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Ministry of Taxation Tower in Baku, Azerbaijan: Turning Away from Prescriptive Limitations

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Abstract

Beginning a few decades ago, Baku, the capital city of Azerbaijan, has experienced a dramatic construction boom that is revitalizing its skyline. The expansive growth looks to uphold the historic past of Baku as a focal point within the Caspian Sea Region while also evoking aspirations for a city of the future. With superstructure complete and interiors progressing, the Ministry of Taxation (MOT) tower is the latest addition to the city, with its stacked cubes twisting above a multi-level podium at the base. Each cube is separated by column-free green roof terraces, creating unique parametric reveals of the developing surroundings. Aside from MOT's stunning shape, its geolocation resulted in unusually high wind loads coupled with high seismic hazards for a tower of its height. In addition, limitations on possible structural systems required stepping away from a typical prescriptive code-based approach into one that utilized Performance-Based Design (PBD) methods. This paper presents the numerous structural challenges and innovations that allowed the design of a new icon to be realized.

Keywords: Azerbaijan, Twisting Skyscraper, Column-Free, Circular Core, Performance-Based Design

1. Introduction

The etymology of Baku can be traced back to ancient Persia, and means "wind-pounding city" - a name aptly chosen as wind tunnel tests reveal wind pressure at street level about 3-4 times higher than most major cities. MOT tower positions itself within this historic city, standing next to icons that pay tribute to Baku's legacy, but also looks to the future with ambitious architectural intentions. Aligned with Heydar Aliyev Avenue, MOT tower neighbors



Figure 1. Baku Architectural Landmarks.

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architectural landmarks such as Flame Towers, Zaha Hadid's Heydar Aliyev Center, Socar Tower by Heerim Architects and Baku Olympic Stadium to name a few. Recently topped out, MOT tower stands next to existing giants as not only a beacon of aesthetic progress, but highlights what is possible with ambitious structural innovations.

2. ATypical Structural Demands

Cantilevering from the ground up to a modest height of 551ft (168 m), MOT tower does not wield the typical tell-tale signs of a complicated structure. However, several atypical factors central to its evocative design created significant engineering challenges. To start, the separate stacked cubes and column-free terraces between them required all eight perimeter columns to rest on 33ft (10 m) cantilevers extending from the central core, with additional 30ft (9 m) cantilevers from the columns to the extreme corners of each floor.

Aside from building form, its geolocation within the highly-seismic Caspian Sea region pushed the building into Seismic Design Category D, with Site Class D soil, thus creating unusually high seismic demands on the structural system. PBD was utilized to verify performance under seismic demands, while special seismic detailing



Figure 2. Topped-out MOT Tower.

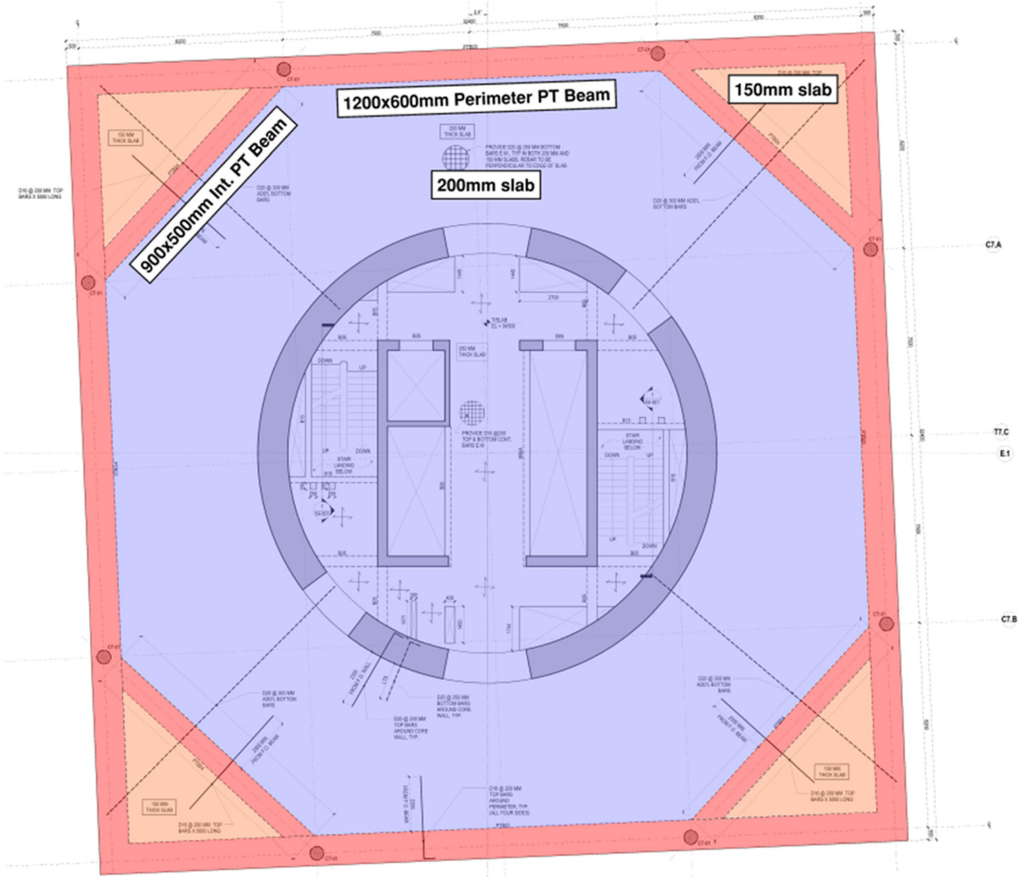


Figure 3. Typical Floor Framing.

was provided where required per code. In addition to the notable challenges above, the region's wind loads - basic wind speed of 118 mph (53 m/s) - ensured the building would have to be designed under extreme conditions.

3. Typical Floor Framing

The overall twist of the tower, achieving a final rotation of 40 degrees, results in each floor articulating away from the floors above and below by approximately 1.2 degrees. Floor area also reduces as elevation increases, resulting in a slimming effect along the building height. Although the tower's twist exudes complexity, the circular shape of the central core created some welcomed simplicities for building function. All vertical shaft and means of egress are located inside the central core, which allows for a typical office layout to be maintained at every floor. Without interior columns and utility rooms at each floor, the floor layout provides maximum flexibility for modifications, tailoring to any future tenant's demands.

After several rounds of iteration, typical office structural floor framing was decided to consist of a 200 mm thick flat slab with 600mm deep perimeter post-tensioned beams (3). Additional diagonal post tensioned beams were introduced at each corner of the floor plate to reduce the floor loads imposed at the corners in an effort to control the excessive deflections at the extreme cantilevered tip. The framing solution provided an efficient and easily reproducible system that could accommodate the relative twist between successive floors.

4. Column Transfer System

Intentional separation of each cube creates impactful sky gardens. However, they also require all perimeter columns to terminate at the base of each cube. To deal

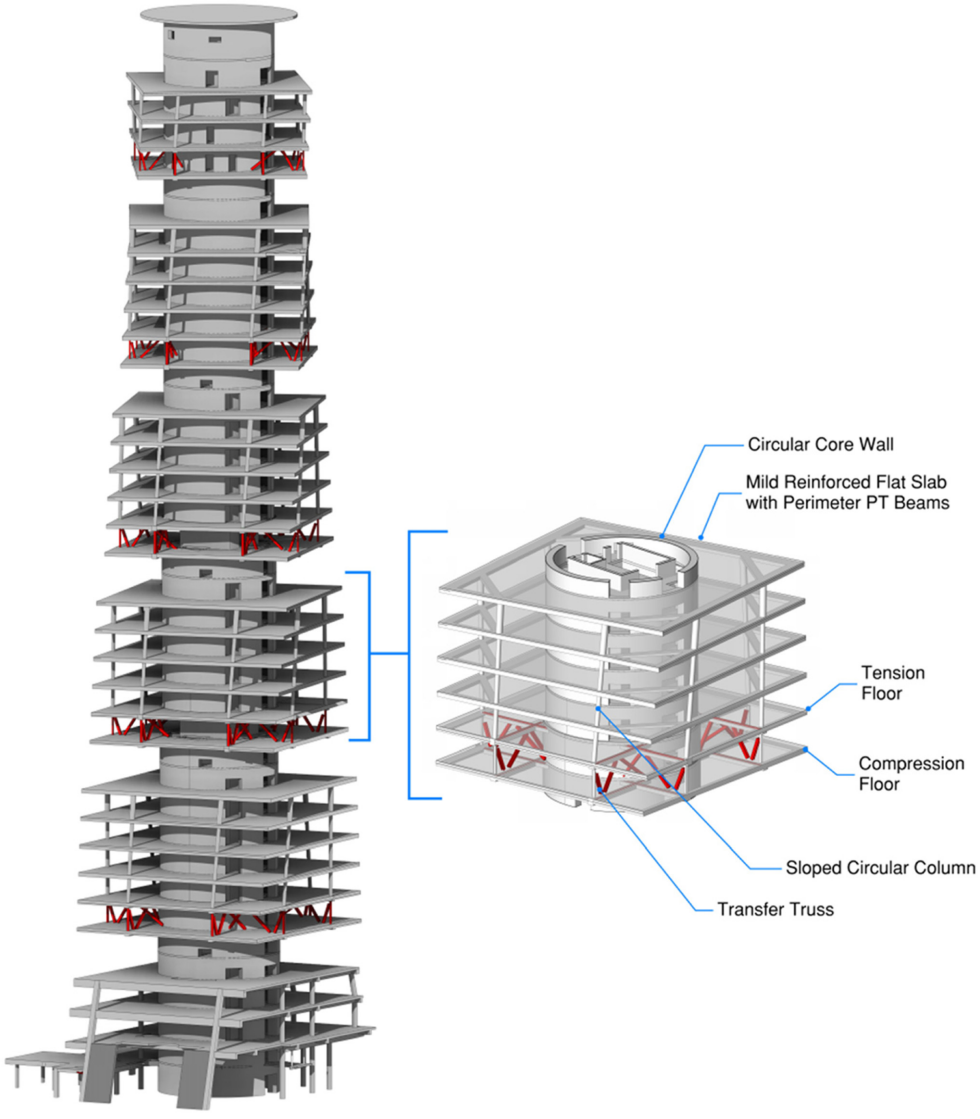


Figure 4. Primary Structural Components.

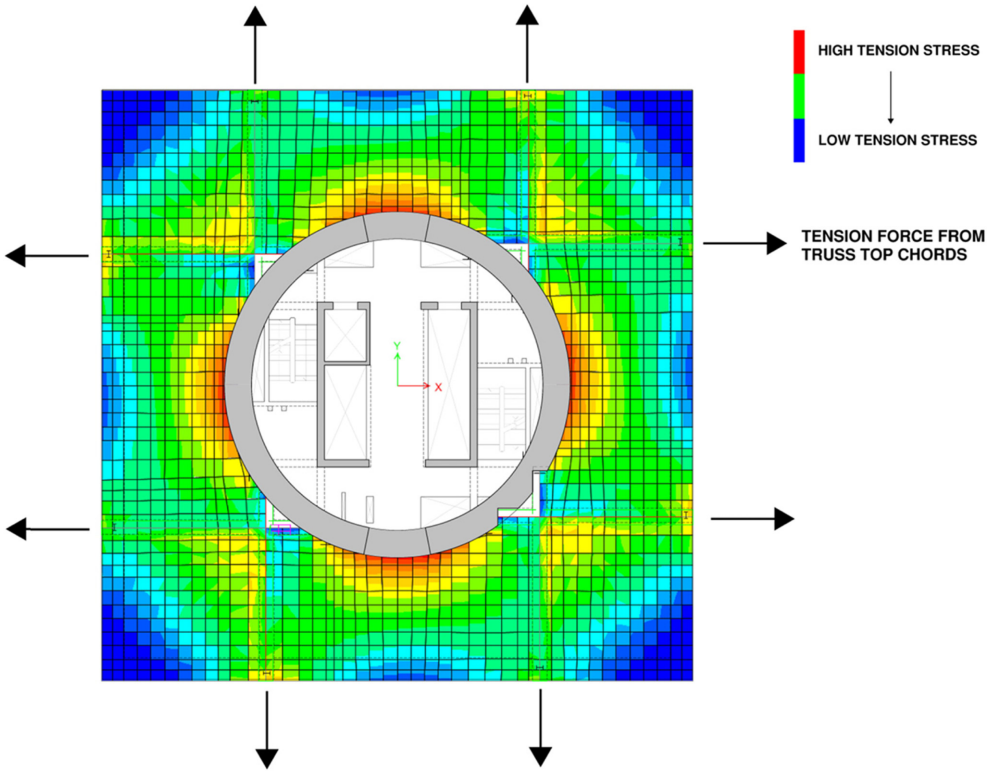


Figure 5. Maximum In-Plane Forces in Tension Slab.

with the column termination, eight steel transfer trusses are situated along each column line in order to direct the column load back to the core. A traditional cantilever transfer truss with a moment fixity at the wall face would create a large force couple, flexing the core wall out-of-plane and causing unwanted additional demand in an already over-worked structural core. To avoid this, an innovative design solution was introduced where vertical load from the columns above are carried through steel diagonal web members, while the induced moment from the cantilevered truss is resisted by a tension and compression force couple in the slabs built integrally with the truss top and bottom chords. This reflects realistic compatible behavior at chords and slabs. (Figure 4).

The novel approach to transferring truss chord forces into slabs was effective in part because of the shape of the core, and symmetry of the column placement along the perimeter of the building. Truss chord forces of similar magnitude occur on opposite sides of the tower-at four lines of symmetry-which allowed the floor slabs to be designed as competing tension and compression "rings" that balance the overturning moment induced by the truss cantilever. As noted, since horizontal forces are designed to bypass the core, truss connections to the core only needed to resist vertical loads, adding another simplification to the system.

Reinforcement of slabs in tension was optimized using nonlinear finite element models with layered shell elements to simulate accurate cracking behavior of the concrete slab under tensile loads. In addition, overall stability was analyzed for a variety of unbalanced live load patterns to ensure each cube remained stable and secure under eccentric loading conditions. In these situations, the core resists modest unbalanced forces applied through slab bearing.

Cantilever truss tip deflections received close attention throughout the design process. Excessive deflection would not only become unsightly but could also cause unwanted strain on the façade panels. Moreover, since slab tension and compression was relied on for truss chord forces, long-term deflection predictions reflected

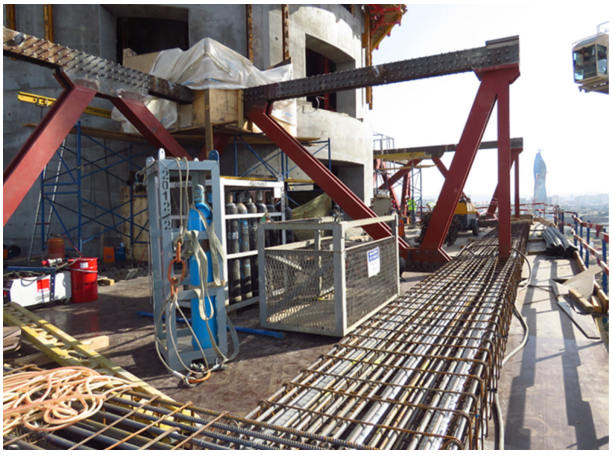


Figure 6. Transfer Truss Construction.

concrete creep and shrinkage effects over the life of the building. Trusses were detailed, fabricated and constructed with upward camber to compensate the anticipated large instantaneous deflection at their outer ends (Figure 5). Relative long-term deflections along the perimeter of the floor plate were coordinated with the façade consultant to ensure the façade joint and connections were detailed accordingly.

5. Construction Sequence

Designing a mechanism whereby structural stability is only achieved with the tension and compressing slabs meant that the transfer system was not self-sufficient until both tension and compression slabs were cast, cured, and achieved design strength. For this reason, the transfer trusses (and the wet weight of the slabs) required shoring at each cube - an added challenge for the design and construction team. However, by choosing steel trusses for the main vertical load-transferring element, the amount of shoring required during construction was dramatically reduced. Other options, such as concrete shear or corbel walls, would have required shoring of more than one cube in order to engage multiple transfer walls to support the added weight of the concrete walls. Relieving this requirement allowed for rapid progression of construction for lower cubes and a reduction in the overall construction schedule.



Figure 7. Shoring the Transfer System.

Comprehensive construction staging and sequence analysis was performed to ensure the construction weight of each cube's transfer system (steel truss and weight of concrete) could be supported by the transfer system of the cube below. This sequencing analysis served as the controlling load case for the transfer truss strength design (Figure 6).

6. Circular Core Wall Lateral Design

A centrally located circular reinforced concrete core wall runs the entire height of the building to resist lateral as well as gravity loads. The wall transitions in thickness at three points along its height, varying from 6ft thick at the base to 2ft at the top, while the core inside radius remains 26ft throughout.

High-Frequency Force Balance (HFFB) Test was conducted to determine the structural wind loading characteristics for the tower design and to predict wind-induced accelerations at the top occupied floor. Wind-Induced acceleration criteria was set with reference to the International Organization for Standardization (ISO). Effective wind static forces were used to determine the force demands in the core wall system at ultimate conditions, as well as to estimate overall deflection and inter-story drift.

Although the circular core wall created simplicity when it came to overall program, it enforced a clear lateral system, without many other options than to assimilate the circular core to a pillar carrying all lateral and vertical load in the tower. ASCE 7-10 imposes a 50 m height limitation for Special RC wall systems for Seismic Design Category D where this project falls into. Considering the total height of the building being 170m, prescribed code provisions require the building to be designed as a Dual System with Special Moment Frames capable of carrying at least 25% of the seismic loads. Having column-less floors between each cube made it impossible meet this code criteria. Therefore, it was required to conduct PBD to capture nonlinear behavior of the tower and ensure performance of a building which is in effect outside of code prescription. The PBD approach involved Nonlinear Response History Analysis (NRHA) using realistic earthquake records and post-yield structural element properties to analyze and guide detailing of the core wall.

Where combined seismic and gravity loading resulted in high compressive demands, confinement reinforcement meeting ACI 318 requirements was provided to enhance concrete performance under cyclic loadings. These conditions occurred throughout the tower height, particularly below transfer trusses due to the sudden increase of compressive forces in the core wall. Heavy confinement was also provided at truss connections to prevent the



Figure 8. Truss Connections to Core Wall.

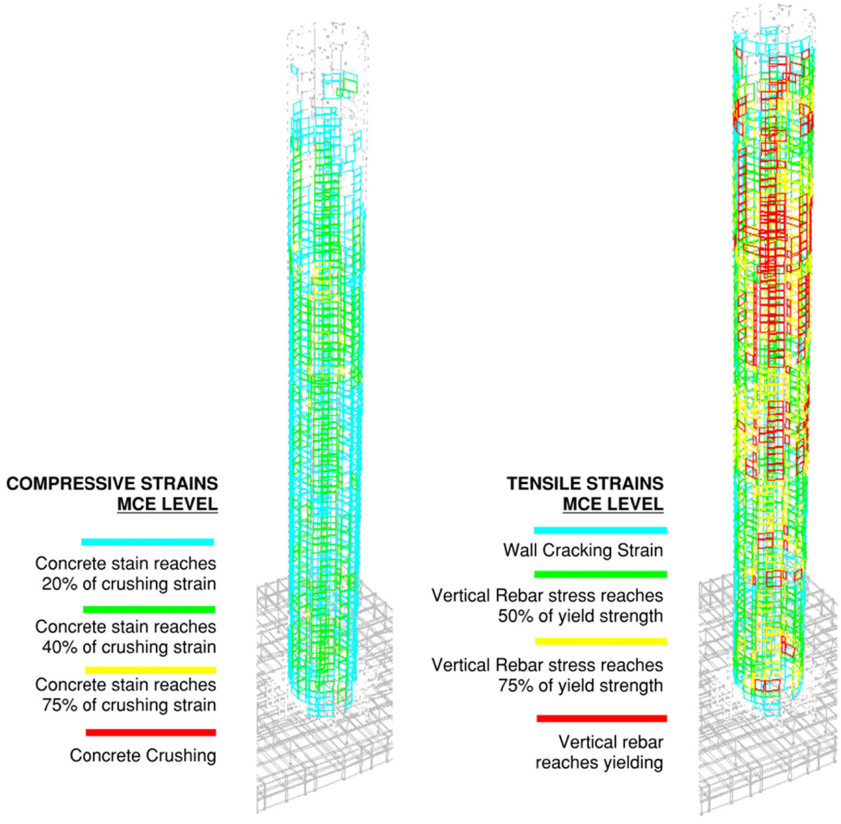


Figure 8. (a) Maximum Compression Strain (b) Maximum Tension Strains in the Core Under Maximum Considered Earthquake (MCE).

already improbable pull-out of the trusses.

PBD output revealed maximum compression strains well below the crushing limit of concrete during the full suite of seismic events. Similarly, monitoring rebar strain along the building height showed localized yielding occurring only at top floor where gravity demands are

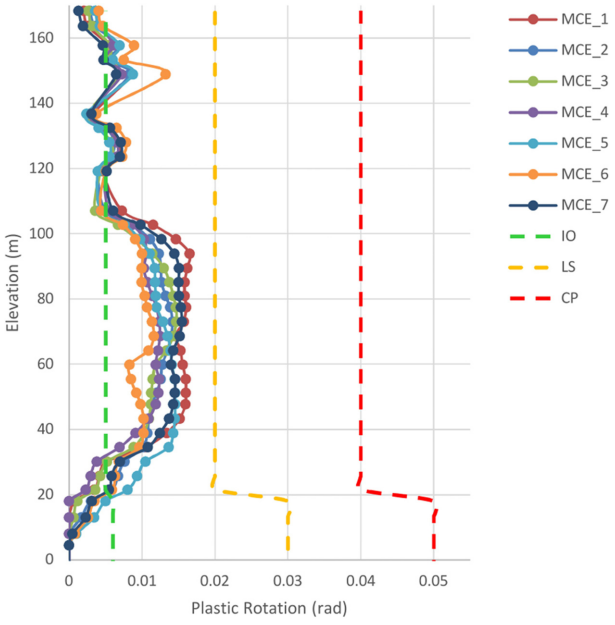


Figure 9. Diagonally Reinforced Link Beam Plastic Rotation vs Building Height. (MCE Level)



Figure 10. Link Beam Construction.

relatively low and wall thickness is significantly reduced (Figure 7).

Coupling beams were the major fuse elements to absorb seismic energy and to limit seismic forces applied to other elements. The NRHA results were very useful in optimizing their design, and showed that most of the coupling beams could be designed with conventional reinforcement while still following capacity design principles; shear reinforcement was sufficient to have flexural hinging occur at beam ends without shear failure. At floors with very large plastic rotation demands, diagonally reinforcement was provided to ensure ductile behavior under cyclic seismic loads. As shown in Figure 8, reported plastic rotations were found to be lower than Life Safety criteria and thus concluded to meet the target performance criteria

Conclusions

Upon reaching structural top-out and façade completion in November of 2018, the unique and futuristic shape of MOT tower became a new national landmark of Azerbaijan. Advanced structural analyses such as a seismic PBD and construction sequence analysis were used to allow the structure to be fully realized. This nimble structural approach will allow MOT to contribute to Baku's skyline for years to come while the city continues to redefine itself.

Acknowledgements

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Additional photos below….







