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The experimental verification on the shear bearing capacity of exposed steel column foot

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Abstract. In terms of the shear bearing capacity of the exposed steel column foot, there are many researches both home and abroad. However, the majority of the researches are limited to the theoretical analysis sector and few of them make the experimental analysis. In accordance with the prototype of an industrial plant in Beijing, this paper designs the experimental model. The experimental model is composed of six steel structural members in two groups, with three members without shear key and three members with shear key. The paper checks the shear bearing capacity of two groups respectively under different axial forces. The experiment shows: The anchor bolt of the exposed steel column foot features relatively large shear bearing capacity which could not be neglected. The results deducted through calculation methods proposed by this paper under two situations match the experimental results in terms of the shear bearing capacity of the steel column foot. Besides, it also proposed suggestions on revising the Code for Design of Steel Structure in the aspect of setting the shear key in the steel column foot.

1. Introduction

Steel structure is one of the important construction structures. As its weight is light and the construction is simple, it is extensively used in the large-scale plants, stadiums and the super-high buildings. With the development of the real estate industry, the aseismic design of the building structure is attracting increasingly more attention. The article 8.4.13 of Code for Design of Steel Structures [1] in China regulates: The anchor bolt at the column foot is inappropriate to bear the horizontal reaction force at the bottom of the column foot. Such a horizontal reaction force shall be borne by the force of friction between the baseboard with the concrete (the friction coefficient could take 0.4) or the shear key. In the nations suffering frequent earthquakes, Japan and European and American nations, they all consider the involvement of the steel column foot in the shear bearing. What's more, Code for Design of Steel Structures does not give specific illustration on how to calculate the shear bearing capacity of the exposed steel column foot. The domestic and overseas researchers made a large quantity of theoretical studies on the shear bearing capacity of the exposed steel column foot^{[2]-[8]}. However, experimental verification is in shortage. On the basis of the domestic and overseas theoretical research, this paper comprehensively considers the contribution of the anchor bolt and the shear key to the shear bearing capacity of the steel column foot. It verifies the reliability of the theoretical analysis on the shear bearing capacity, and suggests raising the separation point of the shear key for the exposed steel column foot, reducing the construction difficulty of the exposed



steel column foot and providing certain experimental evidences to the design and research of the steel column foot.

2.Theoretical evidence

This paper suggests to calculate the shear bearing capacity of the steel column foot in accordance with the literature of the Theoretical Research on the Shear Bearing Capacity of the Exposed Steel Column Foot, i.e.,

2.1.The calculation method for the shear bearing capacity of the steel column foot without shear key

$$\begin{cases} V = \mu N + \beta \mu n_1 A_e \sigma + \beta n_2 A_e \tau \\ \sqrt{\sigma^2 + 3 \tau^2} \leq f_y \end{cases} \quad (1)$$

formula, n_1 is the quantity of the anchor bolt at the tensile side; n_2 is the quantity of the anchor bolts involved in the shear bearing; σ is the positive stress of the single anchor bolt at the tensile side; τ is the shear stress of the single anchor bolt at the tensile side; A_e is the effective cross-sectional area of the single anchor bolt; f_y is the yield strength of single anchor bolt; N is the axial pressure; μ is the friction coefficient between the column baseboard with the concrete, taking the value of the American ACI349-85; β is the reduction coefficient for considering unevenly distributed loads. It is suggested to take 0.65.

2.2.The calculation method for the shear bearing capacity of the steel column foot with shear key

$$V' \leq \frac{f_c b}{l \epsilon_0} \times \left[\frac{4h}{\pi} \times \frac{12\pi^3 h^2 \left(\frac{N}{EI} + \frac{2f_c b}{kAG\epsilon_0 l} \right) + 48\pi h^4 \frac{2f_c b}{EI\epsilon_0 l} - 3\pi^5}{16\pi^2 h^2 \frac{2f_c b}{kAG\epsilon_0^2 l^2} + 128h^4 \frac{f_c b}{EI\epsilon_0^2 l^2}} - \frac{h}{2l\epsilon_0} \times \left(\frac{12\pi^3 h^2 \left(\frac{N}{EI} + \frac{2f_c b}{kAG\epsilon_0 l} \right) + 48\pi h^4 \frac{2f_c b}{EI\epsilon_0 l} - 3\pi^5}{16\pi^2 h^2 \frac{2f_c b}{kAG\epsilon_0^2 l^2} + 128h^4 \frac{f_c b}{EI\epsilon_0^2 l^2}} \right)^2 \right] \quad (2)$$

formula, f_c is the designing value of the compressive strength of the concrete; b is the width of the shear key; ϵ is the strain of the foundation concrete under the pressure of the shear key; l is the calculation width of the foundation concrete along the forced direction; ϵ_0 is 0.002; N is the pressure at the top of column; EI is the flexural rigidity of the shear key; KA is the effective shearing area of the shear key; G is the shearing modulus; h is the buried depth of the shear key.

3.Experimental verification

To verify the reliability of the above mentioned theory, it designs the two experiential models to study the bearing capacity of the steel column foot with shear key and that of the steel column foot without shear key respectively; it establishes three components for each group to study the shear bearing capacity of the steel column foot under the different axial forces.

3.1.Basic assumptions for the experiment

- (1) Under the horizontal force, it neglects the deflection of the steel column;
- (2) When the column foot bears horizontal force, the horizontal reaction force generated by the depressed deformation of the concrete at the largest compression side of the eccentric compression baseboard is negligible;
- (3) It neglects the bending of the anchor bolt at the tensile side and only considers the tensile-shear function of the anchor bolt at the tensile side.

3.2. Model design and manufacturing

The prototype of the experimental model is the real industry plant engineering in Beijing. Its structure is the portal frame structure; the column foot is the exposed low - position anchor bolt steel column

foot; the height of the storey is 5.4m; one storey in total; the flat area is 60.25 x 40.6m. The model selects the connection part between the steel column foot at the bottom of the prototype structure with the foundation. Due to the limitation of the experimental conditions, the column foot takes the height of 700mm. The dimension of the sectional area is the same with the original structure. The material of the steel column is Q345A. The foundation bolt adopts Q235. The diameter is 28mm. The dimension of the experimental model is shown as figure 1:

The physical experimental models are shown as figure 2, figure 3 and figure 4:

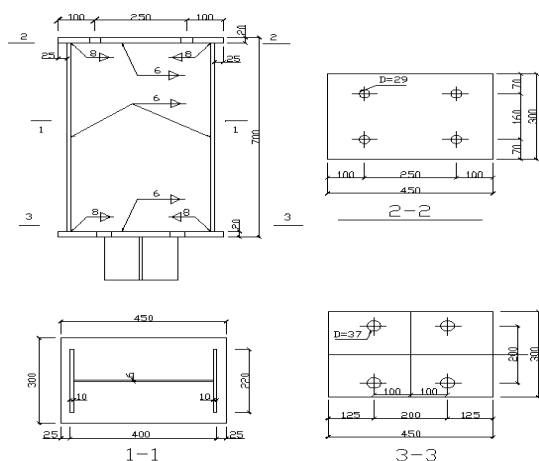


Figure 1. experimental model dimension

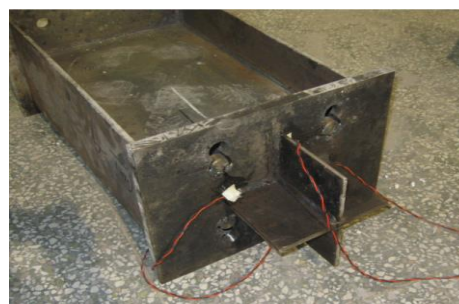


Figure 2. physical steel column

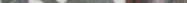


Figure 3. physical anchor bolt specimen



Figure 4. physical secondary pouring completion

The steel column foot model is manufactured in the steel structure processing factory of China Jingye Engineering Corporation limited. The concrete foundation is manufactured in the new Youth Palace and the components are assembled in the structure laboratory of Beijing University of Civil Engineering and Architecture. The mix proportion of the concrete is shown as table 1.

Table 1. The mix proportion of the concrete

The construction mix proportion of the concrete (kg/m3)					
Cement	Coal ash	Sand	Pebble	Water	water reducing agent
350	100	950 (2% moisture content)	860	150	5.18

There are three blocks of test cubes of 100 mm×100 mm ×100 mm during the pouring process of the concrete foundation, which are maintained with the experimental model foundation under the same conditions. It takes the average value as the material indicator for the concrete, which is shown as table 2.

Table 2. Concrete actual test material indicator

concrete actual test material indicator	
Foundation concrete cube Compressive strength (MPa)	secondary pouring concrete cube Compressive strength (MPa)

42.00

44.28

$\phi 28$ anchor bolt adopts Q235. It cuts three pieces of specimen with the length of 50cm to receive the tensile test in the universal testing machine in the material laboratory of Beijing University of Civil Engineering and Architecture. The average value of the yield strength of the anchor bolt is 288 MPa.

3.3. Experiment loading device

The experiment loading device adopts MTS. The experiment is conducted in the static pedestal. The foundation baseboard is fixed in the static pedestal with ground anchor. It places an oil jack in the center of the top of the steel column foot to impose the fixed vertical loading. Meanwhile, it is connected with the model top by the connection accessories through the tensile-compression jack in the reaction wall to impose the low frequency cyclic loading. The loading device of the experiment is shown as the figure:



Figure 5. MTS connection picture



Figure 6. Displacement meter and the strain gage connection picture

The experimental damage is shown as figure 7 and figure 8:



Figure 7. The extension and deformation of anchor bolt yield



Figure 8. Foundation concrete is cracked and damaged

3.4 The comparison between the theoretical analysis value and the experimental results

Table 3. The calculation parameter for the steel column foot without shear key

Column foot code	The effective cross-sectional area of single anchor bolt $A_e(\text{mm})$	Anchor bolt yield strength (N/mm)	a (mm)	b (mm)	c (mm)
GZ-1	448	312	225	100	125
GZ-2					
GZ-3					

Table 4. The comparison between the theoretical value of the column foot's shear bearing capacity calculated as per formula (1) with the experimental value

Axial force N (kN)	Columa foot code	σ (N/mm ²)	τ (N/mm ²)	Vmax (KN) Calculation value	$n_2 = 2$	
					$\bar{V}_{\max}$ (KN) Experimental value	$\frac{V_{\max}}{\bar{V}_{\max}}$

0	GZ-1	292.72	62.34	90.86	110.11	0.83
166.13	GZ-2	292.62	62.58	144.15	186.87	0.77
158.47	GZ-3	292.58	62.64	141.66	166.32	0.85

The experimental data of the table shows: Under the conditions of the same section of the steel column and the same anchor bolt configuration, with the increase of N value, the shear bearing capacity of the steel column foot increases while the ratio of the shear bearing capacity of the anchor bolt in the overall shear bearing capacity of the whole steel column foot decreases. When the N value is: 0KN, 166.13KN and 158.47KN, the ratios of the shear bearing capacity of the anchor bolt in the overall shear bearing capacity of the whole steel column are 33%, 20% and 22% respectively. Even if the axial force reaches 166.13KN, the shear bearing capacity of the anchor bolt is still as high as 20%. Therefore, the shear bearing capacity of the anchor bolt is significant for the design.

Table 5. The calculation parameter for the steel column foot without shear key

Column foot code	The effective cross-sectional area of anchor bolt A_e (mm)	Anchor bolt yield strength f_y (N/mm)	Concrete compressive strength f_c (Mpa)	a (mm)	b (mm)	c (mm)
GZ-4						
GZ-5	422	288	42	225	100	125
GZ-6						

Table 6. The comparison between the theoretical value of the column foot's shear bearing capacity calculated as per formula (2) with the experimental value

Axial force N (kN)	Column foot code	σ (N/mm ²)	τ (N/mm ²)	$n_2 = 2$		
				Vmax (KN) Calculated value	$\bar{V}_{max}$ (KN) experimental value	$\frac{V_{max}}{\bar{V}_{max}}$
0	GZ-4	278.59	42.16	155.86	148.29	1.05
89.05	GZ-5	278.18	43.05	182.08	179.38	1.02
131.87	GZ-6	277.98	43.47	207.68	206.75	1.00

Table 4 and table 6 show: The shear bearing capacity of the steel column foot with shear key is larger than that of the steel column foot without shear key, but the increase is not significant.

3.5. Experimental analysis

3.5.1. The damage process of the steel column foot without shear key. As for the three experimental models without shear key, they stay at the elastic stage at the early phase of the loading and the structural displacement and the anchor bolt strain present linear relationship. With the increase of the horizontal force, the GZ-1 column foot anchor bolt yields. The horizontal force at this moment is $P=110.11\text{kN}$. After that, with the further increase of the horizontal thrust, the anchor bolt generates plastic deformation and the residual deformation generates correspondingly. Since the steel material used by the column foot and the anchor bolt have sound plastic capacity, the column foot at last is damaged as the anchor bolt crushes the concrete. The damage mechanism of GZ-2 and GZ-3 is similar to that of GZ-1. The difference is as follows. Due to the function of vertical loading of GZ-2 and GZ-3, the shear force in the column foot would firstly be borne by the force of friction between the column baseboard with the foundation concrete. Besides, the function of the vertical loading increases the rotational stiffness of the steel column foot, the horizontal overturning displacement is relatively small.

When the GZ-2 anchor bolt yields, the horizontal force $P=156.57\text{kN}$; when the GZ-3 anchor bolt yields, its horizontal force $P=166.32\text{kN}$.

3.5.2. The damage process of the steel column foot with shear key. As for the three experimental models without shear key, they also stay at the elastic stage at the early phase of the loading and the structural displacement and the anchor bolt strain present linear relationship. As for GZ-4, as the shear key is set up, the shear force at the column foot is jointly borne by the shear key and the anchor bolt. With the further increase of the horizontal force, the anchor bolt of the column foot reaches the yield point. At this moment, the horizontal force is 148.29kN . The anchor bolt yields and the foundation concrete is crushed and damaged. The damage mechanism of GZ-5 and GZ-6 is similar to that of GZ-4. The difference is as follows. Due to the function of vertical loading of GZ-5 and GZ-6, the shear force in the column foot would firstly be borne by the force of friction between the column baseboard with the foundation concrete. Besides, the function of the vertical loading increases the rotational stiffness of the steel column foot, the horizontal overturning displacement is relatively small compared with the GZ-4. When the GZ-5 anchor bolt yields, its horizontal force $P=179.38\text{kN}$; when the GZ-6 anchor bolt yields, its horizontal force $P=206.75\text{kN}$.

3.6. The location of the counterforce action point of the concrete foundation

The location of the counterforce action point of the concrete foundation is complicated from theoretical perspective. In the eccentric compression, the counterforce action point location is related to the finite rigidity or the infinite rigidity. According to the research results on the location of counterforce action point of the concrete foundation both home and abroad, it is reasonable to regard the column foot baseboard as the infinite rigidly. However, regarding it as the finite rigidity does not have great differences with the results by regarding it as the infinite rigidity. When the column foot is the infinite rigidity, the compressive resistance figure of the concrete could be the triangle, rectangle and different parabolic waves. Among them, the quadratic parabola is the most advanced on in theory. When it adopts the quadratic parabola, the action point of the foundation compressive resistance joint force is very close to the edge of the biggest compression side of the baseboard of the column foot. The focus of the research in this paper lies in the shear bearing of the column foot. Although the action point of the counterforce is related to the tensile strength of the anchor bolt, it has minor influences on the shear bearing performance. Therefore, it is better to adopt simple and reliable method. Therefore, this research adopts: When the anchor bolt begins to bear the force, the action point of the counterforce is always in the edge of the compressive side of the column web; with the increase of the tensile borne by the anchor bolt, the action point of the counterforce moves outside gradually; when the anchor bolt yields, the action point of the counterforce is in the edge of the baseboard at the largest compressive force side. The above mentioned simplified value taking for the action force location of the counterforce is set for the calculation convenience in the research.

4. Conclusion

- (1). The anchor bolt of the steel column foot has certain shear bearing capacity. It is suggested to consider the involvement of the anchor bolt in the shear bearing when calculating the shear bearing capacity of the exposed steel column foot.
- (2). It is suggested to raise the separation point for the shear key in the exposed steel column foot; the experimental result shows that it is appropriate to calculate the shear bearing capacity of the steel column foot in accordance with the formula (1).
- (3). The shear bearing capacity of the steel column foot with shear key is larger than that of the steel column foot without shear key, but the increase is not significant.
- (4). As for the steel column foot which shall be equipped with the shear key, the experimental results show that it is appropriate to calculate its shear bearing capacity in accordance with the formula (2).

- (5).Under the function of the horizontal shear force, the shear key might tear the concrete foundation. Therefore, it is suggested that the steel column foot with the shear key shall increase the stirrup reinforcement ratio of the foundation short column.
- (6).The theoretical analysis and the experimental verification in this paper do not consider the influences of the factor of the beam bracing and column bracing. It is suggested to design the physical model for further study.

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