentricity in both x and y directions.

By the separation of induced stresses due to the axial load and flexural moments and their algebraic summation, the maximum vertical stress on the base plate will be calculated using Equation (5).

$$q = \frac{P}{B_x \times B_y} + \frac{6M_x}{B_x \times B_y^3} + \frac{6M_y}{B_y \times B_x^3} \quad (5)$$

where, M_x and M_y correspond to the flexural moment around x and y axes, respectively. B_x and B_y are base plate dimensions along x and y directions, respectively. To calculate critical moment in the x-direction, the moment due to M_x in x-Direction (M_{xx}), the moment due to M_y in the x direction (M_{xy}) and the moment due to axial load P should be defined and combined together, as described by Equation (6). The procedure of calculation of M_y is shown in Figure 3.

$$M_o = \frac{3Mm^2}{BB^2} \left(1 - \frac{2m}{3B}\right) , \quad M_e = \frac{qm^2}{2} , \quad M_c = \frac{Pm^2}{8XY} , \quad M_o = M_o + M_e + M_c , \quad (e < \frac{B}{6}) \quad (6)$$

$$M_o = \frac{3Mn^2}{BB^2} \left(1 - \frac{2n}{3B}\right) , \quad M_e = \frac{qn^2}{2} , \quad M_c = \frac{Pn^2}{8XY} , \quad M_o = M_o + M_e + M_c , \quad (e < \frac{B}{6}) \quad (7)$$

where, m and n are critical width and length, q_x, q_y , and q_z are stressed in x, y and z direction, respectively. X and Y are the length and width of distributed stress and are equal to half of the length and width of the base plate, respectively.

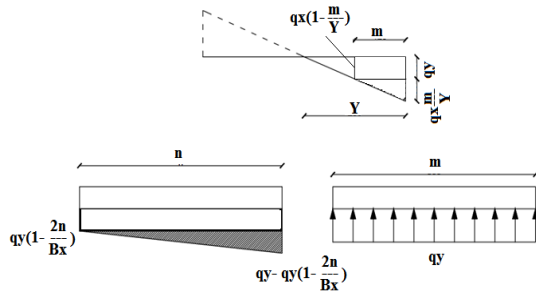


Figure 3. The critical moment of base plate under biaxial small moment loads along x, y and z directions

3. DESIGN OF SPECIMENS

In order to investigate the superposition principle theory for the analysis and design of base plate under biaxial moments, with low eccentricity ($e < B/6$), the finite element software of ANSYS is used. For this purpose, specimens have been designed under different loading conditions: pure axial loading, axial loading with the small uniaxial moment, the axial loading with the small biaxial moment. Then, the results have been compared with the finite element analysis results. The baseplates have been designed and modeled with and without stiffeners. In the first case, a base plate with a dimension of BPL700x700x48 is subjected to the pure axial load. All dimensions are given in millimeters. The base plate is designed with LRFD method. The length and width of the column are Box500x500x30. The critical length and width in the vicinity of columns are 100 mm and the pure axial capacity of the column is equal to 12000 kN. The axial load is applied in the center of the column. The amount of uniform stress under base plate is 24.4 MPa, which is lower than the allowable bearing stress of concrete (27.63 MPa). A flexural moment in the critical zone of the base plate is 122.5 N-m.

In the second case, a base plate with a dimension of BPL750x750x60 is subjected to 8000 kN axial load with an eccentricity of 105 mm, which leads to a flexural moment of 840 N-m around the x-axis. The column is similar to the first case. The length and width of critical sections are 125 mm. The amount of maximum and minimum stress is equal to 26.17 and 2.28 MPa, respectively, which is lower than the allowable bearing stress of concrete and the flexural stress under base plate in critical section zone is 194.18 kN.m

In the third case, a base plate with a dimension of BPL800x800x72 is subjected to axial load and flexural moment with small biaxial eccentricity ($e_x < B_x/6$, $e_y < B_y/6$). The axial load is 6500 kN with an eccentricity of 77 and 108 mm along x and y directions, respectively, that leads to the flexural moment of 500 and 700 N-m in x and y directions,

respectively. The maximum stress under the base plate is 24.22 MPa, which is lower than the allowable bearing stress of concrete. The total critical moment in x and y directions is equal to 268.34 and 266.69 N-m (per unit width). Figure 4 shows the designed base plates under different loading cases. The specimens named according to Table 1.

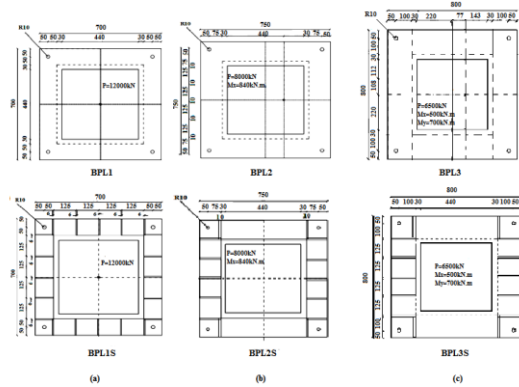


Figure 4. Design of specimens;

Specimen	Dimension*	Axial Load	M_x	M_y	Stiffener
BPL1	BPL700x700x48	12000	-	-	No
BPL2	BPL750x750x60	8000	840		
BPL3	BPL800x800x72	6500	500	700	
BPLS1	BPL700x700x20	12000	-	-	Yes
BPLS2	BPL750x750x25	8000	840		
BPLS3	BPL800x800x25	6500	500	700	

Table 1. The designed specimens

* All dimensions are mm and Loads are kN-m

4. FINITE ELEMENT MODELING

The nonlinear static analysis used to analyze specimens. The steel material type is S235 with the yield strength of 235 MPa. Two percent of the elastic modulus of elasticity considered for strength hardening behavior of steel. Elastic Modulus of elasticity and poisson ratio of steel were 2.1E5 MPa and 0.3, respectively. The concrete strength of foundation after 28 days is 25 MPa. For the modeling of the column and base plate and anchor rods, the SOLID-187 element and for concrete, SOLID-65 were used, respectively. The class 187 of solid element is a hexahedron element which is used for 3D objects modeling [19]. This element has 8 nodes and if some of these nodes coincide to each other, the element converts to simpler forms like a pyramid. Each node has 3 degrees of freedom (transformation in x, y and z directions). This element could be used to analyze linear and

nonlinear problems and also to consider partial and global buckling. In addition, the contact element of TARGET-170 and CONTA-174 are used between base plate and concrete. The lower surface of foundation restrained in all directions. The end of anchor rods is completely restrained in concrete and the strain of anchors prevented. Elements are shown in Figure 5.

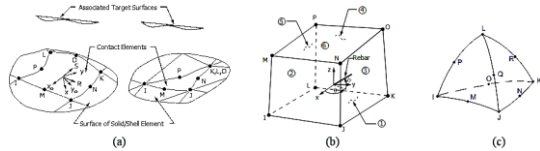


Figure 5 a) Contal174, Target170 Element - b) Solid65 Element - c) Solid187 Element

In order to control the base plate thickness, uniform stress distribution under base plate, cracking, and so on, stiffeners provider on base plates. The finite element model of base plates with and without stiffeners are shown in Figure 6.

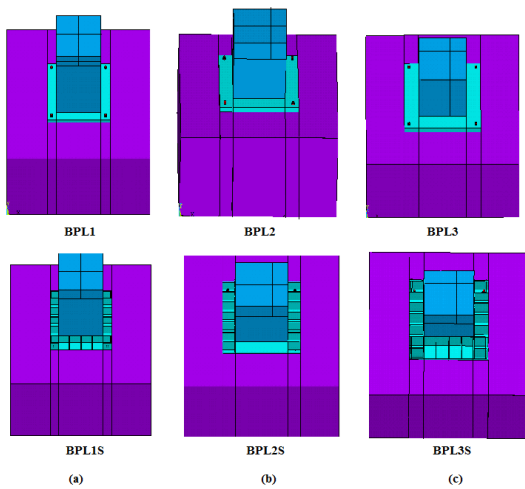


Figure 6. Designed specimens with and without stiffeners.

The size of elements mesh have been selected by trial and error to consider both accuracy and efficient analysis time (see Figure 7).

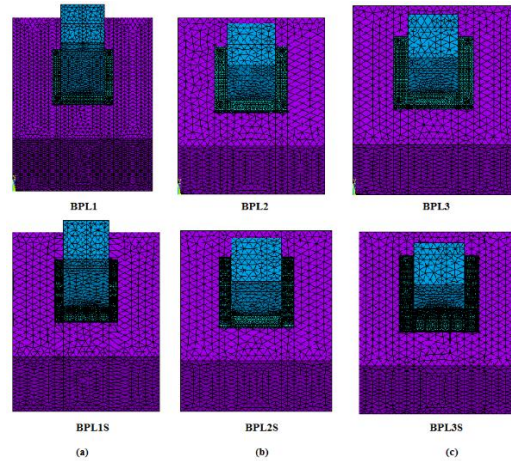


Figure 7. Finite element meshing of specimens

5. ANALYSIS RESULTS

5.1 Bearing Stress

The bearing stress from finite element modeling of specimens without stiffeners for BPL1 is 22 MPa, BPL2 has minimum and the maximum stress of 5.06 and 22.05 MPa, respectively, which is less than the allowable bearing stress. In the finite element analysis, the flexural moment applied to the base plate for specimens BPL1, BPL2 and BPL3 are 110, 178 and 268 N-m, respectively. Providing of stiffeners increases rigidity, and consequently, increases stress and decreases the required thickness of the base plate. In this case, the stresses for specimens BPL1, BPL2 and BPL3 are 24.22, 24.65, 23.98 MPa, respectively. In addition, their critical moment for BPL1S, BPL2S, and BPL3S are 120, 186 and 256 N-m, respectively. It can be seen that providing stiffeners increases the bearing stress and moments inside base plates while providing more uniform stresses with less stress concentration. Figure 8 shows the bearing stresses of specimens in 2 cases of with and without stiffeners.

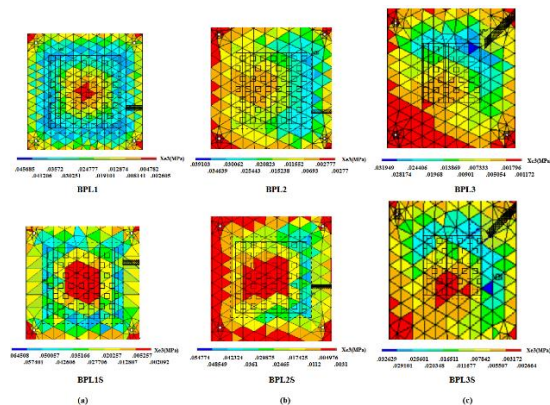


Figure 8. The bearing stress under specimens

5.2 Von Mises stress Distribution

Figure 9 shows Von Mises stress distribution under specimens. Figure 9(a) shows the stress distribution under the base plate for specimens BPL1 and BPL1S. The maximum stress with and without stiffeners is equal to 21.7 and 20.8 MPa, respectively. The stress distributed uniformly and the maximum stress was under the column. Also, providing stiffeners decreased stress concentration under columns. Figure 9(b) shows stress distribution under specimens BPL2 and BPL2S. The stress distribution is linear and the minimum and maximum stresses with stiffeners were equal to 2.2 and 19.6 MPa and without stiffeners 1.96 and 16.87 MPa, respectively. Figure 9(c) shows the stress distribution of specimens BPL3 and BPL3S. The stress distribution model is adopted to superposition principle and is calculated separately with pure loading, one-way small eccentricity, two-way small eccentricity and the final stress is calculated by the superposition principle. The maximum stress of specimens equal to 15.1 and 16 MPa, respectively. In all cases, the stress distributed according to steel structure design codes and thus the design accuracy is confirmed.

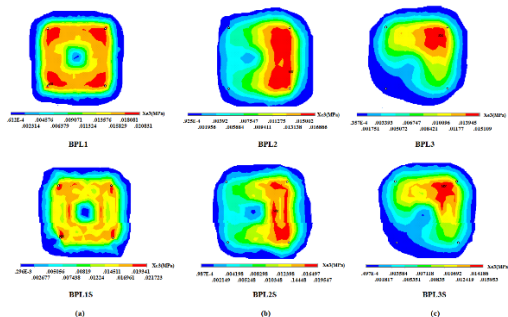


Figure 9. Von Mises stress distribution under specimens

5.3 Contact behavior

Figure 10 represents the base plate behavior under all loading cases. Figure 10(a) shows that the base plate is in an adhesive manner and there is some uplift (near contact) because of the huge load at the center which leads to small uplift in the corner of the base plate. Figure 10(b) shows that a small eccentricity induces a small uplift in the corner of the base plate. Figure 10(c) shows more increase in eccentricity. So, uplift in the corner of the base plate is more than the uniaxial eccentricity and leads to putting it in separation threshold. In addition, the eccentricity in 2 directions increase the uplift amount and put it in complete separation threshold. Figure 10(a) to 10(c) show the behavior of base plate with stiffeners and represents that the presence of stiffeners leads to uniform distribution of uplift and prevent the

great separation. Providing stiffeners decreases the partial uplift and its spread from only one zone. Whatever the eccentricity increase, the presence of stiffener effect is more visible. Thus, in higher eccentricities, the stiffeners have more considerable advantages.

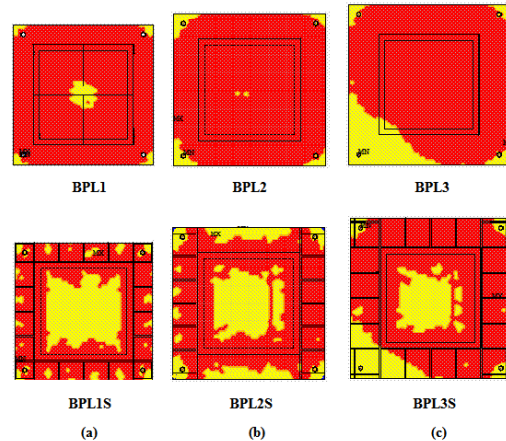


Figure 10. The contact behavior of designed specimens

5.4 Foundation crack development

Figure 11 represents how the cracks developed in the concrete foundation. As it is clear in this Figure, a number of cracks are approximately uniform around the column zone and more cracks observed around anchor rods. The cracks include primary and secondary cracks. It means that the primary cracks will occur when the load increases a little more than foundation capacity. If the load or its eccentricity increase, the secondary cracks will occur. The most critical situation is related to continues loading in secondary cracks which lead to the foundation crush. In BPL1, the amount of primary and secondary cracks are 20 and 2 percent, respectively. The total cracks, in this case, was about 22 percent and no crushing observed.

Figure 11(b) represents a number of cracks in the concrete foundation. The cracking amount is increased by an increase in eccentricity and the most of the cracks occur in column placement zone and such as the first case (Figure 11(a)), more cracking observed around anchor rods. It is observed that primary and secondary cracks are about 25 and 5 percent of foundation volume, respectively and no crushing observed. The total cracking is about 30 percent.

Figure 11(c) shows the cracking of concrete foundation in BPL3. Because there is eccentricity in two directions, more cracking observed in comparison with last two cases. The primary and secondary cracking is about 30 and 10 percent, respectively. The total cracking is about 40 percent.

The presence of stiffeners decreases locally concentrated cracks and the crack distribution is more uniform because of fewer stress concentrations. Therefore, cracking in presence of stiffeners for BPL1S is about 10 and 1 percent for primary and secondary cracks, respectively. For BPL2S, cracks are 12 and 3 percent for primary and secondary cracks, respectively. For BPL3S, the cracks are 14 and 5 percent for primary and secondary cracks respectively. Thus, the stiffeners decreased the cracking about 50% and its distribution has been uninformed. Eventually, Figure 11 shows that by increasing the eccentricity, the cracking increases and using of stiffeners is halved the cracking amount. Using of the stiffeners is necessary to control and decrease the concentrated cracks and distribute cracks in a wider area. In addition, stiffeners limit and decrease the secondary cracks and prevents crushing by decreasing concentrated cracking

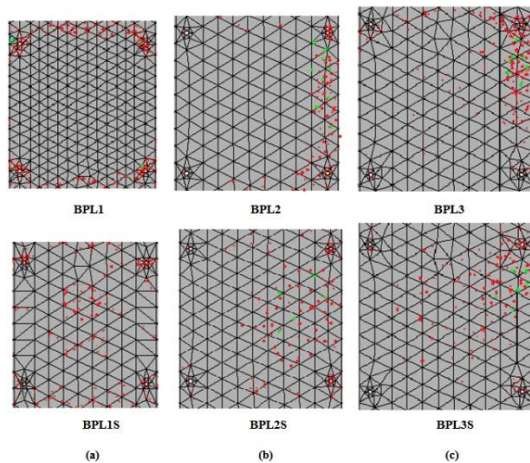


Figure 11. The concrete cracking of the foundation at top surface

6. CONCLUSION

The behavior of steel base plates, with and without stiffeners, studied under pure axial load and axial loads with small one-way and two-way eccentricities. The specimens designed according to current design procedures of LRFD method and analyzed using the nonlinear software. Superposition of direction effects considered separately for two-way moment loads. The material and geometrical nonlinearities along with foundation cracks and uplift of base plates considered in analyses.

Six specimens designed and analyzed and it was considered that the base plate under the pure axial loading has uniform and constant stress distribution. By increasing of the load eccentricity, the stress distribution changes from constant to linear.

The superposition method for design of base plates under bi-directional moment loads

coincides with analytical results. Also, providing stiffeners increases the bearing stress and moments inside base plates, while providing more uniform stresses with less stress concentration. It means that stiffeners decreased stress concentration under columns. Providing stiffeners decreases the partial uplift and its spread from only one zone. Whatever the eccentricity increase, the presence of stiffener effect is more visible. Thus, in higher eccentricities, the stiffeners have more considerable advantages.

The presence of stiffeners decreases locally concentrated cracks and the crack distribution is more uniform because of fewer stress concentrations. Using of the stiffeners is necessary to control and decrease the concentrated cracks and distribute cracks in a wider area. In addition, stiffeners limit and decrease the secondary cracks and prevent crushing by decreasing concentrated cracking.

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