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Guiyang World Trade Center: An Essay on the Concrete Tube Structure

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The acute global concern about resource depletion is driving a reconsideration of the tall-building typology. Expectations for energy and material efficiencies are always increasing – particularly for a highly-engineered building type like the supertall – and it is imperative that the designers, builders, and consumers of large quantities of these resources strive to develop solutions that minimize the burden on the planet. The Guiyang World Trade Center – a 380-meter mixed-use tower at the center of a new district of Guiyang, a city of three million inhabitants located in the hills of China's Guizhou Province – employs an unconventional structural concrete skin that could represent a changing attitude for the design of supertalls away from all-glass towers and towards more sustainable opaque towers.

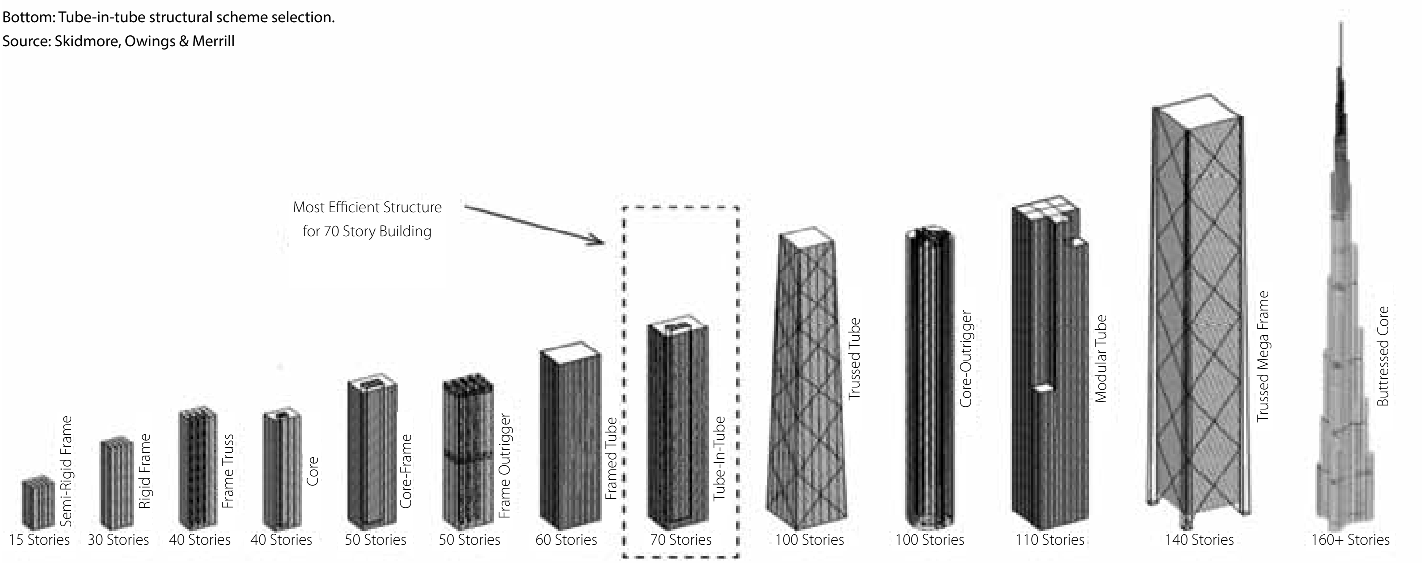
Successful high-rises are born at the convergence of structural, functional, and aesthetic considerations. But now more than ever, this convergence must not only produce buildings that are exquisite and functional, but buildings that also respond to our era's most urgent issues of resource management by minimizing ecological footprints on their sites and on the planet. This is even more critical when the building is a supertall tower in one of China's rapidly growing metropolises.

At every stage in the design process, from the material selection to the building's form to site planning, iterations are examined through the filter of high performance, making this project a case study of an integrated, interdisciplinary design process that is driven by sustainability. It follows the way in which sustainability challenges the different disciplines, starting with the choice of structural system, and will explain how a series of envelope performance analyses produced the tower's unique façade. Finally, it will look at the urban design of the Guiyang World Trade Center, an environmentally sensitive master plan rooted in vernacular typologies.

The Guiyang World Trade Center (GWTC) is a 380-meter mixed-use tower commissioned by the Zhongtian Urban Development Group Co., Ltd to serve as the anchor of a 21-hectare development at the edge of Guiyang, the capital of Guizhou Province, China. Located along a bend of the River Nanming and spanning between a riverfront peninsula to the west and undulating hills to

Opposite: Guiyang World Trade Center rendering with a view from the riverfront. Source: Skidmore, Owings & Merrill

Bottom: Tube-in-tube structural scheme selection. Source: Skidmore, Owings & Merrill



the east, the site is defined by its distinctive topography of rolling hills and the presence of natural features, including an abundance of hot springs that characterize the area.

Reinvigorating the Concrete Tube-in-Tube

Conventional high-rise tower designs typically favors widely spaced perimeter columns to maximize perimeter glazing. But this approach comes at the cost of a reduction in the efficiency of the structural system and requires the use of increased structural materials. Tube-in-tube structural systems offer a compelling alternate approach with a smaller ecological footprint.

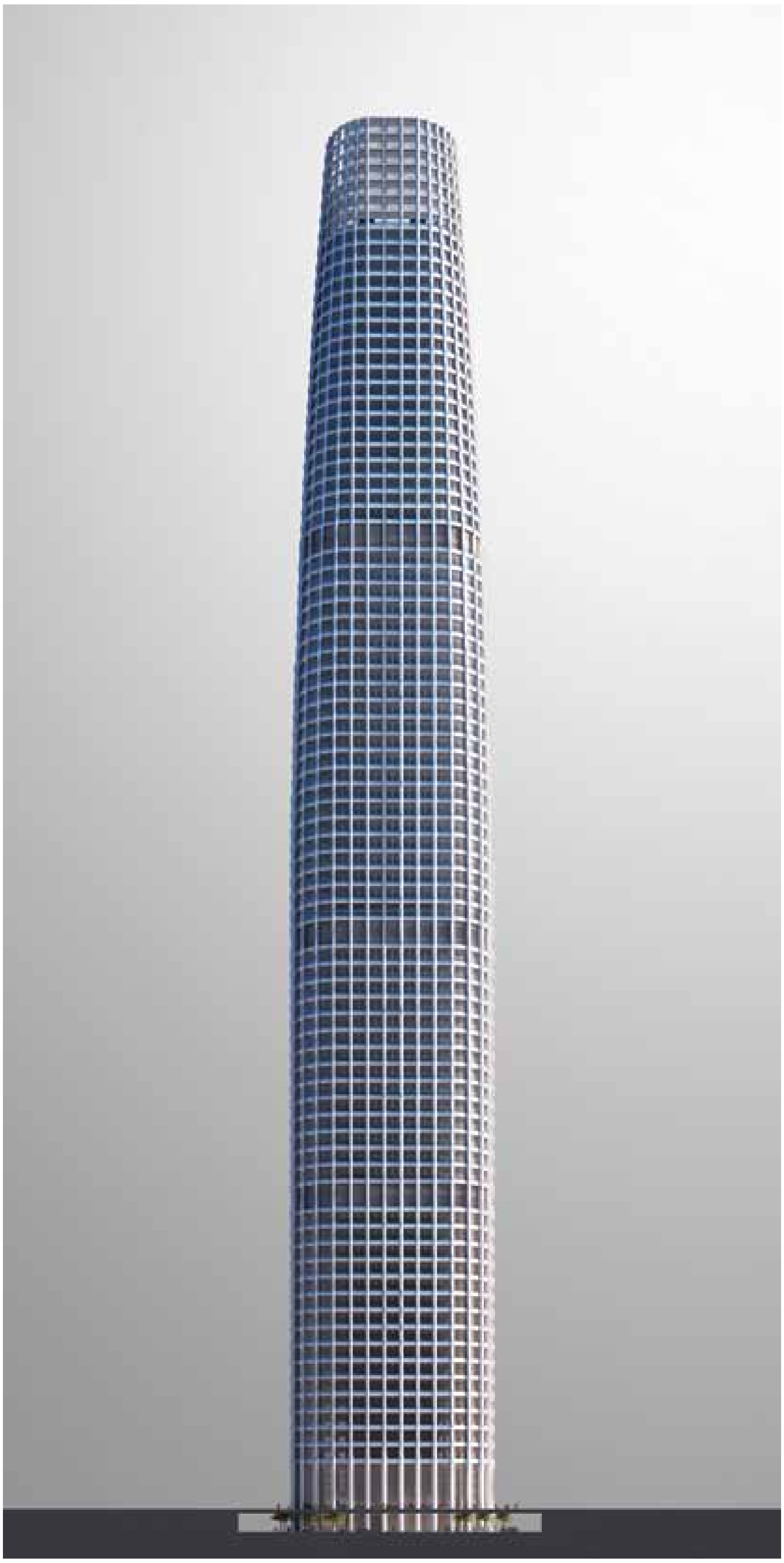
Typical core and frame systems with larger moment frame bays have lower frame efficiency due to the shear lag effect. The relative flexibility of the perimeter frame limits the ability of the overturning forces to "turn the corner" and effectively engage the columns in the middle of the upwind and downwind faces. This reduction in frame effectiveness, results in more overturning moment carried by the building core.
The tube-in-tube system features closely spaced columns which stiffen the moment frame and reduce the shear lag effect. This results in a more even distribution of lateral overturning forces in the columns, which allows more overturning moment in the frame where it can be carried more efficiently than in the core. This reduces the core wall thicknesses and also the overall structural material use.

While outrigger or belt trusses are often needed in towers of this height in regions of more demanding lateral wind or seismic forces, the tube-in-tube system also allows the GWTC to be constructed without outriggers. This allows the construction process to be greatly simplified, as well as accelerated because in an outrigger building construction process, every outrigger floor significantly delays construction. The primary structural system is thus a conventional ductile reinforced concrete core and a highly efficient perimeter-reinforced moment frame "tube."' The perimeter moment frame typically consists of reinforced concrete columns with steel reinforced concrete (SRC) columns in the lower portion of the tower to reduce the size of the largest columns.

Since the mixed-use tower must accommodate different programs, an important advantage of the load-bearing façade is a completely column-free interior that offers ideal layouts with few interruptions. The floor plates can very easily adapt to the changing needs of future tenants.

While the tube-in-tube system is extremely efficient, its structural façades are not as common as could be expected across contemporary skylines. Over time it fell out of favor because the tight perimeter column spacing came to be seen as too opaque. As aesthetic and cultural sensibilities started favoring façade transparency and all-glass building envelopes, the use of tube-in-tube towers declined. The chosen structural scheme acknowledges this desire for increased transparency and makes strides to update the density of the tube-in-tube system. Instead of a typical spacing of around three meters, perimeter columns are spaced at 4.5 meters, increasing the amount of glazing to maximize natural light and views, while preserving the structural integrity of the tube-in-tube system.

The gravity system typically consists of composite floor framing, comprised of composite truss deck that is supported by



steel beams, which span from the perimeter columns to the interior reinforced concrete core. Where the perimeter columns consist of reinforced concrete, a small steel shape will be embedded in the concrete in order to facilitate advanced construction of the composite steel beam floor framing. Typical gravity steel beam spacing is 4.5 meters on center, matching the column spacing. This lightweight efficient system optimizes the selection of structural materials based on their different mechanical properties – employing concrete where it is most effective in columns and core walls which primarily resist axial forces, and employing structural steel in the floor beams where the tension capacity of steel allows it to more effectively resist flexural demands. This approach minimizes the building mass, thereby reducing the overall seismic demands on the lateral load-resisting components, as well as the demands on the vertical gravity components and foundations, and allowing for generous lease spans.

The tower employs a dual lateral load resisting system, consisting of a conventional ductile reinforced concrete core and a perimeter ductile moment frame "tube" system which share lateral loads between them. The reinforced concrete core walls provide strength, stiffness, and rigidity while the reinforced concrete link beams provide ductility to the system as a whole. The moment frame beams consist of reinforced concrete which is designed to yield in a seismic event, thereby providing significant ductility into the moment frame system. Lateral loads are shared between the core and the frame via the composite floor slab system which acts as a horizontal diaphragm.

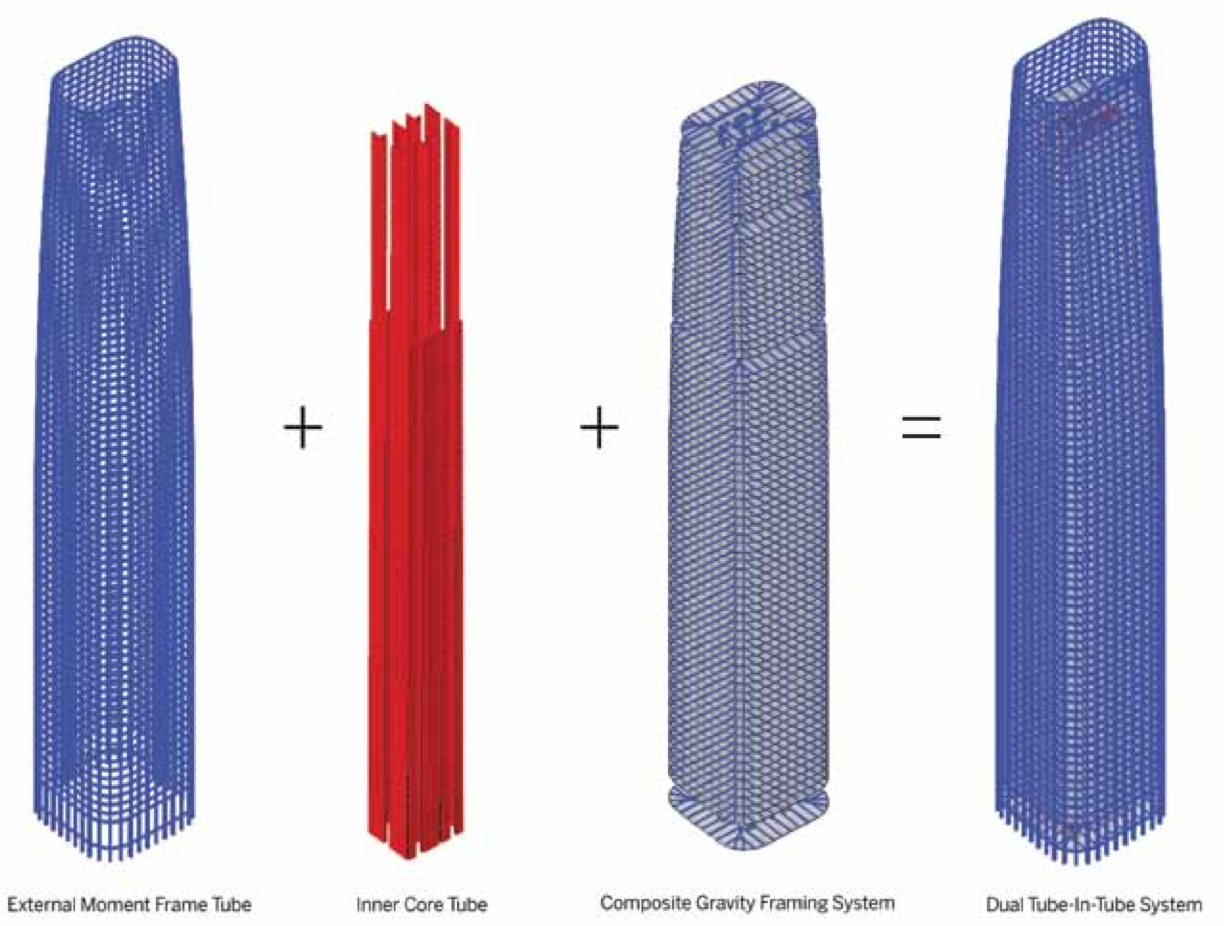
Engineering for Wind: Tapering Form, Rounded Corners and Dimpled Façade

Due to low regional seismic activity and the significant height of the tower, its wind response significantly impacts the structural engineering design. Wind-induced motion of tall, slender towers is driven by the formation of regular, organized vortices

Opposite: Tower Elevation. Source: Skidmore, Owings & Merrill

Bottom: Structural diagram of the tube-in-tube. Source: Skidmore, Owings & Merrill

"While outriggers or belt trusses are often needed in towers of this height in regions of more demanding lateral wind or seismic forces, the tube-in-tube system allows the Guiyang World Trade Center to be constructed without outriggers."



Left: Façade rendering showing inset glass panels,and sculptural metal column covers that double as shading fins. Source: Skidmore, Owings & Merrill

Bottom: The tower's base meets the ground in a multi-story lobby that opens up to a civic park. Source: Skidmore, Owings & Merrill

Opposite: Vortex shedding reduction measures. Source: Skidmore, Owings & Merrill

called vortex shedding. These vortices impart cyclical pressure impulses on the sides of the building perpendicular to the direction of the wind. This force can lead to lateral accelerations which can be uncomfortable to occupants. Three geometric features of the tower's design combine to mitigate the wind-induced motion and loads in order to reduce the overall effect of vortex shedding: first, the variation in plan along the building height; second, the rounded corners; and, third, the rough texture of the tower surface.

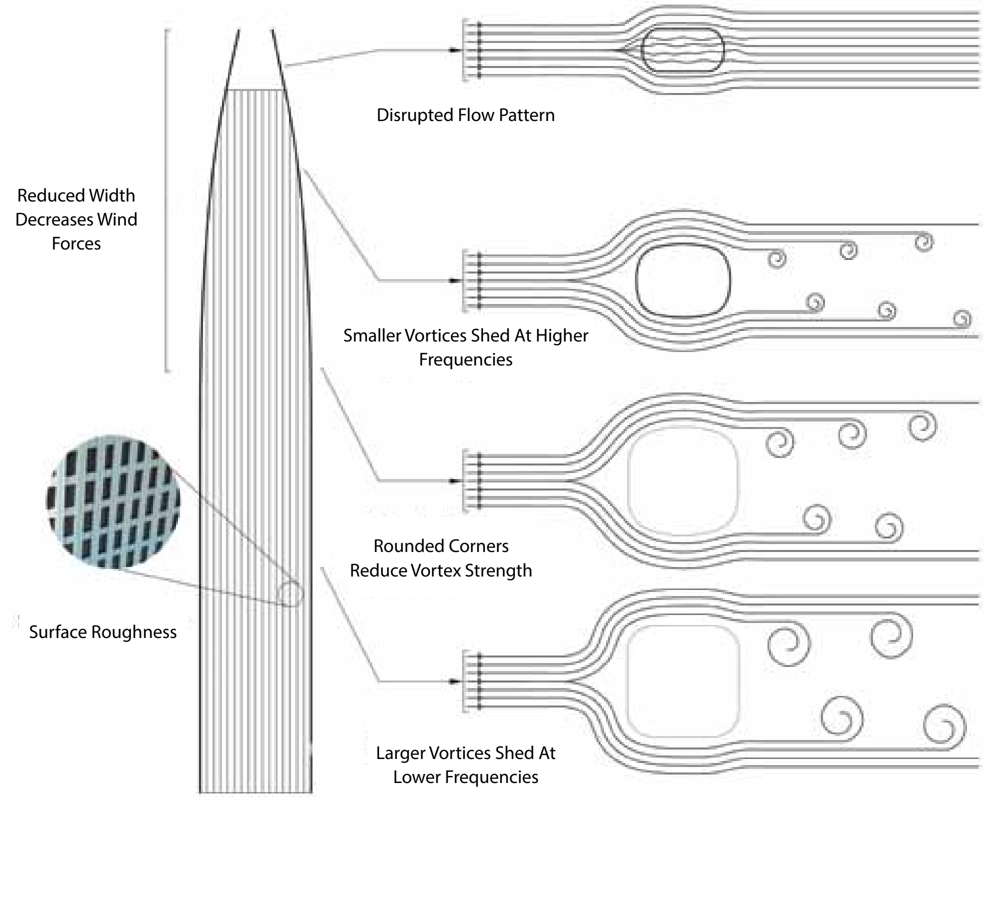
The tower's 69 floors contain four distinct program elements. The lower 49 floors house Class A offices. Above this, a hotel operated by Marriott occupies 17 levels. The following six floors are reserved for serviced apartments, and finally the top floor and

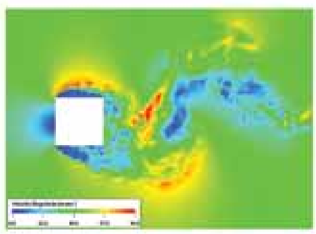
roof deck are dedicated to a Chairman's club house and a health club that will be accessible to the public. Meaningful public spaces are thus distributed through the tower. At the base, the tower meets the ground in a monumental 14-meter-tall lobby that invites the neighboring waterfront park into the building. Flanked by a mall to the north and a ballroom to the south, this porous lobby shamelessly ties the tower to two vehicular drop-off levels and to multiple pedestrian channels. At the top, the hotel's restaurant and bar, as well as the chairman's club house insert elevated communal spaces that will allow the public to experience the surroundings from exceptional heights.

The tower's form was carefully calibrated to respond to the program stack mentioned previously. At the lower levels, the plan is a 55 x 55-meter square that creates lease spans of 13 meters optimized for office suites. In order to create appropriate spans for the hotel rooms, the tower tapers in the north/south direction. The taper begins at the tower's halfway point, reducing the tower's width to 23 meters at the top. The resulting hotel lease spans range from 11 meters on lower hotel floors to nine meters on the upper hotel floors to comply with the hotel operator's strict standards for room sizes. The resulting tapered and gently rounded form is in this way a direct reflection of the programmatic anatomy within.

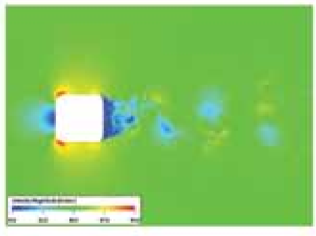
The taper of the tower causes a variation in the strength and frequency of the vortices formed along the height of the tower. This prevents vortices from acting together, reducing the overall wind loading on the tower. In addition to the reduction of the effects of vortex shedding, the tapered profile reduces the width of the tower facing the wind (the wind sail area) at the upper portion of the tower. As the wind speed profile increases with height, the wind pressures exerted towards the top of a building are highest. Thus the tapered form at the top of the building has the maximum effect in reducing overall wind loads.

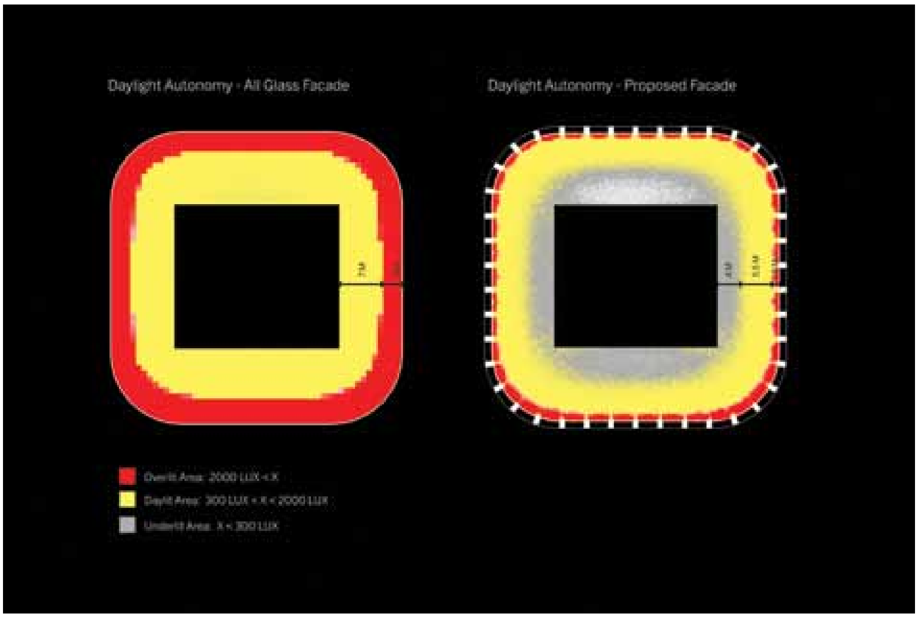
Sharp corners in square and rectangular buildings can generate strong vortex shedding characteristics which can increase the wind response of the tower. In response to this phenomenon, the corners of the tower are rounded. This strategy has been shown

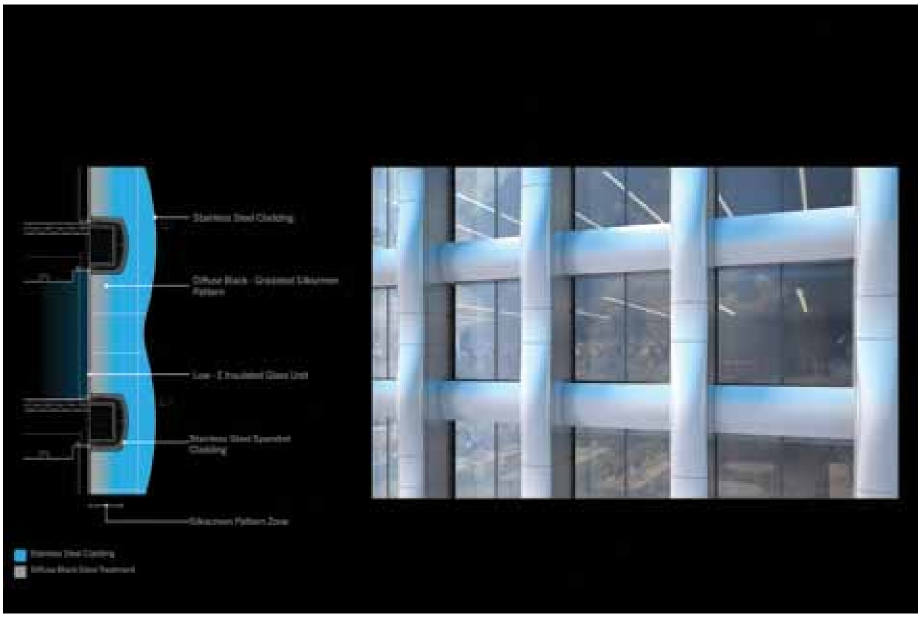


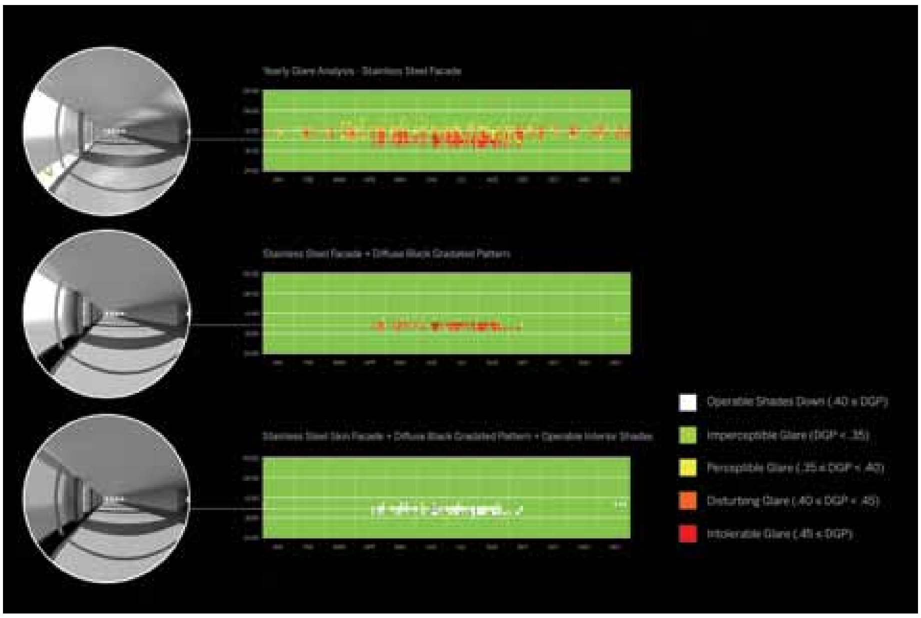


Wind Velocities Showing Vortex Shedding Square Corners (Above) Rounded Corners (Below)









to be very effective in reducing the strength of the vortex shedding by creating a less pronounced flow-separation point on the plan corners, and narrowing the wake of the wind flow. The rounded corners of the plan have the added advantage of preventing lease spans from exceeding an acceptable range at the edges of the floor plates.

At a smaller scale, the design of the façade also participates in reducing vortex shedding on the tower. The nature of the perimeter beam-column "tube" structure, accentuated through the inset glazing, and the added relief of stainless steel architectural column covers creates a non-smooth bluff body surface. This surface "roughness" assists in disorganizing the wind flow close to the tower's surface, reducing the magnitude of the shedding vortices. Aside from the structural advantages, the tube-in-tube scheme introduced multiple features that enhanced the environmental performance of the building from the point of view of embodied energy, envelope performance, and maximizing daylight.

Optimizing Daylight: Another Case for a More Opaque Envelope

A study of daylight autonomy was undertaken to compare a conventional curtain wall envelope with the more solid enclosure of the tube-in-tube. Daylight autonomy is an annual daylight metric that represents a percentage of annual daytime hours that a given point in space is above, or below a specified illumination level. As the structural model was evolving between different column spacings, they were continuously modeled to evaluate their consequences on daylight autonomy. This revealed that a 4.5-meter perimeter column spacing, creating a façade with 50 percent openings, significantly decreased the depth of over lit areas (above 2,000 lux) to a 1.5-meter zone around the edge of the floor plate. In comparison, an all-glass tower would have had a four-meter-deep over lit zone at the perimeter of the floor plate, making a

Opposite Top: Daylight Autonomy comparison between an all-glass façade and the current design. Source: Skidmore, Owings & Merrill

Opposite Middle: Façade detail showing implementation of glare mitigating materials. Source: Skidmore, Owings & Merrill

Opposite Bottom: Analysis of hours of intolerable glare. Source: Skidmore, Owings & Merrill

Bottom: Looming tradition in Guizhou. Source: The Fabrick Lab 2015

"The glass enclosure is set back to align with the interior face of the load-bearing perimeter columns. This allows the protruding structure to participate in the shading of the glass openings, reducing direct exposure to sunlight and reducing solar heat gain considerably as a result."

large part of the floor plate uncomfortable. The under lit area (<300 lux) is concentrated along the tower's core, leaving a five-meter-deep zone of appropriately lit area (ranging between 300 and 2000 lux) in the middle of the lease span.

Reducing Solar Heat Gain: A Sculptural Solution

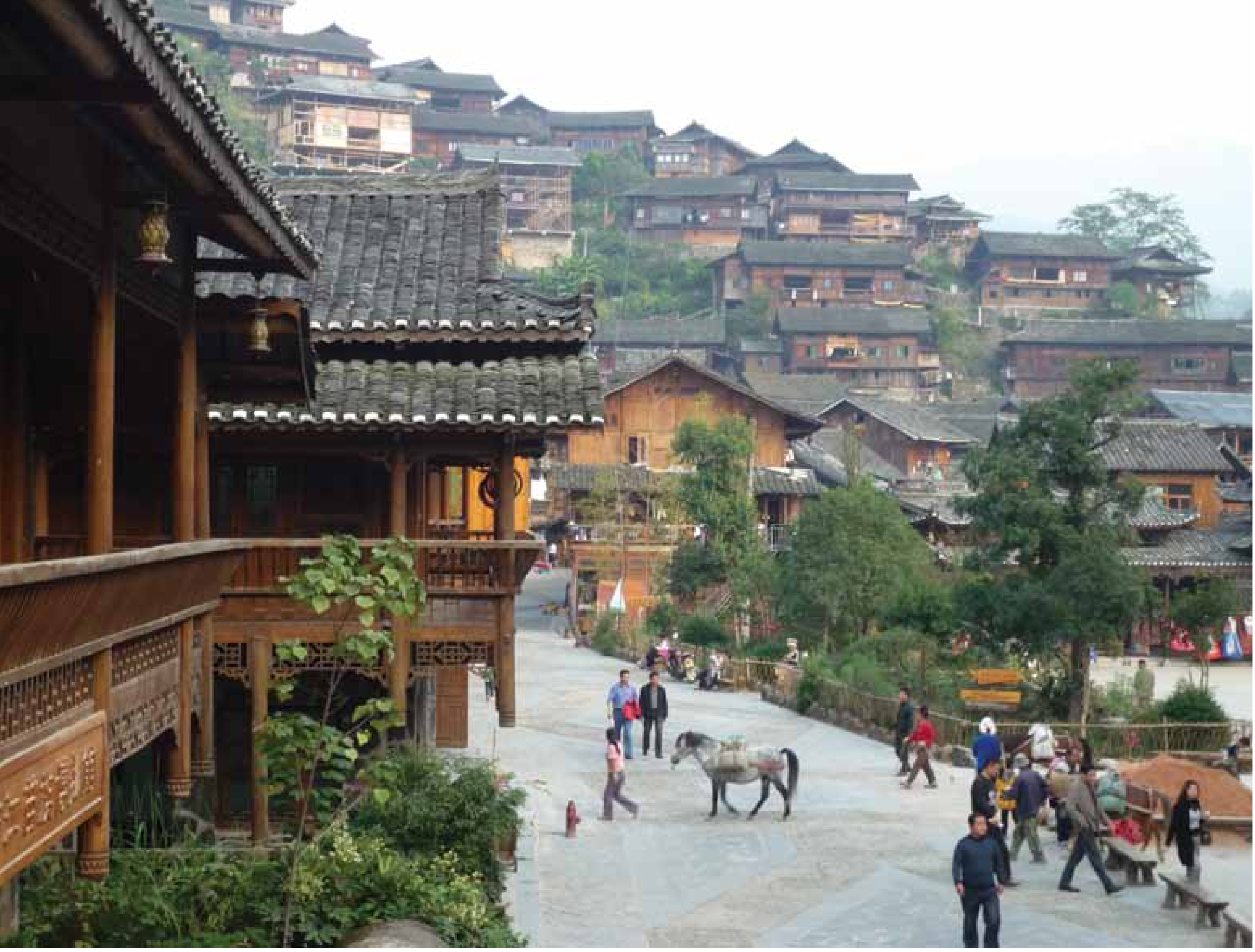
In parallel to the structural expression, the façade expressed the desire to efficiently shade the glazed openings.

The glass enclosure is set back to align with the interior face of the load-bearing perimeter columns. This allows the protruding structure to participate in the shading of the glass openings, reducing direct exposure to sunlight and reducing solar heat gain considerably as a result.

To further reduce solar heat gains, the perimeter columns were clad in rounded stainless steel panels that strategically protrude at the spandrel, providing additional protection for the glazed openings. The rounded column cladding swells at every floor, creating vertical ripples that travel vertically along the façade. This created the tower's signature texture, a watery ripple that directs the gaze up. In the light of Chairman Xi Jinping's desire for an architecture that can 'uphold the Chinese spirit,' parallels were drawn between the façade's woven appearance, and the local traditional practices of looming and weaving textiles, typical of the Guizhou province. Another parallel was made with the rippling waters of the river Nanming, which flows at the foot of GWTC and joins the Wu River, becoming one of the tributaries of the Yangtze River.

Cladding Texture and Materiality: Glare Reduction Analysis

To maximize occupant comfort even further, and assist the design teams in the selection of appropriate cladding materials, a close examination of discomfort caused by glare was undertaken. On the one hand this confirmed that setting the glass back from the building face and aligning it to the inner side of the columns, and reducing the amount of glazed openings significantly reduced the amount of yearly hours of intolerable glare. More importantly, it



revealed that the bottom sill of the glazed opening played the most significant factor in reducing glare (See Figures 9 & 10). The vertical metal panels flanking each opening were also determining factors. After analyzing multiple finishes, using black-colored steel with a diffuse finish on the bottom sill, as well as on the sides of every opening, was found to reduce the intolerable glare by nine percent of occupied hours compared to using the same stainless steel finish used on the rest of the column cladding.

A comparative analysis was undertaken to understand the difference in embodied energy between the chosen design — a concrete tube-in-tube façade — and a typical all-glass curtain wall façade with interior columns. The results revealed that the tube-in-tube structure generated an estimated 15 percent reduction in the embodied energy of a typical tower floor's envelope compared to an all-glass tower floor. This is mostly achieved by a reduction in the amount of insulated glass units used when the façade incorporates the perimeter columns. A further analysis of the embodied energy of different architectural metal claddings was used to compare stainless steel, aluminum and zinc and assist in the selection of cladding material. Stainless steel cladding resulted in the lowest embodied energy, or eight percent less than aluminum and six percent less than zinc.

A Tower in a Contextually Responsive Master Plan: Urban Design Rooted in the Vernacular

While it's not uncommon for architects to simultaneously design a tower and its extended site, the distinctive topography and natural setting surrounding GWTC make it critical to develop a master plan that respects the site's features, allowing for the tower to strategically inhabit its environment without compromising its natural beauty.

Instead of concentrating towers along the waterfront, the master plan takes its cue from local building traditions, where villages agglomerate along the hillsides, reserving the riverbed for agricultural and open space. This vertical separation of density is at the heart of the master plan.

A low-lying park is placed along the riverfront, at the base of the development, and serves two main functions. First, it performs an ecologically critical role by collecting runoff water from the uphill development, filtering it through a series of bioswales before returning it to the river. Second, it integrates generous sports, leisure and health amenities under the park surface. The surrounding site's abundant natural hot springs are harnessed to become a catalyst for health spas and a natatorium and sports facilities embedded under the park's surface and illuminated by glass domes. Small-scale retail pavilions embedded at the park's edges complete the programmatic mix of sports, leisure and entertainment that transform the waterfront into a civic park animated at all times by visitors and inhabitants alike.

A Dense Hillside Village

On the hillside, four high-rises and a World Trade Center tower are interspersed between a dense fabric of low-rise buildings that blankets the steep slopes of the hill. Four-story live/work buildings frame the serpentine roads with retail. A unified palette of local materials resonates with the local vernacular and creates intimate shopping and dining streets that terrace 60 meters up the hill. Here too, the local context has

Opposite: View of a typical Miao village, Guizhou. Source: John Fanai

Right: View of a typical street showing the dense, low-rise terraced fabric. Source: Skidmore, Owings & Merrill

inspired awnings, and covered galleries along the building that enrich the pedestrian experience. Connecting across these different streets, the terraced pedestrian passages cascade between the different levels of the master plan. They form lush shaded corridors that star in the waterfront park and rise to a bus station and transit hub on the upper terrace. These landscaped interstices offer respite from the village-like density of the hillside, and direct rainwater towards the low-lying park to be filtered. From this dense urban carpet, four towers offering live/work units emerge. Ranging between 31 and 63 stories tall, they bring a diversity of inhabitants to the neighborhood, animating it at all hours of the day. A six-story mall anchors the northern part of the hill, spanning across many terraces and adding to the site's programmatic tapestry. From the scale of the master plan to that of the street, the urban design respects the topography of the site and reflects vernacular urban values.

Being at the bottom of a slope requires both upstream and on-site rainwater management. Rainfall occurs almost every other day, with extreme storms exceeding 100 mm. A 150 mm storm would produce approximately 27,000 cubic meters of runoff down the mountain slopes towards the site. This runoff can be captured in reservoirs, which drain to a power house via a pipeline, then discharge to the river. To harvest this potential energy a powerhouse with a 15 kW turbine is proposed. The annual potential energy of the reservoirs is approximately 30,000 kWh. Each reservoir will have a level sensor to control outflow according to the forecasted rainfall. This will be automated to drain the reservoir before the next storm and to produce consistent power. In this way, some of the site's defining characteristics, namely strong topography and consistent rainfall, are mobilized to generate energy for the site's use.

Poised at the threshold of the civic park and the hillside village, The Guiyang World Trade Center becomes the epicenter of the master plan. It soars above the surrounding towers, rising to match the neighboring mountain's peak. Its distinctive form and materiality stand out from the surrounding dense fabric, and the tower's placement allows it to open up to the civic park.

Sustainability as an Interdisciplinary Imperative

To the arsenal of filters through which tall buildings are designed and evaluated, sustainability adds tools that cut across disciplinary lines to inform design at every level. It can lead us to reconsider design beyond trends and creates high-performing towers that rise to the challenge of our time.