

Theoretical research on the shear bearing capacity of exposed steel column foot

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Abstract. This paper makes an overview on the domestic research on the steel column shear capacity in detail. On such basis, in accordance with the 4th theory of strength and the flexural vibration of straight bar, it makes theoretical analysis on the shear-bearing capacity of the steel column foot with the shear key and without the shear key respectively. It proposes the methods for calculating the shear-bearing capacity of steel column foot under two situations. It suggests that Code for Design of Steel Structures should raise the separation point of exposed steel column foot, which would reduce the construction difficulty of the exposed steel column foot, shorten the construction period, improve the construction quality and provide certain theoretical references for the design and research on the steel column foot.

1. Introduction

As parts of shear bearing are different, the exposed steel column foot could be divided into steel column foot with shear key and the steel column foot without shear key. The base shear of steel column foot without shear key is mainly borne by the force of friction and anchor bolt while the base shear of the steel column foot with shear key is mainly borne by the shear key, force of friction and anchor bolt. Code for Design of Steel Structures of China regulates: The anchor bolt of the steel column foot is inappropriate to bear the horizontal reacting force of the steel column foot. Such a horizontal reacting force shall be borne by the force of friction between the baseboard and the concrete (friction coefficient could be 0.4) or borne by the shear key ^[1]. European and American nations all consider make the anchor bolt be involved in the share-bearing. In terms of the value setting of the strength of extension, European and American nations set the strength designing value of anchor bolt as the corresponding designing value of common bolt or materials of bolt. Japan is the nation of frequent earthquakes and it has much research on the shear-bearing performance of steel column foot. In accordance with the Code for Design of Steel Structures, when the force of friction between the steel column foot with the foundation concrete could not resist the horizontal shear, the anchor bolt could be used for the shear bearing.

Besides, Code for Design of Steel Structures only illustrates how to set the shear key when the horizontal reaction force of the steel column foot is large, but does not give specific explanation on the regulation of shear key calculation.

This paper would make analysis from two aspects on the shear bearing capacity of exposed steel column foot: The shear bearing capacity of steel column foot without shear key and that of steel column foot with shear key; besides, it also suggests the new separation points for the steel column foot in setting the shear key, providing certain references for the staff of engineering designing and related researchers. By doing so, it expects to cancel the shear key in common situations, facilitate



construction, save labor force, physical resource and financial resources.

2.Theoretical research on the shear-bearing capacity of steel column foot without shear key

2.1.The damage mode of steel column foot without shear key

The interactive mechanism between shearing force and tensile force of the anchor is quite complicated. At present, it has not been clarified completely. Research on the simultaneous working of flexural force and shearing force is insufficient. To study the tensile status and shear status of the anchor bolt, it analyzes the damage mode of the column foot firstly. When the strength and stability of plates of the column foot are guaranteed, the rigidity of the base board and the whole column foot is relatively large. The damage mode of the column foot mainly has the following several varieties:

- (1) The tensile side anchor bolt yields; without minor sliding, the column foot rigid body rotation could develop continuously;
- (2) The dimension for the obtrusive edge is over small, which leads to the cracking of foundation concrete under the pressure of base board;
- (3) The pressure bearing strength of the concrete is insufficient. Under the pressure of R, the foundation suffers local pressure bearing damage;

Among the above mentioned 3 failure types, the first damage model is the ideal damage model and the other damage models are the concrete brittle failures which shall be avoided in the engineering design. For the other brittle damage models, it could avoid them by increasing the extra reinforced steel bars and extending the length of anchor bolt.

2.2.Analysis on the calculation method for the shear-bearing force of steel column foot without shear key

The shear-bearing force of the steel column foot without shear key is composed of two parts, including: the force of friction between the base board of column foot with the foundation concrete surface, and the shear bearing force of the anchor force of column foot. In terms of the issue about whether the column foot anchor bolt could participate in the shear bearing or not, many overseas experts have done lots of theoretical analysis and experimental study. It introduces these calculation methods one by one.

*2.2.1.The calculation method proposed by Yu Anlin^[2]*As the anchor bolt has sound plastic deformation capability, it shall guarantee the soundness of concrete during the designing process. For the steel column foot featuring appropriate damage model, the horizontal loading of the anchor bolt at its tensile side at the tensile moment is its shear bearing capacity V_{max} .Therefore, Yu Anlin et al. consider the beneficial influences of the phenomenon that the force of friction increases as the bending torque increase. It makes the experiment on the 12-frame test specimen for the low, medium and high-position anchor bolt column foot under the loading of horizontal reciprocating force, gets the anti-bending M- θ hysteretic curve and the anti-shear P- δ hysteretic curve and points out the computational formula of anti-bending bearing capacity:

$$M_y = T_y (d_t + d_c) + Nd_c \quad (1)$$

IFormula: d_t — the distance from the anchor bolt at the tensile side to the axis of the column; d_c — the distance from the foundation counterforce R to the axis of the column, it could take simplified value.

The computational formula of shear bearing capacity:

$$V_{max} = \mu (T_y + N) + V_b = 0.4 (T_y + N) + \beta n_c A_e \frac{f_y}{\sqrt{3}} \quad (2)$$

$$T_y = n_t A_e f_y \quad (3)$$

formula:N— axial force, the pressure force is positive and the tensile force is negative; $(T_y + N)$ — the value of this item is zero when the result is the negative value; T_y — total tensile force of the anchor bolt at the tensile side; n_t — quantity of anchor force at the tensile side; n_c — quantity of the anchor bolt

at the tensile side; A_e — effective cross-sectional area of an anchor bolt; f_y — yield strength of the anchor bolt material; 0.4— the friction coefficient between the column foot board with the concrete, take it as 0.4; β — adjustment coefficient, reflect the unevenly stressing of low-position anchor bolt and the equivalent conversion of medium and high-position anchor bolt, the low-position anchor bolt takes $\beta=0.65$ and the medium and high-position anchor bolt takes $\beta=0.4$;

The calculation method of professor Yu Anlin et al. tacitly proves that the anchor bolt yield at the tensile side and the anchor bolt yield at the pressure side incur at the same time. However, the simultaneous yield of the anchor bolt at the tensile side and at the pressure side is almost impossible. From the probability perspective, the anchor bolt at the tensile side also bears a half of the horizontal force. Besides, as the research is done under the status of complete elasticity and it declares the column foot failure with the anchor bolt failure at the tensile side, so it is not appropriate to take f_y in the calculation method.

2.2.2. The calculation method of the American ACI349-85 ⁽³⁾⁽⁴⁾ According to the American ACI349-85[3][4], the anchor bolt designing depends on the anchor bolt yield failure and the designing value of the bearing capacity of anchor bolt is larger than or the same with the equivalent equal force under the common work of tensile force and shear force. That is:

$$C N_v + N_t \leq \phi A_e f_y \quad (4)$$

formula: $\phi=0.9$ is the reduction coefficient of the bearing capacity, C is the shearing coefficient which equals the reciprocal of the product between the friction coefficient with $\sqrt{3}$, the value is: When the top surface of the column foot baseboard stays in the same level with the foundation concrete surface, it takes $C=1/0.9=1.11$ (friction coefficient is 0.52); when the undersurface of the column foot board stays at the same level with the foundation concrete surface, it takes $C=1/0.7=1.43$ (the friction coefficient is 0.4); when there is the undercourse of cement mortar under the column foot baseboard, it takes $C=1/0.55=1.82$ (friction coefficient is 0.32). Formula (4) considers the influences of the relative coefficient between the column foot baseboard with the concrete surface on the friction coefficient. It is an appropriate factor, but its theoretical evidence is not strong. It is only an experience formula.

2.2.3. The calculation formula proposed by professor Li Dezi ^[5] Li Dezi takes the friction coefficient between the column foot baseboard with the concrete contact surface as 0.4. The horizontal loading which is larger than the fraction is borne by the anchor bolt. The calculation formula for the tensile-shear of anchor bolt is:

$$N_t \leq 1.25 [N_t^b] - 1.6 N_v \quad (5)$$

$$N_t \leq [N_t^b] \quad (6)$$

Formula: $[N_t^b]$ — tensile capacity of single anchor bolt under the tensile force; N_t — the tensile force suffered by single anchor bolt under the force of tensile-shear; N_v — the shear force suffered by single anchor bolt under the force of tensile-shear;

The calculation method recommended by professor Li Dezi only considers the shear capacity of single anchor bolt and does not take the friction force of column foot and the overall shear capacity of the anchor bolt at the column foot. Besides, the formula (5) is simply the combination of shear and tensile of the anchor bolt, which is not appropriate according to the 4th theory of strength.

2.3. The method proposed by this paper

According to the 4th theory of strength, it is suggested that the shear bearing capacity of the steel column foot without shear key to be calculated as per the formula (7):

$$\begin{cases} V_0 = \mu N + \mu n_1 A_e \sigma + n_2 A_e \tau \\ \sqrt{\sigma^2 + 3\tau^2} \leq f_y \end{cases} \quad (7)$$

formula, n_1 is the quantity of the anchor bolt at the tensile side; n_2 is the quantity of anchor bolt participated in the shearing; σ is the positive stress of the single anchor bolt at the tensile side; τ is the shearing strength of the single anchor bolt at the tensile side; A_e is the effective cross-sectional area of single anchor bolt; f_y is the yield strength of single anchor bolt; N is the axial compressive force; μ is the friction coefficient between the column foot baseboard with the concrete, taking the value as per the American ACI349-85.

When the anchor bolt is placed at the outer side of the steel column, it is shown as figure 1:

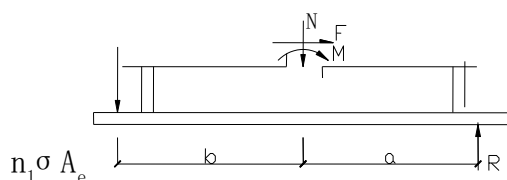


Figure 1 Sketch for the anchor bolt staying at the outer side of the steel column

$$\sigma = \frac{M_y - Na}{(a+b)n_1 A_e} \quad (8)$$

When the anchor bolt stays at the inner side of the steel column, it assumes the column foot baseboard is completely rigid, which is shown as figure 2:

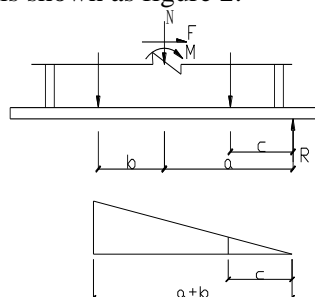


Figure 2 The sketch when the anchor bolt stays at the inner side of the steel column

$$M_y = (a+b) n_1 \sigma A_e + n_3 \sigma' A_e c + Na \quad (9)$$

$$\sigma = \frac{M_y - Na}{(a+b)n_1 A_e + n_3 A_e c^2 / (a+b)} \quad (10)$$

formula, n_3 is the quantity of anchor bolt under pressure; M_y is the bending moment of the anchor bolt yield under tensile.

Formula (1) is established in accordance with the tensile-shear yield of the anchor bolt at the tensile side, that is, the column foot declares to be damaged when the anchor bolt at the tensile side yields. As the bending moment suffered by the anchor bolt is relatively small, which contributes little to the anchor bolt yield, this formula neglects the bending of the anchor bolt at the tensile side. Besides, if it considers the influences of the unevenly stress of the anchor bolt at the tensile side and at the pressure side, it could calculate according to the following formula:

$$\begin{cases} V = \mu N + \beta \mu n_1 A_e \sigma + \beta n_2 A_e \tau \\ \sqrt{\sigma^2 + 3\tau^2} \leq f_y \end{cases} \quad (11)$$

formula, β is the reduction factor considering unevenly stress of the anchor bolt. It is suggested to take

0.75 in accordance with the literature [2] and [3] and other significances of symbols are the same with formula (7).

This paper suggests taking the calculation value of formula (11) as the separation point for the exposed column foot in setting the shear key. When the actual column foot shear force is larger than the calculated value in formula (11), it considers to set the shear key; otherwise, it would not set the shear key.

3.The Calculation Method for the Shear Bearing Capacity of the Column Foot with Shear Key

3.1.Set up the damage model for the column foot with shear key

In the regions where the wind loading is large or the earthquake fortification intensity is high, the horizontal force (shear force) at the column foot bottom is relatively large. The sum of the force of friction between the concrete with the baseboard and the shear bearing capacity of the anchor bolt could not offset the shear force at the column foot. Under such a situation, it needs to set up the shear key under the column foot baseboard. The common types for the shear key include cross steel plate and U-bar. There are reserved holes in the foundation column during the construction. When it installs the column, the shear key is located in the reserved hole. It should use the grouting material to fill the reserved hole and the screed coat. In this way, when the column foot is bearing the horizontal shear force, the shear key and the foundation concrete could work as an integral part. When the column foot is bearing the horizontal shear force, three damage models are possible, including: The damage of the shear key, the tensile failure of the welding seam between the shear key with the column foot baseboard and the foundation concrete is cracked to damage; as the compressive strength of the steel material is much larger than that of the concrete and the strength of the welding seam between the shear key with the column foot baseboard is also much larger than that of the concrete under the prerequisite of appropriate designing and construction, so the damage for the foundation concrete would occur firstly when the column foot bears the horizontal shear force. That is to say, it should take the damage of foundation concrete as the damage control condition when the column foot bears horizontal shear force.

3.2.The analysis on the calculation method for the column foot shear bearing capacity of the shear key

3.2.1.The calculation method proposed by Yang Fengdi^[6]This method only considers the strength of the welding seam between the shear key and the column foot baseboard, failing to consider the strength of the shear key and the foundation concrete.

3.3.The method proposed by this paper

The shear bearing capacity of the column foot with shear key is mainly composed of three parts: The force of friction between the column foot baseboard with the top surface of the foundation concrete, the shear bearing capacity of the anchor bolt and the shear bearing capacity of the shear key. Considering the influences of the shear deformation and axial force on the shear key, it takes the shear key as the object for analysis. The working forces on it include the axial force N of the column transmitted through the column body, the shear force at the bottom of the column foot and the shear force V at the column foot baseboard, and the joint force of the stress force of concrete $F(x)$, which are shown as figure 3:

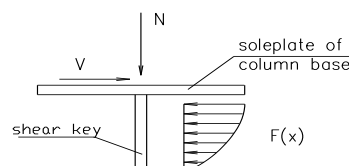


Figure 3 Stress analysis figure of the shear key

It takes the micro-segment dx as the isolator, the stress force borne by the micro-segment is shown as figure 4.

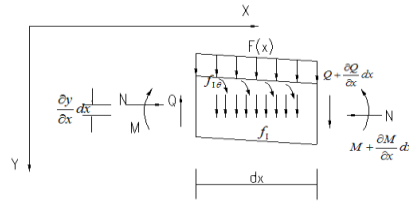


Figure 4. The force diagram of the micro-segment isolator

Under the extreme balance status, the join force of the compressive resistance of the shear key borne by the concrete shall offset the shear force of the column foot, which indicates that it should satisfy:

$$\int_0^h F(x) dx \geq V' \quad (12)$$

$$F(x) = f_c b \left(2 \frac{\varepsilon}{\varepsilon_0} - \frac{\varepsilon^2}{\varepsilon_0^2} \right),$$

Among it, f_c is the strength designing value of the concrete axial compressive resistance strength; b is the width of the shear key; ε is the strain of foundation concrete under the pressure of shear key; l is the calculation width of the foundation concrete along the forced direction; ε_0 is 0.002.

It establishes the equation through the bending vibration of the straight-bar and solve the above mentioned equation in accordance with the method of Galerkin.

The solution is as follows:

$$V' \leq \frac{f_c b}{l \varepsilon_0} \left[\frac{4h}{\pi} \times \frac{12\pi^3 h^2 \left(\frac{N}{EI} + \frac{2fb}{kAG\varepsilon_0 l} \right) + 48\pi h^4 \frac{2fb}{EI\varepsilon_0 l} - 3\pi^5}{16\pi^2 h^2 \frac{2fb}{kAG\varepsilon_0^2 l^2} + 128h^4 \frac{fb}{EI\varepsilon_0^2 l^2}} - \frac{h}{2l\varepsilon_0} \times \frac{12\pi^3 h^2 \left(\frac{N}{EI} + \frac{2fb}{kAG\varepsilon_0 l} \right) + 48\pi h^4 \frac{2fb}{EI\varepsilon_0 l} - 3\pi^5}{16\pi^2 h^2 \frac{2fb}{kAG\varepsilon_0^2 l^2} + 128h^4 \frac{fb}{EI\varepsilon_0^2 l^2}} \right]^2 \quad (13)$$

In the formula, N is the pressure of column top; 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; the meaning of other symbols is the same with the above context.

The above formula is the exclusive shear bearing capacity provided by the shear key. If it includes the force of friction and the shear bearing capacity of the anchor bolt, the shear bearing capacity of the whole column foot should be:

$$V_{\text{total}} = V + V' \quad (14)$$

The secondary pouring concrete could not vibrate, which would generate certain influences on the strength of concrete. It suggests to reduce the in the formula (14) (reduction coefficient β' is 0.6).

4. Conclusion

(1) The exposed column foot without shear key has certain shear bearing capacity and the shear bearing capacity of its anchor bolt is significant; this paper suggests considering the participation of the column foot anchor bolt in the shear bearing and raising the separation point for the shear key of the exposed column foot. That is, it should calculate whether the shear key should be set in accordance with formula (11).

(2) As for the light-steel plant column foot which shall be equipped with the shear key in accordance with the regulation, it is suggested to enhance the shear bearing capacity by increasing the diameter of the anchor bolt at the column foot. By doing so, it could avoid the shear key, reduce the construction difficulty and shorten the construction period.

(3) As for the column foot which shall be equipped with the shear key, the shear force at the column foot is borne jointly by three parts, including the force of friction between the baseboard with the

foundation concrete, the anchor bolt of the column foot and the shear key. This paper suggests making the calculation as per formula (14).

(4) The prerequisite for the function of shear key is that the secondary grouting shall ensure the compactness. Only if the compactness of the secondary grouting is guaranteed, it could ensure the foundation concrete and the shear key work as an integral part and the shear key thus could play its due function.

(5) This paper makes detailed analysis on the shear bearing capacity of the exposed column foot from the theoretical perspective. It is suggested to verify the correctness of the theoretical analysis in this paper by establishing the experimental model.

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