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CANTILEVER ARCHITECTURE AS A STRUCTURAL PROBLEM: STUDY OF MARINA BAY SANDS AND CCTV HQ

[1]Ar. Shayan Zulfiqar, [2]Ar. Muhammad Waleed Mujtaba, [3]Engr. Nouman Zulfiqar, [4]Engr. Hamza Rashid, *[5]Ar. Dr. Omer Shujat Bhatti
[1]Practicing Architect, IEB Nexus Hub, Dubai
[2]Assistant Professor, Dept. of Architecture, University of South Asia, Lahore
[3]Practicing Engineer, Independent Researcher
[4]Practicing Engineer, Infrastructure Development Authority, Punjab (IDAP)
*[5]Associate Professor & COD, Dept. of Architecture, School of Architecture & Planning, UMT, Lahore
[1]arch.shayan064@gmail.com, [2]mwaleedmujtaba@yahoo.com, [3]noumanzulfiqar13@gmail.com,
*[5]omer.shujat@umt.edu.pk

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Corresponding Author: *
Ar. Dr. Omer Shujat Bhatti

Abstract

Cantilevers are a type of structure that is held up at one end and is not held up at the end. This means that Cantilevers can stick out a way to the side without needing any more support. Such structures give us open spaces with no columns allowing architects freedom for innovated architectural designs but structurally, they have to deal with forces that try to bend them. The buildings they built, including the CERN accelerator in Switzerland, are a testament to their ability to tackle complex engineering challenges, such as span and load dynamics and structural stability, in modern mega-projects. This paper explores design, structural behavior and engineering approaches for extreme cantilevered forms through a comparative study of two iconic buildings: the Marina Bay Sands SkyPark, Singapore and the CCTV Headquarters, Beijing. The 340-meter long 64-meter cantilevered SkyPark at Marina Bay Sands is supported by three 200-meter-tall towers. On the other hand, the CCTV Headquarters restates the typology of the high-rise with its looped structure – two leaning towers are connected together by a large 75m cantilevered overhang, achieved by a diagrid structure and deep transfer structures. The study explores wind loading, gravity forces, seismic performance and the use of tuned mass dampers to address the inherent challenges of each large-scale cantilever. This paper offers an analytical discussion of the use of advanced structural systems, materials and construction methods to realize these complex cantilevered forms.

INTRODUCTION:

The cantilever is functional and a symbol of engineering innovation. Although aesthetically pleasing, cantilevers create a structural conundrum. They have large deflection, large bending moments, and are sensitive to the forces of nature and man (Ching, 2014). Large scale cantilevers pose complex challenges to engineers with regards to the distribution of bending moments along the beam, and the design of the beam itself to be both stiff and of sufficient strength, serviceable and stable (Shah et al., 2023). This challenge calls for advanced engineering, materials, and a close collaboration with design (Smith & Coull, 1991). The extreme use of cantilevered forms has been made increasingly feasible due to the development of high-performance materials, advanced physical simulations of structural behavior such as the finite-element method, and a shift in focus to the performance of design (Mukherjee, 2018). However, even with these projects being on the cutting edge, they are the most sensitive of all projects in regard to the geometry of the design and the structural forms as well as the methods of construction (Shah et al., 2023a). This research aims to examine the cantilever from the perspective of the basic structural functions of engineering such as the response to the application of loads, the response in deformations, and the response to dynamic loads. This research will evaluate cantilevers within the field of architecture and offer a structural lexicon to illustrate the risks and benefits of using cantilevers. They are able to offer an eloquent solution to structural challenges.

GENERAL REASONS FOR USING CANTILEVERED STRUCTURES

The use of cantilevered forms is seen frequently in many large-scale architectural projects, mainly due to functional and experiential considerations, summarized in table:

Reason	Description
1. Public Space Creation	Cantilevered forms provide elevated, open areas for communal use, allowing integration of gardens, recreational zones, and gathering spaces.
2. Observation Opportunities	Their extended projection makes them ideal for observation decks, offering unobstructed panoramic views of the surrounding environment.
3. Iconic Architectural Identity	Dramatic overhangs contribute to a city's visual identity, often becoming iconic landmarks that enhance tourism and global recognition.
4. Architectural Innovation	Distinctive cantilever proposals strengthen a project's competitiveness in design competitions and highlight structural and aesthetic innovation (Winston, 2014).

Table 1 General Reasons for Using Cantilevered Structures, Drawn by author

The two selected examples serve to show the problems caused by large cantilevered structures. The examples use a comparative method to show different solutions caused by structural system restrictions and the engineering concepts that allow the control of deflection, structural stability and uniformly distributed loads. (Bhatti et al., 2025) This analysis emphasizes the use of advanced materials, computational modelling and construction methods to achieve important overhangs by drawing attention to the role of trusses, diagrids, transfer structures and dynamic performance measures (Omer et al. 2024). This comparison is a foundation to understand the technical principles that will inform the case studies presented in the subsequent sections.

MARINA BAY SANDS HOTEL:

Steel-concrete is used in the construction of the Marina Bay Sands Hotel. It is made up of three 193.9-meter-tall buildings with 57 stories above ground and three basement stories that include 2,561 rooms. Moshe Safdie and Associates created the expansive "Sky Park," which unites the top of the complex and features a swimming pool, gardens, cafés, bars, jogging trails, and an observatory. Golasz-Szolomicka and Szolomick, 2020).

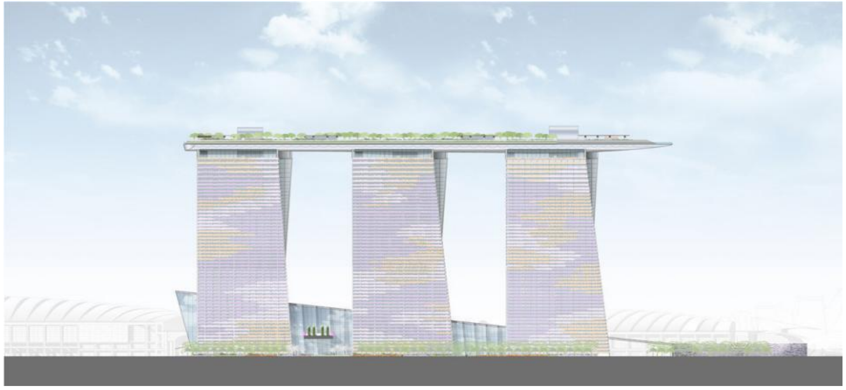


Figure 1 Towers of Marina Bay Sands Reference: https://www.archdaily.com/70186/marina-bay-sands-safdiearchitects/50124aaf28ba0d0a48000201-marina-bay-sands-safdie-architects-elevation?next_project=no

TOWERS:

Each tower is formed by two legs, with the east sides shaped through varying curvature and the west sides remaining vertical. Together, they create a continuous open space at ground level, producing a large central atrium whose height varies from approximately 20 floors in the first tower to 6 floors in the third. The widths of the towers also differ, ranging from 40 meters in the first, to 20 meters in the second, and narrowing to 10 meters in the third (Szolomick & Golasz-Szolomicka, 2020).

SKY PARK:

At 200 meters above ground, the three towers are joined by a 9,941 m² (107,000 ft²) Sky Park that accommodates public amenities and a large tropical landscape. This 1.2-hectare (3-acre) upper-level park is longer than the Eiffel Tower's height and large enough to hold several A380 aircraft. Spanning all three towers, it projects 65 meters (213 feet) as one of the world's largest public cantilevers and extends 340 meters (1,115 feet) from end to end. Its maximum width is 40 meters (131 feet), and it includes a 1,396 m² (15,026 ft²) swimming pool with a 145-meter (475-foot) infinity edge. The Park accommodates up to 3,900 people and features lush landscaping with 250 trees and 650 plants (Marina Bay Sands / Safdie Architects, 2010; Winston, 2014).

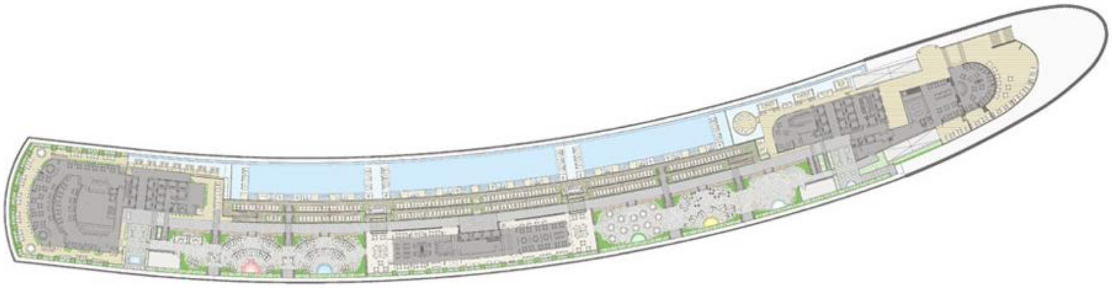


Figure 2 Plan of Sky-Park Reference: https://www.archdaily.com/70186/marina-bay-sands-safdiearchitects/50124aaf28ba0d0a48000201-marina-bay-sands-safdie-architects-elevation?next_project=no

ANALYSIS OF STRUCTURAL PROBLEM AND HOW IT WAS SOLVED:

Cantilevered:

Sky Park, which is made up of 14 prefabricated steel pieces linking the three towers, completes the top of the hotel. These sections are made out of steel bridge girders with a 6 cm flange, 3.5 cm sidewalls, and dimensions of 10 m deep by 3.60 m wide. They serve as the foundation for the segments between the hotel towers and the cantilever segment's structural system. Steel V-shaped struts that emerge from the hotel roof just above the concrete shear walls support this construction. The Sky Park hotel terrace, measuring 340 meters in length, 40 meters in width, and 64.92 meters in cantilever, is the world's longest and highest residential terrace (198,11 meters). Golasz-Szolomicka and Szolomick, 2020).The Sky Park structure is not constructed monolithically with the three main towers. It is composed of five structural segments and four movements joints between them.

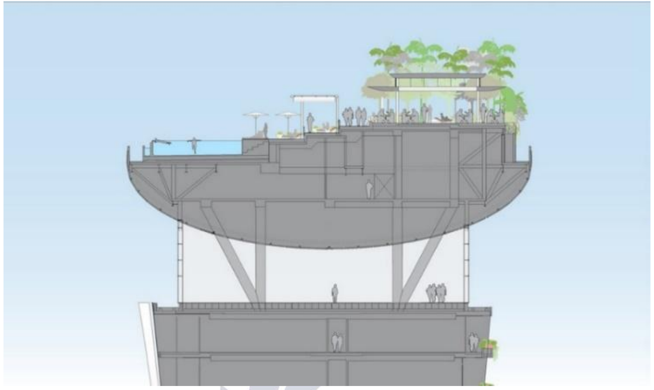


Figure 3Sections of Sky Park Reference: https://www.archdaily.com/70186/marina-bay-sands-safdie-architects

CONSTRUCTION OF CANTILEVER

The cantilevered portion of the Sky Park was constructed using post-tensioned, segmental steel box girders measuring 33 feet in depth and 12 feet in width, with 1 3/8-inch sidewalls and 2 3/8-inch flanges (Qureshi & Yee, 2010). The spans between the towers consist of steel bridge trusses, supported by raking V-shaped struts extending upward from the tower roofs directly above the shear walls (Qureshi & Yee, 2010).

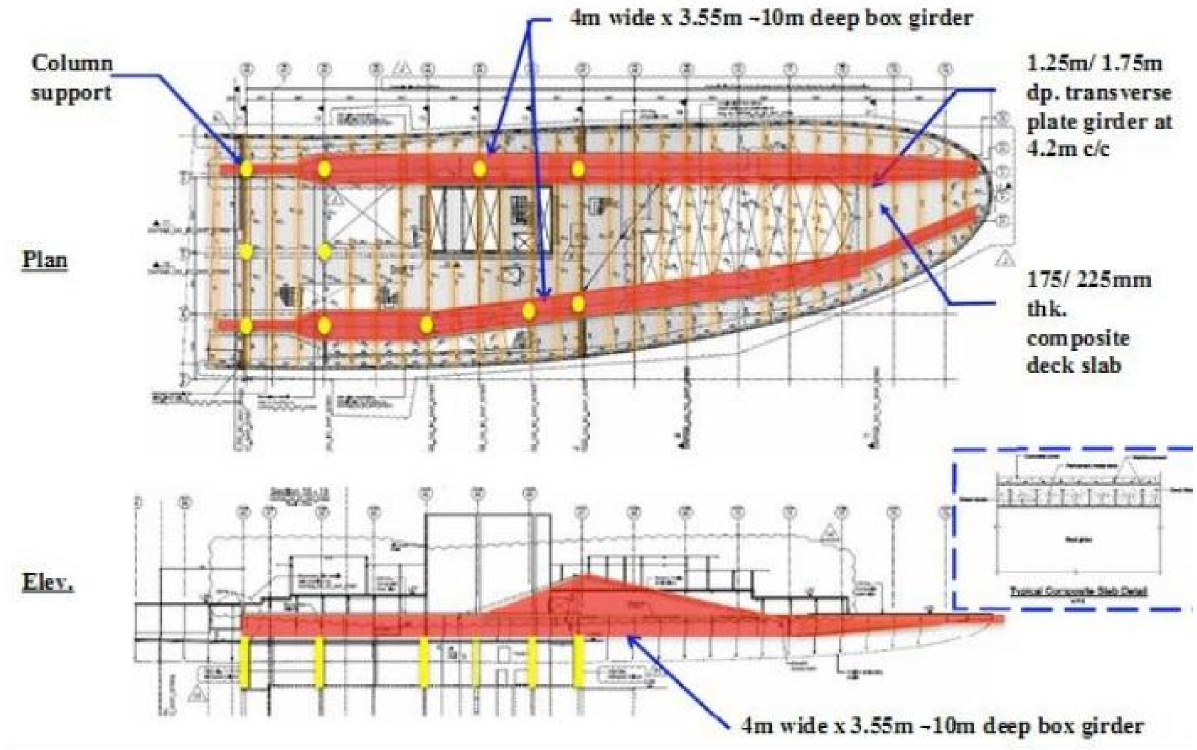


Figure 4 Plan of Cantilevered Area

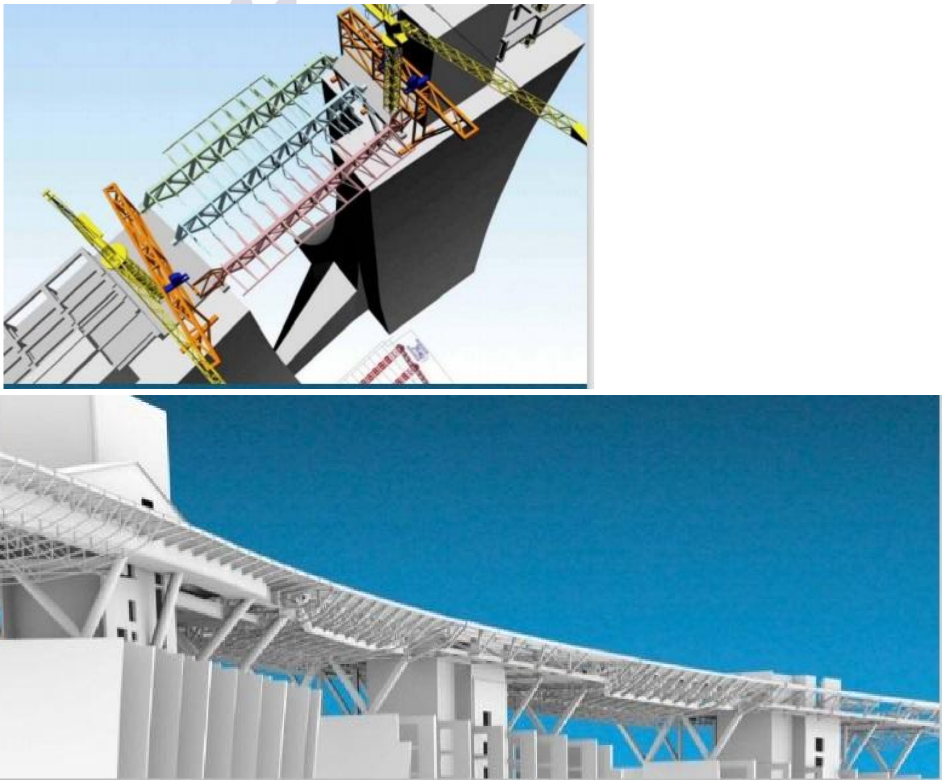


Figure 5: Pictorial view of Structure used in Cantilevered Construction

Because the towers undergo significantly different relative displacements, seismic joints were incorporated between them to prevent structural pounding. These joints accommodate movement caused by thermal expansion, creep, shrinkage, and wind-induced lateral actions (Qureshi & Yee, 2010).

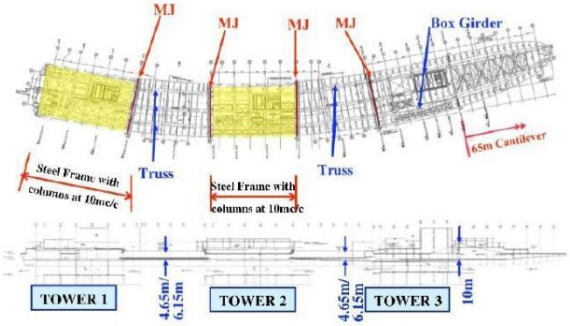
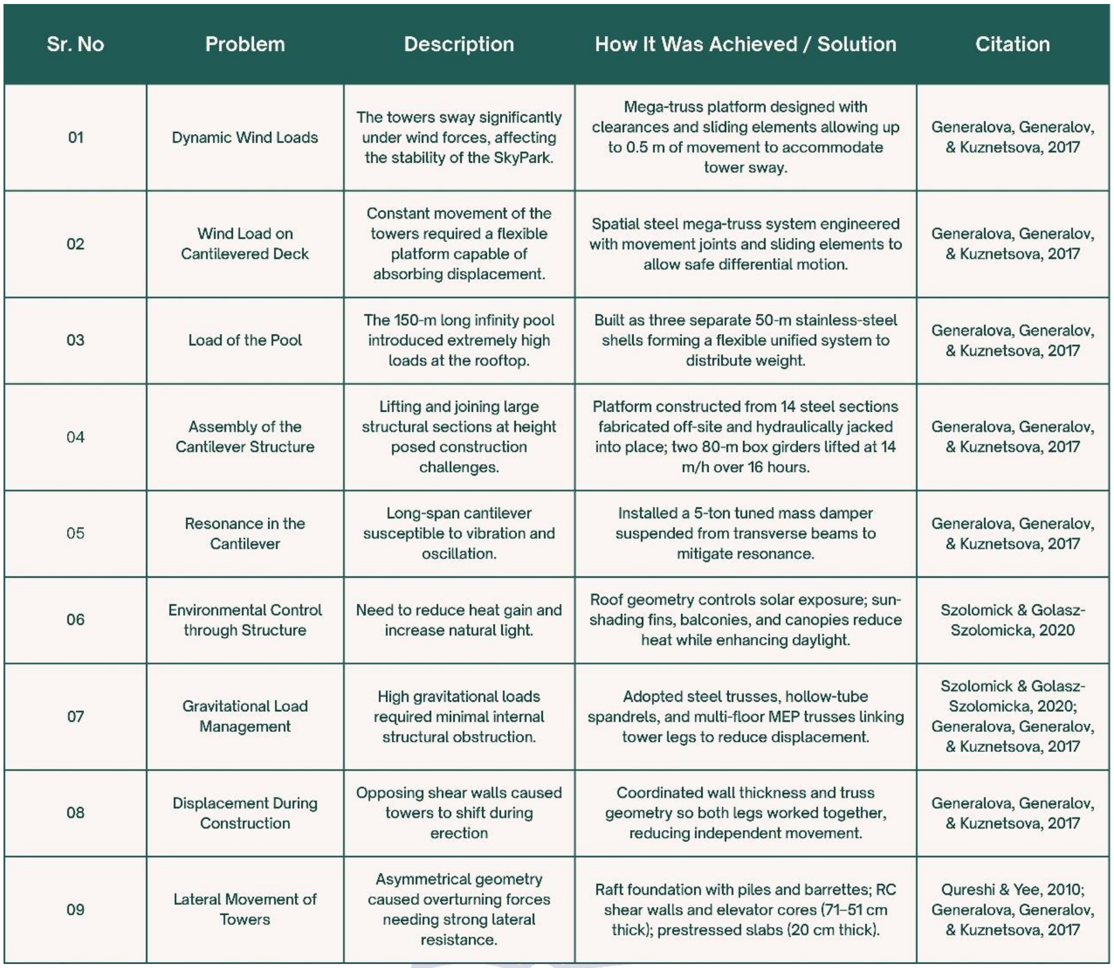


Figure 6 Plan of Joints Reference: moshe safdie: marina bay sands (designboom.com)

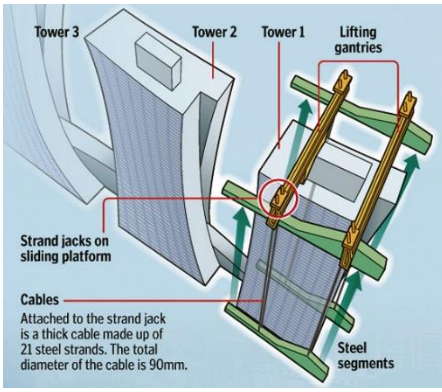
STRUCTURAL PROBLEMS AND HOW THEY WERE ACHIEVED:

The table below outlines the complex engineering challenges encountered in designing and constructing the Marina Bay Sands SkyPark and its long-span cantilever. The challenges were great and included wind induced movement of the towers, high gravitational loads to the towers, environmental performance and the structural requirements of mounting a huge pool on three separate towers. An innovative mega-truss system that accepts up to 0.5 m of displacement of the tower, flexible stainless-steel pool shells and precision assembly of fourteen prefabricated steel sections lifted into place were all considered to address these. Tuned mass dampers, reinforced concrete shear cores, multi-floor truss systems and controlled roof geometry provided for additional stability. All of these solutions provided structural safety, minimized solar gain and allowed the iconic 66-m cantilever to function safely under dynamic environmental and load conditions.

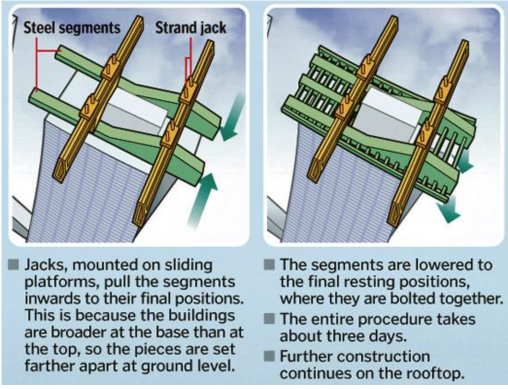


Sr. No	Problem	Description	How It Was Achieved / Solution	Citation
01	Dynamic Wind Loads	The towers sway significantly under wind forces, affecting the stability of the SkyPark.	Mega-truss platform designed with clearances and sliding elements allowing up to 0.5 m of movement to accommodate tower sway.	Generalova, Generalov, & Kuznetsova, 2017
02	Wind Load on Cantilevered Deck	Constant movement of the towers required a flexible platform capable of absorbing displacement.	Spatial steel mega-truss system engineered with movement joints and sliding elements to allow safe differential motion.	Generalova, Generalov, & Kuznetsova, 2017
03	Load of the Pool	The 150-m long infinity pool introduced extremely high loads at the rooftop.	Built as three separate 50-m stainless-steel shells forming a flexible unified system to distribute weight.	Generalova, Generalov, & Kuznetsova, 2017
04	Assembly of the Cantilever Structure	Lifting and joining large structural sections at height posed construction challenges.	Platform constructed from 14 steel sections fabricated off-site and hydraulically jacked into place; two 80-m box girders lifted at 14 m/h over 16 hours.	Generalova, Generalov, & Kuznetsova, 2017
05	Resonance in the Cantilever	Long-span cantilever susceptible to vibration and oscillation.	Installed a 5-ton tuned mass damper suspended from transverse beams to mitigate resonance.	Generalova, Generalov, & Kuznetsova, 2017
06	Environmental Control through Structure	Need to reduce heat gain and increase natural light.	Roof geometry controls solar exposure; sun-shading fins, balconies, and canopies reduce heat while enhancing daylight.	Szolomick & Golasz-Szolomicka, 2020
07	Gravitational Load Management	High gravitational loads required minimal internal structural obstruction.	Adopted steel trusses, hollow-tube spandrels, and multi-floor MEP trusses linking tower legs to reduce displacement.	Szolomick & Golasz-Szolomicka, 2020; Generalova, Generalov, & Kuznetsova, 2017
08	Displacement During Construction	Opposing shear walls caused towers to shift during erection	Coordinated wall thickness and truss geometry so both legs worked together, reducing independent movement.	Generalova, Generalov, & Kuznetsova, 2017
09	Lateral Movement of Towers	Asymmetrical geometry caused overturning forces needing strong lateral resistance.	Raft foundation with piles and barrettes; RC shear walls and elevator cores (71–51 cm thick); prestressed slabs (20 cm thick).	Qureshi & Yee, 2010; Generalova, Generalov, & Kuznetsova, 2017

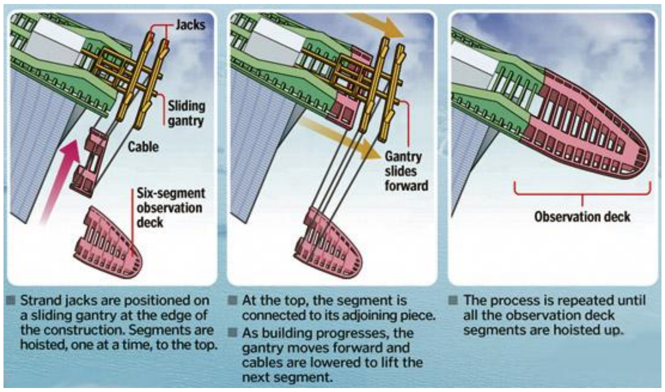
Table 2 Structural Problems and How They Were Achieved Drawn by Author



Attached to the strand jack is a thick cable made up of 21 steel strands. The total diameter of the cable is 90mm.



- Jacks, mounted on sliding platforms, pull the segments inwards to their final positions. This is because the buildings are broader at the base than at the top, so the pieces are set farther apart at ground level.
- The segments are lowered to the final resting positions, where they are bolted together.
- The entire procedure takes about three days.
- Further construction continues on the rooftop.



- Strand jacks are positioned on a sliding gantry at the edge of the construction. Segments are hoisted, one at a time, to the top.
- At the top, the segment is connected to its adjoining piece.
- As building progresses, the gantry moves forward and cables are lowered to lift the next segment.
- The process is repeated until all the observation deck segments are hoisted up.

Figure 7Pictorial Depiction how Cantilevered was built Reference: https://www.designboom.com/architecture/moshe-safdiemarina-bay-sands/

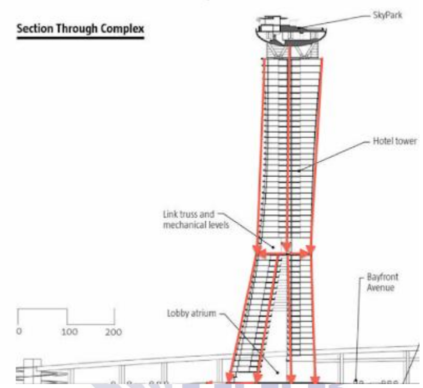


Figure 8Load Diagram Reference: https://www.designboom.com/architecture/moshe-safdie-marina-bay-sands/

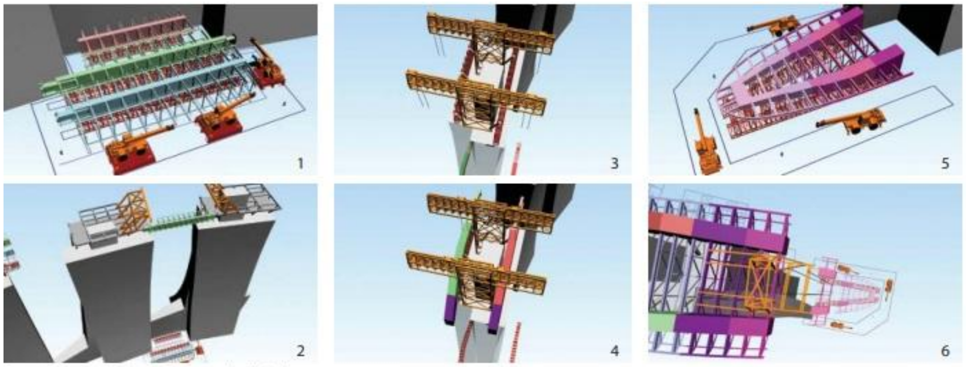


Figure 11. Diagramatic phasing of erecting the SkyPark

Figure 9Phasing of Erecting Sky Park

CCTV HEADQUARTERS, BEIJING:

The CCTV Headquarters in Beijing is a high-rise commercial building designed by OMA (Office for Metropolitan Architecture) under Rem Koolhaas, completed in 2012. Unlike a conventional vertical tower, the project consists of two leaning towers connected at the top and bottom to form a continuous loop. This unique geometry provides both an iconic architectural form and a large, cantilevered structural system. The building has 51 floors above ground and 4 basement levels, office spaces, broadcasting studios, and technical areas. The total height of the towers is approximately 234 meters, making it one of the most structurally daring skyscrapers in the world (Chen & Liu, 2013).

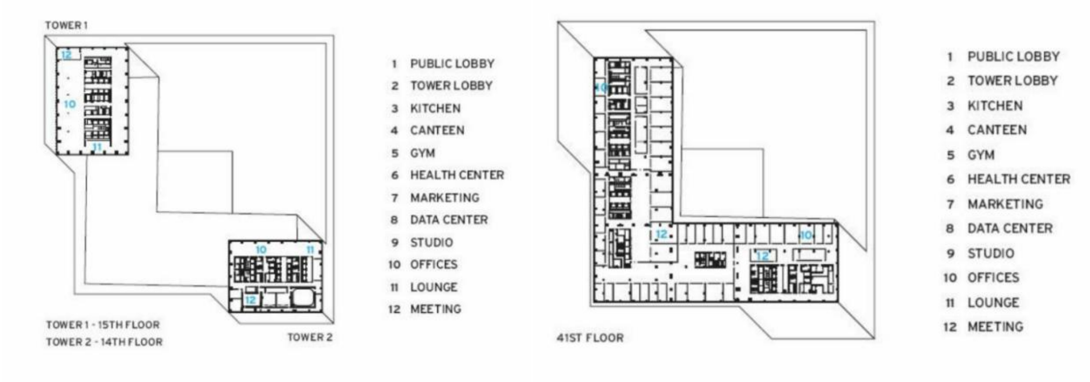


Figure 10 Plan of CCTV HQ, Towers connecting at 41st floor https://www.archdaily.com/236175/cctv-headquarters-oma

TOWERS AND LOOP STRUCTURE:

The two towers lean towards each other at an angle of approximately 6°–12° and connect via a 75-meter-long cantilevered section at the top, forming a continuous "loop." The lower portion of the towers also connects to creating a podium, allowing the building to maintain structural continuity while accommodating its irregular geometry. The building's floor plan varies according to its height to optimize usable office space and accommodate broadcast facilities (Chen & Liu, 2013).

Figure 11CCTV HQ https://www.dezeen.com/2022/05/12/cctv-headquarters-oma-deconstructivism/

ANALYSIS OF STRUCTURAL PROBLEM AND HOW IT WAS SOLVED

CONSTRUCTION OF CANTILEVER

The cantilevered overhang is designed to accommodate a variety of essential functional spaces. It houses offices for different departments, providing a professional setting for staff and administrative work. Conference rooms provide spaces for conducting group meetings and discussions and for engaging in collaborative activities. Moreover, lounges are situated in such a manner to provide spaces for relaxation and informal interactions. The cantilevered section uses a layout of spaces that is efficient and comfortable (Archdaily, 2012). The structure was built in segments, with each segment extending toward the center of the structure from one of the towers, and temporary shoring and supports provided to each segment until it could support itself (Zhang et al., 2015). The cantilever was well connected to the reinforced concrete cores of the towers that efficiently transferred the load and stabilized the structure (Li, 2014 & Chen, 2014). However, the very high bending moments and shear forces were dealt with by adding post-tensioned steel trusses to distribute the stresses along the cantilever and into the cores (Smith & Coull, 1991). Engineers monitored and made precise adjustments throughout construction to ensure that it was aligned, managing deflection and stress at every step. The two towers were then cantilevered over each other, creating a continuous loop (which enabled the removal of the temporary supports as soon as the structure was able to stand on its own with the cores, trusses and diagrid).

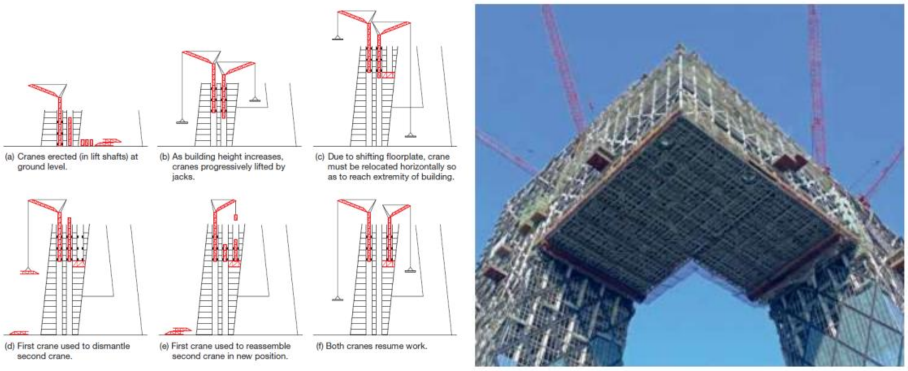


Figure 12 Left: Crane slewing process (The Arup Journal, 2008). Right: The completed Overhang structure, which shows the three 3m diameter circles punched in the deck (The Arub Journal, 2008)

STRUCTURAL PROBLEMS AND HOW THEY WERE ACHIEVED:

The table below outlines the key structural and construction issues encountered during the design of the CCTV Headquarters, a structure characterized by the leaning towers and large cantilevered top section. Problems faced were the unbalanced gravity loads caused by towers leaning at 6° to 12°, the high stresses at the 75m cantilever connection, the dynamic sway of the towers due to the wind and the accuracy of alignment required for construction. An innovative diagrid structural system was devised to channel the load to the reinforced concrete cores, post-tensioned steel trusses were integrated with the cores in order to resist bending and shear, and temporary shoring and segmented assembly were used to ensure the safety of the construction process of the cantilever, as described by Li and Chen (2014) and Zhang et al. (2015). Further stability was provided by cores and trusses that absorbed seismic energy and accommodated movements within the towers, while minimizing the obstructions that would result in internal walls and the structural geometry allowed open floor plans (Smith & Coull, 1991; Li & Chen, 2014). Taken together, they proved to provide structural safety, accurate construction and stability in dynamic environmental and load conditions, thus ensuring that the iconic cantilevered structure of the building was able to function reliably (Zhang et al., 2015).

Sr. No	Problem	Description	How It Was Achieved / Solution	Citation
01	Leaning Tower Geometry	Towers lean at 6°–12°, creating unbalanced gravity loads and high bending moments at junctions.	Diagrid structural system channels loads efficiently to vertical reinforced concrete cores, stabilizing towers against overturning.	Li & Chen, 2014
02	Cantilevered Top Section	75-m cantilever connecting the towers induces extreme stress at junctions.	Post-tensioned steel trusses integrated with cores; temporary shoring supports segments during staged construction; built in precise segments.	Zhang et al., 2015
03	Dynamic Wind Loads	Towers sway significantly under wind forces, affecting structural stability.	Diagrid and trusses accommodate tower movement; cores provide lateral stiffness; aerodynamic shape reduces wind pressure.	Li & Chen, 2014
04	Seismic Forces	Earthquake forces can induce torsion and high shear in leaning towers.	Reinforced concrete cores, diagrid system, and post-tensioned trusses redistribute seismic loads; connections designed for ductility and energy absorption.	Smith & Coull, 1991
05	Construction Sequencing	Complex geometry and cantilever required precise assembly to avoid collapse.	Cantilever built in segments with temporary shoring, precision monitoring of deflection, and staged connection forming a continuous loop.	Zhang et al., 2015
06	Load Distribution of Cantilever	The long cantilever creates concentrated stress at the junctions with the towers	Post-tensioned steel trusses transfer loads into tower cores; structural joints reinforced to handle high bending and shear forces.	Li & Chen, 2014; Zhang et al., 2015
07	Lateral Movement During Construction	Leaning towers shift slightly during erection due to unbalanced loads.	Coordinated truss geometry and temporary shoring allowed controlled movement and alignment of tower segments.	Zhang et al., 2015
08	Gravitational Load Management	Towers carry massive gravity loads with minimal internal obstruction.	Diagrid and trusses reduce displacement; cores provide rigid support; structural geometry allows open floor plans while maintaining stability.	Li & Chen, 2014

Table 3 Structural Problems and How They Were Achieved Drawn by Author

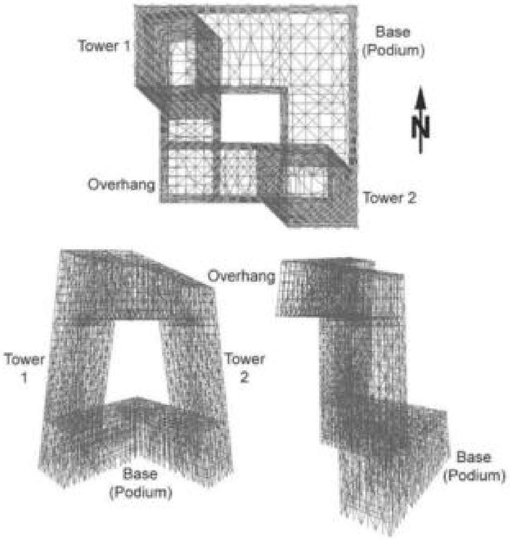


Figure 13 The continuous loop structure of CCTV. https://www.structureinsider.com/

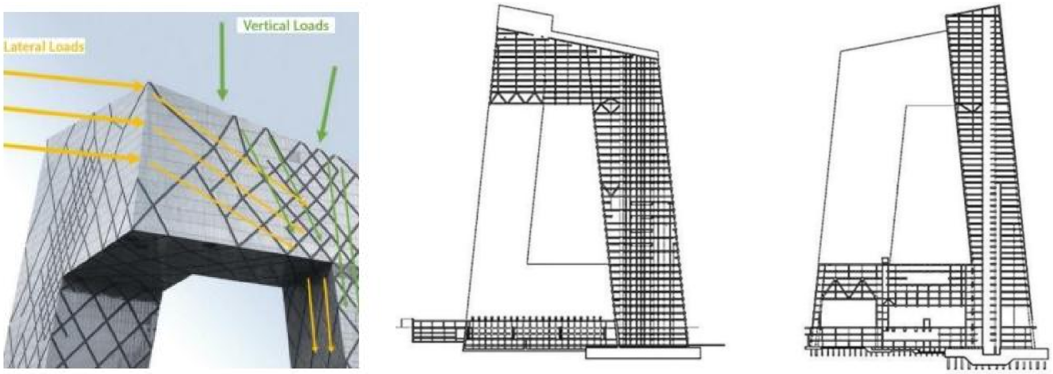
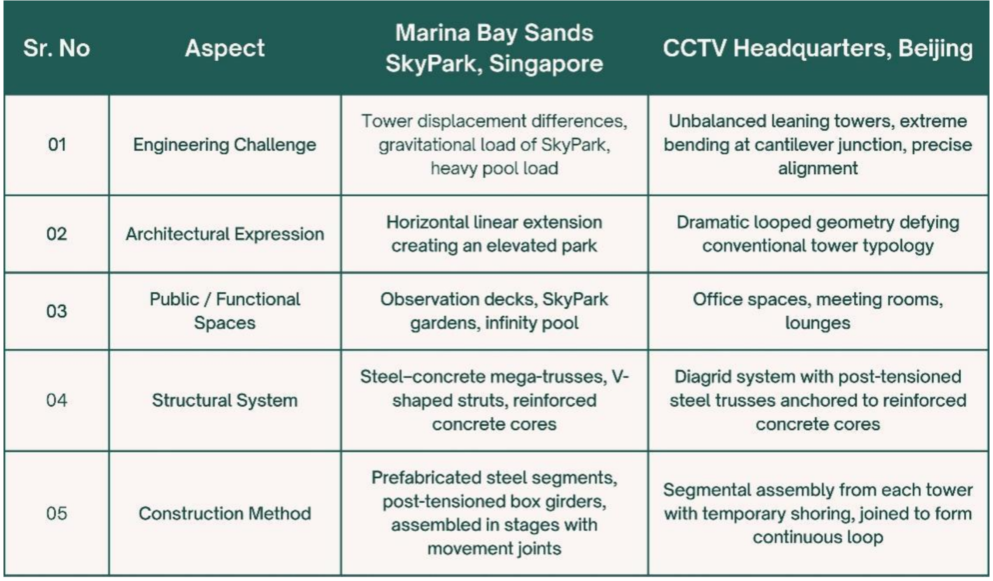


Figure 14 Left: Load Transfer via diagrid system Right: Sections through the building showing vertical internal structure and transfer trusses

CONCLUSION

By comparing the CCTV Headquarters with the Marina Bay Sands SkyPark, it is evident that the use of innovative structural solutions and bold architectural vision are both equally effective in the realization of extreme cantilevered forms. They both show the power of pushing the limits of architecture and structural engineering with cantilevered structures. Marina Bay Sands is horizontal, with a luxurious SkyPark on top of three distinct towers, while CCTV Headquarters is vertical, with a continuous loop created by leaning towers and a gigantic cantilevered junction. Significant challenges for these two projects include long cantilever spans, large gravitational loads, wind and seismic issues, differential movements of the towers, and more. Solutions to these challenges are described in the table below and include structures such as mega trusses, V-shaped struts, diagrids and post-tensioned steel trusses. Achieving complex stability and geometry was accomplished through staged and segmented construction and aided alignment. Beyond structural performance, these solutions also provided for the functional and experiential elements of the SkyPark's garden, observation deck, infinity pool as well as the offices, meeting rooms, and lounges of the CCTV Building. Unique and iconic forms, made possible by load management and the control of dynamics and construction sequencing, demonstrate that cantilevering structures are a creative and artistic means for expressing a city's architectural fabric while proving to be highly functional and engaging.



Sr. No	Aspect	Marina Bay Sands SkyPark, Singapore	CCTV Headquarters, Beijing
01	Engineering Challenge	Tower displacement differences, gravitational load of SkyPark, heavy pool load	Unbalanced leaning towers, extreme bending at cantilever junction, precise alignment
02	Architectural Expression	Horizontal linear extension creating an elevated park	Dramatic looped geometry defying conventional tower typology
03	Public / Functional Spaces	Observation decks, SkyPark gardens, infinity pool	Office spaces, meeting rooms, lounges
04	Structural System	Steel–concrete mega-trusses, V-shaped struts, reinforced concrete cores	Diagrid system with post-tensioned steel trusses anchored to reinforced concrete cores
05	Construction Method	Prefabricated steel segments, post-tensioned box girders, assembled in stages with movement joints	Segmental assembly from each tower with temporary shoring, joined to form continuous loop

Table 4: *Comparative Structural Problems and Solutions – Marina Bay Sands vs CCTV Headquarters, Drawn by author*

LESSON LEARNED

Controlling deflection and alignment with segmental and prefabricated assembly, demanding advanced structural systems that distribute bending and shear forces (i.e., trusses, diagrids), and requiring adept mechanism to mitigate dynamic loads via tuned mass dampers or flexible connections. Additionally, cantilevered spaces can serve functional and experiential objectives, as they can lead to engaging with users and contribute to an architectural identity for a city. Taken together, all of the lessons reinforce the conclusion that cantilevered structures are more about strategic engineering than they are about the innovative benefits of form.

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