Connection Strength of Undercut Anchorage Stone Cladding

Zuohu Wang*, Mingze Shao, Zhanguang Gao and Yuan Yao
School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, Zhanlanguan Road 1#, Xicheng District, Beijing, China
Email: wangzuohu@bucea.edu.cn

Abstract. Experiments were conducted on seventy-two stone panels to investigate the connection strength of undercut anchorage stone cladding. The following factors were considered in this study: the stone type, the distance between the hole center and the edge of the plate, the hole depth and the diameter and type of the undercut anchor. The results show that the stone type and anchor depth are the factors that most strongly influence the anchorage strength. The distance between the hole center and the edge of the plate are secondary factors. The connection strength increases when the distance between the hole center and the edge of the plate from 40 mm to 60 mm. The anchorage strength of percussion anchor is approximately 10% higher than that of a screw-in anchor under the same conditions.

1. Introduction
After more than ten years of rapid development, China has become the world's largest producer and user of architectural curtain walls, of which stone cladding accounts for approximately 30% [1]. Undercut anchorage stone cladding is a common enclosure structure for building. A novel dry hanging method has been introduced that differs from the traditional wet-paste and steel-pin dry hanging method. The novel method produces good connection strength and is widely used. The unique bottom reaming technology used in the novel method is key for obtaining good connection strength [2-6]. Zhao [7] performed a pull-out test on an anchor, in which slate fracture and cone failure occurred. Zhang [8] reported an increase in the tensile bearing capacity of a stone anchor, for which the index of the anchor depth 1.5 and the index of the substrate strength was 0.5. Camposinhos [9] tested 130 stone panels to study the relationship between the flexural strength and the breaking load for different stone types. Lammert [10] studied the relationships between the material strength and the anchorage strength for different anchorage configurations. Conroy [11] founded that the stiffness of stone cladding can significantly affect cladding stresses.

Studies on undercut anchorage stone cladding have also been performed abroad, where influence factors and formulas for the connection strength of stone cladding have been determined through experimental research and theoretical analysis. However, few studies on the connection strength of stone cladding have been performed in China. A formula for calculating the connection strength of undercut anchors is not available. Therefore, studying the connection strength of undercut anchorage stone cladding is theoretical and practically significant.

A study on the connection strength of undercut anchorage stone cladding is presented in this paper. The failure modes and effects of various factors, such as the stone type, the distance between the hole center and the edge of the plate, the hole depth and the diameter and type of anchor, on the strength of undercut stone cladding are investigated in detail.
2. Experimental Study

2.1. Experimental Design

Two types of stone are used in the experiment, white granite and golden granite. The size of the stone panel is 300 mm×360 mm×30 mm, and three stone panels are tested for every set of experimental conditions.

Table 1. Details of stone panels and test results.

| Panel No.  | Stone type   | Anchor type | Anchor diameter /mm | Hole depth /mm | Distance /mm | Ultimate load /N |
|------------|--------------|-------------|---------------------|----------------|--------------|------------------|
| QH11d12C40| Golden granite| Percussion  | 6                   | 12             | 40           | 1720.75          |
| QH11d15C40| Golden granite| Percussion  | 6                   | 15             | 40           | 2457.67          |
| QH11d15C50| Golden granite| Percussion  | 6                   | 15             | 50           | 3029.46          |
| QH11d15C60| Golden granite| Percussion  | 6                   | 15             | 60           | 3369.73          |
| QH11d15C70| Golden granite| Percussion  | 6                   | 15             | 70           | 3052.90          |
| QB11d12C40| White granite | Percussion  | 6                   | 12             | 40           | 3972.46          |
| QB11d15C40| White granite | Percussion  | 6                   | 15             | 40           | 5059.79          |
| QB11d15C50| White granite | Percussion  | 6                   | 15             | 50           | 5667.91          |
| QB11d15C60| White granite | Percussion  | 6                   | 15             | 60           | 6323.19          |
| QB11d15C70| White granite | Percussion  | 6                   | 15             | 70           | 6175.59          |
| QH13d15C40| Golden granite| Percussion  | 8                   | 15             | 40           | 2893.29          |
| QH13d15C50| Golden granite| Percussion  | 8                   | 15             | 50           | 2926.20          |
| QH13d15C60| Golden granite| Percussion  | 8                   | 15             | 60           | 3491.27          |
| QH13d15C70| Golden granite| Percussion  | 8                   | 15             | 70           | 3044.41          |
| QB13d15C40| White granite | Percussion  | 8                   | 15             | 40           | 4973.19          |
| QB13d15C50| White granite | Percussion  | 8                   | 15             | 50           | 5336.34          |
| QB13d15C60| White granite | Percussion  | 8                   | 15             | 60           | 5703.16          |
| QB13d15C70| White granite | Percussion  | 8                   | 15             | 70           | 5276.22          |
| QB13d21C70| White granite | Percussion  | 8                   | 21             | 70           | 6191.25          |
| XH9.5d15C40| Golden granite| Screw-in    | 8                   | 15             | 40           | 2700.57          |
| XH9.5d15C50| Golden granite| Screw-in    | 8                   | 15             | 50           | 2925.55          |
| XH9.5d15C60| Golden granite| Screw-in    | 8                   | 15             | 60           | 2947.73          |
| XH9.5d15C70| Golden granite| Screw-in    | 8                   | 15             | 70           | 2819.59          |

For the label Q(X)H(B)11d15C50, the first letter indicates the type of anchor, where Q and X denote percussion and screw-in anchors, respectively; the second letter represents the stone type, where H and B represent golden and white granite, respectively; the first number represents the diameter of the opening hole, where 11 represents an opening diameter of 11 mm; the third letter represents the anchoring depth, where the following numbers represent the values in mms, i.e., d15 represents an anchor the depth of 15 mm; the fourth letter represents the distance from the center of the hole to the plate edge, and the following number represents the value in mm. C50 indicates that the distance from the center of the hole to the edge of the plate is 50 mm.

b The given values are referenced to the distance between the hole center and the plate edge.

c The given values correspond to the average load for three stone panels.

Two types of undercut anchors are used: a percussion anchor and a screw-in anchor. Percussion anchor with the diameters of 6 mm and 8 mm are used, and the diameter of the screw-in anchor is 8...
mm. Hole depths of 12 mm and 15 mm are used for the 6-mm diameter percussion anchor, whereas the anchorage depths for the 8-mm diameter percussion anchor is 15 mm and 21 mm, and the anchorage depth of the 8-mm screw-in anchor is 15 mm. Four distances between the center of the hole and the edge of the plate are investigated: 40 mm, 50 mm, 60 mm and 70 mm. The specific dimensions of the stone panels are shown in table 1.

2.2. Material Properties
Based on the prevailing standard [12], the measured bending strength and compressive strength of golden granite are 8.41 MPa and 106.72 MPa, respectively, and the corresponding values for white granite are 13.13 MPa and 167.25 MPa, respectively.

3. Loading Scheme
The failure of the stone panels is tested using a 100-kN universal tensile testing machine. Before the test, a panel is placed in distilled water at 20±2 °C, soaked for 48 h and moved out from the water, after which a towel is used to wipe off surface moisture off the sample. The stone panel is installed on the platform with a designed H-steel plate. The test device is connected to the testing machine through an anchor connection with a hole, and the panel is continuously and smoothly loaded until failure. At the time of loading, the loading rod is placed in the center of the axis of the anchor rod, and the loading velocity is 0.2 mm/min. The loading device is shown in figure 1.

During the experiment, the failure process and failure mode of the stone are observed, and the bearing capacity and displacement of the anchor and the strain distribution of the stone near the undercut anchor are measured.

4. Test Results and Analysis

4.1. Destruction Process
There is no clear sign of damage to the test panels during the loading process. When the force reaches the limit load, cracks around the anchor appear and rapidly extend until the anchor is pulled out. The form of the damage is shown in figure 2.

Similar loading and destruction processes are observed for the screw-in and percussion anchors. The stone and the anchor are pulled out together, and the damage modes are all cone-shaped.

4.2. Analysis of Test Results

4.2.1. Effect of Anchoring Depth. The effect of different anchoring depths on the connection strength is shown in figures 3 and 4.

Figures 3 and 4 show that the anchoring depth has an extremely significant effect on the anchor connection strength. Increasing the anchoring depth the 6-mm-diameter undercut anchor from 12 mm
to 15 mm results in a 27.3% increase in the connection strength. Increasing the anchoring depth the 8-mm-diameter undercut anchor from 15 mm to 21 mm results in a 44% increase in the connection strength. White granite has higher connection strength than golden granite under the same working conditions. The ultimate strength of white granite is 105.88% higher than that of golden granite for a 6-mm undercut anchor with a 15-mm anchoring depth.

![Figure 3](image1.png) **Figure 3.** Effect of anchoring depth on ultimate strength of golden granite.

![Figure 4](image2.png) **Figure 4.** Effect of anchoring depth on ultimate strength of white granite.

4.2.2. **Effect of Distance from Hole Center to Plate Edge.** Figures 5 and 6 show the effect of the distance between the center of different holes and the edge of the plate on the connection strength for the same opening depth.

![Figure 5](image3.png) **Figure 5.** Ultimate load versus the distance of hole center from plate edge for golden granite.

![Figure 6](image4.png) **Figure 6.** Ultimate load versus the distance of hole center from plate edge for white granite.

The data in figures 5 and 6 show that the distance from the center of the hole to the edge of the plate also affects the connection strength of stone cladding. Increasing the distance from the center of the hole to the edge of the plate from 40 mm to 60 mm results in an increase in the connection strength with aforementioned distance. However, the connection strength decreases when the distance from the hole center is 70 mm from the plate edge compared to when the hole center is 60 mm from the plate edge. The data show that the aforementioned increase value and decrease value in the connection strength are 13.05% and 11.3%, respectively. The test results indicate that the distance between the hole center and the edge of the plate affect the connection strength when the distance is less than 60 mm. There are two reasons for the slight decrease in the connection strength upon increasing the distance between the hole center and the edge of the plate from 60 mm to 70 mm: 1) heterogeneities of the stone produce discreteness in the test results and 2) errors introduced by panel processing. An analysis of the failure of the stone panel shows a shallower anchoring depth for the panel in which the hole center is 70 mm from the edge of the plate compared to the other stone panels.
4.2.3. Effect of Undercut Anchor Diameter. The data in figures 5 and 6 show that for golden granite, the connection strength for an 8-mm anchor diameter is slightly higher (within 5%) than for a 6-mm anchor diameter under the same working conditions. For white granite, the connection strength is higher (within 16%) for a 6-mm anchor diameter than for an 8-mm anchor diameter. Therefore, the influence of the anchor diameter on the connection strength depends on the type of stone used.

4.2.4. Effect of Anchor Type on Connection Strength. The effect of the anchor type on the connection strength is shown in figure 7. There is no large difference the ultimate loads of the percussion and screw-in anchor. Similar results for the ultimate load are obtained for different distances between the center of the hole and the plate edge, that is, the connection strength of the percussion anchor is approximately 10% higher than that of the screw-in anchor.

![Figure 7. Comparison of ultimate load of percussion and screw-in anchors.](image1)

![Figure 8. Load-strain diagram for different hole-to-edge distances.](image2)

4.2.5. Strain Analysis. Figure 8 is a load-strain diagram of golden granite stone and a 6-mm anchor diameter for a fixed drilling depth. The figure shows that when the distance from the hole center to the plate edge changes from 40 mm to 60 mm, the ultimate strain under peak load gradually increases; however, the ultimate strain decreases when the hole center is 70 mm from the plate edge compared to that when the hole is 60 mm from the edge. The change in the connection strength of the anchor is consistent with the results for the ultimate strain.

5. Conclusion
A total of 72 stone panels were tested to investigate the connection strength of undercut anchorage stone cladding. The main conclusions drawn from experimental results are given below.

(1) The main factors affecting the strength of the anchor connection are the anchoring depth and the stone type. For a 6-mm anchor diameter, increasing the anchoring depth from 12 mm to 15 mm results in a 27.3% increase in the anchor connection strength. For an 8-mm anchor diameter, increasing the anchoring depth from 15 mm to 21 mm results in a 44% increase in the anchor connection strength.

(2) The influence of the anchor diameter on the connection strength of the stone cladding is related to the type of stone, where different stone types exhibit different influence law.

(3) White granite stone has a higher strength and therefore a higher connection strength than gold granite stone, under the same conditions.

(4) The distance from the center of the hole to the plate edge affects the connection strength. Increasing this distance from 40 mm to 60 mm increases the connection strength, whereas increasing the distance to 60 mm has little effect on the strength.

(5) The same variation rule is observed for the connection strength of screw-in and percussion anchors under the same working conditions. The connection strength of the percussion undercut anchor is approximately 10% higher than that of the screw-in anchor.
Acknowledgments
The authors would like to thank the project participants for their cooperation. This research was jointly funded by the National Key Research and Development Program of China, grant number 2017YFC0806100, and the Fundamental Research Funds for Beijing Universities, grant number X19019.

References
[1] Zeng B 2016 Progress on application research of dry-fixing stone cladding system Adhesion 37 53-6.
[2] Li J and Liang Y 2015 Test and comparison of Hanging Method for stone cladding Build. Constr. 27 36-8.
[3] Li F 2011 Hanging-Method of Undercut Anchorage Stone-Walls Law Advantage Xi’an: Chang’an University 16.
[4] Liang Q 2014 Analysis of the advantages and disadvantages of several dry hanging accessories for stone dry hanging curtain walls Modern Decoration (Theory) 4 37.
[5] Hou Q C 2012 Dry hanging system of stone cladding-application and thinking of anchor Stone 3 1-4.
[6] Zhao X A 2006 Design of stone cladding connected by anchor Architect. Tec. 9 648-52.
[7] Zhao J 2014 Research the effect of installation quality on mounting strength of dry hanging stone anchor in large area curtain wall project Guangdong Architect. Civil Eng. 21 39-41.
[8] Zhang Q 2003 The back-cut anchor point connects the granite curtain wall. Stone 1 9-14.
[9] Camposinhos R S 2013 Undercut anchorage in dimension stone cladding Constr. Mater. 166 158-74.
[10] Lammert B T and Hoigard K R 2007 Material strength considerations in dimension stone anchorage design J. ASTM Int. 4 101102-20.
[11] Conroy K and Hoigard K R 2007 Stiffness considerations in dimension stone anchorage design J. ASTM Int. 4 101062-73.
[12] GB/T 9966.2 2001 Test Methods for Natural Facing Stones Part 2: Dry and Water-Saturated Bending Strength Test Methods Beijing: China Standard Press.