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A RECENT TREND IN TALL BUILDING DESIGN: TWISTED FORMS

ABSTRACT

The symbolic value of a tall building is very powerful in an urban landscape. The approach to designing evolutionary tall buildings is an open subject of professional debate, and the role of the architect is very important, from the point of view of form generation. Today, an interesting approach in contemporary tall building design is the twisting forms and facades, which are employed as a reaction to the boxed forms of the recent and the past. A very popular example is the Turning Torso in Sweden, designed by Santiago Calatrava. Many other tall buildings with twisting forms are designed and constructed worldwide. Twisting facades of a tall building perform various surface effects reflecting, refracting and distorting views of the city. However architecturally, structurally and aesthetically, it is a complicated task to develop a twisting form for tall buildings due to the interrelationship of a huge number of building components. The objective of this paper is to explain the morphological scheme and geometrical properties of twisting forms in a systematical approach, and to discuss the difficulties of designation and construction, such as selecting the supporting structure and detailing the façade system. A number of case studies are also presented in the paper.

Keywords: Tall Buildings, Twisted Forms, Structural System, Outrigger System, Facade Design, Diagrid System, Braced Tube

YÜKSEK YAPI TASARIMINDA YENİ BİR YAKLAŞIM: DÖNER FORMLAR

ÖZET

Yüksek binalar kentsel alan içinde oldukça önemli bir sembolik değere sahiptir. Yenilikçi yaklaşımlarla yüksek binalar tasarlamak uzmanlık gerektiren bir konu olup, bu açıdan mimarların üstlendiği rol çok önemlidir. Günümüzde döner formlar ve cepheler çağdaş yüksek bina mimarisinde oldukça ilgi çekici bir yaklaşım olarak karşımıza çıkmaktadır. Uluslararası dönemin geleneksel, prizmatik hacimli kutu formlarına tepki olarak ortaya çıkan bu formların ilk ve en çarpıcı örneği Santiago Calatrava tarafından tasarlanmış olan, Malmö'deki Turning Torso'dur. Bu örneği dünyada pekçok örnek izlemiştir. Bu tür bir yapının döner cepheleri farklı bakış açılarından değişken görüntüler sunmakta ve yapı böylece ikonik bir özellik kazanmaktadır. Ancak bu tür yapıların mimari ve strüktürel tasarımı ile estetiği, henüz çok yeni bir yaklaşım olmaları ve çok sayıda geometrik olarak değişken bileşenden oluşmaları nedeniyle bazı zorlukları da beraberinde getirmektedir. Bu çalışmada bu zorluklara ilişkin çözüm önerileri ve tasarım yaklaşımları incelenmektedir. Öncelikle döner formların geometrik özellikleri araştırılmış ve sistematik bir yaklaşımla sınıflandırılmıştır. Döner formlarda uygulanan taşıyıcı sistemler irdelendikten sonra, tasarım ve yapım süreçlerindeki güçlüklerle değinilmiş, son olarak dünya genelinde uygulanan ve yapım süreci devam eden bir dizi yüksek bina örneği hakkında bilgi verilmiştir.

Anahtar Kelimeler: Yüksek Binalar, Döner Formlar, Diagrid Strüktürler Taşıyıcı Sistem, Cephe Tasarımı,

1. INTRODUCTION (GİRİŞ)

Non-orthogonal tall buildings with complex geometrical shapes are emerging all over the world with an accelerating rate. Beginning the first examples, the architecture of this building type was mostly governed by the engineers such as Louis Sullivan, Daniel Burnham and John Wellborn Root. The technological and aesthetic evolution of tall buildings has gone through many phases hitherto. By the nineteenth century the architects were influenced by traditional styles when designing their buildings for individuals or companies. For example, Woolworth Building constructed in 1911 was influenced by the Gothic Style. Chrysler Building constructed in 1929 has attracted attention by the Art Deco ornamentations and contemporary construction system. The International Style developed in Europe in the early decades of nineteenth century, spread all over the world and became the dominant architectural ideology. The new commercial citadels, which were usually box-shaped, were made of glass, steel and concrete were also stripped of any decoration. During the end of 1960s the image of the tall buildings re-emerged as one of the economic prowess and might. The innovation in the technology of tall buildings offered enormous potential for the construction methods and the new designs of mega structures. In 1980s architects, aware of the power and romance of tall buildings wanted to design buildings, which would represent them, and Post-Modernism emerged as a reaction to the Modernism or International Style. However, in the mid-1980s, people became bored with the box-shaped buildings of the International Style, which were usually clad in aluminium and glass.

Today the number of tall buildings are increasing at an accelerating rate in megacities, as well as in cities, which aims to be a megacity for political, cultural and socio-economic reasons. Due to the boredom with conventional tall building designs, non-orthogonal tall buildings are currently the latest trend. In the last few years twisted forms and freely double-curved surfaces, which have many visual properties in common have been rediscovered. Among many non-conventional and extraordinary shapes, twisted forms are much easier to realize and design for architects, since they are generated by the repetition of straight lines.

2. RESEARCH SIGNIFICANCE (ÇALIŞMANIN ÖNEMİ)

Today, however as is true for other building types, multiple design directions are prevalent for contemporary and iconic tall structures. This extraordinary design approach has produced various geometrical forms, such as twisted, tapered, inclined, tilted and free forms. To design outstanding buildings, architects move away from standard shapes and simple geometries, such as pyramids, boxes, cylinders and cones. As a result non-orthogonal tall buildings are emerging worldwide with an increasing degree of geometrical variations. Employing a twisted form in a tall building is a relatively new approach for architects, as well as engineers. Difficulty of designing, fabricating and constructing superstructures of extraordinary and non-conventional forms increases with the geometrical complexity.

Among numerous non-conventional and complex shapes, this paper investigates the twisted forms for tall buildings in terms of their geometric properties, structural systems, difficulties in design and construction, and also presents a number of buildings constructed or on the process of construction.

3. DESCRIPTION OF TWISTED FORMS (DÖNER FORMLARIN TANIMI)

A tall building with facades that are twisted is an interesting geometrical form, especially for designers, who aims to create iconic structures. However, designing a twisted form is not an easy task, since its geometrical definition may be complex. So a systematic description of the geometrical properties, as well as classification of twisted forms is crucial to expedite the design process, as well as fabricating and construction processes.

Vollers (2001) has developed a method to describe a whole range of complex building models, and then analyzed them by means of external appearance, construction and possible façade connections. Consequently, he describes two main typical forms; the tordo and the twister. A tordo is a building that incorporates at least one twisted façade, and has an orthogonal superstructure (Figure 1). It is a transformed volume with at least one corner, which is moved out from the orthogonal structural grid, thus having one or more twisted facades. The floors are basically repeated in vertical direction with interior walls and columns aligned. The twisted facades of a Tordo introduce floor edges that are not parallel to the orthogonal grid of the structural grid. A rectangular floor plan is an exceptional design in the sequence of floors, and the twisted façade is usually rotated on an axis, which lies in the façade.

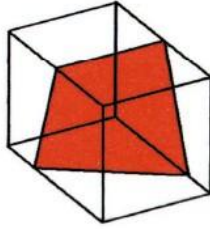


Figure 1. Tordo
(Şekil 1. Tordo)



Figure 2. Twister
(Şekil 2. Döner)

A twister is a building with floors, which are rotated horizontally on a vertical axis, and this axis (not always but) usually lies on the centre of the floor plan (Figure 2). Traditionally, a twisted surface is described as the composition of straight lines (parallel to the floor plane) in which the adjacent lines are not parallel to each other, nor they intersect each other. Today, a twisted surface is defined as the composition of straight lines, and the adjacent lines are moved upward and rotated in the same direction. A recent example of this form is the Turning Torso in Malmö, which is designed by Calatrava (Figure 3). In a simple twisted form, as in the case of Turning Torso, all floor plans are identical and positioned with a fixed incremental rotation degree. The axis of the floor plans is a straight line through the height of the building, whereas the axis of the twisted surfaces are no more straight lines; it will be much more better to define them as being helicals. Structural elements, such as cores with shear walls may be aligned in vertical direction. For a number of examples, vertical structural elements on the façade is designed as inclined columns, as in the case of Infinity Tower (Chicago) (Figure 4a-b), or these elements may be rotated in horizontal direction with a fixed rotation degree as in the case of Al Bidda Tower (Doha) (Figure 5a-b). As the number of twisted facades increase, then the volume starts to resemble a cylinder, thus

necessitating the expression of outer columns (Figure 6). This can allow for arranging a circle of vertical columns behind the façade.



Figure 3. Turning Torso, Malmö, ©Calatrava. (Şekil 3. Turning Torso, Malmö.)



Figure 4a-b. Infinity Tower, Dubai Marina, ©SOM. (Şekil 4a-b. Infinity Kulesi, Dubai Marina.)



Figure 5a-b. Al Bidda Tower, Doha, ©GHD. (Şekil 5a-b. Al Bidda Kulesi, Doha.)



Figure 6. Chicago Spire, Chicago, ©Calatrava. (Şekil 6. Chicago Spire, Chicago.)

According to Vollers (2005), a twisted surface cannot be bended from a sheet of paper, since the surface has to be stretched. He replaced the mathematical plane descriptions and formulae with an inventory of shapes of his own that is geared to actually constructing it rather than understanding the mathematical definitions. For

instance, he described a twisted plane as a plan constructed of straight lines that are formed by copying a line and then translating and rotating the copied line.

Vollers (2009) also describes a number of twistin forms, which are generated from primitive forms, such as a box, cyclinder, and etc. For example, in a tall building, as the floors move upward along a curve, then the form is a *Slider*. With additional rotation of the floors, it is a *Sliding Twister*. A *Helical Twister* has a helical rotation axis (Figure 7). Entangling volumes cover a range of organic connotations. The *Cobra Towers* look like snakes with patterned skins (Figure 8). The *Intersected Helical Twisters* as seen in Figure 9, have the elevator core in the overlap. Circling an assembly of helical volumes in the same direction causes torque. To avoid this torque, the *Merged Sliders* merge from opposite directions (Figure 10). *Tapered Sliding Twisters* are shaped by individually scaling hexagonal based pyramids and rotating them around a three dimensional axis. Often a twisted volume is simplified to a combination of cylindrical and stepped flat surfaces as well (Figure 11). *Hybrid Twisters* have facades of various geometries, that fluently connect, like cylindrical and twisted segments (Figure 12).



Figure 7. Torre Castello, Valencia, ©Calatrava (Şekil 7. Castello Kulesi, Valencia)



Figure 8. Cobra Towers, Kuwait (Şekil 8. Cobra Kuleleri, Kuveyt)

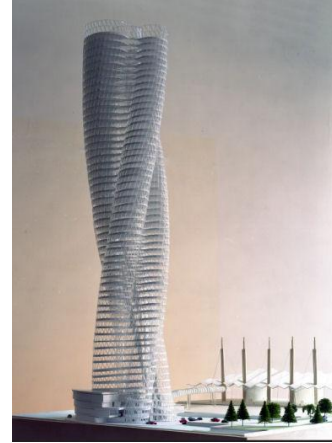


Figure 9. Twisted Trees, Bin Hai Seaport City, China, ©Lee Haris Pomeroy (Şekil 6. Dönel Ağaçlar, Bin Hai Seaport City, Çin)



Figure 10. World Business Center, Busan, S. Korea, ©UN Studio (Şekil 10. Dünya Ticaret Merkezi, Busan, S. Korea, ©UN Studio)



Figure 11. Mode Gakuen Spiral Tower, Nagoya, Japan, ©Nikken Sekkei (Şekil 11. Mode Gakuen Spiral Kulesi, Nagoya, Japan, ©Nikken Sekkei)



Figure 12. Sea Breeze Tower, Dubai, ©Karel Vollers (Şekil 12. Sea Breeze Kulesi, Dubai, ©Karel Vollers)

4. STRUCTURAL SYSTEMS FOR TWISTING FORMS (DÖNER FORMLAR İÇİN TAŞIYICI SİSTEMLER)

Today there are innumerable structural systems that can be employed for the lateral stiffness of tall and slender buildings. However, a cost effective and structurally efficient lateral load resisting system is the best solution for the design of any contemporary tall building.

Although a twisted form is not new in architecture and has been introduced historically in Solomonic columns, employing this form for a tall building is a relatively new approach for today. A twisted form in a tall building is structurally beneficial since it mitigates the effects of across-wind by disturbing organized formation of alternating vortexes around them (Moon, 2010). Studies suggest that structural design of slender tall buildings is governed by lateral stiffness rather than strength (Connor, 2003; Moon et al., 2007). One of the most important stiffness-based design requirements for tall buildings is the maximum deflection at the top, which is generally about 1/20 of the building height (Schueller, 1977). Although there exists many structural systems for tall buildings with straight forms (Özgen and Sev, 2000), only a few of them can be applied for twisted forms due to their complicated geometrical forms. These systems can be stated as follows:

4.1. Rigid Frame and Shear Wall/Core Systems (Rijit Çerçeve ve Kesme Duvarı/Çekirdekli Sistemler)

Rigid frame structures consist of columns and beams joined by moment-resistant connections. The lateral stiffness of a rigid frame depends on the bending stiffness of columns, beams and connections in the plane of the bent. While rigid frames of a typical scale (approximately for spans of 6 to 9 m) that serve alone to resist lateral loads have an economic height of 8 to 10 stories in seismic areas, and they are not efficient for buildings taller than about 10 stories. In this case employing braced frames or shear walls (maybe in the form of a core arrangement) improves the efficiency of a rigid frame (Coull and Smith, 1991; Taranath, 1997; Ozgen and Sev, 2000; Sev, 2001).

4.2. Tube Systems (Tüp Sistemler)

The lateral resistance of rigid frame and core structures can be improved by employing very stiff moment resisting frames that form a "tube" around the perimeter of the building. The frames consist of closely spaced columns (2-4 m), joined by deep spandrel girders (0.6-1.2 m). Although the tube resists the entire lateral loading, the gravity loading is shared between the tube and interior columns or walls. The framed tube and a shear core can also act jointly in resisting both gravity and lateral loading (Taranath, 1997; Özgen and Sev, 2000).

4.3. Braced Tube Systems (Çaprazlı Tüp Sistemler)

A braced tube is a variation of the framed tube and was first applied on the 100-story John Hancock Center of 1970 in Chicago. The main idea in the emergence of braced tubes is that, it is possible to stiffen the widely spaced columns by diagonal braces to create wall-like characteristics. The framed tube becomes progressively inefficient over 60 stories and very slender buildings, since the web frames begin to behave as conventional rigid frames (Taranath, 1997). Consequently, beam and column designs are controlled by bending of the structure and the shear lag effect is aggravated. A braced tube overcomes this problem by stiffening the perimeter frames in their own planes. The braces also collect gravity loads from floors and act as inclined columns. The diagonals of a braced tube connected to columns at each joint effectively eliminate the effects of shear lag throughout the tubular framework. Therefore, the columns can be more widely spaced and the sizes of spandrels and columns can be smaller than those needed for framed tubes, allowing for larger window openings than in the framed tubes (Khan, 1967).

An experimental study on the structural efficiency of braced tube structures for twisted tall buildings, which was conducted by Moon (2010) reveals that, compared to the straight form braced tube structures, twisted braced tubes are less stiff. In his study, three 60-story buildings with braced tubes and different twisted rates were tested. The buildings' plan dimensions were 36 meters by 36 meters with an 18 meters by 18 meters gravity core at the center and height to width aspect ratio were 6.5. The members of non-twisted building were designed to meet the maximum displacement requirement of 1/20 of the height, and the same member sizes were used for the other two examples. The first building was not twisted, the second was twisted by 1 degree per floor and the third was twisted by 2 degrees per floor. The buildings were assumed to be in Chicago. As a result, the stiffness of the braced tube structures decreased as the rate of twisting increased.

4.4. Diagrid Systems (Diyagrid Sistemler)

As a varied version of braced tube systems, diagrid structural systems are structurally efficient and also architecturally pleasing for tall buildings (Sev and Eren, 2010). The main difference between conventional exterior-braced frame structures and diagrid structures is that, almost all the conventional vertical columns are eliminated in diagrid structures, since these systems can carry gravity loads as well as lateral forces owing to their triangulated configuration (Moon, et al., 2007). However the diagonals in conventional braced frame structures carry only lateral loads. Compared with conventional framed tubular structures without diagonals, diagrid structures are much more effective in minimizing shear deformation because they carry shear by axial action of the diagonal members, while framed tubular

structures carry shear by the bending of the vertical columns (Moon, 2008; Ali and Moon, 2007).

The lateral stiffness of diagrid structures is desirable not only for static loads but also for dynamic loads, which generate responses in both the windward and across-wind directions. In most cases, the lateral motion in the across-wind direction due to vortex shedding is much greater than the motion in the windward direction.

A similar experimental study, which was mentioned in Section 4.2, was conducted to analyze the structural efficiency of diagrid structures for twisted tall buildings (Moon, 2010). The experiment revealed that for twisted forms, stiffness reduction is not significant in diagrid structures as much as braced tube systems. The same building designs were used in this study. As the results of the study twisted diagrid structures were less stiff compared to the straight form diagrid structure. While the stiffness reduction with a twisted rate of 1 degree per floor was minimal, the decrease of stiffness accelerated as the rate of twisting increased.

4.5. Systems With Outriggers (Yatay Kafes Kirişli/Perde Duvarlı Sistemler)

The most recent spectacular development regarding the structural systems of tall buildings is the outriggers, which are effectively utilized in the tallest buildings of the world such as the 88-story Petronas Towers (Kuala Lumpur), the 101-story Taipei 101 (Taipei), the 88-story Jin Mao Building (Shanghai), and the 101-story Shanghai World Financial Center (Shanghai). Systems with outriggers consist of a central core, comprising either braced frames or shear walls, with horizontal cantilever "outrigger" trusses or girders connecting the core to the outer frames with (mega) columns. These systems have been historically used in sailing ships to help resist the wind forces in their sails, making the tall and slender masts stable and strong. The core in a tall building is analogous to the mast of the ship, with outriggers acting as the spreaders and the exterior columns like the stays (Taranath, 1997). As for the sailing ships, outriggers serve to reduce the overturning moment in the core that would otherwise act as pure cantilever, and to transfer the reduced moment to the outer columns through the outriggers connecting the core to these columns.

The outriggers, generally in the form of trusses in steel structures or walls in concrete structures, effectively act as stiff headers inducing a tension-compression couple in the outer columns (Ali and Moon, 2007). Belt trusses are often provided to distribute these forces to a large number of exterior frame columns. By linking the core to the exterior columns via outriggers, greater overall rigidity and considerable reduction in tensile forces in load-bearing elements and the foundation, as well as reduction in the structural material, are achieved (Beedle & Rice, 1995; Beedle, et al., 2007).

The outrigger systems may be formed in any combination of steel, concrete and composite construction. Because of the many functional benefits of outrigger systems, this system has lately been very popular for super tall and slender buildings all over the world (Özgen and Sev, 2000; Sev, 2004). The efficiency of this system for twisted buildings is also analyzed by Moon (2010). Two story tall outriggers, which connect the braced core and perimeter mega columns, were located at the mid-height and at the top of the structures. Due to the characteristics of outrigger structures, twisting rates of 1.5 and 3 degrees per floor were used in the study, resulting a total twisting of 90 degrees and 180 degrees at the top of the structures. The results revealed that, the stiffness reduction of outrigger structures due to twisting was significantly larger than the formerly tested

braced tubes and diagrid structures. Compared to the straight form outrigger structure, which produced the maximum displacement of about 47 cm at the top, twisted outrigger structures produced 82.3 cm and 88.8 cm displacement at the top with twisting rates of 1.5 and 3 degrees per floor respectively. According to Moon (2010) this drastic stiffness reduction is caused by the characteristics of outrigger structures. When the outrigger structures are twisted, the location of the mega columns, which extend the resisting moment arm of the structure, is shifted from the flange plane at the base to the web plane or to the opposite flange plane at the top depending on the degrees of rotation per floor. This phenomenon significantly reduces the effectiveness of the system. In order to use outrigger structures effectively in conjunction with twisted towers, he suggests to employ straight vertical mega columns and place them set back from the building perimeter, as is the case with the design of the Chicago Spire in Chicago.

4.6. Core with Cantilever Floor and/or Suspended Systems (Çekirdek ve Konsol Döşemeli ve/veya Asma Sistemler)

In this system, the core constitutes a single vertical structure and the whole vertical load increases linearly towards the foundation. Maximum release of the façade, as well as maximum flexibility in floor space are achieved also, and this approach can be very beneficial for a twisted tall building. The structural penalties are considerable in cantilever floor and core systems especially in areas of high seismicity.

5. DIFFICULTIES IN THE DESIGN AND CONSTRUCTION OF TWISTED FORMS (DÖNER FORMLARIN TASARIM VE YAPIMINDAKİ ZORLUKLAR)

Designing an iconic tall building with an extraordinary shape is not an easy task for architects and engineers due to their complex geometry and a huge number of non-identical components. These buildings often necessitate large construction budgets, however they also offer the opportunity to experiment new and innovative design and construction technologies. Consequently, by the application of initial examples, technological improvements can be achieved, and risk of implementing these techniques in other projects incrementally reduces.

The process of geometrical description of non-orthogonal shapes, such as twisters, necessitates to handle a large number of geometrical data. A twisted tall building design is largely related with digital modeling tools that architects are aware of. Simple modeling procedures enable intuitive shaping of complex geometric designs. Designers are assisted by computer softwares in handling the data related with the shape and dimensions of structural elements, façade components, and etc. Some of these softwares focus on parametric modeling of the volume, others on morphogenetic structures. In order to simplify the design process, the software must allow rapid shape development and quick generation of digital data of components. The parameters must be manipulated numerically, and by adjusting points on the screen easily (Vollers, 2009).

In the first examples of the non-orthogonal building shapes, volumes were mostly geometrically described by straight lines or flat surfaces (Vollers, 2001). In time solid modeling softwares assisted designers to generate new shapes, which were described by their relations between their composing elements. Scripting and parametric modeling procedures greatly simplified the data processing and drawing. However, today new shapes are generated with increasing complexity in geometrical form. The complexity of manufacturing the components and construction process was also anticipated formerly.

Mainly because of aesthetics and construction economy, the initial examples of twisted buildings were generated with a limited number of parameters, not more than 4. For instance, these were generated by scaling a cube or a box, and then twisting it in a single direction. However, as softwares evolved, a variety of commands in softwares emerged and designers are now able to generate non-orthogonal forms in various ways (Figure 13).

Another difficulty related with the twisted forms is the production of façade components and glass panes that cover the superstructure. The number of façade components with different sizes and geometries in twisted tall buildings, not only extends the design process, but also causes high costs in production, assemblage and logistics. Although it is easier to standardize the façade elements in a Tordo, a Twister has a great differentiation of components. The helical mullions of a Twister incline both sideways in and outward. This geometric variation complicates the connection between the superstructure and the façade elements. In a Twister of large scale, (or when a small and constant rotation degree is employed), the twisting of elements and the inclination of mullions are smaller, thus making the connection relatively easier. The connections are more complex when the degree of twisting increases. Therefore, Tordos have more advantages by means of above mentioned difficulties, since usually a type of twisting is applied, and their mullions lie parallel to the vertical surfaces that align with the walls, and do not incline sideways.

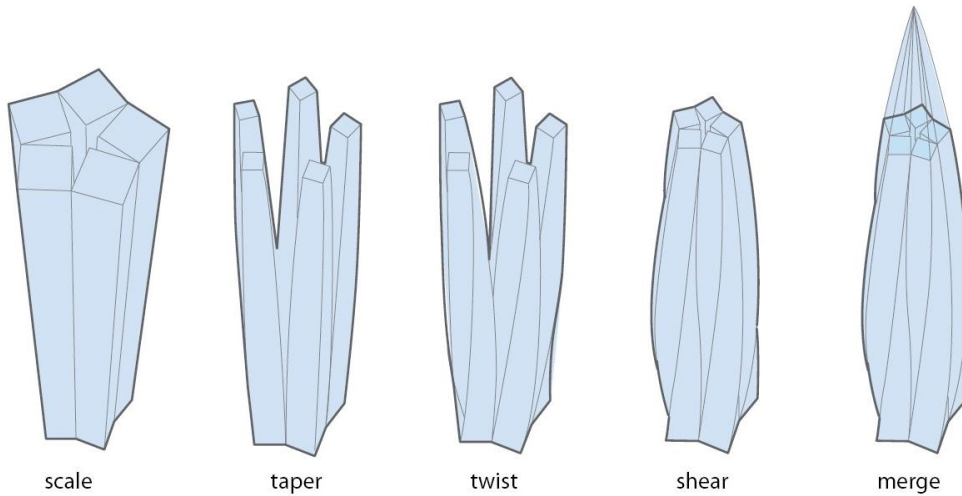


Figure 13. Transforming sequence © Matthew Wilson.
(Şekil 13. Transformasyon sırası © Matthew Wilson.)

For the initial examples of twisted forms, all the facades of the building was clad with flat glass panes, since fluently curved/twisted glass panes have not been produced for a tall building scale. A twisted façade cladding was available with a high number of flat segments, and the stepped twister is a remarkable example of this application (Figure 14). However, as twisted forms became more complicated in time, production and assembling the complex façade components were essential. Connections between a glass pane or metal paneling of complex geometry with a building's superstructure implies that façade panels meet floors and walls under varying angles. Panels in curtain walls usually connect to backing profiles, and are fastened to substructures within the superstructures' grid of columns and

floors. A conventional metal framing profile must be single/double curved and be additionally twisted to connect with a parallel surface to a freely doublecurved glass panel. Curving and additionally twisting a metal profile of simple section is complicated and labour-intensive. The complex sections of most framing profiles don't allow complex bending. A system developed by Vollers (2004) in collaboration with Alcoa Architectural Systems simplifies the connections of complex geometries. This system consists of two profiles, one of which is a straight, single curved and positioned parallel or perpendicular to the superstructure, thus standardizing the connection of the façade to the wall, floor or column. The second is the glazing profile, which has a connecting surface parallel to the glass. The two profiles meet along an essentially cylindrical surface. Whereas the backing profile provides structural strength, the hereto attached glazing profile is torsion weak. The glazing profile of complex section meets the demands of water, sound and fireproofing. It can be bent/twisted by hand to about 10° per metre, which suffices for most façades. The connection to a superstructure may be standardised in fitting and angle, for example to make perpendicular or parallel meetings with floors or columns. This industrialised system consisting of standardised profiles, makes doublecurved façades economically feasible.

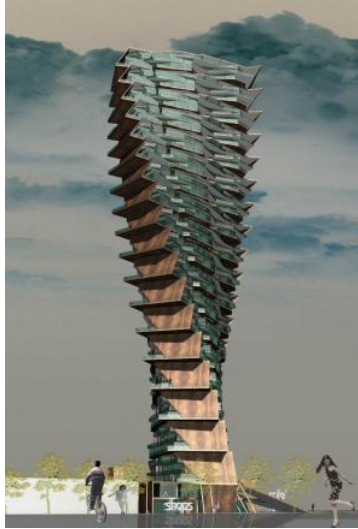


Figure 14. Urban Totem, Mississauga, Canada, ©Donner & Sorcinelli
(Şekil 14. Urban Totem, Mississauga, Canada, ©Donner & Sorcinelli)

6. CASE STUDIES (ÖRNEKLER)

6.1. HSB Turning Torso, Malmö, Sweden, 2005 (HSB Turning Torso, Malmö, İsveç, 2005)

The Turning Torso, designed by Santiago Calatrava, is based on one of his sculptures, which was inspired by the human form in motion (Figure 3). The 54-storey, 190 m high building consists of nine cubes stacked vertically, each cube containing five floors. Each floor rotates approximately 1.6 degrees and each cube rotates about ten degrees from bottom to top, resulting a total rotation of 90 degrees through the height of the building. Office facilities are located in the first two cubes and the rest of the floors incorporates residential units (Ferro, 2005).

The structural system of Turning Torso consists of a reinforced concrete spinal column, a circular core, five perimeter walls and an external steel skeleton outside the building (Figure 15a). The

reinforced concrete circular core enclosing the elevators and stairs, has an inner radius of 10.6 meters and the thickness of the walls vary from 2.5 meters at the base to 0.4 meters at the top. The tower has five perimeter walls, two of which are vertically continuous and form a triangle where they meet. Three 17-meter slightly curved perimeter walls make up the outside of each cube. These walls are set 10 meters from the core. At the apex of the two walls is the reinforced concrete spinal column of 0.6 meters wide, which spirals downward with the rotation of the building and provides extra vertical support to floors of the front facades that span up to 10 meters away from the central core. The bottom floor of each cube is cantilevered from the core on the back side of the structure. The bottom floor is 90 centimeters thick at the core and 40 cm thick at the outer edge; each floor above is 27 centimeters thick. All floors are constructed with lightweight steel, and reinforced with concrete. Each of the five floors above the cantilever is supported by 11 structural steel columns that are hidden at the edge of each floor slab within the walls.

An external steel structural support system augments the internal spine in supporting the tower (Figure 15b). This exoskeleton, which rotates with the building, is formed from a single upright steel column located at the apex of the building's walls. It also includes horizontal and diagonal steel members known as 'cigars'. The steel upright of the exoskeleton is supported by two stabilizers on each floor near the front of the building, and the steel 'cigars' connect the steel upright to shear walls near the back of the building. Each shear wall runs through the top two floors of each cube.

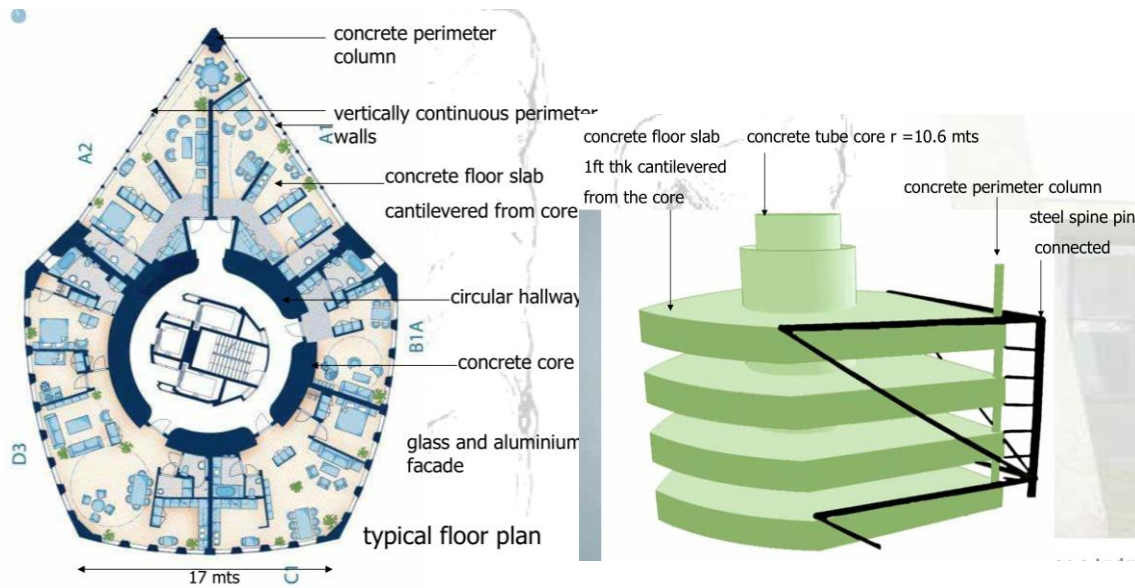


Figure 15a-b. Typical floor plan and structural concept of Turning Torso
(Şekil 15a-b. Turning Torso'nun tipik kat planı ve taşıyıcı sistem şeması)

The central core is responsible for transferring vertical loads downward. At the front of the tower, vertical loadings due to dead loads and live loads are shared between the central core and the perimeter spinal column. The loads are transferred horizontally through the concrete floor slabs and then either down the concrete

spinal column. On the backside of the building, due to the rotation of floors, perimeter columns were not possible. Here the vertical loads are transferred horizontally through the floor slab, and then vertically down through the structural steel columns on each floor. The loads will continue moving through the structural steel until they reach the lowest floor in the cube, where they are then transferred horizontally through the cantilever and then vertically down the central core to the foundation.

The concrete core of the building can carry lateral wind loads also, though the exoskeleton helps in certain wind directions. The main structural purpose of the exoskeleton is to reduce wind-induced motions. This exoskeleton of the building acts as a reinforcing truss that adds stiffness to the central core, thus dampening the building's vibrations and minimizing wind displacements. Any lateral loads on the exoskeleton are transferred through the truss components to the shear walls, which transfer the loads down through the structural steel to the cantilever, and eventually over to the central core (Turning Torso, 2005; Turning Torso Residential Tower, 2011).

The façade of the building is made of approximately 2800 curved aluminum panels with 2250 flat glass windows leaning either inwards and outwards (HSB Turning Torso, 2011).

6.2. Infinity Tower, Dubai, UAE, 2011 (Infinity Kulesi, Dubai, BAE, 2011)

Designed by Skidmore, Owings and Merrill, the 73-storey Infinity Tower is currently the highest twisting tower in the world with its 305 m height (Figure 5). The architects have used open-space planning concepts to ensure that there are no vertical supports throughout the leasing depth of the floor plans. The tower rotates 90 degrees from the bottom to the top through a series of incremental plan rotations at each level. The lateral load-resisting system consists of a combination of a reinforced concrete moment-resisting perimeter tube and a reinforced concrete central core of a circular plan, connected by two way spanning, reinforced concrete flat plates at each level acting as diaphragms. As the perimeter columns ascend from storey to storey, they lean in or out, in a direction perpendicular to the slab edge (Figure 4b). At every level, the columns shift in position along the spandrel beams so that each column maintains a consistent position at each floor relative to the towers envelope. The corner columns and the six interior columns twist as they ascend. The structural system maximizes the effective structural footprint of the tower by utilizing a significant amount of the vertical reinforced concrete for lateral load resistance. This system offers significant construction simplification through formwork repetition, which directly impacts the construction cycle time, as well as leading to residential floor layouts that are repetitive at each level despite the twisting nature of the building form.

The circular central core walls, which ascend purely vertically, are cast using a slip forming system operating through incremental but not continuous advancements, in order to remain ahead of, but in phase with the construction of the perimeter frame of the tower. The perimeter column-stacking configuration means that the forms are identical at each story, simplifying the formwork erection. Cast-in-place reinforced concrete was selected as the primary construction material due to its ability to accommodate the geometry of the tower and its mass and stiffness characteristics, which aid in the reduction of wind-induced movement of the tower (Baker, et al., 2010).

6.7. Chicago Spire, Chicago, USA (Chicago Spire, Chicago, ABD)

The 150-story Chicago Spire will be the tallest all-residential building in the world with its 610 m height, when completed. Santiago Calatrava is the lead design architect of the building, which consists of approximately 1200 residential units with varying types (The Chicago Spire Fact Sheet, 2011).

The building is supported by a composite structural system, combining a reinforced concrete core and light steel floor framing (GoStructural.com, 2007). As the floors progress upward with a rotation degree of 2.44 at each, the seven sides eventually rotate a full 360 degrees from bottom to top. The reinforced concrete central core, which contains the elevators and stairs, decreases in dimension as the building rises and tapers. Depending on the configuration of residential units on each floor, up to twelve walls are cantilevered perpendicularly from the core and serve to divide the residential suits, as well as transferring shear forces and gravity loads from the envelope to the core.

The curved nature of the sides of the building acts to help minimize wind forces and provide lateral stability (Figure 16). The spiral shape also directs some wind around and past the building to reduce lateral loads before the structure has to absorb them.

6.8. Shanghai Tower, Shanghai (Shanghai Kulesi, Shanghai)

Designed by Gensler Architects, the 128-storey and 632 m high Shanghai Tower incorporates office spaces, residences, hotel rooms, retail spaces, restaurants and a public observatory, presents a constantly changing façade from all directions (Figure 17). The tower will be the tallest building in China and the second tallest building in the world when completed in 2014.

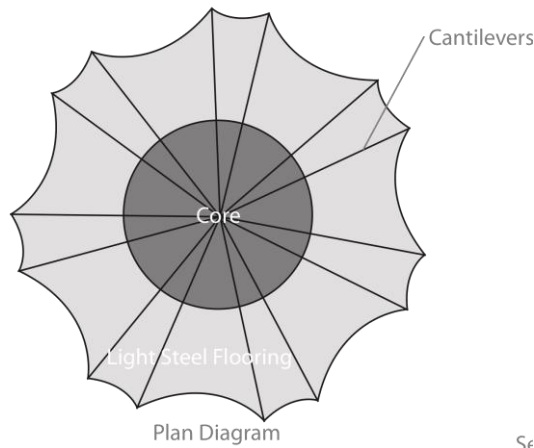


Figure 16. Plan diagram of Chicago Spire
(Şekil 16. Chicago Spire'a ilişkin plan diyagramı)

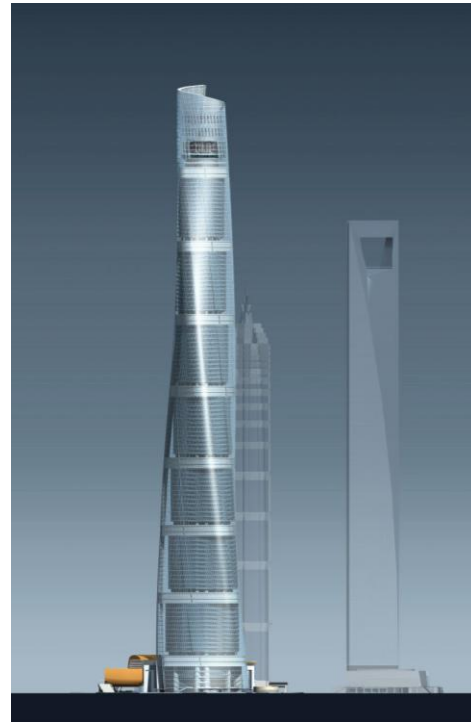


Figure 17. Shanghai Tower, Shanghai
(Şekil 17. Shanghai Kulesi, Shanghai)

Shanghai Tower is organized internally as a series of nine cylindrical buildings stacked one atop another, with nine atria encircling them. The inner layer of the double-skin façade encloses the vertically arranged interior buildings, while a triangular exterior layer creates the second skin or building envelope. The spaces between the building's external and internal facades create the atria.

The structural system of the building consists of a reinforced concrete core of 30 meters square plan, 8 megacolumns on the perimeter of the plan and 4 super columns on the corners, as well as outrigger trusses, interconnecting the columns and the core to act integrally. The tower is divided vertically into nine zones, each with 12 to 15 floors. The inner cylindrical tower steps in each zone, similar to a wedding cake. At the interface of the adjacent zones, a two-story, full floor area is designed to house mechanical, electrical and plumbing equipment and also serve as the zone's life safety refuge area.

The lateral and vertical resistance of the tower is provided by the inner cylindrical tower. The primary lateral resistance is provided by the core, outrigger and the megacolumn system, including the diagonal members together with a double belt truss. At each zone that picks up the intermediate steel columns in each zone and the mechanical and refuge floors. The core is reinforced concrete, the outrigger and belt trusses are structural steel, and the megacolumns are composite structure with concrete encased steel vertical sections. The twisting, asymmetrical shape of the tower reduces wind loads on the building by 24 percent, reducing the structural load on the building (Xia, 2010).

The tower also has a unique design in incorporating two independent curtain wall systems. The exterior skin resembles a triangular plan shape with rounded corners, whereas the inner skin is circular. The plan on the outside gradually reduces in size at each zone, giving the glass tower an elegant tapered profile. In addition, the cam-shaped plan twists around the inner cylindrical tower at each zone, creating the unique spiralling exterior façade that distinguishes the tower's unique form. The outer curtain wall is created by a series of hoop rings that are cam-shaped and rotating around the circumference of the inner cylindrical tower. The hoop ring is held away from the cylindrical tower by struts to create the outer, cam-shaped plan. As the levels progress upward, the hoop ring shifts horizontal position around the inner cylinder by a constant rotation degree, creating the spiral shape. In addition, the cam-shaped hoop rings decrease in circumference incrementally as they rise up the tower.

7. CONCLUSIONS (SONUÇLAR)

Architecturally it is interesting to create a non-orthogonal form, such as a twisted tall building. It is also interesting for the community to view such iconic structures in cities, since these buildings have symbolic values and power in urban centers. However, it is a difficult task for the architects and engineers to design a tall building with a twisting form due to the complex geometrical shapes and interrelationships between the non-orthogonal components. In this study, geometrical descriptions of the most common types of twisted tall buildings is presented and the structural systems employed for these forms are explained. The process of geometrical definition of a twisted building necessitates to handle a large number of geometrical data, thus making the simple modeling procedures deficient. Today, designers are assisted by innovative computer softwares when designing

extra-ordinary shapes. In order to simplify the design process, these softwares must allow rapid shape generations and enable to handle huge number of digital data of the components.

In addition, designing the façade system of a twisted tall building is also a significant issue. Until recently the building industry was not able to produce twisted and curved glass panes and metal framing for the façade system at an affordable price, for a scale of tall building. However, today investigations for twisted metal components and curved glass panes are crucial. Twisted tall buildings often necessitate large construction budgets, however they also offer the opportunity to experiment new and innovative design and construction technologies. Consequently, when they are extensively designed and constructed, technological improvements will be achieved, and risk of implementing these techniques in other projects will significantly reduce.

NOT (NOTICE)

Bu makale, 28-30 Eylül 2011 tarihleri arasında Elazığ Fırat Üniversitesinde "International Participated Construction Congress" IPCC11'de sözlü sunum olarak sunulmuştur.

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