Research Article GU J Sci, Part B, 11(2): 269-282 (2023)

Gazi University

Journal of Science

PART B: ART, HUMANITIES, DESIGN AND PLANNING

http://dergipark.gov.tr/gujsb

Effect of Architectural Design in Twisted-Form Buildings to Structural System Design

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Article Info

Received: 29/05/2023
Accepted: 26/06/2023

Keywords

Architectural Design,
Twisted buildings,
Torsion in buildings,
Structural System Design,
Seismic Behavior,
Inclined Columns,
Stepped Columns,

Abstract

The number of buildings with twisted forms is increasing each day with the development of analysis, drawing methods, material technology, and the increase and optimization of construction techniques, thus the architects and engineers are looking for different solutions in their designs. As the height of the building increase, the forms obtained by the rotation of each floor slab relative to the previous slab can be defined as twisted forms. It is possible to construct many different twisted building forms by using different rules, templates, and parameters while designing. Twisted buildings, which can be accepted as a new design methodology with respect to traditional methods, provide many advantages in design but also give rise to significant and critical problems. In this study, the geometrical features and parameters of twisted buildings are introduced. Architectural features, advantages, and disadvantages of twisted buildings are discussed. The positive and negative effects of the twisted form on the behavior of the structural system are investigated, and types of structural systems are provided as an example for buildings with this form. Case study twisted buildings, the problems encountered during the design and construction of these buildings, and the solutions proposed and applied by the designers to these problems are studied. Consequently, the advantages, disadvantages, applicability, and sustainability of twisted form building are evaluated within the framework of the rules and guidelines in today's regulations, and the issues that should be considered in the design of the building and during the construction are discussed.

1. INTRODUCTION

As the height of the building increase, the forms obtained by the rotation of each floor slab relative to the previous slab in the plan can be defined as twisted forms [1]. Voller also classified twisted buildings as "Twisters" and "Tordos" in his study on buildings with extraordinary forms [2]. The twist can be designed equally and the same on all floors, or different amounts can be designed only on certain floors.

Today, these forms are mostly obtained by floor geometric center (centroid) acting as a pivot point in the design. However, it is also possible to make different design options where the pivot point of rotation is not the geometric center. The location of the pivot point greatly affects the design & form of the building.

The center of rotational motions is the specified pivot point in the plan, and how much movement any specific point in the plan made is determined with respect to its distance to the pivot point. Therefore, different points in the floor plan are affected differently even if the rotation angle is constant. This situation causes the building elements with the same dimensions in the floor plan to differentiate as with the rise of each story. For example, a column in the corner and another column in the interior that is closer to the pivot point will have different slopes even if they have the same cross-sectional dimensions.

One of the factors affecting the form is the value of rotation angle per floor. For example, a 60-story building with a rotation angle of 1.5 degrees per floor is twisted 90 degrees as form, while a 60-story building with

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a rotation angle of 3 degrees per floor is twisted 180 degrees as form. Another important factor affecting the form is the plan geometry. For example, for a building with a circular plan geometry, the rotation of the floor plans does not change the form of the building if the pivot point is also the geometric center. Also, a building with a triangular plan geometry and a building with a square plan geometry will have completely different forms even if the rotation angle per floor is same for the both cases. Schematic drawings for some of the twisted building forms are given in **Figure 1** below.

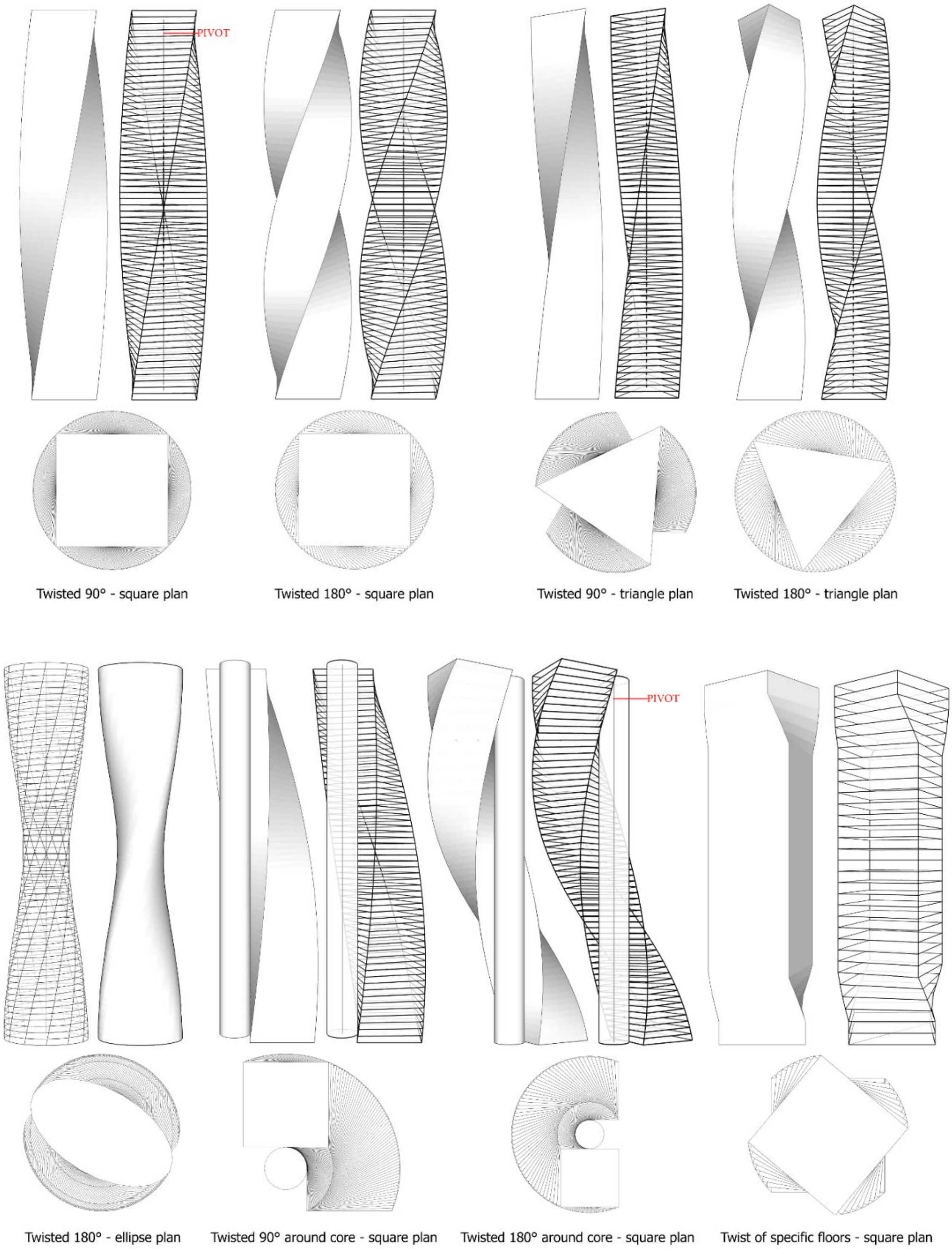

Figure 1. *Schematic drawings of twisted buildings (drawing by the author)*

2. ARCHITECTURAL PROPERTIES OF TWISTED BUILDINGS

Apart from aesthetics, the twisted forms offer different scenery view possibilities for each floor plan. The scenery and the orientation of the building are important elements in the creation of the architectural program. By creating different architectural plans for each floor in twisted-form buildings, it is easier to obtain the desired scenery and building orientation in the program.

If the structural system rotates along with floor slabs, the geographic coordinates of the columns change on each floor, but their position in the architectural plan is fixed. Thus, the architectural floor plans are not affected by the rotation dramatically. It's seen in **Figure 2** below how the coordinates of columns change throughout the building. However, in this case, the columns in the structural system should be designed either inclined or the columns should be designed vertically but offset in accordance with their projection on the next floor slab.

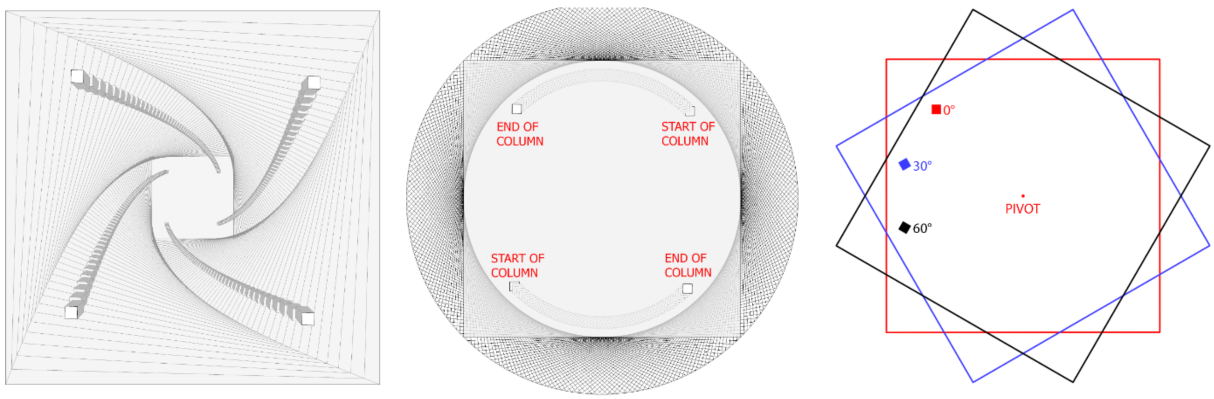

Figure 2. *Plan & perspective view of twisted buildings, and footprint of the 0, 30, and 60° rotated column in the floor plan (drawing by author)*

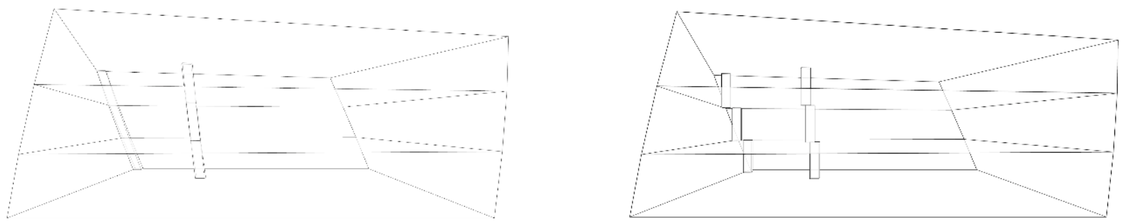

Figure 3. *Schematic drawings of inclined columns and offset columns in twisted buildings (drawing by the author)*

When the columns are designed with inclination, it will be difficult to achieve integrity between columns in the partition walls. In this case, designers have to propose different solutions regarding the design of partition walls. If the columns are built by offset, the basic principle of columns being vertically continuous will be violated, and the section dimensions of the columns in the structural system increase due to eccentricity. The twist effect in the building can also be achieved by shifting the location of cantilever slabs on each floor. In this case, the floor plans are different for each floor but the structural system is not affected by the form itself. It is necessary for the designers to evaluate the locations of cantilevers in the floor plans and adjust the program to obtain the best functionality of the space. A different concept building form design achieved by shifting cantilever positions is shown in **Figure 4** below.

In most regulations besides the special cases, high-rise buildings are required to be positioned at a certain minimum distance from neighboring structures, depending on their height. Unlike standard buildings, the distance to the neighboring building in twisted buildings will change on each floor as the floor plans rotate.

While this change may be limited if the geometric center (centroid) is the pivot point of rotation. However, the change can be much more dramatic if the pivot point of rotation is not the geometric center. For this reason, while locating such buildings on the ground, there is a possibility that problems may occur due to insufficient distances to nearby buildings. When designing a twisted building, this situation must be taken into account when positioning the building on the ground.

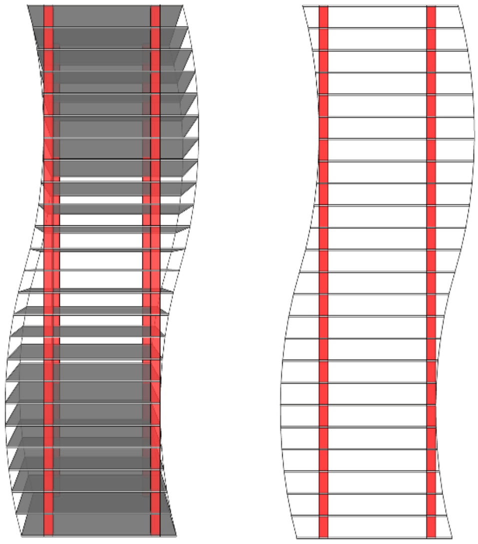

Figure 4. *Building form concept designed with the position of cantilevers (drawing by the author)*

Unlike rotating floor plans, some technical spaces such as elevators, emergency stairs, and shafts should have fixed positions throughout the building. This issue causes the circulation areas in the plan to change on each floor. A possible solution to this problem is the design of a ring corridor with a circular core to ensure that the circulation areas are not greatly affected by twisting from [3]. Still, it is very important to minimize the unusable areas that have occurred because of the form itself. Basement floors are typically designed standard and flat since they do not contribute to the aesthetics. However, the location of the technical spaces in the basement floors should be in line with the upper floor plans to ensure the rotation of the plans doesn't interrupt the continuity of the vertical shafts and elevators.

There are many difficulties encountered in the construction of twisted-form buildings. In particular, it is not possible to standardize the facade elements due to torsion since the dimensions and geometries of the elements may change. In addition, the increase in the amount of rotation per floor increases the detail problems at the wall-facade connection points and facade elements. For this reason, it is easier to apply an equal amount of total rotation angle in a multi-story high building than in a small low-rise building [4]. Still, they also constitute a reference for new projects to be made after them, and the risk of constructing twisted forms in other projects reduces [5].

3. STRUCTURAL SYSTEM PROPERTIES OF TWISTED BUILDINGS

Recent earthquake regulations in many countries state important rules and guidelines for the design of the structural system to minimize the torsional eccentricity in buildings. The main goal of these rules and guidelines is to design a structural system that will not twist as much as possible. This can be achieved simply by superposing the center of stiffness and the center of mass in the structural system. In cases where torsional effects cannot be avoided, the regulations demand uneconomical solutions on structural systems. However, contrary to the directions in the regulations, buildings with twisted forms already have torsional effects due to their form. In order to comply with earthquake regulations in these buildings, it is expected to design non-economic structural systems with structural elements that have a larger cross-sectional area and more rebar.

In the design of a building with a twisted form, if the structural system also rotates along with floor slabs, the columns will either be inclined or step and shift positions according to slab rotations. In the conventional column design, the columns are not exposed to an additional lateral force unless the building is under the effect of wind and earthquake forces and columns are mainly under the effect of vertical axial loads due to gravity. However, in the inclined columns, the element is constantly stressed by lateral loads due to the inclined design, even when there are no additional external horizontal forces [6]. This situation causes the structural elements to always be exposed to additional shear stress and moments even when they are not under the effect of external horizontal forces. Also, the stiffness and capacity of the column decrease when it is designed inclined [7, 8]. This causes many problems in terms of the safety of the structural elements along with the increase in the dimensions of the element sections. Moreover, as the twist angle increases, the collapse probability of the building also increases [9].

The structural system of a building is designed in a way to limit horizontal displacements and story drifts when a building is under the effect of dynamic lateral loads such as earthquakes and wind excitations. In particular, the limitation of horizontal displacement on the last floors of high-rise buildings is a comfort condition. Although twisted form provides some aerodynamic advantages to building, [10], the inclined design of the columns will make it even more difficult for these obligatory limitations to be achieved. Therefore, inclined columns will need to be designed stiffer than standard vertical columns.

The additional lateral loads and moments in the inclined columns are caused by the self-weight of the building and these loads increase as the number of floors in the building increase. When the structural system is analyzed, it is also seen that the lateral stiffness decreases as the rotation angle per floor increases. For this reason, it is expected that the increase in the rotation angle will adversely affect the structural system. When the columns are constructed inclined, the slopes of the columns on the same floor are different from each other. Therefore, it is not possible to use repeating formwork systems. A flat slab, which is not generally recommended floor system, is preferred in twisted-form buildings since it will provide simplicity in formwork and a more aesthetic appearance on the ceiling.

If the columns are constructed vertically and in a stepped arrangement in the twisted form building, additional internal forces in elements will occur due to eccentricity. These internal forces are proportional to the number of floors and the self-weight of the building. Also, as the rotation angle increase, the amount of drift per column on each floor and the amount of additional internal forces will increase [11]. In both inclined column or stepped column cases, it is expected that the dimensions of the structural elements along with the amount of concrete & steel to be used in construction will increase in order to obtain sufficient strength and capacity that can satisfy additional internal forces. This issue causes a significant rise in construction costs and a decrease in the usable net area in the floor plan.

Steel-braced tube systems, diagrid systems, and outrigger systems are preferred in the design of the structural system of high-rise buildings due to their advantages on lateral stiffness. These systems, which are versatile and modular due to their triangular geometry, can also be used effectively in buildings with unusual geometry [12]. However, even if these systems are preferred for high-rise buildings with twisted form, the lateral stiffness will still decrease as the rotation angle increase and the amount of decrease in lateral stiffness is greater in braced tube systems than in diagrid systems. Similarly, in outrigger systems, lateral stiffness decreases as the rotation angle increase [13], and the story drift also increases [14]. Sanjay, on the other hand, states that the steel moment frame system exhibits a better structural system behavior than the reinforced concrete moment frame system in buildings with twisted forms [15]. In addition, Song and Zhang emphasize that for a building with a twisted form, diagrid elements perform better when designed with asymmetrical angles than diagrids designed with symmetrical and equal angles [16]. However, with the increase in the angle of twist, the section dimension of the diagrid elements increases significantly to provide sufficient capacity [17]. Therefore, it is necessary to be careful when choosing the structural system in buildings with twisted forms.

Unless the core, the corridors around it, and the technical units inside are designed in a way that is not affected by slab rotation, the core must also twist along with the columns in order to ensure that the floor plans have the same layout. However, since the inclined or stepped columns already cause additional forces on the structural system, a similar twist in the core would further decrease the stability of the building. It would also affect the design of the elevators radically. For this reason, the cores are designed standard and vertical regardless of the twisted building form [3], and cores are positioned very close to the pivot point in order to be less affected by the rotation of floor plans. However, in order to have enough capacity to meet additional loads caused by twisted form, the dimensions of the core shears walls in twisted buildings are considerably larger when compared to conventional buildings and occupy a significant space in the floor plan.

Another issue to be considered in the design of the structural system is the location of the pivot point of rotation. The structural elements are affected by the rotation more as the structural elements are further away from the pivot, and the lateral stiffness of the column decreases as the inclination slope increases. Therefore, it would be a correct approach to construct the structural elements which are expected to carry more loads and have more strength, closer to the pivot point of the rotation.

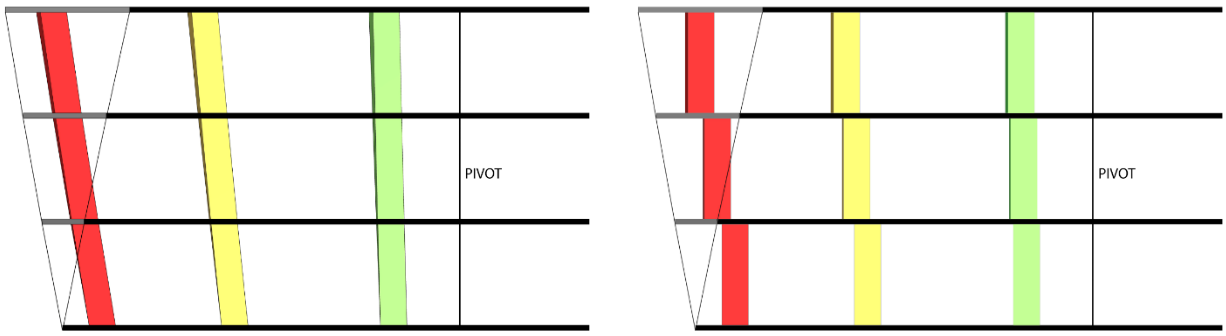

Figure 5. *Effect of location of pivot line on columns in twisted buildings (drawing by author)*

Moon compared the diagrid and braced tube structural system building models, which twist at different angles and have different story heights. As a result, it was observed that the horizontal stiffness of the buildings decreased with the increase in the angle of rotation and the height of the floors [18]. Navya et al. state in their study that the horizontal stiffness of a twisted building is less than that of a normal building and that the horizontal stiffness decreases as the rotation angle increases, while the maximum story displacement increases dramatically in twisted buildings compared to the normal building [19]. In another study by Lee et al, a similar result is obtained that the horizontal stiffness of twisted buildings decreases compared to normal buildings, and the amount of reduction is related to the twist angle [20].

4. CASE STUDIES

Within the scope of this paper, many twisted buildings are researched and a systematic classification is made in the above sections of the paper. Three sample projects selected within the framework of this classification are comprehensively evaluated in terms of architectural design and structural system design. In this evaluation, primarily The Grove at Grand Bay project, which rises by inclined columns, has been discussed.

The Grove at Grand Bay project is two 22-story residential buildings, consisting of north and south towers, in Florida. There are 98 independent units in total in the blocks with a floor height of approximately 370 cm. The building form is twisted 38 degrees in total with respect to the ground. The floor plate of the south tower gets larger as the floors go up and the building twists. The floor plan geometry of the north tower is constantly rectangular throughout its height. The floor plans rotate by approximately three degrees per story starting from the ground floor, only the upper 5 floors are vertically stacked and don't rotate. In a different study, it was determined that the story shear forces increase as the twist angle increase on a structural system with a twist in specific floors [21], which is a very similar case of a structural system with The Grove at Grand Bay project. Towers view and structural model are shown in **Figure 6**.

The columns are designed inclined to comply with the rotating floor plates in the towers. This inclination of the columns creates additional internal forces due to the building's self-weight. Since all the columns are inclined in the same direction, the design of the tower causes torsion in the structural system. The core is designed vertically without any rotation, unlike the building form.

Figure 6. *Groove at Grand Bay Towers view [22] and Structural model [23]*

According to the Desimone Engineers who designed the building's structural system, the most challenging task is finding a cost-effective solution that can resist the torsional forces in the structural system while at the same time having minimal impact on architectural plans. In order to prevent columns from interfering with the architectural plans, a core with very high stiffness is proposed. Based on the initial studies, the wall thicknesses of the concrete shear walls in the core would reach 180 cm. Later, the shear wall thickness could only be reduced to 76 cm with a composite design in which steel plates and reinforced concrete were used together. The view of composite shear walls is given in **Figure 7** below. It should be noted that even 76 cm wall thickness is an indication of heavy torsional forces on the structural system [23].

The concrete strength of the core and columns is approximately 90 MPa on the first 10 floors and 55 MPa on the upper floors. The thickness of the steel plates used in composite shear walls is up to 10cm. The shear walls are composite up to the 15^{th} floor in the tower, then conventional reinforced concrete construction is applied for shear walls up to the roof floors. Although the construction cost has generally increased, approximately 80 square meters of usable area per floor has been gained back with the decrease in wall thicknesses.

Figure 7. *Aerial view of composite shear walls and steel plates within composite core [23]*

Composite shear walls are not sufficient to meet additional torsional force requirements. Therefore, a rigid high-beam system was also formed on the roofs of the towers which is shown in **Figure 8** below. The purpose of a high-beam system is to relieve some of the gravitational loads imposed on the inclined columns and prevent these loads from being transmitted to the core as torsional forces. The beams connecting the inclined columns and the core create an alternative load transfer path to the core for the loads on the columns and transfer the loads to the core as a vertical load component. With analyses, it is expected that columns in the uppermost 9 floors will have net tension force instead of the expected compressive forces once the rigid beam system at the top is installed. With the recommendations of the engineers, the high beam system design is considered as post-tensioned reinforced concrete. As a result, by integrating these beams into the structural system, the total torsional loads on the core were reduced by approximately 30 percent. The foundations of both towers are 230 cm thick mat foundations that are supported on cast piles. At the same time, due to the fact that the project area is a flood zone, additional measures have been applied to meet the local regulation requirements.

Figure 8. *Model of roof high beam system [23]*

In this project, the architectural designers chose to emphasize the aesthetics of the inclined columns by presenting them as a part and feature within the units, rather than trying to enclose the columns with vertical walls. Careful planning has been taken into account to construct flexible open spaces and to ensure that the columns do not occupy the usable space as much as possible. The columns are generally placed at the perimeter of the buildings and their diameter is 76 cm. The flat slab design is chosen for floor plates, and the thickness of this slab, which is 25 cm thick, increases to 40 cm around the core. With the flat slab without beams, a clean floor height of approximately 370 cm is provided in the living areas. To avoid complicated and expensive offsetting of the technical shafts caused by the rotating floors, they are placed inside or immediately adjacent to the central core.

Twisted buildings often require very special solutions to ensure safety and also cause substantial increases in design and construction costs as can be seen from the architectural and structural system design challenges in this example. Due to the difficulties created by the twisted form, the construction cost increased by 18% for the Groove at Grand Bay Project. The additional cost was deemed appropriate by the developers and it was anticipated that the aesthetic value that the form would add to the buildings would be higher as net profit than the additional cost.

The Infinity (Cayan) Tower project can be shown as an example of a twisted building in which the columns are offsetting as floor plans rotate. Infinity Tower is a tower building which twists 90 degrees from its base in total with an incremental rotation on each floor plan. The tower has a total of 75 floors above ground, 6 basement floors under the ground and its height is 305 meters. The construction of the tower, which has a total construction area of 122.000 m^2 was completed in 2013 in Dubai.

Figure 9. *View of Cayan Tower [24] and construction progress [25]*

The tower has a 3 m thick mat, deep foundation system which is supported by bored, cast-in-place concrete piles extending approximately 30 meters below the mat foundation. The structural system of the tower consists of a circular core in the center, 6 inner columns, and perimeter tubular columns. The carrier system material is reinforced concrete. A flat slab is preferred as a flooring type [26].

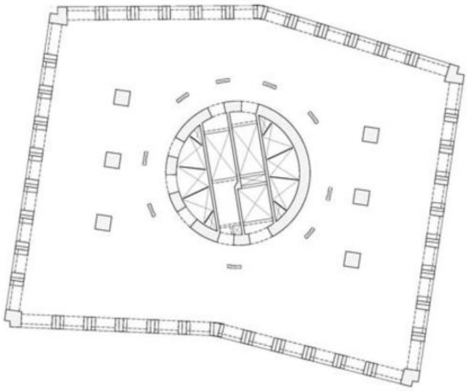

Figure 10. *Cayan Tower typical floor plan [26]*

While designing the tower, great emphasis was placed on the expression of the twisted geometry of the building and the structural system. When all the advantages and disadvantages were compared, it was determined to construct the perimeter tubular columns vertically and offset over the column below. As the tower ascends, the perimeter columns are shifted based on the plan layout so that there is no change in the architectural floor plans. In the Cayan Tower, the columns are perpendicular to the floor slab, but the coordinates of the columns with respect to the ground change on each floor. The columns in the corners and the 6 columns inside are designed inclined and twisted in accordance with the form. The core is constructed conventionally and vertically regardless of the building geometry, as is often the case in twisted types of buildings [26]. In **Figure 11** below, it is shown how the position of the columns changes.

The fact that the structural system consists of perimeter tubular columns constructed by offset ensures that the architectural plans are standardized and repetitive. This situation accelerates the design process of the architectural program and the construction speed. Likewise, the use of vertical offset columns makes a significant construction simplification by permitting possible the use of repeated formwork systems. However, it should be kept in mind that the additional internal forces created by the shifted columns due to the non-coincidence of their axes between the floors have an important impact on the structural system.

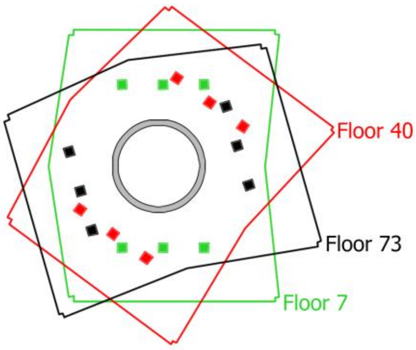

Figure 11. *Cayan Tower footprint of different floor plans (drawing by author) and stepped perimeter columns [26]*

One of the issues caused by the geometric form of the tower is the facade cladding and balconies. With the different offsets of the tubular columns on each floor, the façade cladding required a special detail design and the opening in each bay is slightly larger or smaller than the one next to it. According to the architectural program, each unit is required to have a balcony that is designed behind the façade. By organizing each standard unit to have the flexibility to locate its balconies in one of two or three locations, balconies are prevented from overlapping [26].

Due to its twisted geometry, the tower is exposed to additional shear and torsional forces due to its self-weight, and due to the creep effect of the concrete, these forces are expected to increase during the life cycle of the structure. During the construction phase, a special program was established to monitor the movement of the building to ensure the practical compatibility of the theoretical calculations. With the information obtained from this program, the suitability of the expected theoretical movement was confirmed and unexpected coordinate changes in plans were prevented.

Dubai is a relatively low-risk earthquake zone. For this reason, the design of the tower is mainly governed by expected wind loads. In order to determine the design wind loads for the structure as well as peak pressures for the design of the cladding, a wind tunnel test was performed on a 1/400 scale model. It was observed that the twisted geometry of the structure reduces the wind effect by approximately 25%. Therefore, the horizontal story drifts due to the wind effect decrease in the tower [26]. It is really important to reduce the wind effects in high-rise towers to minimize the horizontal loads. However, the horizontal loads created by the building's self-weight due to the twisted form should not be underestimated.

Baltimore (Arena) Tower is a good example of the type of twisted building in which the perception of twist geometry is evoked without inclination or offset in the columns. Baltimore (Arena) Tower is a 150 m tall, 45-story residential tower building. The construction of the tower was completed in 2016 in London, and it has a total construction area of 115000 m^2.

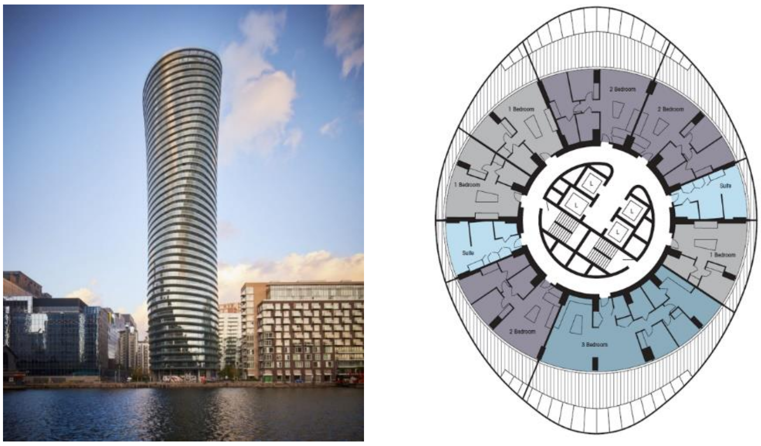

Figure 12. *View of Baltimore Tower [27] and Typical floor plan [28]*

The tower, which has an elliptical plan geometry, has a circular arranged structural system. The structural system elements of the tower consist of a circular core in the center and moment resisting frame with columns. Although the structural system axis is a regular circle, the elliptical form of the floor plans is obtained with cantilever slabs. The structural system of the tower is rather conventional, shear walls and columns are vertical and at the same coordinates through all floors. For this reason, the floor plans in the tower are standard and repetitive with the same footprint on each floor. The living areas are planned in a way that narrows towards the building core and expands towards the facades and balconies as seen in **Figure 13** below, with the design of the structural system being circular [28].

Figure 13. *Baltimore Tower Unit layouts in floor plan [28]*

Balconies are designed as cantilevers in the project. The cantilever, which gives the elliptical geometry to the floor plans, rotates as the tower ascends. With the rotation of the balconies, the twisted form of the building is created. However, the rotation of the cantilevers does not adversely affect the structural system.

Due to the rotation of the cantilevers, the position of the balconies changes on each floor plan. The rotation starts from the 2nd floor and the floors continue to rotate clockwise at certain angles until the 13th floor. After the 13th floor, the consoles start to rotate counterclockwise, return to the starting position at the 23rd floor and continue to rotate counterclockwise until the last floor. In addition to the rotation of the balcony ring, the independent units on the 8th, 22nd, and 29th floors are shifted to the neighboring axis to correspond with the alignment of the balcony ring. Step-by-step changes in the floor plans are shown in **Figure 14** below. The construction of the cantilevers which create a twist effect has a particular importance. Composite polymer formworks are used in the construction of cantilever slabs to speed up the process. For ease of assembly, formworks pieces are given a reference number and color-coded [29].

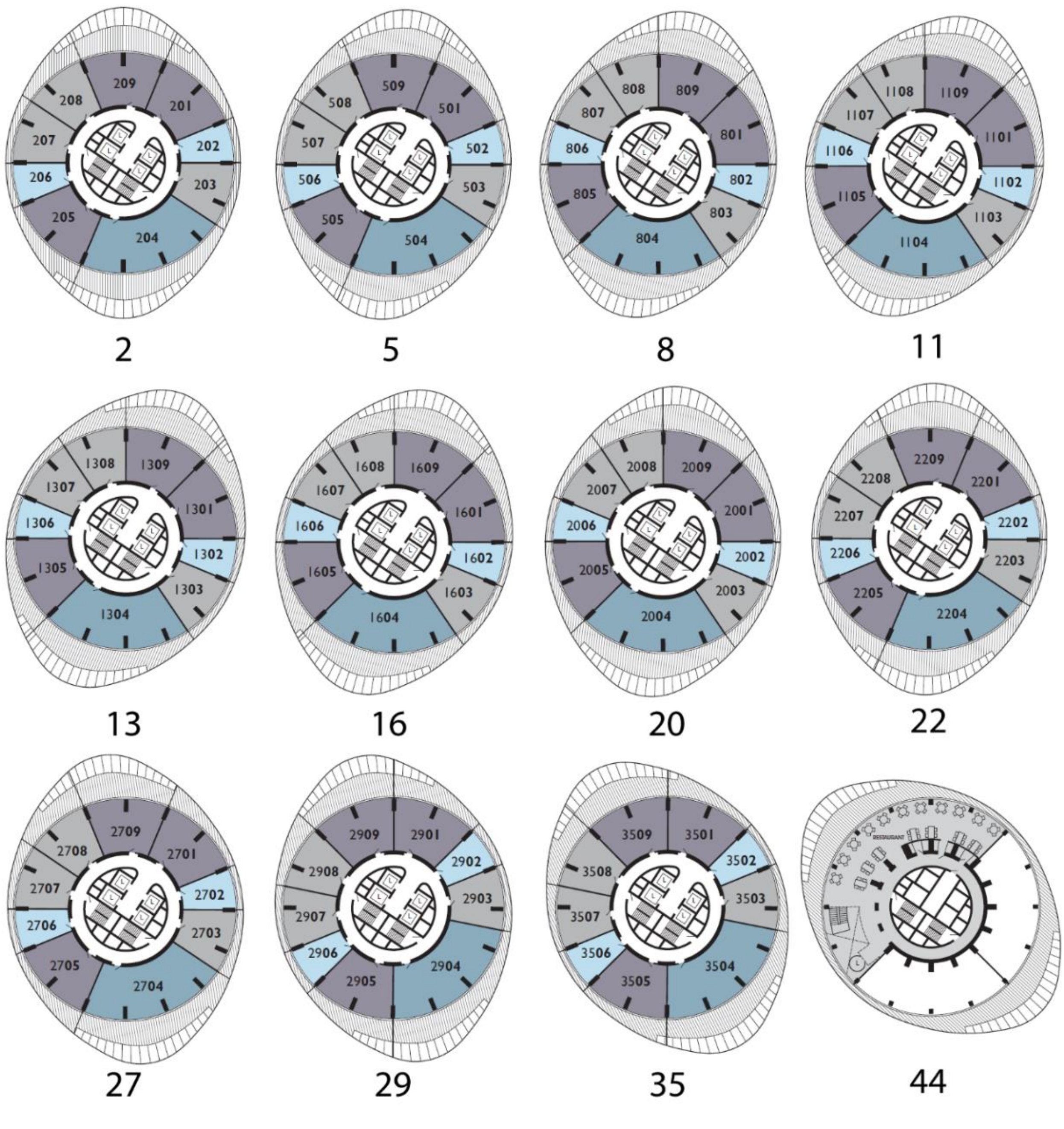

Figure 14. *Rotation of cantilevers based on floor plans [28]*

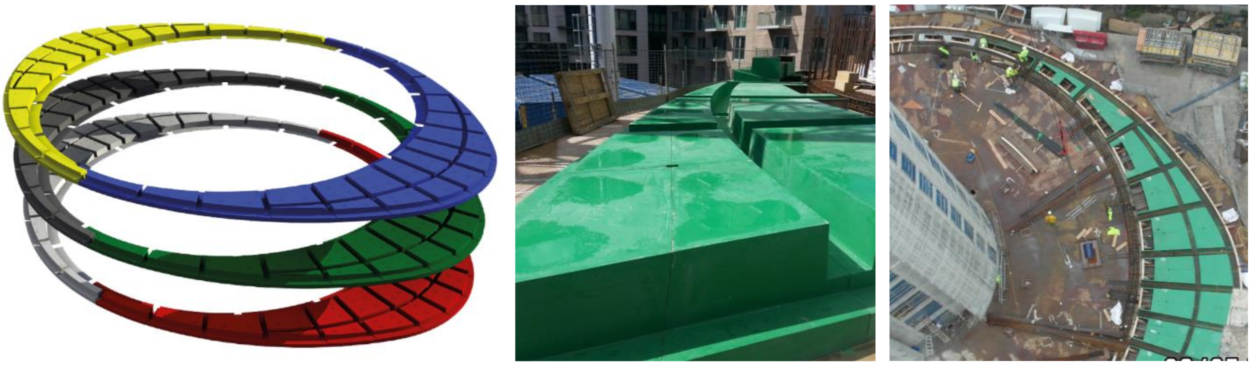

Figure 15. *3D model of formwork and application of composite polymer formworks [29]*

5. CONCLUSIONS

With the advancement of technology and the development of computer-aided drawing, modeling, and analysis methods, the number of buildings with twisted forms keeps increasing each day. Although twisted geometry has some advantages for the building such as aesthetics, façade, and landscape orientation, it also causes problems such as positioning on the ground, inadequacy of conventional construction methods, and slowing down of the design and construction process. Many of today's regulations recommend designing a structural system that will not twist as much as possible to minimize the torsional eccentricity in the buildings. However, buildings with twisted forms already have torsional effects due to their form. Disregarding the guidelines in the earthquake regulations results in a design of non-economic structural systems. When the columns are designed inclined or offset in the structural system additional forces are generated in the structural system, the lateral stiffness decreases, and the section dimensions of the structural elements increase in an uneconomical and substantial amount in order to provide safety and comfort conditions. The increase in the section dimensions of the elements causes a decrease in the usable net area in the floor plan and an increase in the cost as more concrete & steel are used in construction. In addition, as the weight of the building and the angle of rotation increase, the additional forces and the section dimensions of the carrier elements become larger. The importance of designing the core of the building independently from the twisted form and positioning it close to the center in the proposed solutions in order to neutralize the disadvantages caused by the twisted form is also seen in the paper and the examples studied. In a different way, it is also possible to evoke the twist effect of the building without making any challenging design in the structural system to increase the applicability of the design and construction.

Consequently, it is possible to find economical and realistic solutions to the challenges caused by the twisted form only with the cooperative work and decisions of architects, engineers, and contractors. Before designing a building with a twisted geometry, the interests and requests of the developers and end users should be well evaluated. Finally, decisions about the construction of a building with a twisted form, which method to use when constructing it, and what kind of structural system to choose, should be made after the advantages and disadvantages of the mentioned design are carefully analyzed.

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