Academic Journal of Architecture and Civil Engineering
Print ISSN: 2960-0235
Online ISSN: 2960-0243
DOI: https://doi.org/10.61784/ajace3023

DESIGN AND SYSTEM RESEARCH OF LARGE-SCALE CORRUGATED THREE-DIMENSIONAL ARCHITECTURAL GLASS (LIULI) COMPOSITE CURTAIN WALL SYSTEMS

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Abstract: Based on the China Beijing–Hangzhou Grand Canal Museum project, LIULI composite panels are applied to a building façade on a large scale internationally for the first time. To further enhance the efficiency, safety, and stability of LIULI curtain wall installation, an in-depth design of large-scale corrugated three-dimensional LIULI composite curtain wall systems was conducted. According to the façade geometry and visual perception requirements, four categories of LIULI composite curtain wall unit panels were designed. Each unit panel achieves 3D spatial positioning through differentiated elevations at its four corners, and employs a slot-in snap-fit fixing system to simplify the installation and securing of LIULI composite panels, thereby improving both safety and efficiency in large-scale construction. To reinforce the safety rating of the LIULI composite panels, a dual fixation system of "adhesive–mechanical composite" was developed by combining sealant bonding of aluminum alloy auxiliary frames with perimeter mechanical fixing using stainless steel edge protectors, which fully guarantees the high safety and high stability of the structural system of LIULI composite curtain walls.
Keywords: Large-scale corrugated three-dimensional; LIULI composite curtain wall system; "Adhesive–mechanical composite" dual fixation; High safety; High stability

1 INTRODUCTION

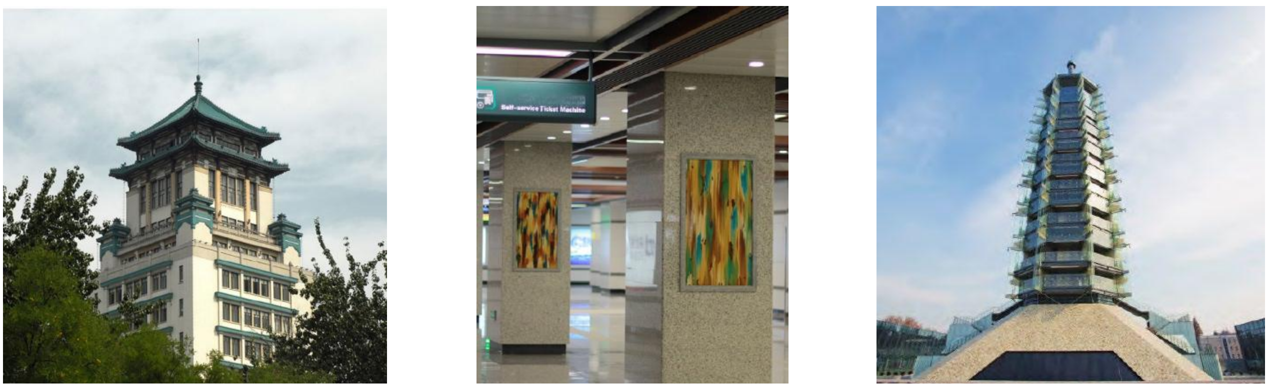
Colored glaze, as one of the appellations for ancient Chinese glass, was also a variety of artistic glass in modern times. From the discovery of colored glaze precursors in the Western Zhou Dynasty to its peak during the Kangxi and Qianlong periods of the Qing Dynasty, China had a long history of colored 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".

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

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].

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

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 (Figure 3).



(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]

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 given that LIULI composite panels, as an innovative curtain wall material, have no prior precedent in building projects, this paper proposes an in-depth design of large-scale corrugated three-dimensional LIULI composite curtain wall systems, aiming to further enhance both safety and efficiency in large-scale construction.

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

3 ANALYSIS OF THE ALUMINUM ALLOY SYSTEM FOR LARGE-SCALE CORRUGATED 3D LIULI COMPOSITE CURTAIN WALLS

The museum façade adopts a LIULI composite panel curtain wall system, featuring a smooth curved profile with an upper–middle–lower three-tier design, and a continuous strip window embedded in the middle section.

The LIULI composite curtain wall employs standard unit panels measuring 2500mm (L) × 1000mm (W). The LIULI layer adopts a variable cross-section design, with the thickness gradually transitioning from 45mm to 130mm. Each unit panel achieves 3D spatial positioning through differentiated elevations at its four corners, forming a rhythmic corrugated texture in Figure 5. A total of four panel types are configured in Figure 6, and a parametric algorithm is used to generate a non-repetitive spatial layout in Figure 7, ensuring that every panel possesses a unique spatial angle. The LIULI slabs are deep blue in color, with a distinctive corrugated surface texture. Under the effect of natural lighting, the non-repetitive spatial layout and the textured surface together produce a shimmering, dynamic visual appearance across the building façade.

The elevation arc of the LIULI composite panel units follows a datum baseline, and each unit panel is required to maintain a specified angular deviation relative to this baseline. Every panel is oriented at a horizontal intersection angle of 2.44° and a vertical intersection angle of 2.40° with respect to the reference plane (Figure 8).

The LIULI composite panels are assembled into four-edge precision frames using aluminum alloy profiles, forming independently installable and removable unit panels. The dedicated (hanging fittings) employed in this system are high-precision aluminum alloy extrusions, custom-die-manufactured to meet the 3D geometric requirements of the curtain wall, thereby ensuring installation accuracy and reliable load transfer between adjacent unit panels (Figure 9).

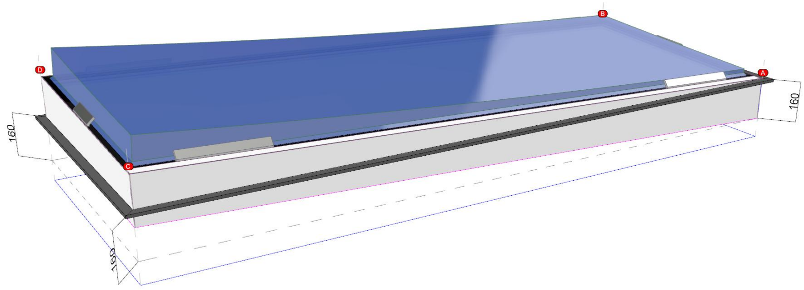


Figure 5 Standard Unit Panel of the LIULI Composite Curtain Wall

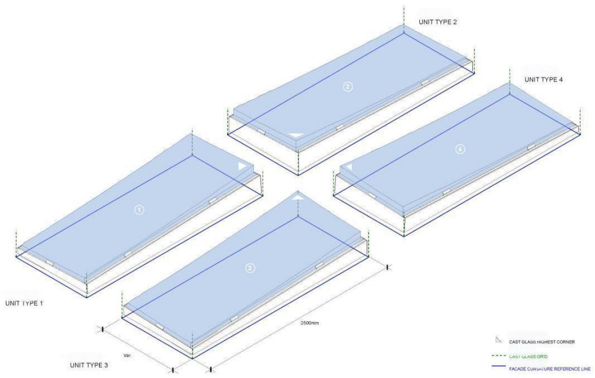


Figure 6 Four Types of LIULI Composite Curtain Wall Unit Panels

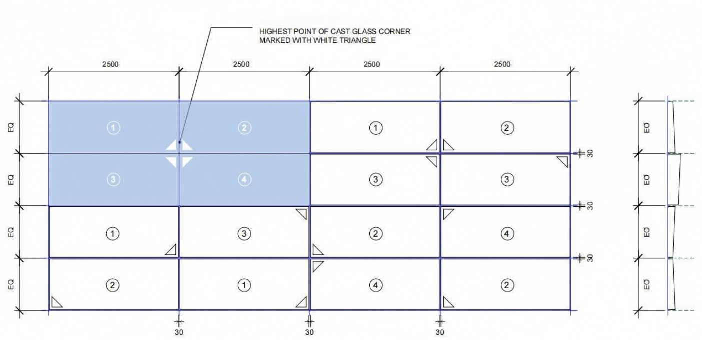


Figure 7 Layout of LIULI Composite Curtain Wall Unit Panels

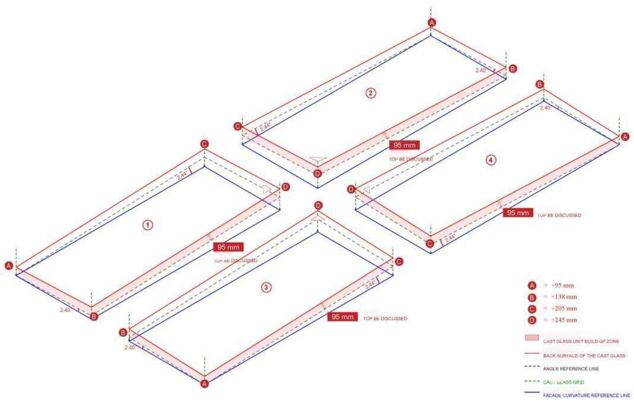


Figure 8 Angular Relationship Between LIULI Composite Curtain Wall Unit Panels and the Reference Plane

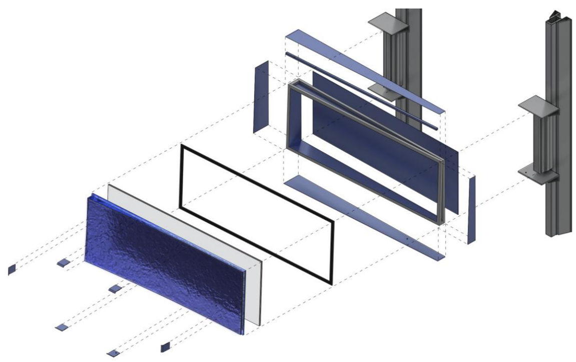


Figure 9 Exploded View of LIULI Composite Curtain Wall Units

To further enhance the safety and efficiency of large-scale construction, the LIULI curtain wall system was optimized, with the core improvement focusing on the installation and fixing method of the aluminum alloy hanging fittings. Specifically, the conventional screw-fastening method was replaced by a slot-in snap-fit fixing system for the. (Figure 10)

Figure 10 3D Model of the Optimized Dedicated Hanging Fitting for LIULI Composite Panel Curtain Walls

4 DESIGN OF ANTI-DISLODGEMENT MEASURES FOR LARGE-SCALE CORRUGATED 3D LIULI COMPOSITE CURTAIN WALLS

The LIULI composite panel consists of a 45~130mm LIULI slab + 2.28mm PVE + 10mm heat-strengthened glass + 1.52mm PVE + 10mm heat-strengthened glass. To address the issue of anti-dislodgement for LIULI composite panel curtain walls, two reinforcement measures are adopted, forming a dual-measure safeguard that further enhances the safety rating of the LIULI composite panels.

Measure 1: Silicone structural sealant is used to bond and fix the LIULI composite panel to the aluminum alloy auxiliary frame. This configuration serves as the primary load-bearing measure for the curtain wall system to resist wind loads.

Measure 2: Stainless steel edge protectors are added around the perimeter of the aluminum alloy auxiliary frame. This measure provides auxiliary mechanical fixing for the LIULI composite panel, and together with the primary structural sealant, constitutes the "adhesive–mechanical composite" dual fixation system.

Considering that the LIULI slab features a variable cross-section, the stainless steel edge protectors are positioned based on the thicker side of the slab. The 16mm thick stainless steel edge protector is connected to the aluminum frame using six M8 stainless steel grooved blind rivets. The most unfavorable cross-section (1–1) and the reduced cross-section (2–2) are calculated in Figure 11. As shown in Figures 12-13, the finite element solid-modeling analysis yields the following results: the normal stress at the most unfavorable cross-section 1–1 is 156.45MPa; the normal stress at cross-section 2–2 is 167.54MPa; the maximum deflection at the front end of the stainless steel support plate is 0.083mm; and the tensile force on a single grooved blind rivet is 6.78kN. All values meet the design requirements.

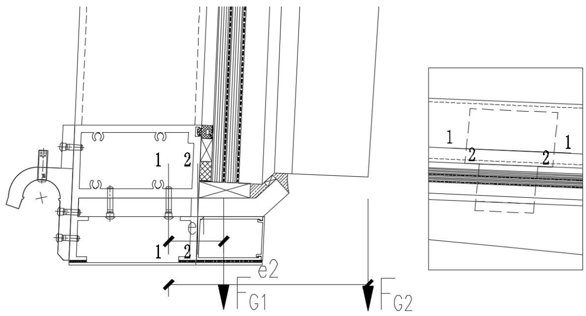


Figure 11 Partially Enlarged Detail of the LIULI Composite Panel

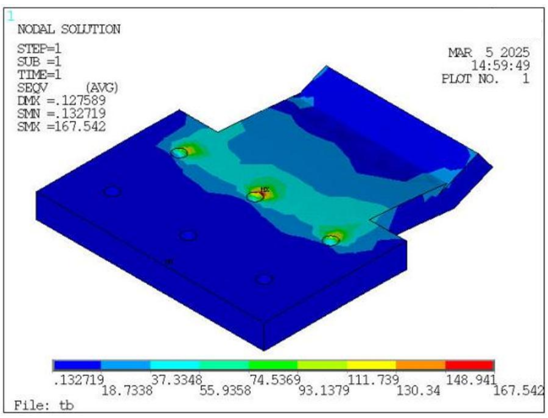


Figure 12 Stress Contour From Solid-Modeling Analysis of the Stainless Steel Edge Protector

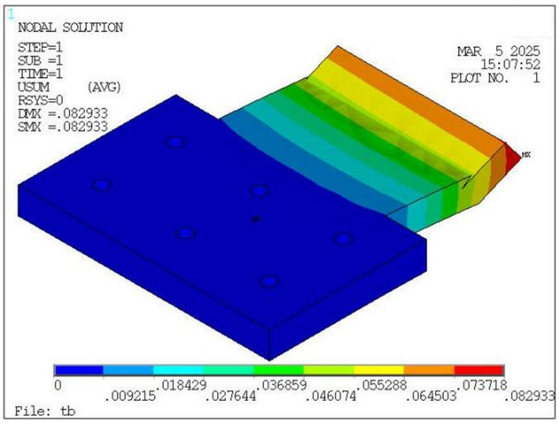


Figure 13 Deflection Contour From Solid-Modeling Analysis of the Stainless Steel Edge Protector

A single LIULI composite panel with its aluminum alloy auxiliary frame weighs approximately 550kg. Both on-site installation and panel replacement are significantly more challenging than conventional curtain wall construction. Therefore, two 16mm thick stainless steel edge protectors are installed along each long side, and one protector centered on each short side, fully ensuring construction safety.

5 CONCLUSION

LIULI composite panels are applied to a building façade on a large scale internationally for the first time, with each individual panel measuring 2.5m² and weighing 350kg net, featuring a gradient thickness of 45–130mm, and covering a total area of approximately 17800m². To further enhance the efficiency, safety, and stability of LIULI curtain wall installation, this paper conducts an in-depth design of large-scale corrugated three-dimensional LIULI composite curtain wall systems. According to the façade geometry and visual perception requirements, four categories of LIULI composite curtain wall unit panels are designed. Each unit panel achieves 3D spatial positioning through differentiated elevations at its four corners, and employs a slot-in snap-fit fixing system to simplify the installation and securing of the curtain wall, thereby improving both safety and efficiency in large-scale construction. To reinforce the safety rating of the LIULI composite panels, a dual fixation system of "adhesive–mechanical composite" is developed by combining sealant bonding of aluminum alloy auxiliary frames with perimeter mechanical fixing using stainless steel edge protectors, which fully guarantees the high safety and high stability of the structural system of LIULI composite curtain walls.

COMPETING INTERESTS

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

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