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Case Study: Evolution Tower, Moscow

High-Rises, High Seismicity

A Car-Free, Polycentric City

Skyscraper Energy Calculator

Tall Buildings in Numbers: Twisting Tall Buildings

Ask the Expert: How Fast Should Elevators Go?

Talking Tall: Engineering China's Skylines

Council on Tall Buildings and Urban Habitat

Inside

20

Structural Engineering

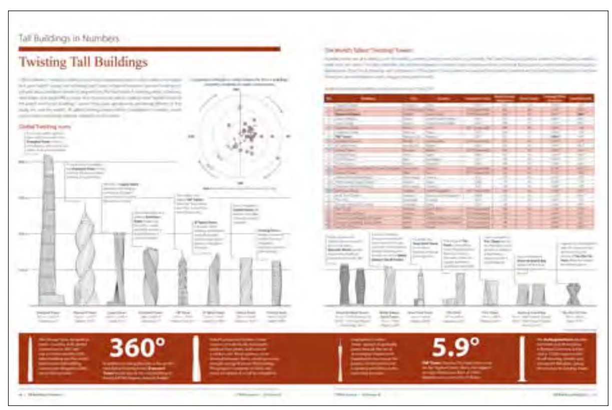
High-Rises, High Seismicity: New Materials and Design Approaches

34

Sustainability/Green/Energy

Skyscraper Energy Calculator

46



Tall Buildings in Numbers

Twisting Tall Buildings

“There was a period of time in which many ‘strange’ or even ugly buildings were built. But, I think that time has passed, and China has come to a more rational stage.”

Dasui Wang, page 48

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Americas

High-rises in **New York City** continue to break construction and design barriers while expanding beyond the traditional high-density node of Manhattan. In Brooklyn, SHoP Architects' **461 Dean Street** – the tallest volumetric modular building in the world – topped out at the Pacific Park complex. The 32-story structure will become the first residential building to open at the nine-hectare development. Meanwhile, in the Bronx, a proposal has been submitted for the city's largest residential passive house high-rise project. The **Mott Haven Passive House** at 425 Grand Concourse is designed to use 70% less energy than conventional buildings. The mixed-use building will feature housing for low- and moderate-income households.

While New York continues to lead the way in the Americas with innovative design strategies, a number of other cities in the United States are embracing the growing transit-oriented development trend. In **Boston,** an office and residential tower has been proposed by Pelli Clarke Pelli Architects as part of the redevelopment of the city's South Station transportation complex. The proposed tower would be the tallest in the city's financial district, rising directly from the train station, thereby integrating with the larger urban network.


461 Dean Street, New York. © Marshall Gerometta


Mott Haven Passive House, New York. © Dattner Architects
Clients: Trinity Financial and MBD Housing Corporation

Similarly, in **San Francisco,** Foster + Partners' and Heller Manus Architects' **Oceanwide Center** has been approved for construction. The two-tower development, which includes the future-second-tallest tower in the city, is part of the massive Transbay Transit Center redevelopment scheme that is set to diversify the largely commercial South of Market (SoMa) neighborhood through increased density and transportation links across the city.

Concepts for mixed-use mega developments go far beyond traditional transit-anchored schemes. The city of **Detroit** has teamed up with developers and Major League Soccer (MLS) to propose a four-tower development linked to a new soccer stadium. The extensive master plan is intended to transform the area into a destination for sports, entertainment, and retail.

Down the road on Ontario Highway 401, a piece of waterfront property in **Toronto** has been sold to the Liquor Control Board of Ontario (LCBO). In accordance with a multi-phase master plan developed by B+H Architects, the provincial agency intends to transform the 4.7-hectare property into a new headquarters space that will include an outlet store, commercial retail space, and offices across several high-rises.


Oceanwide Center, San Fransisco.
© Foster+Partners & Heller Manus Architects

While these mega-developments across North America reflect Daniel Burnham's famous maxim "make no little plans,"


Rosewood São Paulo Tower/Citade Materazzo, São Paulo.
Design Architect: Ateliers Jean Nouvel,
Client: Groupe Allard

RB12, Rio de Janeiro. © Tryptique

architects in South America are grappling with the "big plans" of previous generations. In **São Paulo,** Ateliers Jean Nouvel has proposed a hotel and residential tower on the former site of a 27,000-square-meter maternity hospital complex. Dubbed **Rosewood São Paulo Tower,** the project builds on the existing development, which contains a park and several historic buildings, by vertically continuing the greenery of the local landscape. And in **Rio de Janeiro,** architects have overhauled a 1970s-era office block to incorporate energy-reducing design strategies. The updated **RB12** tower features a "bioclimatic façade" that helps reduce sun exposure, while PV panels were added to the north-facing wall along with a number of other environmentally-minded additions.

Asia and Oceania

Perhaps no tall building project yet has sought to integrate itself with its natural environment more so than Stefano Boeri Architetti's proposed development in **Xingyi,** southwest China. Building on the architecture firm's aesthetic of tree-clad structures, this new proposal will also be sited on and partially built into a reconstructed hill in order to fully blend into the area's mountainous topography.

Although this project will certainly bring attention to what is still a rather remote part of China, for now all eyes remain fixed on the country's largest city, **Shanghai.** Having recently completed and opened to the public, officials at Gensler's **Shanghai Tower** celebrated the historic structure with the

Wanfeng Valley Resort, Xingyi.
© Stefano Boeri Architetti

inauguration of a CTBUH-designed signboard commemorating its status as the country's tallest building and the world's second-tallest.

Another record-setting tower could be built in Shanghai. Otis Elevator plans to build the world's tallest elevator test tower outside the city. At 270 meters, the **Otis Test Tower** would be capable of researching and testing elevators for the world's tallest structures.

This theme of record-breaking accomplishments continues in Southeast Asia. The 314-meter **MahaNakhon** by OMA / Ole Scheeren officially completed in April to become **Bangkok**'s tallest building, surpassing

Shanghai Tower, Shanghai. © Baycrest

MahaNakhon, Bangkok. © PACE

THEY SAID

"Although physical disconnection is softened by ubiquitous social media and the internet, the occupant of an 84th-floor 360-degree apartment in a 'needle tower' in Manhattan, or its equivalent in the Burj, is simultaneously truly urban and truly isolated."

Paul Finch, Editorial Director for The Architectural Review, explores architecture's role in tackling inequality. From "Pipe-Dream or Target," The Architectural Review, World Architecture Festival Special Issue, 2016.

Upward Spiral: The Story of the Evolution Tower

Philip Nikandrov

The Evolution Tower, Moscow, set off a wave of imitators when its design was first revealed in 2004, but it took another 12 years for it to come to fruition. Through the economic crisis and many subsequent design team iterations, the essential twisting form has endured. The appropriately named final product demonstrates the persistent value of a strong concept. The tower, against many odds, has definitively spiraled upward and taken its place in the city's skyline.

Author

Philip Nikandrov, Chief Architect
GORPROJECT
Nab. Academika Tupoleva 15
Building 15, 5th Floor
Moscow 105005, Russia
t: +7 495 500 5571
e: p.nikandrov@gorproject.ru
www.gorproject.ru

Philip Nikandrov
With 25 years of international experience in architecture, Philip Nikandrov is a leading architect specializing in large-scale, complex and unique projects in the high-rise typology. His design approach shows a route between contextualism and minimalism, achieving complexity through simplicity. On joining RMJM in 1997, Nikandrov served as senior designer and project architect on some of the most prestigious projects, working in the firm's offices in the United Kingdom, the Middle East, and Russia. In 2011, Nikandrov joined GORPROJECT as its chief architect and continued delivering his designs, including the Evolution Tower, Moscow, and Lakhta Center, St. Petersburg (currently under construction), set to become Europe's next tallest skyscraper.

Introduction

The spiraling 246-meter Evolution Tower is located in the Moscow-City high-rise business district on the Presnenskaya Embankment along the Moscow River. The new multi-function center occupies a 2.5-hectare area, 80% of which is a landscaped terraced civic plaza. The plaza is an integral part of the development, forming its central open public space. It includes a 10-meter-high ceremonial staircase, leading from the embankment and the pedestrian Bagration Bridge over the Moscow River to the higher terraced levels, as well as landscaped areas with green lawns, trees, water features, travelators, and feature light boxes (see Figure 1).

Under the plaza, a two-story retail mall connects the Evolution Tower with a metro station and the lower level of the Bagration Bridge, thus integrating the new development into the larger Moscow-City district, where 7 of the 10 highest European skyscrapers are located, housing more than four million square meters of office and retail areas, with associated transport and engineering infrastructure.

Part of Phase 1 of the project, the Evolution Gallery Mall within the podium houses a food court and a 6,000-square-meter family entertainment and educational center, where kids can learn about various professions to earn "points" and spend them on the rides (the first such center of that format in Moscow).

Figure 1. Evolution Tower, Moscow – aerial view

The 82,000-square-meter office tower has 52 levels, with each level rotated three degrees from the previous and the overall twist reaching 156 degrees clockwise. With the world's largest cold-bent glazing, the tower façade provides a seamless floating reflection that rotates the panoramas of the Moscow skyline vertically. The reflected clouds moving up the surface enhance the dynamic visual impact of the twisted tower, an unprecedented optical effect on this scale (see Figure 2). The tower's crown, with a supporting steel structure made of two twisted arches, provides a helipad at the very top, as well as an open observation roof deck at level 52 featuring the best panoramas of the Moscow riverside, with views towards the historic city center (see Figure 1).

From the very beginning, the developer and architects set an ambitious goal: to create a recognizable and symbolic building that would be a new icon of contemporary

Moscow. From the onion domes of St. Basil's Cathedral to the iconic Tatlin Tower concept, Russian architecture has long been obsessed with spirals. At the most basic level, the twisting, sculptural DNA-shaped Evolution Tower symbolizes the progress of humankind through its achievements in construction.

However, the original concept of the spiral tower on this site, City Palace Tower, conceived in 2005, was inspired by quite a different metaphor. In 2004, Moscow city authorities had planned the construction of the Wedding Palace: a registry office and ceremonial space within a 16-story, 30,000-square-meter building. The winning entry of the international competition held by the developer Snegiri Group in 2004 proposed a balanced composition of "twisting crystals" – two fully glazed towers of different height, with a slight twist in the geometry of the opposite façades.

A Design Evolution

The original concept, developed by the author in collaboration with RMJM, secured the contract and later led to a series of iterations and design alternatives, combining the city authorities' ambitions to impress the world with an iconic wedding palace building and the developer's intentions to increase the total gross and rentable areas to make the project financially viable. Finally, both parties united around a sketch of two twisted ribbons elevated from the Yin and Yang symbols, where black and white represented the groom and bride embracing each other in dance.

The original manifestation of the duality and union symbolized by Yin and Yang as groom and bride was overly literal and, rendered in black and white, looked a bit like a penguin. So after a few further distillations, a more restrained and stylish sculptural composition emerged, with the wedding palace housed under the curved atrium glazing of the "bride's skirt" (see Figure 3).

The design of the tower crown was further improved by separating two ribbons with the

Figure 2. Evolution Tower, Moscow. © Igor Butyrskii

High-Rises, High Seismicity: New Materials and Design Approaches


Cary Kopczynski


Mark Whiteley

Authors

Cary Kopczynski, Senior Principal
Mark Whiteley, Principal
Cary Kopczynski & Company (CKC)
10500 NE 8th Street, Suite 800
Bellevue, WA 98004
United States
t: +1 425 455 2144
f: +1 425 455 2091
e: caryk@ckcps.com; markw@ckcps.com
www.ckcps.com

Cary Kopczynski
Cary Kopczynski is senior principal and CEO of Cary Kopczynski & Company (CKC), a structural engineering firm with offices in Seattle, San Francisco, and Chicago. CKC designs major urban buildings throughout the United States and internationally. Kopczynski serves on the American Concrete Institute's (ACI) Board of Directors, is a past president of ACI Washington State Chapter, and served for many years on ACI Committees 318 and 352. He serves on the Post-Tensioning Institute's (PTI) Board of Directors and Executive Committee, and chaired the PTI's Technical Advisory Board (TAB) for six years. Kopczynski is a Fellow of both ACI and PTI, and an Honorary Member of the Wire Reinforcement Institute. He is the current president of the Structural Engineers Association of Washington.

Mark Whiteley
Mark Whiteley is a principal at CKC and the senior project manager for Lincoln Square Expansion (LSE). Whiteley has more than 20 years of experience designing a wide variety of significant high-rise projects throughout the United States. He took the lead in developing design procedures and detailing for implementation of steel-fiber reinforced concrete (SFRC) for shear wall coupling beams at LSE.

When construction completes in 2017, the Lincoln Square Expansion (LSE) will add two 135-meter towers to downtown Bellevue, Washington. The nearly 275,000-square-meter development serves as an excellent example of how innovative structural design can respond to demanding seismic requirements while still meeting cost and schedule targets. LSE's most significant and unique design feature is the use of steel-fiber reinforced concrete (SFRC) in the concrete shear wall coupling beams. This is the first major use of this type of material throughout a project as a part of the lateral system in a region of high seismicity.

Project Description

Lincoln Square Expansion (LSE) is the newest high-rise addition to Bellevue, which continues its growth into a vibrant, world-class city in the Pacific Northwest of the United States (see Figure 1). The LSE broke ground in June of 2014 and is scheduled to complete in 2017. The mixed-use project will include a 41-story tower featuring an upscale hotel and luxury apartments, as well as a 31-story office tower providing 66,000 square meters of Class "A" office space (see Figure 2). Both towers integrate with a four-level retail podium structure and six levels of subterranean parking, which includes 2,200 new parking spaces and will connect to adjacent existing underground parking via tunnels (see Figure 3).

The hotel/residential tower is cast-in-place concrete with a mix of one-way and two-way post-tensioned concrete slabs. The office tower and retail podium frame are structural steel. Special reinforced-concrete shear walls resist wind and seismic loads throughout the project. The subterranean parking structure utilizes one-way post-tensioned slabs with wide, shallow post-tensioned beams to create large open space for user-friendly parking.

LSE is the first major use of SFRC in shear wall coupling beams. This is a new method of designing and constructing coupling beams,

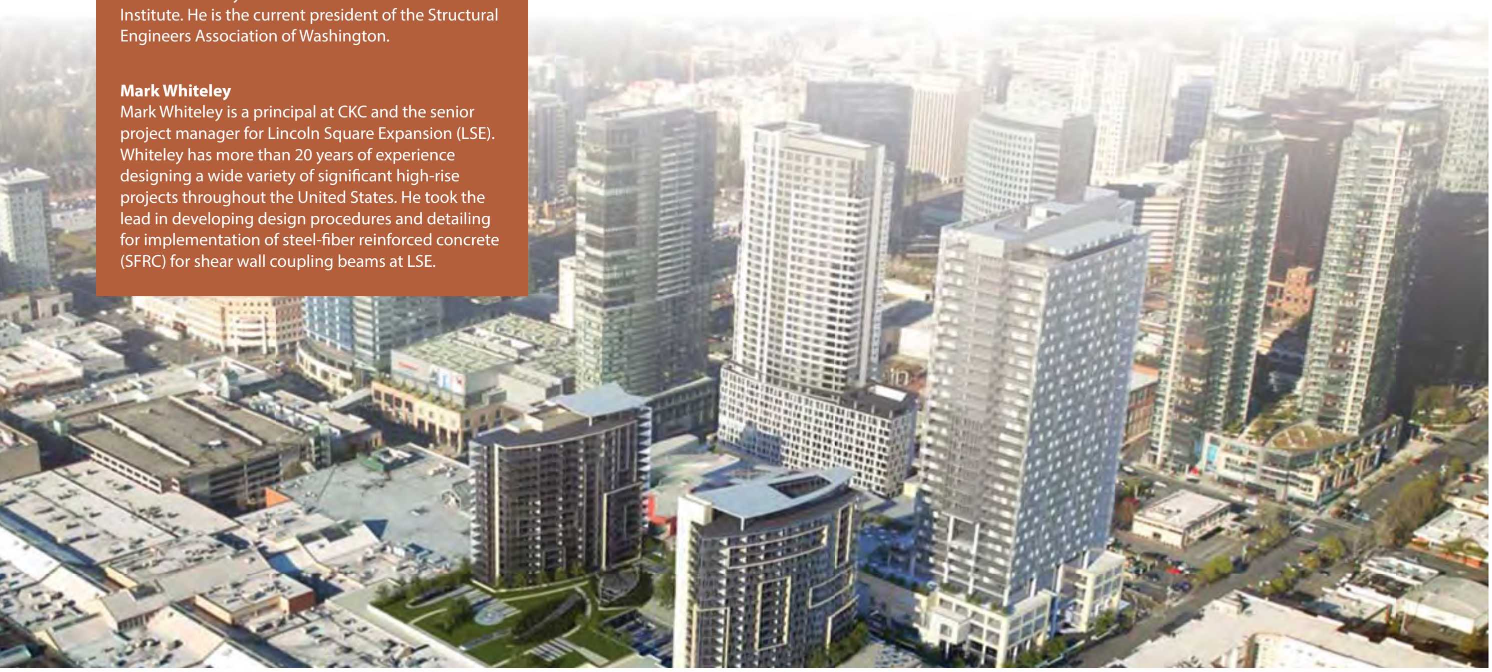


Figure 1. Lincoln Square Expansion, Bellevue. © Neoscape

which can significantly reduce reinforcing bar quantity and improve constructability. The following is a discussion on the process and implementation of SFRC coupling beams in the LSE project, including a description of how performance-based seismic design provided the means for implementation of SFRC coupling beams (see Figure 4).

Performance-Based Design

Since the selected lateral system of special reinforced concrete shear walls is limited to a maximum structural height of 73.2 meters according to a reference standard in ***Minimum Design Loads for Buildings and Other Structures*** (ASCE 2010), a peer-reviewed performance-based design (PBD) approach was necessary for both towers and the below-grade structure. PBD is a methodology for creating acceptable alternates to prescriptive building code requirements, contingent upon explicitly demonstrating that the proposed design meets code-intended seismic performance. This is accomplished by generating a mathematical structural analysis model that is more sophisticated than what would typically be used in a code-prescribed design. The model is used to perform non-linear analyses while considering the stiffness, ductility, and strength of critical structural elements.

Although a more common linear analysis assumes that the stiffness and material properties of the modeled members remain constant throughout the duration of a seismic event regardless of the level of force, utilizing a nonlinear model allows engineers to more realistically define how the various parts of the building move, elongate (stretch), and degrade during an earthquake. The coupling beams and shear wall flexural components have the greatest potential to experience deformations that could lead to strength loss, so nonlinear properties and material definitions were generated for these critical elements.

Walls were modeled using composite vertical fiber elements, which combine both nonlinear concrete and steel reinforcing materials. For the reinforcing steel, a trilinear backbone curve was assumed for both the A706 Grade 60 and Grade 80 materials, using expected material properties in lieu of the specified minimum properties to better approximate in-place behavior. Since the model exhibited limited nonlinear behavior in the vertical concrete elements, a simplified concrete material definition was used in order to reduce computer run time without compromising the analysis results. Capacity-protected elements, such as gravity columns, slab shell elements, slab-column connections, and shear-in-shear and


Figure 2. LSE – Office tower.

basement walls, were modeled with linear properties to capture the intended behavior and detailed to remain elastic.

Seven pairs of site-specific ground motions were developed by the project geotechnical engineer for the location by matching the source, magnitude, frequency, and duration of the risk-targeted maximum considered earthquake (MCEr) spectra, which corresponds to an earthquake with an approximately 2,000-year return period for the project location. Earthquakes from Chile (2010); Tohoku, Japan (2011); and Olympia, USA (1949) were among the base ground motions used. Typically, a building in the

Figure 3. LSE configuration.

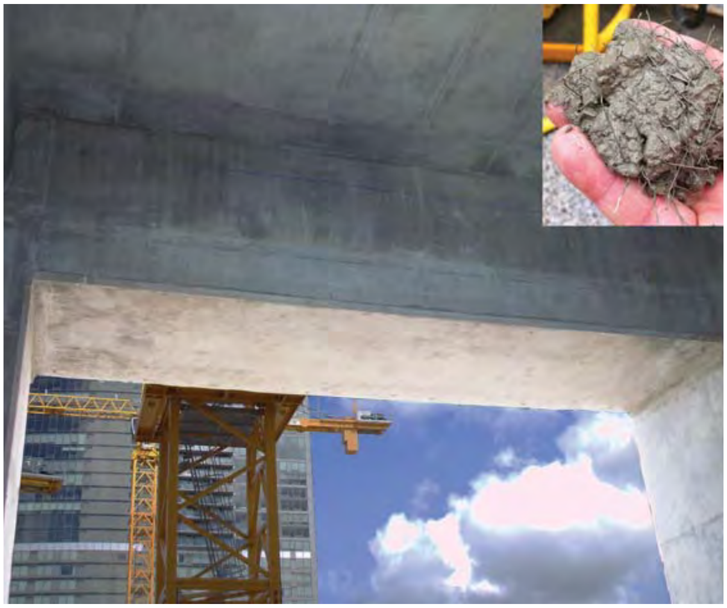


Figure 4. Steel-fiber reinforced concrete (SFRC) coupling beams.

A Car-Free, Polycentric City, with Multi-Level Skybridges and Inter-Building Atria

Richard J. Balling

Author

Richard J. Balling, Professor
Department of Civil and Environmental Engineering
Brigham Young University
368G Clyde Building
Provo, UT 84602
United States
t: +1 801 422 2648
e: balling@byu.edu
www. byu.edu

Richard J. Balling
Richard J. Balling is a professor of Civil and Environmental Engineering at Brigham Young University. He earned his PhD in Engineering and MS in Engineering from the University of California, Berkeley. Balling is the author of more than 110 published, peer-reviewed manuscripts, and nine textbooks. He was the King Husein Professor of Civil Engineering from 2011 to 2013, was on the board of directors of Design Synthesis Inc.in Provo until 2004, and was a visiting scientist on behalf of the International Council of Associations for Science Education (ICASE) at NASA Langley Research Center, 1993–1994.

The concept of cities as self-contained megastructures has fascinated architects and urban theorists for decades. The idea received much attention in the 1960s and 70s, resulting in some experimental built works. With today's renewed interest in sustainability and compact living, along with advances in computerized architectural optimization, there is now an opportunity to revisit this concept. This paper examines the potential for the nearest modern analogue – the college town – to be incorporated in such a self-contained structure, which is nevertheless connected to the world.

Introduction

People love their cars, but what is the cost of this love affair? The average American family spends 17% of its income on transportation (US BLS 2015). The ratio of the number of traffic fatalities to the total number of deaths each year reveals that about one out of 79 dies in a car crash (US NHTSA 2015; US CDC 2015). Air pollution from vehicles causes the premature death of about one out of 49 Americans (Caiazzo et al. 2013). Car use contributes to the pandemic of physical inactivity, which causes about one out of 10 deaths worldwide (Kohl et al. 2012). Congested traffic is a source of wasted time, noise, and stress. The American lifestyle is so dominated by car usage that most people choose to ignore the dangers and costs.

Is it realistic to build car-free cities? The past century has seen the development of high-density ground-access-skyscraper (GAS) cities throughout the world. Such urban intensification has been called the "Paradox of Intensification," which states, "*Ceteris paribus,* urban intensification which increases population density will reduce per capita car use, with benefits to the global environment, but will also increase concentrations of motor traffic, worsening the local environment in those locations where it occurs" (Melia, Parkhurst & Barton 2012). One reason high-density GAS cities are congested with vehicles is that in many cases the horizontal distance between origin and destination is too far to walk. Studies show that people are willing to walk about 800 meters before taking a motorized vehicle (Guerra, Cervero & Tischler 2012). This article examines car-free cities where all daily origins and destinations are located within an 800-meter horizontal walking distance.

Evolution of the Self-Contained City

A city that includes all daily origins and destinations for all its residents will be referred to hereafter as a "self-contained" city, for which there is a significant theoretical precedent. Buckminster Fuller contemplated such cities in conjunction with his famous geodesic dome designs in the 1950s. These ideas influenced the London-based architectural group, Archigram, which was committed to a high-tech, lightweight, infrastructural approach. Metabolism was a post-war Japanese architectural movement that combined ideas from architectural megastructures with organic biological growth in the 1960s. In 1970, construction began on Arcosanti in Arizona, a hyperdense city designed by Paolo Soleri to maximize interaction of its 5,000 inhabitants as an example of architecture coherent with ecology, or "arcology." These ideas are again becoming popular as sustainability becomes a priority. In 2012 Ken King established Vertical City, a not-for-profit organization that aims to ignite a worldwide conversation about vertical cities as a solution to a more sustainable future. In recent years, massive self-contained "hyperstructures" have been proposed, including the X-Seed 4000 in Japan, 1995; Crystal Island in Russia, 2007; and Ziggurat in Dubai, 2008.

"The study showed that wind load per building is much less than for the same buildings without ETFE atria and multi-level skybridges, requiring up to 10% less structural material."

Figure 1. The University City plan.

How much floor space is needed for a self-contained city, and what is a logical population for a city encompassing residences, workplaces, offices, schools, stores, hospitals, restaurants, churches, and entertainment? Everyone who lives in the self-contained city works there. Some of the best contemporary examples of self-contained cities are college towns. The following five college towns in the USA were considered: Auburn, Alabama; Lafayette, Indiana; College Station, Texas; State College, Pennsylvania; and Ames, Iowa. Based on the 2010 US Census, the analysis of the demographics and land use of these five cities revealed that the average population of these cities, including students, is about 100,000 (US Census 2010), and the average total floor area is about seven million square meters.

One blunt-force approach to accommodating the above would be to construct a single mega-building with a floor area of 7 million square meters. If the mega-building has a square 800-meter-by-800-meter footprint, it would require 11 stories. Alternatively, if the mega-building has 100 stories, it would require a square 265-meter-by-265-meter footprint. People would not want to live in an uninspiring mega-building such as this because it lacks architectural diversity and limits natural light penetration and exterior views.

A team of students and faculty from a variety of engineering, management, and social science disciplines designed a car-free University City for 100,000 people including 33,000 students with the same floor space and outer dimensions as the "mega-building," but which instead consists of 46 diverse buildings ranging from 15 to 44 stories (see Figure 1). This University City is an example of an urban paradigm that will be referred to herein by the name "greenplex." At the CTBUH World Conference 2011, the notion of the greenplex was introduced and research needs were outlined (Balling 2011). This article presents research results garnered over the past five years and further refines the greenplex as a "car-free polycentric urban paradigm."

Space Use and Multi-Level Skybridges

The team addressed the optimum allocation of space use throughout the University City by considering results from an optimization study on a simpler city with 25 buildings. This city was divided into 344 zones, in which each zone consisted of three consecutive floors in one of the buildings. Space was optimized with a genetic algorithm that represented a particular design as a chromosome with 344 genes – one for each zone. The value of each gene was an integer between 1 and 16, corresponding to 16 specific residential, commercial, educational, and recreational space uses. The algorithm's objective was the minimization of the average travel time of all trips during the evening peak period. A three-step transportation model was developed: 1) trip generation, 2) trip distribution, and 3) trip assignment.

Four optimization problems were solved (see Table 1). In scenarios 1 and 3, skybridges were located between every building at four equally-spaced levels. In scenarios 2 and 4, there were no skybridges. In scenarios 1 and 3, each building was equipped with one multi-car circulating elevator loop (Hitachi 2006) that stopped at every story and one express multi-car circulating elevator loop that stopped only at skybridge levels. In scenarios 2 and 4, each building had three express and three standard elevator loops. The average travel time was the same for scenarios 1 and 3, 19% longer for scenario 2, and 134% longer for scenario 4.

These results clearly show the value of skybridges in reducing travel time. The fact that increasing the number of elevator loops did not shorten the travel time suggests that pedestrian movement is predominantly horizontal rather than vertical when skybridges are present. When skybridges are present, the optimum location of high-attraction uses such as shopping centers, supermarkets, food & beverage, and athletic clubs was at skybridge levels, while the optimum location of low-attraction uses, such as offices, medical centers, schools, and churches was at non-skybridge levels. Optimization distributed all uses vertically throughout the city. These results suggest that the presence of multi-level skybridges leads to the creation of "multi-level communities" in the optimum design, where people spend most of their time within a few levels of their residence.

The team used these results to design the space use for the 100,000-resident University City (see Figure 2). Recall that the 46 buildings range from 15 to 44 stories. Note that the mixed-use buildings are highly-connected with skybridges every seven stories, and that high-attraction retail space

Optimization problem	Skybridges present	Elev. loops	Average travel time (s)	Longest trip time (s)
1	Yes	3X	168.6	594.2
2	No	3X	196.5	706.2
3	Yes	1X	168.8	594.2
4	No	1X	267.5	1390.3

Table 1. Travel times for optimum designs of generic city.

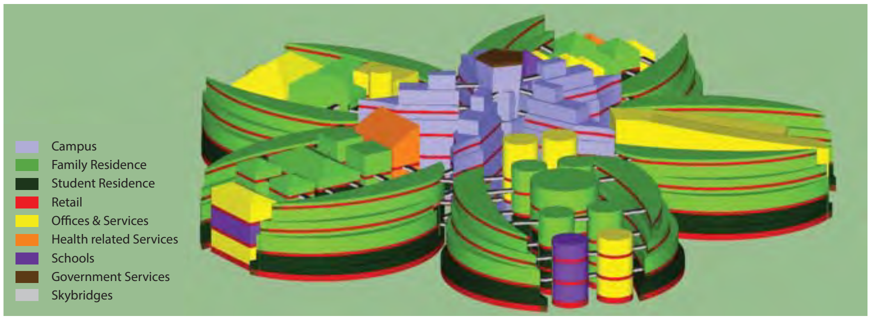


Figure 2. Facility configurations for the University City.

Skyscraper Energy Calculator

Mark Weisgerber

Author

Mark Weisgerber, Designer
Eric Colbert & Associates PC
717 5th Street NW
Washington D.C. 20001
United States
t: +1 202 289 6800
f: +1 202 289 6801
e: maweisg@gmail.com
www.eca-pc.com

Mark Weisgerber
Mark Weisgerber is a sustainable designer and theorist with Eric Colbert and Associates. Weisgerber's career has encompassed over a decade of industrial, commercial, and high-rise projects mainly in the Midwest, with an emphasis upon applicable evidence based design. He is also a frequent contributor to *HeightsRising;* an online treatise on the possibilities of net-zero high-rise design, that can be found at www.heightscalling.blogspot.com.

This paper seeks to add to the growing collection of literature on skyscraper energy use, documenting on-site resource calculation potentials as related to overall collector sizes along a building's surface area. It suggests structures that can use their size, bulk, and physical location to offset total energy use, forgoing any number of complicated baseline standards. These features would better define net-zero aspirations up front, underlining alternative strategies that can be pursued from the outset of design. It also suggests utilizing a wealth of data available from contemporary ASHRAE sources and on-site measurements, showcasing the number of people a potential site could accommodate, as compared to predictive models based on expected user types.

> "A building would have to climb at least 92–152 meters before any potential from wind power was applicable at this selected site. Further, collectors sufficient to generate power would require that large swaths of the building be left open for collection."

Introduction

As skyscrapers soar ever higher and explore greater depths of design efficiency, designers have begun to experiment with more empirical and comprehensive approaches to overall energy use. This recent shift has attempted to transcend the traditional limits incurred by the tall building typology thus far, utilizing opportunities from growing heights or existing site opportunities to better incorporate next-generation design ideals. A range of options, from formal arrangements, to occupant user groups, to internal layouts, is now being considered by which to rework built structures as a sustainable whole. When balanced against a variety of harvestable on-site resources, new empirical approaches seek to exceed reductionist pursuits by creating a true net-zero skyscraper from the initial design outset.

The emergence of such comprehensive planning initiatives follows several design approaches that have been growing in prominence over the last few years. Major research-focused architecture firms have begun to publish procedural steps by which to initiate net-zero buildings in the United States, while theorists abroad continue to push the envelope toward fully integrated, self-sufficient buildings. Such methods first encourage minimizing user point loads upon a building, then seek to offset remaining energy use through an array of various on-site or technological sources. Structures like the Pearl River Tower, Guangzhou and the Bank of America Tower, New York have shown that substantial energy offsets are possible in today's marketplace through such practices, while Chambers et al. (2014) has theorized a point-by-point analysis of how to conceivably reduce current high-rise energy use by up to 90%. Other structures have gone a step further, using tactile biological capture through Living Machines to offset a greater range of human needs.

But while many such theories emphasize reductionist strategies to mediate overall energy use, practitioners in Europe are beginning to address high-rise sustainability from a computational perspective. The PlusEnergy system has recently taken root with German designers and theorists, seeking to create buildings that produce more energy than they need to operate directly from design outset. Such structures first map out energy requirements for a target structure or user group, then implement a variety of design systems to capture enough wind, solar, or geothermal resources to counterbalance user needs. Case studies like Rolf Disch's Heliotrope or the solar settlement of Vauban in Freiburg, Germany, have shown that PlusEnergy is now achievable in shorter structures, even within harsh northern climates. While such facilities have yet to apply a complete biological approach or even expand beyond mid-rise height, they have the added benefit of being easy to calculate and evaluate over time.

Meanwhile, additional possibilities have arisen from the integration of technological- and cloud-based design sources at earlier intervals. Companies such as Google and Mapdwell have been documenting available solar energy to rooftops in select global cities, while plug-ins for BIM design software have begun to showcase the ecological benefits of various design iterations.

For skyscrapers – a building type that uses considerably more energy than low-rise counterparts – the integration of these methodologies can have enormous design connotations. Resource data can now be integrated into final designs at an early stage, creating the possibility of better prediction, or of measuring initial harvest potentials from almost any site. Towers have now been suggested that could incur offsets through height-based "economies of scale," exceeding the original conditions of a site, such as providing external vegetation on multiple levels, beyond what is possible on an undeveloped site, or by using their size or bulk for additional user benefit or resource collection. Such strategies can range from redirecting excess roof rainwater to flush surrounding buildings; to nestling extensive solar panel groupings within exterior façades to facilitate energy production; to applying intensive use of vegetation inside central courtyards, increasing natural biofiltration. What emerges is a layout where a singular tower could potentially link to, or even support, several smaller structures around it. In this manner, theorists have sought to justify new developments with factors other than profit, seeking to capture and utilize the growing opportunities offered by tall buildings to more fully offset their enormous consumption rates. These and other questions led to the following assessment and results presented here.

Initialized Calculations: Alternative Methods to Achieve Net-Zero

This research suggests an agenda similar to the aforementioned PlusEnergy tactics, while superseding several reductionist strategies that have traditionally defined skyscraper energy efficiency. A five-step procedure, could provide parameters for a computational program for designing net-zero skyscrapers and balance those parameters against on-site resources:

1. Select a site and identify desired building size/general program parameters
2. Document all on-site resources available for capture and energy offsets
3. Determine internal occupant types and energy uses that will inhabit a building over the course of its lifetime
4. Balance these users against available on-site resources
5. Exceed all energy minimums

These strategies can be thought of as a comprehensive energy use "calculator," with specific applicability beyond low- or mid-rise building applications. It would continue aforementioned PlusEnergy strategies, balancing on-site resources against rentable building space in skyscrapers. From there, additional energy or municipal criteria can be added to better correspond to each selected site, expanding upon local initiatives or applicable site precedents as needed.

Step 1: Site selection/building sizing

To initiate this net-zero skyscraper calculation methodology, several steps must be taken to balance energy figures of tall buildings below zero energy use. The first is identifying a prospective site and contrasting it against a general building program. From this initial analysis, lessons could be shifted and scaled to other locales, based on data input from local regions.

As all PlusEnergy strategies are highly reliant on site, the City of Chicago was tentatively selected as an initial test locale for many reasons. The region is rich in available capital, investment opportunities, transportation, natural resources, and commitments to green design. It also remains a dense, growing metropolis, with a long history of clients willing to invest and experiment with passive energy buildings. Most importantly, the city is one of the "wettest and windiest" cities with a population of more than 750,000 in the United States, containing major harvest potential for wind and rain resources (Why 2010).

For the purpose of this paper, a 30.5 x 30.5 x 183-meter test structure was also initially considered along the Chicago River (see Figure 1). This suggested size aligns with "standard skyscraper" dimensions prevalent in the current downtown building assemblage (CTBUH 2015), at a location already the subject of a number of ongoing infill proposals. From here, additional criteria and calculations were added after initial design considerations were generally tested.

Step 2: On-site potentials

The next step in this suggested net-zero skyscraper calculation process is to document available on-site resources. Like most North American cities, Chicago maintains an extensive listing of its weather phenomenons and other resource data through the National Climate Data Center. From these and other similar sources, a catalog for the riverside location was created, utilizing engineering calculations acquired through the American Society of Heating, Refrigeration & Air Engineers (ASHRAE). A chart of each potential at this site was then mapped and compared, with the results shown in Figure 2. Additional measurements were taken from online databases and

Figure 1. Chicago test site location, showing current infill proposals. © SOM

A Software Tool for the Analysis of Time-Dependent Effects in High-Rise Buildings

Carlo Casalegno

Mario Alberto Chiorino

Taehun Ha

Sungho Lee

Authors

Carlo Casalegno, Research Fellow
IUAV University of Venice
via Massimo d'Azeglio 179
10081 Castellamonte
Italy
t: +39 34 6372 1142
e: casalegno.c@gmail.com

Mario Alberto Chiorino, Professor Emeritus
Politecnico di Torino
Department of Structural, Geotechnical and Building Engineering (DISEG)
Viale Mattioli 39
10125 Torino
Italy
t: +39 01 1090 4864
e: mario.chiorino@polito.it
www.diseg.polito.it

Taehun Ha, Senior Researcher
Sungho Lee, Senior Researcher
Daewoo Engineering and Construction
20 Suil-ro 123
Jangan-gu, Gyeonggi-do
16297 Suwon
South Korea
t: +82 10 9145 1873; 82 10 8650 7295
e: taehun.ha@gmail.com;
sungho.lee@daewooenc.com
www.daewooenc.com

Increased use of concrete in high-rise buildings has made these structures especially sensitive to delayed deformations due to concrete's natural tendency to creep and shrink. This is exacerbated in particularly tall buildings of hybrid construction, due to the different behavior of concrete and steel elements. In this paper, the authors present a software tool specifically developed to predict time-dependent behavior of high-rise buildings in both the construction and service stages. The specific features of the software are illustrated, and the results of a review and validation study are presented. Finally, the approach is applied to a real high-rise building currently under construction in Malaysia.

Concrete Properties' Effect on Tall Buildings

In recent decades, the use of reinforced concrete as the main construction material for high-rise buildings has significantly increased (Safarik et al. 2014). As a consequence, these structures have become sensitive to the effects of time-dependent concrete properties such as creep and shrinkage (*fib* 2014). The problem becomes particularly relevant in supertall buildings (Gardner & Chiorino 2007).

While the construction of the building proceeds, vertical supporting members, such as columns and cores, are subjected to successive incremental loads and axial strains due to the construction of the overlying floors. In concrete elements, these initial strains increase due to creep and shrinkage, shortening the overall building and causing shortening differences among columns; between cores and columns; or between concrete cores and steel or concrete/steel composite columns. The differences in the initial and time-dependent strains among concrete vertical members are normally due to differences in the stress levels and/or in the creep and shrinkage properties, due to members' volume-to-surface ratio (effective thickness) and/or longitudinal reinforcement ratio. Such differences in strains are intrinsic to hybrid concrete/steel structures, due to the different initial deformability of the two materials and the absence of creep and shrinkage in steel elements. The problem is further complicated by the continuous changes of the structural configuration inherent to construction sequences.

Redistribution of stresses and internal actions as vertical loads in the supporting members, and shear stresses and bending moments in horizontal members, are normally associated with all these effects in rigid connections between floor structures and vertical elements, especially when a stiff horizontal brace or transfer structure is present. In an asymmetrical building structure or in the construction sequence, lateral displacements and vertical deviations can develop as well, affecting the load distribution in vertical elements.

If all these phenomena are not adequately understood and analyzed in the design and construction phases, several serviceability concerns may arise (Gardner & Chiorino 2007; *fib* 2014; Chiorino et al. 2011; Fintel et al. 1986; Lagos et al. 2012). This affects structural members as well as non-structural components, such as the sloping and cracking of floors, cracking of horizontal structures and interior partitions, buckling of elevator guides and piping, misaligned elevator stops relative to floors, and damage to curtain walls and column cladding. In the case of incremental loads in vertical elements, their influence on the ultimate strength cannot be neglected. Special attention must be paid in the case of hybrid structures (which typically feature significant shifts of axial loads from concrete to steel vertical elements), especially when the

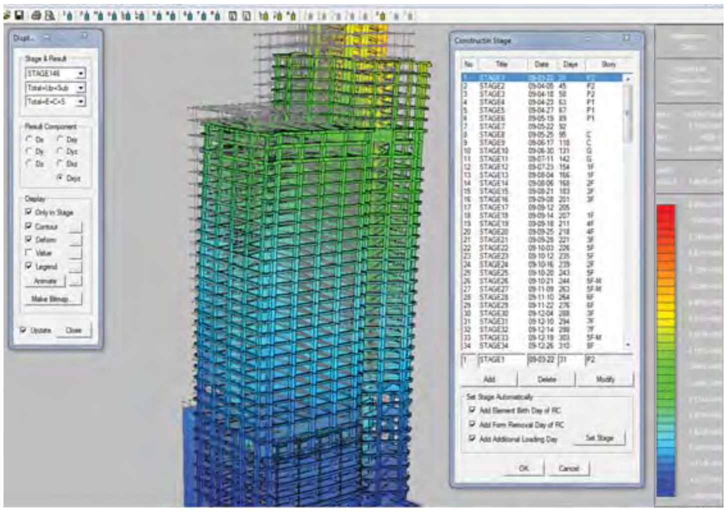


Figure 1. User interface of ASAP for post-processing of results.

“Current commercial software is functionally limited in solving problems typical of high-rise buildings and their complex construction-stage sequences, which consist of a large number of multifaceted steps spread across an extended time.”

buckling of slender steel elements must be considered. In concrete structures between 50 and 100 meters in height, the effects of the delayed deformations are often disregarded without serious consequences. In taller structures, as well as in hybrid structures, ignoring the effects of creep and shrinkage can lead to undesirable service conditions, and in some cases, to concerns for the structural safety of the building.

Axial shortening of a tall building can be predicted relatively easily during the preliminary design stage as the sum of elastic, creep and shrinkage deformations in the single vertical elements, taking into account the construction sequence (Fintel et al. 1986). This prediction method is usually referred to as “one-column shortening analysis.” The most significant limit of this approach is the fact that the restraining effects against differential shortening of the beams or slabs connected to the column or wall are not considered or are considered in an approximate way. The method has been widely used for decades, but recently there has been a move towards sequential construction stage analyses and time-history analyses of 3D models of entire building structures.

Advanced Stage Analysis Program (ASAP)

For assessing building movements, construction-stage and time-history analysis using a 3D finite element (3DFE) model that incorporates the time-dependent effects in concrete gives more accurate and comprehensive results than a one-column shortening analysis. The 3DFE analysis considers the effects of sequences of gravity loading and consecutive changes in the structural system as construction progresses. It also concurrently evaluates the effects of the various time-dependent properties of the concrete elements of the structure on the building structural response. Movements of the building are calculated through time in the construction stage and in service mode, as well as redistributions of internal actions in vertical and horizontal members.

Although there are several types of analysis software that can simulate sequential construction, they were mostly designed for the construction-stage analysis of bridges. As a result, current commercial software is functionally limited in solving problems typical of high-rise buildings and their complex construction-stage sequences, which consist of a large number of multifaceted steps spread across an extended time. Such software has limited capacity to analyze intrinsic aspects of high-rises like axial shortening, deviation from verticality, and redistribution of internal actions.

The Advanced Stage Analysis Program (ASAP) is a 3DFE analysis software specifically developed to analyze time-dependent behavior of high-rise buildings during the construction stage and throughout their service lives (see Figure 1).

The program predicts building movements in the vertical and horizontal directions at any stage of construction and at any desired target time. Redistribution of internal actions and stressed – as a consequence of the delayed concrete strains and the related differential shortenings and deviations from verticality as well as the progressive changes in the structural system – can also be evaluated at any time. In particular, the program calculates the variations over time of internal actions and stresses in rigidly connected floor structures and in stiff horizontal structural members such as transfer beams, outriggers, and belt walls/trusses, as well as the concurrent load variations in vertical elements.

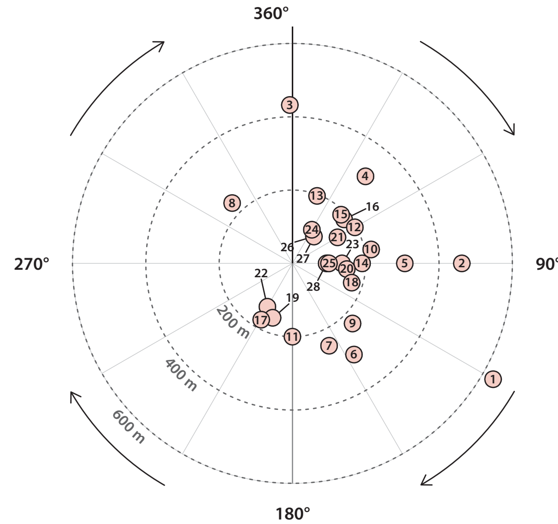
Once the loading dates and duration of column forms and slab supports are defined, the software automatically generates the construction stages. Users can also create specific construction sequences for their own needs.

It is possible to import FE models from software such as SAP2000, ETABS and MIDAS/GEN. Beam and plane FE elements (such as shell, plate, plane stress, etc.) are implemented in the software. For the time-dependent behavior of concrete, creep and shrinkage prediction models can be used in the analysis. Interaction between

Twisting Tall Buildings

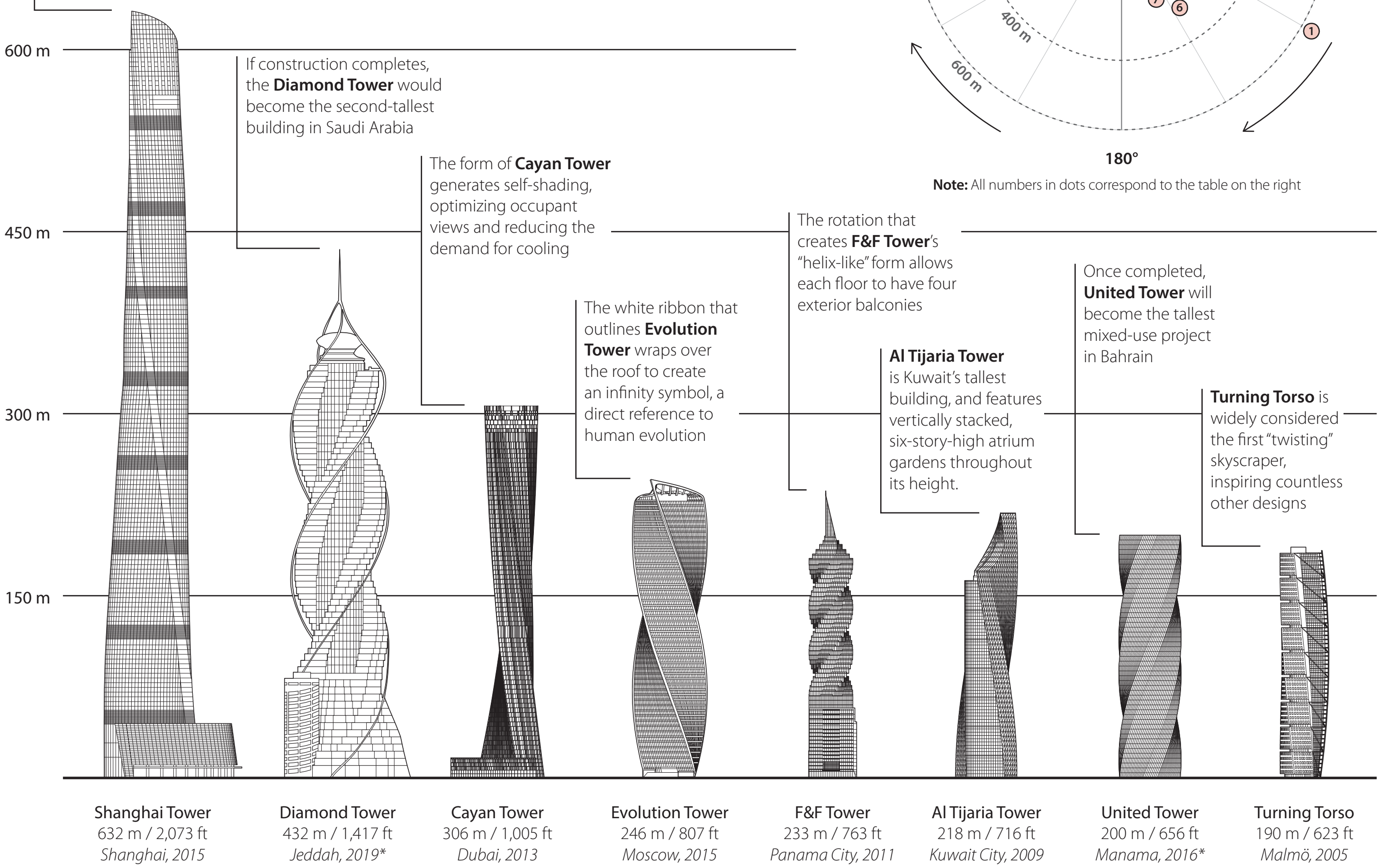
CTBUH defines a "twisting" building as one that progressively rotates its floor plates or its façade as it gains height. Usually, but not always, each plate is shaped similarly in plan and is turned on a shared axis a consistent number of degrees from the floor below. A stunning variety of textures, view angles, and ripple effects results from these manipulations, making these "twisters" some of the world's most iconic buildings – and in many cases, aerodynamic and energy-efficient. In this study, we rank the world's 28 tallest twisting towers (either completed or currently under construction) and display selected variations on the theme.

Comparison of height vs. total rotation for 90 m+ buildings currently complete or under-construction



Note: All numbers in dots correspond to the table on the right

Global Twisting Icons



The Chicago Spire, designed to mimic a nautilus shell, started construction in 2007 and was set to become the USA's tallest building and the world's tallest residential building. Construction stopped in 2008, due to the recession.

360°

In addition to being planned as the world's next-tallest twisting tower, **Diamond Tower** would also be the only building to twist a full 360 degrees along its height.

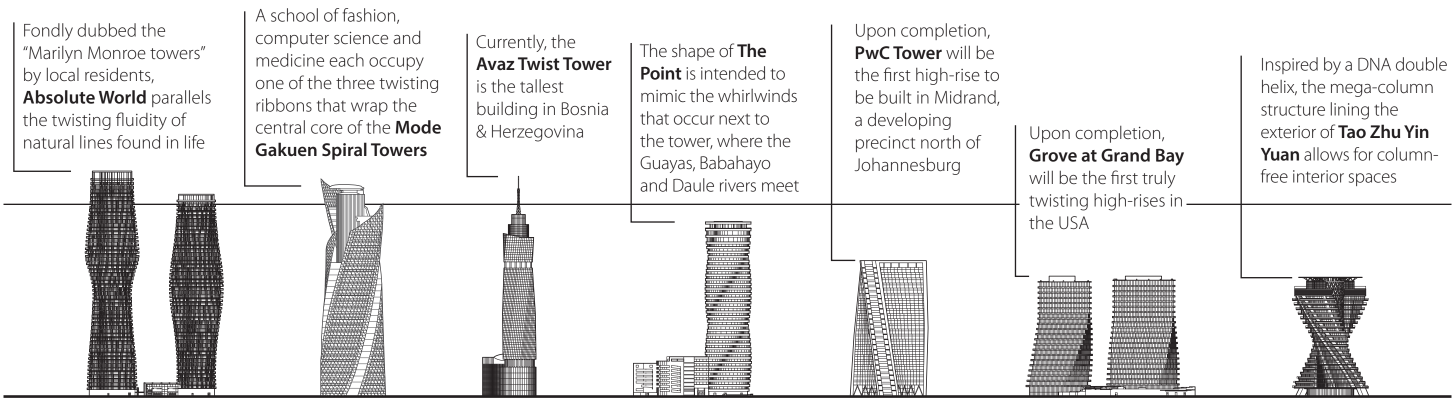
Dubai's proposed Dynamic Tower consists of individually motorized, rotating floor plates, built around a central core. Wind turbines, to be situated between floors, would generate enough energy to power the building. The project is currently on hold, and many are skeptical it will be completed.

The World's Tallest "Twisting" Towers

Included below are all buildings, over 90 meters, currently under construction or complete, that "twist" through a gradual rotation of floor plates, ranked in order from the tallest. The table identifies the absolute degrees of rotation from the ground floor to the top floor plate, typically determined through an examination of technical drawings and comparison of floor plans. It also shows the average floor rotation, determined by dividing total rotation by the total floor count (record holders in each category indicated in bold).

Shaded rows indicate buildings under construction as of July 2016.

No.	Building	City	Country	Completion Year	Architectural Height (m)	Floor Count	Average Floor Rotation	Total Rotation
1	Shanghai Tower	Shanghai	China	2015	632	128	0.938°	120°
2	Lakhta Center	St. Petersburg	Russia	2018 (expected)	462	86	1.047°	90.0°
3	**Diamond Tower**	Jeddah	Saudi Arabia	2019 (expected)	432	93	3.871°	**360°**
4	Ocean Heights	Dubai	United Arab Emirates	2010	310	83	0.482°	40.0°
5	Cayan Tower	Dubai	United Arab Emirates	2013	306	73	1.233°	90.0°
6	Supernova Spira	Noida	India	2017 (expected)	300	80	1.825°	146°
7	Evolution Tower	Moscow	Russia	2015	246	55	2.836°	156°
8	**F&F Tower**	Panama City	Panama	2011	233	53	**5.943°**	315°
9	Al Majdoul Tower	Riyadh	Saudi Arabia	2016 (expected)	232	54	2.500°	135°
10	Al Tijaria Tower	Kuwait City	Kuwait	2009	218	41	1.951°	80.0°
11	United Tower	Manama	Bahrain	2016 (expected)	200	47	3.830°	180°
12	Al Bidda Tower	Doha	Qatar	2009	197	44	1.364°	60.0°
13	SOCAR Tower	Baku	Azerbaijan	2015	196	40	0.500°	20.0°
14	Turning Torso	Malmo	Sweden	2005	190	57	1.580°	90.0°
15	Trump International Hotel & Tower Vancouver	Vancouver	Canada	2016 (expected)	188	63	0.714°	45.0°
16	Generali Tower	Milan	Italy	2017 (expected)	185	44	1.127°	49.6°
17	Absolute World Building D	Mississauga	Canada	2012	176	56	3.732°	209°
18	Mode Gakuen Spiral Towers	Nagoya	Japan	2008	170	38	3.000°	114°
19	Absolute World Building E	Mississauga	Canada	2012	158	50	4.000°	200°
20	Baltimore Tower	London	United Kingdom	2017 (expected)	149	44	2.182°	96.0°
21	Avaz Twist Tower	Sarajevo	Bosnia and Herzegovina	2008	142	39	1.539°	60.0°
22	The Point	Guayaquil	Ecuador	2014	137	36	5.833°	210°
23	Sichuan Radio & TV Centre	Chengdu	China	2010	136	31	2.903°	90.0°
24	PwC Tower	Midrand	South Africa	2018 (expected)	106	26	1.154°	30.0°
25	Xiamen Suiwa Tower	Xiamen	China	2016 (expected)	100	22	4.091°	90.0°
26	Grove at Grand Bay North Tower	Miami	United States of America	2016 (expected)	94	21	1.843°	38.7°
27	Grove at Grand Bay South Tower	Miami	United States of America	2016 (expected)	94	21	1.843°	38.7°
28	Tao Zhu Yin Yuan	Taipei	Taiwan	2016 (expected)	93	21	4.286°	90.0°



Absolute World Towers
176 m / 576 ft (Building D);
158 m / 518 ft (Building E)
Mississauga, 2012

Mode Gakuen Spiral Towers
170 m / 558 ft
Nagoya, 2008

Avaz Twist Tower
142 m / 466 ft
Sarajevo, 2008

The Point
137 m / 448 ft
Guayaquil, 2014

PwC Tower
106 m / 348 ft
*Midrand, 2018**

Grove at Grand Bay
94 m / 308 ft (North Tower);
94 m / 308 ft (South Tower);
*Miami, 2016**

Tao Zhu Yin Yuan
93 m / 306 ft
*Taipei, 2016**

* Expected completion date

Guangzhou's Canton Tower, appears to gradually rotate through the use of an hourglass-shaped steel hyperboloid structure as the primary reinforcement and a spiraling steel lattice as the secondary structure.

5.9°

F&F Tower, Panama City, holds the record for the "tightest" twist, that is, the highest average rotation per floor, at 5.943 degrees across each of its 53 floors.

The **Aufzugstestturm** elevator test tower and observatory, in Rottweil, Germany, will be clad in 17,000 square meters of self-cleaning, durable and translucent fiberglass, giving the structure its twisting shape.

Engineering China's Skylines

Dasui Wang

Interviewee

Dasui Wang, Chief Engineer
East China Architectural Design Institute (ECADI)
151 Hankou Road
Shanghai 200002
China
t: +86 21 6321 7420
f: +86 21 6321 4301
e: email 1
www.ecadi.com

Dasui Wang
Dasui Wang is one of China's foremost thought leaders on the design and implementation of supertall buildings, with experience in both structural engineering and architecture. Wang graduated from Tongji University in 1964. As a Design Master of China and a consultant for ECADI, he is renowned in the field of engineering design. Currently, he holds the position of Deputy Director of the High-Rise Building Committee of the Architectural Society of China. He is a member of the Ministry of Construction High-Rise Building Review Committee and an adjunct professor at Tongji University. He has participated in writing and reviewing a number of national design specifications and codes.

Dasui Wang, China Design Master and chief structural engineer for East China Architectural Design Institute (ECADI), is the recipient of the inaugural CITAB - CTBUH China Tall Building Outstanding Achievement Award. Wang has committed his life's work to designing the structural engineering solutions behind some of China's and the world's outstanding tall buildings. His long list of projects includes the Oriental Pearl TV Tower, CCTV New Headquarters, Tianjin International Financial Center, Shanghai World Financial Center, and Shanghai Tower. Wang sat with CTBUH Journal Editor Daniel Safarik to talk about his 52-year career and the tremendous amount of change he has seen during this time.

What do you consider to be your greatest accomplishment?

I don't know that I can say I have a single great accomplishment, but I think of myself as walking along with the development of China. Specifically, the last 30 years have been a golden period of time in China's development. I have been working at ECADI for 37 years, since 1979. In this period, my colleagues and I really did something for our country. We were lucky to have participated in building most of the important tall buildings in China. That is a source of great pride for me.

One of your groundbreaking works was the Oriental Pearl TV Tower in Shanghai (see Figure 1). Can you talk a little about how that project came to be?

The project is a truly original one for China. ECADI did all of the work independent of the transmission technology. We got the project in 1989, when I was the lead structural engineer. During that period, there were few communications with overseas professional architects. And we had never seen foreign TV towers to use as a reference. There were several TV towers under construction at Tianjin, Liaoning, Wuhan, and Beijing, but they were all smaller than the Oriental Pearl Tower.

So this was an unprecedented structure, meant to be not only a TV tower but a symbol and an observation tower. What accounted for the tripod-like, ball-and-stick design for which it is famous?

Originally it was created for broadcasting purposes. There was no cable TV back then; only high-frequency transmissions, which required height to cover all of the city's territory. The location chosen was the geographic center of Shanghai.

The architects proposed the initial formal concept of "Oriental Pearl," which was based

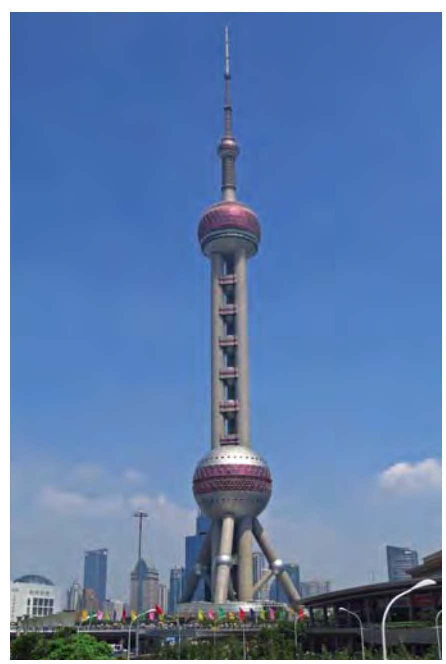


Figure 1. Oriental Pearl TV Tower, Shanghai.
© Tansri Muliani

> "Since the economic opening, China has benefited from foreign architecture techniques, and has closed the gap with the world. Now that we have the confidence to execute complex projects, we need to focus on originality in design and innovation."

on Shanghai's central position on China's coastline and its role as the brightest city of eastern China. You can see the tower has six balls, which the Chinese call *mingzhu* (pearls). There is an ancient Chinese poem that refers to "big and small pearls falling into a jade plate." We structural engineers made great efforts to realize this concept. In conclusion, the achievement of the Oriental Pearl Tower is owed to several architects and structural engineers, rather than the work of one person.

There were many proposals, and ECADI presented several of them. The former President Jiang Zemin, who was mayor of Shanghai in 1989, chose this proposal after consulting with the relevant experts' opinions.

There is a painting in the China Art Museum, which features what appears to be Deng Xiaoping looking admiringly out a window at Oriental Pearl Tower. What is the story behind that?
Jiang showed Deng Xiaoping a model of the Oriental Pearl, which was highly praised by Deng.

It is impressive that this was at a time when Chinese architecture was not as open to international expertise as it is now. How was a feasible concept realized?
Most of the tall TV towers around the world consist of one single tube with cable-stayed supports. The Chinese don't like the cable-stayed style. They like self-supporting towers. Since the design called for a big ball to be put up to 300 meters' height to accommodate tourism needs, a single tube would not be strong enough to support it. To support the three vertical tubes and the ball, the inclined, triangulated tubes composed a stable structure. The structural concept is very clear.

It must be satisfying to see the tower remains popular to this day.
At the same time, considering that there are a large number of visitors – about five million a year – we need six elevators in those three tubes. Recently, the owner has requested more elevators to increase capacity, which is not easy. We are working on developing a feasible plan for them.

What do you think are the greatest challenges that you have overcome?
I think this is best answered in the context of the development progress of China in tall buildings over three decades. In the 1920s and 1930s, Shanghai had some tall buildings constructed, like the Park Hotel, and it looked like a small Manhattan. But because of World War II and the Chinese Civil War, it all stopped, and most of the work in engineering was in industry. After the 1970s, as the population increased, we had to consider high-rise residential development. At that time, China was a closed-off country without foreign communication. Chinese engineers had to do their own research and development. Before 1986, nearly all of the engineering work was done domestically.

The important projects I was involved in at that time were the Huating Hotel, 1982–1985, and the Huadong Diandi (East China Electrical Power Distribution) building in 1989 – both in Shanghai. From about 1986, foreign architects and engineers began to be involved in Chinese projects, firstly in Shanghai, including the Jinjiang Hotel on Huaihai Road. Since 1990, when Pudong opened to development, more high-level foreign architecture companies have been involved.

What was different about working with those firms?
The government set relevant policies at that time, which welcomed foreign architects to be involved. But another policy was that foreign designers could only be involved up to the concept period. Before the construction drawing stage, the foreign architects and engineers were more involved. And Chinese architects and engineers got more involved in the later stages. We had these policies in effect for a long time, which I think was the right decision.

The two groups of architects paid attention to different stages but kept in constant contact, which was good for Chinese architectural development. We were exposed to new technology and new expression methods, both architectural and structural.

Figure 2. Shanghai World Financial Center, Shanghai.
© Mori Building

There is still, it seems, a lot of responsibility that rests with the Chinese design institutes, more so than in the West, where the design architects often insist on being involved all the way through the projects. Do you think the projects have achieved a higher level of quality through this more rigid separation of duties?
Before 1990, we did not have many tall buildings in Pudong's Lujiazui District. Then, Lujiazui became a showcase of China's "opening up," with a great number of excellent tall buildings. These buildings, which combined foreign technology and Chinese engineers' skills, are our pride.

Two projects, in particular, impressed me deeply. One is the Jin Mao Tower. You can see that there are some Chinese elements in the design. From the structural standpoint, I find that an efficient outrigger system was used.

The other is Shanghai World Financial Center (see Figure 2). The structural engineer was Leslie Robertson, who is really a genius. He was an electrician on an aircraft carrier in World War II. After the war, he came to university and finally became an excellent engineer.

Since the opening up, China has benefited from foreign architecture techniques. Nowadays, we don't have a big gap with high-level architecture around the world. We can design all kinds of buildings. Now that we have the confidence to do that, we need to focus on originality in design and innovation.

About the Council

The Council on Tall Buildings and Urban Habitat (CTBUH) is the world's leading resource for professionals focused on the inception, design, construction, and operation of tall buildings and future cities. Founded in 1969 and headquartered at Chicago's historic Monroe Building, the CTBUH is a not-for-profit organization with an Asia Headquarters office at Tongji University, Shanghai; a Research Office at Iuav University, Venice, Italy; and a Research & Academic Office at the Illinois Institute of Technology, Chicago. CTBUH facilitates the exchange of the latest knowledge available on tall buildings around the world through publications, research, events, working groups, web resources, and its extensive network of international representatives. The Council's research department is spearheading the investigation of the next generation of tall buildings by aiding original research on sustainability and key development issues. The Council's free database on tall buildings, The Skyscraper Center, is updated daily with detailed information, images, data, and news. The CTBUH also developed the international standards for measuring tall building height and is recognized as the arbiter for bestowing such designations as "The World's Tallest Building."

Global Headquarters
The Monroe Building
104 South Michigan Avenue, Suite 620
Chicago, IL 60603, USA
Phone: +1 312 283 5599
Email: info@ctbuh.org
www.ctbuh.org
www.skyscrapercenter.com

Asia Headquarters
College of Architecture and Urban Planning (CAUP)
Tongji University
1239 Si Ping Road, Yangpu District
Shanghai 200092, China
Phone: +86 21 6598 2972
Email: china@ctbuh.org

Research & Academic Office
Iuav University of Venice
Dorsoduro 2006
30123 Venice, Italy
Phone: +39 41 257 1276
Email: research@ctbuh.org

Chicago Research & Academic Office
S. R. Crown Hall
Illinois Institute of Technology
3360 South State Street
Chicago, IL 60616
Phone: +1 312 567 3487
Email: academic@ctbuh.org

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