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- RESEARCH ARTICLE -

An Investigation of Base Plate Connections of a Steel Industrial Building Having Different Column Cross-Sections

Pinar Salahaldin Hussein Hussein[1], Günnur Yavuz[2*]

[1]Department of Civil Engineering, Kirkuk University, Kirkuk, Iraq
[2] Department of Civil Engineering, Konya Technical University, Konya, Turkey

Abstract

In this study, steel column base plate connections of a steel industrial building that are one of the most important connection regions were studied. Two dimensional static analysis of a steel industrial building was performed and exposed column base plate dimensions were determined according to American Institute of Steel Construction Code-LRFD (Load and Resistance Factor Design) method. The effects of selected steel column cross section types on the behaviour of column base plate connections were investigated by using RFEM finite element analysis program. For this purpose, finite element analysis of three types of column base plate connection models were performed and evaluated comparatively. From results, the best value for top column lateral displacement was obtained in W column section-base plate connection and the best behaviour for Von Mises stresses values was obtained in square hollow section column. The undesired behaviour was determined in circular hollow section column-base plate connection type.

Keywords:
Industrial building, Column, Base plate, Finite element analysis, LRFD.

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Introduction

The column base plate connections are one of the most important regions of steel structures. The typical column base plate connection consists of steel column, base plate, anchor bolts, grout and concrete foundation. The column base plates transfer axial loads, moments, tension and shear forces from building to concrete foundation and it may be designed with special parts to sufficiently

* *Corresponding Author: Günnur YAVUZ, e-mail: gyavuz@ktun.edu.tr*

loads transfers and to increase its strength. The column base plate types used in steel structures are exposed and embedded base plates. The exposed base plate connection is used in both seismic and non-seismic regions (Kingsley, 2005). The exposed column base plate connection consists of a steel column welded to a base plate and anchor bolts. The base plate is bolted by anchor bolts to a concrete pedestal or foundation. This connection type, are withstand the moment and axial loads through the bearing on the foundation in compression and tension in the anchor rods. Also these connections are withstand the shear forces through the shear in the anchor rods and friction between the base plate and foundation (Kingsley, 2005). Exposed column base plate connection is one of the most important connection types in a steel structure, especially in a steel Moment Resisting Frame (MRF). In a MRF, base plate connects the column to the concrete foundation directly therefore lateral forces that form of wind or seismic effects can be transferred through the base plate and anchor bolts to the grout layer and concrete foundation (Lee et. al., 2008).

In the past, the best way of studying the behaviour of column base plate connections was testing experimental models. Although the results of such experiments are closer to reality, their cost is expensive. Additionally, in order to understand the behaviour of connections with different models, these experiments should be repeated several times. Therefore, understanding the behaviour of different types of base plates, failure modes and their advantages and disadvantages by using computer simulations can result in great savings. The relation between experimental and analytical model of column base plates was shown in many studies. Most of these investigations were on simple base plates without stiffeners and the verification among results seemed to be satisfactory (Shafieifar & Khonsari, 2012, Stamatopulos & Ermopoulos, 2011). Until one of the failure modes of column base plate connection such as formation of a plastic hinge in the column, a plastic mechanism in the base plate, crushing of concrete in bearing, yielding of the anchor bolts in tension, or tear off of the concrete by the anchor bolts in tension was not effective, the general behaviour of a column base plate connection will be elastic (Roşca et. al., 2013).

In this study, nonlinear finite element analysis for a single story steel industrial building with exposed column base plate connections having different column types were performed. The support reactions which obtained from two dimensional analysis for the building were used to determine the base plate dimensions according to American Institute of Steel Construction (AISC)-Guide 1, Load and Resistance Factor Design (LRFD) method. Then the base plate and anchor bolts details were used in different models with W, square hollow and circular hollow column cross-sections. The finite element analysis of these types of steel column base plate connections were performed and evaluated comparatively.

Materials and Methods

Single story steel industrial building

The column and beam sections were selected as W18x119 (depth d=18.97 in (482 mm), flange width b_f =11.265 in (286 mm)) in the industrial building (Figure 1). Steel material was selected as Grade 36, for this material yield stress Fy equals to 36 ksi (244.8 MPa) and concrete compressive strength f_c' equal to 4 ksi (27.2 MPa). The dead, snow and wind loads were applied on the frame in two dimensional analysis of the industrial building.

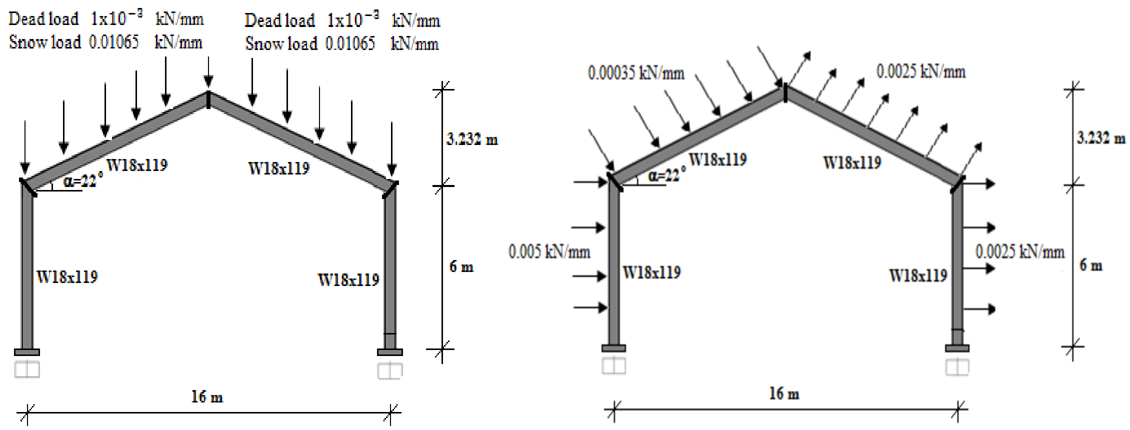
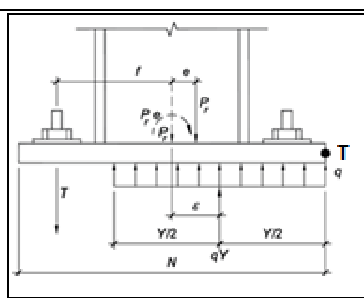
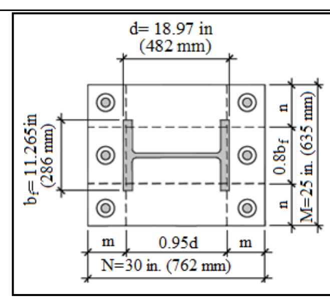


Figure 1. Load values applied on industrial building (a) dead and snow loads, (b) wind loads.

Two dimensional analysis of the industrial building having fixed supports was performed in SAP2000 program and the support reactions were obtained according to LRFD load combinations. The support reactions were used to determine the base plate dimensions and anchor bolt details according to AISC-Design Guide 1. The maximum support reactions which obtained from (1.2D+1.6S+0.8W) load combination were M_u= -2350.279 kip.in (-265.55 kN.m), P_u= 39.076 kip (173.82 kN) and V_u= -22.136 kip (-98.466 kN). According to AISC Base Plate and Anchor Rod Design Guide 1- LRFD method, if equivalent eccentricity greater than critical eccentricity which calculated as shown in Table 1, the column base plate will be under large moment effect, so the design procedure for large moment case was used to evaluate the base plate dimensions. The base plate dimensions (NxB) and plate thickness were determined as 30x25 in (762x635 mm) and 2 in (50.8 mm), respectively. 6 pieces 1 1/4 in (31.75 mm) diameter bolts were used according to AISC Steel Design Guide 1-Table 2.3 (Yavuz & Hussein, 2015). The applied design procedure for the base plate under large moment effect is presented in Table 1.

Table 1. Design procedure for base plate with large moment effect according to AISC Design Guide 1-LRFD method.





1. Determining the axial load and moment. P_u= 39.076 kip (173.82 kN), M_u= -2350.279 kip.in (-265.55 kN.m).
2. Determining a trial base plate size, N× B. *N > d+ 2 (3 in) ; N> 18.97+ 2*3 = 24.97 in (634.2 mm)* *B > bf + 2 (3 in); B> 11.265 + 2*3 = 17.267 in (438.5 mm),* Trial base plate size *N x B = 30 x 25 in (762 x 635 mm).*

3. Determining the equivalent and critical eccentricities,
Equivalent eccentricity : e $=M_r/P_r$
Critical eccentricity : $e_{crit} = \frac{N}{2} - \frac{P_r}{2\,q_{max}}$
If $e \leq e_{crit}$, go to next step (design of the base plate with small moment); otherwise, refer to design of the base plate with large moment.

$$f_{p(\max)} = \phi_c (0.85 f_c^{'}) \sqrt{\frac{A_1}{A_2}} = 0.65 * 0.85 * 4 * 1 = 2.21 \ ksi \quad (15.028 \ MPa)$$

$$q_{(\max)} = f_{p(\max)}.B = 2.21 * 25 = 55.25 \ kip/in \ (9.675 \ kN/mm)$$

Eccentricity: $e = \frac{M_u}{P_u} = \frac{2350.279}{39.076} = 60.15 \ in. \ (1527.8 \ mm)$

$$e_{crit} = \frac{N}{2} - \frac{P_u}{2q_{\max}} = \frac{30}{2} - \frac{39.076}{2*55.25} = 14.65 \ in \ (372.11 \ mm)$$

$e > e_{crit}$, so base plate is at large moment effect. The anchor rod edge distance was assumed *2.5 in. (63.5 mm).*

4. Determining the bearing length, *Y*. $Y = N - (2)(e)$

$$f = \frac{N}{2} - 2.5 = \frac{30}{2} - 2.5 = 12.5 \ in \ (317.5 \ mm)$$

$$\left(f + \frac{N}{2}\right)^2 = \left(12.5 + \frac{30}{2}\right)^2 = 756.25 \ in^2 (487902.25 \ mm^2) \geq \frac{2P_u(e+f)}{q_{\max}} = \frac{2*39.076*(60.15+12.5)}{55.25} = 102.76 \ in^2 (66296.64 \ mm^2)$$

5. Determining the required minimum base plate thickness $t_{p(req)}$.

If $Y \geq m$ $\quad t_{p(req)} = \sqrt{\frac{4\{f_p\left(\frac{m^2}{2}\right)\}}{0.90\,F_y}} = 1.49m\sqrt{\frac{f_p}{F_y}}$; If $Y < m$ $\quad t_{p(req)} = 2.11\sqrt{\frac{f_p\,Y\left(m-\frac{Y}{2}\right)}{F_y}}$

a) Thickness calculation at bearing interface:

$$m = \frac{N - 0.95d}{2} = \frac{30 - (0.95*18.97)}{2} = 5.99 \ in \ (152.1 \ mm) \qquad f_p = f_{p(\max)} = 2.21 \ ksi \ (15.028 \ MPa)$$

$$for \ Y < m: \quad t_{p(req)} = 2.11\sqrt{\frac{f_{p(\max)}.Y.(m - Y/2)}{F_y}} = 2.11\sqrt{\frac{2.21*1.94*(5.99 - 1.94/2)}{36}} = 1.63 \ in (41.4 \ mm)$$

b) Thickness calculation at tension interface:

$$X = \frac{N}{2} - \frac{d}{2} + \frac{t_f}{2} - 2.5 = \frac{30}{2} - \frac{18.97}{2} + \frac{1.06}{2} - 2.5 = 3.545 \ in \ (90.04 \ mm)$$

$$t_{p(req)} = 2.11\sqrt{\frac{T_u.x}{B.F_y}} = 2.11\sqrt{\frac{68.109*3.545}{25*36}} = 1.09 \ in \ (27.69 \ mm)$$

The thickness was checked using the value of *n*.

$$n = \frac{B - 0.8b_f}{2} = \frac{25 - (0.8*11.265)}{2} = 7.994 \ in \ (203 \ mm)$$

$$t_{p(req)} = 2.11\sqrt{\frac{f_{p(\max)}.Y.(n - Y/2)}{F_y}} = 2.11\sqrt{\frac{2.21*1.94*(7.994 - 1.94/2)}{36}} = 1.93 \ in \ (49 \ mm)$$

6. Determining the anchor rod size.

According to base plate dimensions and the tension force that must be carried by anchor bolt, three anchor bolts were used on each face of the column. The tensile force per rod = *68.109/3=22.703 kip (302.96 /3=100.988 kN)*. From AISC Steel Design Guide 1, Table 3.1 *1 1/4 in (31.75 mm)* diameter anchor bolt was selected (tensile strength= *40 kip (177.92 kN))*, the hole size was *2 1/16 in (52.4 mm)* (Table 2.3), the anchor bolt concrete pullout strength was determined as *50.2 kip (223.29 kN)* (Table 3.2). Anchor bolt embedment length, concrete block thickness and concrete block dimensions were selected as *20 in.(508 mm)*, *40 in (1016 mm)* and *80 x 80 in. (2032 x 2032 mm)*, respectively.

The base plate thickness was taken as 2 in.(50.8 mm) according to thickness calculation at bearing and tension interfaces.

Nonlinear finite element analysis of steel column base plate connections

For the industrial building, nonlinear finite element analyses of three types of column base plate connection models by Picard method in RFEM 5.05 program were performed. In the program, bolts were selected as rigid connection, column height was 39.37 in (1000 mm) and foundation was modelled as Winkler foundation. The three connections models were subjected to axial force as 40 kip (177.92 kN) and the horizontal force have been taken as 22.046 kip (100 kN) for nonlinear finite element analysis purpose. The base plate and anchor bolts details have been taken as calculated according to AISC-Guide 1 as mentioned before. The parameters were selected as W column section, square hollow structural section (HSS) column and circular HSS column for different connection models. The details of models are presented in Table 2. The finite element analyses for three types of column base plate connection models were performed under same horizontal and axial load. Maximum Von Mises stress distributions of models and stresses on the base plates are presented in Figure 3 and Figure 4, respectively.

Table 2. Details of column base plate models.

Model type	**Variables**	
Model 1	Column section	W18 x 119
	Base plate dimensions	30x25 in (762x635 mm)
	Plate thickness	2 in (50.8 mm)
	Anchor bolts	6 bolts- 1 1/4 in(31.75 mm), hole diameter 2 1/16 in (52.4 mm)
	Materials	Grade 36; Fy = 36 ksi(244.8 MPa), f_c'= 4 ksi (27.2 MPa)
Model 2	Column section	Square HSS 16x16x 5/8
	Base plate dimensions	30x25 in (762x635 mm)
	Plate thickness	2 in (50.8 mm)
	Anchor bolts	6 bolts- 1 1/4 in(31.75 mm), hole diameter 2 1/16 in (52.4 mm)
	Materials	Grade 36; Fy = 36 ksi(244.8 MPa), f_c'= 4 ksi (27.2 MPa)
Model 3	Column section	Circular HSS 12.75x0.50
	Base plate dimensions	30x25 in (762x635 mm)
	Plate thickness	2 in (50.8 mm)
	Anchor bolts	6 bolts- 1 1/4 in(31.75 mm), hole diameter 2 1/16 in (52.4 mm)
	Materials	Grade 36; Fy = 36 ksi(244.8 MPa), f_c'= 4 ksi (27.2 MPa)

Column top lateral displacement values, displacement ratios, maximum Von Mises stress values and stress ratios are presented in Table 3. W column section-base plate connection model was selected as reference model, the lateral displacement ratios and stresses ratios were determined by "the model values/reference model values". The minimum column top lateral displacement value was determined from Model 1 analysis and the maximum lateral displacement value was determined from Model 3. When comparing the displacement and stresses values of HSS section columns, the greatest values were shown in circular HSS column further than square HSS column ones. Failures were concentrated on column flanges for Model 1. Stresses concentrations were obtained on column-base plate connection regions and column surfaces for models with HSS columns (Model 2 and 3).

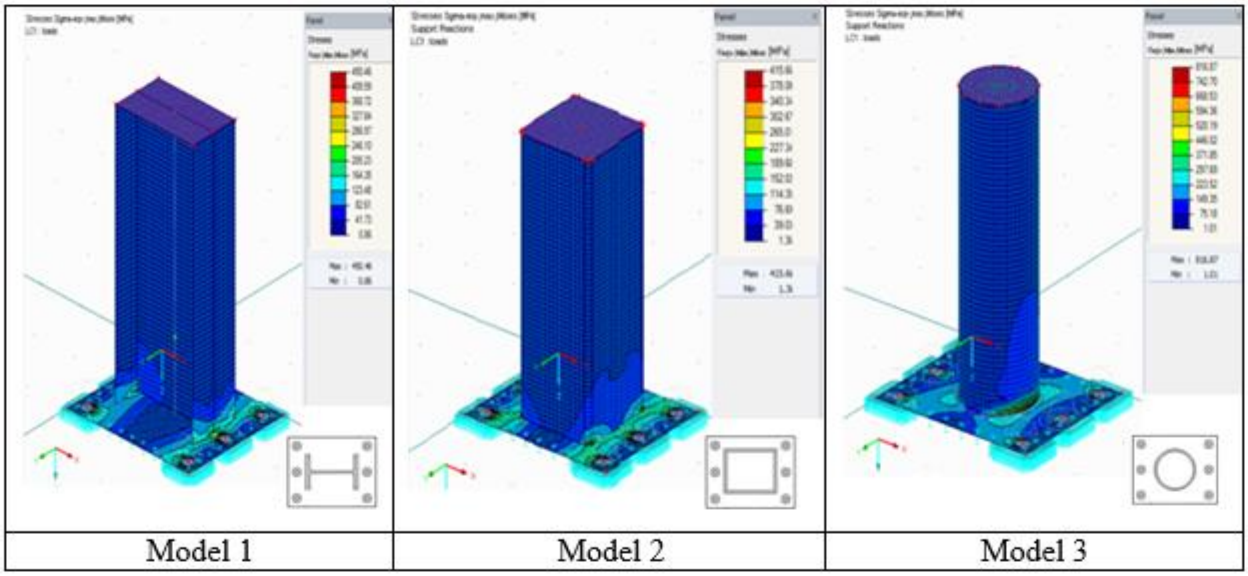


Figure 3. Maximum Von Mises stress distributions of models at 100 kN load level.

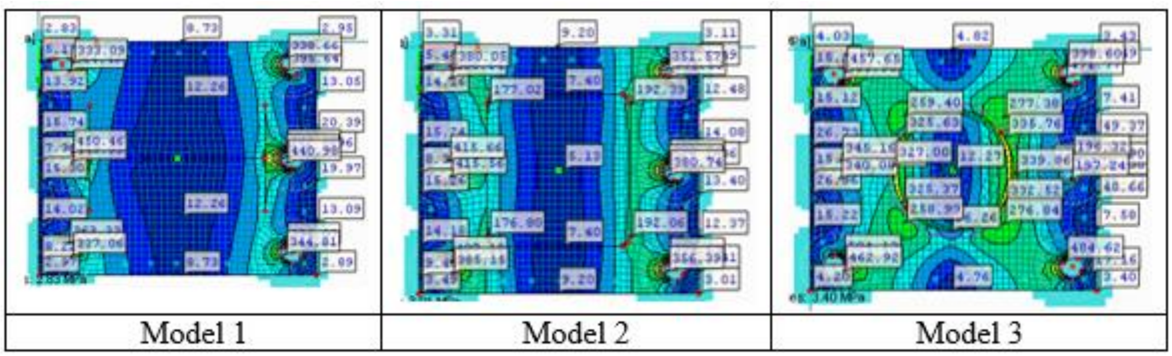


Figure 4. Von Mises stresses distributions on the base plates at 100 kN load level.

Table 3. Von Mises stresses and top column lateral displacements for connection models.

	Model 1*	Model 2	Model 3
Displacement (mm)	5.3	6.6	13.2
Displacement ratio	1.00	1.25	2.49
Max. Von Mises stresses (MPa)	450.46	415.66	816.87
Stresses ratio	1.00	0.92	1.81

* Reference column base plate connection

Table 4. Von Mises stresses distribution behaviour for steel column base plate connection models.

Location of stresses distribution	Model 1	Model 2	Model 3
Stresses distribution on column section	Stress distribution in column lower end and on column flange line	Stress distribution on column lower end and along column-base plate contact line	Less stress distribution in column lower end
Stresses distribution on the base plate	Moderate distribution on column flanges and around bolts	More distribution on base plate than W section	Too much distribution on base plate than other two models

Minimum lateral column top displacement values were determined for Model 1 with W column cross-section, Model 2 with square HSS column-section and Model 3 with circular HSS column-section, respectively. In terms of maximum Von Mises stresses on the column base plate, maximum stress value was obtained in Model 3 with circular HSS column-section and the minimum stress value was obtained in Model 2 with square HSS column.

When the stresses distributions on the base plates were examined, most different and concentrated stresses distributions were observed for circular HSS column-base plate connection. Generally, increasing of stress intensity was determined around the anchor bolts.

Conclusions

Steel column base plates have a great importance of whole structural behaviour, these connections are responsible of transferring the loads from structures to the foundations. In this study, exposed column base plate behaviour in a single story industrial building was investigated. The column base plate connection of the industrial building was found under large moment effect according to the AISC Base Plate Design Guide 1. The nonlinear finite element analyses for three connection models showed that, the best behaviour connection in terms of column top lateral displacement was obtained in W steel column-base plate model (Model 1) and in terms of maximum Von Mises stress values was obtained in square HSS section (Model 2). The undesired behaviour for column top lateral displacement value and maximum Von Mises stress value was obtained in circular HSS section (Model 3). For all three connection models, critical areas occurred around anchor bolts and around column base plate connection lines. The used hollow steel column sections were selected as that section which gave sufficient results in static analysis of the industrial building and according to the base plate size. The finite element analysis for hollow steel column sections shows adequate results in case of use square HSS column section (Model 2).

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Appendix

Symbols

B : Base plate width
b_f : Column flange width
D : Dead loads
d : Overall column depth
e : The eccentricity
e_{crit} : The critical eccentricity
$f_{c'}$: Specified compressive strength of concrete
Fy : Specified yield stress of base plate
L : Live loads
M_u : Factored bending moment
N : Base plate length
P_u : Factored axial force
S : Snow loads
V_u : Factored shear force
W : Wind loads

Abbreviations

AISC : American Institute of Steel Construction
HSS : Hollow Structural Section
LRFD : Load and Resistance Factor Design
MRF : Moment Resisting Frame