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The Effect of Structural System Elements on the Dynamic Behavior of High-Rise Buildings

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Abstract

The study examined whether the structure facade emerged as an ornament or as a result of the effort to structure the ornament in the structural elements design. Study focused on high-rise buildings, which have historically been an important indicator of power and prestige in relation to countries and societies. With literature review, it has emerged that the structure is used as an ornament in high-rise buildings designed in the architecture of the twentieth century. Three high-rise buildings based on this hypothesis were then designed. The different load-bearing systems of these structures, referred to in the study as Type 1, Type 2, and Type 3. are the tubular frame system (TFS), the tubular diagrid system (TDS), and the tubular and lattice diagrid system, respectively. The structural analysis and seismic behavior of these designed buildings were carried out using the SAP2000 according to different soil properties. The reason for including the soil properties is to see the effect of the soil on the structural performance of these three different buildings. Type 1, Type 2, and Type 3 have distinct structural behavior. The findings of the studies indicated that the different facade formations of these three buildings completely separated the seismic behavior of the structures from each other. Furthermore, the seismic behavior in rigid and soft ground conditions predicts all the factors and processes related to the facade formations and ultimately to the construction of architectural objects in high-rise buildings.

1. Introduction

Karl Botticher, one of the 19th-century theorists, divides architecture into two main categories in his book “Studies in Tectonic culture-the Poetics of Construction in 19th and 20th-century Architecture”: Kernform (self-form) and Kunstform (symbolic art form). The author proposes a form consisting of structural order and ornamentation and states that the ornament should reveal and emphasize the essence of the construction [1]. Again, one of the theorists of the same century, John Ruskin, in his book "Stones of Venice", regrets that the human body does not display the skeletal system. However, he imagines that a careful pair of eyes can immediately notice the secrets in this anatomy. He mentions that the same idea is valid for the structure in an architectural structure. In addition, he mentioned that ornamentation is not like a dress worn on the human body, but a concept that represents the soul that constitutes the essence of the human being [2]. Eduardo Torroja, in his work titled “Philosophy of Structures”, mentions that structure is often left in the background when evaluating the aesthetic concerns of buildings. According to him, the aesthetic approach required for the beauty of the structure is directly related to the form of the structure. Its robustness forms part of the architectural language. He adds the concept of honesty to his discourses. In his examples, he characterizes the dressing of reinforced concrete with stones as dishonest. He continues by mentioning that these two materials do not have the same expressive characteristics. He emphasizes that this system contains important features for form and that it cannot reach a noticeable aesthetic value without a skeletal system in this form [3].

Owen Jones focused on the source of architectural forms in his work "The Grammar of Ornament". He established the nature and plant forms that contributed to the architecture in 37 basic rules. Twenty of these rules, most of which are about form and construction, are about color and balance, and eleven of the first 13 are only about visual form. The use of natural objects as decoration is mentioned in the 13th article. What brings to mind the architectural image are traditional displays with sufficient clarity. He described ornamentation as a natural result of cultural development. He evaluated the ornament by categorizing it and evaluated these categories under the headings of cultural and stylistic characters. According to him, the ornament is an element that can develop continuously and should feed its foundations from geometry [4].

The German architect Gottfried Semper's work "The Four Elements of Architecture and Other Writings" states that it is necessary to find its existential roots in order to analyze the functions underlying ornamentation. According to him, the origin of ornament is weaving, and ornament forms the beginning of architectural form. He thinks that architecture is essentially an ornamental activity [5]. The ornamentation of the structure and the structuration of the ornament, which is considered under the heading of "meanings obtained with the material", mentioned by Robert Kerr, one of the 19th-century theorists and architects, in his speech titled 'Architectures' at the conference held at the 'Royal Institute of British Architecture' on January 18, 1869, is the decorated structure and embellished construction idea. Robert Kerr has placed architecture in a mathematical pattern as building+architecturesque [6]. In addition to the 4 basic principles Robert Kerr created on structure and ornament, Özlem Demirkan stated that there may be a fifth principle in her master's thesis titled "Examination of the Relationship between Structure and Decoration in Architecture" in 2006. This principle, according to her, is Form and Decoration [7].

High-rise buildings, arising from the needs of individuals and societies, are realized in a process that is based on the selection of appropriate materials and shaping that material with technological possibilities as objects of function and use. Lynn S. Beedle and Dolores B. Rice define the concept of a high-rise building in the "Structural systems for tall buildings, CTBUH committee 3" as a structure that, due to its high building height, creates a different design, construction, and usage condition [8]. On the other hand, when looking at the development map of high-rise buildings constructed with concrete steps from conceptual and theoretical foundations; Load-bearing systems used in high-rise buildings are classified according to vertical loads, horizontal loads, and load-bearing system materials. In 1965, Khan [9] realized that the structural system classification can be categorized in terms of resistance to horizontal loads. On one side of this classification, there are moment-resistant frames that are up to 20-30 times more efficient, and on the other side, there are new-generation tubular systems with high cantilever efficiency. In addition, Fazlur Khan has separated these systems from each other as concrete and steel systems according to the building material. Ali Mir & Moon [10] brought a new approach to Fazlur Khan's classification. By dividing the structural systems into two main groups as 'Internal and External' structural systems, this classification includes both primary structural systems and auxiliary damping systems. In order to determine the best height for high-rise buildings, the classification of the bearing systems of high-rise buildings according to their resistance to horizontal loads has been preserved as before. In determining these strengths, it is designed to take into account the analyses made from the applications and the possible results with the developing technology. These analyses, called structural modal analysis, are an important tool for tall buildings. The analyses can show the strength of tall buildings under static and dynamic loads [11]. These loads can be wind loads, seismic loads, etc. The analysis of each software programme will differ according to these loads. In a study on the resistance of tall buildings to wind loads, it is emphasized that the building structure cannot be considered separately from the facade system [12].

In order to transform these iconic buildings, which must have a structure resistant to aesthetic, functional, static, and dynamic loads, from an abstract idea to a concrete object, the architect must have a command of architectural theories and trends, have a high design power, and have sufficient knowledge of structure for multidisciplinary studies [13]. Each of these design parameters directly impacts the structural behavior. According to this perspective, even if a structure is to be designed to withstand natural disasters, it should be designed not only in terms of strength but also by integrating all these factors [14]. This is one of the most important responsibilities and roles of architects. These approaches, which form a whole, should feed each other and the work to be created should be presented as a gift to the artificial environment.

As a result of conceptual readings of high-rise, facade, structure, and ornament, ornamentation is a superficial process. However, it has been determined that this process should be nourished by the inner forces of people, things, or places, namely the spirit, and act in harmony with the components of architectural design. It is depicted as the process of creating a pleasant face by hiding unseemly things behind it by its nature. However, it can be said that one should not harm the essence of architecture by feeling the presence of the remaining structural elements. Facade design for high-rise buildings; It emerges as a language of prestige, power, and architectural expression. The dynamics that make up the facade constitute the structural elements (columns, beams, floors) that are part of the structural system, architectural elements (solid-void ratio, proportions, axis, etc.), and aesthetic concerns. Blending the constraints of the structural system with aesthetic concerns, integrating with architectural elements, and the idea of showing this holistic approach on the exterior formed the content of the study.

1.1 Theoretical Method

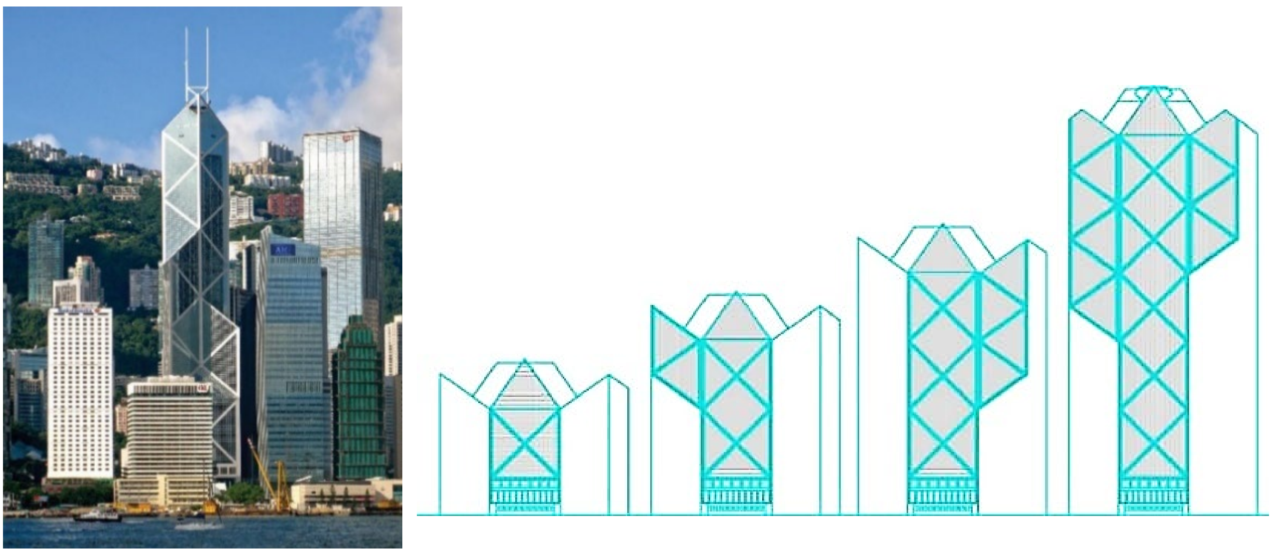
This study consists of two stages. In the first stage, the high-rise buildings built in the 20th century were conceptually divided into four by Robert Kerr, one of the 19th-century architectural theorists; The ornamentation of the structure, the structuration of the ornament, the ornamented structure, and the ornamented construction thought were discussed with examples. To verify the conceptual framework of the study and to illustrate how it is applied, 3 examples of high-rise buildings, where the structures can be read from the outside, were selected. The sample building groups of the research were formed from the buildings that reflect their periodical features in the history of architecture and that are referenced because they have new systems on them at the time they were built. Before starting the fieldwork, how the structural elements that shape the facade and how aesthetic concerns are blended are interpreted through examples, plan schemes, and facade studies are evaluated to verify the conceptual basis, and the structure-facade-form setup is read. The examples of structures examined are given below in the following order.

1. Bank of China, Hong Kong: The preferred load-bearing system in the structure of the Bank of China and the materials that are the components of the system formed the form. It is not possible to keep the structural elements separate from the facade. The questions asked during the structural analysis to discover the starting point of the design are:

a) How was the form of the facade surface carried?

b) How was the form of the facade surface created?

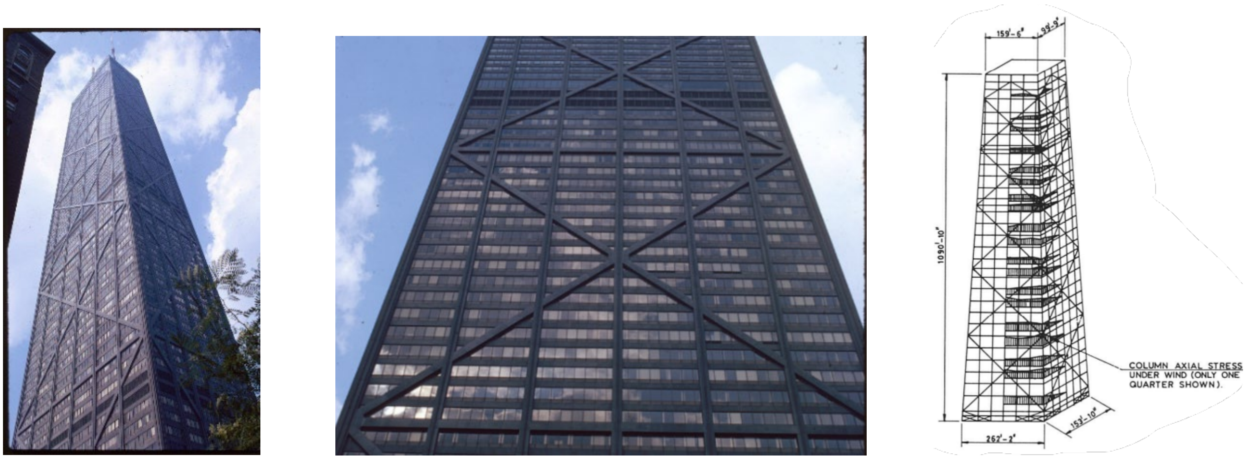
The first thing to do here is to look at how the plan setup is expressed on the facade. Considering the building in particular, the plan setup is free, and the structural elements placed on this free plan plane are chosen as thick as possible at the corners of the form. It is not possible to answer the above questions only with these plans. At this stage, the facade comes into play. The form of the structural elements on the facade is different from the plan. In the third dimension, the cross effect is felt more on the facade and inside the space. The building, which decreases geometrically from the square floor plan and ends with a triangular floor plan, rises in a fractal order. Among the geometric shapes, triangles show the most rigid behavior. For this reason, the building was divided into triangular areas and supported by the structural system. The facade surfaces did not continue straight along the height, and the design was strengthened with triangular inclined surfaces. A strong and unique form of structural order was created and therefore no ornamental elements were added to the facade surface afterwards. The form alone created a very dominant visual effect and was ornamented (Fig. 1).



(a) (b)

Fig. 1 *Bank of China, Hong Kong. (a) Bank of China (center); (b) Descriptive facade geometry diagram edited by authors; [15], [16]*

2. John Hancock Building, Chicago: The John Hancock building, which is symbolized by its inclined form (cut pyramid) and the integration of the expressive structure with the architecture, is seen as an architectural icon. Fazlur Rahman Khan stated that the facade braces designed to allow wider column spacings compared to the frame-tube system will not be exposed to tensile forces even under large wind loads by acting as columns [17]. The facade pattern of the John Hancock building is provided with cross-bracing systems (CBS). Although the structural system reduces the frequent column layout on the facade, the CBS carrying vertical and horizontal loads interrupt the visual perspective in the interior, especially at joints. However, the filled surfaces of the building are less than the density on the facade of the vertical structural elements designed at an equivalent height (Fig. 2).



(a) **(b)** **(c)**

Fig. 2 *John Hancock Center, Chicago, Illinois. Exterior. (a) View from below at corner; (b) View from below; (c) Axial stress distribution of exterior diagonal members; [18]–[20]*

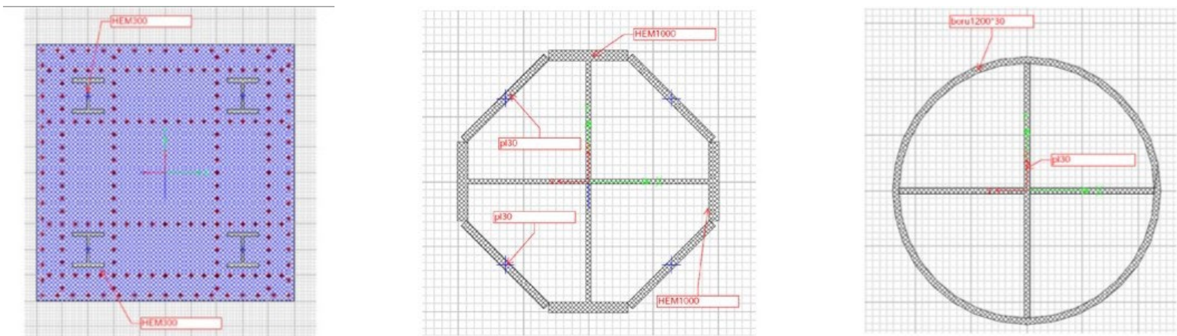
3. Willis Tower, Chicago: Willis Tower, one of the important structures built in the second half of the century, was removed from the building mass as it rose. The structural elements placed on the facade continue in the same rhythm direction. However, the evacuation and withdrawal of the masses at certain floors contributed to the formation of the form. The desire for free floor planning in the interior has guided what kind of structure system should be used in the design phase. Here, the task falls on the facade and the existence of the structural elements placed inside. The facade has undertaken a significant bearing role in this order and reflects the internal dynamics of an aesthetically simple form. There is an ornamental element added later on the facade. The preferred structural system in the Willis Tower allowed wider column spacing and greater height compared to the frame tube. The tower consists of 9 frame tubes and the column spacing is 4 m, while the column spacing is 1.02 m in the 110-floor World Trade Center Twin Towers at the same height. The aforementioned wider column spacings provided freedom in the architectural form and the Willis Tower structure came to the forefront by integrating with the architectural design [21]. Its structural form provided greater stability and required it to be widespread on the ground in line with improved proportions. The only thing desired to be presented aesthetically is the simplicity of the structure. It has been studied among the examples where the structure is decorated with its plain geometry (Fig. 3).

(a) **(b)** **(c)**

Fig. 3 *Willis Tower, Chicago (a) Skyline view of Chicago, dominated by Willis Tower; (b) Willis Tower illustrated by authors; (c) Modular floor configuration of Wills Tower [22], [20]*

2. Case Study

In the first stage, it discusses with examples, which of the high-rise buildings built in the 20th-century architecture emphasizes the ornamentation of the structure, the structuration of the ornament, the ornamented structure, and the ornamented construction thoughts [13]. And they are conceptually divided into four categories by Robert Kerr, one of the 19th-century architectural theorists. In order for the concept under discussion to have an impact on the design, three 320 m high-rise buildings, whose structure can be read from the outside, were designed according to the findings. The reason for choosing this height is that, in the world, 64% of tall buildings are in the range of 300-349 m. The floor areas of the three high-rise buildings are fixed and have a 45 x 45 m square plan. In the study of Alaghmandan and others, it was stated that 58% of the high-rise buildings built between 1949 and 2012 were square and/or rectangular in plan [23]. The profile plans of the mega column, 2HEM1000 profile, and cross members (CM) used in the architectural models are given in Fig. 4 in detail and the architectural setup of the three types of models designed is shown in Fig. 5. The dimensions of the three high buildings are 45 x 45 m and they are designed with a floor height of 4.5 m and 80 floors. The distance between the columns in the X and Y directions is 7.5 m. A core is formed with reinforced concrete shears at the center of the plan for the stairs and elevators. Mega columns are defined in each of the four corners of the plan. The mega column is 2.5 x 2.5 m in size and has 4 HEM300 steel profiles inside, and the profiles are surrounded by stirrups and longitudinal reinforcements. Sheer walls with a thickness of 60 cm were preferred in the reinforced concrete core, and the other columns were designed as steel 2HEM1000. HE550B profiles for main beams and IPE270 profiles for secondary beams are planned. A rigid diaphragm is assumed by using a stud (shear key) on floors. The CM's used on the facades of the designs are composed of the BORU1200*30 profile. In order to prevent regional crushing of the pipe profile and to increase the moment of inertia, it was added with a 30mm plate in the form of a plus.



(a) **(b)** **(c)**

Fig. 4 *(a) Mega column plan; (b) 2HEM1000 profile plan; (c) Profile plan used in CM's*

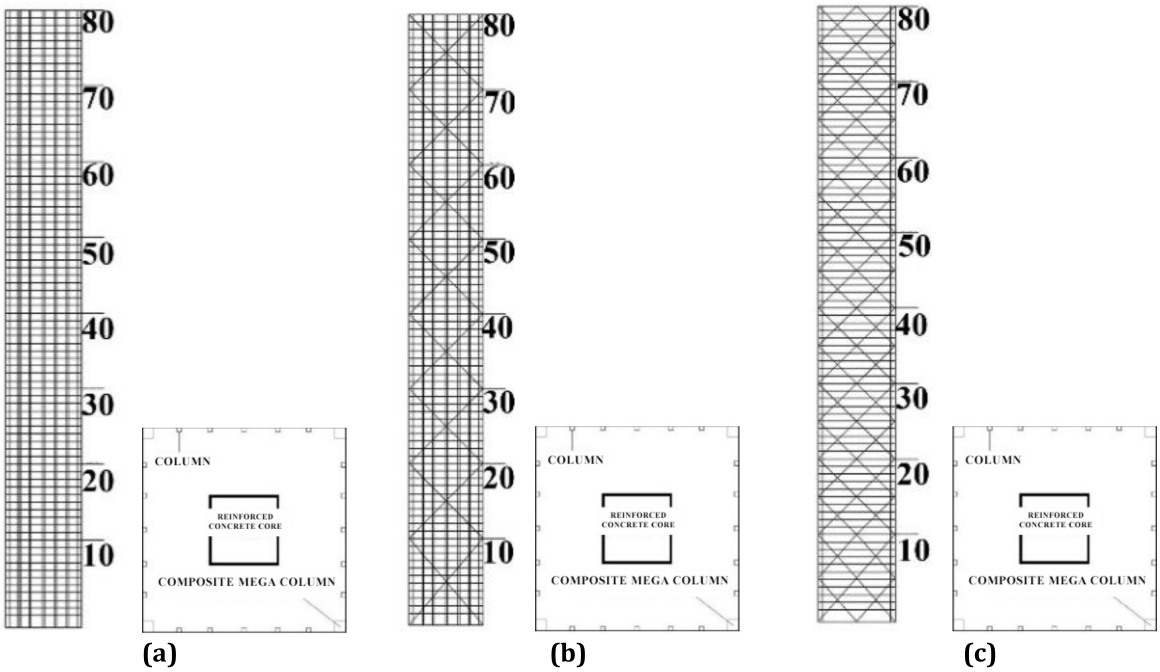


Fig. 5 *Views of the tall building facades designed (a) Type 1 plan and elevation; (b) Type 2 plan and elevation; (c) Type 3 plan and elevation*

In the first stage of the analysis, some values of the models were kept the same. For example, these include floor levels, total building load, reinforced concrete core layout and corner composite mega columns are used in the same way in all models. The evaluation constraints of the analyses consist of the evaluation of their performance within the floor height, 1st-degree earthquake zone, Z1 and Z4 soil class. The 3 types of high-rise buildings designed have equal floor area and consist of a reinforced concrete core, with different facade structural elements. The aim of this research is to examine the structural effectiveness of varying structural components that affect the formation of the facade. In this way, the structural elements, which are frequently used in high-rise facades, are modeled in 3D in the light of different arrangements, and their static and dynamic behaviors are examined over real data. Analyzes were prepared with the SAP2000 software program [24] and earthquake loads were given as response spectrum (RS).

The first-degree seismic zone and the local soil classes Z1 and Z4 were taken into consideration when modeling the structural system of the planned high-rise buildings using the SAP2000 software. While calculating the loads that the structure will be exposed to, TS498 [25], TEC2007 [26], TS648 [27], AISC-ASD89 [28], and IBC 2009 (Deflection Classes) [29] regulations and standards were generally used. For Z1, the spectrum characteristic periods were taken TA:0.10 and TB:0.30; for Z4, they were taken TA:0.20 and TB:0.90 [26] (Table 1).

Table 1 *Spectrum characteristic periods (TA, TB) [26]*

Local Soil	T_A	T_B
Z1	0.10	0.30
Z2	0.15	0.40
Z3	0.15	0.60
Z4	0.20	0.90

For the high-rise buildings modeled by the RS method, a core consisting of reinforced concrete material, columns made of steel material, mega-columns made of composite material, and CM's made of steel were used. The flooring material is designed as concrete flooring on the trapeze. A rigid diaphragm is assumed by using shear wedges on the floor. A rigid diaphragm is assumed by using shear wedges on the floor. The mechanical features of the structural steel (Hea, Heb, and I profile) utilized in the system's design, Sts. 52 (S355 JR) and 44 (S275 JR), are listed in Table 2.

Table 2 *Elements used in the finite element models*

Element	Element Type	Modulus of Elasticity (GPa)	Tensile Strength (GPa)	Yield Limit (GPa)	Shear Module (GPa)	Poisson Ratio	Coefficient of Thermal Expansion (1/^{0}C)	Unit Weight (kN/m^3)
St 52-S355JR	Frame	210.00	510.00	355.0	80.769	0.30	1.17x10	76.97
St 44-S275JR	Frame	210.00	430.00	275.0	80.769	0.30	1.2x10	76.97

Load Combinations; Fixed loads acting on the building system, dead loads, snow loads, horizontal and vertical earthquake loads were taken in accordance with AISC-ASD89 [28]. Loads included in the calculations: The coating loads are transferred as a uniformly distributed load on the purlin elements. Loads included in the calculations are transferred as a uniformly distributed load. The loads considered for the 3 types in the calculations are:

- Coating load (reinforced concrete flooring + coating): 500 kg/m^2
- Live load: 350 kg/m^{2}s
- Wall load: 1050 kg/m
- Glass facade: 500 kg/m
- Snow: 75 kg/m^2
- Temperature: ± 20 degrees
- Wind load: 50-80-110-130 kg/m^2

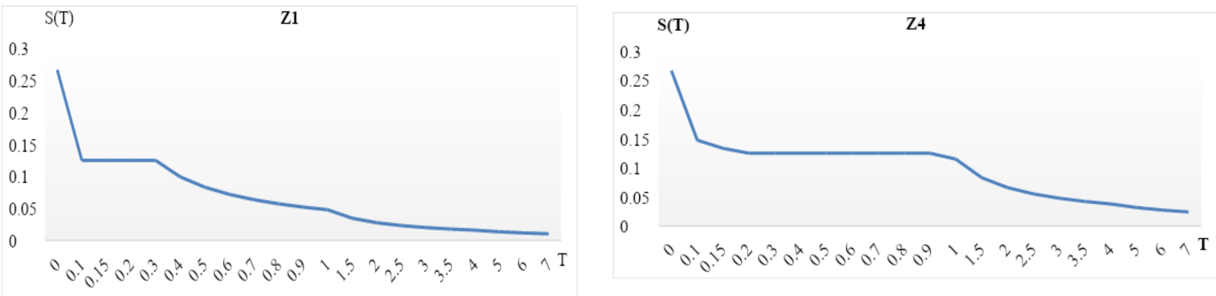
Fixed loads are defined in the TS498 [25] and TS648 [27] codes as static forces as a result of the self-weight of all the components that make up the system. In this system, the self-weight of the components that make up the tall structure and the support system are considered as constant loads.

Spectrum coefficient: The spectrum coefficient is a value that depends on the local soil conditions and the natural period of the building. Local soil classes Z1 and Z4 are considered, as shown in Table 3.

Table 3 *Elements used in the finite element model*

Local Ground	T_A	T_B
Z1	0.10 sec.	0.30 sec.
Z4	0.20 sec.	0.90 sec.

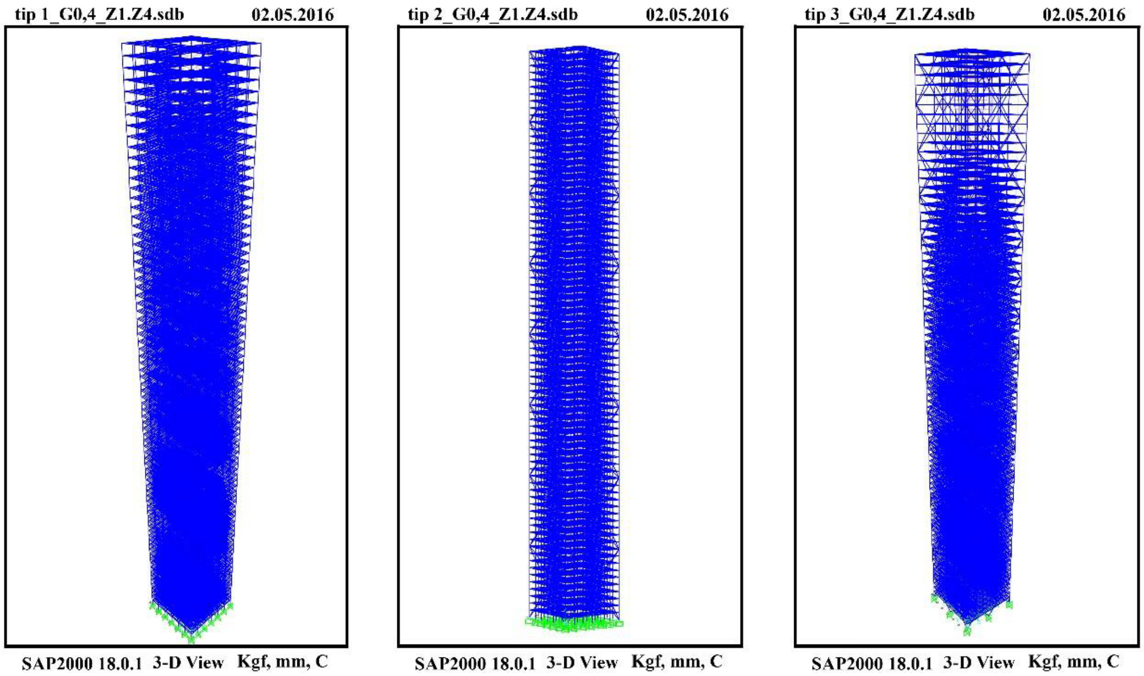
The dynamic analysis of the three-dimensional modeled structure was analyzed with the SAP2000 software program, using the RS diagrams shown in Fig 6.



(a) **(b)**

Fig. 6 *RS diagrams (a) Type 1 spectrum curve for the soil class Z1; (b) Spectrum curve for the soil class Z4*

Modeled views of high-rise buildings with three different facade types designed in the SAP2000 program are given in Fig 7. The structural system on the facade of the Type 1 model was designed using steel tubular profiles and composite mega-columns at the corners and was solved with a tubular frame system (TFS). The structural system on the facade of the Type 2 model was designed using steel pipe profiles, composite mega columns at the corners, and diagrid steel elements, and was solved with a tubular diagrid system (TDS). The structural system on the facade of the Type 3 model is designed using composite mega columns and diagrid steel elements at the corners and is solved with a diagrid system that exhibits tubular behavior and lattice characteristics.

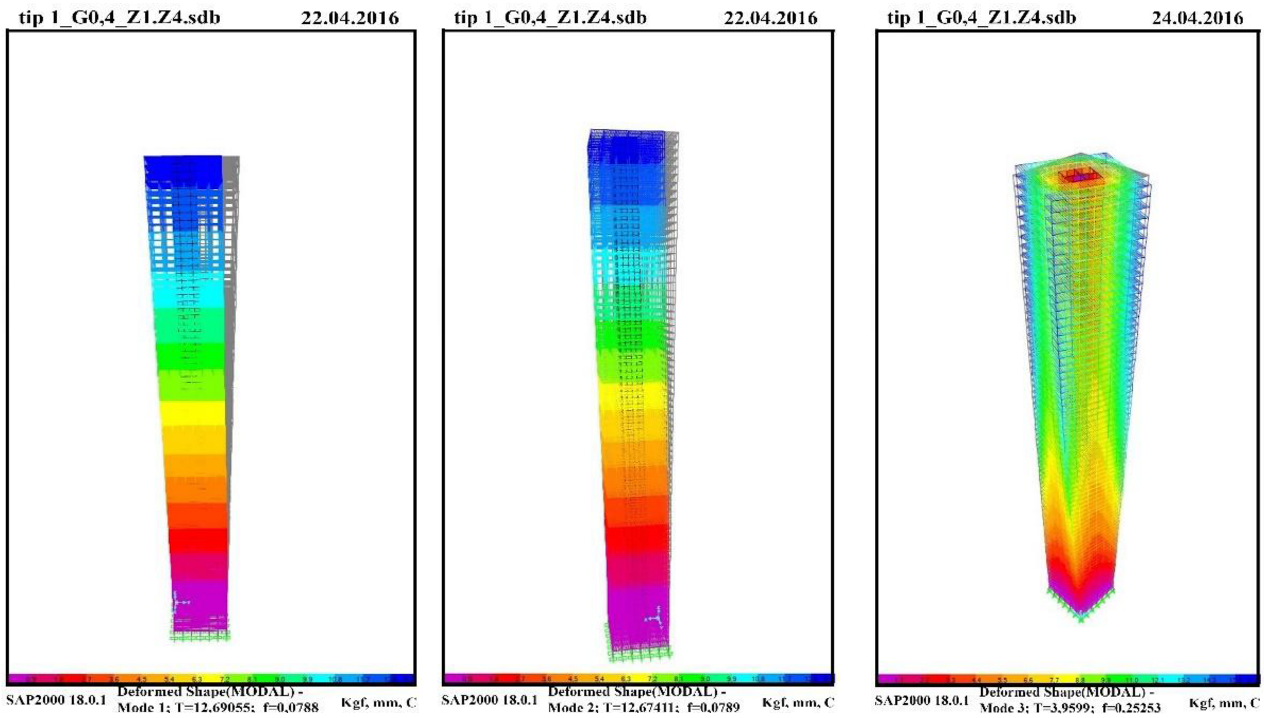


(a) **(b)** **(c)**

Fig. 7 *Views of the high-rise building facades designed (a) Type 1 plan and elevation; (b) Type 2 plan and elevation; (c) Type 3 plan and elevation*

2.1 Comparisons of Findings for the Structure Models of Type 1, 2 and 3

The modal analysis of the three types of tall buildings designed by considering the first 3 modes is shown in Fig. 8, and the comparison of the first 3 Mode values shown in Fig. 9.



(a) **(b)** **(c)**

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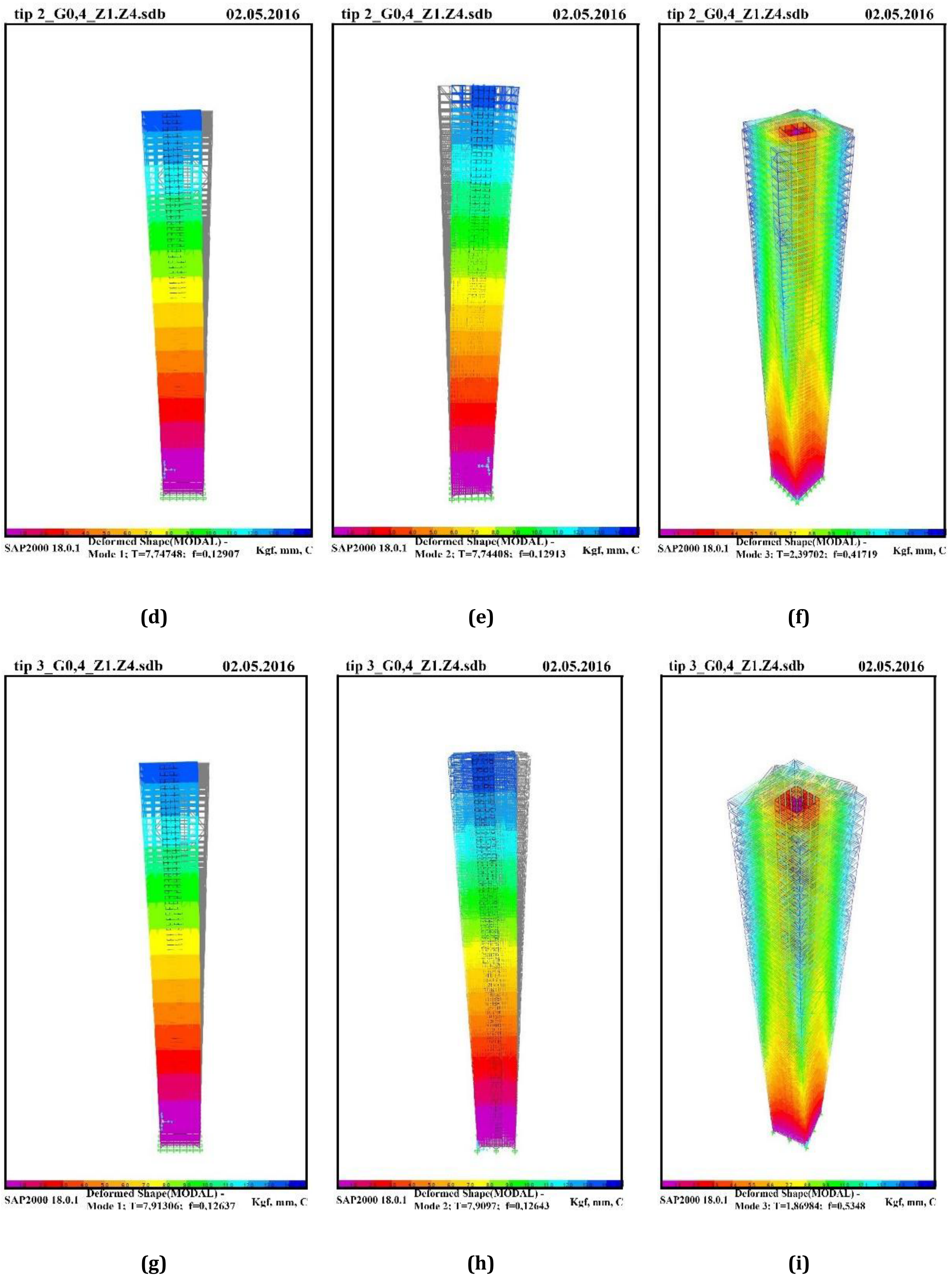
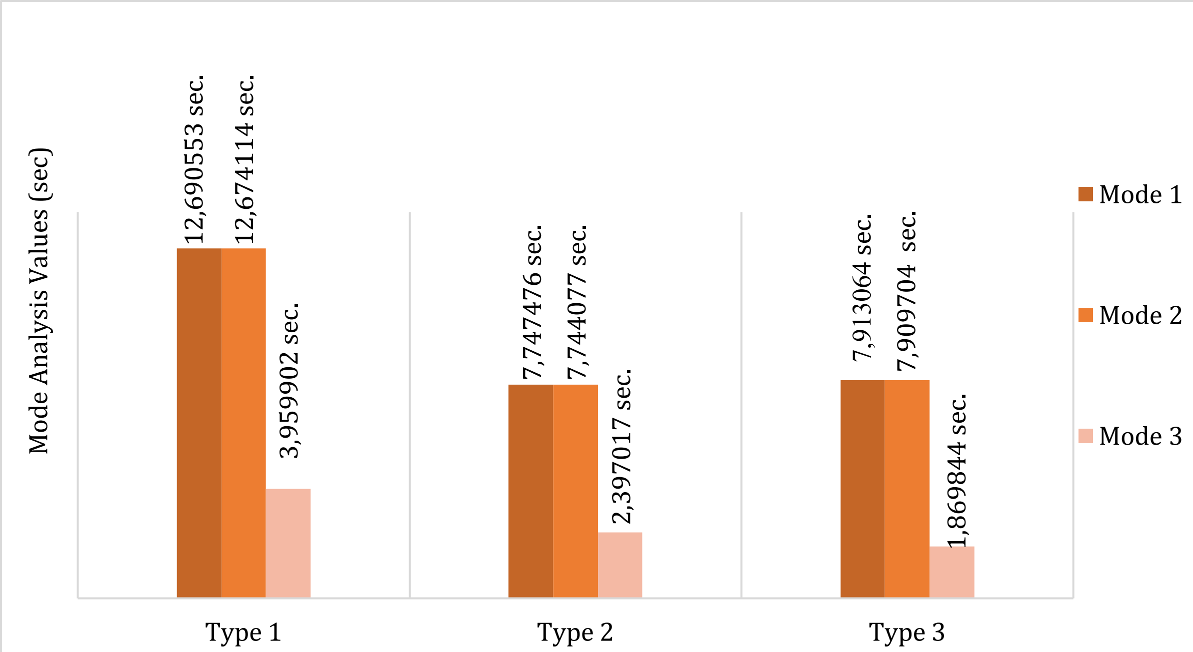


Fig. 8 *The modes of three different types of buildings (a) Type 1 Mode 1; (b) Type 1 Mode 2; (c) Type 1 Mode 3; (d) Type 2 Mode 1; (e) Type 2 Mode 2; (f) Type 2 Mode 3; (g) Type 3 Mode 1; (h) Type 3 Mode 2; (i) Type 3 Mode 3*

The comparison of the first 3 Mode values for Type 1, Type 2, and Type 3 is evaluated in Fig 9.



(a)

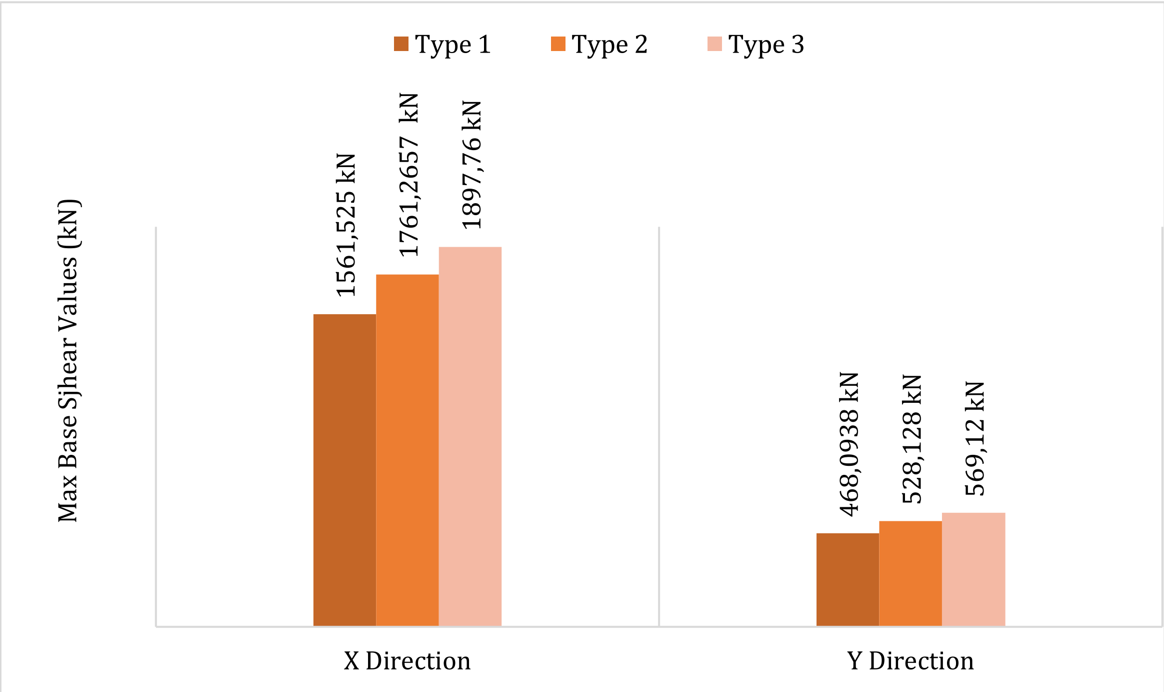
Fig. 9 *(a) Comparison of Type 1, Type 2, and Type 3's first three Mode values (sec.)*

Fig. 10 shows the structural weight values for the three alternative steel facade designs for the designed high-rise.

(a)

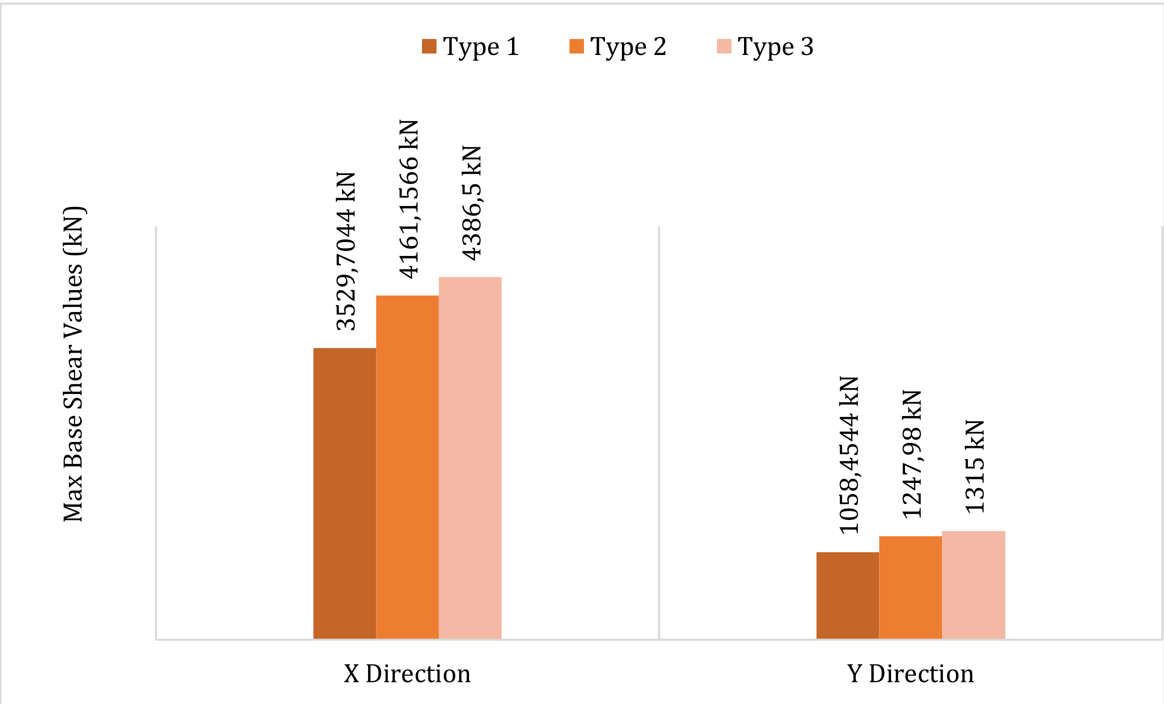
Fig. 10 *(a) Values of the three different facade designs' structural weights (tons)*

The maximum base shear values (MBSV) of the three different facade designs of the designed building, D1Z1 and D1Z4, are shown in Fig. 11 and Fig. 12.



(a)

Fig. 11 *(a) Comparison of Type 1, Type 2, and Type 3 MBSV (kN) in D1Z1*



(a)

Fig. 12 *(a) Comparison of Type 1, Type 2, and Type 3 MBSV (kN) in D1Z4*

The joint points considered for the maximum displacement (relative story drift) value (MDV) according to the type 1 model, Z1 and Z4 soil classes are taken from three different points of the high building. The nodes are numbered as number 1 on the 28th floor of the high building, number 2 on the 50th floor, and number 3 on the 80th floor, starting from the base, respectively. The MDV of the designed tall structure, taking into account D1Z1 and D1Z4, are shown in Fig. 13 and Fig. 14.

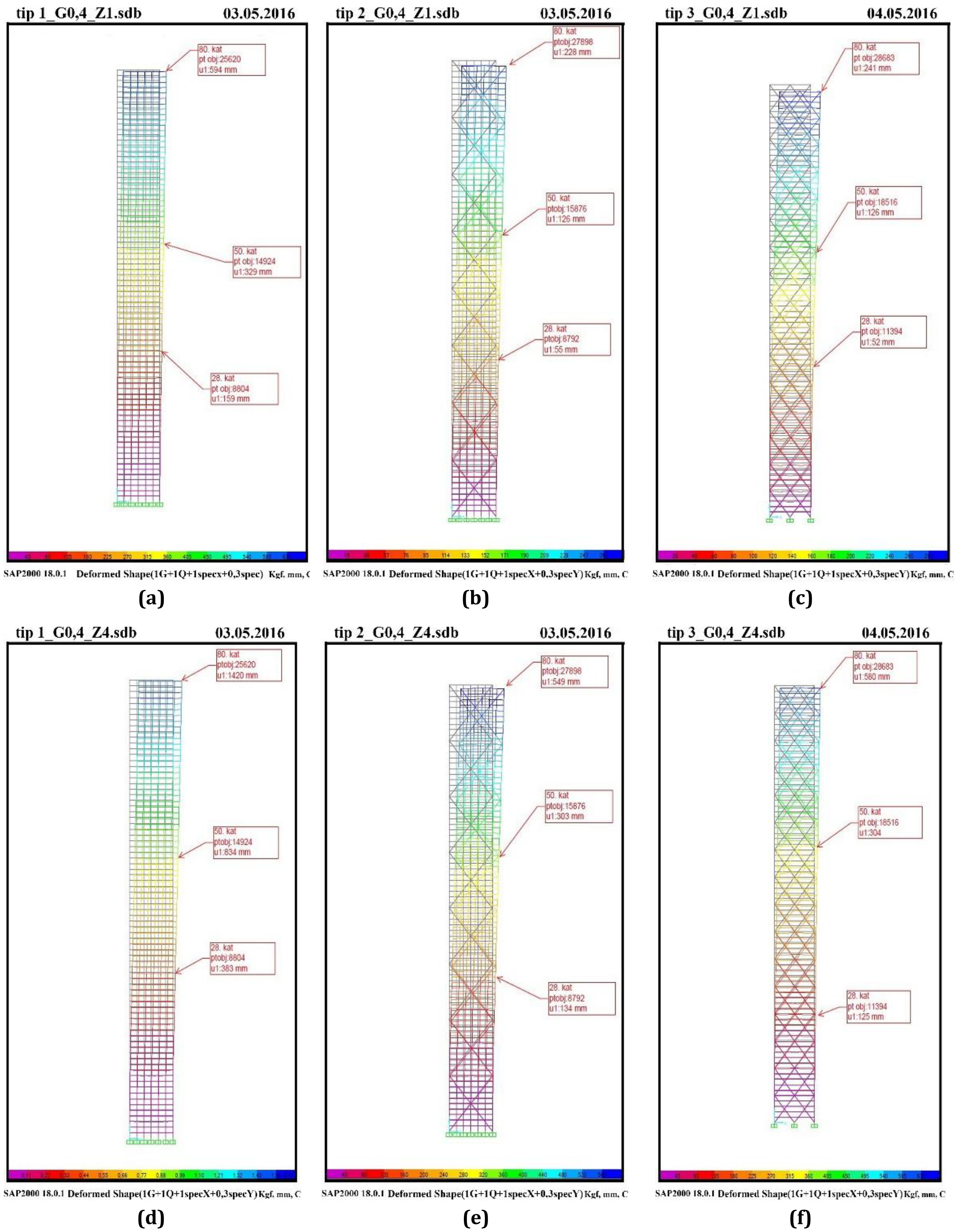
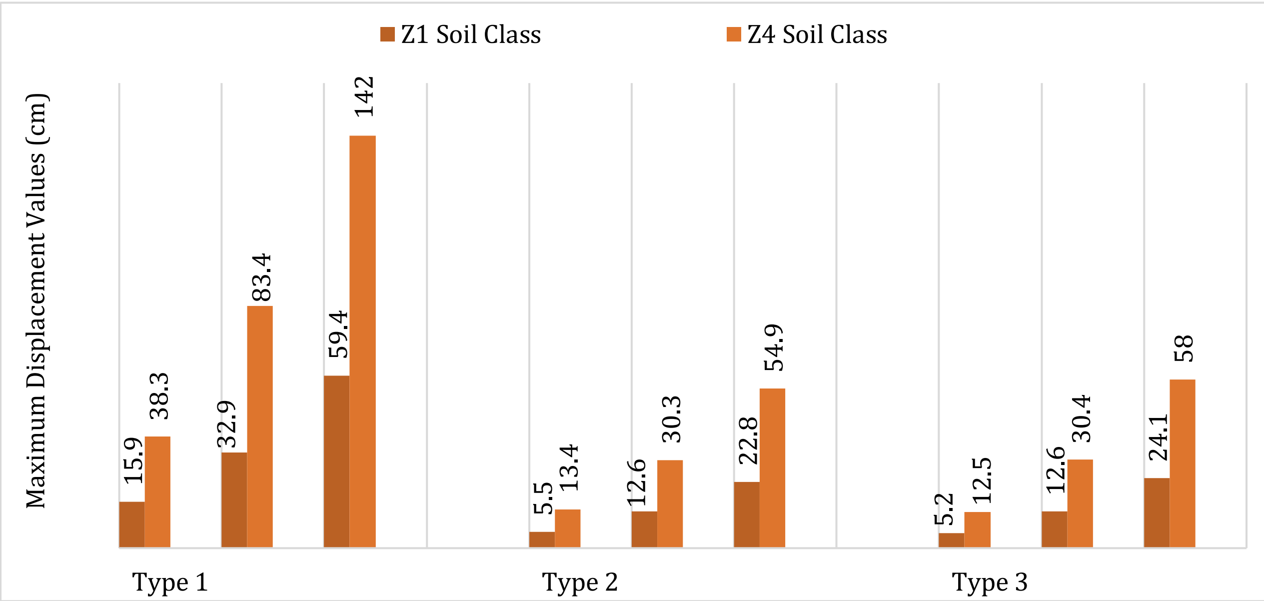


Fig. 13 *MDV for Type 1, Type 2, and Type 3 (cm) are compared in D1Z1 and D1Z4 as follows: (a) Type 1 Z1; (b) Type 2 Z1; (c) Type 3 Z1; (d) Type 1 Z4; (e) Type 2 Z4; (f) Type 3 Z4*

Penerbit UTHM



(a)

Fig. 14 *(a) Comparison of Type 1, Type 2, and Type 3 MDV's (cm) in D1Z1 and D1Z4*

As seen in Fig. 9, 10, and 11, base shear, and displacement values in RS analysis are compared for the Z1 and Z4 soil class in the first-degree earthquake zone. The MBSV in the X-direction is taken as 1761,2657 kN 100% in the Z1 soil class of Type 2, which has the traditional column layout and the system using diagrid structural elements on the facade, and it showed a result of 11,34% compared to Type 1 and 7.74% lower than Type 3. With a MBSV of 528,128 kN 100% in the Y direction, Type 2 performed 11.36% higher than Type 1 and 7.76% lower than Type 3. In the X and Y directions, Type 2's MBSV's were higher than Type 1's and lower than Type 3's (Fig 11).

As can be seen in Fig. 12, the MBSV in the X direction is taken as 4161,1566 kN 100% in the Z4 floor class of Type 2, which has a system using traditional column layout and diagrid structural elements on the facade, and it showed a 15,17 % higher result than Type 1 and 5.41% lower results than Type 3. The MBSV in the Y direction of Type 2 was taken as 1247.98 kN 100% and it showed a result 16.18% higher than Type 1 and 5.37% lower than Type 3. The MBSV's of Type 2 were higher than Type 1 and lower than Type 3. MDV's are found at the 3rd node according to each building type and both ground conditions. As can be seen in Fig 13 and Fig 14, the MDV of Type 2 in the Z1 soil class when taken as 22.8 cm is 100% 160.5% lower than Type 1 and 5.7% lower than Type 3, respectively. The MDV of Type 2 according to the Z4 soil class, when taken as 54.9 cm is taken as 100%, is 158.6% lower than Type 1 and 5.6% lower than Type 3, respectively. When the soil classes are compared, the MDV's of Type 1, Type 2, and Type 3 in themselves were lower in the Z1 soil class compared to the Z1 and Z4 classes, and it was determined that the horizontal drift was higher as the soil class deteriorated.

In addition, as seen in Fig 9 and Fig 10, Mode values and structure weight are compared for three alternative steel facade designs. As shown in Fig 10, the Mode 1 value of Type 2 is taken as 100% for 7.747476 sec, and it is 63.8% lower than the Mode 1 value of Type 1 and 2.1% lower than the Mode 1 value of Type 3. The Mode 2 value of Type 2 was taken as 100% for 7.744077 sec, and it was 63.6% lower than the Mode 2 value of Type 1 and 2.1% lower than the Mode 2 value of Type 3. The Mode 3 value of Type 2 was taken as 100% of 2.397017 sec, and it was 65.2% lower than the Mode 3 value of Type 1 and 22% higher than the Mode 3 value of Type 3.

As can be seen in Fig. 10, the Type 2 model has increased the weight of the structure due to the use of CM's used in the facade compared to the Type 1 model. According to Type 3, the reason for the increase in the weight of the building is due to the columns used on the facade, except for the mega column. In the Type 3 model, vertical columns were removed from the facade and only CM's were used instead. Diagrid structural elements used are lighter than vertical columns. The total structure weight of Type 2, in which cross and vertical members are used together, is taken as 203,715 tons 100% is planned, 2.6% heavier than Type 1 and 0.9% heavier than Type 3.

The facade formation of the 3 types of structural systems selected as a result of the analysis was shaped under vertical and horizontal loads. A reinforced concrete core at the center of the building and a mega composite column system at the four corners of the building were considered in all three types of systems with a height of 80 floors. Evaluation of the efficiency of the facade layouts in Z1 and Z4 ground conditions constituted the basic input of the analysis. What differs in the facade is the structural arrangement of the structural elements preferred among the mega-columns. Type 1 is planned to use steel columns, a modern material interpretation of the traditional column layout, between mega columns. Type 2 is supported by CM's in addition to the Type 1 facade layout. On the other hand, in the Type 3 model, vertical elements were not used on the facade, except for the mega columns, and only double CM's were used for the lattice appearance.

Therefore, the Mode 3 value of the Type 3 model (1,869844 sec) was lower than the other facade models. However, the first two Mode values of Type 2 (respectively 7,747476 sec and 7,744077 sec) namely the horizontal translations in the Y and X directions, were lower than Type 1 (respectively 12,690553 sec and 12,674114 sec) and Type 3 (respectively 7,913064 sec and 7,909704 sec) (Fig. 9). In addition, the MDV in high-rise buildings emerged at the highest peak of the structure, and these values differed for each type according to the Z1 and Z4 soil classes. Type 1 has the highest displacement values with 142 cm according to Z4 soil class. Type 3 has the lowest displacement values with 5,2 cm according to Z1 soil class. However, Type 2 model has lower displacement values than the Type 1 and Type 3 models according to Z1 and Z4 soil classes with overall results (Fig. 14).

The justification for the analyses is to reveal how these different facade formations affect structural behavior. When evaluating the facade structure layouts of the three high-rise buildings used in the literature, it was found that the horizontal and vertical loads are shaped against the height problem. Diagrid elements are used as a solution to the height problem in the facade layout. In this context, the fact that structural elements can be expressed as ornaments has emerged at the intersection of structural and architectural concerns. Within the framework of the idea of showing the structure on the exterior, the structural elements that shape the high-rise facade have been evaluated in light of their effective contribution to the architecture, resulting in the necessity of creating facade models.

3. Conclusion

Every structure belonging to the environment we interact with in our daily life is first perceived with its shell, facade, and form. This perception has been strengthened in the history of high-rise buildings, and the effect of the high-rise building on the city silhouette has increased considerably. For this reason, within the scope of the high-rise study area, the visuality of the facade, its structural order, and aesthetic concerns have come to the fore.

In light of the developments brought by the Industrial Revolution in the 19th century: the materials found, the tools discovered, and the construction techniques made it easier to raise the structures and to read the structure from the outside. Over-indulgence in ornamentation in this century led to the exclusion of ornamentation in the 20th century. In the 19th and 20th century cross-sections, examples where ornament was used in the first sense were also exhibited. In the second half of the century, the structure simply showed itself and the ornament became the structure itself. In addition, in the 21st century, a return to ornament has begun. However, architects and engineers have begun to structure their inspirations from nature like an ornament in their buildings. Evaluations in this context shaped the facade characters of the 3 high-rise buildings examined before the field study and formed the base of the models. The relationship between various facade techniques, structural arrangements, and decoration approaches has affected the high-rise facade formation and determined the dynamic behavior of the models. A reinforced concrete core and 4 composite mega-columns at the corners are considered fixed load-bearing elements in the models. In the facade analysis, the data of the models other than the facade design; core area, floor area, and total loads acting on the building are taken as the same. As the facade models changed, the weight of the building changed due to the changing load-bearing elements. However, the dimensions of the load-bearing elements did not change. The application limit of the research; It is 80 floors high, 1st-degree earthquake zone, and Z1/Z4 ground class. These limits were determined based on the data on the application areas and areas of the 10 high-rise buildings examined. The following conclusions have been reached over 3 types of models regarding the effect of architectural facade formation.

1. As mentioned above, in high-rise buildings, parallel to technological developments, the structural system has produced some solutions against height, and in the traditional high-rise building technique, the facade arrangement has been shaped by vertical columns and horizontal beams. In this framework, the exterior setup of the Type 1 model is fed from the traditional structural order. However, the limitation of the 80-story height necessitated the Type 1 model to be purged from traditional building materials and shaped with steel, which is a contemporary building material. In addition, the number of floors that the model's load-bearing system can reach efficiently and economically determines the type of system selected. The Type 1 model's facade structural system was designed with steel tubular columns and composite mega columns at the corners and solved with a TFS. Due to the vertical rise of tall buildings, horizontal loads (earthquake and wind) are felt more on the structure. For this reason, the structural design has been shaped under these forces in order to keep the lateral translations at a reasonable level. The period values of the Type 1 model in Mode 1 (12,690553 sec.) and Mode 2 (12,674114 sec.) directions were higher than Type 2 (respectively 7,747476 sec., 7,744077 sec.) and Type 3 (respectively 7,913064 sec., 7,909704 sec.) due to the use of vertical structural elements on the facade. Mode 3, that is, the torsion value is also higher

than other models. The displacement value was higher in Z1 and Z4 soil classes than in Type 2 and Type 3. When the static and dynamic behaviors of high-rise buildings designed using only vertical elements on the facade are evaluated, it is concluded that the lateral displacements are high.

2. Type 2, which is the second of the facade models, was created by adding a diagrid structural element in 10 layers to the facade of the Type 1 model. The structural system on the facade of the model is designed using steel pipe profiles, composite mega columns at the corners, and diagrid steel elements, and is solved with a TDS. Therefore, the structure is designed to weigh 2.6% more than Type 1 and 0.9% more than Type 3. However, the period values and MDV's in Mode 1 and Mode 2 were lower in Z1 and Z4 soil classes compared to other models. CM's, which meet the horizontal loads, have contributed positively to the static and dynamic behavior of the building and have balanced the horizontal and vertical effects by breaking the vertical emphasis of the building mass.
3. The facade structural system of the Type 3 high-rise model was designed using composite mega columns at the corners and diagrid steel elements on the surface and was solved using a diagrid system with tubular and lattice characteristics. Unlike Type 1 and Type 2 models, vertical load-bearing elements are not used on the facade, except for the composite mega-columns used at the corners. The facade design carries horizontal and vertical loads, and a geometric pattern is established on the building. Compared to Type 1 (198333 tons), the structure's weight was higher (201951 tons), but it was lower than Type 2 (203715 tons). Analysis revealed that Mode 1's period values (7,913064 sec.) were lower than Type 1's (12,690553 sec.) and higher than Type 2's (7,747476 sec.). Also, MDV's were lower than Type 1's and higher than Type 2's. However, the Mode 3 (torsion) period value (1,869844 sec) gave lower results than both models thanks to the double cross system used. As a result of the static and dynamic behavior analysis of the model, it can be said that the strong language of geometry strengthens architectural expression.

As a result, the structure and ornament phenomenon, which is defined as construction activity on the facade, follows the technology of its age with its changing structural elements, facade characteristics, and technical features, and shapes the high-rise facade setup. In this context, it has been determined that the technical accumulations of the 19th, 20th, and 21st centuries are at the core of the changing facade language. In particular, the facade-structure-ornament relationship will be evaluated as an effective language by the architecture and engineering circles. The justification for the analyses is to show how these different facade formations affect structural behavior and highlighted the necessity for architects and engineers to work collaboratively.

Behavioral analyses of high-rise facade models designed on conceptual and theoretical foundations will provide a concrete framework for designers and researchers. In conclusion, the dialectic of structure and ornamentation in the design of facades, the dynamic behavior impacts on the design of facades of high-rise buildings are undeniable, and the structure should be expressed clearly. The dynamics of the facade behavior of tall buildings is analyzed from an architectural point of view and includes a basic analysis. As technology develops and the climate changes, these analyses will need to be developed together with environmental factors. Future studies can also consider statistical and probabilistic analyses by taking into account different factors such as wind loads and can improve the study by working on different structural systems.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

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References

[1] Frampton, K. (1995). *Studies in Tectonic Culture-The Poetics of Construction in 19th and 20th Century Architecture*, Cambridge: MIT Press, 3-21.
[2] Ruskin J. (1980). *The Seven Lamps of Architecture*, John Wiley&Sons, New York, U.S.A., 1980.
[3] Torroja, E. (1958). *Philosophy of Structures*, The Beauty of Structures, Los Angeles: University of California Press, 268.
[4] Jones, O. (1910). *The Grammar of Ornament*, New York: The Ivy Press Limited, 5, 1910.

[5] Semper, G. (1889). *The Four Elements of Architecture and Other Writings* (Transl. H. F. Mallgrave, W. Herrmann), Cambridge: Cambridge University Press, 29.
[6] Kerr, R. A. (1869). *Development of the Theory of the Architecturesque*, Royal Institute of British Architecture Conference, 89-102.
[7] Demirkan, Ö. (2016). *The Research of the Relation Between Structure and Ornament in Architecture*, Master Thesis, Graduate School of Natural and Applied Sciences of Gazi University, Ankara.
[8] Beedle, L. S. & Rice, D. B. (1995). *Structural Systems for Tall Buildings*, CTBUH Committee 3, New York: McGraw-Hill Inc, 7.
[9] Khan, F. R. (1973). *Evolution of structural systems for high rise buildings in steel and concrete*, In J. Kozak (Eds.), Tall Building in The Middle and East Europe: Proceedings of the 10. Regional Conference on Tall Buildings-Planning.
[10] Ali Mir, M. & Moon, K.S. (2007). Structural developments in tall buildings: current trends and future prospects, *Architectural Science Review*, 50 (3), 205-223, https://doi.org/10.3763/asre.2007.5027
[11] Abdulmajeed, M.W. & Ahmed, I. (2017). Design of High Rise Reinforced Concrete Buildings. *Civil and environmental research*, 9, 41-54.
[12] Rybakov, V. A. & Deriugin, K. S. & Pushkarskaya, M. A. & Urmanceva, K. A. (2020). Facade Systems Modal Analysis in Consideration its Own Dynamic Characteristics of the Frame. *Construction of Unique Buildings and Structures*. *89*, 8906.
[13] Kozan, F. (2016). Structural Analysis of the Bearing Elements Affecting the Facade Shaping in High-Rise Buildings, Master Thesis, *Graduate School of Natural and Applied Sciences of Gazi University*, Ankara.
[14] Yılmaz, F. & Soyluk, A. (2023). Examination of Avalanche-Resistant Building Design Through Countries' Development Levels and Their Code of Ethics for Architects. *Journal of Namibian Studies: History Politics Culture*, 35, 3992–4017, https://doi.org/10.59670/jns.v35i.4341
[15] Britannica (2013). Bank of China Tower. *Encyclopedia Britannica*, 2013, Retrieved June 1, 2024, from https://www.britannica.com/topic/Bank-of-China-Tower
[16] Jhon B. Townsend (2004). Bank of China, Retrieved June 1, 2024, from http://skyscrapermodels.us/models/bank_china_hkc.html edited by authors.
[17] Günel M. H. & Ilgın H. E. (2010). *Yü*ksek Binalar: Taşıyıcı Sistem ve Aerodinamik Form, ODTÜ Mimarlık Fakültesi Basım İşliği, Ankara, Türkiye. https://hdl.handle.net/11511/70255
[18] Skidmore, O., M. & Balthazar Korab Studios, L., photographer. (n.d.). *John Hancock Center, Chicago, Illinois. Exterior. View from below at corner*. Illinois Chicago, None. [Between 1975 and 1989] [Photograph] Retrieved June 1, 2024, from the Library of Congress. https://www.loc.gov/item/2021636629/
[19] Skidmore, O. M. & Balthazar Korab Studios, L., photographer. (n.d.). *John Hancock Center, Chicago, Illinois. Exterior. View from below*. Illinois Chicago, None. [Between 1975 and 1989] [Photograph] Retrieved June 1, 2024, from the Library of Congress. https://www.loc.gov/item/2021636628/
[20] Beedle, Lynn S. & Iyengar H. (1982). Selected works of Fazlur R. Khan (1929-1982), John Hancock Center, Chicago, Illinois (USA), *IABSE Structures = Constructions AIPC = IVBH Bauwerke*, *6*(C–23), 74–77. https://doi.org/10.5169/seals-17602
[21] Kerr R. A. (1869). *Development of the Theory of the Architecturesque,* Ö. Demirkan (Trans.), Royal Institute of British Architecture Conference, London-England, 85-102.
[22] Highsmith, C. M. photographer. (n.d). *Skyline view of Chicago, Illinois, dominated by Willis Tower, long known as Sears Tower*. United States Illinois Chicago, None. [Between 1980 and 2006] [Photograph] Retrieved June 1, 2024, from the Library of Congress. https://www.loc.gov/item/2011636232/
[23] Alaghmandan, M. & Bahrami, P. & Elnimeiri, M. (2014). The future trend of architectural form and structural system in high-rise buildings, *Architecture Research Journal*, 4(3), 55-62. https://doi.org/10.5923/j.arch.20140403.01
[24] SAP2000 (2005). Integrated Structural Analysis and Design Software, *Computers and Structures, Inc*., Berkeley, California.
[25] TS498 (1997). Design Loads for Buildings, Account Values of Loads to be Taken into Consideration the Dimensioning of Structural Elements, *Turkish Standardization Institute*, Ankara, Türkiye.
[26] TEC2007 (2007). Specification for Buildings to be Built in Earthquake Regions, *Ministry of Public Works and Settlement*, Government of the Republic of Türkiye.
[27] TS648 (1997). Account and Construction Rules of Steel Structure, *Turkish Standardization Institute*, Ankara, Türkiye.
[28] AISC-ASD89 (2005). *An American National Standard*, Specification for Structural Steel Buildings, Chicago, U.S.A.
[29] IBC2009 (2009). International Code Consortium, *International Building Code*, Chicago, U.S.A.