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DESIGN AND PERFORMANCE STUDY OF LARGE-SCALE CORRUGATED THREE-DIMENSIONAL ARCHITECTURAL GLASS (LIULI) COMPOSITE PANELS

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Abstract: Based on the China Beijing–Hangzhou Grand Canal Museum project, this study addresses the challenge that no existing manufacturer, domestically or internationally, could provide an off-the-shelf product meeting the safety and stability requirements for the first large-scale application of LIULI to a building curtain wall. Without a proven solution, the installation faced severe risks including physical damage, spontaneous fracture and falling debris, and dislodgement due to the substantial self-weight. Therefore, a design and performance study of large-scale corrugated three-dimensional LIULI composite panels was conducted. The final design adopts adhesive bonding of a double-layer heat-strengthened glass backing to a large-format, heavy corrugated 3D LIULI slab measuring 2.5m², 350kg, with a gradient thickness of 45–130mm. After comprehensive evaluation, a modified enhanced ethylene-vinyl acetate copolymer (PVE) interlayer was selected for lamination. The resulting structural configuration is defined as: LIULI slab + 2.28mm PVE + 10mm heat-strengthened glass + 1.52mm PVE + 10mm heat-strengthened glass. This composite system ensures high safety and high stability for large-scale corrugated 3D LIULI architectural applications.
Keywords: Large-scale corrugated three-dimensional; LIULI composite panel; High safety; High stability

1 INTRODUCTION

Colored glaze, as one of the appellations for ancient Chinese glass, was also a variety of artistic glass in modern times. From the discovery of colored glaze precursors in the Western Zhou Dynasty to its peak during the Kangxi and Qianlong periods of the Qing Dynasty, China had a long history of colored glaze manufacturing. At that time, it not only inherited the traditions of ancient colored glaze but also continuously innovated according to modern trends, inheriting from innovation, thus forming the subsequent long-term development[1]. The earliest colored glaze was made by the ancestors using local raw materials, and the formula was somewhat accidental. After accumulating experience and obtaining the mature formula, products with the required performance could be mass produced. With the advancement of science, analytical testing techniques were used to analyze formulas and raw materials, resulting in the formation of experimental components. Up to that era, Boshan-produced colored glaze was the most representative of China, and it was known as the "Hometown of Chinese LIULI (Colored Glaze)". Its series of works gained a high reputation both domestically and internationally (Figure 1) [2]. Its colored glaze firing technique was officially awarded the "National Intangible Cultural Heritage".

In recent decades, glass had been used by architectural engineers in non-traditional forms. In addition to its traditional uses as a window to make the inside and outside of a building visible and to introduce light, glass was increasingly becoming a medium for artistic expression rather than just an architectural material[3-5]. Terms such as "beyond transparency" had been used to describe architectural visions with a more extensive use of glass. The simplest and most widespread use of glass in architecture was as a curtain wall. Typically, transparent glass panels were suspended on aluminum alloy or stainless steel metal frames to form the building facade enclosure structure, but they did not bear the structural loads of the architecture itself. Glass was also used for internal partition walls and architectural decoration. Architectural glass was usually of the safety type. Tempered glass and laminated glass were commonly used in the curtain wall. From the all-glass architectures in New York, Beijing and Shanghai, to the glass facades of iconic architectures and airport terminals around the world (Figure 2), and then to tourist attractions such as the Zhangjiajie Grand Canyon Glass Bridge, glass had witnessed rapid progress in the field of architecture[6]. In addition, in other buildings, such as Apple Stores, glass was also used as a structural load-bearing material in the form of blocks[7].

In the field of building engineering, LIULI has thus far been used exclusively for roof decoration and interior ornamentation. Representative examples include the glazed tile roofs of the Beijing Cultural Palace of Nationalities and the National Library of China, as well as the Tang tri-color (Sancai) ceramic columns inside the Xi'an Metro Zhonglou Station[8]. For the new Nanjing Porcelain Tower, the outward-cantilevered wing slabs of the tower are encapsulated with ultra-clear (low-iron) glass[9]. The inner glass panels undergo a series of processes—pattern etching, hand glazing, and high-temperature firing—to achieve the tower's distinctive glazed wing appearance.

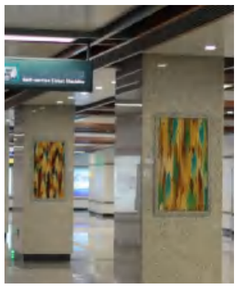
In summary, this paper reviews the origin and evolution of glass materials both domestically and internationally, and conducts a comparative analysis of glass material classifications, casting processes, and mold selection. It is found that glass materials are gradually shifting from traditional decorative crafts to functional products for modern architecture.

With the rapid development of contemporary society, glass is achieving an ingenious integration of traditional culture and building functions. However, despite its distinctive cultural and artistic characteristics, Chinese LIULI materials have thus far remained confined to craft artworks, with no involvement in the field of modern building functions. Based on the project background of the China Beijing–Hangzhou Grand Canal Museum, and considering that this LIULI product is applied to a building curtain wall on a large scale for the first time, no existing manufacturer, domestically or internationally, can currently provide an off-the-shelf product that meets the required safety and stability standards. In practical application, this gives rise to severe risks including physical damage, spontaneous fracture and falling debris, and dislodgement due to the substantial self-weight. Therefore, a design and performance study of large-scale corrugated three-dimensional LIULI composite panels is proposed, with the aim of providing reliable technical support for engineering implementation (Figure 3).

Figure 1 Works of Chinese LIULI (Colored Glaze) Craftsmanship[2]: (a) Lotus Pond Moonlight Series of Works; (b) Chicken Fat Yellow Engraved Snuff Bottle; (c) Lotus Breeze and Clear Rhyme Series of Works; (d) Lunar Colored Glaze Lamp

Figure 2 Typical Glass Curtain Wall Architectures[6]: (a) Shard, London; (b) Shanghai Central Business District; (c) Shanghai Tower; (d) Jewel Changi Airport, Singapore; (e) Apple Store on Fifth Avenue, New York

(a) Glazed Tile Roof of the Beijing Cultural Palace of Nationalities



(b) LIULI Column Decoration at Xi'an Metro Zhonglou Station

(c) Glazed Tower Wings of the New Nanjing Porcelain Tower

Figure 3 Decorative Applications of Liuli Products in Building Engineering[8-9]

2 PROJECT OVERVIEW

The China Beijing–Hangzhou Grand Canal Museum is one of the cultural preservation, inheritance, and utilization projects under the National Development and Reform Commission's 14th Five-Year Plan, and has been incorporated into the National Grand Canal Cultural Park Development Program. It is of great significance for promoting the Grand Canal culture, improving the heritage conservation system, and enhancing urban cultural development and comprehensive supporting service capacities. The project reflects the canal's status as a heritage-level landmark within China's cultural and natural landscape, with the design concept of a "museum that mirrors the canal." To embody the "water-reflecting façade" design philosophy, the entire podium curtain wall is ingeniously assembled from 7240 corrugated LIULI slabs, covering a total area of 17800m². The architect specifically required that, under sunlight and against the backdrop of the Grand Canal, each panel should present a distinct visual effect, shimmering like the surface of flowing water. To achieve this, large-format LIULI slabs with gradient thicknesses were mandated: the thickness of each slab gradually transitions from 45mm to 130mm, and every panel measures 2.5m × 1m (Figure 4).

Figure 4 Rendering of the Colored Glaze Curtain Wall of the Architecture: (a) Overall Effect; (b) Local Effect; (c) Detailed Effect

3 DESIGN OF LARGE-SCALE CORRUGATED 3D LIULI COMPOSITE PANELS

3.1 General Provisions for LIULI Composite Panels

To prevent falling debris in the event of accidental fracture of a LIULI panel, a LIULI–glass composite configuration is adopted to ensure the service safety of the curtain wall. A LIULI composite panel is defined as a laminate consisting of a LIULI slab and glass, bonded together using an ionoplast interlayer (SGP) or a modified enhanced ethylene-vinyl acetate copolymer (PVE) interlayer, specifically engineered for building curtain wall applications.

The ionoplast interlayer contains a small amount of metal salts and is primarily based on ethylene–methacrylic acid (EMA) copolymer. It serves as an interlayer material capable of forming a strong bond with glass, and shall comply with the relevant provisions of Ionoplast interlayer used for laminated glass (JC/T 2763-2023)[10]. The modified enhanced EVA (PVE) interlayer features high light transmittance, low water absorption, and no edge sealing requirement. It exhibits excellent low-temperature impact resistance and stable bonding strength, allowing for direct roll-press lamination or autoclave lamination. It shall comply with the relevant provisions of Technical specification for glass structure engineering (T/CECS 1099-2022)[11].

The appearance quality of a finished LIULI composite panel covers both the LIULI product and the composite layer. The appearance quality of the composite panel shall meet the requirements of the current national standard Safety glazing materials in building—Part 3: Laminated glass (GB 15763.3-2009)[12].

The allowable dimensional deviations in length and width of LIULI composite panels shall conform to the requirements specified in Table 1.

Table 1 Allowable Dimensional Deviations in Length and Width of LIULI Composite Panels (mm)

Nominal dimension	Interlayer glass nominal thickness ≤ 8	Interlayer glass nominal thickness＞8	
(Length L)		Each glass nominal thickness < 10	At least one glass nominal thickness ≥ 10
L≤600	+1.0 -1.0	+1.0 -1.0	+1.0 -1.0
600＜L≤1200	+2.0 -3.0	+2.0 -3.0	+3.0 -3.0
1200＜L≤2400	+3.0 -4.0	+3.0 -4.5	+3.0 -5.0
L＞2400	+4.0 -4.0	+4.5 -5.0	+5.0 -7.0

The maximum allowable offset of LIULI composite panels (Figure 5) shall conform to the requirements specified in Table 2.

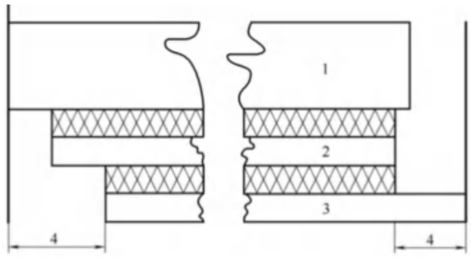


Figure 5 Panel Offset: 1-LIULI; 2-Glass; 3-Glass; 4-Offset

Table 2 Maximum Allowable Offset of LIULI Composite Panels (mm)

Dimension L	Maximum allowable offset
L≤1000	2.0
1000＜L≤2000	2.5
2000＜L≤4000	3.0
L＞4000	5.0

The allowable thickness deviation of LIULI composite panels shall conform to the requirements specified in Table 3.

Table 3 Allowable Thickness Tolerance (mm)

Total thickness	Maximum allowable tolerance
H<50	±1.5
50≤H＜100	±2.5
H≥100	±3.5

For rectangular LIULI composite panels, the diagonal deviation shall not exceed 4mm when the long-side dimension is ≤ 2400mm; when the long-side dimension exceeds 2400mm, the diagonal deviation shall be subject to mutual agreement between the supplier and the purchaser.
The warpage of flat LIULI composite panels shall not exceed 0.3% for bow and 0.2% for wave.
The performance requirements and test methods for LIULI composite panels shall conform to the provisions specified in Table 4.

Table 4 Performance Requirements and Test Methods for LIULI Composite Panels

Test item		Requirement
Safety performance	Heat resistance	After testing, cracks are permitted in the specimen; no blistering or other defects shall occur beyond 13mm from the edge or crack[12].
	Humidity resistance	After testing, no blistering or other defects shall occur within the areas extending 15mm from the original edge, 25mm from the cut edge, or 10mm from any crack[12].
	Radiation resistance	After testing, no significant discoloration, blistering, or turbidity shall be observed. The change rate in visible light transmittance before and after testing (ΔT) shall not exceed 3%[12].
	Falling weight impact delamination	Drop height: 1200mm; impact face: LIULI surface. After testing, the interlayer shall not fracture, nor shall it be exposed due to fragment glass[12].
	Pummel bag impact resistance	Impact face: LIULI surface. After each impact height test, the specimen shall remain either unbroken or safely broken[12].
	Flatwise tension bond strength	≥ 2.46MPa[13]
	In-plane shear strength	≥ 2.36MPa[14]

Building upon the performance requirements for laminated glass, the LIULI composite panel incorporates an additional flatwise tension bond strength criterion. In accordance with the current national standard Test method for flatwise tension strength of sandwich constructions (GB/T 1452-2018), the characteristic strength value of the LIULI composite panel is 18MPa, and with a partial factor for materials γ_m of 2.0, the design strength value is taken as 9MPa[13]. The deflection limit for LIULI composite panels is set at l/200, where l denotes the short-side dimension of a four-edge simply supported panel.

3.2 Structural Calculation of LIULI Composite Panels

The LIULI composite panels in this project are categorized into outer-ring panels and inner-ring panels. The cross-section of the outer-ring panel is inward-concave: the upper segment is outward-tilted, the middle segment is vertical, and the lower segment is inward-tilted. The cross-section of the inner-ring panel is outward-tilted with a relatively small tilt angle, which can be treated as a vertical curtain wall (Figure 6).

The typical panel module measures approximately 1000mm × 2500mm. The LIULI slab adopts a non-uniform thickness ranging from 45mm to 130mm, while the glass façade comprises 10mm + 1.52mm PVE + 10mm ultra-clear tempered glass, with a 2.28mm modified enhanced ethylene-vinyl acetate copolymer (PVE) interlayer.

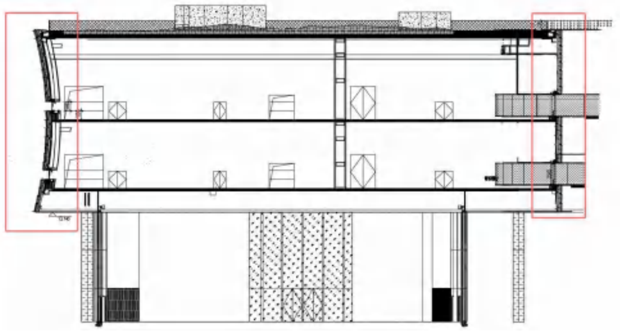


Figure 6 Partial Sectional View

Taking the outward-tilted panel as an example (Figure 7), the required LIULI strength is 9MPa and the allowable deflection is 1200/200 = 5mm (i.e., l/200, where l = 1200mm — the short-side dimension). The maximum outward tilt angle is located at the top of the podium, with an angle to the horizontal plane of 72.7°, a calculation elevation of 35.07m, and the maximum wind pressure at this location reaching +1.55kPa / –2.55kPa.

Figure 7 Outward-Tilted LIULI Composite Panel

3.2.1 Calculation by formula method

The structural configuration of the LIULI composite panel is illustrated below (Figure 8).

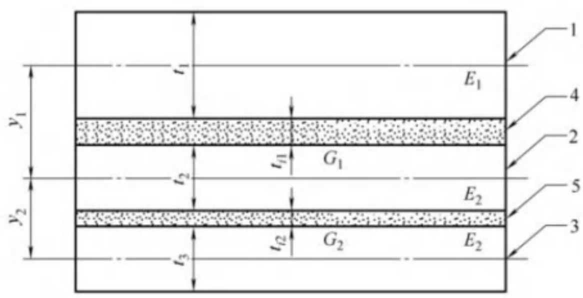


Figure 8 Schematic Diagram of the Three-Layer LIULI Composite Panel Structure: 1-Outer Liuli Slab; 2-Middle Glass; 3-Inner Glass; 4-Laminating Interlayer Between Outer LIULI and Middle Glass; 5-Laminating Interlayer Between Middle and Inner Glass

When calculating the deflection of the LIULI composite panel, its equivalent bending stiffness shall be calculated using the following formula.

$$\frac{1}{D} = \frac{\eta}{D_{tot}} + \frac{1-\eta}{D_i} \tag{1}$$

$$\frac{1}{\eta} = 1 + \frac{168}{17\left(\frac{1}{D_i}+\frac{1}{D_0}\right)\left(\frac{G_1 y_1^2}{t_{i1}}+\frac{G_2 y_2^2}{t_{i2}}\right)l^2} \tag{2}$$

$$D_i = \frac{E_1 t_1^3}{12} + \frac{E_2 t_2^3}{12} + \frac{E_2 t_3^3}{12} \tag{3}$$

$$D_0 = E_1 t_1 d_1^2 + E_2 t_2 d_2^2 + E_2 t_3 d_3^2 \quad (4)$$

$$D_{tot} = D_0 + D_i \quad (5)$$

$$y_1 = 0.5t_2 + 0.5t_1 + t_{i1} \quad (6)$$

$$y_2 = 0.5t_2 + 0.5t_3 + t_{i2} \quad (7)$$

$$d_1 = \frac{E_2 t_2 y_1 + E_2 t_3 (y_1 + y_2)}{E_1 t_1 + E_2 t_2 + E_2 t_3} \quad (8)$$

$$d_2 = \frac{E_1 t_1 y_1 - E_2 t_3 y_2}{E_1 t_1 + E_2 t_2 + E_2 t_3} \quad (9)$$

$$d_3 = \frac{E_2 t_2 y_2 + E_1 t_1 (y_1 + y_2)}{E_1 t_1 + E_2 t_2 + E_2 t_3} \quad (10)$$

When calculating the stress in the LIULI slab, its section modulus for bending resistance shall be calculated using the following formula.

$$\frac{1}{W} = \left(\frac{t_1}{2D} + \frac{\eta d_1}{D_{tot}}\right) E_1 \quad (11)$$

Where

D—Bending stiffness of the LIULI composite panel;

η—Composite factor for bending stiffness of the LIULI composite panel;

Dtot—Bending stiffness of the LIULI composite panel when the interlayer shear stiffness is infinite;

Di—Bending stiffness of the LIULI composite panel when the interlayer shear stiffness is zero;

D0—Composite bending stiffness of the LIULI composite panel;

G1、ti1—Shear modulus and thickness of the interlayer between the outer LIULI slab and the middle glass;

G2、ti2—Shear modulus and thickness of the interlayer between the middle and inner glass;

y1、y2—Distances between adjacent slabs;

l—Calculated span: short-side length for four-edge simply supported panels; support-edge span for opposite-edge supported panels; distance between long-edge support points for four-point supported panels;

E1、E2—Elastic moduli of the LIULI slab and glass in the composite panel;

t1、t2、t3—Thicknesses of the outer LIULI slab, middle glass, and inner glass;

d1、d2、d3—Distances from the neutral axis to the outer LIULI slab, middle glass, and inner glass;

W—Section modulus for bending resistance of the LIULI slab when calculating stress.

The characteristic strength value of LIULI is taken as 9MPa, and the partial factor for materials is 2.0. The stress in the LIULI slab is calculated as follows.

$$\sigma = \frac{mql^2}{W} \quad (12)$$

Where:

m—Bending moment coefficient: for four-edge supported panels based on aspect ratio (a/b); for opposite-edge supported panels, m=0.125.

q—Design value of the combined surface load on the LIULI composite panel.

The deflection of the LIULI composite panel is calculated as follows, with a deflection limit of l/200.

$$d_f = \frac{\mu q_k l^4}{D} \quad (13)$$

Where:

μ—Deflection coefficient: for four-edge supported panels based on aspect ratio (a/b); for opposite-edge supported panels, μ=0.01302;

qk—Characteristic value of the combined surface load on the LIULI composite panel.

Panel basic parameters:

Glass type: 10TP + 1.52 PVE + 10TP laminated glass;

LIULI type: 45–130mm non-uniform thickness LIULI slab;

Outer LIULI thickness: t11=45mm、t12=130mm;

$$t_1 = \frac{t_{11} + t_{12}}{2} + \frac{t_{12} - t_{11} - 30}{2} = 60mm \quad (14)$$

Middle glass thickness: t2=10mm;

Inner glass thickness: t3=10mm;

Short-side length of rectangular panel: a=1000mm;

Long-side length of rectangular panel: b=2500mm;

Elastic modulus of glass: Eg2=72000MPa;

Poisson's ratio of glass: νg2=0.2;

Elastic modulus of LIULI: Eg1=60000MPa;

Poisson's ratio of LIULI: νg1=0.2;

Shear modulus of PVE interlayer: G1=3MPa, G2=3MPa;

Support condition: Four-edge simply supported

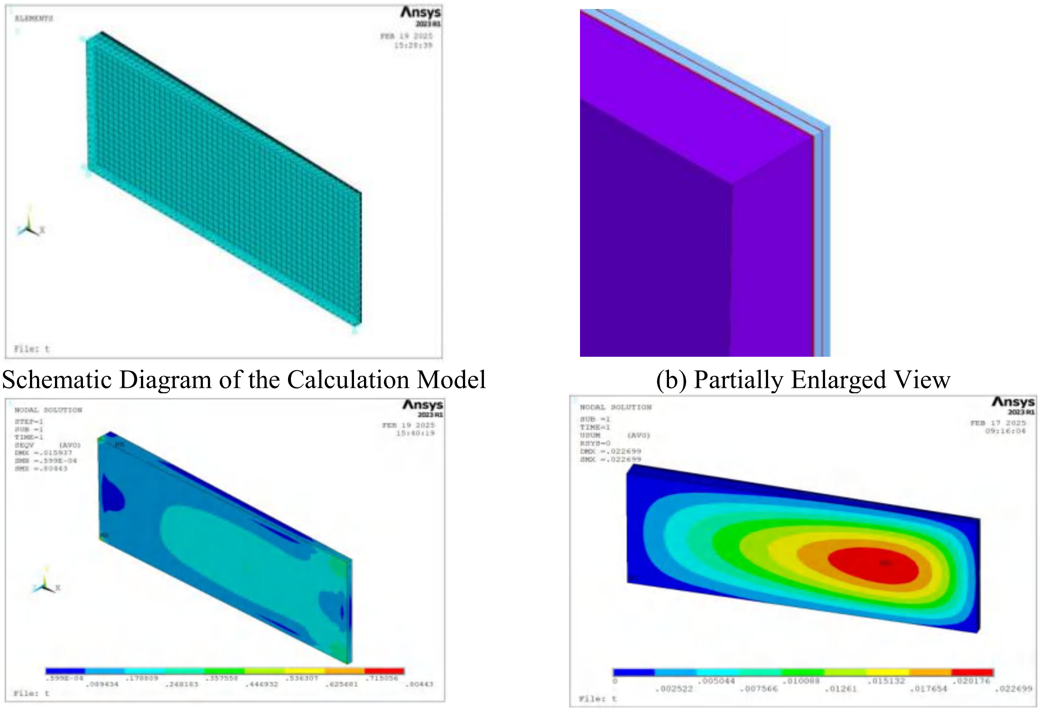
Panel inclination: Outward-tilted at α=72.7◦ (angle between panel and horizontal ground)

Calculation results: The stress in the LIULI slab is σ=0.86MPa ＜ 9MPa; the deflection limit is df=0.03mm ＜ df,lim=5mm.

By the same method, the calculations for vertical and inward-tilted LIULI composite panels yield the results in Table 5.

Table 5 Formula-Method Calculation Results for LIULI Composite Panels

Panel type	Outward-tilted panel	Vertical panel	Inward-tilted panel
LIULI strength calculation σ/MPa	0.86	0.72	0.56
Composite panel deflection calculation df/mm	0.03	0.023	0.018



(a) Schematic Diagram of the Calculation Model (b) Partially Enlarged View

(c) Stress Contour of the LIULI Slab (d) Deflection Contour of the LIULI Composite Panel

Figure 9 Finite Element Calculation

3.2.2 Finite element calculation

Due to the non-uniform thickness of the LIULI slab in this project, a 3D solid-element finite element model was developed for the simulation and analysis. The elastic moduli of the glass and LIULI were set to 72GPa and 6GPa, respectively, while the shear modulus of the PVE interlayer was taken as 3.0MPa. Based on the model and analysis of the outward-tilted LIULI composite panel, the results are presented below. The stress in the LIULI slab is σ=0.804MPa ＜9MPa, and the deflection is df=0.023mm＜df,lim=5mm (Figure 9).

3.2.3 Comparison between formula method and finite element analysis

Based on the theoretical calculation and the 3D solid-element finite element analysis of the outward-tilted LIULI composite panel, the results of both methods are summarized in Table 6.

Table 6 Comparison of Calculation Results Between Formula Method and 3D Solid-Element Modeling for Outward-Tilted LIULI Composite Panels

	Formula method	3D Solid-element modeling
LIULI strength σ/MPa	0.86	0.804
Composite panel deflection df/mm	0.03	0.023

Because the LIULI slab in this project features a non-uniform thickness, the formula method averages the slab thickness for calculation purposes. Therefore, a 3D solid-element finite element model was employed to verify and cross-validate the results. As shown above, the discrepancy between the formula method and the finite element modeling is negligible, and the calculated values show a substantial margin of safety when compared with the allowable limits for strength and deflection. Thus, the structural safety of the LIULI composite panels in this project is theoretically guaranteed.

4 MECHANICAL PERFORMANCE TESTS OF LARGE-SCALE LIULI COMPOSITE PANELS

4.1 Flexural Performance Analysis of LIULI Composite Panels

Based on the panel module dimensions and thickness variations in this project, scaled-down specimens measuring 1250mm × 500mm were prepared, consisting of a 30mm thick LIULI slab + 2.28mm PVE/SGP interlayer + 10mm heat-strengthened glass. Static bending load tests and failure tests were conducted on-site to evaluate flexural behavior. The test results are presented in the figures and tables below (Figure 7-8).

A 3D solid-element finite element model was developed to replicate the specimen dimensions and boundary conditions (opposite-edge simply supported) used in the on-site bending tests. The analysis results show that when a 7.96kN point load is applied at the center of the panel, the calculated LIULI stress reaches 19.49MPa, which is in close agreement with the characteristic bending strength of 18MPa. This indicates that the theoretical assumptions align well with the actual stress state. See Figure 12 for details.

Figure 10 Static Bending Load Test

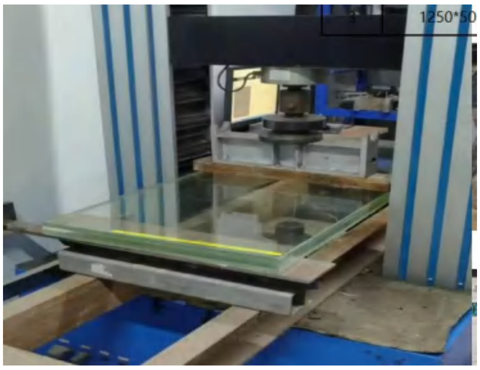


Figure 11 Bending Failure Test

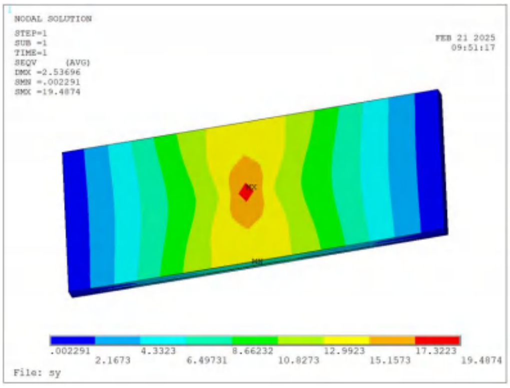


Figure 12 Stress Contour of an Opposite-Edge Simply Supported LIULI Composite Panel Under a 7.96kN Central Point Load

Table 7 Static Bending Load Test Data

Number	Specification	Panel weight (kg)	Static load (kg)	Failure mode
1	1250×500×30 LIULI + 2.28mm PVE + 10mm heat-strengthened glass	53.7	100	No deformation or fracture
2	1250×500×30 LIULI + 2.28mm SGP + 10mm heat-strenghened glass	52	100	No deformation or fracture

Table 8 Bending Failure Test Data

Number	Specification	Failure load (kN)	Failure mode
1	1250×500×30 LIULI + 2.28mm PVE + 10mm heat-strengthened glass	7.96	Surface cracking of LIULI
2	1250×500×30 LIULI + 2.28mm SGP + 10mm heat-strenghened glass	4.57	Surface cracking of LIULI

4.2 Bonding Performance Analysis Between LIULI and Glass

The LIULI composite panel is fabricated using a laminating process, consisting of heat-strengthened glass and LIULI bonded together. While its structure bears similarity to that of laminated glass, the slab thickness of LIULI far exceeds that of a single glass ply. Consequently, its load-bearing structure and physico-mechanical properties differ significantly from those of conventional laminated glass. Therefore, the test protocol references the testing methods for laminated glass and stone honeycomb composite panels (sandwich constructions). For the bond strength tests between LIULI and glass, the primary parameters evaluated are flatwise tension bond strength, in-plane shear strength, and freeze-thaw resistance. Two types of test specimens are prepared: Grade 6 LIULI + PVE interlayer + glass, and Grade 6 LIULI + SGP interlayer + glass (Figure 13).

Figure 13 Test Specimens

4.2.1 Flatwise tension bond strength

A tensile load is applied in the direction perpendicular to the face sheet of the sandwich construction using a tension fixture with automatic self-aligning capability. Failure may occur as core tensile failure, adhesive tensile failure at the panel–core interface, or face-sheet delamination (Figure 14). The test data for flatwise tension bond strength are presented in Table 9.

Figure 14 Flatwise Tension Bond Strength Test

Table 9 Flatwise Tension Bond Strength Test Data

Original strength (tensile)				
Number	Area (mm²)	Failure load (kN)	Tensile strength (MPa)	Failure mode
1（PVE）	60×60	17.89	4.97	LIULI fracture
2（PVE）	60×60	19.20	5.33	LIULI fracture
3（PVE）	60×60	22.68	6.30	LIULI fracture
1（SGP）	60×60	11.06	3.07	LIULI fracture
2（SGP）	60×60	9.66	2.68	LIULI fracture
3（SGP）	60×60	8.87	2.46	LIULI fracture

The test results indicate that the PVE specimen exhibits a higher LIULI tensile fracture strength of > 5MPa, while the SGP specimen shows a tensile fracture strength of > 2.4MPa. Generally, the tensile performance of the interlayer surpasses the inherent strength of the LIULI material itself. Based on the material properties of LIULI, a 100 mm thick LIULI slab has an areal density of approximately 235kg/m². The minimum bond strength provided by the interlayer exceeds the self-weight of the LIULI slab, which is sufficient to retain broken fragments and prevent falling debris.

4.2.2 In-plane shear strength

By applying a tensile or compressive load to the bonded metal loading blocks, an in-plane shear force is induced along the direction of the sandwich face sheets, thereby determining the in-plane shear strength of the specimen (Figure 15). The test data for in-plane shear strength are presented in Table 10. The results indicate that, under the current fabrication process, the shear strength of the PVE interlayer is higher than that of the SGP interlayer.

Figure 15 Shear Failure State of the Specimens

Table 10 In-Plane Shear Strength Test Data

Original strength (compression-shear)				
Number	Area (mm²)	Failure load (kN)	Shear strength (MPa)	Failure mode
1（PVE）	60×60	18.84	5.23	Interlayer failure
2（PVE）	60×60	14.82	4.12	Interlayer debonding
3（PVE）	60×60	15.38	4.27	Interlayer debonding
1（SGP）	60×60	15.66	4.35	LIULI fracture
2（SGP）	60×60	11.72	3.26	Interlayer debonding
3（SGP）	60×60	11.74	3.26	Interlayer debonding

4.2.3 Freeze-thaw resistance

As shown in Figure 16, the specimens were immersed in clean water at (20 ± 2) °C for 48h, then removed and immediately placed in a freezing chamber at (–20 ± 2) °C for 4h, followed by thawing in flowing clean water for 4h. After 25 freeze–thaw cycles, the specimens were visually inspected for any abnormal appearance changes, including spalling, debonding, cracking, hollowing, or significant deformation. The percentage reduction in the average flatwise tension bond strength after the freeze–thaw test was measured and calculated. The test results indicate that the cohesive strength of the PVE laminate is higher than that of the SGP interlayer.

Figure 16 Freeze-Thaw Resistance Test of Specimens

4.3 Safety Performance Analysis of LIULI Composite Panels

The objective of the safety performance tests for LIULI composite panels is to ensure the post-impact safety of the panels—particularly the LIULI slab—after being subjected to external impact. The primary focus is on the performance of the large-format LIULI slab and the behavior of the laminating interlayer after panel fracture. The key evaluation tests are the falling weight impact delamination test and the pummel bag impact resistance test.

4.3.1 Falling weight impact delamination test

Three panel specifications were tested in the falling weight impact test. The results are shown in Figure 17 and Table 11.

The test results show that among the six LIULI panels subjected to falling weight impact at a drop height of 1.2m, no panel dislodged. Two panels developed through-thickness cracks, but the interlayer remained intact, meeting the design requirements. When the impact intensity was further increased, the LIULI surface fractured, with small spalling observed after impact.

(a) Specimen 1 (b) Specimen 2 (c) Specimen 3

Figure 17 Falling Weight Impact Test

Table 11 Falling Weight Impact Test Data

Number	Specification	Drop height (m)	Weight (kg)	Failure mode
1	1250×500×45~130 LIULI + 2.28mm PVE + 10 mm heat-strengthened glass + 1.52mm PVE + 10mm heat-strengthened glass (textured surface)	1.2	1.04	LIULI surface fractured
2	610×610×45~130 LIULI + 2.28mm PVE + 10 mm heat-strengthened glass + 1.52mm PVE + 1.52mm PVE + 10mm heat-strengthened glass	1.2	1.04	LIULI surface fractured
		1.9		LIULI surface fractured
		2.4		LIULI surface fractured with debris
		3		LIULI surface fractured, through-thickness crack
3	1250×500×30 LIULI + 2.28mm PVE + 10mm heat-strengthened glass	1	1.04	LIULI surface fractured; spalling after minor impact

4.3.2 Pummel bag impact resistance test

Furthermore, the pummel bag impact test was conducted using the actual engineering thickness configuration: 45~130mm LIULI + 2.28mm PVE/SGP + 10mm heat-strengthened glass + 1.52mm PVE/SGP + 10mm heat-strengthened glass. The pummel bag was dropped from heights of 300mm, 750mm, and 1200mm (Figure 18).

Figure 18 Pummel Bag Impact Test

The test results indicate that all PVE/SGP LIULI composite panel specimens passed the pummel bag impact test, confirming they are qualified. This demonstrates that the LIULI composite panels possess sufficient strength to withstand high-mass impacts, thereby meeting the design requirements.

5 CONCLUSION

This section addresses the challenge that no existing manufacturer, domestically or internationally, could provide an off-the-shelf product meeting the safety and stability requirements for the first large-scale application of this LIULI product to a building curtain wall. Without a proven solution, the installation faced severe risks including physical damage, spontaneous fracture and falling debris, and dislodgement due to the substantial self-weight. Therefore, a design and performance study of large-scale corrugated three-dimensional LIULI composite panels was conducted. The final design adopts adhesive bonding of a double-layer heat-strengthened glass backing to a large-format, heavy corrugated 3D LIULI slab measuring 2.5m², 350kg, with a gradient thickness of 45–130mm. After comprehensive evaluation, a modified enhanced ethylene-vinyl acetate copolymer (PVE) interlayer was selected for lamination, resulting in a structural configuration defined as: Liuli slab + 2.28mm PVE + 10mm heat-strengthened glass + 1.52mm PVE + 10mm heat-strengthened glass. This composite system ensures high safety and high stability for large-scale corrugated 3D LIULI architectural applications.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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