Technical Article

STEEL STRUCTURES

Steel Structures 6 (2006) 387-391

www.kssc.or.kr

China Central Television Headquarters - Structural Design

Chris Carroll, Xiaonian Duan, Craig Gibbons*, Richard Lawson, Alexis Lee, Andrew Luong, Rory Mcgowan and Chas Pope

Ove Arup and Partners Hong Kong Limited, Level 5, Festival Walk, 80 Tat Chee Avenue, Kowloon Tong, Hong Kong

Abstract

CCTV new headquarters building is a 234 m tall building in the form of a three-dimensional continuous cranked loop formed by a 9-storey podium structure joining two 50-storey high leaning towers which are linked at the top via a 13-storey cantilevered "overhang" structure at 36 storeys above the ground. This innovative and iconic shape of the building is exploited to provide the primary structural support system, as well as achieving the architectural vision of high-rise occupancy with occupant interface maintained within short distances in a continual loop. The building's primary support, in high-seismic intensity Beijing, is achieved by its external skin of leaning columns, horizontal beams and triangulated bracings forming a network of diagrids in an extremely strong closed braced tube structure. This external diagrid structure is also expressed boldly in the building's façade. It reinforces the transparency between structure and architecture, a central philosophy to the building's design. The internal structure is supported by vertical columns and steel cores which diminish in size progressing up the building height, in tune with the shape of the leaning towers. The columns emerge and terminate up the height of the building, again influenced by the angled towers. Transfer trusses are located at various levels to collect these column loads into the cores and external structure.

Keywords: Steel, Diagrid, Composite, Headquarters, Multi-Storey, Seismic.

1. Introduction

The China Central Television new headquarters building will be located in the Central Business District on the east side of the East Third Ring Road, north of Guang Hua Road and south of Chao Yang Road.

When completed, the building will form the new headquarters to China Central Television (CCTV), the principal state-run broadcaster in China. It will provide approximately 450000 m of floor area, (equivalent to three standard high-rises) to sufficiently house the studios, facilities and offices for CCTV's projected operations expansion to over 200 broadcast channels by 2008.

The building was initially unveiled in the winning design in an international competition in 2002 attracting some of the biggest names in architecture. It is one of the synergistic conceptions between Rem Koolhaas' practice Office for Metropolitan Architecture (OMA) and Cecil Balmond of Arup.

Arup is the engineering force behind the building, providing consultancy for structure, building services, geotechnical design, fire, communications and security. The East China Architecture and Design Institute (ECADI) in China will act as the Local Design Institute (LDI) of record.

*Corresponding author
Tel: +852-2268-3163; Fax: +852-2268-3945
E-mail: craig.gibbons@arup.com

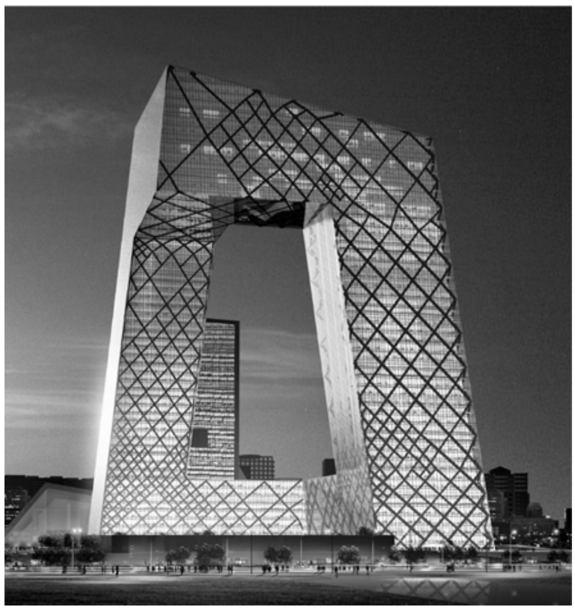

Figure 1. CCTV New Headquarters Building.

2. Structural System

The innovative and iconic shape of the building is capitalised upon to provide its main structural support and stability system. The form warranted a primarily structural steel building, for a "light-weight" solution and enhanced

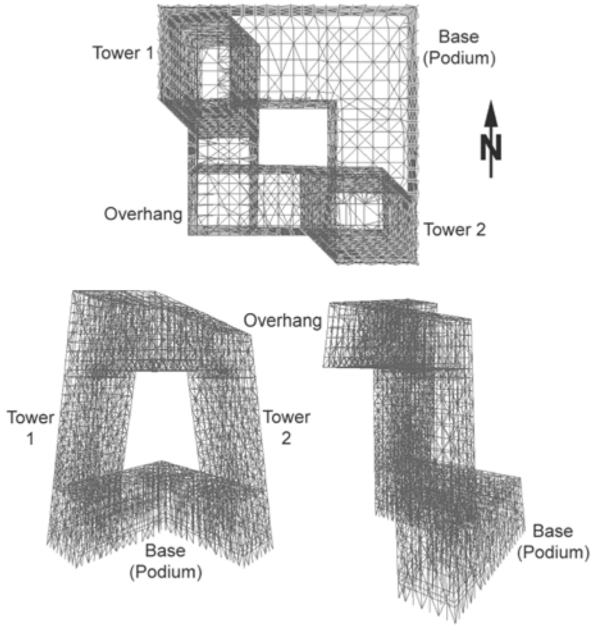

Figure 2. The continuous loop structure of CCTV.

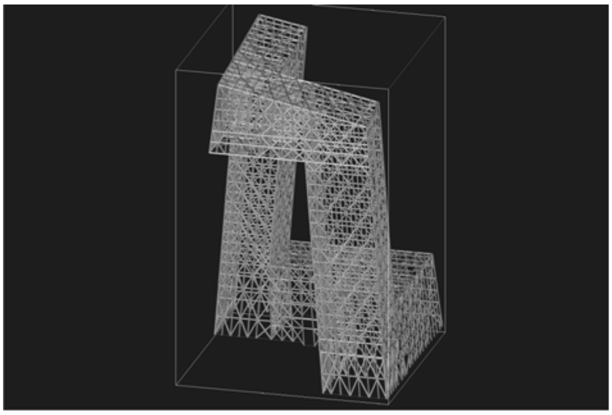

Figure 3. External primary structure (drawn using Xsteel).

seismic performance. As such, all the structural support elements in the building are of structural steel, except some external columns are steel-reinforced concrete columns due to the magnitude of loads they are designed to carry. The floors are composite slabs on steel beams.

2.1. External primary structure

Form the onset, it was decided to adopt an external skin of leaning columns, horizontal edge beams and triangulated bracing on a two-storey pattern to form an enclosed tube structure to support the building. Furthermore, the braced tube structure affords a multitude of alternative load paths. Such a robustness feature is highly desirable, especially in seismically sensitive Beijing. It also provides safety in the event of an extreme design incident, such as blast removal of a major column in the building. The external diagrid structure is also boldly expressed in the building's façade. It visually expresses the pattern of forces in the external tube, reinforcing the transparency between structure and architecture, a strong philosophy in the building's design. The unique diagrid pattern in the external structure was arrived at after extensive iteration and optimization, in close collaboration with the architect.

2.2. Internal structure

The internal structure is supported by vertical steel columns and cores. Sloping cores were initially considered in the design, in order to align with the sloping towers and to allow consistency of the floor plate layout. However they were ruled out for various reasons including constraints on the procurement of the lift systems. In addition, in supporting as much of the structure as possible on vertical structure, the overturning moment on the foundations is reduced. The sloping external tube walls and the vertical internal elements combine to create unique floor configurations for every floor of the building. That is, the floor span between cores or internal columns and the changes on every floor. Moving up the building, the floor spans increase on two adjacent sides of the building and decrease on the other two opposite sides. As a consequence, where floor spans decrease on the inward sloping sides of the building, some internal columns can be removed once the distances become structurally manageable in one span. For the same reason, once the increasing floor spans on the outward leaning sides of the building start to impact on the finished floor height due to increased beam depth, additional columns are introduced.

2.3. Transfer trusses

The looping form of the building, combined with the sloping external faces and the need for large open internal spaces for studios and facilities, lead to the introduction of transfer trusses at strategic locations in the building.

2.3.1. Transfer trusses in the towers

Transfer trusses are introduced to collect the columns required at intermediate heights in the towers to cope with the increasing floor spans. The transfer trusses span between the internal core and the external tube structure. They are typically located in plant floors in the building so as to be hidden from view and minimize impact to the architecture and floor usage.

The large member sizes of the transfer trusses mean a potential for these trusses to act as outriggers as they link up the external tube with the internal steel cores. An outrigger effect would be undesirable because this would then complicate the primary seismic load path. (The seismic stability of the building is achieved through the diagrid framing of the external tube structure). To prevent this condition, the transfer trusses are connected to the internal cores and the external columns at singular pin-joint locations only. Detailed analyses were carried out to verify no outrigger effects result from the transfer truss geometry.

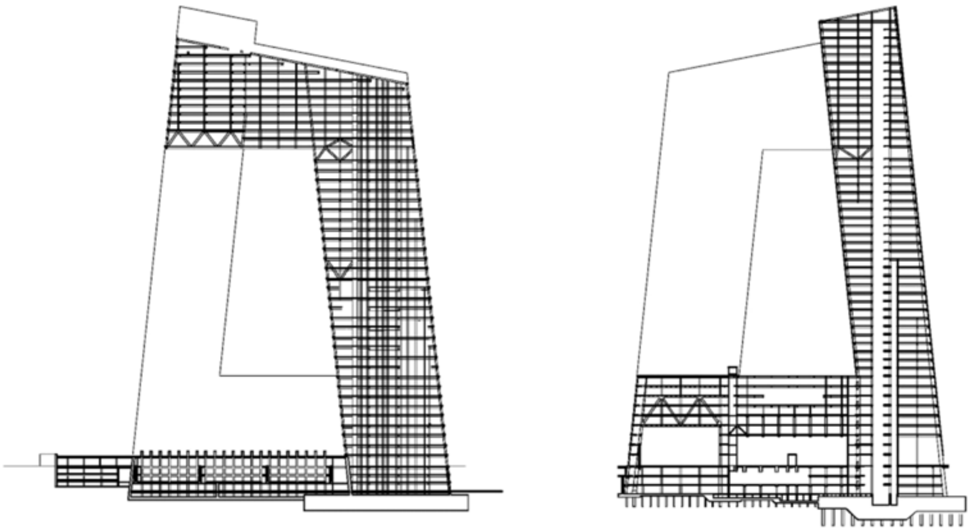

Figure 4. Sections through the building showing vertical internal structure and transfer trusses.

2.3.2. Transfer trusses at the underside of the overhang

At 36 storeys above the ground, the two leaning towers crank horizontally and cantilever 75 m outwards in the air to join together forming the continuous loop defining the building shape. This 75 m cantilever structure encompasses 13 storeys and is known as the "overhang". The overhang floor are supported by columns landing on transfer trusses. These trusses span the bottom two storeys of the overhang in two directions connecting back to the external tube structure. Thus the overall overhang structure is ultimately supported off the external tube structure.

2.3.3. Transfer trusses in the studios

Major transfer trusses are also located in the base (podium) part of the building. These trusses span over the major studios to support the columns and floors above them in the building.

2.4. Foundations

The bearing capacity of the subsoil around the main towers of CCTV is not sufficient to support the entire load from the superstructure whilst remaining within acceptable settlement limits. A piled raft foundation has been adopted under the main towers. The piles are 1200mm in diameter and up to 35 m in length following optimisation. The total settlement of the building is estimated to be less than 100 mm and differential settlement is kept to 1 : 500.

As the foundation loads in the towers are concentrated at the inside face, the piled raft is designed to be up to 7 m thick and extends beyond the footprint of the towers in order to distribute forces more favourably into the ground. The foundation system is arranged such that the centre of the raft is close to the centre of load at the bottom of the tower, and no permanent tension is allowed in the piles. Limited tensions are permitted in some piles only in seismic events.

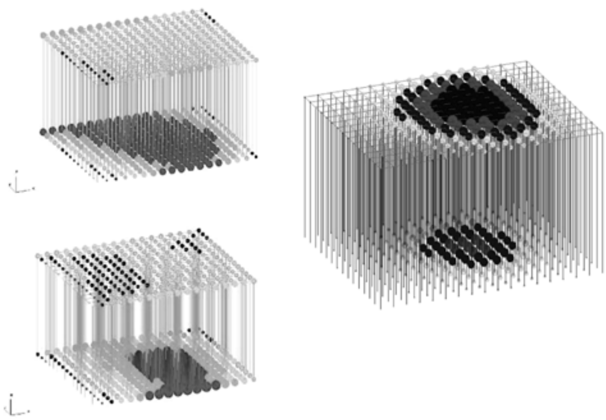

Figure 5. Tower base analyses results.

Away from the tower, for the 9-storey Base and the 3-storey basement under the rest of the site, a traditional raft foundation is used, with tension piles between column locations to resist uplift due to water pressure on the deep basement. Additional deep 1200 mm diameter piles are required under secondary cores and columns supporting large transfer trusses.

The design of the foundation requires that the loads are redistributed across the pilecap, and the soil properties of the site were non-linear. Therefore the analysis of the piled-raft solution became highly iterative.

3. Expert Panel Review And Approvals

The Chinese code for seismic design of buildings, GB50011-2001, prescribes a set of limits to the heights of buildings depending on their structural system and limits to the degree of plane and vertical irregularities in the building. The design of buildings exceeding these code limits must obtain approval from a project-specific seismic design expert panel review, as set out by the Ministry of

Construction's Ordinance 111-Regulations on Seismic Fortification for Buildings Exceeding Code Limits.

Although the height of the CCTV building of 234 m is within the code's height limit of 260 m for steel tubular structural systems (framed-tube, tube-in-tube, truss-tube etc.) in Beijing, the gravity-defying shape of the building means it is non-compliant in irregularity requirements. As a result, the seismic design of the CCTV building is required to pass through a project-specific expert panel review process for approval. For this purpose, the Seismic Administration Office of the Beijing Municipal Government appointed an expert panel consisting 12 eminent Chinese engineers and academics to closely examine the structural design with special focus on the seismic resistance, seismic structural damage control and life safety aspects of the design.

4. Performance Based Seismic Design Approach

As the design of the CCTV building is well outside the scope of the prescriptive Chinese codes of practice, a performance-based design approach was used. Performance targets for the building at different levels of seismic event were set by the Arup design team in consultation with the Expert Panel.

The performance objectives set out that:

When subjected to the design frequent earthquake (level 1) with an average return period of 50 years (63% probability of exceedance in 50 years), the building shall not sustain structural damage.

Under the design intermediate earthquake (level 2) with an average return period of 475 years (10% probability of exceedance in 50 years), the building may undergo repairable structural damage.

When subjected to the design rare earthquake (level 3) with an average return period of 2500 years (2% probability of exceedance in 50 years), the building is permitted to sustain severe structural damage but must not collapse.

5. Non-Linear Superstructure Design And Performance Verification

To demonstrate that the performance objectives are achieved in the building design, linear and non-linear seismic response simulation methods were carried out to verify the building's seismic performance under the three levels of design earthquake.

The process of establishing the inelastic deformation acceptance limits of various structural members (braces, SRC columns, steel beams and steel columns) is illustrated by the non-linear numerical simulation of the post-buckling behaviour of the concentric braces. These braces in the external tube are critical members both in the lateral as well as the gravity systems of the building. They are also the primary sources of ductility and seismic energy dissipation. Non-linear numerical simulation of the post-

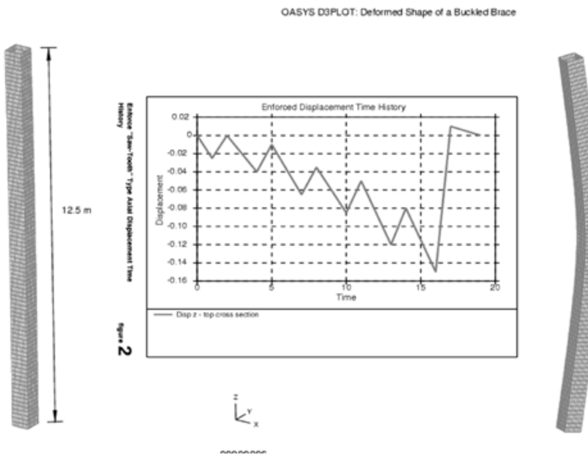

Figure 6. Non-linear modelling of inelastic deformation acceptance limits of steel braces

buckling behaviour of the braces was necessary in order to establish:

(i) The post-buckling axial force-axial deformation degradation relationship to be used as input in the global structure non-linear seismic response simulation; and

(ii) The inelastic deformation (axial shortening) acceptance limit. The post-buckling inelastic axial force-axial deformation degradation relationship curve illustrates strength degradation as the axial shortening increases under the cyclic "saw tooth" type axial displacement time history prescribed at the top end. The brace inelastic deformation acceptance limit was then established from the strength degradation backbone curve based on the required strength to support the gravity load.

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 CCTV building subjected to the Level 2 and the Level 3 design earthquakes. Both the non-linear static pushover analysis method and the non-linear dynamic time history analysis method were employed to perform this task. Finally, the seismic deformation demands were compared against the structure's deformation capacities to verify seismic performance. This verification was carried out on a storey-by-storey and a member-by-member basis. For the CCTV building, all global and local seismic deformation demands are shown to fall within their respective acceptance limits, confidently demonstrating that the building achieves the quantitative performance objectives when subjected to both the design intermediate (Level 2) and the design rare (Level 3) earthquakes.

6. Connection Assessment

As explained the braces in the external tube structure are critical members in the structural system. The connection of these braces to the columns requires careful design and

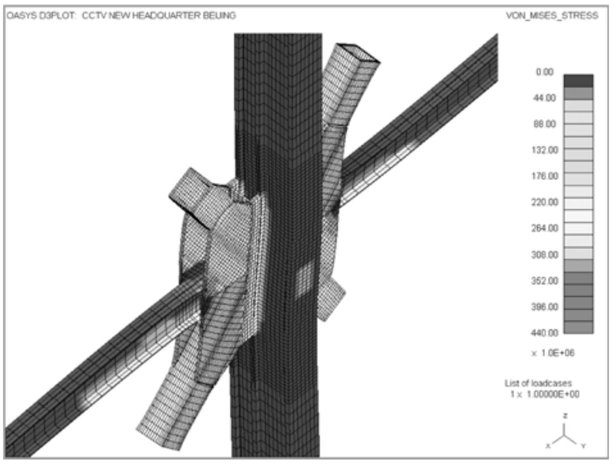

Figure 7. Brace connection detail studies.

detailing consideration to ensure a "strong joint-weak member" capacity.

The connections must resist the maximum probable load delivered to them from the braces with minimum yielding and a relatively low degree of stress concentration. The force from the braces and edge-beams must be transferred into the column sections with minimal disruption to the stresses already present in the column. "Butterfly" plates were conceived to facilitate smooth load transfer.

It is important to prevent 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). "Butterfly" brace connections were modelled and analysed using a 3D finite element code MSC/NASTRAN to evaluate the stress magnitude and the degree of stress concentration in the joints subjected to the full range of forces that can be developed before the braces buckle or yield.

7. Construction sequencing and thermal analyses

The chosen method of construction and sequencing of the works have an important impact on the dead load distribution and final locked-in stresses in the structural elements. Therefore, staged construction sequencing forms an integral part of the design and analyses of the structure.

To allow flexibility in the contractor's construction method and programme, upper and lower bound construction conditions are considered in the design analyses. The lower bound conditions assume minimal construction of the leaning towers before the construction of the overhang commences. The lower bound thus puts the most loads into the overhang structure as it acts as a prop between the two towers. The upper bound conditions assume the two towers are well constructed before the construction of the overhang commences. This assumption results in the largest stresses into the tower since they carry more of the load in bending as a cantilever. Between these two extremes, the contractor can choose his program and erection procedures to suit.

The construction joining of the two towers to form the closed loop overhang link was also assessed and designed to great detail. The successful connection of the link is especially sensitive to wind and solar path thermal effects and rigorous checks and measures are outlined in the project technical specifications to facilitate the proper implementation of this part of the works.

Despite its size, the continuous loop of the completed building structure, framed by the 160 m × 160 m × 234 m volume of space, contains no movement or expansion joints. This is against code requirements but is necessitated given the shape and structural stability system of the building. To justify the omittance of movement joints, analyses were performed to check the design against the extreme temperature ranges in Beijing (the 30 year maximum temperature range is –27.4°C to +40.6°C). The analyses and design involved assessing the effects of locked-in thermal stress in the building elements during construction, taking consideration of the season and temperature at which the elements are erected, and seasonal temperature fluctuations post-construction. The thermal design also particularly focused on the sizing and construction linkage of the overhang link structure.

8. Conclusion

The entire CCTV development covers a site area of 187,000 m^2 and will provide a total of 550,000 m^2 gross floor area. The project as a whole includes:

- The China Central Television headquarters building (CCTV building) - presented in this paper
- The Television Cultural Centre (TVCC)
- A service & security building
- A landscaped media park with external features

The official ground breaking ceremony for the CCTV building was held on 21st September 2004, and construction work of the foundations is progressing.

This paper has attempted to introduce the technical complexities and innovative structural solutions in achieving such an astounding design. The rigorous nature of Arup's design work is of vital importance to the success of this building, with a core team of international engineers who travelled with the project to 4 cities and in the process delivered the Scheme Design in 4 months and Extended Preliminary Design in 6 months, and finally gaining approval from the Expert Panel Review.

It is not possible to cover the extensive details and all the interesting technical aspects of the building and its design within a single paper. Each of the technical topics touched upon here are themselves worth an entire dissertation.

This paper has only commenced to tell the design story of the CCTV building.