Safety Evaluation of Dry-fasten Stone Curtain Wall Structure of Existing Building

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Abstract. Stone curtain walls are more and more widely used due to their good decorative effect and hard texture. However, with the increase of their service life, many safety issues have gradually appeared and caused widespread concern from all walks of life. The dry-fasten stone curtain wall of an office building has been used for more than 12 years. Through on-site inspection and testing of the verticality of the stone curtain wall, the connection node between the stone curtain wall and the main structure, the stone curtain wall framework system, the curtain wall stone panel and weather resisting silicone sealant, some suggestions for transformation are proposed for the existed problems.

1. Overview
With the rapid development of China's reform and opening, the building curtain wall of our country has grown from nothing to something, and its development has gradually expanded. It has experienced more than 30 years of development[1]. Building curtain wall technology is constantly innovating and progressing, and the project scale has entered the forefront of the world. As a decoration on the exterior of a building, the curtain wall has been widely used[2]. Building curtain walls mainly include metal, man-made panels, glass and stone curtain walls. Among them, stone curtain walls are favored by design and construction units because of their good decorative effect and hard texture. Common structures of stone curtain walls include dry-fasten stone curtain walls and wet-attached stone curtain walls. The projects using dry-fasten stone curtain walls in China have ranked first in the world in terms of quantity and application area[3]. The dry-fasten stone curtain wall has significantly improved the overall safety and durability of the curtain wall structure compared to the wet-attached stone curtain wall[4-6]. It uses notch-type stone suspensions to connect the keel and hang on the external wall. With the influence of gravity and long-term outdoor environment, the stone may fall off, and the safety issue has received widespread attention[7-8].

This article combines with engineering examples, through conducting on-site inspection and testing of the verticality of the stone curtain wall of the dry-fasten stone curtain wall structure of an office building, the connection node between the stone curtain wall and the main structure, the stone curtain wall framework system, the curtain wall stone panel and the weather resisting silicone sealant, we evaluates the safety of the dry-fasten stone curtain wall structure of the external wall according to the inspection and testing results.

2. Project Overview
An office building is an eight-story (five-story skirt building) reinforced concrete frame structure house with a construction area of approximately 80,755 square meters. The building's exterior wall and type are all dry-fasten stone curtain walls. It was completed and delivered in August 2007. The
curtain wall adopts an enclosing wall structure with pillars hanging on the outside of the side beams of the building. The total area of the stone curtain wall is about 40,000 square meters. The calculated maximum elevation is 41.70m, the basic wind pressure is 0.3kN/㎡, the designed maximum temperature difference is 80 o C, and the seismic fortification intensity is 7(0.1g), the design service life is 25 years.

3. On-site Inspection, Detection and Preliminary Identification

3.1. Stone Curtain Wall Verticality Detection

Sampling tests were performed on site for the verticality of the stone curtain wall of the house (including construction deviation). The summary of the test results is shown in Table 1. The test points were selected based on the comprehensive consideration of the shape of the house and deformation joints. The sampling tests result shows that the verticality (containing the construction deviation) of the 48 measured points of the house are less than the installation allowable deviation of the "Technical Specifications for Metal and Stone Curtain Wall Engineering" [9].

Table 1. Summary of test results of verticality (containing construction deviation) of stone curtain wall

| Test Point | Horizontal Distance (m) | Vertical Distance (m) | Deviation (mm) | Test Point | Horizontal Distance (m) | Vertical Distance (m) | Deviation (mm) | Test Point | Horizontal Distance (m) | Vertical Distance (m) | Deviation (mm) |
|------------|-------------------------|-----------------------|----------------|------------|-------------------------|-----------------------|----------------|------------|-------------------------|-----------------------|----------------|
| 1          | 12.743                  | 1.526                 | 0              | 16.215     | 0.223                   | 10                    | 3              | 12.896     | 0.171                   | -4                     |
| 2          | 12.743                  | 16.081                | 2              | 16.225     | 18.127                  | 10                    | 3              | 12.892     | 17.485                  |
| 3          | 21.854                  | 0.565                 | 9              | 42.389     | 10.419                  | 5                     | 6              | 42.093     | 10.052                  |
| 4          | 21.863                  | 19.658                | 12             | 42.394     | 26.996                  | 4                     | 9              | 38.668     | 0.946                   |
| 5          | 36.367                  | 10.117                | 6              | 38.975     | 18.294                  | 4                     | 9              | 38.656     | 32.942                  |
| 6          | 36.373                  | 32.193                | 11             | 42.447     | 10.218                  | 3                     | 12             | 42.493     | 10.616                  |
| 7          | 66.064                  | 1.138                 | -5             | 42.450     | 28.969                  | -9                    |                | 42.484     | 29.125                  |
| 8          | 66.059                  | 31.780                | -10            | 38.979     | 31.445                  | -12                   |                | 38.656     | 32.942                  |
| 9          | 13.391                  | 0.164                 | 3              | 9.323      | 0.187                   | 0                     | 15             | 9.236      | 0.410                   |
| 10         | 13.394                  | 18.833                | 14             | 9.323      | 19.029                  | 0                     | 15             | 9.236      | 18.058                  |
| 11         | 7.355                   | 0.386                 | 17             | 8.673      | 0.386                   | -10                   | 18             | 7.414      | 0.317                   |
| 12         | 7.357                   | 11.884                | 2              | 8.663      | 19.555                  | -6                    |                | 7.408      | 15.397                  |
| 13         | 7.007                   | 0.124                 | 20             | 4.203      | 0.171                   | 6                     | 21             | 28.334     | 1.363                   |
| 14         | 7.010                   | 10.161                | 3              | 4.209      | 12.106                  | -10                   |                | 28.324     | 21.054                  |
| 15         | 28.257                  | 0.621                 | 23             | 13.756     | 0.406                   | -9                    | 24             | 25.934     | 0.662                   |
| 16         | 28.248                  | 21.067                | -9             | 13.747     | 19.201                  | -9                    | 24             | 25.941     | 20.415                  |
| 17         | 24.969                  | 0.605                 | 26             | 27.975     | 0.619                   | -5                    | 27             | 26.580     | 0.653                   |
| 18         | 24.972                  | 20.469                | -5             | 27.970     | 20.972                  | 9                     |                | 26.589     | 20.411                  |
| 19         | 24.093                  | 0.598                 | 29             | 17.118     | 0.526                   | 7                     | 30             | 13.378     | 6.898                   |
| 20         | 24.090                  | 10.634                | -3             | 17.125     | 19.233                  | 7                     |                | 13.373     | 19.288                  |
| 21         | 53.753                  | 2.472                 | 10             | 37.598     | 0.905                   | -10                   | 33             | 31.157     | 0.789                   |
| 22         | 53.763                  | 29.487                | 32             | 37.588     | 28.951                  | 7                     |                | 31.164     | 31.997                  |
The lateral displacement terms in the table include construction deviation; the vertical distance is the vertical distance of the test position to the instrument; the horizontal distance is the horizontal distance of the test position to the instrument; the allowable deviation of the verticality of the stone wall surface is ≤10mm (the height of the curtain wall H is ≤30m), The allowable deviation of wall verticality is ≤ 15mm (height of curtain wall 30m <H ≤ 60m).

3.2. The Connection Node between the Stone Curtain Wall and the Main Structure

The endoscope was used on site to check through drilling or existing air-conditioning tube holes, and it was found that:

(1) The dry-fasten stone curtain wall and the reinforced concrete beam are bolted to the steel plate. The steel plate and the connector (steel corner code) are welded to the curtain wall column with bolts. The nuts of the connecting bolts in some parts are missing (see Figure 1); Bolt deformation, slipping, or loosening were not found at the joint between the stone curtain wall and the reinforced concrete beam.

(2) The floor of the bottom of the stone curtain wall is not hardening treated with concrete, and it is wet and poorly drained. The bottom of the curtain wall of the terrace on the second floor and above is partially wet and stagnant, resulting in some column legs or the steel corner codes, bolts and beams at the joints of the beams of the first column are corroded, with obvious corrosion at some locations (see Figure 2).

3.3. Stone Curtain Wall Framework System

3.3.1. Columns and Beams. After sampling inspection on site, the steel frames are connected by angle steel, bolted or welded, the embedded steel plate and the main structure are back-cut bolted; the curtain wall’s main keel column adopts 8 # channel steel (section size is 80×43×5mm, for 4.2m layer
height), 10 # channel steel (section size is 100×48×5.3mm, for 4.5m layer height), and 6.3 # channel steel (section size is 63×40×4.8mm, for small span); the horizontal keel adopts L50×5 angle steel.

At the same time, the sampling inspection of the main force-bearing members within the height of about 2m on the outdoor floor and the terrace above the second floor shows that there are obvious corrosion (see Figure 3) on parts of the bottom (within about 1.5m height range, some of the components are located at the evaluation of the first level of the window sill) of main force-bearing members of the stone curtain wall (including the connection between the column and the beam), and the remaining parts have good appearance without obvious defects such as deformation, cracks, and marks, and the surface anti-corrosive coating is not damaged or slightly rusted (see Figure 4).

3.3.2. Buckle Pendant. The dry-fasten stone curtain wall adopts the short-groove support of the side fixing method, and the stone panel is connected to the beam with a buckle pendant. At the same time, the buckle pendant is made of 5mm stainless steel and is bonded with the stone by marble glue. Except for individual buckle pendants, the appearance of others is good and the surface anti-corrosive coating is not damaged.

3.4. Curtain Wall Stone Panel
The curtain wall stone design uses 30mm thick granite slabs, and the maximum separation of granite slabs is 600 × 1200 (mm). After sampling inspection on site, the panels used in the sampling inspection are granite panels with a thickness of 29mm ~ 30mm; some bottom curtain wall stone panels crack, and some curtain wall stone panels crack at the slot (see Figure 5); Part of the inside of the slot of the bottom (the first row above the outdoor floor) curtain wall panel is flat, and no slot is formed, the cement is used for caulking, and the panel protrudes outwards and is misaligned. The large surface of the stone curtain wall is flat without obvious deformation and displacement.
3.5. Weather Resisting Silicone Sealant
The width of the weather resisting silicone sealant seam of the stone curtain wall panel is 8mm; the glue seam is horizontal and vertical, the seam width is uniform, and the surface is smooth. Except for some deformed seams and cracks between the curtain wall panels at the window sill, and some curtain wall panels at windowsills are loose, the rest parts have no obvious cracking, aging, peeling, etc.

4. Transformation Recommendations
There are hidden safety dangers in the stone curtain wall structure of the house. The stone curtain wall should be maintained. According to the evaluation opinions, the following transformation suggestions are proposed: closed repair of the cracked seam of the stone curtain wall; derusting and anti-rust treatment of the rusted steel skeleton, and strengthen the drainage at the bottom to maintain a dry environment; replace the components with large cross-section losses from rusting; supplementing the severely rusted back-cut bolts; supplementing for the missing nuts; replacing the damaged part of the stone panel or treated by other methods to enhance the integrity of the panel; the loose parts of the stone should receive reliable treatment; and the stone that failed to meet the requirements should also receive reliable treatment.

5. Conclusion
According to the engineering case, conducting safety evaluation of the dry-fasten stone curtain wall, and the corresponding identification and analysis methods can provide reference for similar projects. By analyzing the case of dry-fasten stone curtain wall, the following main conclusions can be obtained:

(1) Take full consideration of environmental impacts such as temperature, humidity, and moisture during design and construction, and consider the effects of temperature stress during the calculation of the force member. At the same time, take anti-corrosion measures on the material surface to avoid being affected by water and moisture.

(2) Adopt hardware accessories bolts which are made of stainless steel, and galvanize the steel corners and connectors to prevent corrosion.

(3) The rusted parts of the main stress members and their connectors (pillars, beams, connecting bolts, buckle pendants, etc.) concentrate on the outdoor floor and windowsills.

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