Gensler

Shanghai Tower Façade Design Process

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In designing the façade for Shanghai Tower, a 124-level, 632-meter (2,074 feet) highrise, Gensler introduced a combination exterior and interior curtain wall system totaling 210,000 square meters (2.26 million square feet) of glazing area. This paper traces the development of the overall curtain wall system, focusing on exterior proposed design options and the issues associated with each of them, and discusses the underlying decision-making that led to the final documented option.

This paper was delivered at the 2010 International Conference on Building Envelope Systems and Technologies (ICBEST 2010) held in Vancouver, Canada. Shanghai is located at 120°51'~122°12' east and 30°40'~31°53' north, in the eastern part of Asia. It is on the west coast of the Pacific Ocean, the center-point of the north and south coast in the Peoples Republic of China, on the edge of the East China Sea. The prevailing climate is a subtropical monsoon climate, with weather that is hot and very humid during summer. It has four distinct but mild seasons with full sunshine and plentiful rain.

Outside atmospheric temperature range from $27F(-2^{\circ}C)$ to $95F(35^{\circ}C)$, with an annual average temperature in the urban district of 64F (18°C). Humidity levels vary daily but are constant through the year. Annual precipitation is more than 1,440 mm. Fifty percent of the annual precipitation falls in the flood season between May and September. There are many northwestern and southeastern winds throughout the year. The average annual amount of sunlight is 1,547 hours, with insulation varying from 2.56 to 5.15 kWh/m²/day.

Now under construction, Shanghai Tower is the third and final planned super-high-rise building in Shanghai's Pudong area that completes the development of the Lu Jia Zui Central Financial District. With a large program totaling about 540,000 m² (5,815,000 square feet) of built enclosed area, 380,000 m² (4,100,000 square feet) are above grade and 160,000 m² (1,715,000 square feet) are below grade.

The tower has been designed as a soft vertical spiral rotating at about 120 degrees and scaling at 55% rate exponentially. The tower functions as a self-sustaining vertical city. It is a mixed-used building of unique, vertically interconnected neighborhoods that evolve as the tower slowly rises toward the sky. The building will comprise 120 floors plus four additional



Figure 1: Shanghai Tower Site, Lu Jia Zui

floors of equipment rooms and Tuned Mass Damper (TMD). The top of the structure is at 632 meters (2,074 feet) height.

The building is divided into nine zones with five main functions: office; boutique office; luxury boutique hotel; themed retail, entertainment and cultural venues at the podium; and the observation experience at the tower's pinnacle. Within each zone are atrium spaces that operate as activity centers and a gathering place for people within their "zone" community. Additionally, each atrium is designed to accommodate access by the general public. The concept of the podium is to become activated with people, allowing uninterrupted public circulation between three adjacent "super-high-rises," and be open and interconnected with the neighboring community.

Design Considerations

Building Geometry

The tower's profound twist expression is the result of its geometry, which can be broken down into three key components that are controlled in total by four variables:

1. *Horizontal profile* (Figure 3): The profile shape is based on an equilateral triangle. Two tangential curves offset at 60 degrees were used to create a smooth shape. This



Figure 2: Proposed vertical zone division



Figure 3: Horizontal profile geometry



Figure 4: Vertical profile geometry

shape is driven by two variables: the radius of the large circle and its location relative to the center of the equilateral triangle (profile). It should be noted that the actual shape of the profile is independent of the remaining two key geometric drivers. As a result, Gensler had the ability to look at the effect of modifying the horizontal profile and the impact such changes had on the tower form at all stages of the design.

2. Vertical profile (Figure 4): The concept of the form is to take the horizontal profile and extrude it vertically and conform to the vertical profile. From a functional point of view, it was important to maintain a wide footprint for the lower third of the tower, with a slender footprint at the upper third—a reduction of about 55% overall. This proportional distribution allowed for large lease spans within the office portion of the tower and smaller spans within the upper-level hotel/boutique offices. Early in the design, it was found that a basic exponential curve provided the desired result. This is the same basic formula used in the finance industry for continuous compounding and/or discounting. Adjusting the two values in the horizontal profile and this third value in the vertical profile, we now have complete control of vertical ratio, gross floor area and building form.



hPV - horizontal profile value gIPV - profile value at given location in height e - euler number - numeric constant equals to 2.2 in - percentage reduction

Discounting formula based on exponential function adapted to suit geometric analysis for Shanghai Tower

3. *Rate of twist:* This is a simple linear rotation from base to top. The fact that this final value can be changed independently allowed for great flexibility in the design stage, especially in selecting the best combined overall building performance.

Wind Tunnel Testing Results

Wind tunnel testing was essential for understanding building performance and was conducted at Rowan, Williams, Davies & Irwin Inc. (RWDI). The wind tunnel test procedures were based on requirements set out in Section 6.6 of the ASCE



Figure 5: Wind tunnel study model, 1:500 scale



Figure 6: Reynolds number study model, 1:85 scale (RWDI)





Figure 7: Wind tunnel study scaling models

7-05 Standard and the Load Code for the Design of Building Structures GB 50009-2001 for the P.R.C. Additionally, to predict the full-scale structural response and more detail pressure loads, the wind tunnel data were combined with a statistical model of the local wind climate. The wind climate model was based on local surface wind measurements taken at Hong Qiao International Airport and a computer simulation of typhoons provided by Applied Research Associates, Raleigh, North Carolina. All testing was conducted on a 1:500 model. Additionally, a 1:85 scale model was tested for results of the Reynolds number correction factor that was used for more precise data on loading and the impact of wind vortex split on round exterior wall surfaces.

The Gensler design team had anticipated that significant reduction in both tower structural wind loading and wind cladding pressures could be established if the building further improved its proposed geometry following the variables previously explained. To establish the best possible case for reducing these loads, several scenarios were proposed involving rotation at 90°, 120°, 150°, 180° and 210° and then scaling off 25%, 40%, 55%, 70% and 85%. All these scenarios were analyzed against each other and then compared to the base case scenario that was proposed, in the form of a tapered box.

Results acquired through this process have shown that a scaling factor of about 55% and rotation at 120° can account for up to 24% savings in structural wind loading and cladding pressure

Figure 8: Wind tunnel study rotation models



Figure 9a: Main structure and building systems diagram

reduction as compared to base-case tapered box. This equates to about \$50 million (USD) in savings in the building structure alone. Additionally, it helped optimize and distribute maximum cladding loads on the building while maintaining desired aesthetics. Aesthetic concerns prevented the 180° rotation from being pursued, even though it would reduce loading by an additional 9% (Figure 10).

Ongoing testing procedures included Reynolds number testing conducted with a final model at 1:85 scale. During this testing, constraints particular to the site were exemplified with Jin Mao and Shanghai World Financial Center, which combined generate a localized increase in lateral turbulence intensity between 14% and 40%. During testing for the high Reynolds number, the following was concluded:



Figure 9b: Comparison models used for RWDI final studies



| Configuration | My (N-m) | Ratio | Mx (N- m) | Ratio | Ref.Resultant | Ratio |
|-----------------------|----------|-------|--------------|-------|---------------|-------|
| Base (Tapered Box) | 5.45E+10 | 100% | 4.98E+10 | 100% | 6.22E+10 | 100% |
| 100° (107°) | 4.53E+10 | 83% | 4.19E+10 | 84% | 5.18E+10 | 83% |
| 110° (118°) | 3.97E+10 | 73% | 4.31E+10 | 87% | 4.92E+10 | 79% |
| 120° (129°) | 3.43E+10 | 63% | 4.29E+10 | 86% | 4.75E+10 | 76% |
| 180° (193°) | 3.39E+10 | 62% | 3.65E+10 | 73% | 4.18E+10 | 67% |

Total Construction Cost 9.0 billion RMB Structure 24% - 288m USD 5% load reduction = 70 m RMB = 10 million USD

Figure 10: Wind loading testing results comparison (RWDI)

"While the positive pressures are unaffected by the Reynolds number, the negative pressures could be increased at a high Reynolds number. Approaching wind turbulence tends to reduce the Reynolds-number effects. To account for potential Reynolds-number effects for cladding design, it is recommended that the exterior peak negative pressures around the building corners determined from the 1:500 scale model tests should be increased by 10%. This correction is applicable to the upper third of the building. For lower portions of the building, the Reynolds-number effects tend to be insignificant due to high turbulence levels. Similar corrections should also be considered in the structural wind loads for the curtain wall support system."¹

Final cladding loads testing results revealed that peak positive loads (pressure) are at about 2.0 to 2.5 kPa for about 97% of the building, with 2.75 kPa maximum. Peak negative loads (suction), on the other hand, is at 4.5 kPa for about 85% of the building, with 6.5 kPa maximum. Peak negative loads are distributed considerably around corners and at the upper building half toward the top. At the same time, the highest instant differential pressure between two subsequent curtain panels on exterior wall can reach +/-1.5 kPa in either horizontal or vertical direction. Interior curtain wall cladding loads were at 2.1 kPa.

Here the Gensler team made an assumption in order to coordinate the erection sequence of Curtain Wall B, which will not see real wind-imposed pressures. The proposed curtain wall design strategy suggested addressing 85% of the negative 4.5 kPa with a standardized segmented unitized system that is uniform throughout the building's exterior glass wall. Peak loads of up to 6.5 kPa corresponded to locations on the building where curtain panels were smaller in width due to the tower scaling factor on the same number of curtain panels per floor. This allowed that design glass thickness stayed uniform while vertical mullions were reinforced where needed to respond to high lateral stresses.

Curtain Wall Support System

Responding to an array of conditions in Shanghai, Gensler's team proposed a building design that employs a curtain wall system designed as a symbiosis of two glazed walls—an exterior curtain wall (Curtain Wall A) and an interior curtain wall (Curtain Wall B)—with a tapering atrium in between. The main support for the exterior curtain wall is a horizontal ring beam consisting of a horizontal pipe 356 mm in diameter laterally supported, at 10 meters on-center in Zone 2 and 7 meters on-center in Zone 8, by a radial pipe strut support. This variation is a result of the geometry that included tapering and rotation of the tower.



Figure 11: Diagram of positive and negative wind cladding loads (RWDI)

The horizontal radial pipe strut supports consist of a 219-mm diameter pipe (with varied but mainly 22 mm wall thickness) that transfers the exterior façade lateral load to the inner circular building slab edge. The radial strut pipes are rigidly connected with the horizontal girt while using a hinge connection on the other side—at the interior slab edge steel support—to allow the exterior façade to move up and down relative to the inner structure.

To carry the gravity load of the façade and façade support structure, two 60-to-80-mm high-strength rods (depending on the zone) are hung from the mechanical room/refuge area above, with a robust steel structure designed within, to the horizontal 356-mm ring pipe beams at 4.5 meters (4.3 meters in Zones 7 and 8) on-center vertically at every strut location, including an amenity floor that uses steel bushings instead of perpendicular struts to limit lateral movement. Steel bushings move in vertical direction to allow for expected combined closing and opening movements to be largest at Zone 2, at 114 mm.

This is also where the curtain wall system vertical expansion joint is located. In the horizontal direction, there are total of eight expansion joints, each allowing typically about 56 mm of combined open and closing movement. Special considerations were given to fire protective requirements of the Curtain Wall Support System (CWSS), and additional allowances had to be provided to total vertical and horizontal movements.²





Figure 12: Section perspectives with curtain wall systems description



Figure 13: Tower curtain wall support system (CWSS)



Figure 14: Typical atrium top and bottom Curtain Wall A connections

Energy Performance

The main feature considered for the exterior wall performance is based on a bio-climatic concept of a passive atrium system, where two skins are located in such a way as to create a large, full-height atrium space capitalizing on all the benefits that captured air—and the natural convection of air—can provide. Although a completely passive "greenhouse" effect could not be utilized alone for the atrium, there is minimal need for additional cooling and heating, and total thermal stresses and energy use in office spaces and the hotel are significantly reduced, as confirmed in energy modeling.

Zones 1 through 8 have three atria per floor that function together with an exterior and interior glazed skin to provide the level of thermal comfort desired for a built environment in Shanghai (Zone 9 is designed without either interior curtain wall or atrium spaces). This is done with a great degree of efficiency, with only the first 15 feet of atrium mildly conditioned with the use of a perimeter Fan Coil Unit that either heats or coolsprimarily during weather extremes—leaving the majority of the atrium to be ventilated with a combination of natural updraft and regulated top exhausts, as well as with spill air on the first and last floor of each zone.

The whole system (inclusive of other LEED strategies in the building) creates about 21% energy efficiency, compared to ASHRAE 90.1-2004 in LEED Rating and about 12.5% over China's nationally recognized "Three-Star Rating." Seven percent of total efficiency is achieved as a result of various features used for exterior skin design (more about this later in this paper).

Prescriptive Constraints

Creating inner atrium spaces to be vertically accessible public gardens and an integral part of a super-high-rise building, as a building statement concept, was in a way a pragmatically new idea that Gensler proposed. Probably the best known conceptual precedent is Norman Foster's Commerzbank in Frankfurt. Shanghai's considerably different climate, with constant and high relative humidity (up to 95%), combined with prescriptive city codes that are used to define required performance and make-up of exterior glazed walls components, provided a new challenge to the design team.

Some of the requirements: the exterior-wall-to-glass ratio could not be more than 70%: reflectance out could not be more than 15%; the shading coefficient had to be between 0.4 to 0.5; and, if exterior glass created a conditioned enclosure, then makeup had to be with a K value of 1.5W/m² °C. If the exterior Curtain



MEP / Refuge Floor

Conditioned Office Space:

Warm air is supplied throi standard HVAC system to the offices. Air that is used in office spaces is than circu lated through open plenum space back to the return sys-tem. At each atrium first and top floor, in office or hotel zone stack, controlled vented diffuser on inner curtain wall ring releases warm air to the

Ventilated Atrium Space

of 27F, inside temperature of atrium should not drop below 64 F Weekdays / 72 F

First Floor Regulated Exhaust:

amenity floor ceiling plenum nto the atrium. Spill air from top office floor is rele 72 F and at Velocity of 10,000

Bottom Regulated Exhaust / MEP Unit: Takes fresh Air that is than heated, conditioned and introduced in each atrium at 85 F and at 6000 CEM

Figure 15a: Atrium energy performance: winter concept

SKY GARDEN SUMMER SCENARIO

MEP / Refuge Floor Top Regulated Exhaust Releases used warm air from atrium up bac to system and out while allowing conditioned a from top office floor to "spill " into the atrium, reducing with that heat level at atrium top. Spill I Air is at 78 F and Velocity Air is at 78 F and velocity is 10,000 CFM. In the hot summer day, with outside temperatur at 95 F, atrium top sho not exceed 109 F with velocity of 250 FPM . It will not exceed 118 F during weekends wher HVAC system is not WALL "A": Laminated Glass Assembly: 25 Frit 12mm1o.lr.+1.54 SGP+ Sp.Se. N Low E + 12mn SC=0.88% VT=0.81% K-AGwi K= 4.6 w/max WALL "B": Insulated Glass m2C Assembly 10mm Cl.Li. + Sp.Se Neutral Low E @ #2 +12mm Air+ 8n m CILL 0.43% -VT=0.67% K= 1.64 w/m2C Fan Coil Unit ig at 56 200 nd 9,000 CEM MEP / Refuge Floo Intake Area

Conditioned Office Space Cooled air is supp through standard HVAC system to the offices. Air hat is used in office space is than circulated through open plenum space back to the return system. At each atrium first and top floor, in office or hotel zone stack, controlled vented diffuse on inner curtain wall ring releases air to the atriur That coupled with regulated diffusers located at bot-tom amenity floor allows exchange of cavity atrium air at the rate of 6 times during one hour and maintaining with that comfortable co tions at occupied portion of each amenity floor, Extensive Energy modeling and CFD studies were developed to Ventilated Atrium Space: at 95 F, inside temperature should be at 72 F not to exceeded 79 du when HVAC system is not First Floor Regulated Exhaust: or ceiling p nto the atrium, forcing warm ai

to circulate and go upward, and eventually out. Spill Air Velocity 10 000 CFM with 78 F Bottom Regulated Exhaust / MEP Unit: Takes fresh Air that is than con

atrium at 56 F and at 6000 CFM

Figure 15b: Atrium energy performance: summer concept



Temperature profile in C°



Temperature profile in C°



Velocity profile m/s



Temperature profile in C°

Exterior Glazing Temperature in C°

Figure 16: Computational Fluid Dynamics (CFD) Simulation: Performed for worst-case scenario atrium in either winter or summer mode. Atrium proved to be within required ASHRAE 55 (Cosentini)

Summer Weekday Afternoon

Sunny solar load Spill Air On Supply Cooling Fan Coil Cooling Top return open

Top exhaust air, C /F: 41 / 106 Average lobby (2m), C / F: 22 / 72 Ceiling surface, C /F: 43 / 109

Withouts Spill Air Average lobby temperature would be 26/79

Summer Weekday Afternoon

Cloudy solar load Spill Air On Supply Cooling Fan Coil Cooling Top return open

Top exhaust air, C /F: 32 / 89 Average lobby (2m), C / F: 19 / 66 Ceiling surface, C /F: 31 / 88

Winter Weekday Morning

30% solar load Spill Air On Fan Coil Heating Supply Air No Fin tube heat Top return open

1.50

0.750

0.37

0.000

Top exhaust air, C /F: 21 / 70 Average lobby (2m), C / F: 18 / 64 Ceiling surface, C /F: 22 / 72 Atrium Glass, C/F: 14/57

Winter Weekday Night

No solar load No spill air Fan Coil Heating Supply Air Fin tube heat 600 Btu/ft Btu/ft Top return closed

Top exhaust air, C /F: N/A Average lobby (2m), C / F: 22 / 72 Ceiling surface, C /F: 23 / 73 Atrium Glass, C/F: 19/66

Wall A was to be considered as an enclosure for conditioned space of the building, then makeup for it had to be an insulated glass unit.

This created an additional challenge given the large size of the glass panels—varying from 2.2 by 4.5 meters to 1.2 by 4.3 meters. The glazing unit would have to be not only insulated unit make-up, impacting with that desired visual transmittance ratio (targeted very high—up to 0.8), but would also require individually thicker glass lights to respond to high wind-load peaks. In-plane glass deflection had to be less than 25 mm and with the insulated unit, there was a danger of two lights touching each other at high peak loads, thus creating the danger of possible peak incidental breakage.

The idea of adding a spacer in the middle of the glass unitalthough possible—was not entertained. It has been calculated that if units were required to be insulated, then glass would have to be of a 15 mm glass + 10 mm air + 15 mm glass makeup. This was a significant increase from the 12 mm glass + SGP interlayer + 12mm glass laminated make-up that was targeted. At current weight, between 800 to 1,000 kilograms (2,200 pounds) per glass unit (the largest units at Zones 2 and 3), this direction would result in an additional 25% increase in exterior glass weight. Ultimately, this would impact the CWSS in its effective size and visual appearance in atrium spaces, as well as on individual member weight, which would also impact the total building weight expected to be approximately 850,000 metric tons, spiraling all the way to potential redesign of an already approved complex foundation system (including about 3,500 piles at 1,000 mm in radius and 6,000 mm high matt foundation) on a limited site area. It is common that the total exterior wall weight is within the ratio of up to 2% of total building weight; however, the intent of the design team was to truly follow principles of China's Three-Star Rating, based on implementing high-efficiency standards with reduction and multiple usage of individual members where possible-"Do more with less."

After going through an extensive and complex review process with various client, city and government expert panels, it was determined that Exterior Curtain Wall A was to be considered as a weather enclosure for ventilated and unconditioned atrium space, and that the true exterior wall is to be Interior Curtain Wall B. This allowed for Curtain Wall A to employ a laminated glass assembly and maintain efficient exterior wall-to-weight ratio, while maintaining desired transparency and glassarea ratio. Additionally, various strategies were employed to maintain atrium performance at a comfortable level (Figures 15 and 16).

Final Glass Selection

As final glass selection will be contingent to series of mockups that are scheduled to be prepared in the next 12 months, the Gensler team has proposed the following generic glass types for two major curtain wall Systems:

Curtain Wall A: 26 mm laminated glass assembly: 12 mm low-iron glass +1.52 mm SGP interlayer + low-e coating + 12 mm low-iron glass. The upper 25% of the panel will have dissolving frit pattern from 75% down to 15%

Curtain Wall B: 30 mm insulated glass assembly: 10 mm low-iron glass with low-e coating + 12 mm air space + 8 mm low-iron glass. The middle portion of the panel between "chair rail" to the finish floor will have dissolving frit pattern from 15% down to 75% and 15% again



Figure 17: Curtain Wall A and B standard panels

Curtain Wall Design Options

Curtain wall design development began as an exercise that at first attempted to resolve complex building geometry. The remainder of this paper will focus primarily on Curtain Wall A, analyzing ideas and various options, with an overview at the end of this paper on the current status of Curtain Wall B.

Curtain Wall A Studies

In developing resolutions for curtain wall geometry and final design, Gensler's façade team used a variety of available software that involved scripting parametric flexibility in analysis. Early digital tools were Revit and Generative Components; however later studies on exterior wall were conducted exclusively through Rhino with Grasshopper parametric mechanism as well as 3D Max and AutoCAD. This allowed for a constant precise geometrical understanding of the various exterior wall schemes being proposed and their relationship to building form. Figures 19 through 22 and the associated discussion captures the results of these complex studies, highlighting the geometry involved. It should be noted that Revit was used as main software for tower documentation and consultant coordination.



Figure 18: Curtain Wall Systems B and A



Figure 19: Curtain Wall A-Curtain panels sizes change vertically



Figure 20: Typical zone plan view with superimposed curtain wall structural supporting system



Figure 21a: Curtain Wall A: Profile control points division-partial view



Figure 21b: Curtain Wall A: The layout of two adjacent floors



Figure 22: Curtain Wall A: Control points interaction between subsequent floors

The starting point for all studies was a default profile and desire to have division along the curve established efficiently. In the competition phase, the Gensler team decided not to pursue surface diagrid or triangulation schemes, given that the design intent was to have two curtain wall skins with as minimal obstruction of the view out as possible.

Going forward, this was a major design criterion for the client. Understanding glass-size limitation and desired scaling, the Gensler team decided that a single piece of glass should not be larger than 2.3 meters in width (~7'-6") to accommodate Chinese floating, coating and thermal glass-processing capabilities. The default profile is divided along the curves into 144 control points; this 144-point division resulted in 144 panels. The largest distance between control points was about 2.25 meters (~7'-4") at Zone 1 (first floor) and about 1.25 meters (~4'-2") at Zone 9.

Early studies suggested that the best location for a starting point for division was to be at "V-strike" area, with full panel size following. However, coordination of major structural elements behind the curtain wall required that a second point on the curve be moved 33% of the panel size to allow for a clean connection of the strut, and sag rods to the perimeter girt, avoiding possible conflict with the vertical glass fin and mullion assembly. This is why the first and last panel along the curve are 33% or 66% of an actual panel.

The logical starting point in resolving the curtain wall was to connect these control points directly and have a smooth appearance on the exterior of the wall. This involved angling the vertical mullions in two directions, which is what the Gensler team proposed as one of the early schemes. Due to a combination of rotation and scaling of two adjacent floors, one out of four points defining the panel will always be out of the glass plane (Figures 21a and b), creating a warping of the glass and, in some situations, separation as large as 60 mm (2.5").

This situation prompted a series of schemes that proposed vertical "shingling" of glass panels with a "three-part" mullion system (three individual components in a single structural line of vertical mullions) to deal with panel plane deflection on the fourth point. There were three distinct shingled schemes proposed: shingling along vertical mullions, along horizontal mullions, and along both. As the process moved forward, the horizontal shingle remained the only option.

To reduce the effective vertical size of the aluminum profile, a glass fin was introduced along the vertical mullion, braced at top, bottom and mid-span, reducing the mullion's effective depth. However, using a tri-part mullion system could work only if the mullion depth was at about 230 to 250 mm due to out-of-plane glass points and floor-to-floor heights varying 4.5 to 4.3 meters. The design intent was to have a glass wall system that would reveal as much as possible toward the inside. With a curved exterior skin, any extensive mullion depth would be even more accentuated. An additional challenge resulting from the geometry was the large number of different panels per floor in the case of shingling, there were about 10 to 14 per floor, resulting in more than 2,000 for the whole building and requiring large attic stock.

This being the case, the curtain wall team proposed a set of schemes with the intent of reducing the number of different panels and minimizing the vertical mullion size—and possibly eliminating the mullion altogether. Two schemes that were proposed included staggering of glass panels between floors—one employing simply a glass fin at two panels' joint line—thus eliminating the aluminum vertical mullion while depending on point-supporting of the glass (or patch-fitting mid-span in sub-scheme). In this case, the glass would be vertical to the ground and staggered between floors. Another option was to use a structural gasket attached directly to the glass fin, keeping the glass in one plane while adapting a gasket in the vertical direction to bridge the joint line between two panels that are angled but staggered between floors.

Of major concern in both of these cases was the impact that peak negative wind-load pressure may have on vertical mullion line. In both cases—structural sealant or gasket—the vertical mullion has no hard material used to stabilize vertically, increasing the possibility of glass being dislocated from the vertical joint causing danger to people below. Even though these two systems had significantly less glass panels per floor, and provided desired visual transparency, they did not provide the desired level of safety for both the client and the Gensler façade design team, and therefore could not be utilized. However, they did inform the next set of schemes that used the best ideas from all systems analyzed thus far.

It should be noted that during the design process, the Gensler façade design team frequently presented progress work to the client and various expert groups in panel reviews. These experts represented the highest bodies within the Chinese and Shanghai governments and were critical in the dialog that defined the direction of the final design. Ultimately, the goal was that everyone involved in the project and reviewing teams was in consensus with the proposed curtain wall design, including all systems described earlier.



Figure 23: Shingled schemes: Horizontal (left); horizontal and vertical (right)



Figure 24: Horizontal shingled scheme with glass fin

In one of the meetings, it was concluded that to ease access for building maintenance equipment, all unnecessary horizontal ledges should be avoided. This suggestion, along with earlier constraints and challenges as how to deal with vertical mullions in geometric transition, inspired the team to propose a unique idea for the next set of schemes that would eliminate the need for a tri-part mullion and in some cases dramatically reduce the size of the vertical mullion depth. The design team proposed a series of ideas on custom-casting design that would consequently include cold-bending of the glass to accommodate geometric change.

The first casting system relied on tension cable connecting two castings, resembling tripods that sat on the girt and then transferred laterally the load of the glass and shallow vertical mullion at four points. To keep the glass panels at a minimum per floor, the staggered concept was adopted. The challenge with this system was that by offsetting mullions in vertical direction between floors and having only tension connections between castings, we could not address differential instant



Figure 25a: Glass fin with point-support and structural gasket scheme

pressure between two subsequent panels that from RWDI testing was concluded to be at +/- 1.5 kPa (~32 P/ft²) in any direction—horizontal or vertical. To accommodate this system, the vertical mullion had to be much larger than expected—possibly around 220 mm.

This prompted the next casting system, which was designed to connect offset vertical mullions, creating continuity between them and addressing differential pressure issues (Figures 26 and 27). The system included rotational bushings to address thermal stress on the girt and other combined movement expected to be 114 mm cumulative vertically in the single worst case (bottom of Zone 2). This proposed casting system, although a structurally workable solution, together with cold-glass bending, inspired a lot of discussion about safety, installation sequence and future maintenance. Although cold bending as a process is a safe procedure that is more than occasionally used in the U.S. and Europe, it still remained an undesirable solution for the expert panel and, ultimately, the client.

At that time, all of the different studies on the curtain wall were summarized in three main schemes—"shingle," "staggered" and "smooth"—with pros and cons inclusive of estimated cost. While these issues were being resolved, the "light pollution" issue was asked to be addressed. The resolution of this issue ultimately decided the scheme that will be used for the tower.

It should be noted that triangulation, as a form of curtain wall resolution, was considered but decided against after client input during the initial design stage. Similarly, hot bending was left abandoned as an option due to high cost and the limited number of curtain wall fabricators who could successfully produce a final system.



Figure 25b: Variations on "smooth" schemes with castings



Figure 26: "Smooth" scheme rotational bushing detail

Figure 27: "Smooth" scheme

Light Pollution Studies

The light pollution category was the single most impactful variable in the overall exterior wall concept design and glass selection. In China's urban districts, light pollution is considered a harmful impact of glass reflectance out to surrounding residential, civic or public buildings or institutions. The ratio of glass on the building cannot be more than 70%, and the glass has to have reflectance that does not exceed 15%.

Shanghai Tower's Exterior Curtain Wall A glass ratio is very high, at about 87% (including spandrel area), and the Interior Curtain Wall B has a glass ratio of about 60%. With these high glazing ratios, the Gensler team needed to prepare a light pollution study conducted by a third-party consulting group. Two final schemes—"staggered" and "smooth"—were selected for testing in a three-kilometer radius of the surrounding neighborhood.

Considering all of the variables involved, the ultimate result was purely geometric, as the curtain panels confirmed the modeling and testing of both scenarios with the Ecotect model. Simply put, glass perpendicular to the ground reflects less than glass angled to the sun. The largest angle on the tower was about 9°. The glass selected for the exterior will have minimal visible light reflectance of about 12%. However, Ecotect results revealed a difference favoring the staggered system, which ultimately became the system recommended by Gensler's façade design team.



Figure 28: Light pollution study model (Light pollution consultant)









Figure 29a: "Staggered" and "smooth" schemes comparison



Figure 29b: "Staggered" and "smooth" schemes comparison (Light pollution consultant)



Figure 30: Final Curtain Wall A system

Curtain Wall A: Final Design

Final Curtain Wall A design (Figure 30) will accommodate about 129,915 m² (nearly 1.4 million square feet) of glass, and about 28,315 curtain panel units in total. From 144 panels per floor, there will be eight different panel types, with a larger number of same panel types (95%) except on accent V-strike areas. The efficient design approach here also includes glass and aluminum fabrication tolerances. Each curtain wall unit will be hung from the perimeter girt. Control points for each unit are established through geometry analysis, as discussed earlier, and are set at 400 mm outward offset from the girt centerline.

The intention with setting this dimension was to address all profile conditions between two adjacent floors resulting from twist and taper (Figure 20). The largest "ledge" projections are about 600 mm, representing about 15% of total conditions,

with about 350 mm being the more typical condition (70%) and extending under the glass line above approximately 80 mm. The total vertical aluminum mullion depth is 114 mm (4½") plus addition of the glass fin, continuously connected to back side of the mullion. The glass fin is a laminated assembly with a total 26-mm thickness and up to 300 mm in depth. The top of the building at Zone 9 has an iteration of vertical mullion without a glass fin due to easier maintenance and exposure to the weather conditions. The total depth of mullion at this zone is designed at 250 mm.

Another variation of the vertical mullion is at the area of accent "V" strike. Vertical mullions here are used to house and support a dense LED lighting fixture layout, and to use a deeper mullion was a practical necessity.





Figure 31: Curtain Wall A: Panel types

Last, the exterior wall at mechanical floor intake and exhaust areas (each zone division) is a variation of the overall system that allows flexibility for building maintenance equipment use (Figure 34). Everywhere else, mullions were intended to be used with minimum depth and profile width, corresponding to the general design intent of maximum transparency. To address the issue of excessive torsion on the girt resulting from 400 mm offset of the curtain wall control point, Gensler's team has proposed a rigid moment frame connection as part of the inset into each vertical mullion stack. Units will be delivered to the construction site prefabricated with this element and will be hanged as standard segmented unitized panels.

Gensler's façade design team had a key goal in mind—designing a system that will achieve flexibility for procurement and



Figure 33: Curtain wall installation process



Figure 34: Building maintenance equipment access for Curtain Walls A and B



Figure 35: Curtain wall typical atrium (left) and main entry (right)

encourage competition between the best fabricators in China and elsewhere in the world, allowing the client more balanced and controlled cost. Designing a system as described allows that approach; in the coming months, it is expected that the final curtain wall contractor will be selected, which will follow with a series of performance and visual mockups and shop drawings documentation.

To address thermal comfort in the public zones of each atrium, a series of computational fluid dynamics studies were conducted for each of three atria per zone. Additionally, horizontal projections act as exterior fin shades and, with the frit pattern on glass exterior surfaces, help reduce glare.

Curtain Wall B: Progress Design

As stated earlier, the focus of this paper was to analyze the design process for Curtain Wall A. Curtain Wall B will be summarized relative to only a few critical points. Similar to Curtain Wall A, Curtain Wall B is proposed as a standard segmented, single-floor unitized system. This system spans the entire cylindrical stack of each zone, with some differences at torsion restraint connections for Curtain Wall A tab areas (Figure 36). The cylindrical stack varies from 12 stories at Zone 2 to 15 stories at Zone 8. It has been determined that a 1.0-meter curtain wall module will work best for the stacked radius floor plates, as opposed to the standard 1.5-meter for office tenant planning and future flexibility. This module is uniform through all building zones, with slight variations.







Figure 36: Curtain Wall B system at tab area and at typical location

Figure 37: Current design for Curtain Wall B system—atrium view



Figure 38: Current design option for Curtain Wall B system

Design constraints for Curtain Wall B are considerably different than those analyzed for Curtain Wall A, as this system is designed not to be pressure-equalized since it is in enclosed spaces and with maximum wind loading pressures of about 2.1 kPa, anticipated to be experienced during the construction sequence with partial exposure of the system to outside pressures. Additional constraints of stack effect and airflow through open atria are controlled with very tight air infiltration criteria—1.0 liter/m2/sec at 75Pa. As stated, extensive computational fluid dynamics studies were conducted to confirm both thermal comfort and air velocity.

The most critical issue for Curtain Wall B was a requirement for one-hour fire-rating of all atrium glazing and CWSS assemblies, where Curtain Wall B is a major component. This issue is still in testing and awaiting a final resolution. At this time, several options are proposed, and more testing will be conducted in the coming months. The current approach to resolving this issue is to use one-hour, fire-rated glass (DFB glass) and steel mullions clad with aluminum extruded profiles for the first three floors in each atrium. This will be in addition to the designed fire suppression system. Figures 37 and 38 represent the current design for Curtain Wall B. It should be noted that a "stick system" approach has been suggested to address the fire protection concept more thoroughly.

Conclusion

Shanghai Tower represents a new vision in super-high-rise building design for the cities of tomorrow. This vision is being realized with the firm support of the Chinese government, which aims to lead the world in promoting sustainable, high-performance building design. In the last decade alone, great examples of these buildings have been designed and constructed in cities across China. Shanghai Tower's building envelope is one integral part of an overall strategy to achieve these broader sustainable goals.

The tower's design process began with a focus on resolving geometric uniqueness and optimizing its performance while balancing aesthetics with production costs, constructability, serviceability, energy efficiency, safety, environmental impact and other factors. The lengthy and intensive decision-making process involved a broad pool of specialists from Gensler's design team, its consultants, the client—with its experts and specialty teams, and outside local and government expert panel groups.

While producing actual tower drawings for documentation, weekly meetings were held with outside design team reviewers, expert groups, and city and government officials. These gatherings would address all issues and forge consensus for the next step in the design process. These meetings were in addition to weekly team coordination meetings that occurred over the course of the past 20 months prior to tendering (at the time of this writing, it was expected that tendering would take place in late March of 2010).

In developing numerous options to best address the design goals, I can certainly say that I felt how each day, another step was made toward making this project a global success. Long and critical as it was, perhaps this process will set an example of a process for future super-high-rise building envelope design to which we as professionals, together with our clients, can aspire.

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