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STRUCTURAL AND GEOTECHNICAL DESIGN OF A HIGH-RISE BUILDING USING A 3D BIM GENERATED MODEL

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This paper presents the work performed by an undergraduate student group at the American University in Cairo as a first phase of their graduation project that mimics a state-of-the-art industrial experience in structural and geotechnical design of a high-rise building using building information model (BIM). A 3-D BIM was developed for the structure and used to generate an analytical model which is exported to a structural numerical analysis program, followed by a full design of the building elements and foundation. The considered building is 218 m high, in which the architectural design requires a successive 2-degrees twist per floor through the building height, resulting in a total twist of 80 degrees between the first and last floors. The architect also retracted the slabs every six stories from a group of columns, leaving 24 m-height laterally unsupported peripheral columns. As such, the vertical and horizontal building irregularities present challenges in the structural modeling and design and requires thorough analyses, particularly for seismic and wind considerations. Due to the high water table at the building site and the existence of a 12.5 underground basement, a special dewatering technique was proposed, along with the full tanking design consideration of the building basement.

Keywords: Building information modeling, Dewatering, Numerical modeling, Seismic analysis, Tall buildings.

1 PROJECT OVERVIEW

The tower is 218 m high in which the architectural design requires a successive 2-degrees twist per floor through the building height resulting in a total twist of 80 degrees between the first and last floors. Furthermore, the architect also retracted the slabs every 6 stories from a group of columns leaving 24 m-height laterally unsupported edge columns. As such, the vertical and horizontal building irregularities present significant challenges in the structural design and requires thorough structural analyses, particularly for seismic and wind considerations, as well as the construction sequence. Due to the high water table at the building site and the existence of a 12.5 underground basement, special dewatering technique was proposed along with the "full-tanking" design consideration of the building basement.

Building information modeling (BIM) is a digital representation of the structural composition and function. For the past decades, conventional Civil Engineering relied on 2D drawings only, such as elevations, plans, and sections, and each engineering discipline was working in its own field. Therefore, extensive coordination problems arose when the designs from different disciplines were integrated, which impacted the project's design time, cost and even quality. It is evident that BIM eliminates such dilemma and allows for a live-interdisciplinary coordination between the different design disciplines, therefore minimizing the impact on time, cost and quality.

In this work, BIM for the building was first built on Revit, then, an analytical model was developed. This analytical model was imported to ETABS for numerical analysis of the tower. Beside gravity loads, seismic and wind loads were considered in the structural analysis of the building according to ASCE/SEI 7-16 (2016) provisions. The tower was designed as a reinforced concrete framed structure with shear walls according to ACI 318M-14 (2014) provisions. The structural design was performed using ETABS as well as SAFE; the later was used to design the floor flat slabs of the tower. Geo5 was also used to design the retaining walls in the basement considering the soil properties and the groundwater table. Moreover, additional software such as STAAD and PCA columns were also employed to validate ETABS' outcomes. Finally, a 4D simulation model that shows the detailed schedule and construction process of the tower was performed on Navisworks.

After many design iterations, all structural members of the tower were designed and the students submitted complete structural drawings, a 3D BIM along with the 3D structural numerical model and full calculation sheets. The project was challenging and mimicking a typical industrial application, which serves to prepare the students for their post-graduate career in structural analysis and design.

2 STRUCTURAL MODELLING AND ANALYSIS

A reinforced concrete structural system was chosen and shown in Figure 1 is the generation and development of the model for the structure using Revit.

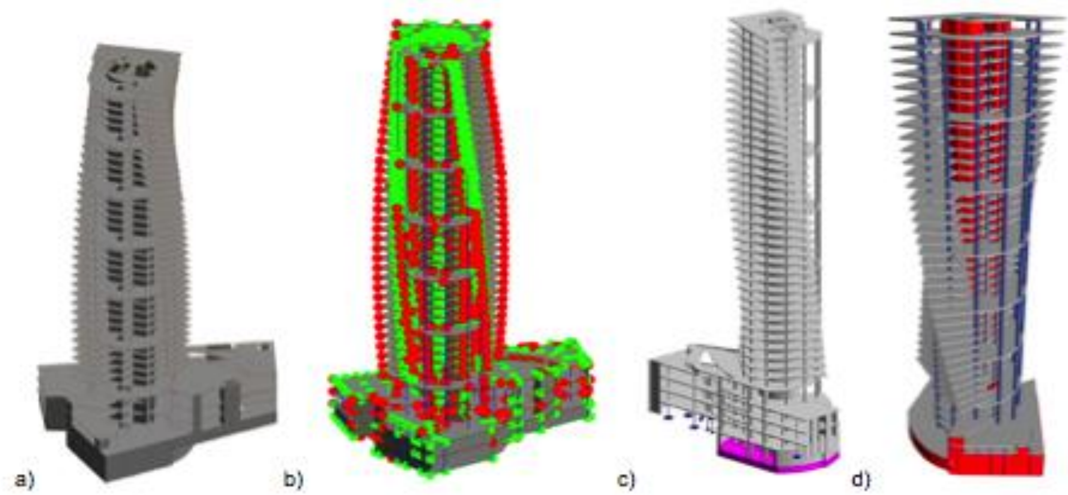

Figure 1. 3D model development. a) Initial BIM, b) Analytical model, c) ETABS model, d) Updated BIM.

The chosen structural system was composed of flat slabs supported by reinforced concrete columns and shear walls. Then, an analytical model was produced from the BIM: this analytical model needed significant adjustment to fit the numerical analysis requirements. This process by itself presents a challenge to undergraduate students and requires building knowledge in both modeling and analysis phases. The adjusted analytical model was exported to ETABS, where the building was analyzed under the effects of gravity and lateral loads. The analysis was performed according to ACI 318M-14 (2014) with all loads and load combinations satisfying the requirements of ASCE/SEI 7-16 (2016).

For seismic analysis, the building type, the vertical and horizontal irregularities, the seismic zone requirements, the risk category, the importance factor, etc. were all considered in the numerical modeling of the building using ETABS. Wind load with all its combinations was also analyzed. The base shear, overturning moment and distribution of forces per floor were obtained and checked.

Modal analysis was performed using Modal participation mass ratios as the results in Table 1 demonstrate and the time period of each mode was calculated where internal forces were obtained based on the SRSS technique.

Table 1. Modal participation mass ratios.

TABLE: Modal Participating Mass Ratios

Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	5.773	0.5421	0.0228	0	0.5421	0.0228	0	0.0098	0.3549	0.0433	0.0098	0.3549	0.0433
Modal	2	4.383	0.0516	0.4468	0	0.5937	0.4697	0	0.2996	0.0352	0.074	0.3094	0.39	0.1173
Modal	3	2.811	0.0248	0.125	0	0.6185	0.5947	0	0.1083	0.0085	0.464	0.4177	0.3985	0.5812
Modal	4	1.362	0.0795	0.0585	0	0.698	0.6532	0	0.0605	0.0972	0.0033	0.4782	0.4957	0.5846
Modal	5	1.156	0.0702	0.1184	0	0.7682	0.7717	0	0.0881	0.0672	0.000008285	0.5663	0.563	0.5846
Modal	6	0.834	0.0146	0.0141	0	0.7828	0.7857	0	0.0182	0.024	0.091	0.5845	0.587	0.6756
Modal	7	0.603	0.0209	0.0172	0	0.8037	0.8029	0	0.0257	0.028	0.0125	0.6102	0.615	0.6881
Modal	8	0.487	0.0262	0.0267	0	0.8299	0.8297	0	0.0398	0.0361	0.0004	0.6501	0.6511	0.6885
Modal	9	0.434	0.0057	0.0044	0	0.8356	0.8341	0	0.0091	0.0094	0.0225	0.6591	0.6605	0.711
Modal	10	0.37	0.00003172	0	0	0.8356	0.8341	0	7.994E-07	0.00004876	0.000006204	0.6591	0.6605	0.711
Modal	11	0.369	0.0001	0.000007454	0	0.8357	0.8341	0	0.0000109	0.0002	0.000007071	0.6592	0.6607	0.711
Modal	12	0.365	0.00000643	0.00001494	0	0.8357	0.8341	0	0.00002553	0.000008906	0.000007375	0.6592	0.6607	0.711

The maximum period of the building for the first mode was found to be 5.8 seconds. The first mode of the building was a translational mode in the x-direction. The second mode was also a translational mode but in the y-direction, while the third mode was a torsional mode: the chosen a central reinforced concrete shear walls delayed this torsional effect. Mass participation for each mode was checked and the first 20 modes were considered in the analysis.

3 GEOTECHNICAL ANALYSIS AND DESIGN

Based on the geotechnical investigation performed on the building site, different dewatering methods were scrutinized as the ground water level was found to be 8.5 m below ground level. A polymer plug was chosen to counterweight the uplift pressure and to prevent water from seepage through the foundation. Full tanking was also adopted for the basement in order to act after the lifetime of the plug when it decays. The basement's retaining walls were analyzed and designed using Geo5; struts were designed to act as their support for large distances.

As illustrated in Figure 2, which is a cross-section for the foundation system details for the model, isolated footings were adopted for the three-floor podium columns (above the water level) while raft foundation with retaining walls was chosen under the tower (below the water level).

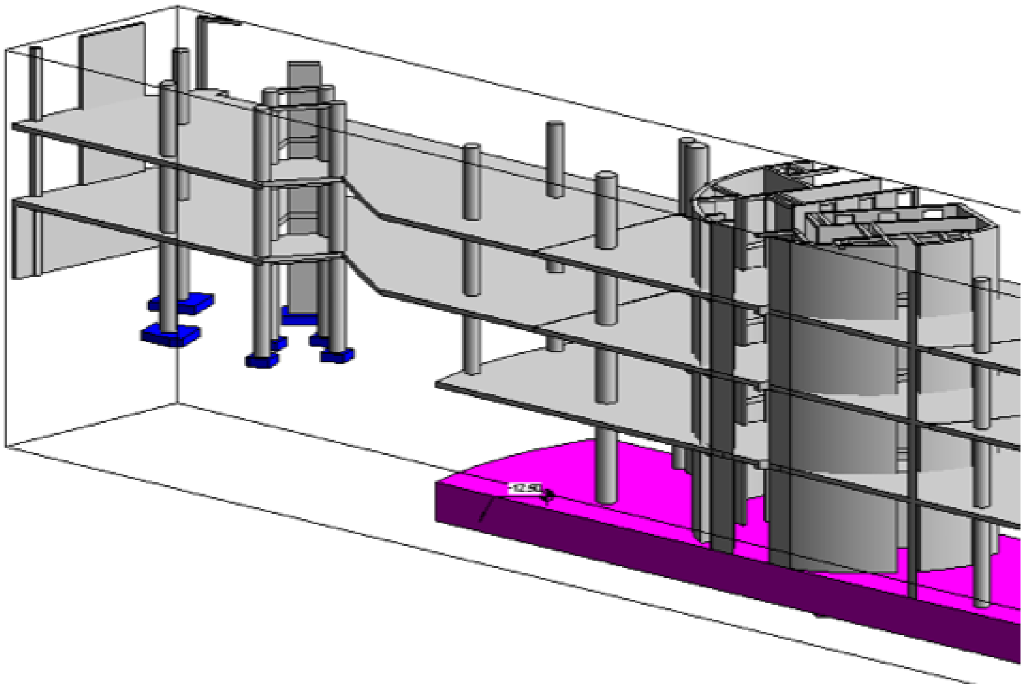

Figure 2. Section of the foundation systems.

The analysis and design of the raft was done using SAFE, considering the soil modulus of subgrade reaction, maintaining the differential settlement within acceptable limits as per the results shown in Figure 3.

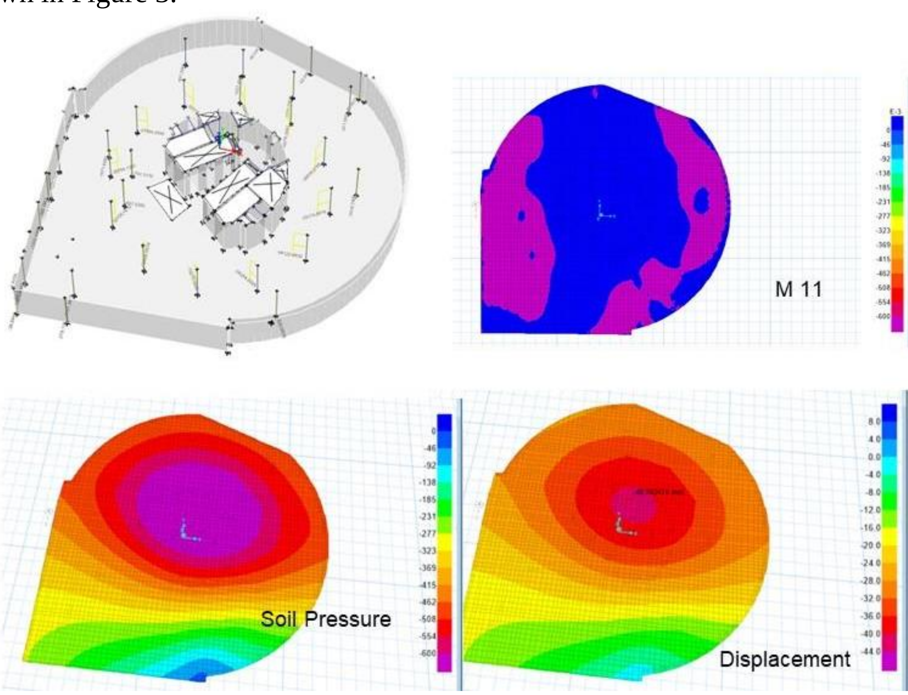

Figure 3. Analysis and results of tower raft.

4 STRUCTURAL DESIGN

Columns were designed on ETABS according to ACI 318M-14 (2014) provisions. To validate the design performed by ETABS, random samples of the columns were chosen and designed on PCA Columns; another software specifically used for RC columns design. The results showed that, the design performed by ETABS was close, to that performed by PCA Columns. Some of the columns in the atrium gardens (Figure 1) had an unsupported length of 24 m. This led to design these columns with a 1.7 m diameter circular cross-sections; a huge section but required for column stability and for minimizing the second order (p-d) effect. Therefore, an alternative design was also proposed where these columns were designed as composite steel-concrete sections (with steel hot-rolled section embedded inside a concrete circular section). This design allowed the column cross section to be reduced from 1.7 m to 1.0 m; therefore, increasing the area that can be used by the client and of course reducing the cost of construction.

The shear walls were designed for bending moments and shear forces using ETABS and the walls boundary zone was checked where reinforcement was added according to the ACI 318M-14 (2014) provisions. Displayed in Figure 4 is the reinforcement drawn according to the design. These walls serve to reduce the torsional effect, which arises from the severe horizontal and vertical irregularity of the structures imposed by the architectural design.

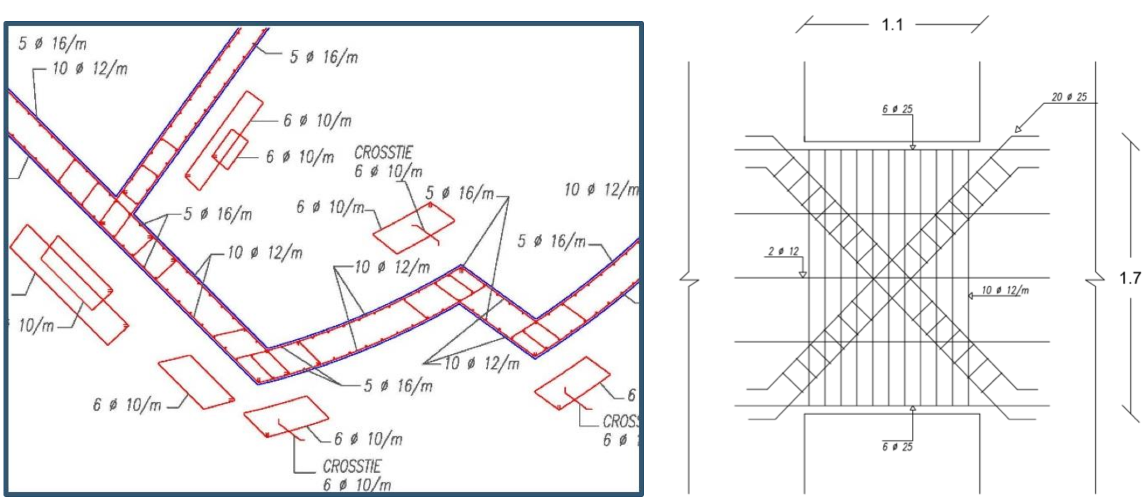

Figure 4. Core wall and link / coupling beam reinforcement.

Beams were designed using the 3D model on ETABS according to ACI 318M-14 (2014) provisions. However, to validate this design, random beam samples were chosen and manually designed. This check proved that the design performed by ETABS is both safe and economic. Almost all the beams were used to connect the shear walls in the core area in order to add additional lateral stiffness to the building in resisting lateral loads. As such, these beams were manually designed as coupling beams based on ACI318M-14 (2014) provisions and their reinforcement is shown in Figure 4.

The slabs were exported from ETABS to SAFE to be analyzed and designed as flat slabs. The short- and long-term deflections were checked against the limits specified by ACI 318M-14 (2014) provisions. Due to the presence of a 9 m cantilever slabs at three tips of the building floors as they twist by 2 degrees (Figure 3), the slab thickness was increased to make sure the cantilever long-term deflection is within the acceptable limits of ACI 318M-14 (2014). As illustrated in Figure 5, a typical mesh was added, and additional reinforcement was needed at certain areas. For the podium, a waffle slab system was designed due to their huge spans and area.

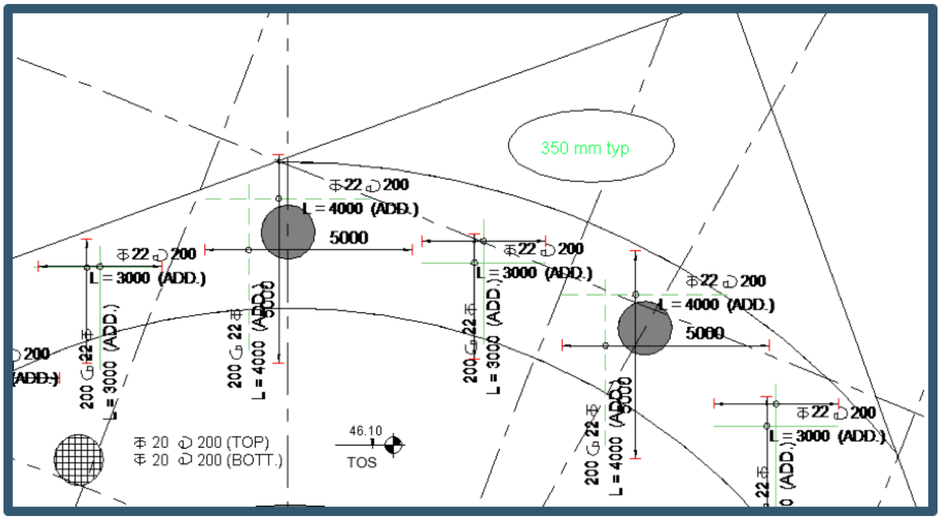

Figure 5. Tower slab reinforcement.

5 CONCLUSIONS

Significant learning outcomes and lessons were gained/ learned by the students in this capstone course. Full 3D BIM and analytical model, construction methods for the substructure, 3D numerical analysis, calculation sheets, and design development structural drawings were delivered. Using different software was a real challenge as moving a model or data from one software to the other took a time and efforts to adjust these models between software. This gave the students knowledge and prepared them for their professional career. Designing different structural elements such as coupling beams, waffled slabs in the podium, composite column for long column, and reinforced concrete raft foundation on elastic support added another edge to the students in this capstone course.

References

ACI 318M-14, *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*, American Concrete Institute, Committee 318, Farmington Hills, MI, USA, 2014.

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