Experimental Study on Cold Bending and Temperature Change of Toughened Glass

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Abstract. In order to study the temperature strain of the insulating tempered glass under certain cold bending test, cold bending test and temperature test were carried out on the glass plate. Taking the self-made cold-formed steel frame as the tool and the hollow laminated tempered glass as the object, the cold bending test of the glass was carried out. The results show that the stress of each measuring point increases linearly with the increase of cold bending displacement, and the maximum principal stress appears at the end of the loader near the loading point of the outer sheet glass. The temperature changes test of the glass shows that the stress of each measuring point is linear with the increase in temperature difference. The results show that the maximum principal stress appears near the constrained angle steel on the displacement side of the upper edge of the outer sheet glass; the stress changes greatly during the short-term cooling test, and the tensile and compressive stresses transform each other. The internal stress produced by cold bending is coupled with the maximum principal stress produced by temperature load, and the maximum principal stress appears at the lower edge constraint of the loading displacement side.

Keywords. Toughened glass; cold bending test; temperature test; principal stress.

1. Introduction

Curtain wall glass is widely used in modern architecture. There are more and more arc-shaped glass curtain walls. The traditional forming methods are plane fitting method and hot bending method. Hot bending is a common method. Cold bending forming method is a new method, which uses curved glass curtain wall glass to have the advantages of elastic bending. When installing, the curved surface frame is installed first, and then the flat insulating glass is forced to bend in place reasonably to form the construction method of the designed curved surface modeling. Compared with the cold bending molding method, it has the advantages of shorter time and cost, safety, low cost, and better simulation of the shape. In recent years, it has been widely used, such as Nanning Wuwei International Airport \cite{1}, high-rise office building \cite{2}.

The mechanical behavior of glass after cold bending is an important issue related to safety, which has been widely concerned in the world. In this experiment, the mechanical properties of tempered glass filled with insulating glue after cold bending and affected by temperature are studied. Hollow laminated toughened glass is composed of traditional PVB or new sandwich technology, butyl rubber, silicone adhesive, aluminum spacer and tempered glass. Among them, the properties of traditional PVB \cite{3}, butyl rubber and silicone rubber are greatly affected by temperature, which belong to temperature dependent materials, while the properties of aluminum spacer and tempered glass are less

\begin{thebibliography}{9}
\bibitem{1} Nanning Wuwei International Airport
\bibitem{2} High-rise office building
\bibitem{3} Traditional PVB
\end{thebibliography}
affected by temperature. Therefore, domestic and foreign scholars have carried out corresponding research. Vericurt [4] analyzed the residual stress produced in the cold bending process of laminated glass according to the principle of composite structure and combined with mechanical method. Belis [5] of Ghent University, Belgium, and others conducted single curvature cold bending experiments on laminated glass with different properties of PVB glue, and combined with numerical simulation images, analyzed the position of maximum principal stress and crack initiation during cold bending. Jin and Xu [6, 7] respectively carried out forward and reverse load tests on cold-formed laminated glass, and combined with ABAQUS model, analyzed the influence of glass thickness, PVB adhesive thickness and cold bending twist rate on the cold bending performance of laminated glass; Jiang [8] carried out unidirectional cold bending test on insulating glass, and verified the feasibility of ABAQUS model. Finally, the model was used to deduce the effect of unidirectional cold-formed insulating glass on the cold bending performance of laminated glass. The formula of maximum principal stress and maximum deflection under wind load. Wang et al. [9] simulated the temperature stress distribution of glass under fire and predicted the cracking under thermal load; Zhou [10] obtained the allowable tensile stress of glass curtain wall under the condition of 0 degree outdoor and 25 degree indoor; and Samieian et al. [11] studied the temperature stress of laminated glass under different thickness of PVB interlayer, and obtained the mechanical properties of laminated glass under temperature after cracks; Jiang [12] gave priority to the analysis of roof glass of Guangzhou south railway station, and obtained the variation law of glass surface stress under the influence of temperature, shields [13] and others studied the stress behavior of insulating glass in indoor fire, and obtained the temperature, stress and crack time of glass. After cold bending, the glass plate will produce internal stress, which will not disappear after the glass is installed in place. The temperature has an impact on the mechanical performance of non cold bending glass, and there will be more problems after cold bending (cold bending stress, etc.), which may lead to different results from non cold bending glass, so special research should be conducted. However, there are few published literatures on the performance of glass after cold bending, and the research on the influence of temperature is even more missing, especially for the research on the cold bending of insulating laminated glass, and there is no specification for cold bending test of glass curtain wall in China. Therefore, it is necessary to solve the theoretical problems of mechanical performance design of glass curtain wall under the action of temperature after cold bending as soon as possible, so as to provide the basis for the specification.

Based on the above reasons, this paper explores the mechanical effects of cold-formed glass and temperature on cold-formed glass, and provides theoretical basis for future design, construction and specification.

2. Test Overview

2.1. Specimen Design

Taking the cold bending displacement and temperature as the influencing factors, a hollow laminated tempered glass specimen was designed. The maximum cold bending displacement of the specimen was 20 mm, and the length and width of the specimen were 1195 mm × 2255 mm. The insulating laminated tempered glass is composed of three pieces of tempered glass, PVB glue, aluminum partition strip, butyl rubber and silicone adhesive. One side of laminated glass is defined as indoor, and one side of insulating glass is outdoor. The glass surface is marked with inner glass a, middle glass B, outer glass C and outer glass D, as shown in figure 1. The glass curtain wall is composed of 8 mm tempered glass, 1.52 mm PVB glue, 8 mm tempered glass, 12 mm air layer and 8 mm tempered glass. The size of the sample is designed as 1:1 and produced by a professional glass manufacturer.
2.2. Experimental Device

The device is designed for cold bending test, including curtain wall steel frame and cold bending displacement forced positioning device. The short side of the curtain wall steel frame is unconstrained, and the long side is constrained by the steel frame; the cold bending displacement forced positioning device includes Q235 steel pipe, steel pipe buckle and screw.

On the basis of the cold bending test, a light angle steel frame, a heat insulation rigid foam board, a heating bulb, a cooling and heating air conditioner, and a water supply and drainage facility are added on the basis of the cold bending test device, as shown in figure 2. Because there are many uncontrollable factors such as solar radiation, temperature, humidity and so on in outdoor field detection, the temperature test simulation room is chosen to carry out the experiment. The indoor space is segmented to ensure the temperature difference of the experiment. The simulation room is made of thermal insulation rigid foam board, and the simulation room is divided into two spaces along the glass plane with the same material, and is defined as the chamber cavity and the outdoor chamber. The simulation room is divided into two chambers [14].

2.3. Arrangement of Test Points

The strain on the glass surface is measured by strain flower. The arrangement of measuring points on A and D sides is the same, and that of B and C planes is the same. The serial number of measuring points is shown in figure 3. During the cold bending test, the dial indicator is installed at the four corners to measure the displacement at the four corners to ensure that the fixed three corners are in the same plane. During the temperature change test, a thermometer is arranged in the outdoor cavity far away from the heat bulb and close to the insulation wall; in the room, the thermometer is arranged far away from the air outlet and away from the air outlet, and a dial indicator is installed at the center of the glass to measure the middle displacement. There are five temperature measuring points on the glass surface, that is, there are five temperature measuring points on the inner and outer glass surface,
as shown in figure 4.

![Figure 3. Arrangement of strain gauge points.](image)

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![Figure 4. Temperature measuring point layout.](image)

Figure 4. Temperature measuring point layout.

2.4. Test Method

The test load is divided into cold bending test load and temperature change test load, and the temperature change test is divided into heating test load and short-term cooling test load. Firstly, the cold bending test is carried out. On the cold bending displacement forced positioning device, the displacement perpendicular to the glass plate surface is loaded at P2 point of the cold bending corner, with a total displacement of 20 mm. The loading system is graded loading, and 20% of the maximum cold bending displacement is defined as the first level loading. The cold bending loading history curve is shown in figure 5. After collecting the stable data, the next level of loading is carried out when the cold bending displacement is 20 mm, after collecting the data, unload the cold bending displacement forced positioning device.

![Figure 5. Curve of cold bending load.](image)

Figure 5. Curve of cold bending load.

On the basis of cold bending test, the temperature of indoor chamber is controlled at 18°C by air conditioner, and the outdoor chamber is heated by heating bulb to realize the loading of temperature load. The data are collected once every 5°C rise of outdoor temperature, and the data of corresponding dial indicator and thermometer are recorded until the maximum power of heating bulb is reached, and the outdoor temperature is 80°C as shown in figure 6.

On the basis of the temperature rise test, the short-term cooling test is carried out, and the initial
state of the short-term cooling test is the final state of the temperature rise test. In the short-term cooling test, the outdoor chamber uses water spraying facilities to directly spray water on the glass surface to realize the temperature load loading until the outdoor temperature does not change, as shown in figure 7. During the test, the drenched water should be discharged in time to avoid the water retention from affecting the temperature of the glass surface twice. As the temperature changes rapidly in a short time, monitoring facilities should be used to record the data of dial indicator and thermometer.

![Figure 6. Panoramic view of glass at temperature load.](image1)

![Figure 7. Short-term cooling test glass panoramic view.](image2)

3. Analysis and Test of Cold Bending

From the beginning of loading to the maximum cold bending displacement of 20 mm, the stress values of corner points in each stage of cold bending are shown in table 1, and the cold bending stress nephogram of each surface when the cold bending displacement is 20 mm is drawn, as shown in figure 8. It can be seen from table 1 that the stress of measuring points increases linearly with the increase of cold bending displacement. The location of the maximum principal stress is different in the four glass plates. When the cold bending displacement reaches 20 mm, it can be seen from figure 8 that the maximum principal stress of the insulating laminated glass appears at the short corner P1 adjacent to the cold bending corner point on the D side of the outer glass. When the displacement is loaded, the P2 corner is directly acted by the loader, increasing the cold bending displacement and increasing the tensile deformation. At P1 corner point, the main stress is the largest due to the large constraint on the external surface of curtain wall steel frame, P1 corner can not be lifted, resulting in tensile deformation.

4. Temperature Change Test Results and Analysis

4.1. Temperature Rise Test Results and Analysis

In the heating test, the temperature difference between the inner and outer glass increases gradually with the increase of the temperature of the outdoor chamber, and the glass deforms to the outdoor cavity. This is because the temperature of the outdoor chamber increases greatly, and the temperature of the indoor chamber rises slowly, and the glass expands and shrinks in cold, resulting in outward bulge, as shown in table 2.

It can be concluded from table 1 that the deformation of the glass center increases with the increase of the temperature difference between the indoor and outdoor cavities, and the deformation trend of the glass plate on the side of the outdoor cavity is convex. This is because with the increasing temperature of the outdoor cavity, the deformation of the outer glass plate is larger than that of the indoor glass plate.

The strain of the measuring point at the middle point of the long side of the glass a is large and gradually decreases to both sides, while the strain at the middle point of the short side of the glass is small and gradually increases to both sides; the strain of the B side of the middle glass is larger near the four corner points, and the strain is relatively small in the middle of the glass. During the heating
test, the temperature of the middle glass is slow, the temperature of the outer glass is faster, the
deformation of the outer glass is large, and the edge angle of the middle glass is larger. The strain of
C-plane of outer glass is smaller, and the maximum strain appears at P3 corner, which is because the
expansion deformation of outdoor sheet glass is constrained by indoor side glass; the strain at the
middle part, loading side and middle point of glass plate is large after the temperature rise of d-side
glass, because the glass protrudes to the outdoor cavity and the curtain wall frame is limited. The
deformation of the corner.

According to the strain situation and measured data after heating, the heating strain nephogram
figure 9 is drawn.

Table 1. Corner stress during cold bending.

| Stress | Grade |
|--------|-------|
|        | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
| A side P4 | 0.45 | 0.91 | 1.39 | 1.98 | 2.42 |
| B side P2 | 0.52 | 0.99 | 1.56 | 2.03 | 2.51 |
| C side P1 | 1.15 | 2.31 | 3.50 | 4.66 | 5.80 |
| D side P2 | 1.88 | 3.87 | 5.69 | 7.64 | 9.47 |

Figure 8. Cold bending stress nephogram.

Table 2. Central deformation of outer glass during heating.

| Temperature difference (°C) | Deformation (mm) |
|-----------------------------|-------------------|
| 0                           | 0.00              |
| 13                          | 0.29              |
| 25                          | 0.45              |
| 38                          | 0.65              |
| 49                          | 0.77              |
| 58                          | 0.90              |

Figure 9. Temperature rise nephogram of stress.

4.2. Short Term Cooling Test Results and Analysis

In the short-term cooling test, the center deformation of glass goes through two processes of
subsidence deformation and slight rebound of subsidence deformation with the sudden drop of
temperature, as shown in table 3.
Table 3. Center deformation of short-time cooling outer glass.

| Temperature difference (°C) | Deformation (mm) |
|-----------------------------|------------------|
| 35                          | 0.00             |
| 26                          | -1.10            |
| 12                          | -2.60            |
| 3                           | -3.59            |
| -1                          | -3.68            |
| -10                         | -2.72            |

After the short-term cooling test, there is a large strain at the long side of the inner sheet glass A. Because of the short-term cooling, the deformation of the free edge shrinks rapidly, while the temperature transfer speed is slow in the middle, so the middle strain is small; the strain of the B-side of the middle glass is at the four corner points, and the tensile deformation retraction at the four corner points causes the strain to be large; the maximum strain point of the C-plane of the outer sheet glass is near the cold bending corner point. The results show that the strain at the cold bending corner is the largest due to the rapid retraction of the middle deformation, and the maximum strain at the cold bending corner point is the largest; the d-plane strain of the outer sheet glass is relatively large, and the maximum strain occurs near P2 and P3; the d-plane is affected by the temperature drop most, and the deformation shrinks rapidly, and the corner is constrained to deform, forming the maximum strain near the corner, rather than the maximum strain at the corner. This is because it takes time for the A and B sides of the inner glass in the laminated glass to pass to the indoor cavity due to the influence of the external cooling during the short-term cooling, so the indoor side temperature changes little, resulting in the small strain; the expanded glass of the C and D sides of the insulating glass shrinks sharply and the strain is large.

5. Relationship between Heating Test and Cold Bending Test

In the heating test of insulating glass, the linear strain in the middle of the glass increases with the increase of temperature [15]. The strain of the insulating laminated glass plate is basically linear with the temperature difference. The strain in the plate has little effect on the change of temperature, while the strain at the edge of the plate changes greatly with the temperature difference. When the corner points are fixed, the strain generated at the edge of the plate is larger than that in the middle of the plate [16], figure 10 shows the stress nephogram produced by only heating test on the glass plate.

![Figure 10. Stress nephogram produced by heating test on glass plate.](image-url)
middle of the insulating glass plate is smaller. The temperature difference between the indoor and outdoor cavities is about 17 °C, and the overall linear strain of the glass plate is small, so it is within a certain range. The increase of internal temperature is beneficial to the mechanical properties of cold-formed glass.

6. Conclusion
(1) This test has achieved a good condition control, for the use of loading device in cold bending test, temperature control of indoor and outdoor cavity during temperature change test, many interference factors, such as natural temperature, natural light, etc., are removed, and the stress of glass is correctly obtained.

(2) In the cold bending test, the maximum strain appears near both ends of the loader or near the boundary constraint, and the strain in the middle is small. The P2 corner is directly affected by the loader, and the tensile deformation becomes larger and larger, resulting in larger strain. However, at P1 corner, the tensile deformation is constrained by the curtain wall steel frame, resulting in smaller strain than P2 corner.

(3) During the heating test, the deformation of the glass center increases with the increase of the temperature difference between the indoor and outdoor cavities, which basically shows a linear relationship; the glass surface protrudes outward and the strain increases, and the maximum strain occurs near the middle point of the upper edge of the glass and the middle point of the glass plate on the side of the displacement loading point. The temperature rise test can reduce the linear strain at the corner of the cold-formed glass plate, and the increase of temperature in a certain range is beneficial to the mechanical properties of the cold-formed glass.

(4) When cooling for a short time, the outer glass expands and contracts rapidly, and the maximum strain occurs near the cold bending corner of the outer sheet glass.

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