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Finding Structural Solutions by Connecting Towers

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Andrew is a Director with Arup in China and he leads the Arup Structures team in Shanghai. Andrew has over 17 years of experience and has worked in different parts of the world including Australia, Hong Kong, London, India and China. He has an in-depth knowledge of design codes from different parts of the world, and has a holistic, inter-disciplinary approach to the design and management of projects, from inception through to construction.

He has made key contributions to a number of award-winning, landmark and complex buildings including Two International Finance Centre, Beijing Olympic Green Convention Centre, CCTV New Headquarters Beijing, Hong Kong International Airport Terminal 2, Rajiv Gandhi Airport, Hyderabad, and City University of Hong Kong Multi-media Building.

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Michael Kwok is a Director with Arup in China and Hong Kong. He is also a member of Arup Group Board and East Asia Board. He is a member of the Institution of Structural Engineer in the UK and Registered Structural Engineer (Class 1) in the People's Republic of China. He has been in-charge of a number of major projects in China from inception to completion, including the National Stadium (Bird's Nest), CCTV New Headquarter Building, China World Trade Centre Phase 3 and Beijing Capital International Airport Terminal 3; Korean Pavilion and Danish Pavilion of Shanghai World Expo; Shenzhen Stock Exchange Square and Shenzhen Energy Building. Michael graduated with a Bachelor Degree in Civil Engineering from Imperial College in the UK in 1984. He joined Arup in 1986 and since then he has been involved in many large scale building and infrastructure projects in Hong Kong and in China. His expertise covers a wide range of projects including commercial, residential, retail, hotel and leisure, transport terminal, railway station and sports buildings. Michael has been working on projects in China since 1992. He set up Arup offices in Shanghai, Beijing, Wuhan and Chongqing, and he is responsible for developing Arup's business and operation in Mainland China.

A study of a number of linked high-rise towers in China finds designs anchored by innovative, unimposing structural solutions, which address issues of costs and buildability. More than simply making a dramatic visual statement, the links play an integral role in the buildings' functions.

Linked towers are still a rarity in the design of skyscrapers. Perhaps the most famous is the Petronas Twin Towers in Kuala Lumpur, but the linkage in the Petronas served as more than just an architectural gesture. Structurally there is little purpose to the skybridge, although the link it is an integral part of the fire evacuation strategy and allows facilities to be shared between the two towers over those several levels, in addition to offering an observation deck, a popular attraction. Traditionally, the structural treatment for such linkage bridges has been to design them to "breathe," through the use of movement joints or clever articulation, allowing the two connecting towers to act independently.

Recently a number of high-rise projects in China have taken the connected form beyond the mere passage link. These projects have been bold and innovative in developing the link as part of the overall building design, as well as an architectural expression and symbolic use, such as that of a gateway. The links in these projects serve a greater role, solving a number of problems and offering new opportunities in the design and usage of the buildings including:

- providing better masterplanning and massing relationship in the site and to the neighboring architecture;
- effective use of a limited and constrained site;
- increasing floor plate size;
- providing a functional link of the two connecting towers, where the link structure houses an important functional allocation of the overall architectural program of the buildings. In fact in all of these buildings, the link is a critical part of the building, without which it will not work functionally.

Function through Form

Several of the China projects illustrate the way the links in the towers can serve important roles within the building design beyond aesthetics.

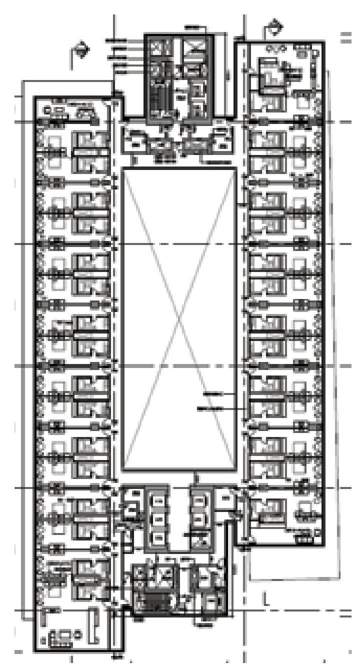


Figure 1. Pazhou 1401. © Aedas

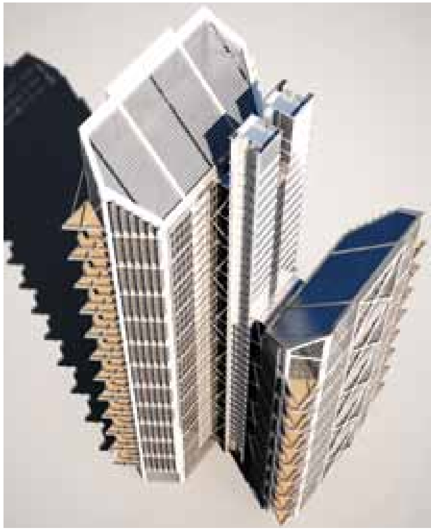


Figure 2. Ningbo Gate. © RSHP

The Pazhou projects, Block 1301 and Block 1401, are characterized by emphatic building forms which are a play on the massing of monolithic blocks ruffled in the vertical (podium part of the buildings) and horizontal (tower part of the buildings) directions. With the 1301 tower housing offices and the 1401 tower designed as a hotel (see Figure 1), the architectural designs have successfully produced two very different buildings with a common aspiration of showcasing slender, solid structural blocks linked by light common circulation corridors. In the process, the linked blocks address the issues associated with a long rectangular floor, while providing adequate but not excessive floor depth, plenty of external frontages and a naturally lit internal atrium.

In a similar manner to the Pazhou buildings, the Ningbo Gate tower form shows off the two slender wings of the building, with minimal linkage. Like Pazhou, the linkage in Ningbo is driven by the architectural intention to arrange the two residential wings of the building between a "minimal" vertical circulation core (see Figure 2). The building inhabitants step out of the lifts before heading to one of the building wings. The link serves the function of both vertical and horizontal circulation.

Notably the Pazhou and Ningbo projects are not truly linked towers. However they are clearly a breakaway from the single building

Featured linked towers

Pazhou 1301 & 1401 Developments, Guangzhou

Both towers comprise two very slender blocks linked by a common lift corridor

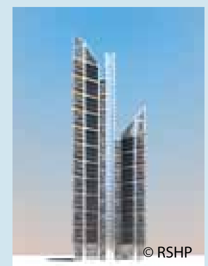
Height:	100 m (Block 1301),120 m (Block 1401)
Total Area:	74,000 sq m (Block 1301), 100,000 sq m (Block 1401)
Configurations:	5 levels of podium & 3 levels of basement (Block 1301), 4 levels of podium & 2 levels of basement (Block 1401)
Primary Use:	Office (Block 1301), Hotel (Block 1401)
Client:	Guangzhou ZhanHui Real Estate Development
Design Architect:	Aedas

Block 1301. © Aedas

Ningbo Gate

Two very slender tower blades connected through a common lift corridor

Height:	152 m
Configurations:	2 levels of podium & 2 levels of basement
Primary Use:	Residential
Client:	Ningbo Hongtai Real Estate Development Co., Ltd
Design Architect:	Rogers, Stirk, Harbour, and Partners (RSHP)
LDI:	Ningbo Architectural Design & Research Institute



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Shenzhen Energy Headquarters Building

Two office towers linked at the podium

Height:	North Tower – 208.5 m, South Tower – 100 m
Configurations:	Linkage structure connects the two towers at podium level from levels 2 to 9, 4 levels of basement
Primary Use:	Office
Client:	Shenzhen Energy Group Co. Ltd.
Design Architect:	Bjarke Ingels Group

© BIG

Suzhou "Gate to the East"

Twin towers linked at the top

Height:	280 m
Stories:	61 stories (Tower 1), 67 stories(Tower 20
Configurations:	8 stories linkage structure at the top 40 m & 5 levels of basement
Primary Use:	Office & hotel (Tower 1), Residential (Tower 2)
Architect:	RMJM

© RMJM

china Central Television New Headquarters, Beijing

Sloping twin towers connected at the base, and the top by a 14-story "cranked" cantilevering link structure to form a three-dimensional loop

Height:	234 m
Total Area:	450,000 sq m
Configurations:	9 story cranked podium links bottom of two towers & 3 levels of basement
Primary Use:	Mixed use television production, broadcasting and offices
Client:	China Central Television
Design Architect:	Office for Metropolitan Architecture (OMA)

© OMA

block, with the emphasis of the link celebrating a light and minimally-structured volume and providing access between two occupied wings of the building.

Compared to Pazhou and Ningbo, the Shenzhen Energy Headquarters Building's linked twin tower massing is about access linkage and borne out of necessity. The building sits on a long and very narrow site. Height restrictions were also imposed on the development. The architect BIG resolved these challenging constraints by establishing rectangular towers of 100 and 200 meters, side by side, and innovatively linking them with an elevated bridging structure. The result is a podium linking the two towers at L2 to L9 (see Figure 3). The link not only addresses the needs of the building program, but it also frees up the ground level to successfully provide for the combined building's entrance needs, with public and urban space in such a confined and restricted site.

In the Suzhou "Gate to the East," the twin tower design concept was the result of a design competition with the theme of creating a "Gateway" to Suzhou (see Figure 4). This principal architectural concept is strongly expressed by the iconic linking towers facing to the west shore of Jinji Lake, the most prominent location of the new Central Business District in Suzhou, with the light rail line passing under the "gate." The eight stories of linked floors at the top of the towers are 156 meters long and provide support for the hotel and serviced apartments.

The link in the much-publicized CCTV building plays a much different role. In the looped form of linking the two leaning towers with a folded cantilevering overhang at the top, the architect OMA has housed the entire process of Chinese television production into a single building (see Figure 5). The design is without a doubt revolutionary in many ways, and will certainly inspire a new generation of revolution building forms based on the gravity-defying structural solution.

Designing the Link Structure

Many special requirements are already part of the design process of "standard" tall buildings in China. These include:

- Wind tunnel testing;
- Designing for vertical seismic action;
- Ensuring the design has robustness and resilience to withstand rare seismic events;
- Comfort requirements under vibration and wind acceleration;
- Guaranteeing diaphragm action in critical floors/slabs.

Linked towers are recognized as complex tall buildings in the Chinese Codes and their design is further complicated by stringent requirements, both at a structural system and member component level. For these buildings, a review by a seismic expert panel review for buildings exceeding Code limits is a must. The CCTV building design involved more than a year of intense design assessments and consultations with the top level national structural experts in China, before design approvals were granted.

Linked building shapes are less predictable with respect to wind loading and wind accelerations which affect the comfort of occupants. Wind tunnel studies are encouraged early on in the design process. The rigid link also requires an assessment for thermal loading for the additional stress it places on the structure and elements.

Any design with linked towers should also address constructability - feasible construction methodology, and the sequencing and additional stress brought on the structure depending on the chosen construction method. Under the lateral loads due to wind and earthquake, two towers would deflect laterally and twist in different amounts, even in different directions. With the link up to the two towers requiring tremendous stiffness and mass, the linking structure should be in possession of both stiffness and strength to adequately accommodate the effects of shear, bending and torsion attributed to restraining the two towers.

> "The linked building shapes are less predictable with respect to wind loading and wind accelerations which affect the comfort of occupants."

Figure 3: LS-Dyna Analysis Model of the Shenzhen Energy Headquarters Building. © Arup

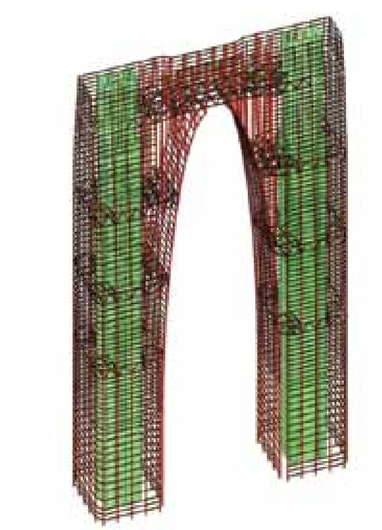

Figure 4: Suzhou "Gate to the East" – structural model for lateral stability analysis. © Arup

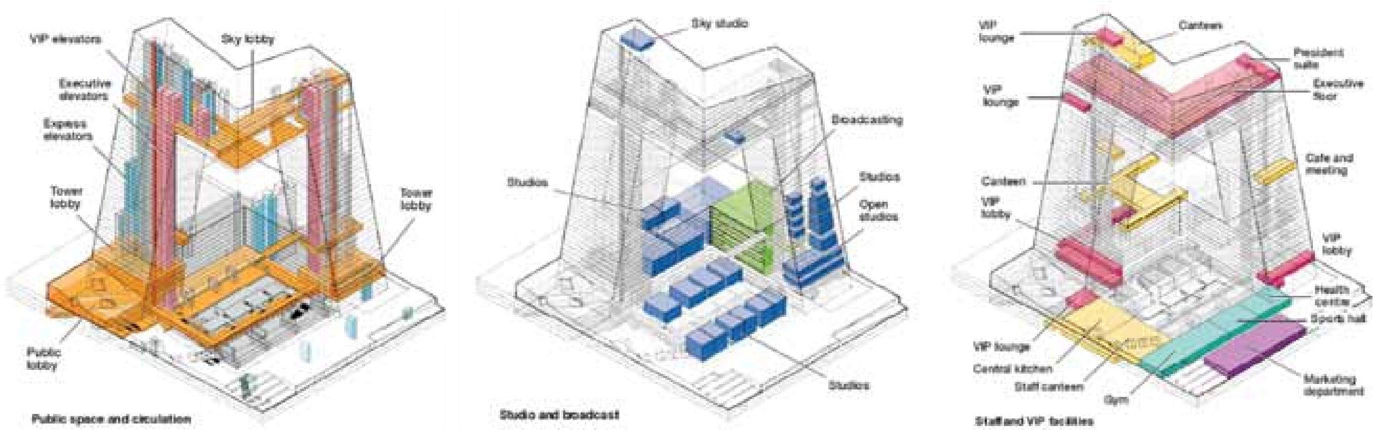

Figure 5: Functions and layout within the CCTV building. © OMA

In fact the structural challenge is often to minimize the linkage to deliver the architectural image of slender towers joined by light linking structures, yet at the same time providing sufficient structure. The design of the linking structure is a balance of satisfying opposing requirements - providing the linking structure with sufficient stiffness, but not making it overly stiff, which would attract additional forces leading to larger member sizes. These considerations of stiffness and strength must be given to all the axis of interaction.

This exact philosophy was implemented in the Pazhou and Ningbo structures. The building "halves" by themselves were too slender and required the linkage for structural stability (see Figures 1 and 2). The successful structural solution came about with sufficiently minimized linkage to ensure the architectural aspirations were delivered.

For the Shenzhen Energy Building, the initial approach was to have a movement joint in the link, and the buildings to be structurally independent. In the winning competition design, the link consisted of three stories. As the design developed and more programs were placed in the link, it expanded to eight stories deep (see Figure 3). It was inevitable to rigidly link the two towers. This was brought about by a series of trusses connecting the two adjacent towers. The trusses were strategically coordinated with the architecture and program so as to minimize impact on layout and views. The linkage structure design was subject to strenuous analyses, including for non-linear seismic response and performance. Detailing of the link members and connections also required robustness under severe seismic loading.

In the Suzhou "Gate to the East," the linkage is at the top of the towers. The form is such that, in the north-south direction, the floor plates in the upper half of the towers are enlarged significantly (see Figure 4). At the same time, the floor plate is reduced in dimension in the east-west direction. This form change contributes to multiple impacts on the structure, including considerable enlargement of the frontal area. As a result, the towers would be subjected to much larger wind, mass and seismic loads than two typical towers of the same height, and there would be a significant reduction in stiffness and strength of the tower in the east-west direction in resisting these increased lateral forces.

Coupled with the structural difficulties, the prime location of hotel and serviced apartments in the link portion further complicated the design. The obvious solution of using diagonal bracing members was ruled out. The columns also must be slimmed to minimize the protrusions from the room partitioning.

The innovative structural solution called for the use of one-story-deep steel trusses located at the fourth refuge floor, the lowest floor of the linking structure (see Figure 4), as the basic structural form to support the linking portion of the tower. A total of four trusses were adopted as the vertical support system of the linking structure, of which two also were part of the belt trusses to resist the lateral forces. The belt trusses supplemented the required torsional stiffness to the linking portion of the tower. Horizontal steel trusses were introduced to the top three and bottom two floors of the link structure. Together with the composite floor slabs, they provide the required shear, bending and axial stiffness and strength to accommodate the effects of restraining the connected two towers and to transfer the lateral loads to the primary lateral stability systems of the two towers.

The structural challenges for linking the top of the Suzhou Gate magnified and multiplied when designing the CCTV building. With the towers leaning at six degrees on each face, the vertical steel braced cores tapered off at the height of the building, such that their structural contribution was significantly minimized. Added to the challenge was the 80-meter cantilevering "overhang," which connected the two leaning towers at the top of the building in a folded form. The structural solution had to be a global system. At the outset, it was decided that the only feasible structural solution for the three-dimensional gravity-defying CCTV building was to mobilize the entire external envelope of the building form, to create an external continuous diagrid tube system (see Figure 6). In the process of refining the solution, the diagonal braces within the continuous tube structure are used to visually express the pattern of forces within the structure. This was achieved in close coordination with the architect.

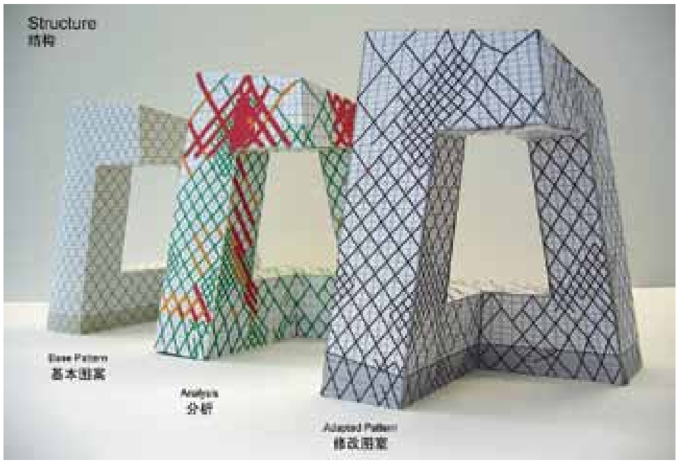

Figure 6: CCTV diagrid tube system with bracing pattern expressing structural forces. © Arup

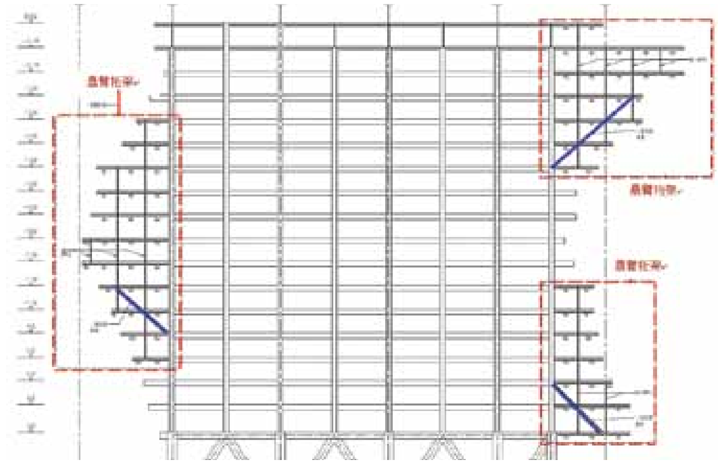

Figure 7: Shenzen Energy Building – structural steel use restricted to the cantilevering blocks (South Tower wing elevation). © Arup

Seismic Fortification Level	Level 1	Level 2	Level 3
Description	Minor	Moderate	Severe
Peak ground acceleration	0.07 g	0.20 g	0.40 g
Average Return Period	1 in 50 years	1 in 475 years	1 in 2475 years
Probability of exceedance	63% in 50 years	10% in 50 years	2% in 50 years
Fortification Criteria	No damage (remain elastic)	Repair-able damage	No collapse

Table 1: CCTV seismic performance objectives. © Arup

Horizontal and vertical accelerations of the overhang under wind loading were checked. Due to the inherent stiffness of the structural system, the predicted accelerations were small and found to be well within criteria for occupant comfort. It was concluded that perceptible vertical motion would occur no more than once a year. This process involved extensive research into the likely occupant perception of low-frequency vertical vibration, since there was little available design information. The design also included analyzing the effects on vibration and comfort due to a coordinated crowd (based on a crowd load of 50 people) jumping at the tip of the linked cantilever.

Arup proposed a performance-based design approach to the building, adopting first principles and state-of-the-art methods and guidelines to achieve set performance targets at different levels of a seismic event. Explicit and quantitative design checks using appropriate linear and non-linear seismic analysis were made to verify the performance for all different levels of the design earthquake (see Table 1).

Cost and Construction Feasibility

With a focus on providing a structural design which balances aesthetics, function, build-ability and cost, it is thus imperative to have the participation of the structural engineers at the outset of the architectural concept design development of highly complicated building forms such as linked towers.

Reinforced concrete is used where appropriate and structural steel, of a higher comparative price, is only adopted in the areas of the design where required. For the Shenzhen Energy Building, aside from the SRC columns in the lower floors of the taller tower (to minimize column area), and two zones of small outriggers (again in the very slender taller tower only), structural steel is only used in the link bridge structure (see Figure 7).

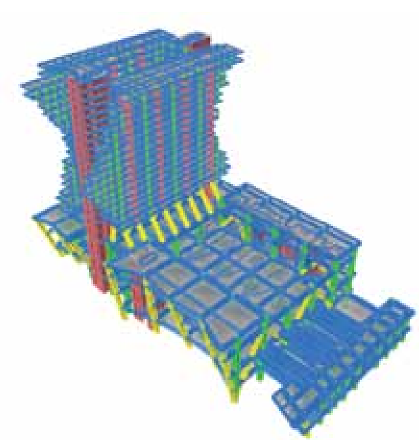

Figure 8: Pazhou 1401 – structural analysis. © Arup

The Pazhou towers had similar strategies whereby the majority of the building is in reinforced concrete, with structural steel adopted in:

- The transfer columns
- The gravity-defying cantilevering blocks in the building
- The more non-standard ruffled architectural blocks in the floors toward the top of the building (see Figure 8).

In addition, the cost and construction complexity for Pazhou is controlled through engineering the bold architectural "moves" in the building to secondary components.

The primary structural stability system remains relatively standard, a combination of shear walls, cores and moment frames.

With its 450,000 square-meter gross floor area, the CCTV building is equivalent to four buildings the size of One Canada Square in London's Canary Wharf, or two and a half times the size of Two International Finance Centre in Hong Kong. Costs for such a large building, as well as the obvious concern for the cost of the structural gymnastics, was a design preoccupation from the start.

The total structural steel content of the building is approximately 250 kg/m^2 of constructed floor area. This steel rate is comparative to a conventional building in Beijing of 300 to 350 meters, and is reasonable, considering the iconic landmark design and structural wonderment of the CCTV building. The steel usage also compares well with that of other high-rise towers.

For the CCTV building, significant studies were carried out on its build-ability, even during the early design stages. The innovative form of the CCTV building posed many construction challenges, from the large concrete pour of the building founding pile raft, to the tilting towers, to the construction and linkage of the cantilevered overhang. Arup's design considered upper and lower bound conditions to facilitate flexibility in the contractor's construction method (see Figure 9). The design assessed and allowed for construction locked in stresses and detailed specifications on construction precambering.

Conclusion

Height is not the only objective or challenge in the race for excellence in designing and building landmark skyscrapers. A number of recent buildings in China have added new dimensions through inventively linked tower forms that deliver uniqueness in architecture, prestige and innovative functions. They are also cost effective and can provide important aspects to the structural design, if planned appropriately from the outset.

The fact that all these China projects have won international design competitions reinforces the success of linked towers as an important step forward for tall buildings. In all these designs, the contribution from the structural solutions in a holistic approach cannot be understated. ■

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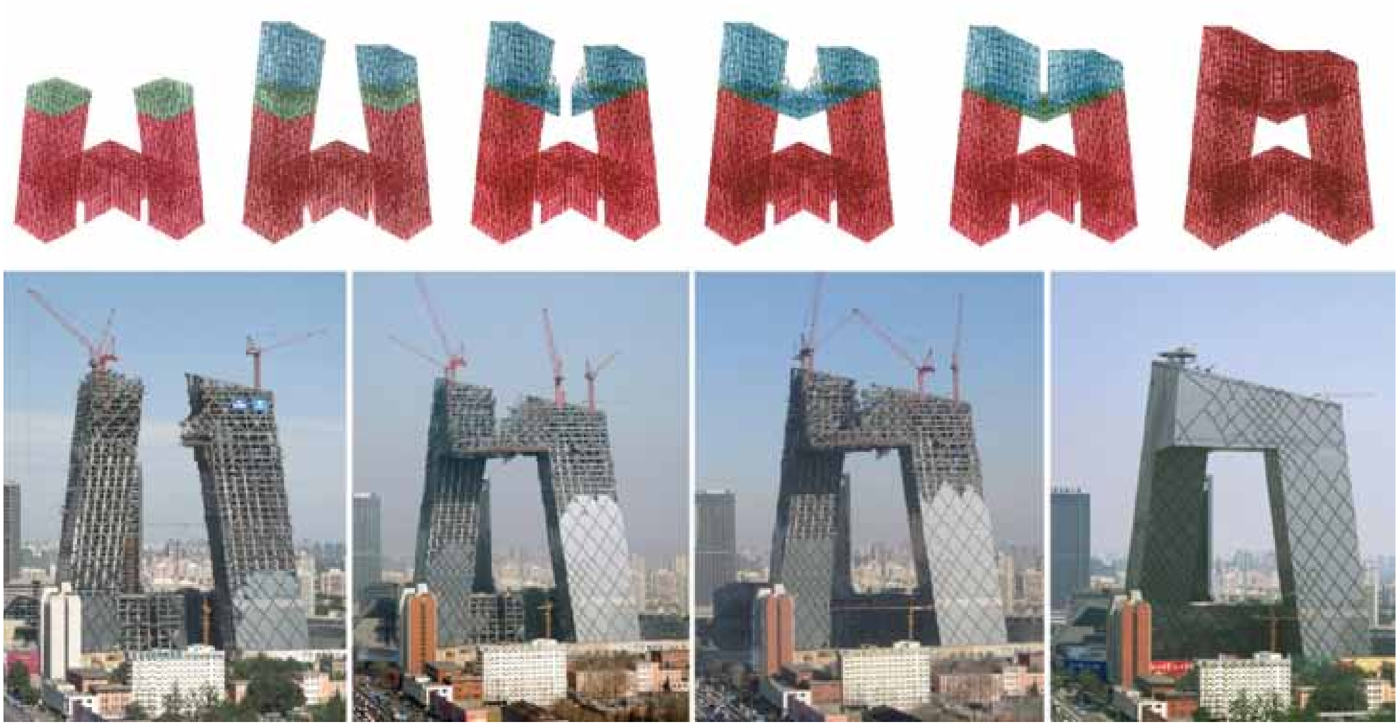

Figure 9: CCTV construction sequence. © Arup