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DESIGN OF A HIGH-RISE BUILDING USING BIM: A CAPSTONE COURSE PROJECT

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1. Project Overview

This paper presents a case study that involves the first phase of a graduation project of an undergraduate students group at the American University in Cairo. In this project, complete structural and geotechnical analyses and design were performed for a high-rise building using BIM. It is the first time in Egypt for undergraduate students to develop a 3D building information model for a structure, and use it to generate an analytical model which is exported to structural numerical analysis followed by full design of the building structural elements and foundation.

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.

The BIM was first built on Revit, then the 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 provisions. The tower was designed as a reinforced concrete framed structure with shear walls according to ACI 318M-14 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 mimic a typical industrial application, which serves to prepare the students for their post-graduate career in structural analysis and design.

2. BIM Model

Building information modelling 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.

3. Structural Analysis

A reinforced concrete structural system was chosen and BIM for the structure is generated using Revit (Figure 1). 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 modelling 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 with all loads and load combinations satisfying the requirements of ASCE/SEI 7-16.

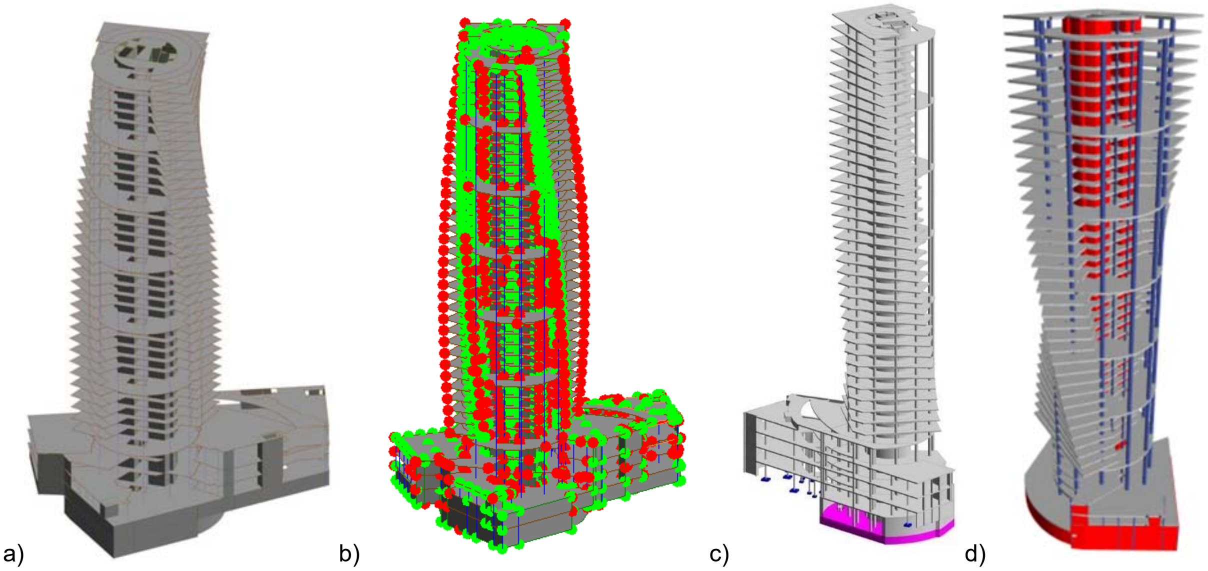

Figure 1: 3D Model Development. a) Initial BIM, b) Analytical Model, c) ETABS Model, d) Updated BIM.

For the 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 model of the building using ETABS. Wind load with all its combinations was analyzed. The base shear, overturning moment and distribution of forces per floor were obtained and checked.

Modal analysis was performed and the time period of each mode was calculated where internal forces were obtained based on SRSS technique. 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 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.

4. 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.

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). The raft was analyzed and designed using SAFE considering the soil modulus of subgrade reaction, maintaining the differential settlement within acceptable limits (Figure 2).

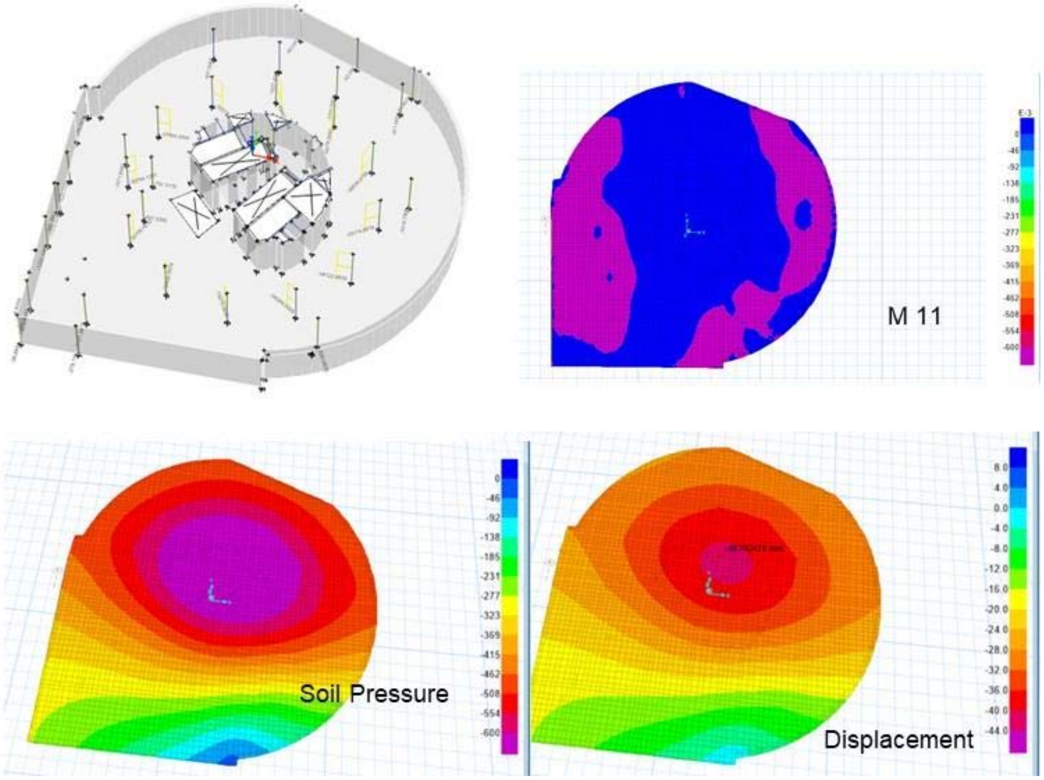

Figure 2: Results of the tower raft analysis.

5. Structural Design

Columns were designed on ETABS according to ACI 318M-14 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 3) 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 by a significant value.

The shear walls were designed for bending moments and shear forces using ETABS and the walls boundary zone was checked where reinforcement were added according to the ACI 318M-14 provisions. 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.

Beams were designed using the 3D model on ETABS according to ACI 318M-14 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 provisions.

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 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. For the podium slabs (Figure 3), a waffle slab system was designed due their huge spans and large area.

6. Learning Outcomes and Lessons Learned

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.

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