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The Structural Engineering Design and Construction of the Highest Occupiable Skybridge in the World: The Address Jumeirah Resort, Dubai, UAE

Zaher Hadow[1†] and Yamen Dannan[2]

[1]*Senior Technical Director, WSP Middle East, UAE*
[2]*Principal Structural Engineer, WSP Middle East, UAE*

Abstract The Address Jumeirah Resort is a mixed-use 77-story tower reaching a height of 301 meters with a slenderness ratio of 13.5:1. The development is situated in the Jumeirah Beach District and accommodates 217 key five-star hotel suites, 478 residential apartments, 444 serviced-branded apartments, retail shops, ballrooms and entertainment facilities around the premises. The building has over 242,000 m2 of usable area. The project is an award-winning development that broke multiple Guinness records. The focus of the paper is to present the challenges faced in the structural design and construction of the super tall tower and the highest occupiable skybridge in the world.

Keywords Super Tall Tower, Skybridge, Reinforced Concrete Shear Wall System, Composite Link Beams, Composite Columns Strand Jacking Construction, High Strength Concrete, Wind Tunnel Test, Belt Wall System

†Corresponding author:
Zaher Hadow
E-mail:
Zaher.Hadow@wsp.com

1. Architectural Design

The tower's shape on plan is a 130 m × 30 m ellipse with a void in the center that serves to increase daylight penetration and enhance views. The building is connected at the lobby and at the roof levels through multi story skybridges that host a restaurant and also an infinity pool. The orientation of the tower is aligned exactly with due north, and the narrow sides face east and west, resulting in reduced solar heat gain.

The building has three podium levels, the west tower has 14 hotel and 54 serviced-branded apartment levels, and the east tower has 68 floors of residential apartments. Both towers have three mechanical floors at levels 18, 42 and 75.

Two skybridges span 30 meters across the building at the upper and lower floors, which is intended to form the shape of the Jumeirah gate. The upper bridge extends 15 levels between level 63 all the way to the roof, and the lower bridge extends from level 8 to level 13.

2. Tower Floor System

Typical levels have a uniform span of 8.5 meters between blade walls and are designed as 220 mm reinforced concrete flat slabs. The construction cycle was 4 days per typical level, making it one of the fastest floor cycles in the region.

3. Tower Superstructure – Blade Wall System

The twin tower vertical structure is formed in plan by



Figure 1. Tower photo at completion – viewed from northwest.

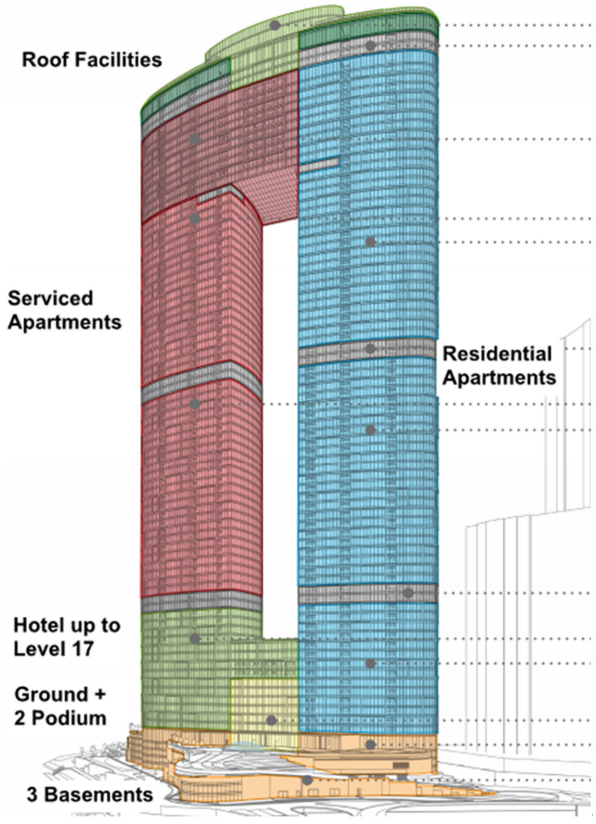


Figure 2. Tower different occupancies – southeast elevation.



Figure 3. Plan view of the project development plan.

a series of reinforced concrete shear walls placed strategically along internal partitions, corridors, and around lift shafts in uniform 8.5 m spans. The shear walls thickness starts from 1000 mm at the basement and reduces

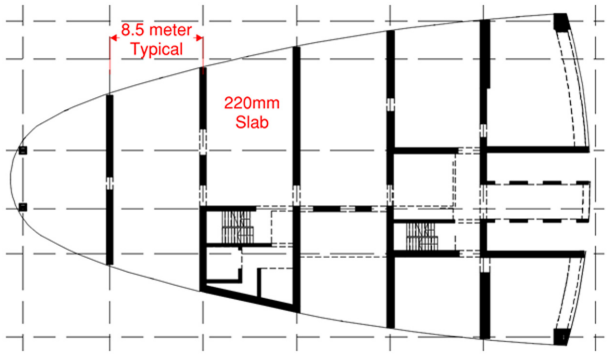


Figure 4. Typical tower floor slab.

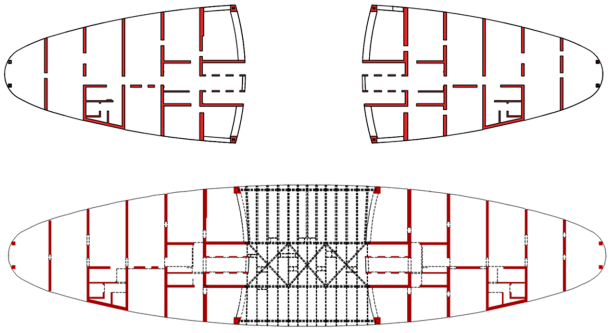


Figure 5. Structural floor plan unconnected levels and at skybridge connected levels.

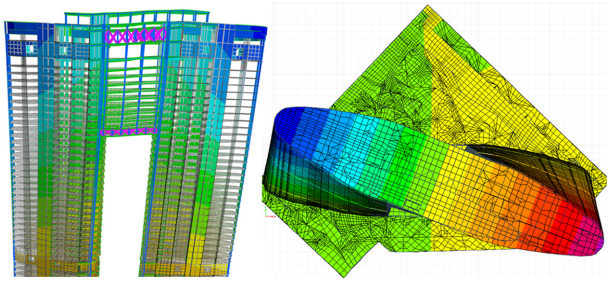


Figure 6. Lateral and torsional modes of vibration indicate considerable stiffness of the skybridges on the tower's behavior.

gradually to 550 mm toward the top. In addition, there are four composite reinforced concrete columns with encased steel sections located at the corners of each building to support the slabs and sky bridges.

4. Lateral Stability System

The building stiffness and stability in the short direction is achieved by the reinforced concrete shear wall system. Lateral stability in the long direction from the shear walls is supplemented by the two skybridges spanning across the towers. Due to the considerable bridge depth and diaphragm stiffness, both buildings are coupled together and thus behave as one under lateral loads.

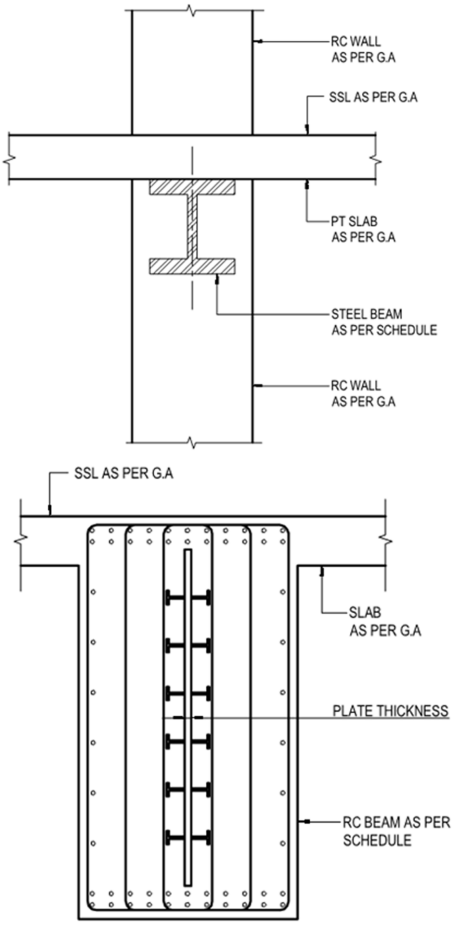


Figure 7. Sample of different types of coupling link beams utilized.

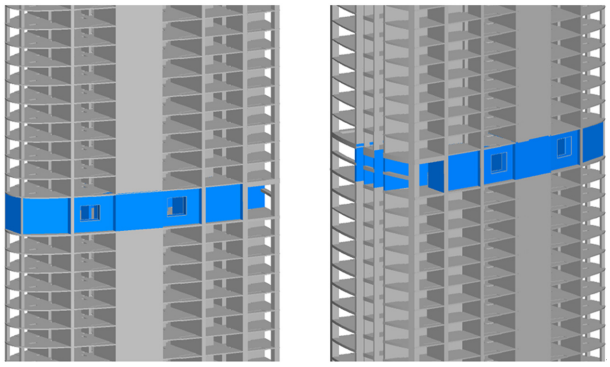


Figure 8. Belt wall system at mechanical floors.

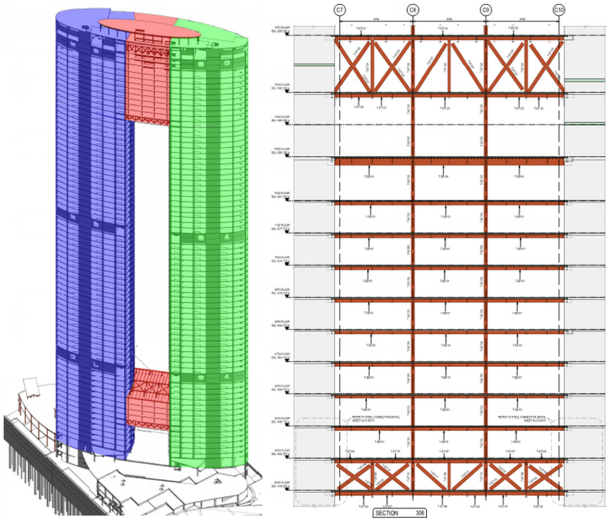


Figure 9. Left image illustrating skybridges in red, the right image shows an elevation through the upper bridge structural system.

Due to a limited structural zone at typical floors, different types of coupling link beams were used to connect shear walls at the openings to improve the overall story stiffness of the building.

The coupling members varied in material between reinforced concrete beams, steel link beams and a mix of both using embedded plates at double height levels.

The lateral stability is further enhanced by utilizing a belt wall system at three mechanical levels 18, 42 and 75. This helped in balancing the lateral force-induced deformations and stresses between the adjacent wall lines, as well as enhancing the torsional stiffness of the towers without affecting clear views at residential levels.

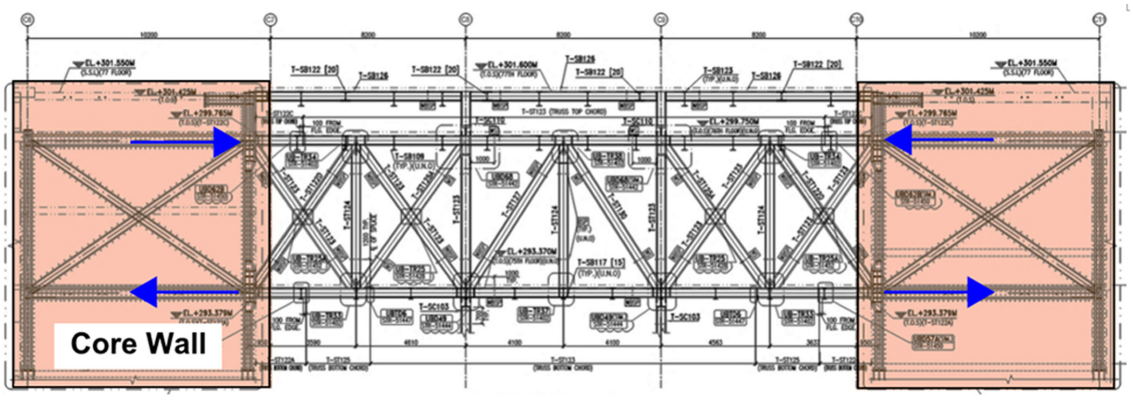


Figure 10. Section view showing steel embedded members through the tower walls at truss levels.

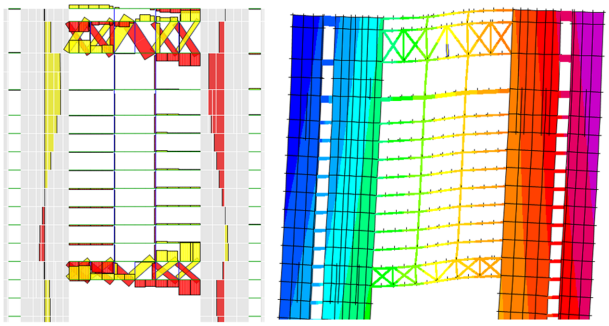


Figure 11. Axial forces and enlarged deformation to demonstrate the coupling effect under wind load from the west bound.

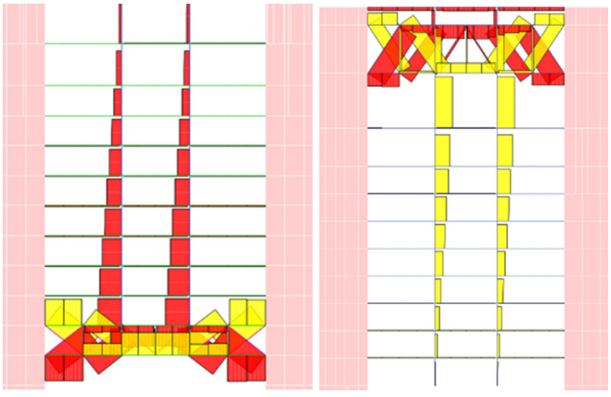


Figure 12. Axial forces diagram in the case of accidental failure of the upper or lower truss used in progressive collapse prevention.

5. Bridge's Structural System

Both upper and lower skybridges have similar structural systems comprising of composite floor deck and secondary beams, which are supported on primary steel trusses placed along four main grids spanning across the central void. The lateral stability of the skybridge structure is achieved by horizontal floor braces to limit the horizontal movement due to wind and seismic loads that are transferred back to the tower's diaphragm.

The trusses are connected to the main RC shear walls by full penetration weld connections to steel embedded members placed inside structural walls and composite columns. The intention was to avoid concentrated stresses on the face of vertical elements, instead, the forces transferred from the steel elements to the concrete over the length of the embedded steel members.

The upper skybridge has two truss levels at 63 and 75. Together, they connect the RC shear walls, forming a push-pull couple. This coupling effect results in increased lateral stiffness along the long direction of the tower to resist lateral forces. The axial force diagram plotted in the diagram below demonstrates the coupling behavior example for a westward wind.

To enhance robustness, each set of trusses was designed to support the gravity load of the upper bridge entirely in case of a local failure, allowing for redundancy in design and ensuring an alternative load path to prevent progressive collapse.

6. Structural Materials

The majority of the tower is a reinforced concrete structure, the concrete cube strengths for the tower's columns, walls and link beams range from 75/90 MPa to 55/70 MPa and utilize high strength cement, Ground Granulated Blast-furnace Slag (GGBS), fly ash and Micro Silica (MS). The 75/90 MPa concrete was specified as high-modulus concrete to achieve increased stiffness to the system, with a minimum Young's Elastic Modulus of 43,000 MPa. Both the strength and stiffness specifications of concrete were limited by the local authority at the time of design.

Bridge members, composite columns and steel link beams are specified as structural steel ranging from 345 MPa to

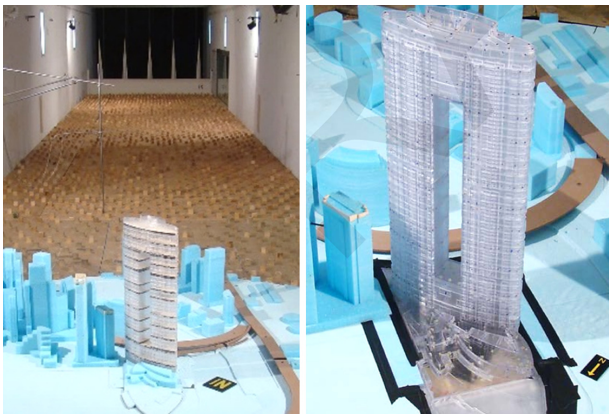


Figure 13. Pictures from CPP Wind tunnel, HFFB model on the left, HFPI model on the right, showing pressure taps as blue dots.

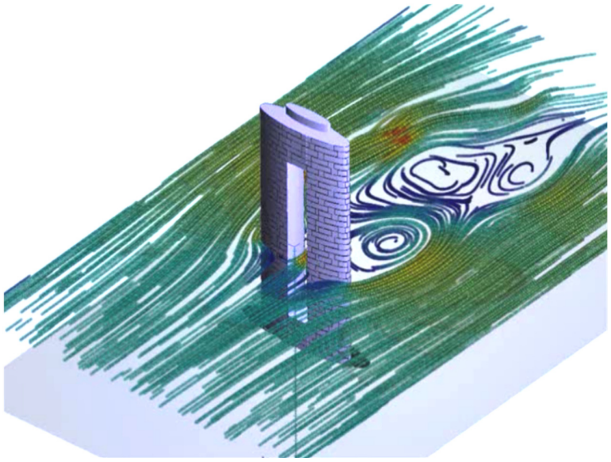


Figure 14. In-house CFD showing wind flow and behavior.

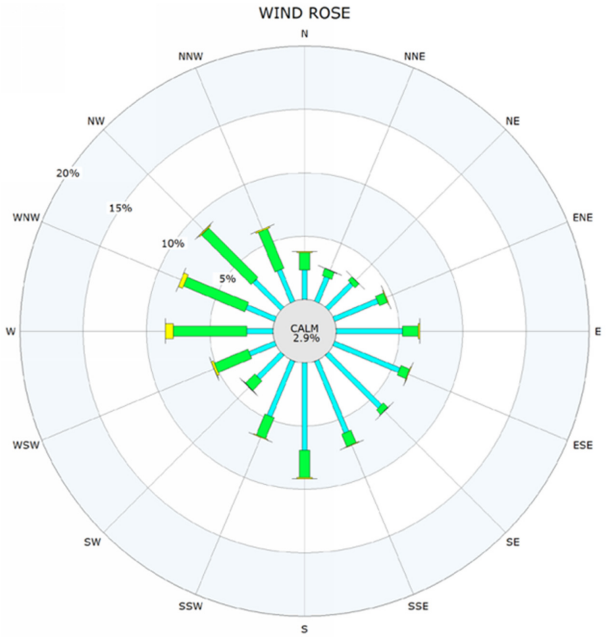


Figure 15. Wind Rose obtained from the Dubai & Sharjah Airports Anemometer at 10 m, 1983-2008.

450 MPa yield strength, and reinforcement bars are specified as 460 MPa yield strength.

7. Wind Engineering

The wind tunnel test was performed by CPP wind engineering consultants, two different methods were used: High Frequency Force Balance (HFFB) for the general tower loading and High Frequency Pressure Integration (HFPI) to measure fluctuating pressures and local effects such as the tunneling behavior between the towers.

A total of 132 different wind cases of existing and future surroundings were simulated in the wind tunnel at a 10-degree azimuth to cover all directions. Human comfort was also verified by assessing the wind-induced peak accelerations and torsional velocities and ensuring they are within acceptable magnitudes.

An in-house Computational Fluid Dynamics (CFD) analysis was performed by WSP during early design stages to gain a better understanding of the wind flow and behavior from different directions. This method was also used to perform high-level wind studies, such as the impact of façade extrusions and tunneling effects.

The building outer ellipse shape was described by wind engineers from CPP as an optimum aerodynamic shape to minimize the structural wind loads and adverse dynamic effects such as vortex shedding.

The governing wind in the United Arab Emirates is mainly northwest, which in the case of the Address Jumeirah Resort was from the beach side at north elevation, which was the dominant wind direction for the lateral resisting system. The wind speed considered for ULS in the design during 2016 was 45 m/s 50-year 3-second gust wind speed at 10 meters.

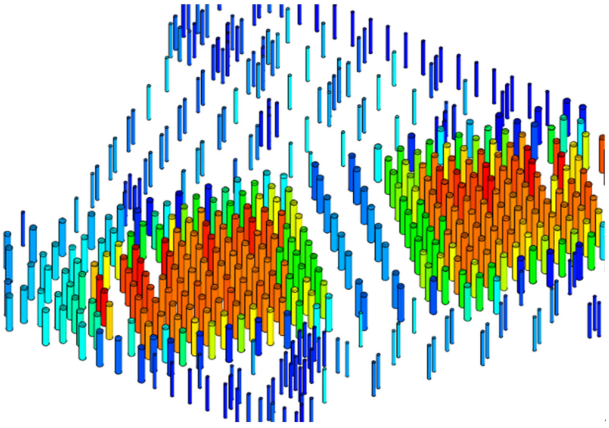


Figure 16. Pile reaction illustration showing highly loaded piles under the tower footprint.

8. Foundation Design

The building is founded on a 3.0 m thick reinforced concrete piled raft under the tower that reduces to 0.7 m below the podium structures. The raft system is supported by 828 bored cast-in-place piles, which range from 0.75 m in diameter up to 1.5 m and extend up to 45 m deep into the soil. The concrete mix was selected to provide high resistance to sulfate and chloride, and the raft concrete mix is 55/70 MPa, incorporating 50% Ground Granulated Blast-furnace Slag (GGBS) + 5% Micro Silica (MS) to slow the heat of hydration, thereby reducing thermal stresses.

WSP optimized the piled foundation design by specifying and undertaking additional in situ testing, including pressuremeter testing and down hole seismic profiling, to better understand the stiffness of the ground. WSP also specified a preliminary test pile (PTP) programme comprising six bi-directional load tests with single and multi-level load cell arrangements loaded to between 2.5 to 3 times the working load (250-300% WL). Each PTP was instrumented with up to eleven levels of vibrating wire strain gauges positioned at various levels to enable the assessment of load distribution along the pile shaft. The introduction of multiple load cells located within the PTP allowed shaft friction to be mobilized to a higher percentage along different segments of the pile shaft rock socket.

After analyzing the test results, WSP was able to prove a significant increase in unit skin friction compared to those derived using the original ground investigation data and empirical relationships. The overall outcome was a significant decrease in pile lengths. The savings in construction materials associated with an overall pile length reduction of approximately 13,600 linear m corresponding to approximately 700 tonnes of steel reinforcement and

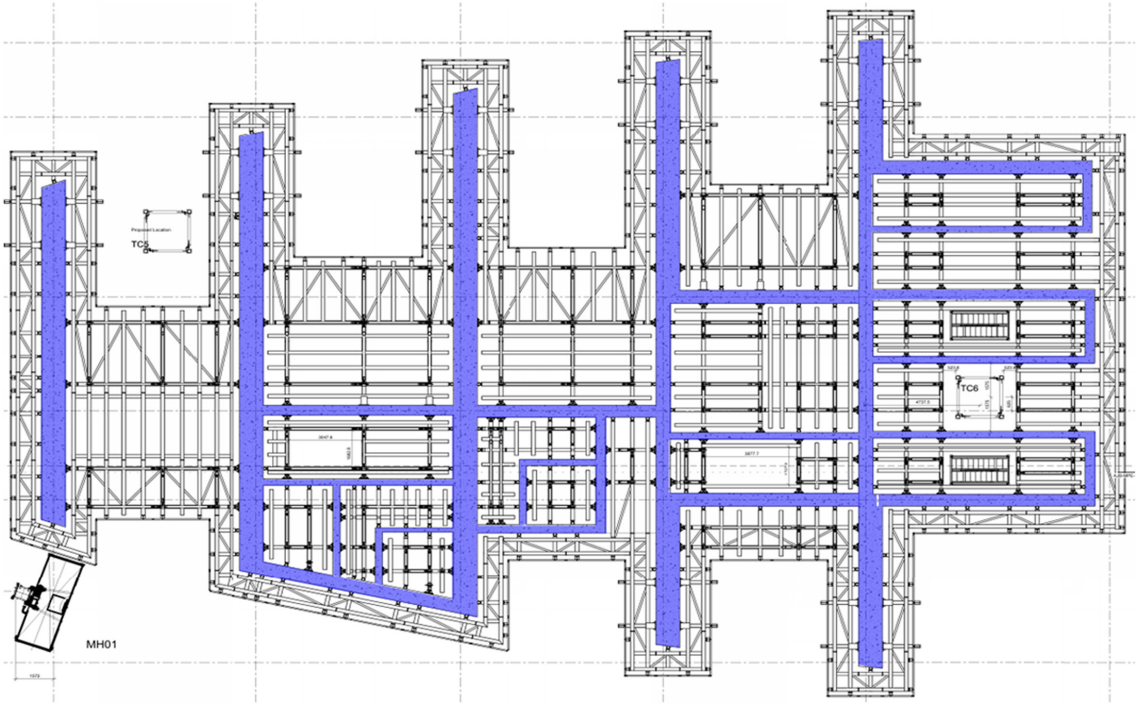


Figure 17. Jump form structures utilized in the construction of tower walls.

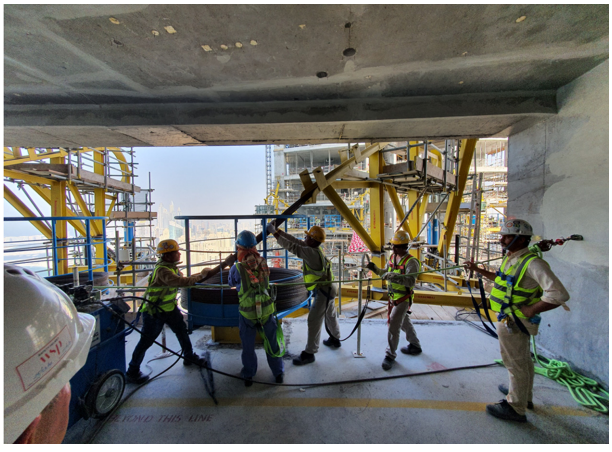


Figure 18. Strand jacking system lifting the bridge from level 65.

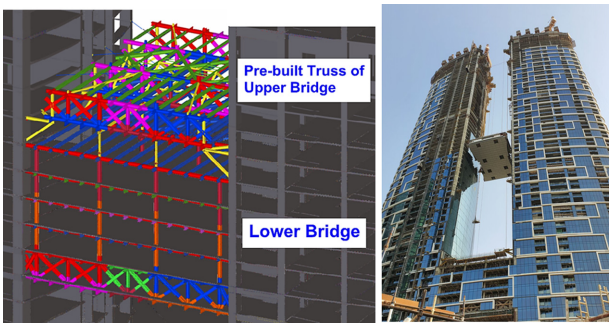


Figure 19. The temporary construction of the upper truss on the lower bridge and the lifting progress on site during construction.

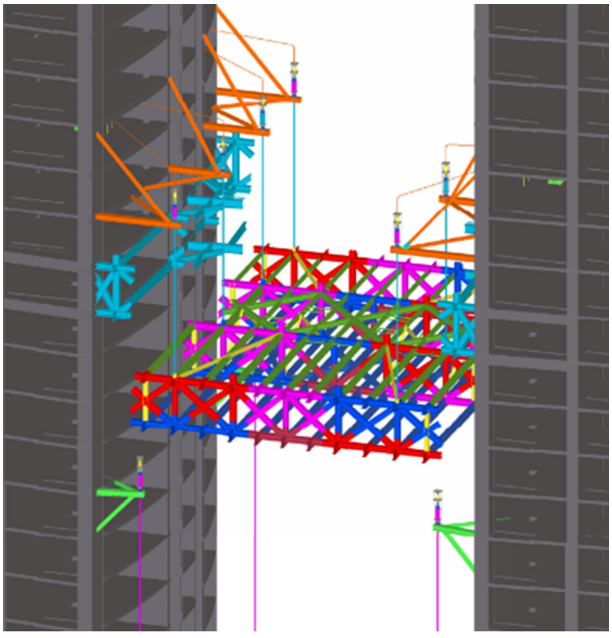


Figure 20. Upper bridge construction sequence lifting stage using the strand jacking mechanism.

17,000 m^3 of foundation concrete established a new precedent in sustainable foundation design in the Emirate of Dubai.

9. Tower and Bridge Construction Method

A self-climbing steel jump form was utilized to construct

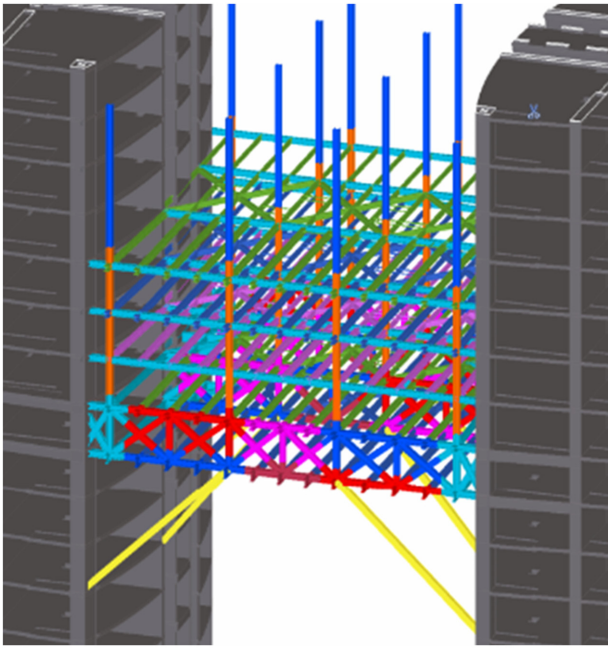


Figure 21. Temporary knee supports shown in yellow.

the tower reinforced concrete walls, Additionally, structural steel members were strategically embedded in walls to enable practical connections to the skybridge steel elements.

The lower bridge was lifted into place using traditional cranes; hence, it was relatively straightforward to install the lower trusses and working platforms to support the construction of floors above it. However, the upper bridge was strand jacked into place as one single preassembled 650T module.

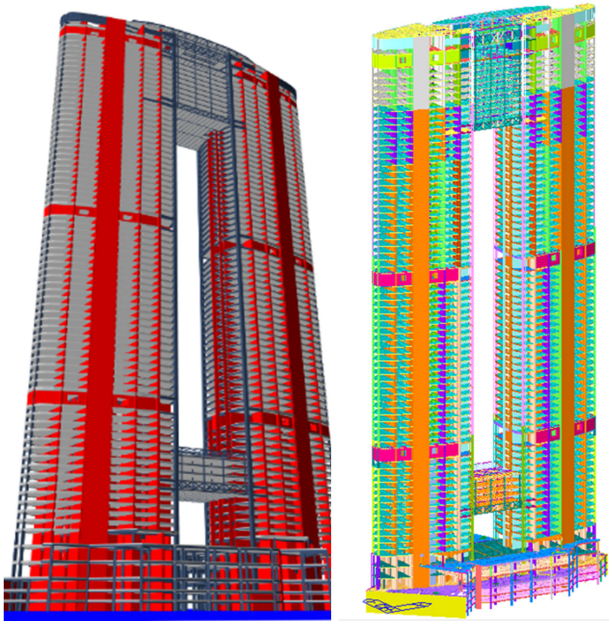


Figure 22. ETABS and Midas Gen models used to assess long-term creep and shrinkage effects.



Figure 23. Highest Outdoor Infinity Pool in the World.

After lifting the upper bridge to place, it was temporarily supported by knee braces to complete the remaining levels of construction. The composite concrete decks were cast before releasing the temporary supports. This was sequenced to ensure that the self-weight load was distributed between the upper and lower trusses as per the design intent.

The temporary knee braces were kept in place until the upper truss was completed to ensure the intended distribution of forces between the upper and lower truss. The disassembly of temporary members was performed using multi-axis wire ropes pulling machines gradually to ensure that axial stresses were gradually released to reach the permanent design connection forces and to ensure they would not swing and collide with the tower after release.

10. Long-term Effects

The effects of creep and shrinkage on the concrete structure were a major consideration when sizing the wall and column elements. For instance, the corner columns were sized to provide equal gravity stress to the interior walls to minimize the differential deformation caused by creep. Additionally, the belt walls and outriggers also provided an opportunity to equalize the long-term axial shortening effects between the wall ends and corner columns.

Nonlinear construction sequence analysis was performed to account for creep and shrinkage based on site material tests to evaluate the long-term axial shortening effect. The study indicated that no additional compensation was required during construction. Moreover, monitoring site survey results at different ages of construction and after completion showed minimal differential deformations over time between vertical elements.

11. Conclusion

The structural system and architectural form of the Address Jumeirah Resort are the result of extensive collaboration among all members of the design team.

The project has won the Award of Excellence, Best Tall Building 300-399 m by CTBUH. It is also recognized by Guinness World Records as the "Highest Outdoor Infinity Pool in a Building in The World" and the "Highest Occupiable Skybridge Floor in The World".

12. Project Data

1) Owner: Al Ain Holding
2) Project Management: Mirage Leisure and Development
3) Architect: Killa Design
4) Structural Engineer: WSP Middle East
5) MEP Engineer: Ramboll
6) Contractor: Multiplex & Eversendai

13. Acknowledgment

The authors would like to thank all of the professionals involved in the design, management and construction of this unique project. This article would not be complete without acknowledging the contribution and dedication of the following individuals:

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