Stress Response Analysis of Semi Hidden Frame Glass Curtain Wall Plane Support Structure in High-Rise Buildings Under Wind Load

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Abstract. A planar support structure model of a semi hidden frame glass curtain wall for high-rise buildings was constructed by preparing tempered glass panels with a length of 1500 mm, a width of 1000 mm, and a thickness of 10 mm, 6061-T6 aluminum alloy main keel, and silicone structural adhesive as experimental materials. By combining finite element analysis, wind tunnel testing, static loading testing, and on-site testing, the stress response, deformation characteristics, and stability of the curtain wall were evaluated. The research results show that under simulated and extreme weather conditions, the curtain wall system exhibits obvious stress distribution and deformation characteristics. The center of the glass panel and the connection point of the main keel are the stress concentration points, and the deformation increases with the increase of wind speed. Meanwhile, the curtain wall specimens have high load-bearing capacity and stable deformation performance, but further attention needs to be paid to safety performance under actual high wind speed conditions. These research results provide strong technical support and scientific basis for the design, optimization, and maintenance of curtain walls, which helps to improve the wind resistance and safety performance of curtain walls.

Keywords: Wind load; High rise building; Semi hidden frame glass curtain wall; Force response analysis; Wind resistance performance

1 Introduction

With the acceleration of urbanization, high-rise buildings, as an important component of the urban skyline, are increasingly receiving attention for their safety and stability [1]. As a commonly used peripheral protective structure for high-rise buildings, semi hidden frame glass curtain walls not only have a beautiful appearance, but also effectively isolate external noise and heat, enhancing the comfort of the building. However, under strong winds, the stress response and stability of curtain walls have become urgent issues to be addressed [2-3]. Especially under extreme weather conditions, curtain walls may face serious wind load challenges, and their mechanical performance and safety are highly tested. On the one hand, the curtain wall structure is complex,

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including multiple components such as glass panels, main keels, connectors, and structural adhesives, and the interactions and overall stress performance between these components are difficult to accurately predict [4]. On the other hand, wind loads have complexity and uncertainty, and their magnitude and direction change over time, significantly affecting the force response of curtain walls [5]. Therefore, how to accurately evaluate the stress performance and stability of curtain walls under wind loads has become a hot and difficult topic in current research.

Reference [6] overcomes the uncertainty in the dynamic performance evaluation of glass curtain walls under soft impact through a series of original experiments and finite element numerical analysis. Reference [7] developed experimental devices and methods to test the seismic performance of a full-size fully tempered hollow glass curtain wall system under three loading protocols: quasi-static plane loading. Reference [8] proposes a wind debris probability model that combines numerical solutions of three-dimensional flight trajectories of debris and computational fluid dynamics simulations of local wind environments for risk assessment and vulnerability analysis of high-rise building envelope structures under the influence of wind debris in hurricanes or typhoons.

These research results not only provide strong technical support and scientific basis for the design, optimization, and maintenance of curtain walls, but also help improve the wind resistance and safety performance of curtain walls.

2 Materials and Methods

2.1 Test Materials

In order to deeply analyze the influence of wind load on the planar support structure of semi hidden frame glass curtain walls in high-rise buildings, this study used tempered glass panels with a length of 1500 mm, a width of 1000 mm, and a thickness of 10mm, matched with 6061-T6 aluminum alloy main keels (section 50 mm × 30 mm, wall thickness 3 mm) as the support structure, and bonded with silicone structural adhesive (width 15 mm, thickness 8 mm). The specific parameters of these materials are shown in Table 1.

Table 1. Test Materials

Components/Materials	Type /Specification	Size/Parameters	Strength/modulus
Glass panel	Materials	Tempered glass	Tensile strength ≥ 90 MPa, compressive strength ≥ 120 MPa, elastic modulus 70 GPa
	Size	Length 1500 mm, width 1000 mm, thickness 10 mm	-

Supporting structure	Main keel material	Aluminum alloy profile, model 6061-T6	Elastic modulus of 70 GPa, yield strength ≥ 240 MPa
	Main keel section size	50 mm × 30 mm, wall thickness 3 mm	-
	Connecting components	Stainless steel bolts and nuts, specification M10	-
Structural adhesive	Materials	Silicone structural adhesive	Elastic modulus 2 MPa, tensile strength ≥ 1.5 MPa, compressive strength ≥ 2.5 MPa
	Size	Width 15 mm, thickness 8 mm	-

The planar support structure of semi hidden frame glass curtain walls in high-rise buildings mainly consists of glass panels, main keels, auxiliary keels (if necessary), connectors, and structural adhesives. The glass panel [9] is bonded to the main keel with structural adhesive to form a semi hidden frame structure, and cross tie rod supports are set at the corners, as shown in Figure 1.

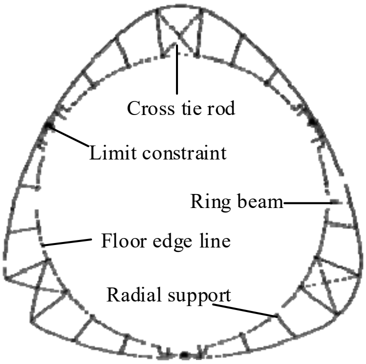


Fig. 1. Layout of plane support structure for semi hidden frame glass curtain wall in high-rise buildings

2.2 Experimental Instruments

When analyzing the stress response of the planar support structure of the semi hidden frame glass curtain wall in high-rise buildings, multiple testing instruments and methods were used in this study. As shown in Table 2.

Table 2. Experimental instruments

Instrument name	Model	Usage description

ANSYS software	-	Simulate stress distribution and deformation characteristics of curtain walls
Anemometer	FT-WQX2	Measure wind speed in a wind tunnel
Pressure sensor	SM9541-010C-S-C-3-S	Measure the wind pressure distribution on the surface of the curtain wall model
Displacement sensor	DP-10VAL	Measure the deformation of the curtain wall model
Anemometer	EC-A6	Record the wind speed data of the actual curtain wall at different wind speeds
Strain gauges	KYOWA KFG-3-120-C20-11	Record the strain data of the actual curtain wall at different wind speeds
Displacement sensor	DK812SBVR5	Record the displacement data of the actual curtain wall at different wind speeds
Universal testing machine	CTS-F5	Perform static loading on curtain wall specimens, record strain, displacement, and failure load data

2.3 Test Methods

(1) Finite Element Analysis Method

This study used ANSYS software [10-11] to construct a finite element model including glass panels, main keels, connectors, and structural adhesives based on the parameters in Table 1.

(2) Wind tunnel testing method

In the wind tunnel laboratory [12], wind tunnel tests were conducted on a scaled down (1:10 scale) curtain wall model using anemometers, pressure sensors, and displacement sensors. By adjusting the wind speed to 25 m/s and simulating wind loads under extreme weather conditions, the wind pressure distribution and deformation on the surface of the curtain wall were measured, and the force response and stability of the curtain wall were analyzed in depth.

(3) Static loading test method

Static loading tests were conducted on curtain wall specimens containing glass panels, supporting structures, and connectors using a uniform loading method on a universal testing machine. During the loading process, key data such as strain, displacement, and failure load were recorded.

(4) On site testing method

Anemometers, strain gauges, and displacement sensors were installed at key locations of semi hidden frame glass curtain walls in actual high-rise buildings, recording the strain and displacement data of the curtain wall under different wind speeds (5 m/s to 25 m/s). Through on-site testing, the stress response and safety performance of the curtain wall under actual wind loads were directly evaluated.

3 Results Analysis

(1) Finite Element Analysis Method

The parameters of the curtain wall calculation model are set as the cross-sectional area of the transverse cable 736 mm^2, the cross-sectional area of the longitudinal cable 373 mm^2, the pre strain 0.0016, the plane size of the glass panel 1500 mm × 1500 mm, and the thickness of the glass panel 12, 14, 16, 18, 20, 22, and 24mm, respectively. The dynamic load on the glass panel is set to simulate wind pressure for the first 120 seconds. The first ten natural frequencies of the structure are shown in Table 3:

Table 3. The first ten natural frequencies of the structure

Order	Natural frequency
1	3.022
2	4.182
3	5.205
4	6.302
5	6.360
6	7.362
7	8.841
8	10.942
9	11.195
10	11.423

The wind load causes the overall lateral bending of the tower, resulting in vertical deformation of the curtain wall support structure, manifested as tensile deformation of one side of the curtain wall and compressive deformation of the other side, as shown in Figure 2.

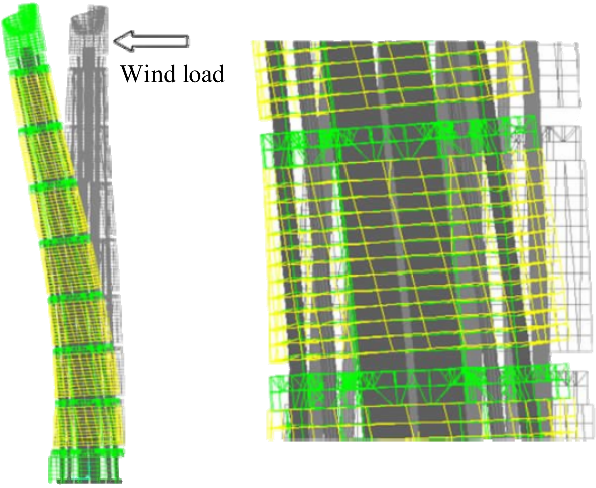


Fig. 2. Deformation caused by wind horizontal load

Based on the deformation results in Figure 2, the stress distribution, deformation characteristics, and stress state of the supporting structure of the curtain wall were analyzed under a glass panel thickness of 16mm. The results are shown in Table 4.

Table 4. Stress Status of Curtain Wall

Location of monitoring points	Maximum flexibility (MPa)	Maximum strain(με)	Maximum displacement (mm)
Glass panel center	10.5	525	2.5
Horizontal cable midpoint	8.2	410	1.8
Longitudinal cable midpoint	6.8	340	1.5
Main keel connection point	12	600	1.2 (Relative displacement)

According to Table 4, under simulated wind loads, the curtain wall system exhibits significant stress distribution and deformation characteristics. The maximum stress at the center of the glass panel reached 10.5 MPa, indicating that this area is a relatively concentrated area of stress. At the same time, the transverse and longitudinal cables also bear corresponding stress and strain, but their stress levels are lower compared to glass panels. The main keel connection point, as a key part of the supporting structure, has a high stress level of 12.0 MPa and a relative displacement of 1.2 mm, indicating that the supporting structure has undergone some deformation under wind load, but still within an acceptable range.

Figure 3 shows the measurement results of the stress response analysis of the planar support structure of the semi hidden frame glass curtain wall in high-rise buildings under wind load. The left side is a side view of the out of plane displacement deformation of the curtain wall glass panel under multi-level wind load; On the right is the initial shape of the curtain wall without wind load obtained by interpolating surface fitting for all sampling points. By analyzing the characteristics of the curtain wall edge and its displacement away from the surface during the process of gradually increasing wind load, it can be observed that the displacement of the large area and edge center area along the normal direction of the curtain wall is positive (3977 Pa: 0.15 mm~0.84 mm), while the four corner areas are negative (3977 Pa: -0.41 mm~1.42 mm). This indicates that under wind load, the silicone structural adhesive as a connecting component undergoes complex deformation states of tension and compression. Further analysis of Figure 3 reveals that the wind resistance performance evaluation method based on the current standard's dependence on surface normal deflection has limitations in characterizing the complex stress response of semi hidden frame glass curtain walls in high-rise buildings. On the one hand, the initial shape of the curtain wall is not an ideal plane. Therefore, in the method of evaluating surface normal deflection based on displacement measurement results, the arranged measuring points do not have a common initial zero reference plane; On the other hand, the four corner points of the curtain wall marked with red dots present a spatially heterogeneous state, which will result in inconsistent results of the calculated surface normal deflection of the measuring points arranged along the two diagonal directions, making it impossible to uniquely and quantitatively characterize the stress and deformation of the curtain wall. More importantly, the negative displacement of the bottom corner of the curtain wall on the left side of Figure 3 is significantly smaller than that of the top corner, and the difference between the two increases with the increase of wind load. The reason for this phenomenon is the difference in torsional response on each side of the back frame and the coupling effect of uneven deformation of the gel, which causes the curtain wall to tilt and bend, thereby driving the glass panel to produce rigid motion. This also causes the position of the maximum out of plane displacement on the curtain wall plane to constantly change.

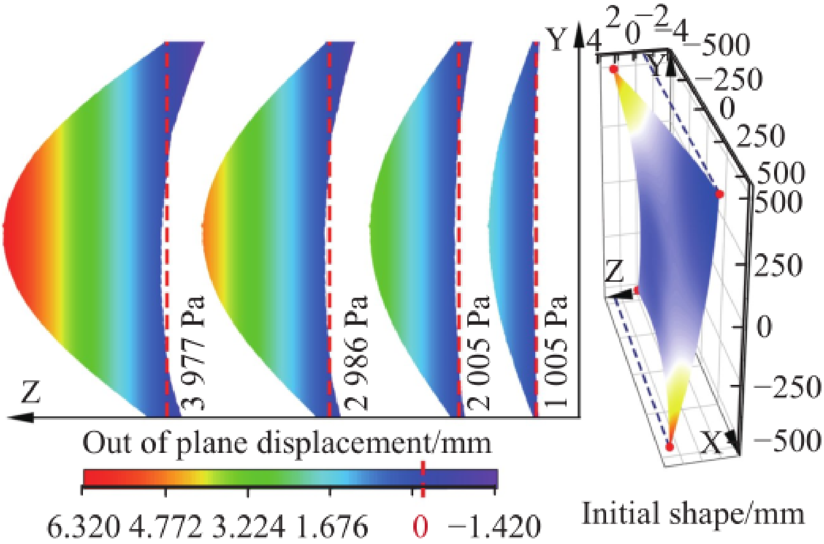


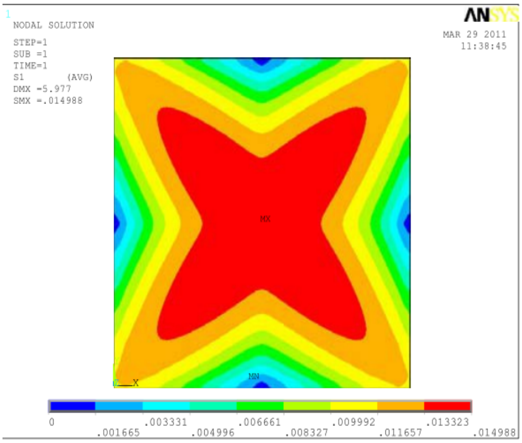
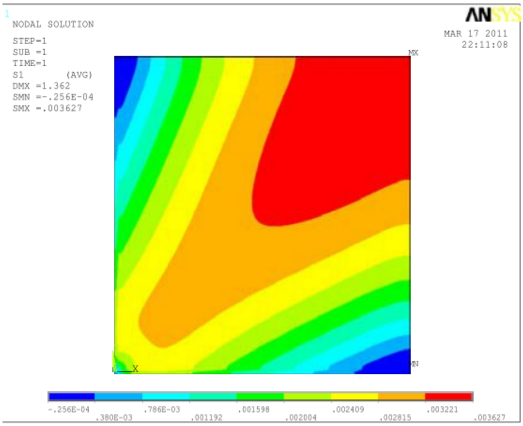
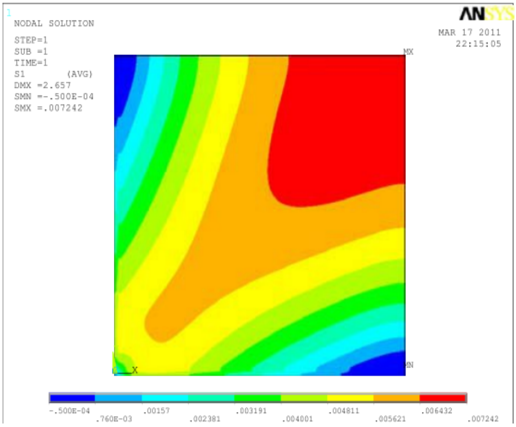
Fig. 3. Finite Element Analysis Results

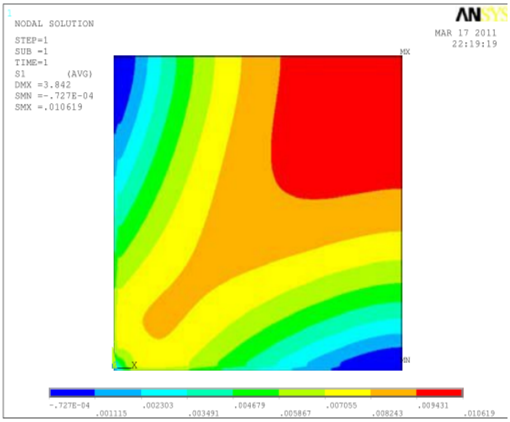
(2) Wind tunnel testing method

The wind pressure distribution and deformation of a scaled down curtain wall model were tested in a wind tunnel simulating extreme weather conditions using wind tunnel testing methods. The experimental results are shown in Table 5.

Table 5. Wind Tunnel Test Results

Wind speed (m/s)	Wind pressure distribution on the surface of the curtain wall (Pa)	Deformation of curtain wall (mm)

0	 Reference Value	0
10	 Distribution Map A	0.2
15	 Distribution Map B	0.6

25	 Distribution Map C	1.2

According to Table 5, under extreme weather conditions with a wind speed of 25 m/s, the wind pressure distribution on the surface of the curtain wall exhibits significant non-uniformity (as shown in distribution diagram C), and the deformation of the curtain wall reaches 1.2 mm. Compared with the data at lower wind speeds, the increase in wind pressure and deformation indicate that the curtain wall has a higher stress response under extreme wind loads. According to the benchmark value, the maximum principal stress of the glass panel under uniformly distributed load is located at the center of the glass panel, and the area of the maximum stress is the red area of the panel that approximates the square star. In the stress distribution diagram of the glass panel, negative stress values appear at the center of each edge of the panel, i.e. in the blue area. When the wind speed increases from 10 m/s to 25 m/s, the most obvious changes in the graph are represented by the stress values in the red and dark yellow areas near the red. At a wind speed of 10 m/s, the red area represents the region of maximum stress that extends from the center of the panel to the midpoint of the diagonal of the 1/4 glass panel. As the pressure increases, the red area gradually shrinks towards the center area of the glass panel. When the wind speed is 25 m/s, the red area appears approximately square. The trend of the second largest stress region represented by the dark yellow area is that as the wind load increases, this region expands towards the center area of the glass panel, showing a change in overall shape from V-shaped distribution to Y-shaped distribution.

(3) Static loading test method

The static loading test method was used to uniformly load the curtain wall specimens on a universal testing machine, and key data such as strain, displacement, and failure load were recorded in detail. The experimental results are shown in Table 6.

Table 6. Results of Static Loading Test

Loading load (kN)	Flexibility (με)	Displacement (mm)	Failure load (kN)
0	0	0	-
50	100	0.1	-
100	200	0.3	-
150	300	0.6	Undamaged
200 (Destruction)	-	-	220

According to Table 6, in the static loading test, when the load reached 150 kN, the strain and displacement of the curtain wall specimen showed linear growth and no damage occurred. However, when the loading load increased to 200 kN, the curtain wall specimen failed, and the failure load at this time was 220 kN. This indicates that the curtain wall specimen has a high load-bearing capacity and its deformation performance remains stable during the loading process.

(4) On site testing method

Sensors were installed at key locations of the actual high-rise building curtain wall to directly monitor the strain and displacement changes of the curtain wall under different wind speed conditions. The installation site is shown in Figure 4. The experimental results are shown in Figure 5.

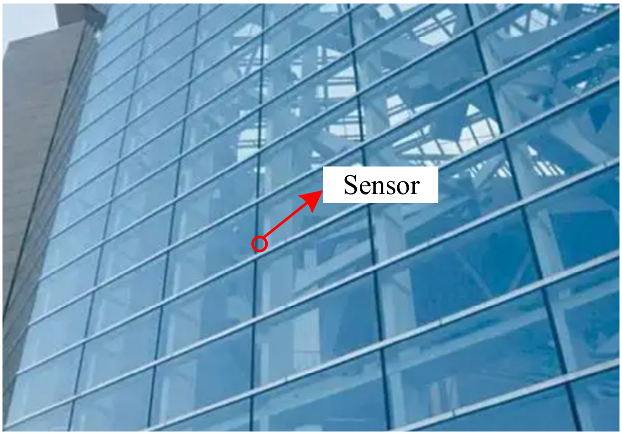


Fig. 4. Installation Site

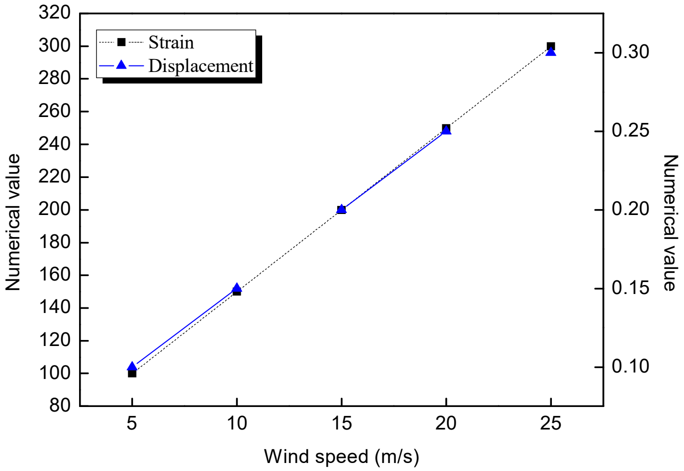


Fig. 5. On site Test Results

According to Figure 5, in the on-site testing of semi hidden frame glass curtain walls in actual high-rise buildings, the strain and displacement of the curtain wall show a linear growth trend with the increase of wind speed. When the wind speed reaches 15 m/s, the strain and displacement of the curtain wall are 200 με and 0.2 mm, respectively, indicating that the curtain wall has good stress response and stability under actual wind loads. However, as the wind speed continues to increase to 25 m/s, the strain and displacement growth rate of the curtain wall slightly accelerates, indicating that we may need to further focus on the safety performance of the curtain wall under high wind speed conditions.

4 Conclusion and Outlook

This study investigates the stress response of semi-hidden frame glass curtain wall planar support structures in high-rise buildings under wind loads through experimental and field analyses. The key findings and implications are summarized as follows:

(1) Stress Distribution and Deformation Characteristics:

Under simulated wind loads, the curtain wall system exhibits non-uniform stress distribution with critical stress concentrations at the glass panel center (10.5 MPa) and main keel connection points(12.0 MPa).While the deformation remains within permissible limits, the supporting structure demonstrates noticeable flexibility.

(2) Wind Speed-Dependent Behavior:

At extreme wind speeds(25 m/s), non-uniform wind pressure distribution induces a maximum deformation of 1.2mm. Stress redistribution occurs as wind speed increases: the glass panel's maximum stress zone contracts toward the center, while secondary stress regions expand.

Field tests reveal a linear increase in strain (200 us) and displacement(0.2 mm) at 15m/s. However, beyond 15 m/s, strain-displacement growth accelerates.

The stress-wind speed response model constructed based on experimental and field data provides a generalizable optimization solution for predicting the dynamic performance and enabling parametric design of the planar support structures of curtain walls in complex wind environments.

(3) Structural Resilience and Safety Margin:

Static loading tests demonstrate the specimen's high load-bearing capacity:

Linear strain-displacement

response up to 150 kN without failure.

Destructive load reaches 220 kN, indicating a safety factor of 1.47,relative to the design load (150 kN).

This confirms the system's robust deformation control under static loads but underscores the need for dynamic load considerations in design codes.

(4) Practical Recommendations:

Design Optimization: Reinforce connections at stress-concentrated regions (e.g., main keel joints) and incorporate asymmetric wind pressure profiles in simulations.

Monitoring Protocols: Implement real-time strain monitoring for curtain walls in typhoon-prone regions when wind speeds exceed20 m/s.

(5) Limitations and Future Work:

This study focuses on a single specimen under controlled conditions. Future research should:

Expand sample diversity (e.g., varying glass thickness, keel materials).

Investigate long-term fatigue effects and aerodynamic instability under turbulent flows.

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