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Jinao Tower – The Design Integration of Structural Efficiency, Architectural Expression and High Performance Exterior Wall Systems

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ABSTRACT: The 56 story, 232 m tall Jinao Tower in Nanjing, China, is a next-generation tower which maximizes performance, efficiency, and occupant experience. Its faceted form is derived from the juxtaposition of an innovative double-skin façade and an external lateral braced steel frame that wraps the tower from crown to base and defines the dimensions and folds of the building envelope. The structural system responds harmoniously to the faceted exterior form with a reinforced concrete tube-in-tube structure wrapped with a perimeter braced steel frame. Introducing the diagonal steel brace system on each side of the structure (outside of the tube-in-tube structure and between the double-skin facade) resulted in additional stiffening of the structure and a 40% design reduction in concrete and rebar in the concrete lateral load resisting system and a 20% design reduction in concrete and rebar for the overall building structure. The integrated double-skin façade provides solar shading and creates a climatic chamber of air, offering improved insulation in both the hot summer and cool winter months. Vented openings in the outer exterior wall allow wind pressure to extract built-up heat out of the cavity, lowering temperatures along the inner exterior wall. Together, the external steel bracing system, integrated into the high performance double-skin façade, provides an easily identifiable iconic tower with cultural references to “lantern” forms.

1 INTRODUCTION

Many buildings around the world are considered to be structures “decorated" by the exterior wall system. Some clever structural systems and their inherent ideas are thus covered up, to only be rediscovered with the eventual building demolition. The exterior wall certainly serves many other purposes beyond providing a desired aesthetic. These include providing a weather resistant enclosure, controlling exposure to sunlight, and responding responsibly to energy use. From a structural engineering perspective, this exterior boundary defined by the building form provides great opportunities for sustainability, structural efficiency and design integration.

2 STRUCTURAL DESIGN INTEGRATION

The initial structural system for the Jinao Tower was conceived considering an interior tubular reinforced concrete shear wall core and an exterior tubular frame. The perimeter folded planes of the architectural expression provided an opportunity to incorporate a perimeter bracing system along the fold lines to achieve greater structural efficiency. The additional stiffness provided by a perimeter bracing system allowed the central shear wall core to be progressively “punched” into an interior tubular frame, thereby providing greater flexibility to meet programmatic needs as well as material economy. The structural system evolved to include an innovative diagonal bracing system with single diagonal steel pipe braces along each facade located outboard of the concrete tube-in-tube structure in the interstitial space between the inner and outer walls of the double skin façade. The 500mm diameter steel pipe braces connect to the base building reinforced concrete structure at the four corner composite columns every 16 m in height (4 stories at office levels and 5 stories at hotel levels) with cast steel pin assemblies.

The steel braces efficiently direct lateral loads from the superstructure to the foundation. Loads are managed, optimally shared between the core, perimeter frame and perimeter steel braces. Introducing the wrapping diagonal steel brace system on each side of the concrete tubular structure resulted in a 40% design reduction in concrete and rebar in the lateral load resisting system, and a 20% design reduction in concrete and rebar for the overall building structure.

Several special studies were conducted to explicitly ensure the redundancy, ductility, and overstrength of the structural system. First, 3D non-linear pushover and time-history analyses were conducted to verify “life-safety” performance during rare earthquake demands (2000 year return) exceeding “collapse prevention” goals typically associated with such events. Second, key members and components including the steel pipe braces were designed to enhanced criteria to ensure that they would remain elastic well beyond the baseline frequent earthquake (50 year return). Third, the force levels in the perimeter steel pipe braces were rechecked after the removal of any one brace to verify the redundancy of the structural system. Lastly, reduced scale shake table testing of the entire building and full scale testing of the typical exterior brace corner connection were conducted to validate expected performance.

3 EXTERIOR ENCLOSURE

The double skin exterior enclosure consists of an inner wall (building enclosure), interstitial space, and the exterior aluminum and glass screen. The inner wall is the weather resistant skin separating the building occupants from the exterior elements. At occupied spaces (offices and hotel floors), it consists of floor to ceiling insulated low-e glass set in extruded aluminum prefabricated unitized frames.

The interstitial space consists of tapered steel outriggers at each floor to establish the geometry work points for the triangular faceted exterior glass screen and to support horizontal aluminum grating catwalks. The interstitial space creates the air cavity between the wall systems.

The exterior aluminum and glass screen triangular sections consist of extruded aluminum factory pre-fabricated unitized frames with monolithic, lightly tinted glass spanning floor to floor and are connected to the steel outriggers. Horizontal formed aluminum openings occur at every 16m in height to allow air intake (windward side) and exhaust (leeward side).

A Computation Fluid Dynamic (CFD) analysis was performed to study the interstitial space air temperatures and movement. CFD analysis results revealed that air within the interstitial space moves horizontally as air is drawn in on the windward side and extracted on the leeward side lowering temperatures along the inner wall. The buffered air temperatures along the inner wall in both the hot summer and cool winter months effectively reduce demands on the base building mechanical systems by up to 20%.

Fig. 1: Jinao Tower

4 CONCLUSION

The exterior envelope of a building, often defined by the building form, can provide unique structural design opportunities by utilizing an integrated design approach. Through early design collaboration, major design elements can be organized to create a superior multi-disciplinary design engaging architectural, structural, and other building disciplines.

Jinao Tower – The Design Integration of Structural Efficiency, Architectural Expression and High Performance Exterior Wall Systems

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1 INTRODUCTION

How do we see structures? Frames decorated with exterior walls? Some of these walls are quite elaborate, using expensive materials to create a desired aesthetic; often responding with color and geometry to particular site conditions, or sometimes simply ignoring them.

In building construction, many have drawn analogies to the human body, citing the comparative relationship between skeleton (frame), circulatory system (mechanical / electrical / plumbing systems), and the skin (exterior wall). Isn't there more?

Many buildings around the world are considered to be structures "decorated" by the exterior wall system and architectural finishes. Some clever structural systems and their inherent ideas are thus covered up, to only be rediscovered with the eventual building demolition, removal and replacement of the exterior enclosure, or, occasionally, publication in a technical paper.

The idea that a structure is designed, built, and merely decorated to achieve a desired aesthetic is, of course, not accurate; although one might wonder the motivation behind many building projects. The exterior wall certainly serves many other purposes. These include providing a weather resistant enclosure, controlling exposure to sunlight, protecting the occupants, providing natural daylight to occupants, and responding responsibly to energy use. From a structural engineering perspective, this exterior boundary defined by the building form provides great opportunities for sustainability, structural efficiency, and design integration.

2 ARCHITECTURAL CONTEXT

The Hexi (west of the river) master plan for Nanjing, China, called for a pair of towers with simple, pure forms accommodating office and hotel uses and forming a gateway to a large neighboring park. The Jinao Tower serves as one of these towers.

The Jinao Tower occupies a 198,310 square meter site. The project consists of a 56-story office/hotel tower, a 5-story multi-use podium structure, and a 20-story service apartment building. The Tower is located at the south east corner of the site. The Tower consists of two stories below existing grade and 56 stories above grade for a height of 209m to the floor of the last occupied floor and 232m to the top of the architectural crown. The tower footprint is approximately 42m by 42m square with a total floor area of 105,000 sq. m.

Fig. 1: Jinao Tower

3 STRUCTURAL DESIGN INTEGRATION

3.1 Historical Perspective

Technical developments in the 1960s, spearheaded by Dr. Fazlur Khan, structural design partner at Skidmore, Owings & Merrill LLP, and others, resulted in buildings where the exterior structure not only dominated their architectural expression but led to great advancements in management of imposed loads and structural efficiency. Many would argue that it was not until the design and construction of the John Hancock Center (1969) in Chicago that architecture and engineering were synergistically bonded with optimal structural efficiency.

Dr. Fazlur Khan, the John Hancock Tower's designer, understood the limitations of conceiving a tall building as a tube, with solid but thin walls. Introduction of openings for windows, thereby reducing stiffness, was a must. He discovered, however, that the considered placement and portioning of openings could still lead to efficient tube structures. He transformed this idealistic concept into a constructible, affordable system by developing closely spaced columns and beams to form a rectilinear grid. Simply introducing diagonal members into the tubular frame resulted in greater efficiency with height. This system was conceived for buildings consisting both of all-steel and all-concrete. [Khan, 2004]

Fig. 2: John Hancock Tower, Chicago, IL

3.2 Initial Concepts

The initial structural system for the Jinao Tower was conceived considering an interior tubular reinforced concrete shear wall core and an exterior tubular frame as shown in Figs. 3a and 3b. Drawing upon the historical past, the perimeter folded planes of the architectural expression provided an opportunity to incorporate a perimeter bracing system along the fold lines to achieve greater structural efficiency. The additional stiffness provided by a perimeter bracing system would allow the central shear wall core to be "punched" into an interior tubular frame as shown in Fig. 3c providing greater flexibility to meet programmatic needs as well as material economy. Initial concepts for the perimeter braced frame included traditional chevron bracing with conventional horizontal, vertical and diagonal members. Further developments led to the conception of an innovative diagonal bracing system as shown in Fig. 3d. When viewed holistically, the diagonal bracing members on opposite faces form X-braces through the structure as shown in Fig. 3e.

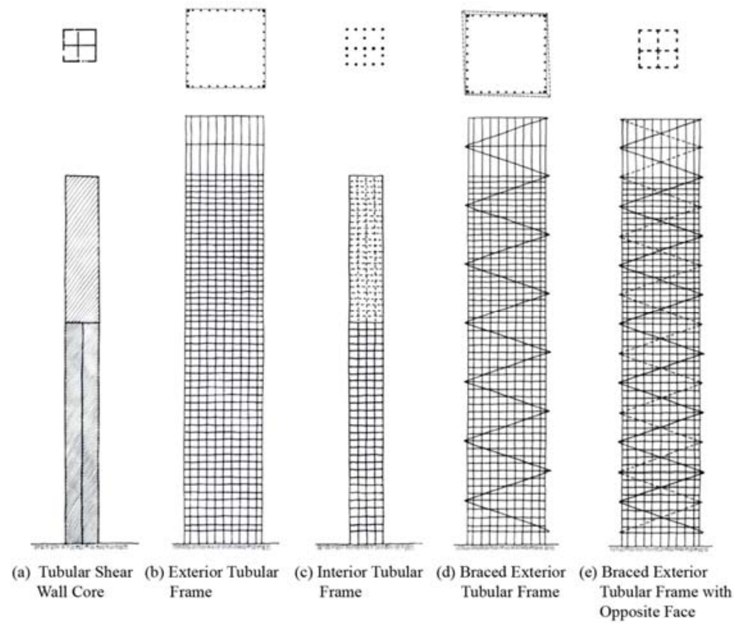

Fig. 3: Evolution of the structural system

3.3 Design Refinements

The reinforced concrete tube-in-tube structure integrated with the typical office and hotel programs defined the overall tower plan footprint of approximately 42m x 42m. The interior shear wall core was developed to be approximately 20m x 20m. The resultant column free lease span between the interior shear wall core and the exterior tubular frame is 11.3m. The exterior tubular frame columns, along with the typical reinforced concrete floor framing beams, are spaced at 4.5m on center. Typical floor framing consists of 135mm thick reinforced concrete one-way slabs spanning between the 750mm deep reinforced concrete floor framing beams. Typical office and hotel floor framing plans are shown in Fig. 4 and Fig. 5 respectively.

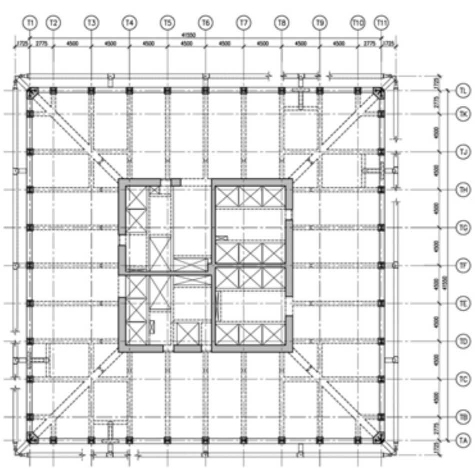

Fig. 4: Typical Office Level Framing Plan

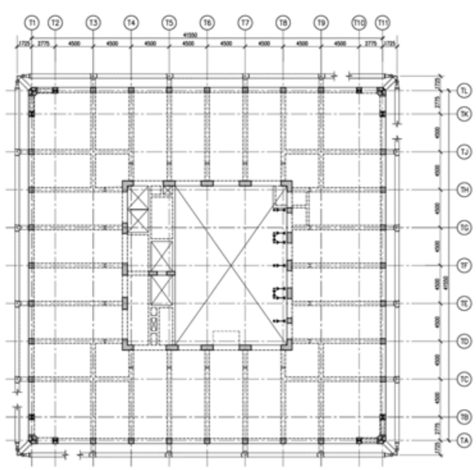

Fig. 5: Typical Hotel Level Framing Plan

The interior shear wall core was specifically punched to create increased flexibility for occupancy use while adjusting stiffness properties. In the lower office floors of the tower, the walls contain typical openings for entry to elevator lobbies and other service areas while in the upper hotel floors, more significant openings were created allowing for a grand central open atrium space. The engineered reduction in central core stiffness allowed for lateral forces to be efficiently shared with the exterior steel braces.

The perimeter external steel bracing system consists of a single 500mm diameter steel pipe diagonal member on each façade. The centerline of the external steel bracing system is located 1350mm outside the face of the perimeter reinforced concrete tubular frame and between the inner and outer enclosure of the double-skin façade as shown in Fig.6. The steel pipe braces connect to the base building reinforced concrete tube-in-tube structure at the four corner composite columns every 4 floors at the office levels and every 5 floors at the hotel levels with cast steel pin assemblies. With floor-to-floor heights of 4.0m at office levels and 3.2m at hotel levels, the perimeter external brace connections to the corner columns occur every 16.0m along the entire height of the Tower. The steel pipe braces also connect to the base building structure at every 9.0m along the elevation for lateral bracing support. The elevations of the interior shear wall core, exterior tubular frame and the external perimeter bracing system are shown in Figs. 7, 8 and 9 respectively. An enlarged composite elevation is shown in Fig. 10.

Fig. 6: Perimeter System Model

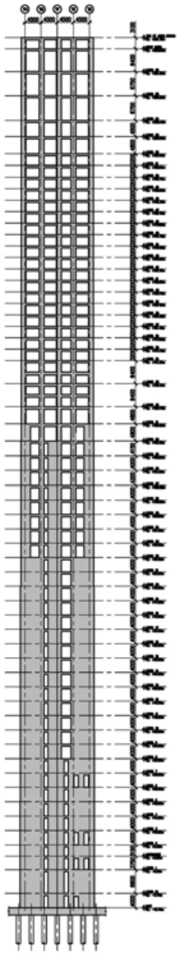

Fig. 7: Interior Shear Wall

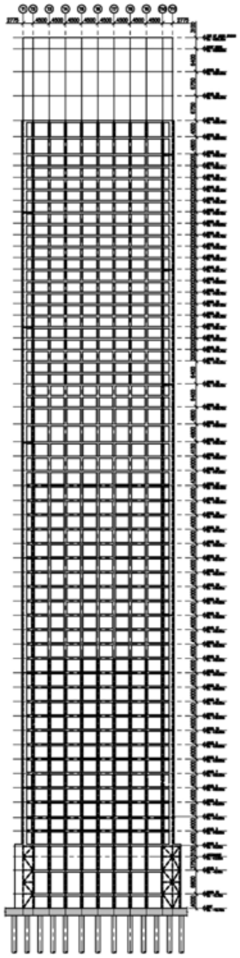

Fig. 8: Exterior Tubular Frame

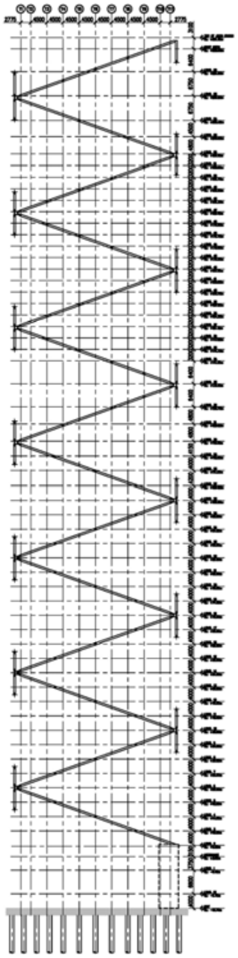

Fig. 9: External Bracing System

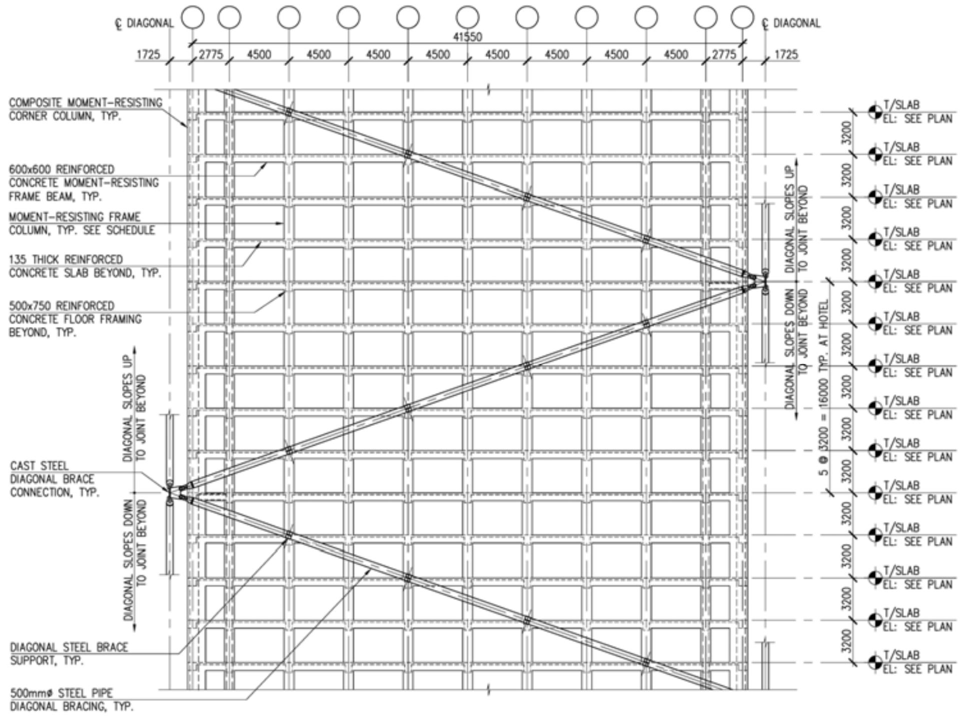

Fig. 10: Enlarged Composite Elevation at Typical Hotel Levels

3.4 Structural Efficiency

The steel braces, only 500 mm in diameter with a typical wall thickness of 25 mm, are designed to resist only lateral loads and superimposed live loads by stipulating a construction sequence and appropriate joint details. The braces efficiently direct lateral wind and seismic loads from the superstructure to the foundation. Loads are managed, optimally shared between the core, perimeter frame and perimeter steel braces through the “tuned” stiffness of the individual systems. The distribution of lateral load between the interior shear wall core, the exterior tubular frame and the external perimeter steel braces over the building height is shown in Fig. 11.

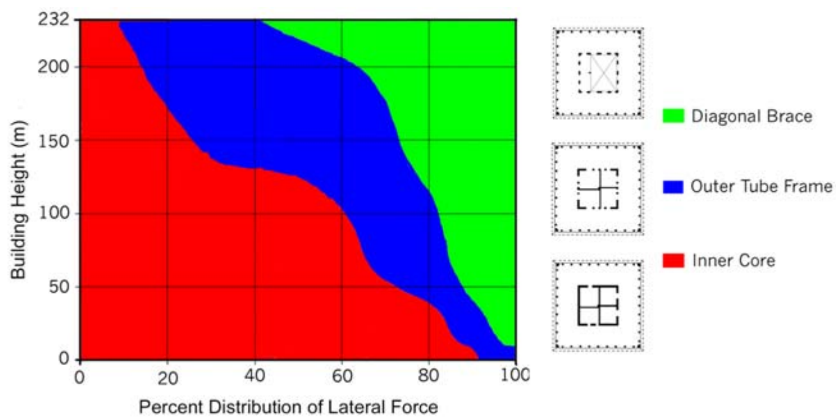

Fig. 11: Percent Distribution of Lateral Force vs. Building Height

Introducing a wrapping diagonal steel brace system on each side of the concrete tubular structure resulted in additional stiffening, a 40% design reduction in concrete and rebar in the lateral load resisting system, and a 20% design reduction in concrete and rebar for the overall building structure. Since less material was required for each lift of the structure, the construction time was estimated to reduce from 6 days per story to 4.5 days per story.

3.5 Design Verification

Many super-tall building structures in China fall outside the prescriptive Chinese code limits for their respective structural system or contain unique design aspects not directly addressed in the codes. Such non-prescriptive buildings are subject to expert panel reviews (EPR) that provide comments and ultimately render a judgment that the structural system of choice meets the intent of the codes. For the Jinao Tower, the Tower height, along with the hybrid structural system of reinforced concrete tube-in-tube and external steel bracing, triggered the need for such a review.

Several studies beyond typical code checks were conducted to explicitly ensure the redundancy, ductility, and overstrength of the proposed structural system. First, a 3D non-linear pushover analysis was conducted using a loading function proportional to the first mode. The results show that the plastic deformation within the structural elements do not exceed a "life-safety" (cyan colored) performance level at maximum roof displacement. Furthermore, a 3D non-linear time-history analysis was conducted using three sets of appropriately scaled rare earthquake (2000 year return) time-history records again verifying "life-safety" performance. This level of performance exceeds the "collapse prevention" goal typically associated with rare earthquake events. The maximum interstory drift was found to be H/180, less than the code maximum H/100.

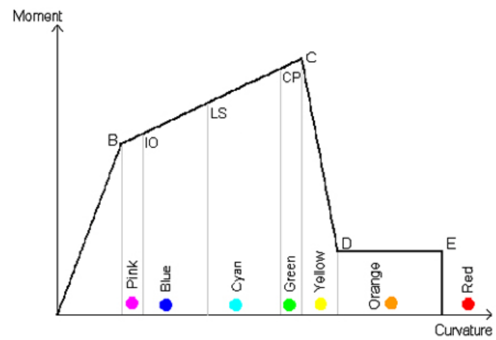

Fig. 12: Moment Rotation Hinge Definitions

Second, key members and components were designed to enhanced criteria to ensure that they would remain elastic well beyond the baseline frequent earthquake (50 year return) design requirements as defined by the Chinese code. The key members and components were also detailed to be more ductile than typical lateral system members and components. These include the base of the core shear walls where plastic hinging is expected to occur. The external perimeter steel pipe braces were also designed not to buckle and their connections not to yield under a moderate earthquake (475 year return period) as defined by the Chinese code.

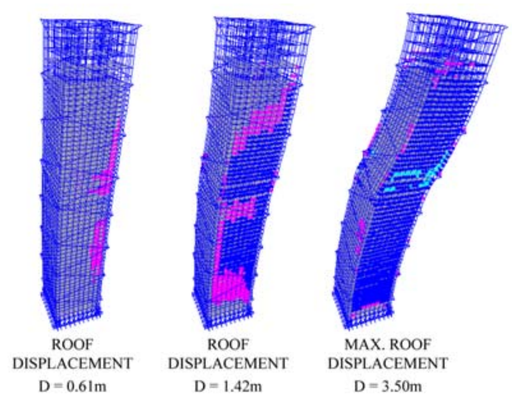

Fig. 13: Pushover Analysis Steps

Third, the force levels in the perimeter steel pipe braces were re-checked after the removal of any one brace to verify the redundancy of the structural system. The redundancy capability of the structure is measured by the ability of the loads to satisfactorily redistribute around the removed member and throughout the structural system.

Lastly, reduced scale shake table testing was conducted of the entire building. All lateral load resisting structural elements were appropriately scaled and constructed including shear walls, moment frame columns and beams, and the perimeter external steel braces. Results of the shake table testing confirmed expected performance levels. Full scale testing was also performed on a typical exterior brace corner connection.

Fig. 14: Shake Table Testing

4 EXTERIOR ENCLOSURE

The double skin exterior enclosure begins above the granite clad tower base and repeats in 16m high (4 stories at office levels and 5 stories at hotel levels) triangular faceted inward and outward sloping sections to the top of the Tower. The hypotenuse of the 16m high aluminum and glass façade sections follows the diagonal steel bracing members. The primary elements and zones of the double skin enclosure are:

1. Inner wall (building enclosure)
2. Interstitial space
3. Exterior aluminum and glass screen

These elements are shown in Fig. 15. The design criteria established by the design team was:

1. Increased exterior wall performance
2. Reduction in mechanical space thereby increasing occupied floor use and efficiency
3. Increased acoustic performance

The inner building enclosure is the weather resistant skin separating the building occupants from the exterior elements. At occupied spaces (offices and hotel floors) it consists of floor to ceiling insulated low-e glass. The glass is held in thermally broken extruded aluminum factory prefabricated unitized frames. The spandrel zones are clad in 5 mm thick custom fabricated aluminum plate with a high performance coating. The interior side of the aluminum plate has 75 mm thick semi-rigid insulation and continuous flashing from the window head of each floor to the window sill of the floor above. The flashing and aluminum spandrel plates are handset on site. The flashing is sealed around penetrations for the diagonal cast steel bracing nodes attached to the tubular concrete frame and the tapered steel outriggers spaced at the 1500 mm on center mullion spacing.

The interstitial space consists of tapered steel outriggers at each floor at 1500 mm on center spacing with varying lengths to establish the geometry work points for the triangular faceted exterior glass screen and aluminum grating catwalks spanning between outriggers. The interstitial space creates the air cavity between the wall systems and accommodates building maintenance for the outer surface of the inner wall and the inner surface of the exterior glass screen. Light fixtures are mounted on the grating for exterior night lighting.

The exterior aluminum and glass screen triangular sections are defined by the hypotenuse parallel to the diagonal steel brace, vertical leg at the building corners and horizontal leg every 16m in height. The triangular sections slope inward/outward and are connected to the steel outriggers at each floor. Extruded aluminum factory pre-fabricated unitized frames with monolithic, lightly tinted glass span floor to floor and are connected to preset anchors connected to the steel outriggers. Horizontal formed aluminum openings (200 mm net clear opening) occur at every 16m in height. The openings allow air intake (windward side) and exhaust (leeward side). The hypotenuse of the triangular sections allows for the geometry transition in section from outward

Fig. 15: Exterior Enclosure

Fig. 16: Jinao Tower

or inward slopes. A continuous silicone gasket between unitized frames runs parallel to the hypotenuse, allows thermal expansion and contraction, and accommodates deflection of the diagonal steel brace.

The double skin enclosure climate performance by element consists of the following:

- Insulated inner wall: The performance requirement for glass areas and opaque areas (aluminum plate with insulation) were initially established without the benefit of the interstitial air space or exterior glass screen to generate baseline criteria for material selection, insulation thickness/thermal properties and glass performance criteria.
- Interstitial air space: Computational Fluid Dynamic (CFD) analysis for air cavity temperatures and air movement were performed for summer and winter conditions. The CFD model included air temperatures on the exterior glass screen, the resulting cavity air temperature, and air movement within the cavity. Meteorological data on wind speeds and direction were incorporated into the CFD analysis. CFD analysis results revealed that air within the interstitial space moves horizontally as air is drawn in on the windward side and extracted on the leeward side as shown in Fig. 17. The horizontal slot openings were sized to optimize air movement horizontally around the structure.

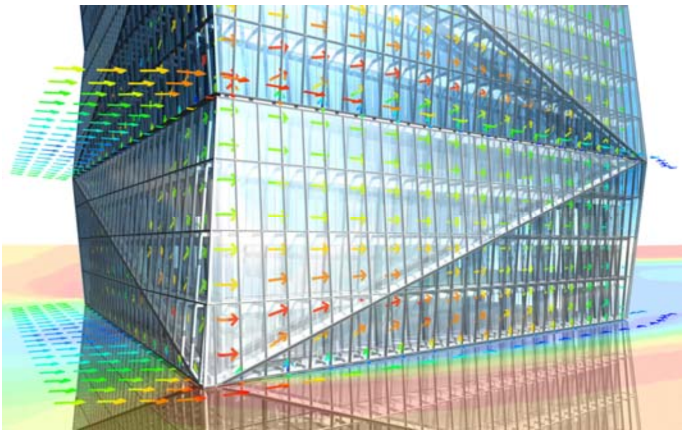

Fig. 17: Computational Fluid Dynamic (CFD) Analysis

The exterior aluminum and glass screen wall provides solar shading and creates a climatic chamber of air, offering improved insulation in both the hot summer and cool winter months. In hot summer months, the vented openings in the exterior aluminum and glass screen allow wind pressure to extract built-up heat out of the cavity, lowering temperatures along the inner wall. In cool winter months, built-up heat in the cavity, although partially extracted through the vented openings, increases temperatures along the inner wall. The buffered air temperatures along the inner wall in both the hot summer and cool winter months effectively reduce demands on the base building mechanical systems by up to 20%.

5 CONCLUSION

The exterior envelope of a building, often defined by the building form, can provide unique structural design opportunities by utilizing an integrated design approach. Through early design collaboration, major design elements can be organized around site objectives, a particular design parti, or other influential factors to create a superior multi-disciplinary design engaging architectural, structural, and other building disciplines. Structural engineering design goals such as strength, serviceability, structural efficiency, and sustainability, can be not only achieved, but achieved with grace and beauty.

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