Experimental Study and Calculation Theory on the Uplift Bearing Capacity of Split Double-Pawl Type Anchor Bolt

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Abstract. In order to study the anchorage performance of split double-pawl bolt, the tensile strength tests of smooth round anchor bolt and split double-pawl type anchor bolt with different anchorage lengths were carried out, and the test results were compared with the relevant literature specifications. The test shows that the strain of anchor bolt is small in the concrete, and the strain is the largest at the contact with the concrete surface. The bond failure capacity of smooth round anchor bolts increases with the increase of anchorage length, but the deeper the anchorage length, the slower the increase of the bearing capacity. The uplift bearing capacity of anchor bolts can be greatly improved by installing the pawl bolt head. The calculation method of the bonding failure bearing capacity of the smooth round anchor bolt is relatively conservative, and the experimental value of the bearing capacity is smaller than the theoretical value because the anchor head is straightened when the pawl type anchor bolt is pulled up.

Keywords: anchorage performance; split double-pawl bolt; uplift bearing capacity; anchorage length

1 Introduction

Anchor bolt, also known as anchor bolt, is an important engineering fastening component, usually used for the connection of engineering components and concrete foundation. At present, the calculation of the uplift bearing capacity of the anchor bolt has been more detailed in the design codes at home and abroad, but it is not comprehensive enough. GB50017-2017 [1] and related design manual [2,3] regard the ultimate tensile bearing capacity of bolt as the ultimate uplift bearing capacity. DL/T1236-2021 [4] adopts the same provisions, and specifies the different types of anchor bolts and the anchorage lengths to be met. However, these regulations are more general, and lack the introduction of anchorage mechanism, stress state and failure modes when the anchor bolt is actually buried. ACI-318 [5] has made a detailed introduction and regulation on the damage conditions, influencing parameters and bearing capacity calculation of anchor bolts under uplift load, but it does not involve the influence of the bond between anchor bolts and concrete on the bearing capacity, and lacks the relevant introduction of the bonding capacity.

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Tong et al. [6,7] reviewed and compared the anchor bolt design methods at home and abroad, summarized the failure mode and bearing capacity of a single anchor bolt, and proposed the design criteria for a single anchor bolt. Xiao et al. [8] systematically summarized the design method of the column foot of the embedded anchor bolt type light steel structure, analyzed the types and characteristics of the anchor bolt at home and abroad, and proposed the design and calculation method of the anchor bolt according to the possible failure forms of the column foot. Chen et al. [9], Chen et al. [10] have related discussions on the calculation methods of the bearing capacity of anchor bolts. But these arguments are mainly based on the relevant calculation theory and calculation assumption, lack of concrete test support. Liu et al. [11] carried out the uplift test of M20 and M30 anchor bolts to explore the experimental phenomena and the stress state parameters of anchor bolts under the uplift load, but there was a lack of research on the anchoring mechanism of anchor bolts and comparison with relevant design calculation methods. Wu et al. [12,13] made a detailed study on the pulling capacity of L-type, J-type and pawl-type anchor bolts through experimental research and simulation analysis, and innovatively proposed the corresponding bearing capacity calculation method by comparing with the calculation method in ACI318. The difference is that the pawl type studied by Wu is an external pawl, and the anchorage performance is different from that of the split double pawl, and this part is relatively blank. Munemoto et al. [14] analyzed the failure mechanism and strength of anchor bolt under static pulling load and found that the combination failure mode of concrete cone and bonding failure would occur in anchor bolt, resulting in the depth of the damaged part of the cone decreasing and the inclination angle of the cone narrowing. And put forward the corresponding safety factor to ensure the safety of the bolt structure. Based on the shear-displacement model, Xu et al. [15] and Delhomme et al. [16,17] determined the anchoring depth of head anchor and bond anchor in concrete through tests, analyzed the load distribution of anchor in the elastic deformation stage, and studied the influence of the length of anchorage zone on the distribution of axial force and shear stress in the anchorage zone. Fu et al. [18] discussed the relationship between the maximum anchoring force and the anchoring length of the anchor bolt anchoring system, and proposed the main sliding interface relationship model based on the maximum anchoring force and the anchoring length, which could successfully break through the strength limit or the type restriction of surrounding rock. Fan et al. [19] studied the shear stress in the inner anchoring section based on the axial strain test results of high, medium and low strength anchors. Gao et al. [20] conducted a test and numerical study on the critical blind bolt system of reinforced hollow concrete embedded in concrete anchorage slip. The system can be used to join steel beams and reinforced concrete columns to form rigid moment connections. Shafei et al. [21] studied the seismic tension of cast-in-place anchor rod considering composite stiffness and strength degradation. On this basis, a nonlinear damage plastic model based on fracture is established, and it is found that seismic loads cause significant degradation of structural stiffness (damage) and tensile strength. Pitrakkos et al. [22,23] took a new type of blind bar member as the research object and studied the load transfer mechanism of the member through the monotony drawing test.

Torres-Rodas et al. [24] studied the cyclic response of a particular type of column base connection, namely the exposed base plate with extended anchor bolts, and showed that its desirable cyclic and hysteretic properties can improve the seismic performance of the structure. The anchorage force characteristics of anchor bolts in concrete is always a complicated problem, which prompts many scholars to reveal the anchorage mechanism through FEA [25].Although the research on the anchorage of anchor bolt has gradually formed a system at this stage, it still does not represent a comprehensive coverage of the research in this field. The current design specifications and related research on the uplift bearing capacity of anchor bolts are not specific and comprehensive, and there is a lack of research on the mechanical anchoring mechanism of split double-pawl anchor bolts. At the same time, it is explored whether the bolt can be divided into itself to meet the anchoring performance, to achieve cost saving and improve the construction convenience. This paper will carry out experimental research on the anchoring bearing capacity of split double ratchet type anchor bolts at different anchoring depths, focusing on exploring the effect of mechanical anchoring on the uplift bearing capacity of anchor bolts, and comparing the experimental bearing capacity with the theoretical design value, so as to provide references for further improving the calculation theory and design method of the uplift bearing capacity of anchor bolts.

2 Test Program

2.1 Test Specimens

In order to study the anchorage performance of split double-pawl bolt, pull up test was carried out to simulate the force action of anchor bolt in practical engineering. A total of six groups were designed with three anchor bolt specimens of the same type and anchorage length in each group. The concrete strength grade was C30. The specimen is shown in Fig. 1. The nominal diameter of the anchors is M30 and the material is Q235 steel. There are three different anchorage lengths for smooth round anchor bolt and split double-pawl anchor bolt respectively. Detailed parameters of anchor bolt specimens are shown in Table 1.

Table 1. specimens of anchor bolt

Specimens	Type	Diameter of bolt d/mm	Anchorage length l_d/mm	Anchorage concrete $L \times W \times H$/mm^3	Group
SDP-1	split double-pawl type	30	150(5d)	1200×1000×1000	3
SDP-2			300(10d)		
SR-1	Smooth round type	30	300(10d)	1200×1000×1000	3
SR-2			600(20d)		

split double-pawl type

smooth round type

Fig. 1. anchor bolts and anchorage concrete

2.2 Test Rig and Data Measurements

In the test, a simply supported steel beam is used as a reaction beam for loading, and the loading rig is shown in Fig. 2. The distance between the two supporting points of the simply supported steel beam is determined by the anchorage length of the anchor bolt. The loading device is mainly composed of reaction beam, hollow electrohydraulic jack and hollow force sensor. The tie rod is fixed through the upper part with tight nuts, and the lower part is connected with the anchor bolt through a coupling sleeve.

Fig. 2. Test rig

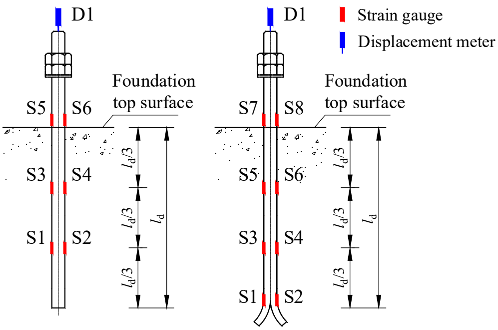

Fig. 3. Set of strain gauges and displacement gauge

DH3821 acquisition system was used to manually collect the uplift load, vertical displacement and bolt strain. Two strain gauge arrangement methods were set for different types of bolts in this test, namely, eight groups of strain gauges (S1-S8) were set symmetrically along the bolt for split double-pawl bolt, and 6 groups of strain gauges (S1-S6) were set symmetrically along the bolt for smooth round type bolt. The strain gauge is arranged at $l_d/3$ and $2l_d/3$ of the anchorage length of the bolt surface, the bolt root and the junction with the anchorage concrete surface, respectively, to measure the strain change of the anchor bolt during loading, as shown in Fig. 3. One displacement meter (D1) is arranged at the top of the tie rod to measure the vertical displacement of the anchor bolt.

2.3 Loading Criterion

Hydraulic jacks are manually calibrated before loading. Before the test, pre-load is applied to eliminate errors caused by factors such as component gap and support slip, and let the anchor bolt enter the normal working state. This test adopts the force control method to carry out the loading. Firstly, the loading is carried out step by step at 6.45kN. When small cracks appear at the contact point between the concrete surface and the anchor bolt, the loading is carried out step by step at 3.23kN until the concrete cracks or the anchor bolt is obviously pulled out. The load is directly read by the force sensor, and the surface strain and uplift displacement of the bolt under various loads are recorded by the acquisition system.

3 Test Results

3.1 Test Failure Phenomenon

The failure mode of the smooth round bolts with different anchorage lengths is bonding failure under the uplift load. When the load is increased to a certain value, the contact surface between concrete and anchor bolts has a small crack, which further expands as continuous loading. Under the ultimate bearing capacity, the bolt is obviously pulled out and the surrounding concrete surface is stripped, as shown in Fig. 4(a).

When the anchorage length is 5*d*, the typical failure mode of split double-pawl type anchor bolt under the uplift load is concrete tensile fracture. As the load reaches 60kN, the junction of concrete and the anchor bolt has a slight crack, accompanied by a slight pull out phenomenon; As the load continues to increase, the concrete cracks suddenly and the cracks spread rapidly to the edge. When it is loaded to approximately 75kN, the anchorage concrete sounded split double-pawl type bolt is completely pulled apart, and the vertical displacement of the anchor bolt is about 5.4mm. As shown in Fig. 4(a).

The failure mode of split double-pawl type bolt with anchorage length 10*d* and 15*d* under uplift load changes from concrete tensile fracture to bonding failure. The test phenomenon is similar to that of smooth round anchor bolt, because the pawl opening amount after split cannot meet the large anchorage length, and thus cannot drive the concrete to crack fracture. And the split double-pawl of the anchor bolt has been straightened in the test, as shown in Fig. 4 (b).

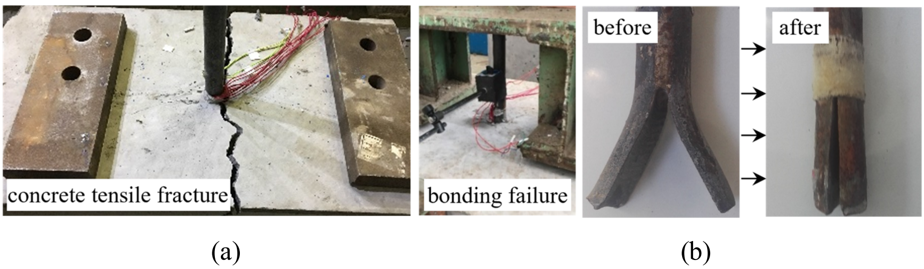

Fig. 4. Typical failure modes: (a) anchorage concrete; (b) anchor bolt

3.2 Load-Displacement Characteristics

The load-displacement curves of split double-pawl bolt and smooth round bolt obtained by the test are shown in Fig. 5. For specimen SDP-1, its failure mode is different from other specimens. The vertical displacement of bolts increases gradually with the increase of load. When the load reaches the ultimate bearing capacity, the load decreases while the bolt displacement continues to increase until the bolt is obviously pulled out and the specimen fails. However, under this special failure mode, the load-displacement curve of SDP-1 showed a relatively similar trend to that of other specimens.

When the anchorage length is 5*d*, the ultimate bearing capacity of specimen SDP-1 and SR-1 is similar. It can be seen that the mechanical anchorage performance of split double-pawls has little effect on the uplift bearing capacity at a small anchorage length. For deeper anchorage lengths (10*d* and 15*d*), the mechanical anchorage performance of split double-pawl showed advantages, and the ultimate bearing capacity of intersecting smooth round bolts increased by 6.53% and 8.27%, respectively. It is found that the greater the anchorage length, the greater the ultimate bearing capacity and the greater the maximum displacement of the anchor bolt under the same anchorage type. Table 2 lists the test results of anchor bolts with different anchorage types and anchorage lengths, such as the average value of ultimate bearing capacity.

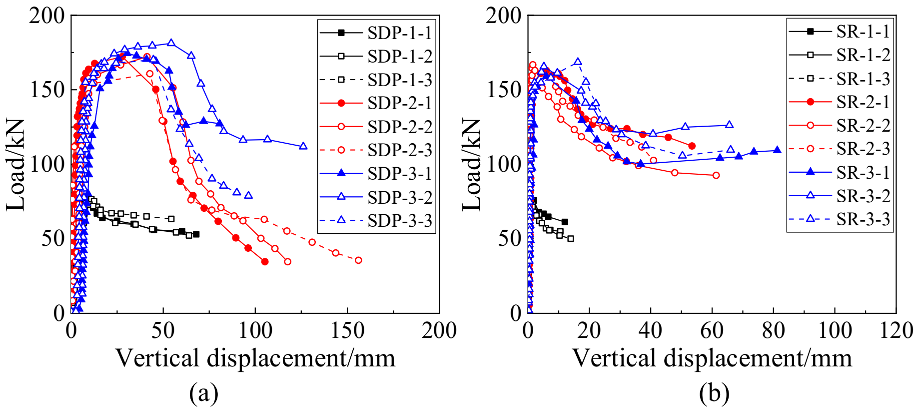

Fig. 5. Load-displacement curve: (a) spilt double-pawl type; (b) smooth round type

Table 2. summary of test results

Specimens	T_u^t/kN	Vertical displacement /mm	Test failure mode
SDP-1	74.67	23	Concrete tensile fracture
SDP-2	158.41	43	Bonding failure
SR-1	74.12	6	Bonding failure
SR-2	157.41	24	Bonding failure

3.3 Stress-Strain Distribution Characteristics

The load-strain distribution and development of anchor bolts at different anchorage lengths obtained by the test are shown in Fig. 6. The strain distribution on the surface of the split double-pawl bolt is uneven under the uplift load. The strain of the anchor bolt on the anchorage concrete surface is the largest, and the strain of anchor bolt in the concrete is small. When the uplift load reaches the yield load, the stress-strain of the anchor bolt shows a linear change relationship, and the anchor bolt is in an elastic state. With the increase of load, the stress-strain presents nonlinear characteristics. In particular, the circular anchor bolts with anchorage length of 25*d* yield at the contact with the concrete surface.

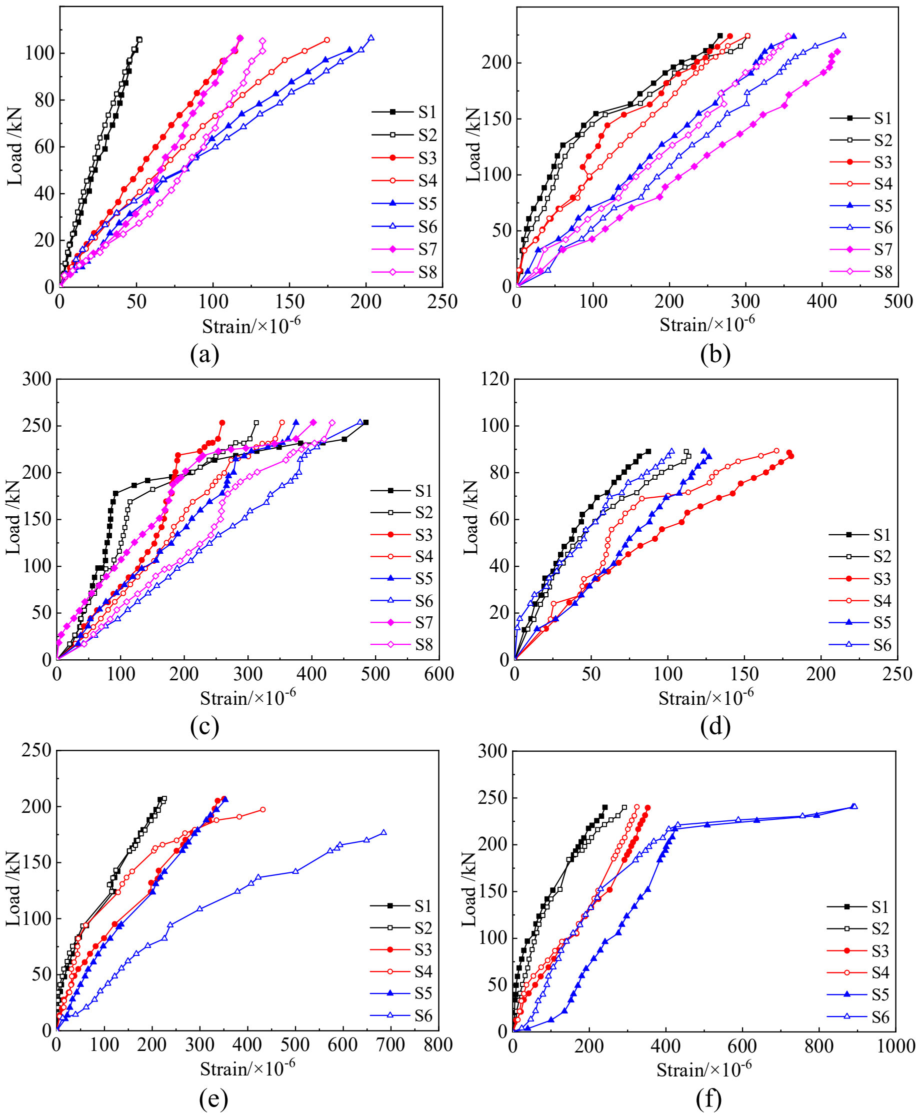

Fig. 6. Load-strain curve of anchor bolt: (a) SDP-1; (b) SDP-2; (c) SDP-3; (d) SR-1; (e) SR-2; (f) SR-3

4 Calculation Theory of Uplift Bearing Capacity

4.1 Calculation Methods of Uplift Bearing Capacity

According to ACI-318 [5] and the existing studies [6,7], the uplift bearing capacity of single anchor bolt can be calculated according to three failure modes.

Anchor bolt reaches tensile capacity limit, bolt pull break:

$$T_{u1} = f_y A_e \tag{1}$$

Where A_e is the effective tensile area of the anchor bolt; f_y is the yield strength of the anchor bolt.

Failure of bond between foundation concrete and bolt:

$$T_{u2} = \pi l_d d f_t \tag{2}$$

Where d is the diameter of bolt; l_d is the anchorage length; f_t is the tensile strength of concrete.

When conical concrete reaches the limit of tensile capacity, Tong [6] gives the suggestion is that the distribution of tensile stress along the surface of the concrete failure cone is variable, the maximum is at the lowest buried end, and it is 0 on the concrete surface. Take 2/3 of the average tensile stress of the concrete on the failure surface, and consider the stress of the entire failure surface to be the same (this hypothesis has been verified by tests). Horizontal projection plane is used for calculation:

$$T_{u3} = 0.66 f_t \pi (l_d + d_0 / 2) l_d \tag{3}$$

Where d_0 is the diameter of the anchor head.

ACI-318 makes the following provisions for the calculation of uplift bearing capacity of concrete:

$$T_{u3} = 10 \frac{A_{NC}}{A_{NCO}} \lambda_a \sqrt{f_c'} l_d^{1.5} \tag{4}$$

Where A_{NC} is the calculated area of the actual conical failure surface; A_{NCO} is the area of the ideal conical failure surface without considering the edge distance, which is take $9l_d^2$; λ_a is the adjustment coefficient of light concrete, which is 1.0 for ordinary bulk weight concrete; f_c' is the standard compressive strength of concrete.

4.2 Comparative Analysis of Uplift Bearing Capacity

The theoretical uplift bearing capacity of the anchor bolt used in the test was calculated according to the formula in 3.1, and compared with the actual test bearing capacity, as shown in Table 3.

Table 3. Comparison of the uplift bearing capacity

Specimens	T_u^t / kN	T_u^c / kN	Test failure mode	Theoretical failure mode
SDP-1	74.67	66.68/82.36*	concrete tensile fracture	concrete cone breakout
SDP-2	158.41	196.00	bonding failure	bolt yield
SR-1	74.12	40.41	bonding failure	bonding failure
SR-2	157.41	80.82	bonding failure	bonding failure

Based on the comprehensive analysis of Table 2 and Table 3, it is found that the maximum uplift bearing capacity of anchor bolts with the same anchorage type increases with the increase of anchorage length, but the deeper the anchorage length, the slower the growth rate of uplift bearing capacity. This is because the larger the anchorage length of anchor bolts, the more uneven the distribution of bonding stress and the lower the average bonding strength.

When the anchorage length l_d=300mm, the ultimate uplift bearing capacity of smooth round anchor bolt is 74.12kN, and the ultimate pulling capacity of the spilt double-pawl anchor bolt is 158.41kN, which is 2.13 times of smooth round anchor bolt. The anchorage length of the two anchor bolts is the same, and the mechanical anchorage capacity provided by the two anchor bolts is the same. Therefore, the mechanical anchorage capacity provided by the split double-pawl anchor head is 84.29kN, accounting for about 53.21% of the total ultimate bearing capacity. Therefore, the ultimate uplift bearing capacity of anchor bolts can be greatly improved by setting the pawl type anchor head.

The test uplift bearing capacity of smooth round anchor bolts with different anchorage lengths is compared with the theoretical calculation value. It can be seen that the bond failure bearing capacity of smooth round anchor bolts is smaller than the theoretical value. It can be judged that the bond failure capacity specified in formula (2) is relatively conservative. In addition, the test uplift bearing capacity of split double-pawl type anchor bolts with different anchorage lengths is compared with the theoretical calculation value. When the anchorage length is 150mm, the concrete foundation will have tensile failure. In comparison, the calculated bearing capacity of concrete tensile fracture specified in ACI-318 is larger than that in formula (3), and the test bearing capacity value is not much different from the theoretical calculation value.

When the anchorage length of the pawl type anchor bolt is 300mm and 450mm, the uplift bearing capacity calculated by formula (3) of the concrete is much larger than that calculated by formula (1), and theoretically the anchor bolt should break. However, the bond failure of the pawl type bolt occurred in the test, and the test bearing capacity was much smaller than the theoretical calculation value. As shown in Fig. 4, the anchor head of the pawl bolt will be deformed on the bolt under uplift load. When the uplift load exceeds a certain value, the anchor head will be straightened, thus losing its mechanical anchorage effect, and eventually bond failure will occur. The calculation method in 3.1 does not take this situation into account, and the calculation theory in 3.1 will no longer be applicable. In order to ensure safety, the bearing capacity of pawl type anchor bolts with large anchorage length should be reduced to some extent, and the calculation theory of bearing capacity of such anchor bolts should be further improved. In practical engineering applications, the design and use of such anchor bolts should be treated with special care, and the possibility of anchoring failure due to the deformation of the anchor head should not be ignored.

5 Conclusion

Based on the above test and analysis, the following conclusions can be drawn:

(1) The strain distribution of the two type anchor bolts is uneven under the action of tension, and the strain inside the concrete is small, and the strain at the contact with the concrete surface is maximum.

(2) The maximum uplift bearing capacity of both smooth round anchor bolts and split double-pawl type anchor bolts increases with the increase of anchorage length, but the larger the anchorage length, the slower the growth rate of the uplift bearing capacity.

(3) The setting of pawl bolt head can greatly improve the ultimate uplift bearing capacity of anchor bolts, and the mechanical anchoring capacity provided by this anchor head accounts for a large proportion of the total bearing capacity.

(4) When the anchorage length is large, the pawl type anchor bolt does not have the theoretical phenomenon of bolt breaking, and the main form of failure is still bonding failure, because the anchor head is straightened under the uplift load and the anchorage performance is lost. The bearing capacity calculation method proposed by relevant norms and studies is no longer applicable. In order to ensure safety, the calculated value of bearing capacity should be reduced to a certain extent. The bearing capacity calculation theory of such anchor bolts needs to be further improved.

(5) In practical engineering applications, the anchor bolt similar to the split double-pawl type should be treated with caution, because the pawl is easy to deform when pulled, so that the anchor loses the role of mechanical anchorage.

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References

1. GB50017-2017. Code for Design of Steel Structure. China Architecture & Building Press, Beijing, China; 2017.
2. Luo B, Wei M, Shen Z. Steel structure design manual[M]. China Architecture & Building Press, Beijing, China;1989.
3. Li H. Steel structure joint design manual[M]. China Architecture & Building Press, Beijing, China; 1992.
4. DL/T1236–2021. Anchor bolts and nuts for poles and towers of electric power transmission line. China Electric Power Press, Beijing, China; 2021.
5. ACI318-19. Building code requirements for structural concrete. American Concrete Institute, Farmington Hills, Michigan, 2019.
6. Tong G, Wu G. Design of bearing capacity of single anchor bolt at steel column foot[J]. Building Structure, 2004, 34(2): 10-14.
7. Tong G, Wu G. Summary of design internal force calculation method of anchor bolt of steel column foot[J]. Building Structure, 2004, 34(6): 55-57.
8. Xiao Q. Calculation method of anchor bolt for column foot of light steel structure [D]. Hangzhou: Zhejiang University, 2002.
9. Chen Y, Liu X. Tower anchor bolt and foundation ring design [J]. Process Equipment Piping, 2001, 38: 32-36.

10. Chen Y, Zhang X, Liu H, Li L. Design of anchor bolts [J]. Industrial Construction, 2013, 43(S1): 549-554.
11. Liu S, Zhang Q, Ni J, Gu M. Experimental study and finite element analysis of tensile capacity of a single anchor bolt[J]. Building Structure, 2008, (10): 102-105+16.
12. Wu T, Huang F, Zhang D, et al. Anchorage failure mechanism and uplift bearing capacity of L-& J-anchor bolts in plain concrete[J]. Engineering Failure Analysis, 2024, 159: 107991.
13. Wu T, Liu L, Han L, et al. Anchorage force transfer mechanism and bearing capacity theoretical of pawl bolt anchored in plain concrete[J]. Construction and Building Materials, 2024, 438: 137145.
14. Munemoto S, Sonoda Y. Experimental analysis of anchor bolt in concrete under the pull-out loading[J]. Procedia engineering, 2017, 171: 926-933.
15. Xu X, Tian S. Load transfer mechanism and critical length of anchorage zone for anchor bolt[J]. Plos one, 2020, 15(1): e0227539.
16. Delhomme F, Roure T, Arrieta B, et al. Pullout behavior of cast-in-place headed and bonded anchors with different embedment depths[J]. Materials and structures, 2016, 49: 1843-1859.
17. Delhomme F, Debicki G, Chaib Z. Experimental behaviour of anchor bolts under pullout and relaxation tests[J]. Construction and Building Materials, 2010, 24(3): 266-274.
18. Fu M, Huang S, Fan K, et al. Study on the relationship between the maximum anchoring force and anchoring length of resin-anchored bolts of hard surrounding rocks based on the main slip interface[J]. Construction and Building Materials, 2023, 409: 134000.
19. Fan J, Shi X, Kong F, et al. Calculation Method of the Effective Anchorage Length of Anchorage Structures Based on Analysis of the Ultimate Bearing Capacity[J]. Geotechnical and Geological Engineering, 2021, 39(6): 4205-4212.
20. Gao X, Wang W, Teh L H. Experimental and numerical investigations of tensile behavior of slip-critical blind bolts anchored in concrete-filled steel tubes[C]//Structures. Elsevier, 2023, 55: 354-369.
21. Shafei E, Tariverdilo S. Seismic pullout behavior of cast-in-place anchor bolts embedded in plain concrete: Damage plasticity based analysis[C]//Structures. Elsevier, 2021, 34: 479-486.
22. Pitrakkos T, Tizani W. Experimental behaviour of a novel anchored blind-bolt in tension[J]. Engineering Structures, 2013, 49: 905-919.
23. Pitrakkos T, Tizani W, Cabrera M, et al. Blind bolts with headed anchors under combined tension and shear[J]. Journal of Constructional Steel Research, 2021, 179: 106546.
24. Torres-Rodas P, Medalla M, Zareian F, et al. Cyclic behavior and design methodology of exposed base plates with extended anchor bolts[J]. Engineering Structures, 2022, 260: 114235.
25. Chen J, Zeng B, Liu L, et al. Investigating the anchorage performance of full-grouted anchor bolts with a modified numerical simulation method[J]. Engineering Failure Analysis, 2022, 141: 106640.