Shenzhen Shum-Yip Tower One – Gravity and Lateral Load Resisting System Optimization

Charles Besjak[1], Preetam Biswas[2], Syed Uzair Ullah[3], Xiaoyu He[4], Jing Zhuang[5]

[1] PE, SE, AIA, Director, Skidmore, Owings and Merrill, LLP. 14 Wall Street New York, NY 10005
[2] PE, Associate Director, Skidmore, Owings and Merrill, LLP. preetam.biswas@som.com
[3] PE, Associate, Skidmore, Owings and Merrill, LLP. syed.uzairullah@som.com
[4] PE, Skidmore, Owings and Merrill, LLP. xiaoyu.he@som.com
[5] PE, Skidmore, Owings and Merrill, LLP. jing.zhuang@som.com

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ABSTRACT

In the pursuit of a highly efficient high-rise structure, structural engineers have been developing new systems. Almost all of these techniques involve use of the entire width of the building.

Legacy systems, such as outriggers, belt trusses, and perimeter braces, provide efficient systems, but they have an impact on the ductility, redundancy, and uniformity of the stiffness of structure. In regions of high seismic activity, the cost of adopting such legacy systems can be significant in terms of structural and architectural efficiency.

The design team for Shum-Yip Tower One developed a structural system which allows for maximum architectural flexibility without compromising efficiency of the structure. This system has been named the Ladder System.

The architectural requirement of unobstructed views has resulted in fewer perimeter columns. Gravity loads at the perimeter are directed through eight mega-columns; the resulting higher gravity loads have eliminated tension due to overturning. This gravity system is instrumental in the success of the Ladder System.

Key Words: Structural Integration, Lateral System Optimization, Ladder System, Composite Coupling Beams

INTRODUCTION

Shenzhen Shum-Yip Upperhills is a mixed use development located in Shenzhen, People's Republic of China. Shenzhen is one of the fastest growing cities in China, and its proximity to the Asian financial hub of Hong Kong has been a major factor in its phenomenal growth.

Figure 1: Architectural Rendering of Shum-Yip Upperhills Development

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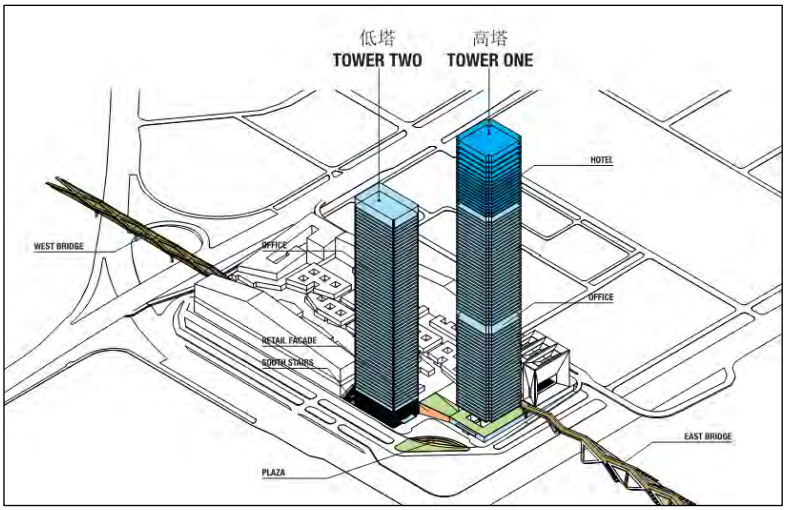

Figure 2: Spatial Planning Diagram of Shum-Yip Upperhills Development

Situated at the northwest corner of the intersection between Huanggang Road and Sunggang Road in the Futian District of Shenzhen, Shenzhen Shum-Yip Upperhills is one of the most ambitious real estate ventures in the city, consisting of Class A office buildings, a luxury hotel complex with banquet facilities, and varied retail development on a single property. The development links Lotus Hill Park and Beacon Hill Park on either side of the property via pedestrian bridges across major arterial roadways.

Due to Shenzhen's economic growth and active construction, the real estate market is poised to have increased demand and supply of leasable office space. The client for this project provided a very clear directive to the design team: the quality of the office spaces needs to set Shum-Yip Upperhills apart from other offerings in the real estate market. Along with creating premium office spaces, the overall form of the two towers themselves should be simple, yet iconic in nature. Tower Two, the smaller of the two towers at 300m, contains Class A Office space. Tower One targets the high-end of the commercial market, with an international brand five-star luxury hotel in the upper segment of the tower.

Tower One, the subject of this paper, contains 80 floors and is approximately 390m tall - it is the tallest building in the development. The program consists of high-end Class A Office space in the lower 66 floors and hotel guest rooms and related amenities on the upper floors. The topmost floor houses an observation deck and a helipad. The architectural design and the complementing structural system of Tower One are an emphatic response to the desire of the client.

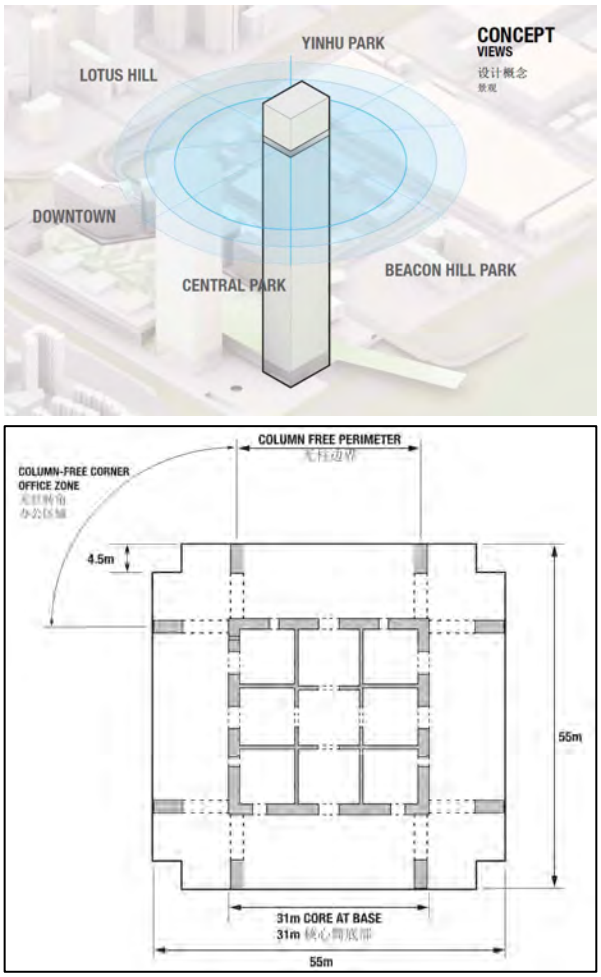

Figure 2: Architectural and Structural Concept

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ARCHITECTURAL INTENT AND EXPRESSION

In addressing the wishes of the client, the architectural and structural design teams aim to emphasize the world-class, spatial experience for each visitor, tenant, and employee. Given the project site, Shum Yip Tower One has the unique opportunity to juxtapose Shenzhen's natural beauty with its modern cityscape. Connecting to Beacon Hill Park and Lotus Hill Park, Tower One is at the forefront of the city's urban economic expansion, even as it maintains its foothold in nature. The design seeks to take advantage of the expansive space and unobstructed views out to the parks and bustling metropolis.

Figure 4: Unobstructed Side and Corner Views

In order to achieve this liberating plane of vision, the structural system is designed to accommodate a column-free exterior façade as well as a long-span uninterrupted interior space. The gravity system features eight steel reinforced composite mega-columns strategically located on the perimeter, concealed as the divisions between open office space and premium, cantilevered, corner office space. Through structural beam and slab integration, structural framing is devoid of any girders spanning to the core. Orienting the larger depth members along the perimeter and maintaining shallower depths elsewhere allows for a continuous mechanical loop on each floor. The built-up steel girders spanning between the mega-columns along the perimeter are optimized for a uniform 3.0m clear height for the entire floor.

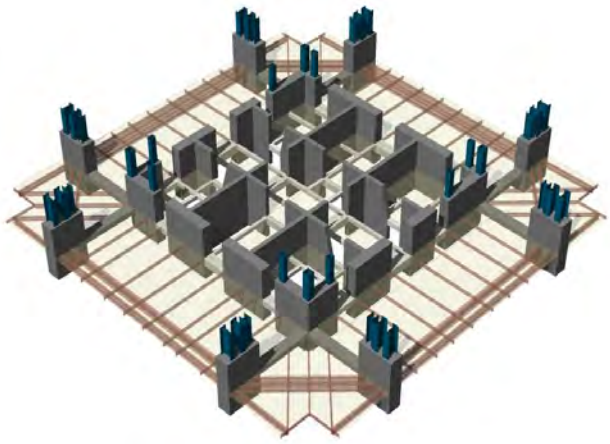

Figure 5: Typical Office Level

Cladding modules of 3.0m width, not the usual 1.5m width, are utilized to further reduce obstructions to outside view. The result is a clear, breathtaking perspective from anywhere in the office.

INTEGRATION WITH OFFICE PLANNING MODULE

Though typical Chinese office plans have enclosed compartments, the client desired Class A office space with high floor to

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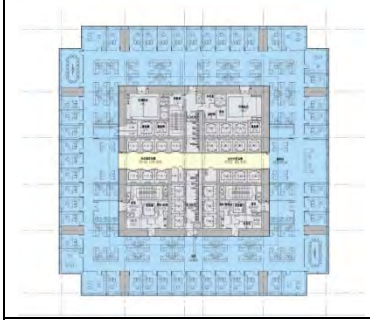
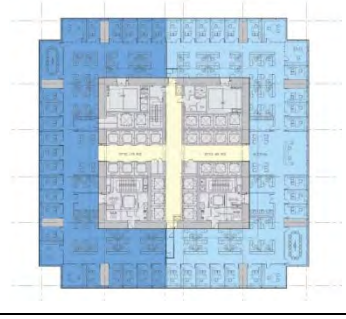
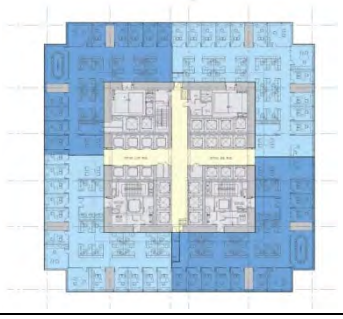
ceiling heights and uninterrupted views. The mega-columns are shaped to a uniform 4.5m in depth in the office levels and varying in width along the height of the building to match the typical office module. Columns are strategically placed along the perimeter of the office floors to align with the outer core walls, creating two zones of office spaces: one with 28.5m between columns on the four sides of the floor plan, and another with an expansive view at the four corners of the floor plan. Such "Open Office" spatial arrangement minimizes the visual impact of the structural elements, allows more flexibility for planning for a global workplace, and encourages collaboration and knowledge sharing.

The architectural layout is designed such that the elevator lobbies within the core walls also serve as corridors, allowing up to 4 tenants per floor without adding an additional perimeter corridor. This layout effectively increases the floor efficiency compared to a conventional office floor layout. The internal corridor layout also yields a core with a larger footprint, which is inherently stiffer and results in more optimum use of concrete.

Architectural Diagram for 1 tenant layout	Architectural Diagram for 2 tenant layout	Architectural Diagram for 4 tenant layout
		

INTEGRATION WITH MECHANICAL ZONES

At mechanical floors, where an unobstructed view is not valued, the floor framing is optimized for heavy loads by introducing a perimeter truss that utilizes the entire height of the floor. Perimeter belt trusses provide required stiffness for mechanical floor operation, including gravity, vibration and acoustic performance. These belt trusses are integrated with louvers for exterior air exhaust and intake.

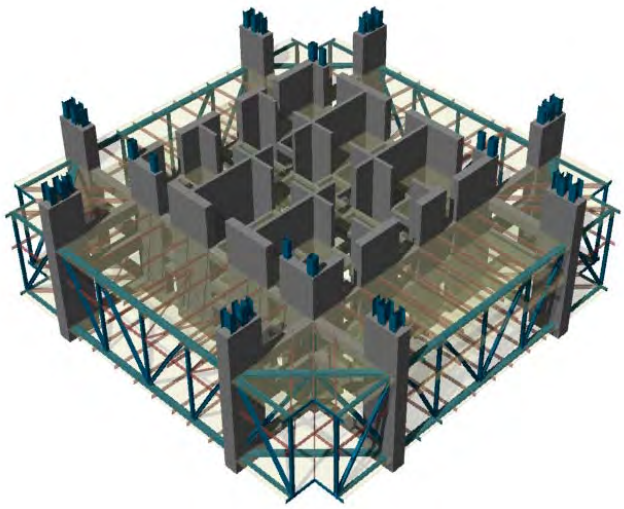


Figure 6: Typical Mechanical Zone

The large column-free interior spans provide more flexibility for MEP Planning. Absence of outrigger trusses within the floor plate enables more direct mechanical transfers and reduced clashes with structural elements. The open space allows more equipment to be placed on each floor, resulting in the elimination of one mechanical floor from the building stack during the design process.

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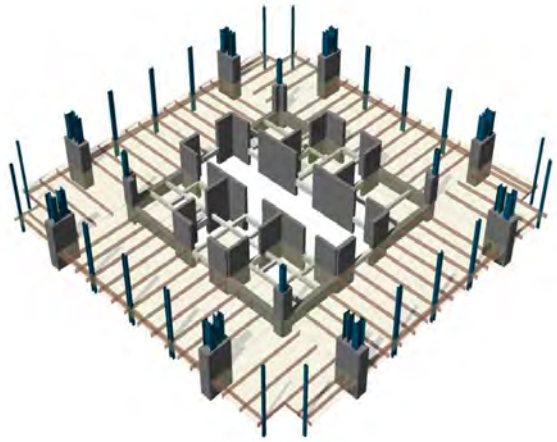

Figure 7: Typical Hotel Level

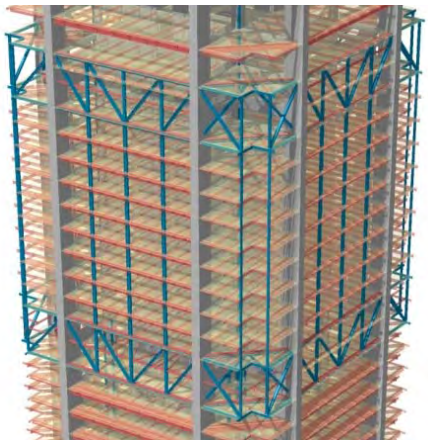

Figure 8: Tower One Hotel Segment

INTEGRATION WITH HOTEL PLANNING MODULE

The mechanical level trusses above and below the hotel floors double-up as transfer mechanism for perimeter hollow steel square HSS posts at the hotel floors. The vertical members of the perimeter trusses above and below guest rooms are aligned with the hotel guest room module, providing direct support for the HSS posts, which are located in line with the demising partitions between the hotel rooms. The conventional framing at the hotel levels results in shallower perimeter beams and eliminate the need for long-span perimeter girder, reduce story height, and reduce required steel quantities without compromising the architecture of the space.

Progressive collapse prevention is taken into account in the design of the hotel floor gravity system. Redundancy is achieved by having a transfer truss both above and below the hotel guest room zone and by designing the members for magnified loads in the event that certain elements lose load resisting capacity. This in effect creates an alternate gravity load path to the mega-columns from for the perimeter frame in the hotel segment.

MANAGING GRAVITY LOAD PATH

Floor framing beams span between the concrete core and the perimeter girders. From the floor framing design perspective, the location of the mega-columns creates a balanced cantilever system along each side. This reduces the depth of the interior span as well as the cantilever span of the perimeter girder. A double perimeter girder provides a redundant load path to the mega-columns. Load transfer between the perimeter girders and mega-columns is achieved by the connection of the girder with the embedded steel in each mega-column.

For a conventional framing system, where columns which are not part of lateral force resisting system share gravity load with the mega-columns, designing for tension due to lateral loads in mega-columns can be challenging. In case of Shum Yip Tower One, all gravity loads at the perimeter are funneled through the eight mega-columns, while the rest of the gravity loads are directed towards the center core. This has eliminated tension in Mega-Columns and Core walls due to lateral loads.

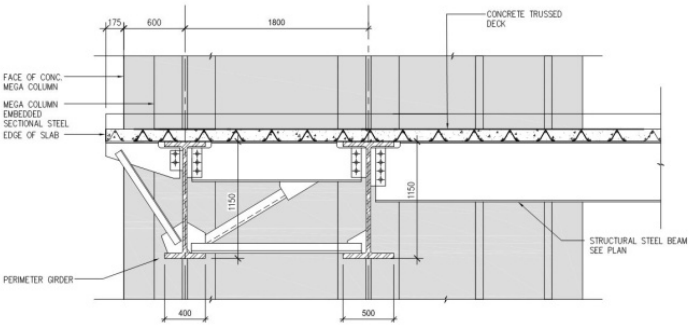

Figure 9: Double Perimeter Girder Section

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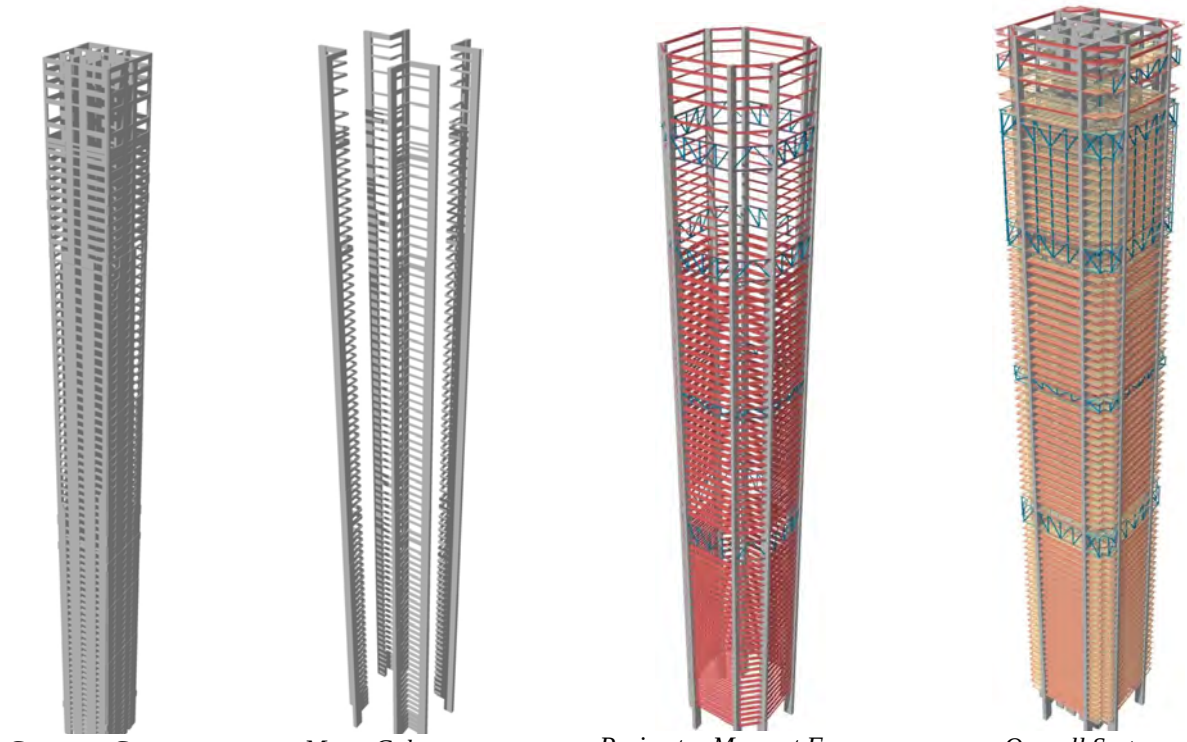
LATERAL LOAD RESISTING SYSTEM OPTIMIZATION

The lateral system is comprised of a center concrete core and eight mega-columns. These columns are aligned with the four corners of the center core. Each mega-column is engaged with the concrete core by a composite coupling beam at each story level, forming the ladder system.

Figure 10: Section showing Core, Coupling Beams and Mega-Column forming the Ladder System

From the lateral system point of view, the elongation and alignment of the mega columns with the exterior core walls creates an efficient lateral load path. Locating the mega-columns at the extreme edge of the building footprint produces the largest coupling moment arm with the core. This results in maximized lateral load resisting capacity for the system and an aspect ratio of 7.2 to resist overturning.

On upper levels where the ladder action is strong and ladder system contributes higher percentage of lateral stiffness, efficiency is achieved by reducing the concrete core stiffness. Opening sizes within the core walls are gradually increased along the height and web wall openings are introduced.



Concrete Core | *Mega-Column Coupling Beams* | *Perimeter Moment Frame with Belt Trusses* | *Overall System*

Figure 11. Elements of Ladder System

To ensure highly ductile performance, the steel section in each composite coupling beam is moment connected to the embedded steel in the mega-column. The perimeter girder is also moment connected with the embedded steel in the mega-columns, providing moment frame action which complements the ladder system.

The ladder system provides numerous advantages over conventional outrigger systems. Providing coupling beams at each level effectively distributes an ideal percentage of story shears to the perimeter of the building. Overall performance of structure is uniform and results steady variation of story stiffness along the height. Composite coupling beams provide excellent ductile performance and produce more plastic hinges on various locations. This ensures higher energy dissipation and greater redundancy.

The ladder system of Tower One is designed to resist various levels of extreme wind and seismic loads per Chinese Standards GB 50009-2012 and JGJ 3-2010. All serviceability criteria are fulfilled for a 50 year return period of wind loads and elements are designed for a 100 year return period. The seismic performance objectives set for Shum-Yip Tower One refer to Frequent, Moderate, and Rare levels of seismic loading. Frequent earthquake loading corresponds to a probability of exceedance in 50 years, or a 50 year return period. Moderate earthquake loading corresponds to a probability of exceedance of 10% in 50 years (or a 500 year return period); and Rare earthquake loading corresponds to a probability of exceedance of 2% in 50 years (or a 2500 year return period).

高塔地震水准/性能水准 **Tower One Performance Level**		关键构件 **Critical Members**			
		巨柱 **Megacolumns**	带状桁架 **Belt Truss**	加强区钢筋砼剪力墙 **RC Corewalls in Strengthened Zones**	筒体角部墙和柱 **RC Core Corner**
抗震等级 Seismic Grade		特一级 Super Grade 1		特一级 Super Grade 1	特一级 Super Grade 1
多遇地震 Frequent Earthquake	弹性 Elastic	X	X	X	X
设防地震水准 Moderate Earthquake	受剪承载力不屈服 Shear Non-Yield				
	正截面承载力不屈服 P & M Non-Yield		X	X	
	受剪承载力弹性 Shear Elastic	X	X	X	X
	正截面承载力弹性 P & M Elastic	X			X
罕遇地震水准 Rare Earthquake	受剪承载力不屈服 Shear Non-Yield	X	X	X	X
	正截面承载力不屈服 P & M Non-Yield	X			
	构件塑性变形满足"生命安全"要求 "Life Safety" Plastic Deformation Limit	X	X	X	X

高塔地震水准/性能水准 **Tower One Performance Level**		竖向及耗能构件 **Vertical and Energy Dissipating Members**				
		钢筋砼剪力墙 **RC Corewalls**	钢筋砼连梁 **RC Link Beams**	型钢砼连接梁 **Composite Coupling Beams**	框架梁 **Moment Frame Beams**	筒体角部墙和柱 **RC Core Corner**
抗震等级 Seismic Grade		特一级 Super Grade 1	一级 Grade 1	一级 Grade 1	一级 Grade 1	特一级 Super Grade 1
多遇地震 Frequent Earthquake	弹性 Elastic	X	X	X	X	X
设防地震水准 Moderate Earthquake	受剪承载力不屈服 Shear Non-Yield		X			
	正截面承载力不屈服 P & M Non-Yield	X				
	受剪承载力弹性 Shear Elastic	X		X	X	X
	正截面承载力弹性 P & M Elastic			X	X	X
罕遇地震水准 Rare Earthquake	受剪承载力不屈服 Shear Non-Yield	X		X		X
	正截面承载力不屈服 P & M Non-Yield			X		
	构件塑性变形满足"生命安全"要求 "Life Safety" Plastic Deformation Limit	X	X	X	X	X

Figure 12: Performance Objectives

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A superior set of design objectives were selected for the essential elements of ladder core system. mega-columns and composite coupling beams are expected to remain elastic under Frequent and Moderate earthquake loading and non-yielding under Rare earthquake loading. Reinforced concrete core wall corners are also expected to remain elastic under Moderate earthquake loading and non-yielding in shear under Rare earthquake loading.

Additionally, from a lateral system performance point of view, the belt trusses positioned at the regular intervals along the height of the building provide added coupling between the core and perimeter. In addition to transferring the heavy mechanical gravity loads to the mega columns, the trusses increase stiffness along the height of the tower, limiting deflections under lateral loads. Under severe lateral loads, such as an extreme earthquake event, the combined effect of belt trusses and mega-columns produces a mega-frame action and induces a second line of defense when hinges start forming in certain lateral elements such as the link beams and composite coupling beams.

LADDER SYSTEM CONCEPT

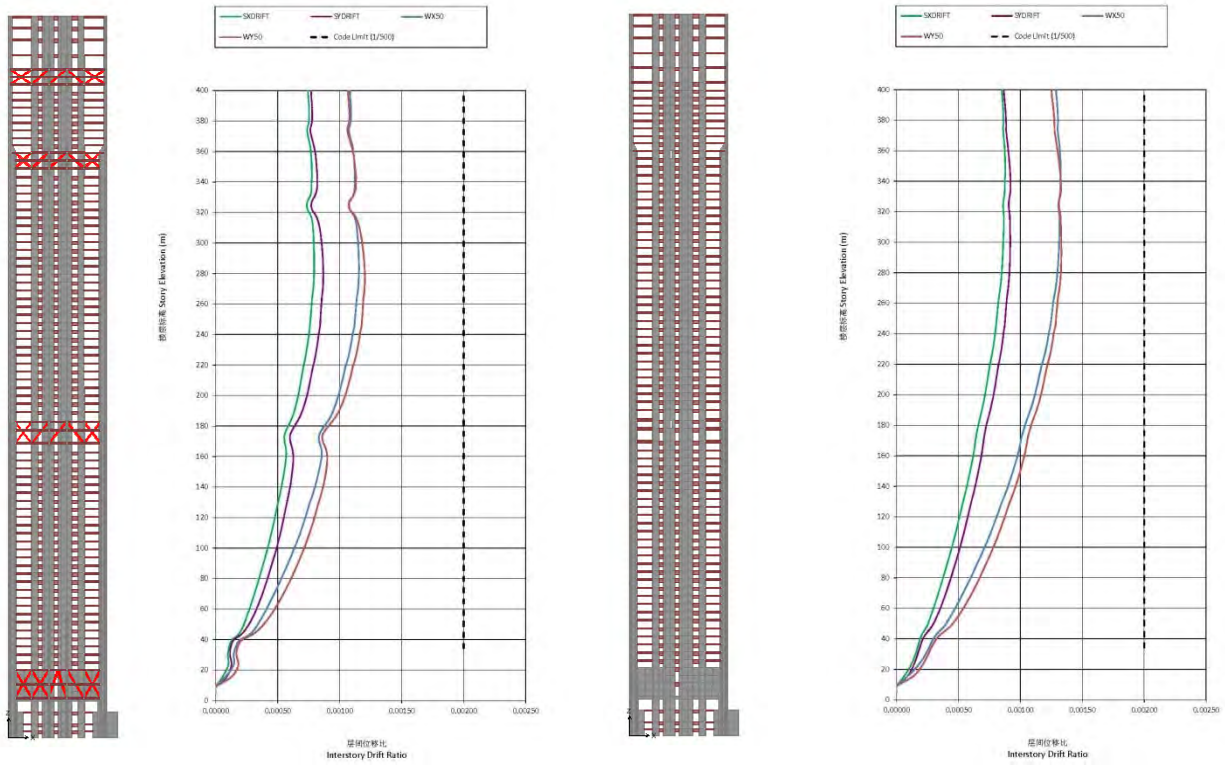

Figure 13: Lateral System Performance Comparison between a traditional Outrigger System and a Ladder System

Rather than a lateral system with outriggers at discrete locations, the *Ladder System*, by linking the mega-columns and the core walls with steel embedded composite coupling beams at every floor, has been adopted on this project. At early stages during the design process, a study was done to compare the performance of an outrigger system and the ladder system. The result of the study shows that the ladder system presented the following advantages:

Firstly, due to the stiffness of the coupling beams, a more evenly distributed axial stress ratio is observed between the mega columns and the core walls which results in better creep and

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shrinkage performance. Secondly, rather than having the lateral stiffness concentrated at the outrigger floors, the composite coupling beams uniformly distribute stiffness and load path throughout the height of the building, preventing sudden changes in lateral stiffness and producing a smoother curve when looking at the building drift for wind and seismic loads. Lastly, the Chinese code requires the frame to take a certain percentage of the base shear at every floor outside of the "strengthened floor", i.e. floors with outriggers or belt trusses. With the large column spacing, it not possible to achieve the frame shear ratio with the outrigger system. The composite coupling beams effectively engage the mega-columns in shear at very floor and an average of 8% of the base shear is achieved in the frame at every floor through the ladder system.

One other advantage not to be overlooked is the level of redundancy in the interlocking of the core and the mega-column that is achieved by linking the two at every floor level rather than at select levels with outrigger truss along the height of the building. This very repetitive nature of the Ladder System will also lead to simplifying and speeding up construction compared to a conventional outrigger system

COMPOSITE COUPLING BEAM PERFORMANCE

The advantage of the Ladder System lies in its multiple connections between the core and the perimeter, uniformly distributed throughout the height of the building and in not having a few connections concentrated at discreet locations along its height. Thus performance of the Ladder System, consisting of the mega-columns, the composite coupling beams, and their connectivity to the corners of the core, is crucial to the success of this structural system. Because of their critical nature, the design for these Ladder System elements is based on the stringent seismic performance objectives set forth in the Lateral System Optimization section.

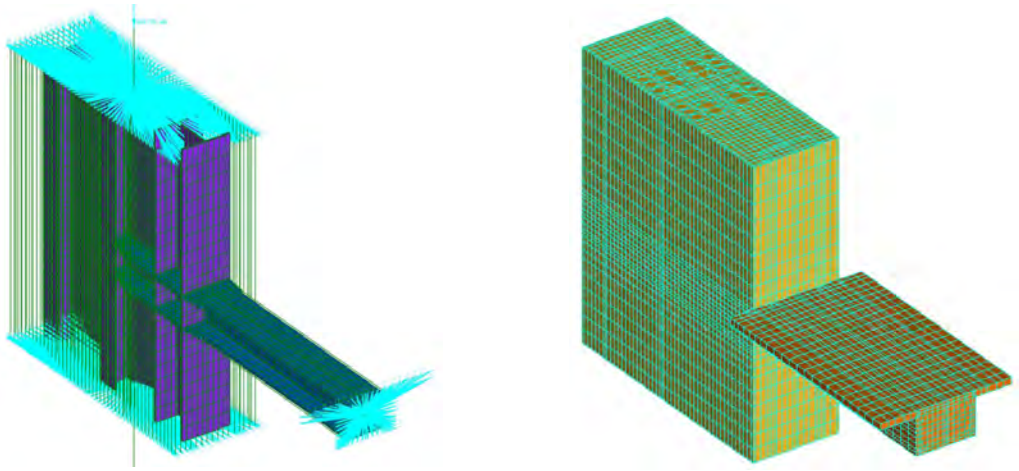

Figure 14: Finite Element Mesh of Steel Elements and Concrete: Composite Coupling Beam to Mega-Column Connection Model

3D FEM analysis of composite coupling beam connections to the mega-column and core corner walls are used to visualize and verify stress levels and transfer under Moderate and Rare earthquake load combinations. The connections are analyzed by means of the general purpose finite element software Strand7.

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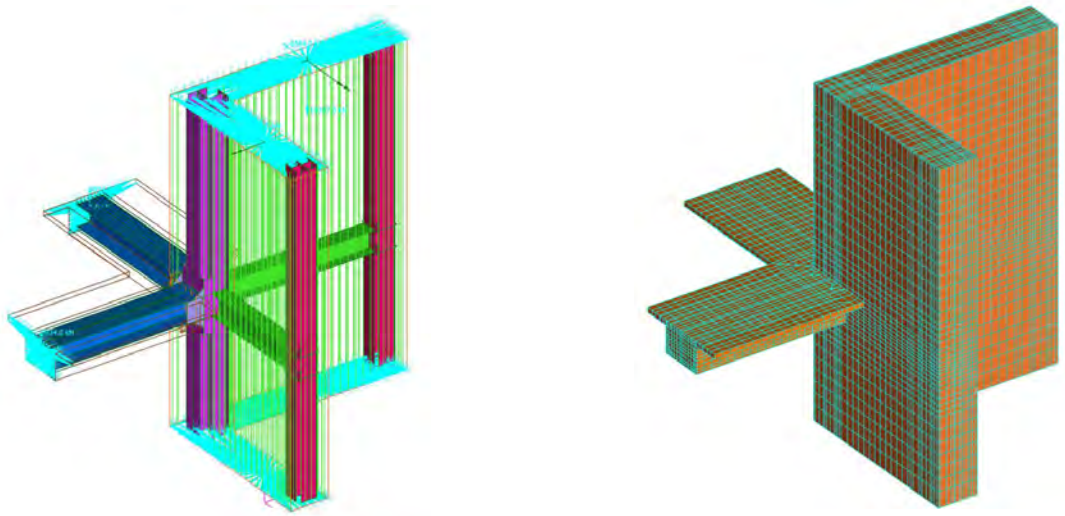

Figure 15: Finite Element Mesh of Steel Elements and Concrete: Composite Coupling Beam to Core Corner Connection Model

The detailed modeling of the Ladder System is also utilized to verify the following:

- Constructability of the connection, with the inclusion of rebar, embedded steel elements, and concrete cover and clear spacing requirements
- Restraint of the Composite Coupling Beam by the Mega-Column
- Continuity of the Mega-Column embedded steel section through the connection
- Full engagement of the embedded steel section in the Mega-Column by the embedded steel section of the Composite Coupling Beam by the use of stiffeners
- And full development of Coupling Beam steel reinforcement within the Mega-Column cross section.

The loads for the finite element models are extracted from the overall building ETABS model. Several cases of these already conservative elastic forces are then considered for the FEM analysis, including maximum axial force on the mega-columns, maximum bending moment in the mega-columns about both axes, and maximum differential axial load on the two mega-columns framing into the core corner connection. Results for the governing Moderate and Rare earthquake load combinations from Chinese Code are shown below.

Earthquake Level	Concrete	Steel		Rebar
		Q345	Q420	HRB400
		Range	Range	
Elastic (Medium EQ)	Compression: 32.3 MPa (f_c/γ_{RE} = 27.5/0.85 = 32.3)	fy = 250~295 MPa	fy = 325~360 MPa	fy = 360 MPa
	Tension: 2.4 MPa (f_t/γ_{RE} = 2.04/0.85 = 2.4)			
Non-Yield (Rare EQ)	Compression: 38.50 MPa	fy = 275~325 MPa	fy = 360~400 MPa	fy = 400 MPa
	Tension: 2.85 MPa			

Figure 16: Material Design Limits

As shown below, in each type of composite coupling beam connection, steel plates in the connection stay elastic under Moderate earthquake loading. Steel reinforcement also remains elastic under Moderate earthquake loading, although some cracking of the concrete occurs. Concrete crushing does not occur under Moderate earthquake loading. The performance objectives for the Ladder System elements are met for the Moderate earthquake load level.

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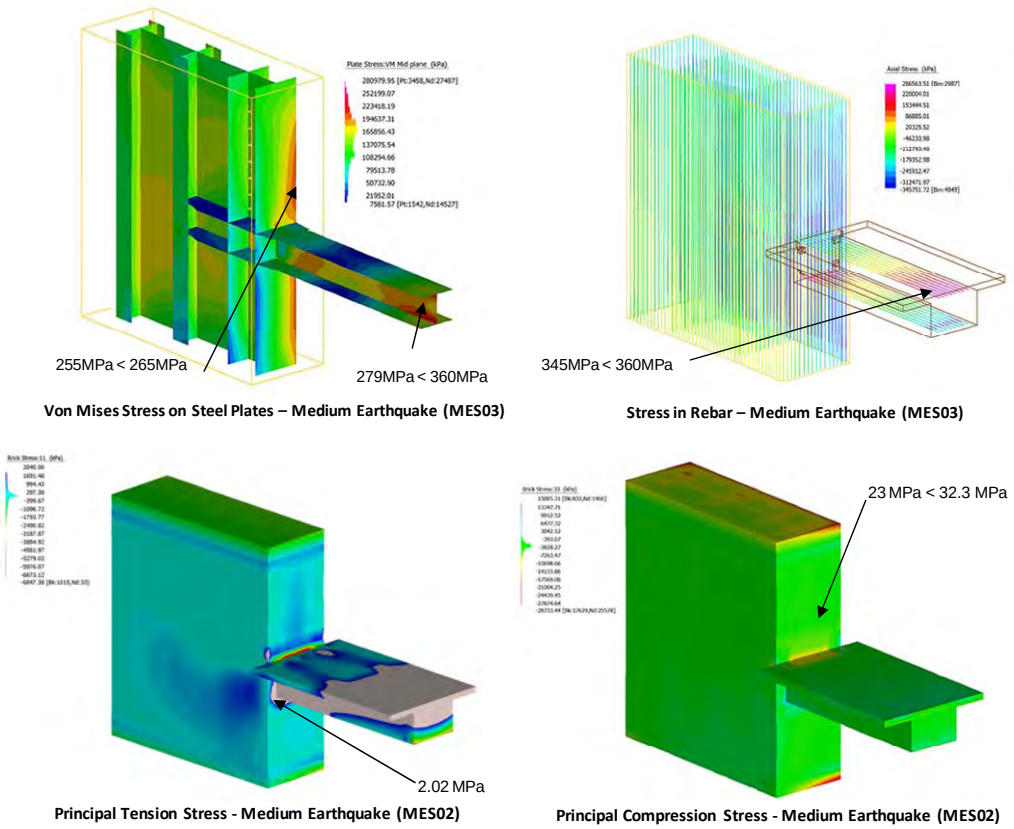

Figure 17: Moderate Earthquake Steel and Concrete Stress Results: Composite Coupling Beam to Mega-Column Connection Model

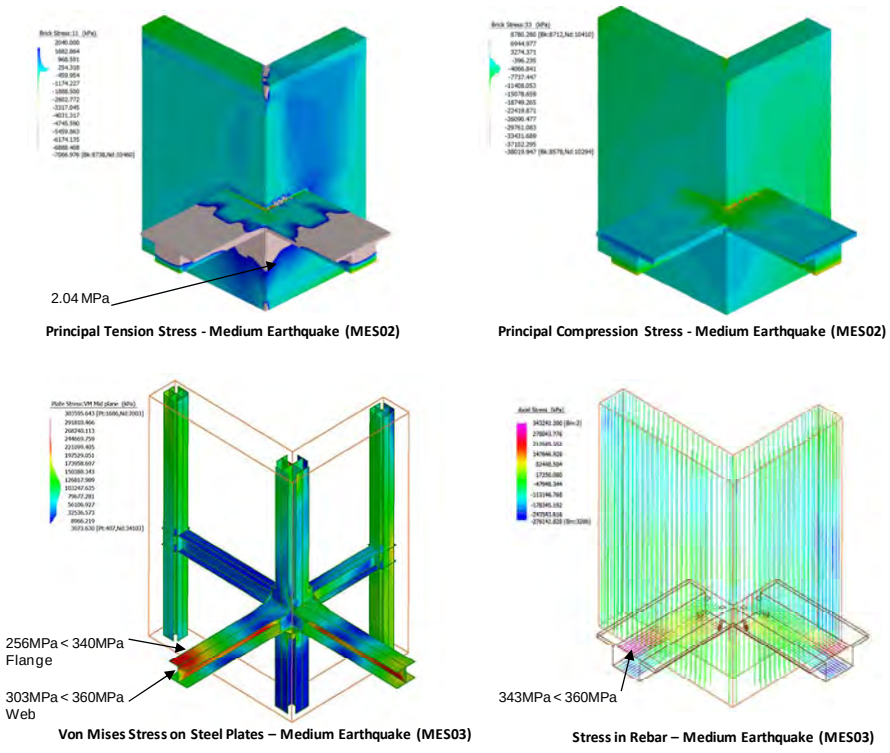

Figure 18: Moderate Earthquake Steel and Concrete Stress Results: Composite Coupling Beam to Core Corner Connection Model

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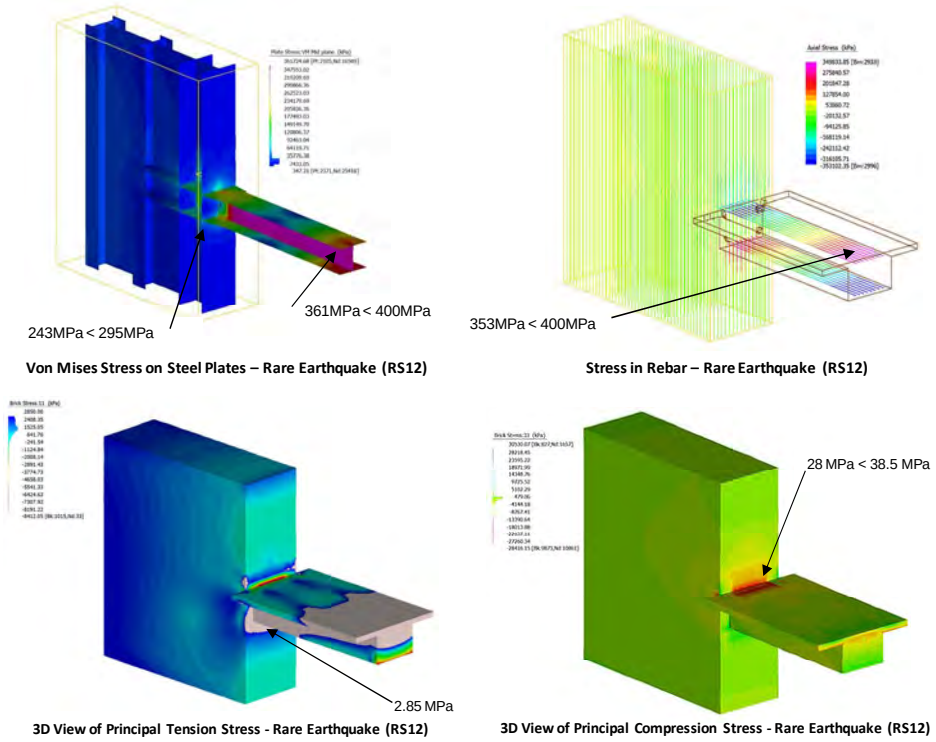

Figure 19: Rare Earthquake Steel and Concrete Stress Results: Composite Coupling Beam to Mega-Column Connection Model

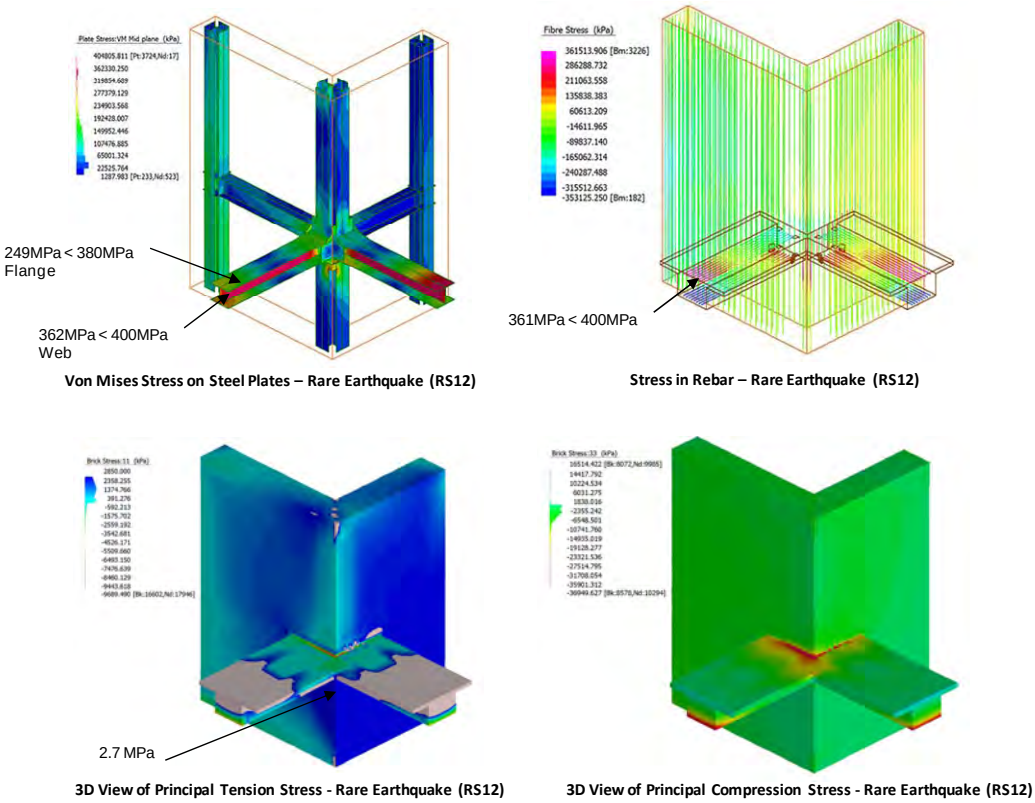

Figure 20: Rare Earthquake Steel and Concrete Stress Results: Composite Coupling Beam to Core Corner Connection Model

For the Rare Earthquake load level depicted in the stress diagrams above, the performance of each connection is similar to that of the Moderate earthquake load level. Stresses in the steel plates of each type of connection remain below yielding levels. Stresses in concrete are below crushing levels. Although cracking occurs in the concrete under Rare Earthquake loading, tensile stresses in rebar are below yielding stress.

By meeting the high performance targets set for these crucial elements, we ensure that the Ladder System has a robust performance even during an extreme seismic event and there is no potential for development of a weak zone or failure mechanism, anywhere in the system.

CONCLUSION

The Ladder System of Tower One provides a superior performance by utilizing the entire depth of the tower footprint, without comprising ductility, redundancy and regularity of stiffness along the height of the tower. Having the mega-columns as the only gravity load resisting system for the entire perimeter fully utilizes the compression due to gravity to counterbalance the tension due to the lateral loads, resulting in net zero tension at the base of the building for wind and earthquake loading. No tension in the composite columns allows optimum use of both concrete and steel, and therefore a reduction in overall steel quantities.

Other projects in China with similar objectives of creating large open unobstructed perimeter have had to introduce a perimeter brace system in order to achieve the proportional lateral load sharing between the interior core and the secondary perimeter system stipulated in the Chinese building codes. However, in case of Shum-Yip Tower One, the strategic location of composite mega-column and double perimeter girder system in a closed loop connected to the central core with uniformly distributed composite coupling beam achieved the required ratio of lateral load distribution without utilization of obtrusive perimeter bracing system.

The project has been approved by the Chinese Authorities and is currently under construction with completion slated in late 2017.

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