Analysis of Stress State of Bolts under Different Anchorage Qualities

Sheng Zeng[1], Jie Zhou[1], Bing Sun[2*] & Xia Wen[1]

[1]School of Resource Environment and Satety Engineering, University of South China,
Hengyang 421001, China
[2]School of Civil Engineering, University of South China,
(NO28, West Changsheng Road), Hengyang 421001, China
*E-mail: sunbingnh@126.com

Abstract. A series of pull-out tests were conducted in order to study the stress states of bolts under different anchorage qualities and to simulate the influence of quality defects in empty-slurry and low-strength mortar anchorage in actual engineering. The tests mainly investigated strain characteristics at different positions of the bolts and the effects of strains at the same positions under different anchorage conditions. The research led to the following conclusions: (1) under ultimate bearing capacity, the strain values decayed the fastest along the length of the bolt in the full-length anchorage, the strain values decayed the slowest in the empty-slurry and low-strength mortar anchorage, and the decaying speed of strains in the empty-slurry mortar anchorage was between that of the above two kinds of anchorages; (2) at almost 50% of the ultimate bearing capacity, the strain values were slightly different between the empty-slurry and low-strength mortar anchorage and the empty-slurry anchorage. Obvious differences in strain values occurred when the bolts were continued to be loaded. The strain values of the full-length anchorage bolts were different from those of the other two kinds of anchorages; (3) from the analysis of stress variation characteristics, the safety reserve was the highest for the full-length anchorage under the condition of ultimate bearing capacity, followed by the empty-slurry mortar anchorage, while the safety reserve was the lowest for the empty-slurry and low-strength mortar anchorage. However, in terms of uniformity of force and utilization of the material, the result was reverse.

Keywords: *anchor bolt; anchoring defect; anchoring quality; pull-out test; stress characteristics.*

1 Introduction

As active reinforcement members, bolts are widely used in many engineering fields. A bolt and its anchor medium constitute a new structure that can carry greater force [1-2]. Accordingly, bolts have certain economic benefits. However, the anchorage quality of bolts cannot be ensured in construction, which leads to several urgent problems to be solved. The shear stress value of a bolt increases rapidly from zero to its maximum along its length and then declines exponentially in the elastic state of the bolt. After a certain length, the

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value of the shear stress is almost zero [3-5]. Considering the characteristics of bolt force, scholars have carried out a large amount of research on the state of bolts, anchor medium and anchorage body under pull-out loads.

The effect of the strength of the anchorage medium on the mechanical properties of bolts cannot be neglected [6]. Zeng, *et al.* have examined the distribution of shear stress in bolts through experimental tests on bolts in three kinds of surrounding rocks with high strength, medium strength and low strength, and argued that the shear stress of the bolts decreased faster in a high-strength medium [7]. When a bolt is installed in a soil layer, the law of bolt force is similar to that in other media [8].

The stress states of bolts have been examined by changing the water content of the soil around the bolts and is obviously in the elastic stage at low water content, but there is no obvious elastic-plastic stage at higher water contents [9]. The anchorage performances can be improved by varying the anchorage media [10]. Current research on bolts focuses on their shape and strength to optimize their mechanical properties. It has recently become a subject of much interest to study bolts that are suitable for all kinds of complicated stress states [11-14]. The development of composite anchorages and the optimization of reinforcement design are effective and reliable ways to improve the mechanical behavior and supporting effects of bolts [15-18]. Studies on anchorage media and bolts concentrate on full-length anchorage bolts when the force characteristics and ultimate bearing capacity of bolts are investigated. Some researchers have discussed the difference between defect anchorage and full-length anchorage bolts under stress. The conclusion about defect anchorage bolts is that the farther removed from the orifice, the smaller the impact on the bolt's stress. A defect anchorage has little effect on the bolt under small loads, while obvious influence will appear under increased load [19-20].

At present, little research has been done on bolt force under different anchorage qualities, especially referring to stress states at various positions of the bolt under empty-slurry or low-strength mortar defects anchorages, but the problem of bolt defects cannot be ignored in the engineering process. Therefore in this study, bolt stress was investigated under different anchorage qualities. In a laboratory test, bolt stress was measured by strain gauges installed at different positions of the bolt. Bolts were anchored by a full-length anchorage, an empty-slurry mortar anchorage, and an empty-slurry and low-strength mortar anchorage. Analysis of the similarities and differences is necessary to find the reaction of the bolts to several anchorage qualities under different conditions of stress. This paper puts forward important recommendations for engineering practice.

2 Basic Theory

Under a pull-out load, a bolt experiences axial stress and shear stress from the anchorage body, as shown in Figure 1.

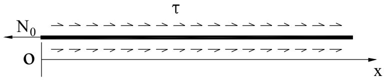


Figure 1 Bolt force diagram.

The equation that expresses the force balance of a given micro-body from the bolt is:

$$Ad\sigma_b = -\tau_b \pi d_b dx \tag{1}$$

where A is the sectional area of the bolt.

Assuming that there are no cracks at the interface, the values of shear stress τ_b of the rock bolt under full-length anchorage decrease in the following form:

$$\tau_b(x) = \frac{\alpha}{2}\sigma_{b0} e^{-2a\frac{x}{d_b}} \frac{d\sigma_b}{dx} \tag{2}$$

The axial stress σ_b is expressed as:

$$\sigma_b(x) = \sigma_{b0} - \frac{\pi d_b}{A}\int_0^x \tau_b(x)d(x) = \sigma_{b0} e^{-2a\frac{x}{d_b}} \tag{3}$$

Based on Eqs. (2) and (3), Eq. (4) can be got as:

$$\begin{cases} \sigma_b(x) = \dfrac{2}{\alpha}\tau_b(x) \\ \alpha^2 = \dfrac{2G_r G_g}{E_b\left(G_r \ln\dfrac{d_g}{d_b} + G_g \ln\dfrac{d_0}{d_g}\right)} \\ G_r = \dfrac{E_r}{2(1+r_r)} \\ G_g = \dfrac{E_g}{2(1+r_g)}\mathrm{b} \end{cases} \tag{4}$$

where σ_{b0} is the maximum axial stress of the bolt, and d_b, d_g and d_0 are the diameter of the bolt, the drilling diameter of the bolt, and the radius of the annular area affected by the bolt, respectively; E_b is the Young modulus of the bolt, and E_r and E_g represent the Young modulus of rock and mortar, respectively; r_g and r_r are the Poisson ratios of the mortar and rock, respectively.

From Eqs. (3) and (4) it can be seen that σ_b is only related to the length from the left side of the bolt in the full-length anchorage state, while τ_b is related to the Poisson ratio and Young modulus of the anchorage medium, i.e. in Eq. (5):

$$\tau_{\mathrm{b}} \propto \frac{xE_g}{y(1+r_g)+zE_g} \tag{5}$$

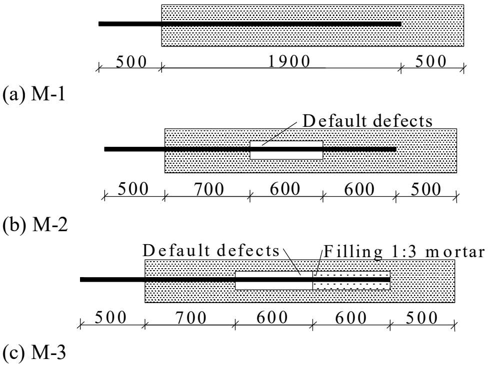
where x, y and z are constants. The values of τ_b are different under various intensities of anchorage media. An empty-slurry anchorage can be regarded as an anchorage medium with a Young modulus of zero, while the Young modulus of a low-strength mortar anchorage is between that of an empty-slurry anchorage and a full-length anchorage.

3 Laboratory Tests

3.1 Model Design

The model experiment used a 50t jack to draw the bolts, making three anchor bolts, which were numbered M-1, M-2 and M-3, as shown in Figure 2. M-1 was a full-length anchorage bolt. M-2 was a bolt with an anchorage defect near the middle of the bolt. M-3 was an empty-slurry and low-strength mortar anchorage bolt. The specific sizes and locations of the defects are shown in Figure 3.

Figure 2 Bolt drawing test.



(a) M-1

(b) M-2

(c) M-3

Figure 3 Bolt structure diagram. (Unit:mm)

The bolt used rebar of 28 mm diameter, with a free length of 500 mm and an anchorage length of 1900 mm. In the construction, grouting was adopted, followed by inserting the bolts. The mixing ratio of the concrete was 1:2:4. In order to complete the pouring of the experimental model, a 200-mm diameter PVC drainpipe was used as a template. A 75-mm PVC pipe was used to set internal defects. The specific locations of the defects are depicted in Table 1.

Table 1 Bolt design parameters for model test.

Bolts	Construction Procedure	Defect Settings
M-1	First insert the reinforcement, then pour the concrete.	Complete bolt and concrete with uniform density.
M-2	First leave a hole, then insert the reinforcement and pour the concrete.	A hole with 50 mm diameter is left at a distance of 700 and 1300 mm from the anchoring end.
M-3	First pour mortar with a cement/water ratio of 1:3 and leave holes, then insert the reinforcement and pour the concrete.	A hole with 50 mm diameter is left at a distance of 700 and 1300 mm from the anchoring end. Mortar with a cement/water ratio of 1:3 is poured into 50 mm diameter pipe at a distance of 1300 and 1900 mm from the anchoring end.

3.2 Layout of Measuring Points

Strain gauges were installed to measure the development of stress during loading, as displayed in Figure 4. X2 and X3 were located on both sides at a position of 700 mm from the left anchoring end, and X4 and X5 on both sides at a position of 1300 mm from the left anchoring end.

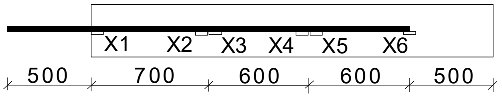


Figure 4 Locations of strain gauges. (Unit: mm)

4 Experimental Results and Analysis

4.1 Strain Variation Characteristics of the Bolts at Different Measuring Points

4.1.1 Full-length Anchorage Bolts

The displacement of bolts under extreme loading of about 250 kN is obvious. The loading level of the bolt often takes 10% of the maximum experimental load in actual engineering. In order to attain more accurate test results, loads from 0 to 250 kN were applied on the left side of the bolt with a load step of 10 kN, as shown in Figure 3(a). It was assumed that the strain value at each measuring point was zero when the load was zero. The strain values at different points of M-1 were obtained by subtracting the initial values from the strain values under varying loading conditions, as shown in Figure 5.

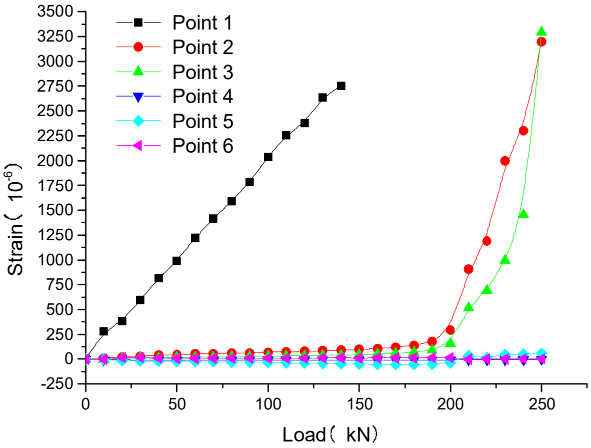


Figure 5 Strain values at different measuring points of M-1 under varying loading.

Figure 5 shows that the strain values were very small under comparatively small loading values. As for the points 2-6, the gauge strain values did not change significantly until the drawing load reached a value of 200 kN. The gauge strain values increased sharply with increasing load at points 2-3 under a load of more than 200 kN. The strain values at point 2 were higher than those at point 3 until the load reached a value of 240 kN. The bolt was subjected to larger stress at point 2. The values at point 1 changed linearly with increasing load until failure. The gauge strain reached an ultimate value of about 150 kN due to the influence of stress concentration at the end. The values at points 4-6 did not keep increasing with continuous loading, because re-loading takes place during loading, which causes redistribution of stress. The values at points 2-3 had little difference compared with those of other points under full-length anchorage condition. Points 4-6 were far removed from the part subjected to pull-out loading and displayed only a small change in strain values compared with points 2-3, which indicates that the main force on the bolt was concentrated in a limited area on the left side of the bolt under ultimate loading conditions.

4.1.2 Empty-slurry Mortar Anchorage Bolts

M-2 was subjected to a pull-out test. For comparison with the full-length anchorage bolt, loads from 0 to 250 kN were applied on the left side of M-2, with the load increasing gradually in steps of 10 kN, as shown in Figure 3(b). The strain values at different measuring points of M-2 under varying loads are shown in Figure 6.

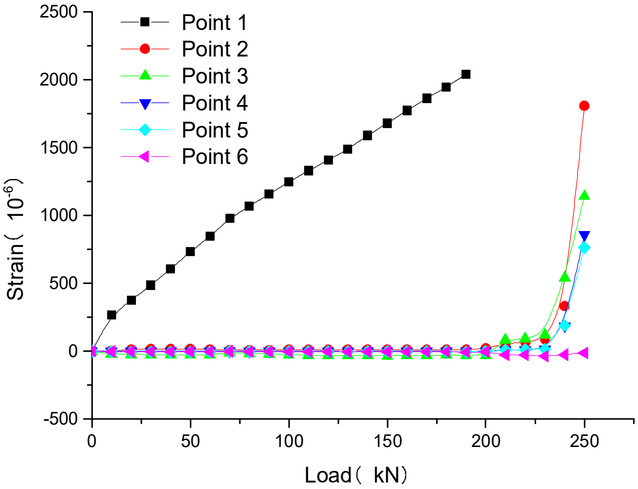


Figure 6 Strain characteristics at different measuring points of M-2 under varying loading.

Figure 6 shows that the strain values for measuring point 1 rose along a certain slope under loads from 0 to 190 kN. Similar to point 1 in Figure 5, the strain values were proportional to the stress of the bolt in the elastic deformation stage, but the slope of the strain-stress values was relatively low here. The strain values for M-2 were smaller than those for M-1 at point 1 under the same load. The strain gauges had been loaded to failure phase when the load reached a value of 200 kN. The strain values at points 2-6 were approximately zero and did not change quickly until the load of 200 kN was reached. The values began to vary significantly after the load reached a certain value. The strain values of point 1 were far greater than those of points 2-6 before the load reached 200 kN, and the pull-out load was mostly carried by positions between point 1 and 2 of the bolt. The strain values at points 4-5 were different from those of the full-length anchor bolt, because the values were low at the beginning and increased rapidly after the load up to 200kN, which was caused by an empty-slurry defect between point 3 and 4. The position of point 6 had been under compression and its strain values changed little compared with other points. The empty-slurry defects resulted in an effective range of the bolt's force expanding from part to full length.

4.1.3 Empty-slurry and Low-Strength Mortar Anchorage Bolts

M-3 was subjected to a pull-out test. Due to two types of defects existing in this bolt, a load from 0 to 240kN was only applied on the left side, with the load increasing gradually at steps of 10 kN, as shown in Figure 3(c). The strain values at different measuring points of M-3 under varying loading are expressed as follows.

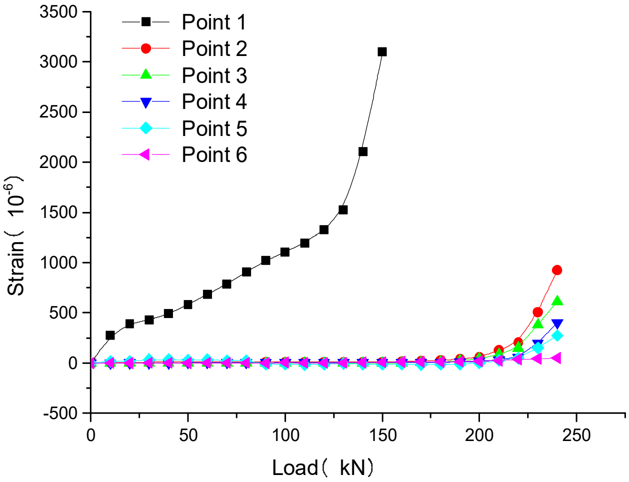


Figure 7 Strains at different measuring points of M-3 under varying loading.

It can be seen from Figure 7 that the strain values of point 1 roughly rose linearly under loads from 0 to 120 kN. Small differences in strain value were observed for M-3 and M-2 but large differences for M-3 and M-1, where the strain values changed fast. The strain values increased linearly in a steeper way and reached its ultimate value rapidly under loads of 120 to 150 kN. M-3 failed earlier near the position of the pulling action when compared with M-2. The situation of points 2-6 of M-3 was similar to that of M-2 before loading up to 200 kN, with small changes in the gauge strain values. There was no obvious change in strain value under further loading over 200 kN. This part of the load was also carried by the sections between point 1 and 2. The strain values at points 4-5 were small until the load reached 200 kN and then rose rapidly with further loading. Thus, the strain characteristics at points 4-5 are similar to those for M-2, but different from those for M-1. The position of point 6 was in a tension state and its strain values varied slightly. The empty-slurry and low-strength mortar anchorage made the range of the bolt's force reach the full-length state.

4.1.4 Comparison and Verification Analysis

The main force position of the bolt is close to the position of pull-out load under the full-length anchorage. The force range of M-2 was wider compared with M-1. The full length of M-3 was in tension. The strain values of M-1 and M-2 increased linearly at point 1. However, strain variation of M-3 is expressed by two linear profiles with different slopes. The strain values for M-3 were similar to those of M-2 at an earlier stage but later increased rapidly. The main difference between the three kinds of anchorage qualities existed in points 4-6. The strain values of M-1 along the length direction of the bolt decayed the fastest, while those of M-3 had the slowest decay, with those of M-2 between M-1 and M-3.

As shown by Eq. (4), when the full-length anchorage bolt is pulled out, axial stress is proportional to shear stress when there are no cracks in the interface between the bolt and the anchorage body. Eqs. (4), (6) and (7) reveal that pull-out load is proportional to shear stress. The relationship between the pull-out load and the shear strain at point 1 under three kinds of anchorage states is consistent with the theory, except for the late load in the third anchorage state, in which case the bolt is separated from the anchorage body or the strain sheet has been destroyed at point 1. At present, no one has studied the law of shear strain changes with increasing pull-out load of bolts under different anchorage qualities. However, the experimental results obtained from point 1 confirm the feasibility of the test and the correctness of the results.

$$N = A\sigma_b \tag{6}$$

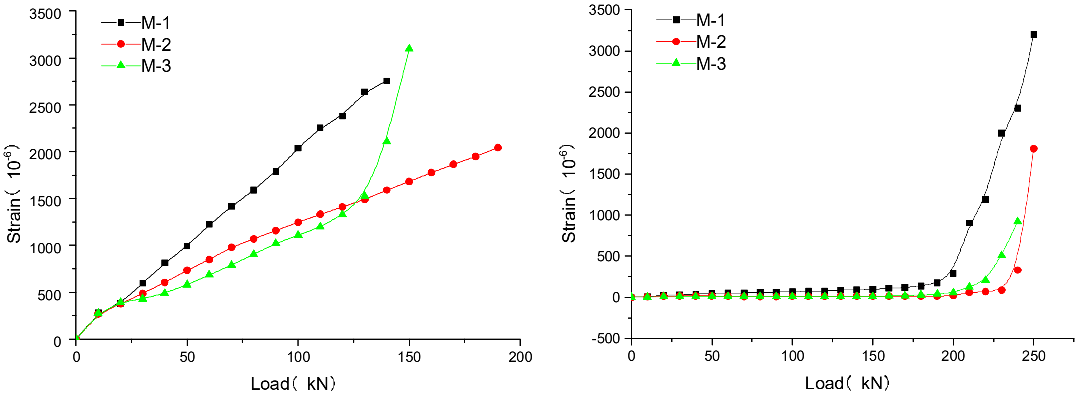
$$\gamma_b = \frac{\tau_b}{G} \tag{7}$$

where N is pull-out load and γ_b is shear strain.

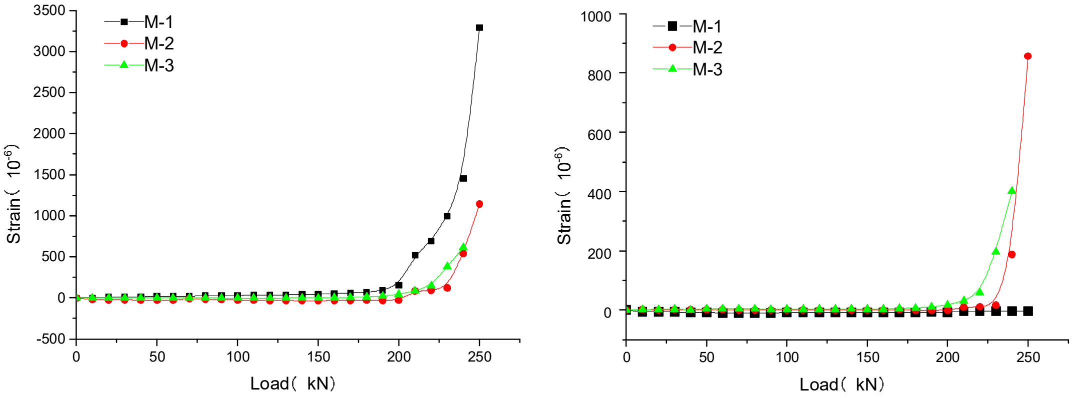
4.2 Stress Analysis at the Same Measuring Points under Different Anchorage Qualities

The foregoing analysis suggests that the influence on the strain of the bolts under different anchorage qualities is inevitable under pull-out loading. The test results at the six measuring points under different anchorage qualities are shown in Figure 8. It can be seen that the strain values rose with increasing external force at most measuring points except point 6, especially when the load reached 200 kN. The strain values were close to zero near the position of point 6 in the case of full-length anchorage and empty-slurry mortar anchorage.

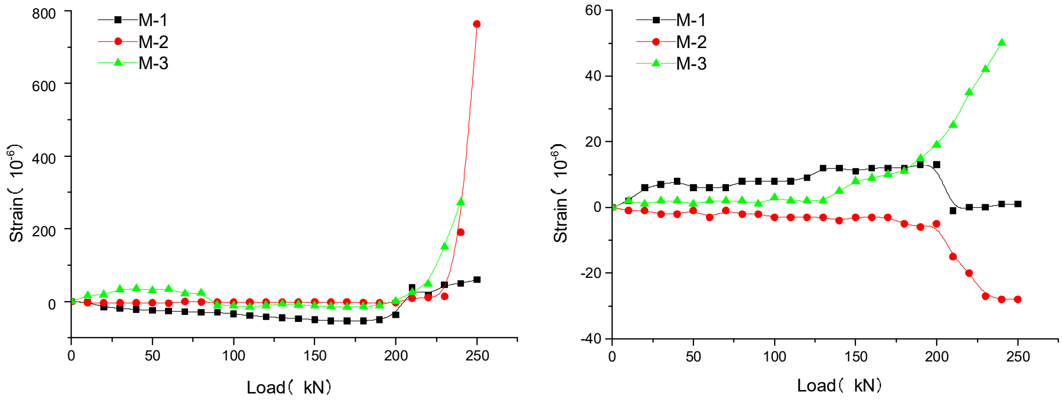
1. From Figure 8(a) it can be seen that the strain values at point 1 were relatively large under three kinds of anchorage qualities and the point failed earlier due to stress concentration compared with the other measuring points. The force characteristics of M-3 were similar to those of M-2 at point 1 before loads up to 120kN. The strain values of M-3 increased rapidly and reached the strain values of M-1 at point 1 under loads of more than 120 kN. The low-strength mortar anchorage did not reveal its weakness when the force was small. The shortcomings of M-3 gradually appeared with increasing pull-out load.
2. The strain gauges of point 2 and 3 were attached to both sides of the interface of the anchoring and the empty-slurry mortar, respectively. Comparing with Figure 8(b) and (c), it can be concluded that the strain values changed a little under the full-length anchorage state during loading, but the strain values for M-2 and M-3 were significantly different when the load was over 220 kN. M-1 was subjected to maximum stress at points 2-3 under ongoing loading, followed by M-2, and M-3 carrying the minimum force. M-1 was anchored on the right side of point 3 compared with the other two kinds of anchorage qualities with empty-slurry mortar defects. M-2 and M-3 at point 3 transferred stress to the position of point 4, which resulted in M-1 being subjected to a larger load at points 2-3 compared with the other two kinds of anchorage bolts.
3. The strain value of M-1 was about zero at point 4, showing that the stress of the bolt was negligible when the bolt nears its ultimate bearing capacity, but the strain values of the other two kinds of anchorage qualities remained at high levels. The differences in stress between M-2 and M-3 were small because of the presence of empty-slurry defects between points 3 and 4. However, the strain values of M-1 had great differences at points 3-4 and the majority of forces of the bolt act on the parts before point 4 under pull-out loads.
4. The strain values ranged from negative to positive at point 5 under full-length anchorage, showing obvious stress redistribution. The strain values of M-2 were larger than those of M-3 at points 2-5. Additionally, the strain of these two kinds of anchorages decreased slower than those of the full-length anchorage. The forces of M-2 and M-3 were more uniform compared with M-1.
5. The strain values were very small at point 6 at the beginning of loading. The strain values for M-3 were the largest under increasing loads and the bolt remained in tension. The strain values for M-1 and M-2 at point 6 slightly changed with the increasing drawing load. M-3 remained in tension along the full length and the strain values of this bolt were more reasonable than those of the other two kinds of bolts.



(a) Measuring point 1 (b) Measuring point 2



(c) Measuring point 3 (d) Measuring point 4



(e) Measuring point 5 (f) Measuring point 6

Figure 8 Strains at the same measuring points under different anchorage qualities.

5 Conclusions

M-3 remained in tension from point 1 to 6 and its strain values decreased slowly. M-2 remained in a state of tension until the positions between point 5 and 6. However, M-1 did not remain in tension any more before the position of point 4, and therefore had a long safety reserve. As a result, the bolt is the safest and the most stable under full-length anchorage condition. The anchorage body will be more dangerous and vulnerable with more types of defects, regardless of the effect of other variations. For the whole length of the bolt, it was found that the stress distribution of M-3 was superior to that of M-1 and M-2, except for the position of point 1. One part of the bolt can avoid failing when the other part starts elastic deformation in this situation. An empty-slurry and low-strength mortar anchorage state is conducive to the full use of materials.

The anchorage states of M-2 and M-3 differed in the strength of the mortar on the right side of the anchorage. M-2 had a longer safety reserve than M-3. Consequently, it is necessary to give priority to pumping a high-strength binder in the depths of the anchorage, which can increase the levels of security and stability. The strain diagrams of special points under the three kinds of anchorage qualities roughly depict the force states of the bolts and the response of the strain values under varying pull-out loads. In this paper, a new systematic method for the analysis of bolt stress was proposed. Further study is needed on the strength of the bolt, other anchorage qualities and bolt force under strong external loads.

Acknowledgments

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