CCTV Headquarters, Beijing, China:

Structural engineering design and approvals

Chris Carroll Paul Cross Xiaonian Duan Craig Gibbons
Goman Ho Michael Kwok Richard Lawson
Alexis Lee Andrew Luong Rory McGowan Chas Pope

Introduction

Growth in China is happening at an historically unparalleled rate. China Central Television (CCTV), the principal state-run broadcaster, currently has 13 channels, but by 2008 it plans to be operating over 200 channels and competing successfully with CNN, NBC, Sky, and the BBC in the global market. To enable this expansion, and to place CCTV firmly on the global map, a new headquarters facility was needed, with the entire television-making process housed in one location within Beijing's newly-designated Central Business District (Fig 1).

In early 2002, CCTV organized an international design competition, which attracted some of the biggest names in architecture. After much effort it was won in August 2002 by Rem Koolhaas's practice Office for Metropolitan Architecture (OMA), based in Rotterdam, working with Arup. To secure the project, OMA formed an alliance with the East China Architecture and Design Institute (ECADI), which would act as the local design institute (LDI) of record for both architecture and engineering. Working with an LDI is a statutory stipulation for all projects in China, and the LDI's local knowledge and contacts can make the relationship very beneficial.

'Who says that structure should not be reinvented? ... Who says that reinventing structure cannot be creative?'

Rem Koolhaas, from a discussion at Tsinghua University, 5 August 2003.

The design team

When the SD (scheme design) started, the project was divided between Arup offices in Hong Kong and London. The core team, including six staff seconded from Hong Kong and one from Beijing, was located in London to work closely with OMA in Rotterdam. Given the many engineering disciplines involved, and the need for dedicated project teams for each of the three buildings on the site, Arup had a near-permanent presence in OMA's offices. Four of ECADI's engineers joined the Arup team in London for most of the EPD (extended preliminary design) phase, while their architectural colleagues worked alongside OMA in Rotterdam.

Another Arup team in Hong Kong provided information and guidance on Chinese design and procedures, maintained contact with local authorities and the client, and offered specialist input such as wind and fire engineering. As the design progressed, additional input was received from Arup offices in Beijing and Shenzhen.

This close co-operation proved invaluable in delivering a scheme design within four months and the EPD and EPR (expert panel review) approvals within a further six.

Arup provided engineering and consultancy input for structural, building services, geotechnical, fire, communications, and security design, leading the engineering design through SD, EPD including the associated approvals processes to tender, working with ECADI engineers. ECADI currently leads the production of the final construction information and is to provide site assistance with support from Arup.

1. CCTV in the new Beijing CBD.

Architectural concept

The client stipulated in the competition brief that the facility should all be housed on one site, but not necessarily constrained to one building. In his architectural response, however, OMA decided that by doing just this, it should be possible to break down the 'ghettoes' that tend to form in a complex and compartmentalized process like the making of TV programmes and create a building whose layout in three dimensions would force all those involved – the creative people, the producers, the technicians, the administrators – to mix and produce a better end-product more economically and efficiently.

The winning design thus combines administration and offices, news and broadcasting, programme production and services – the entire process – in a single loop of interconnected activities. The specifics of the structure evolved in tandem with the specifics of the building as they in turn evolved, a notable example being the placement of double-height studios within the Towers and Base, which significantly influenced the structural form.

The public facilities included in the project are located in a second building, the Television Cultural Centre (TVCC); both buildings are serviced from a single support building which houses major plant as well as the site security.

Progress to construction

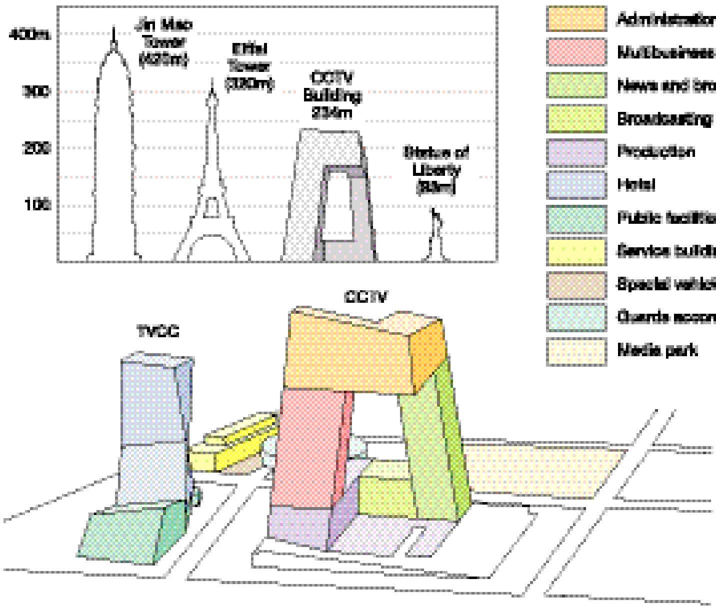
Given the challenging and unprecedented nature of the winning design, the competition was followed by a further period of justification and persuasion, during which Arup applied considerable effort at substantial risk. During the next four months, feasibility studies were made and two key proof-of-concept meetings held between the client's technical advisors and key members of the Arup team. These primarily addressed the safety, buildability, and overall cost of the scheme, and concluded that though there was no precedent for such a building, it could be achieved. Once the client was convinced of this, contracts were signed and the experienced international design team required to deliver the project was mobilized. The official ground-breaking ceremony took place on 22 September 2004, but although construction started relatively recently, it is felt that rather than wait more than three years until completion, the fantastic story of the realization of CCTV should start to be told now. This first article is principally a description of the structural design, analysis, and approvals process for the main CCTV building. Subsequent editions of *The Arup Journal* will contain episodes on the building services and security engineering for the main building, on the TVCC and support buildings, and on the construction process to completion and opening.

The new CCTV headquarters development

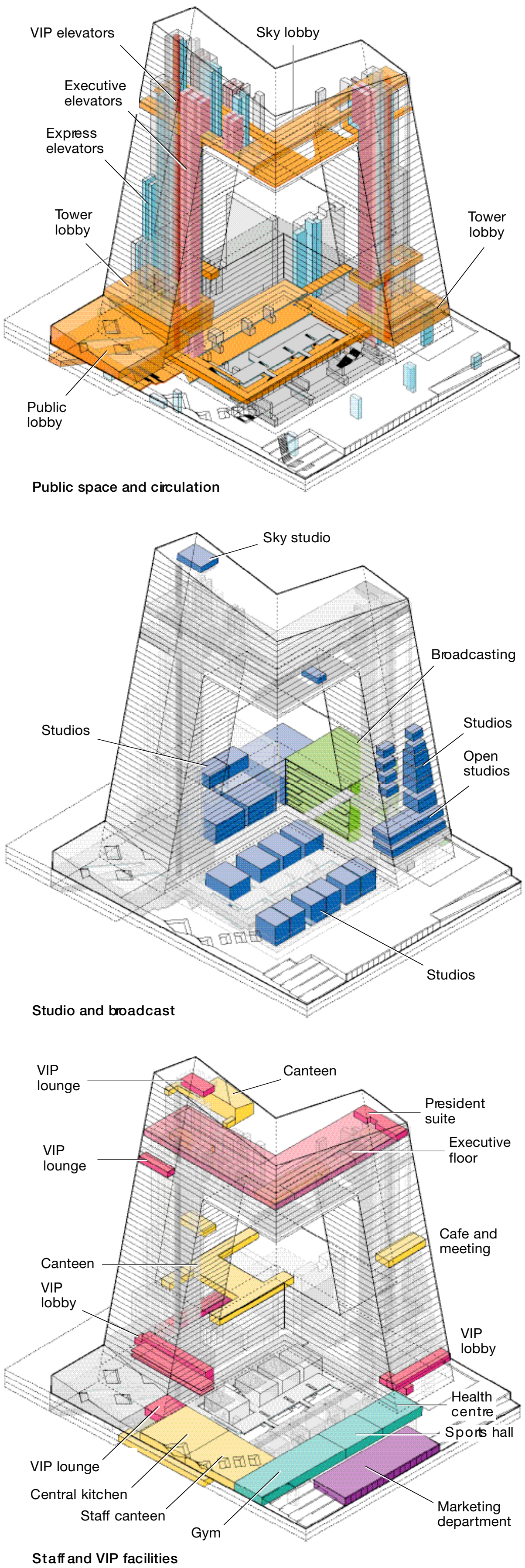
The entire CCTV development has a site area of 187 000m^2 and will provide a total of 550 000m^2 gross floor area. The estimated construction cost is around 5bn RMB (or $US600M), and the project as a whole (Fig 2) includes:

- the China Central Television headquarters building (CCTV building)
- the Television Cultural Centre (TVCC)
- a service and security building
- a landscaped media park with external features.

The 450 000m^2, 234m tall (Fig 3), CCTV building consists of a nine-storey 'Base' and three-storey basement, two leaning Towers that slope at 6° in each direction, and a nine to 13-storey 'Overhang', suspended 36 storeys in the air, all combining to form a 'continuous tube'. Viewed in other terms,the total building form can be seen as four distinct volumes, each approximately the size of One Canada Square in London's Canary Wharf, two of them leaning towards each other from opposite corners of the site, and joined at the top and bottom by the other two, both horizontal and with opposite 90° angles in their middles.



2. The site layout, showing programme distribution.



3. The functions and layout within the CCTV building.

Structural form

Superstructure – the 'continuous tube'

Early on, the team determined that the only way to deliver the desired architectural form of the CCTV building was to engage the entire façade structure, creating in essence an external continuous tube system. Adopting this approach gave proportions that could resist the huge forces generated by the cranked and leaning form, as well as extreme seismic and wind events.

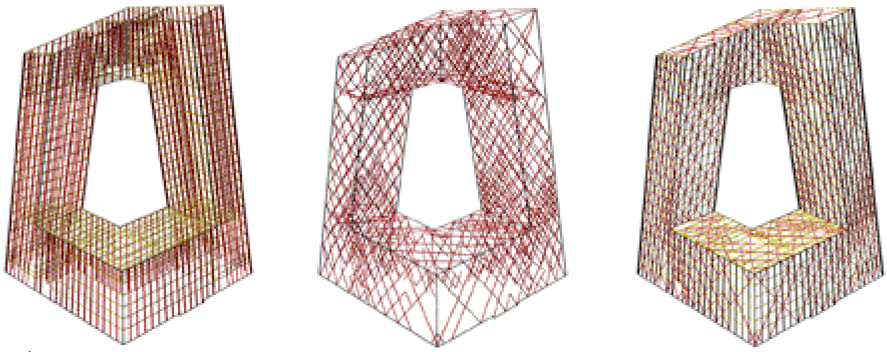
This 'tube' is formed by fully bracing all sides of the façade (Fig 4). The planes of bracing are continuous through the building volume in order to reinforce and stiffen the corners. The continuous tube system is ideally suited to deal with the nature and intensity of permanent and temporary loading on the building, and is a versatile, efficient structure which can bridge in bending and torsion between the Towers, provide enough strength and stiffness in the Towers to deliver loads to the Base, and stiffen up the Base to reinforce the lower Tower levels and deliver loads to the foundations in the most favourable possible distribution, given the geometry.

Vertical cores housing lifts, stairs, and risers are oriented and stepped so that they always sit within the footprint of the sloping Towers. Sloping cores, to allow consistency of floor plate layout, were considered but ruled out due to constraints on the procurement of the lift systems.

In addition to the cores, the floor plates of the Towers take support from many vertical columns. Given the nature of the sloping Towers it is not possible to continue vertical column lines from top to bottom, so a two-storey deep system of transfer trusses is used at approximately mid-height. The floor plates of the Overhang are also supported by vertical columns that are transferred to the external tube structure via a two-storey deep transfer deck (Fig 5).

The continuous tube structure has behind its final irregular arrangement a regular base pattern of perimeter steel or steel-reinforced concrete (SRC) columns, perimeter beams, and diagonal steel braces set out on a typically two-storey module. The regular base pattern was tuned or optimized by adding or removing diagonals and changing brace plate thickness to match the strength and stiffness requirements of the design.

The two-storey base pattern was chosen to coincide with the location of several two-storey high studios within the Towers. A stiff floor plate diaphragm can only be relied on every two storeys, hence lateral loads from intermediate levels are transferred back to the principal diaphragm levels via the internal core and the columns.



4.
Principles of the tube structure: regular grid of columns and edge beams + patterned diagonal bracing = braced tube system.

The braced tube structure gives the leaning Towers ample stiffness during construction, allowing them to be built safely within tight tolerances before they are connected and propped off each other. The tube system also suits the construction of the Overhang, as its two halves will cantilever temporarily from the Towers.

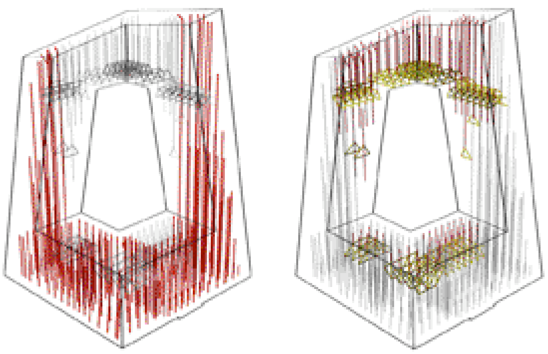
Robustness

The continuous tube has a high degree of inherent robustness and redundancy, and offers the potential for adopting alternative load paths in the unlikely event that key elements are removed. This was studied in detail and provides the building with a further level of safety.

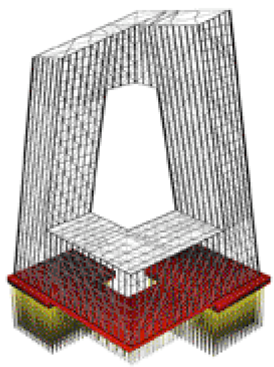
Substructure and foundations

The main Towers stand on piled raft foundations. The piles are typically 1.2m in diameter, and about 52m long. Given the magnitude and distribution of the forces to be transferred to the ground, the raft is up to 7.5m thick in places and extends beyond the footprint of the Towers to act as a toe, distributing forces more favourably into the ground. The foundation system is arranged so that the centre of the raft is close to the centre of load at the bottom of each Tower, and no permanent tension is allowed in the piles. Limited tensions in some piles are only permitted in major seismic events.

For the Base plus three-storey basement, a traditional raft foundation is used, with tension piles between column locations to resist uplift from water pressure acting on the deep basement. 15-20m long, 600mm diameter tension piles will be arranged under the raft with additional 1.2m diameter piles under secondary cores and columns supporting large transfer trusses from the studio areas (Fig 6).



5.
(a) Internal columns starting from pilecap level.
(b) Internal columns supported on transfer structures.



6.
The foundation system.

A performance-based design approach

Chinese approvals process

The legal framework in China governing building design practice is similar to those of Japan and some continental European countries where the design codes are legal documents published and enforced by the state government. Design engineers must comply with the codes when designing buildings and structures covered by their scope, but equally the codes provide legal protection to the design engineers who are relieved of any legal responsibilities by virtue of compliance. The Chinese code for seismic design of buildings (*GB50011 – 2001*), sets out its own scope of applicability, limiting the height of various systems and the degree of plan and vertical irregularities. Design of buildings exceeding the code must go through a project-specific seismic design expert panel review (EPR) and approval process as set out by the Ministry of Construction.

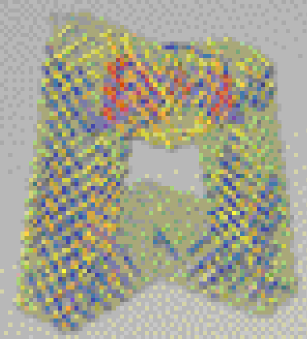
Although the 234m height of the CCTV building is within the code's height limit of 260m for steel tubular structural systems (framed-tube, tube-in-tube, truss-tube, etc) in Beijing, its geometry is non-compliant. The Seismic Administration Office of the Beijing Municipal Government appointed an expert panel of 12 eminent Chinese engineers and academics to closely examine the structural design, focusing on its seismic resistance, seismic structural damage control, and life safety aspects.

Arup realised the importance of engaging the expert panel early in the design process, and three informal meetings were held to solicit feedback and gain trust before the final formal presentation. The panel was under enormous public and state scrutiny to closely examine Arup's design, the rigorous nature of which - aided by successful collaboration with ECADI - was of vital importance. From day one the building received wide publicity in China, and concerns were voiced by both the general public and the government over the safety of the adventurous design - indeed it came to be referred to by the public and the media as 'Wei Fang' (the dangerous building): an indicator of the scrutiny the project and hence Arup were under.

Seismic requirements

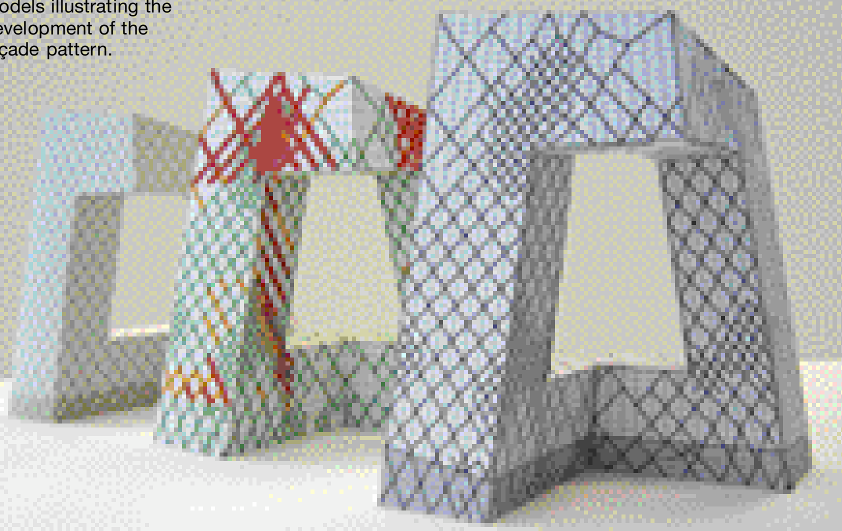
As the seismic design lay outside the scope of the prescriptive Chinese codes of practice, Arup proposed a performance-based design approach from the outset, adopting first principles and state-of-the-art methods and guidelines to achieve set performance targets at different levels of seismic event. Explicit and quantitative design checks using appropriate linear and non-linear seismic analysis were made to verify the performance for all three levels of design earthquake.

7.
Brace stresses for a uniform grid.



8.
Unfolded view of the structure, showing areas to densify or rarefy the mesh.

9.
Models illustrating the development of the façade pattern.



Developing and optimizing the bracing pattern

The diagonal braces within the continuous tube structure visually express the pattern of forces within the structure and are an important aesthetic aspect of the cladding system. The bracing pattern was determined through an intense iterative analysis and in close collaboration with the architect.

The principal structure of the building was modelled in Oasys GSA and representative loading applied, including a static equivalent load for a level 1 earthquake. Initially, a uniform bracing pattern (Fig 7) was adopted, and the SRC and steel columns sized appropriately. The distribution of forces within the braces was then investigated, and the results categorized into three groups with an appropriate action applied to the braces within a particular group:

- densify the mesh by adding braces; 'doubling'
- keep the same
- rarefy the mesh by removing braces: 'halving'.

The structure is highly indeterminate, so changing the bracing pattern resulted in a new distribution of forces within the columns, braces, and edge-beams. Changes in stiffness also changed the dynamic behaviour of the structure and hence the seismic forces that are attracted. Patterning became an extremely involved iterative process.

An unfolded stress pattern view of the structure was developed (Fig 8) to clearly display the results of the whole building in one view, or alternatively folded up into a 3-D model (Fig 9). This enabled the design team to visually process the results quickly, while keeping the architect up-to-date and involved in the development of the pattern.

The criteria for this performance-based design are beyond those usually applied to such buildings in China, and were set by the Arup design team in consultation with the expert panel to reflect the importance of the building both to the client and to the Chinese Government. The basic qualitative performance objectives were:

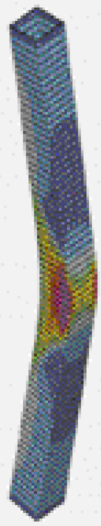
- no structural damage when subjected to a level 1 earthquake with an average return period of 50 years (63% probability of exceedance in 50 years)
- repairable structural damage when subjected to a level 2 earthquake with an average return period of 475 years (10% probability of exceedance in 50 years)
- severe structural damage permitted but collapse prevented when subjected to a level 3 earthquake with an average return period of 2500 years (2% probability of exceedance in 50 years)

For the CCTV development site, the peak horizontal ground acceleration values associated with the three levels of design earthquake are 7%, 20% and 40% of gravity respectively.

Elastic superstructure design

With the bracing pattern determined from the initial concept work, a full set of linear elastic verification analyses were performed, covering all loading combinations including level 1 seismic loading, for which modal response spectrum analyses were used. All individual elements were extensively checked and the building's global performance verified. Selected elements were also initially assessed under a level 2 earthquake by elastic analysis, thus ensuring key elements such as columns remained elastic.

The elastic analysis and design was principally performed using SAP2000 and a custom-written Chinese steelwork code post-processor, which automatically took the individual load cases applied to the building and combined them for the limit state design. Capacity ratios were then visually displayed, allowing detailed inspection of the critical cases for each member. Due to the vast number of elements in the model – 10 060 elements representing nearly 90 000m of steel and SRC sections – and the multitude of load cases, four post-processors were run in parallel, one for steel columns, one for SRC columns, one for braces, and another for the edge beams that together form the continuous tube. The SRC columns used a modified post-processor to account for the differences between the steel and SRC codes; section properties of these columns were determined using XTract, which also computed the properties for the subsequent non-linear analyses.



Software

Many software packages were used to deliver the CCTV structural design, some developed in house by Arup:

CSI SAP2000: limited non-linear structural analysis and design with static, dynamic and push-over capability

Oasys LS-DYNA Environment: non-linear explicit time history analysis

Oasys GSA: linear structural analysis with static and response spectrum analysis dynamic capability

Oasys Vdisp: plug-in for GSA to analyze non-linear soil stiffness

Oasys GSRaft: iterative non-linear soil-structure interaction analysis

Oasys Compos: composite steel beam and concrete slab analysis and design

Oasys Adsec: composite (SRC) cross-section analysis

Oasys ADC: reinforced concrete design package

Xtract: non-linear large strain composite (SRC) cross-section analysis

MSC/Nastran: heavy duty finite element analysis package

Xsteel: 3-D CAD package.

10. Non-linear finite element simulation model showing local buckling of a typical steel brace.

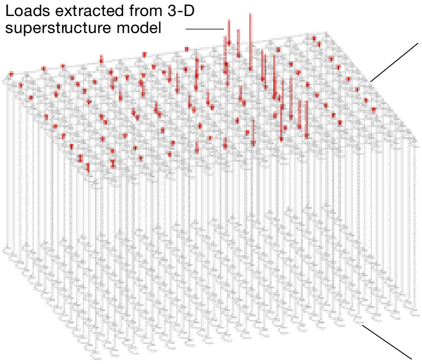
The post-processor provided a revised element list which was imported back into SAP2000, and the analysis and post-processing repeated until all the design criteria were met. As the structure is highly indeterminate and the load paths are heavily influenced by stiffness, each small change in element property moves load around locally. Optimizing the elements only for capacity would result in the entire load gradually being attracted to the inside corner columns, making them prohibitively large, so careful control had to be made of when an element's section size could be reduced and when there was a minimum size required to maintain the stiffness of the tube at the back face.

To further validate the multi-directional modal response spectrum analyses, level 1 time-history checks were also made using real and artificially-generated seismic records.

Non-linear superstructure seismic design and performance verification

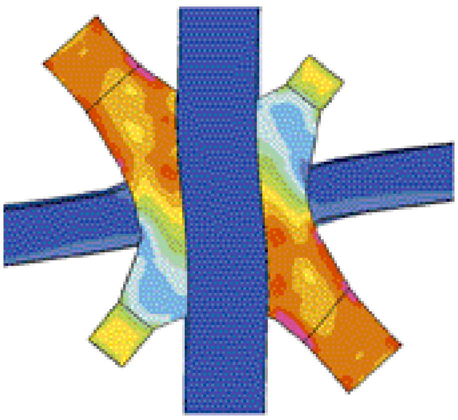
For the performance-based design, a set of project-specific 'design rules' were proposed by the design team and reviewed and approved by the expert panel, creating a 'road map' to achieve the stated seismic performance objectives. Appropriate linear and non-linear seismic response simulation methods were selected to verify the performance of the building under all three levels of design earthquake. Seismic force and deformation demands were compared with the acceptance limits established earlier to rigorously demonstrate that all three qualitative performance objectives were achieved.

Inelastic deformation acceptance limits for the key structural brace members in the continuous tube were determined by non-linear numerical simulation of the post-buckling behaviour. LS-DYNA, commonly used to simulate car crash behaviour, was used for this work. The braces are critical to both the lateral as well as the gravity systems of the building and are also the primary sources of ductility and seismic energy dissipation. Non-linear numerical simulation of the braces was needed to establish the post-buckling axial force/axial deformation degradation relationship to be used in the global 3-D non-linear simulation model. It was also used to determine the inelastic deformation (axial shortening) acceptance limit in relation to the stated performance criteria. Post-buckling inelastic degradation relationship curves illustrate the strength degradation as the axial shortening increases under cyclic axial displacement time history loading. The acceptable inelastic deformation was then determined from the strength degradation 'backbone' curve to ensure that there was sufficient residual strength to support the gravity loads after a severe earthquake event.



11. GSRaft model of the piled foundation.

Having established the inelastic global structure and local member deformation acceptance limits, the next step was to carry out non-linear numerical seismic response simulation of the entire 3-D building subjected to level 2 and level 3 design earthquakes. Both the non-linear static pushover analysis method and the non-linear dynamic time history analysis method were used to determine the seismic deformation demands in terms of the maximum inelastic inter-storey drifts and the maximum inelastic member deformation. These deformation demands were compared against the structure's deformation capacities storey-by-storey and member-by-member to verify the seismic performance of the entire building. All global and local seismic deformation demands were shown to be within their respective acceptance limits, demonstrating that the building achieves the quantitative and hence qualitative performance objectives when subjected to level 2 or level 3 earthquakes.



12.
The von Mises stress distribution of a large connection plate under the most unfavourable loading combination.

Foundation design

The design of the foundations required that the applied superstructure loads be redistributed across the pilecap (raft) so as to engage enough piles to provide adequate strength and stiffness. To validate the load spread to the pile group, a complex iterative analysis process was used adopting a non-linear soil model.

The superstructure loads were applied to a discrete model of the piled raft system. Several hundred directional load case combinations were automated in a spreadsheet controlling the GSRaft soil-structure interaction solver (Fig 11). This procedure iteratively changed the input data in response to the analysis results to model the redistribution of load between piles when their safe working load was reached. The analysis was then repeated until the results converged and all piles were within the allowable capacities. The envelope of these several-hundred analyses was then used to design the reinforcement in the raft itself.

Connections

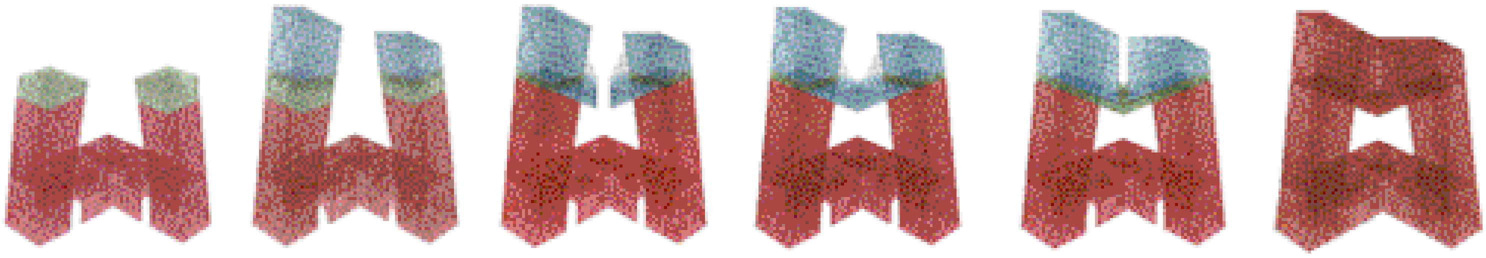
The force from the braces and edge-beams must be transferred through and into the column sections with minimal disruption to the stresses already present in the column. The connection is formed by replacing the flanges of the steel column with large 'butterfly' plates, which pass through the face of the column and then connect with the braces and the edge-beams. No connection is made to the web of the column to simplify the detailing and construction of the concrete around the steel section.

The joints are required to behave with the braces, beams, and columns as 'strong joint/weak component'. The connections must resist the maximum probable load delivered to them from the braces with minimal yielding and a relatively low degree of stress concentration. High stress concentrations could lead to brittle fracture at the welds under cyclic seismic loading, a common cause of failure in connections observed after the 1994 Northridge earthquake in Los Angeles. Two connections, representing the typical and the largest cases, were modelled from the original AutoCAD drawings using MSC/NASTRAN. The models were analyzed, subjected to the full range of forces that can be developed before the braces buckle or yield - assuming the maximum probable material properties - to evaluate the stress magnitude and degree of stress concentration in the joints. The shape of the butterfly plate was then adapted by smoothing out corners and notches until potential regions of yielding were minimized and the degree of stress concentration reduced to levels typically permitted in civil and mechanical engineering practice. CAD files of the resulting geometry of the joints were exported from the finite element models and used for further drawing production (Fig 12).

Transfer structures

Whilst the external tube structure slopes to give the unique geometry, the internal steel columns and cores are kept straight for functional layout and to house lift and services shafts. This resulted in a different configuration for every floor - the spans from core to façade, and internal column to façade, change on each. Consequently, internal columns can be removed where the floor span decreases sufficiently on one side of the core. Similarly, additional columns are needed up the building height where the floor spans increase significantly on the other side of the core. Transfer trusses support these additional columns, spanning between the internal core and the external tube structure. They are typically two storeys deep and located in plant floors so as to be hidden from view and to minimize the impact on floor planning.

The sizes of the transfer trusses mean that they could potentially act as outriggers linking the external tube to the internal steel cores - undesirable as this would introduce seismic forces into the relatively slender internal cores. The design preference is to keep all the seismic forces in the more robust diagrid framing of the continuous tube. The transfer trusses are thus connected to the internal cores and the external columns at singular 'pin-joint' locations only. Detailed analyses were made to ascertain that no outrigger effects result from the transfer truss geometry.



13. One of several construction sequence loading arrangements considered.

The floors cantilevered from the two leaning Towers to form the Overhang are enclosed by the continuous tube structure on the outside. This supports a two-way transfer deck in the bottom two storeys of the Overhang, carrying the columns for the floors above.

The Base also contains major transfer trusses, spanning over the principal studios to support the columns and floors above.

Construction issues

The building's unique form necessitated careful consideration of the construction method throughout the design process. Both the method and sequencing of the works (Fig 13) will affect the permanent distribution of dead load through the continuous tube.

To allow the contractor some flexibility in method and programme, upper and lower bound analyses were performed, using staged construction and loading to build up the final dead load incrementally. The lowest bound of loading when the two Towers are connected puts the highest stresses into the Overhang structure since it acts as a prop between the Towers, while the upper bound puts the largest stresses into the Towers since they carry more of the load in bending as a cantilever. Between these two extremes there is scope for the contractor to choose his programme, and to propose alternative erection procedures.

The timing of the connection between the Towers is also important, so as to minimize the relative movement between them from thermal and wind effects. It is also important to minimize future thermal movements between the Towers that could put large stresses into the Overhang where it is restrained by the Towers.

14. Site work begins, September 2004.

Conclusion

The structural design of CCTV posed many technical challenges to the large international team. They were successfully overcome, within a very tight programme. Arup's unique global depth of experience and knowledge made this possible, enabling the right people to be involved at the right stages of the project. The Arup team delivered the design through a seamless global collaboration, transcending time zones, physical distance, cultures, cost centres, and even the SARS outbreak. Foremost in the team's collective mind was the need to deliver the complex design on time for the client and in so doing win the approval of the Chinese Ministry of Construction expert panel.

Credits

Client: China Central Television **Architect:** OMA Stedebouw BV **Geotechnical, structural, MEP, fire, and security consultant:** Arup - Abdel Ahmed, Chuan-Zhi Bai, Cecil Balmond, Carolina Bartram, Chris Carroll, Wayne Chan, Mark Choi, Dean Clabrough, Paul Cross, Roy Denoon, Omar Diallo, Mimmy Dino, Xiaonian Duan, Gary Ge, Craig Gibbons, Sam Hatch, Guo-Bo He, Xue-Mei He, Colin Ho, Goman Ho, Yi Jin, Jonathan Kerry, Michael Kwok, Francis Lam, Peter Lam, Richard Lawson, Alexis Lee, Jing-Yu Li, Zhao-Fan Li, Ge-Qing Liu, Peng Liu, Quan Liu, Pierre Lui, Man-Kit Luk, Andrew Luong, John McArthur, Rory McGowan, Hamish Nevile, Gordon Ng, Xiao-Chao Pang, Jack Pappin, Steve Peet, Bill Peng, Dan Pook, Chas Pope, Qun Shi, Andrew Smith, Stuart Smith, Derek So, G Y Sun, George Thimont, Alex To, Fei Tong, Paul Tonkin, Ben Urick, Bai-Qian Wan, Yang Wang, Will Whitby, Robin Wilkinson, Michael Willford, Michelle Wong, Stella Wong, Eric Wu, Jian-Feng Yao, Angela Yeung, Kenneth Yeung, Terence Yip, George Zhao, Julian Zheng (analysis, geotechnical, structural) **Illustrations:** 1, 9 ©OMA; 2 Nigel Whale; 3 -14 Arup

The next article in this series, discussing the building services design of the CCTV development, will appear in *The Arup Journal* 3/2005.