Experimental Investigations on the Connection Strength of Kerf Anchorage Stone Panels

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Abstract. Seventy-two stone panels were tested to investigate the failure mode and connection strength of the kerf anchorage stone cladding panel. The following factors were considered in this study: the distance between the kerf and the edge of the stone panel, the stone type, the kerf depth and the insertion depth of the connector. The experimental results show that the connection strength of white granite is twice as high as that of golden granite under the same conditions. Increasing the insertion depth of the connector increases the connection strength of the stone panel. The connection strength increases when the distance between the kerf and the edge of the panel is increased from 70 mm to 90 mm, and the connection strength for a 20-mm kerf depth is higher than that for a 30-mm kerf depth under the same conditions. There is still a certain error between the test results and the calculation results of current standard.

1. Introduction
The kerf anchorage stone curtain wall is an evolution of the steel dowel anchorage stone curtain wall. The kerf anchorage stone curtain wall has the advantages of convenient installation and good connection strength compared with the steel dowel anchorage stone curtain wall, and it is widely used in practical projects [1]. Lammert and Hoigard [2] tested the connection strength of back anchors, and edge kerfs with strap and split-tail anchors, and finite element computer analyses of the stress states of stone panels were presented. Conroy and Hoigard [3] investigated the interaction of relative stiffness on loading and stress distributions of the dimension stone cladding. Camposinhos [4] proposed partial factors of the dimension stone cladding safety depending on the types and coefficients of variation of the distributions of resistances. Hess and Rangaswamy [5] illustrated a few problems associated with curtain walls, especially in rehabilitation projects. Camposinhos [6] tested two limestone and various marble specimens to study on kerf anchorage behaviour, and stress concentration factors were proposed to account for the kerf geometry and the specimens’ specific properties.

Studied on kerf anchorage stone cladding have been performed at home and 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 effect of the kerf size and location on connection strength of stone panel have been performed. Therefore, studying the connection strength of kerf anchorage stone cladding is theoretically and practically significant.

This paper presents a study that investigates the connection strength of kerf anchorage stone cladding. The failure modes and effects of various factors, such as the distance between the kerf and the edge of the panel, the stone type, the kerf depth and the insertion depth of the connector, on the strength of kerf stone cladding are investigated in detail.
2. Experience Programme

2.1. Experimental Design
The length of the stone panel is 400 mm. The kerf length and the distance between the kerf and the edge of the panel determine the width of the stone panel. The insertion depth of the connector is 10 mm, 12 mm and 15 mm, respectively. The kerf is arc-shaped. The length and width of the kerf is 120 mm and 7 mm, respectively, and the kerf depth is 20 mm or 30 mm. The distance between the kerf and the edge of the panel is 70 mm, 80 mm, 90 mm and 100 mm, respectively. Two types of stone are used in the experiment, white granite and golden granite. Three stone panels are tested for every set of experimental conditions. The specific test parameters are shown in Table 1.

Table 1. Details of stone panels and test results.

| Panel No. a | Stone type        | Size (mm)       | Distance b (mm) | Insertion depth (mm) | Kerf depth (mm) | Ultimate load c (N) |
|-------------|-------------------|-----------------|-----------------|----------------------|-----------------|---------------------|
| HC150D70d10 | Golden granite    | 260x400x25      | 70              | 10                   | 30              | 807.67              |
| HC150D80d10 | Golden granite    | 280x400x25      | 80              | 10                   | 30              | 816.84              |
| HC150D90d10 | Golden granite    | 300x400x25      | 90              | 10                   | 30              | 930.30              |
| HC150D100d10| Golden granite    | 320x400x25      | 100             | 10                   | 30              | 858.13              |
| HC150D100d12| Golden granite    | 320x400x25      | 100             | 12                   | 30              | 908.68              |
| HC150D100d15| Golden granite    | 320x400x25      | 100             | 15                   | 30              | 943.44              |
| HC190D100d10| Golden granite    | 320x400x25      | 100             | 10                   | 20              | 964.53              |
| HC190D100d12| Golden granite    | 320x400x25      | 100             | 12                   | 20              | 1118.04             |
| HC190D100d15| Golden granite    | 320x400x25      | 100             | 15                   | 20              | 1398.84             |
| BC150D70d10 | White granite     | 260x400x25      | 70              | 10                   | 30              | 1718.06             |
| BC150D80d10 | White granite     | 280x400x25      | 80              | 10                   | 30              | 1762.11             |
| BC150D90d10 | White granite     | 300x400x25      | 90              | 10                   | 30              | 2123.41             |
| BC150D100d10| White granite     | 320x400x25      | 100             | 10                   | 30              | 1534.18             |
| BC150D100d12| White granite     | 320x400x25      | 100             | 12                   | 30              | 1872.50             |
| BC150D100d15| White granite     | 320x400x25      | 100             | 15                   | 30              | 2080.08             |
| BC190D100d10| White granite     | 320x400x25      | 100             | 10                   | 20              | 2284.62             |
| BC190D100d12| White granite     | 320x400x25      | 100             | 12                   | 20              | 2490.14             |
| BC190D100d15| White granite     | 320x400x25      | 100             | 15                   | 20              | 2526.46             |

For the label H(B)C150D70d10, the first letter indicates the type of stone, where H and B represent golden granite and white granite, respectively. The second letter represents the diameter of the grinding wheel, where the following numbers represent the value in mm, i.e., C150 represents a diameter of the grinding wheel is 150 mm; the third letter represents the distance between the kerf and the edge of the panel, where the following numbers represent the value in mm, i.e., D70 indicates the distance from the kerf to the edge of the panel is 70 mm; the fourth letter represents the insertion depth of the pendant, where the following numbers represent the value in mm, i.e., d10 represents the insertion depth of the pendant is 10 mm.

The given values are referenced the distance between the kerf and the edge of the panel.

The given values are the average load for three stone panels.

2.2. Material Properties
Based on the prevailing standard [7], 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 Plan
During the experiment, the failure process, failure mode, ultimate load and ultimate displacement of the stone panel are observed, and strain and displacement are collected by DHDAS3820 dynamic
signal collection and analysis system.

The failure of the stone panels is tested using a 100-kN universal tensile testing machine, and the loading velocity is 0.2 mm/min. The loading device is shown in figure 1.

4. Test Results and Analysis

4.1. Failure Mode

The loading process is an elastic stage. When the specimen is damaged, the force drops sharply, and a sound will be heard. The stone slab at the kerf position is peeled off, and the overall shape is arc-shaped. The failure mode of the specimen is shown in figure 2.

4.2. Test Results

4.2.1. Effect of Distance from Kerf to Edge of the Panel. The effect of the distance between the kerf and the edge of the panel on the connection strength is shown in figure 3.

![Figure 1. Test loading device.](image)

![Figure 2. Failure mode.](image)

![Figure 3. Ultimate load versus the distance of kerf from panel edge.](image)

![Figure 4. Effect of insertion depths of connector on ultimate load.](image)
The data in figure 3 shows that in the distance from the kerf to the edge of the panel affects the connection strength of stone panel. Increasing the distance from the kerf to the edge of the panel from 70 mm to 90 mm results in an increase in the connection strength. However, the connection strength decreases when the distance from the kerf to the edge of the panel is 100 mm compared to when the distance is 90 mm. The data show that the aforementioned increase and decrease in the connection strength of golden granite panel are 14.1% and 7.7%, respectively, compared to the connection strength when the distance from the kerf to the edge of the panel is 70 mm. The increase and decrease in the connection strength of white granite panel are 23.1% and 27.7%, respectively, compared to the connection strength when the distance from the kerf to the edge of the panel is 70 mm. There are two reasons for the decrease in the connection strength upon increasing the distance between the kerf and the edge of the panel from 90 mm to 100 mm: 1) heterogeneities in the stone produce discreteness in the results and 2) errors are introduced by panel processing. An analysis of the failure of the stone panel shows a thicker slab in which the distance from the kerf to the edge of the panel is 100 mm compared to the other stone panels. Increasing the distance between the kerf and the stone panel to 100 mm has little effect on the connection strength through finite element analysis [8].

4.2.2. Insertion Depth. The effect of different insertion depth of connector on the connection strength of the stone panel is shown in figure 4. Figure 4 shows that the insertion depth of the connector has a significant effect on the connection strength of the kerf anchorage stone panel. Increasing the insertion depth of the connector from 10 mm to 15 mm results in a 9.6% increase in the connection strength of golden granite panel, and results in a 33.2% increase in the connection strength of white granite panel.

4.2.3. Stone Type. The influence of the stone type on the connection strength is shown in figures 3 and 4. Figures 3 and 4 show that the connection strength of white granite is twice as high as that of golden granite under the same insertion depth of the connector.

4.2.4. Kerf Depth. Figures 5 and 6 show the effect of kerf depth on the connection strength of golden granite and white granite.

The data in figures 5 and 6 show that the insertion depth of kerf has an extremely significant effect on the connection strength. Increasing the kerf depth results in decrease in the connection strength of golden granite and white granite under the same insertion depth of connector. The ultimate strength of golden granite panel with a 20-mm kerf depth is higher 48.2% than that of a 30-mm kerf depth when the insertion depth of connector is 15 mm. The ultimate strength of white granite panel with a 20-mm
The kerf depth is higher 21.4% than that of a 30-mm kerf depth when the insertion depth of connector is 15 mm. Increasing the insertion depth of connector from 10 mm to 15 mm results in a gradual increase in the connection strength of golden granite for a 20-mm kerf depth and a 30-mm kerf depth. However, the rate of increase is gradual decrease in in the connection strength of white granite for a 20-mm kerf depth and a 30-mm kerf depth.

5. Calculation of Connection Strength

According to the shear stress formula and bending stress formula of the kerf anchorage stone curtain wall given in the specification [9], the maximum principal tensile stress formula is multiplied by the force area to calculate the ultimate load. Camposinhos [6] also presented the formula to calculate the connection strength of kerf anchorage stone curtain wall panels. The comparison between the test values, calculated values and error analysis of the two formulas are shown in tables 2 and 3.

Table 2. Comparison of test values and calculated values.

| Panel No.  | Ultimate load test value \( F \) (N) | Standard JGJ133 calculated value \( F_1 \) (N) | Camposinhos formula calculated value \( F_2 \) (N) | \( F_1/F \) | \( F_2/F \) |
|-----------|-----------------------------------|---------------------------------|---------------------------------|--------|--------|
| HC150D70d10 | 807.67                            | 965.35                          | 624.39                          | 1.20   | 0.77   |
| HC150D80d10 | 816.84                            | 1001.78                         | 673.44                          | 1.23   | 0.82   |
| HC150D90d10 | 930.30                            | 1049.17                         | 690.67                          | 1.13   | 0.74   |
| HC150D100d10| 858.13                            | 1036.40                         | 670.58                          | 1.21   | 0.78   |
| HC150D100d12| 908.68                            | 1195.98                         | 732.56                          | 1.32   | 0.82   |
| HC150D100d15| 964.53                            | 1388.36                         | 786.25                          | 1.44   | 0.84   |
| HC190D100d10| 1398.84                           | 1074.37                         | 823.26                          | 0.77   | 0.78   |
| HC190D100d12| 943.44                            | 1202.67                         | 945.23                          | 1.27   | 1.27   |
| HC190D100d15| 1118.04                           | 1350.48                         | 1123.56                         | 1.21   | 1.64   |
| BC150D70d10 | 1718.06                           | 977.46                          | 1342.96                         | 0.57   | 0.78   |
| BC150D80d10 | 1762.11                           | 1008.70                         | 1353.03                         | 0.57   | 0.77   |
| BC150D90d10 | 2123.41                           | 1040.77                         | 1378.36                         | 0.49   | 0.65   |
| BC150D100d10| 1534.18                           | 1075.72                         | 1078.30                         | 0.70   | 0.70   |
| BC150D100d12| 1872.50                           | 1179.27                         | 1310.23                         | 0.63   | 0.70   |
| BC150D100d15| 2080.08                           | 1352.42                         | 1489.20                         | 0.65   | 0.72   |
| BC190D100d10| 2284.62                           | 1071.51                         | 1598.20                         | 0.47   | 0.70   |
| BC190D100d12| 2490.14                           | 1184.10                         | 1700.23                         | 0.48   | 0.68   |
| BC190D100d15| 2526.46                           | 1329.64                         | 1800.23                         | 0.53   | 0.71   |

Table 3. Error analysis.

| Formula type          | \( F_i/F \) average | Standard deviation | Coefficient of Variation (%) | Mean absolute error (%) |
|-----------------------|----------------------|--------------------|------------------------------|------------------------|
| Standard JGJ133 formula| 0.88                 | 0.34               | 38.94                        | 32.81                  |
| Camposinhos formula   | 0.83                 | 0.24               | 28.58                        | 14.10                  |

From the data in tables 2 and 3, there is still a certain error between the test results and the calculation results of the two formulas. The result of Camposinhos calculation formula is better than the calculation result of Standard formula. The effect of the kerf size and location should be considered to further study the formula of the connection strength of the kerf anchorage stone cladding panel.
6. Conclusion
The major findings form the results of the experimental are as follows:
   (1) The connection strength of the stone slab increases with the increase with the distance of the
   kerf to the edge of the panel is changing from 70 mm to 90 mm.
   (2) The connection strength of stone curtain wall panel increases as the insertion depth of the
   pendant increases.
   (3) The connection strength for a 20-mm kerf depth is higher than that for a 30-mm kerf depth
   under the same conditions.
   (4) The connection strength of white granite will be twice as high as that of golden granite, and the
   stone type has a greater effect on the connection strength.

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