ISSN 2029–9990

JOURNAL OF SUSTAINABLE ARCHITECTURE AND CIVIL ENGINEERING

DARNIOJI ARCHITEKTŪRA IR STATYBA

2014. No. 2(7)

Integration of Architectural Design with Structural Form in Non-Orthogonal High-Rise Buildings

Ayşin Sev[1*], Fazilet Tuğrul[2]

[1] Assoc. Prof. Dr., Mimar Sinan Fine Arts University, Faculty of Architecture, Building Technology Department, 34427, Findikli, Istanbul, Turkey.
[2]Res. Asst., Gebze Institute of Technology, Faculty of Architecture, Department of Architecture, 41400, Gebze, Kocaeli.

**Corresponding author: aysinsev@yahoo.com*

crossref http://dx.doi.org/10.5755/j01.sace.7.2.7046

Although high rise buildings were designed mainly in box forms throughout the 19th and 20th centuries, their architectural forms have undergone dramatic changes in the second half of the 20th century due to the demand for iconic buildings in growing cities. With the beginning of the 21st century, a number of unconventional, non-orthogonal forms can be seen throughout the Middle Eastern and Asian cities, which are now the leaders of high rise building construction throughout of the world. Until the 1980s, the International Style and modernist tall buildings were characterized by repetitive, prismatic and vertical combinations were predominant, as well as the flat roofs. The exterior facade was generally of a constant or a smoothly varying profile designed with rigourous disciplines. With the boredom of this monotony, these box forms were then replaced by non-orthogonal and non-conventional forms, such as cylindric, curvilinear, aero-dymanic shapes, by the advent of advanced structural systems, such as diagrids, mega frames, outrigger systems, and etc. By these advances in the form and structure of tall buildings, the non-orthogonal and iconic structures have emerged. Such changes in the architectural form and organization of high rise buildings were necessitated by the emerging architectural and structural trends in design, economic demands, and technological developments in the realms of technological innovations, such as structural analysis and digital design methods made possible by the advent of high-speed digital computers.

This paper tends to draw attention to the close interaction between the architectural and structural design of high-rise buildings of non-orthogonal forms. Initially the emergence of non-orthogonal forms is defined, and the non-orthogonal forms utilized for high-rise buildings are classified. After dealing with the structural design considerations and presenting a number of structural systems widely used for non-orthogonal high-rise buildings, the significance and necessity of the integration between architectural and structural design process is presented. Finally a framework is adviced for achieving a successful integration in order to evolve an architecturally pleasing and structurally efficienct high-rise building.

Keywords: *sustainability, non-orthogonal high-rise buildings, architectural form, structural system, megaframes, diagrid system, outrigger, integration.*

1. Introduction

Until recently high-rise buildings have been viewed as mega-scale structures, which are unsustainable not only dur to their large amount of energy consumption, but also because of their ordinary, box forms that do not reflect any architectural quality, design originality and regional character. However, this is changing with a new generation of high-rise buildings that are designed for sustainability, in order to reduce environmental impacts, and reflects social and cultural qualities as well. According to World Commision on Environmental Development or Brundtland Report (WCED, 1989), sustainability is an effort to meet the requirements of the present withot compromising the needs of the future generations. Although this definition seems only to encourage the reduction of resource consumption, while increasing the environmental quality, in fact it also involves the need for social quality of the built environment. Sustainable development is not a fixed state of harmony, but rather a process of change, in which the technological developments are adopted while preserving the social and cultural aspects of the built environment, and enhancing the architectural quality of our buildings. In this manner, high-rise buildings, which are inevitable for contemporary cities, have a significant role in the sustainable development of societies, by also affecting the image and identity of the city which it belongs to. The design and construction of innovative and iconic high-rises serves to extend the frontiers of social, economic and environmental sustainability.

There have been many examples of high-rise buildings that have been poorly designed, detailed and constructed in the past. These buildings has mostly box forms that have emerged from the pioneers of this building typology; New York and Chicago. However today, the existence for a high rise building, which reflects an original, iconic design innovation, as well as cultural and regional aspects of the society, not only satisfies its owner, but also the citizens as well. Although this building typology emerged in the late nineteenth century in North American cities, such as New York and Chicago, today most of the World's tallest buildings are located in the Middle Eastern and Asian cities. This shift in high-rise building construction from the West to the East is partly due to the demand for economic growth in these cities. It is obvious that this building typology has a symbolic value, expressing the economic prosperity and attracting the attention of foreign investors.

With the demand for being distinguished from the competitors, cities are now racing for inserting the most unconventional, thus iconic high-rise building in their urban silhouttes and skylines. Responding to the growing demand for iconic elements in the cities, a new trend has emerged in the shape and form of the high-rise building typology. Today a number of unconventional and non-orthogonal high-rise buildings are being designed and constructed with the advent of new structural schemes and computational architectural design methods. These out-of-box, free forms can be stated as cylindrical, curvilinear, aerodynamic, leaned, twisting, tilting, and etc.

In the past a number of free-form and non-orthogonal high-rise building projects were proposed by innovative and notional architects, such as Frank Lloyd Wright, Peter Eisenmann and Frank Gehry. However due to the inefficiency of structural forms, inadequate knowledge about material properties, as well as limited architectural design methods, they were unable to be built. By the development of tubular systems and variations by Fazlur R. Khan in 1960s, buildings of unconventional forms, such as the John Hancock Center, the Willis (formerly Sears) Tower and One Magnificent Mile (Chicago) could be built. Also the advancements in computational design and construction methods by 1980s, gave way to the realization of diagrid systems, which was once developed in 1970s, but could not be built due to the constructional inabilities until the 2000s. The first utilization of the diagrid system, in the form of trussed tube, was the United Steelworkers (formerly IBM) Building in Pittsburg, which was constructed in 1963. However, this innovative and very efficient structural form could not be improved until the construction of Swiss Re Building in London in 2004.

Because of the advancements in structural engineering and architectural design methods, today architects can design any non-orthogonal building forms in order to generate iconic high-rises. The desire to build these unconventional forms are no longer imaginary sights, by the advent of successful interactions between the architects and the structural engineers of the extraordinary forms. The formal, technical and most importantly the ecological complexities of these new generation high-rise buildings with non-orthogonal forms force the architects and engineers to interact with each other during the whole design and realization, through an integrated design process. Only this interaction between architects and engineers can lead the innovation of high-rise buildings for the future.

This paper tends to develop a framework for the integration of architectural and structural design of non-orthogonal high-rise buildings from the early stages of design. The methodology to achieve this task is to make an investigation about the high-rise building examples throughout the world, which have out-of box, non-orthogonal forms. Since the structural form is one of the main constraints when decision making of the architectural form a high-rise buildings, the structural systems, which are widely employed in non-orthogonal buildings are selected and defined as well. Then the significance and necessity of the integration between architectural and structural design process is presented. Finally a framework is advised for achieving a successful integration in order to evolve an architecturally pleasing and structurally efficient high-rise building.

2. Classification of Non-Orthogonal Forms in High-Rise Buildings

The geometrical complexity of high-rise buildings is increasing rapidly by the impact of digital tools and techniques utilized during the design process. According to Vollers (2008) the buildings have non-orthogonal forms to improve their performance; for example by minimising outer façade/floor surface ratio, material usage/costs/energy consumption decreases, or by optimising wind flow windage reduces or wind generators activate more efficiently. In the shifting terrain of tools and techniques, a detailed and also practical way of understanding of what constitutes elegance, beauty, structurally efficient and environmentally conscious meaning in the design of these complex shaped buildings are provided. These buildings not only ornament the skylines of the cities and urban centers, but also signify the economical growth and cultural status of the citizens, as well.

The out-of-box, non-orthogonal forms employed in high-rise buildings can be classified into four primary schemes according to geometrical forms; (i) Pyramidal; (ii) Leaning; (iii) Twisted, and (iv) Free forms. In addition, free forms can be classified into sub-schemes, related with the design inspirations, such as for the task of reducing wind loads on the structure (aerodynamic forms), incorporating cultural motif into the design (regional forms), and for creating unsteady outlooks (dynamic forms). In the following sub-sections, these forms are explained and exemplified.

2.1. Pyramidal Forms

Perhaps the first examples of pyramidal forms in high-rise buildings are the ancient pyramids in Egypt. However, they are not considered to be buildings, since they do not have occupied floors.

In the historical development of multi-storey high-rise buildings, the John Hancock Center in Chicago (1969) can be mentioned as the first example of pyramidal forms, although it is truncated on the top (Fig. 1). It is a trussed tube with large diagonals on the façade, tapering upwards, as well as representing a structural expressionist high-rise. Another pyramidal high-rise is the Transamerica Pyramid in San Francisco (Fig. 2). Designed by architect William Pereira, this 48-storey and 260-m tall building was completed in 1972, earning the degree of eighth tallest building in the world and currently the second tallest building in San Francisco (Transamerica Pyramid, 2010).

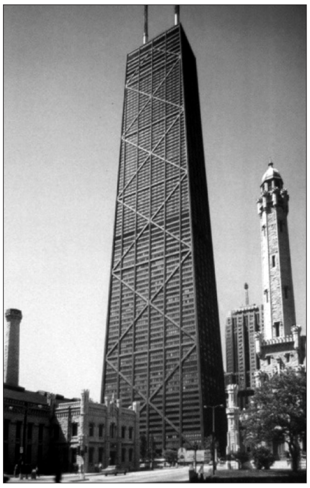

Fig. 1. *John Hancock Center, Chicago, 1969*

Fig. 2. *Transamerica Pyramid, San Francisco, 1972*

The Al Faisaliah Center Building in Riyadh (2000) (Fig. 3) and the Shard of London (on construction) (Fig. 4) are the other remarkable examples of pyramidal-formed high-rise buildings in the world.

Fig. 3. *Al Faisaliah Tower, Riyadh, 2000*

Fig. 4. *The Shard, London, on construction*

2.2. Leaning Forms

After the first (accidentally) leaning tower, Pisa Tower in the history of architecture, the Gate of Europe, with the other name KIO Towers in Madrid, Spain, are the most remarkable examples of leaning high-rise buildings of the contemporary era (Fig. 5). Designed by Philip Johnson and John Burgee, the 115 meters tall towers tilt toward each other at a 15° slant. The structural system of the buildings constitute diagonal, vertical and horizontal steel members which surround a vertical reinforced core (Puerta de Europa Towers, 2010).

A recent example of the leaning forms in high-rise buildings is the Capital Gate Building, which is completed in 2011, in Abu Dhabi (Fig. 6). At 160 m and 35 stories, it is one of the tallest buildings in the city and features an 18° incline to the west with its curvaceous shape.

Fig. 5. *The Gate of Europe (KIO Towers), Madrid, 1989*

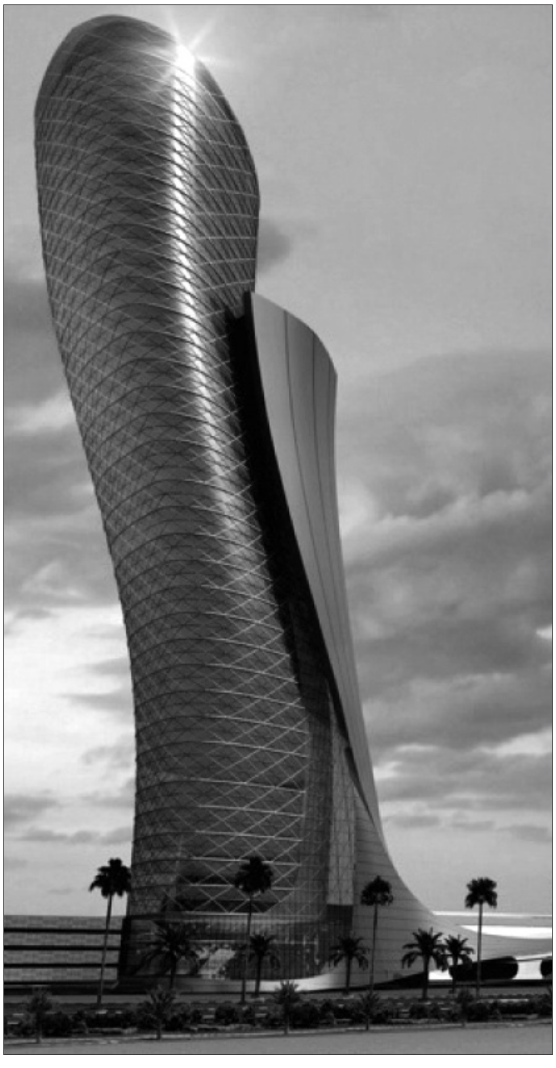

Fig. 6. *The Capital Gate, Abu Dhabi, 2011*

2.3. Twisted Forms

A twisted form for a high-rise building can be defined as a form created by the combination of twisted facades. In other words, as the floors are multiplying upwards along an axis, if a rotation is added to the floors, then the resulting form is a twister. When applying a constant rotation around a vertical axis, all floors are identical and the façades will also be repeated. Vollers (2005) classifies buildings with twisted surfaces into two groups, as Tordos and Twisters (Fig. 7). A Tordo is a building with one or more twisted façades connected to an orthogonal superstructure and the floors are basically repeated in vertical direction, with interior walls and columns aligned. The twisted façades of a Tordo at one or more sides introduce floor endings that don't parallel the orthogonal grid of the building. All elements in upright and in horizontal direction in a Tordo's twisted façade are different. Vollers (2005) defined a Twister as a building with floors that lie horizontally rotated around a vertical axis. This axis usually lies in the centre of the floor plan. The structural members, mullions and contours all circle helically upward around the rotation axis, resulting in a non-orthogonal superstructure. In a simple Twister all floors are identical and rectangular. Some structural elements, such as cores with walls, may be aligned in vertical direction, close to the axis of rotation, but basically interior walls are not aligned with the ones of the floors above or under.

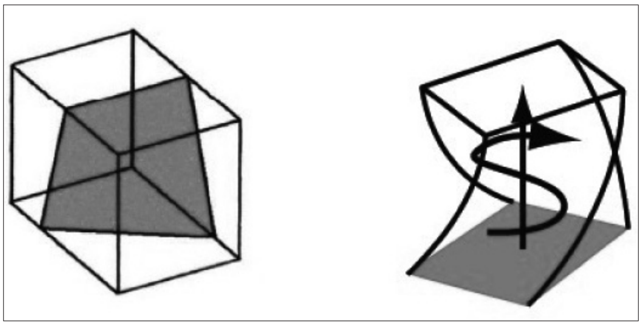

Fig. 7. *A Tordo (on the left) and a Twister (on the right) (Vollers, 2008)*

Twisted forms have been very attractive in the last decade for architects, who are willing to design extraordinary iconic buildings. The 54-storey, 190 m tall Turning Torso designed by Santiago Calatrava in Malmö, is the first twisted high-rise building throughout the world, and rapidly became a landmark for the city (Fig. 8). Calatrava was inspired by the motion of a human body in the design of his iconic buildings. From the bottom to the top, the 90° twisted tower, obtains stability from a central cylindrical concrete core. An external steel structural support system augments the internal spine in supporting the tower. This exoskeleton, which rotates with the building, is formed from a single upright steel column located at the apex of the building's walls. Each floor rotates approximately 1.6 degrees and most of the weight of the concrete floors rests on the core (Ferro, 2005).

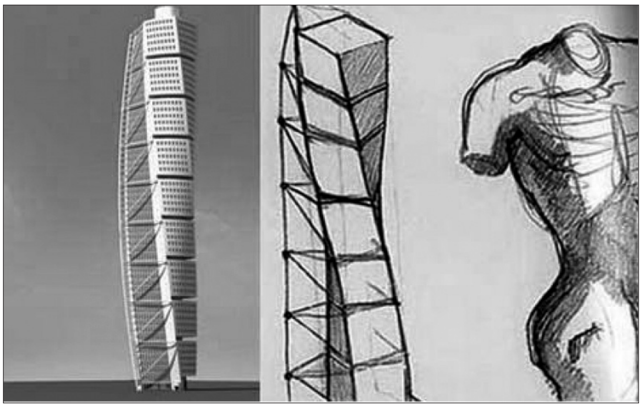

Fig. 8. *The Turning Torso, Malmö, 2005*

The other remarkable examples of the twisted high-rise buildings are the Al Bidda Tower in Doha, Infinity Tower in Dubai, Chicago Spire in Chicago (on construction), Mode Gakuen Spiral Tower in Nagoya and the very recent two examples, Shanghai Tower in Shanghai with Absolute World Tower (also known as Merilyn Monroe Towers) in Missauga (Sev and Başarır, 2012) (Fig. 9–12).

Fig. 9. *Al Bidda Tower, Doha, 2005*

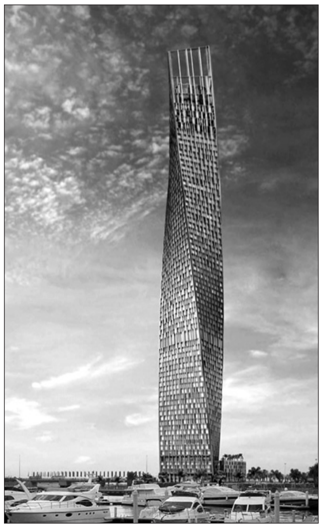

Fig. 10. *Infinity Tower, Chicago, 2006*

Fig. 11. *Mode Gakuen Spiral Tower, Nagoya, 2008*

Fig. 12. *Absolute World Towers, Missauga, 2014*

2.4. Free Forms

In the past, a number of high-rise buildings with free forms have been designed by imaginative and creative architects, such as Frank Gehry and Peter Eisenman. However, these projects could not be realized, due to the inadequate technical capabilities. According to Ali and Moon (2007), Willis (formerly Sears) Tower and One Magnificent Mile can be stated as the first examples of free forms, by the introduction of bundled-tube system. Today many free-form high-rise buildings can be designed and constructed by the advent of digital technologies, as well as the developments in structure and construction systems. CCTV Building in Beijing, Phare Tower in La Defense, Signature Towers in Dubai, PGCC Building in Dubai, Desert Tower in Peru and Apeiron Building in Dubai are the remarkable examples of free-form high-rise buildings (Fig. 13–16).

Fig. 13. *CCTV Tower, Beijing, 2012*

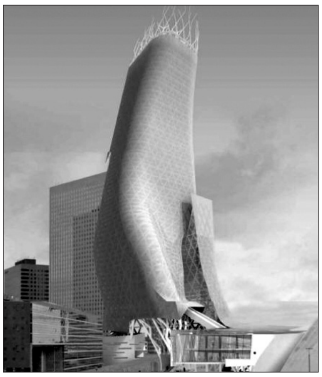

Fig. 14. *Phare Tower, Paris, on construction*

Fig. 15. *Signature Towers, Dubai, proposed*

Fig. 16. *Apeiron Building, Dubai, proposed*

Free forms can also emerge with various design inspirations and objectives by their architects, engineers and owners as well. For example in order to create changeable outlooks instead of a constant and stable one, dynamic forms are designed; to reduce the wind loads on the structure and achieve structural efficiency, aerodynamic forms emerge, and; if the inspiration is to incorporate cultural motifs to the design, regional or cultural forms are created by the architects. These free forms are briefly defined and exampled in the sub-sections.

2.4.1. Dynamic Forms

Dynamics is a branch of mechanics that is concerned with the effect of forces on the movement of objects. Inspired by this, the concept of movement is integrated with buildings and structures, thus introducing dynamic architecture (Crespo, 2007). In this context, a dynamic high-rise is a building, which changes its shape, to create various views and visual attraction. This concept is applied in the Rotating Tower by the Italian Architect David Fisher. He proposed a 420 meters tall residential building in Dubai, in which every floor rotates from a central core (Fig. 17). Each floor consists of a separate module that the resident can rotate at will or follow a particular configuration in synchronization with the whole building.

Fig. 17. *Dynamic Tower designed by David Fisher, Dubai*

There are other dynamic high-rise buildings, which are proposed for London, Paris, New York and Moscow, also.

2.4.2. Aerodynamic Forms

As the height of a building increases, it is subjected to greater wind loads and vibration. This wind-induced motion, in particular crosswind response, endangers the dynamic response of high-rise buildings, the performance of cladding and windows, and decreases the comfort of occupants. Therefore increasing the lateral stiffness against the wind loads will be beneficial for the liability of the structure, as well as providing comfort for the occupants. In order to achieve this task, a recent trend in high-rise building design practice is to improve aerodynamic properties of the overall form (Ilgın and Günel, 2007; Lee, 2011). By applying various treatments on the plan shape and overall form of the structure, such as chamfered or rounded corners, streamlined forms, tapered forms, openings through a building, and notches, the wind loads impacting on the structure can be decreased. Commerzbank Tower in Frankfurt can be stated as being one of the first aerodynamic forms, for having a triangular plan shape with rounded corners. Also the Swiss Re Tower in London is the most remarkable aerodynamic high-rises (Fig. 18). The Shanghai World Financial Center (Fig. 19) and the Kingdom Center in Riyadh employ a large through-building opening at the top combined with a tapered form. The Pearl River Tower's (Guangzhou) opennings on its facade catch the wind flow not only to reduce the building motion but also to generate energy using wind

(Fig. 20). Due to the nature of this strategy which manipulates building masses and forms, this approach blends fittingly with architectural aesthetics (Ali and Moon, 2007).

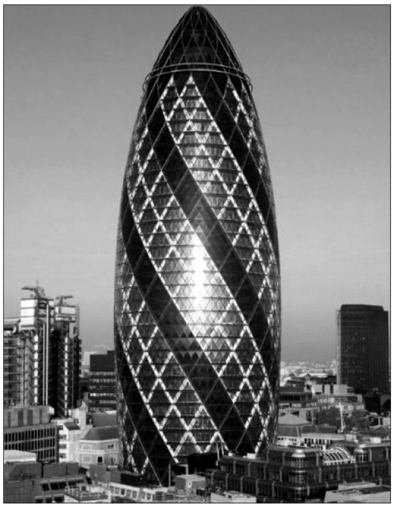

Fig. 18. *Swiss Re HQ Building, London, 2004*

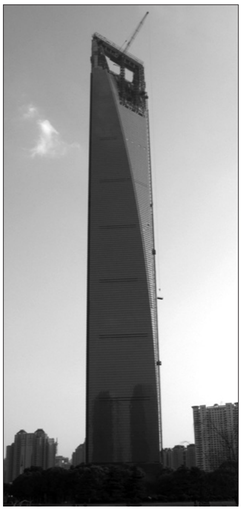

Fig. 19. *Shanghai World Financial Center, 2008*

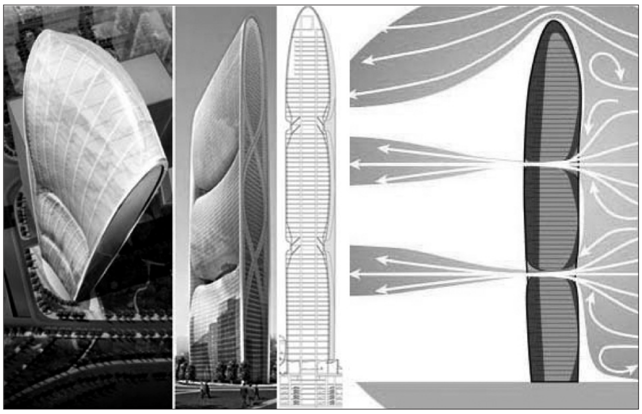

Fig. 20. *Pearl River Tower, Guangzhou, 2011*

2.4.3. Regional Forms

A recent trend in the design approach of high-rise buildings, especially in Middle East and Asian cities is to use regional motifs in the plan shape or overall form. For example Petronas Twin Towers in Kuala Lumpur (1997), can be mentioned in this context, for resembling the slender minarets of Malaysian mosques, as well as emphasizing the Islamic and oriental use of symmetrical geometry both in the outer view and on the interior (Fig. 21). The plan shape of the towers consists of two overlapping squares – interlocking heaven and earth- to create an eight pointed star, which is the dominant feature of Islamic architecture.

Another typical example of regional high-rise buildings is the Jin Mao Tower in Shanghai, constructed in 1999 (Fig. 22). SOM designed the tower with traditional Chinese forms so that the building would be less of a stark tower emerging from Shanghai skyline, but more of a holistic representation of the Chinese culture. The words 'jin mao' means 'much gold' in Chinese. In China, gold represents both the emperor and wealth. The building's setbacks throughout the facade create the ancient form of stepped pagodas. The building follows the Chinese good luck charm of the number eight with its 88 floors. In the Chinese culture the number eight is considered to be a number that represents luck, wealth and prosperity. It has eight vertical segments with decreasing height of each higher segment by one-eighth of the height of the adjacent segment below.

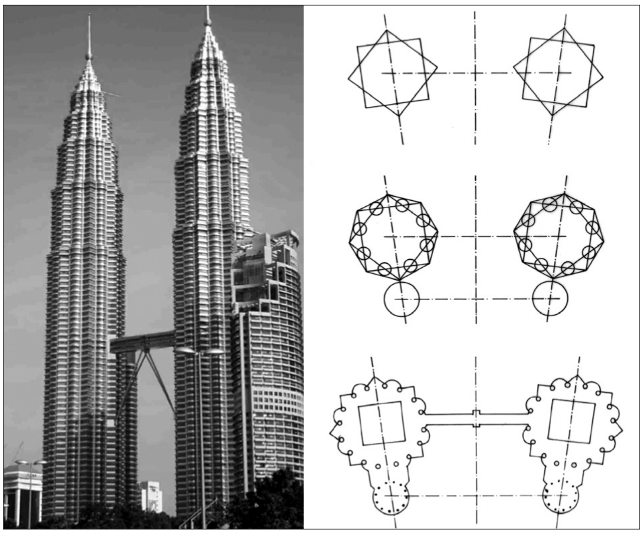

Fig. 21. *Petronas Towers, Kuala Lumpur, 1997*

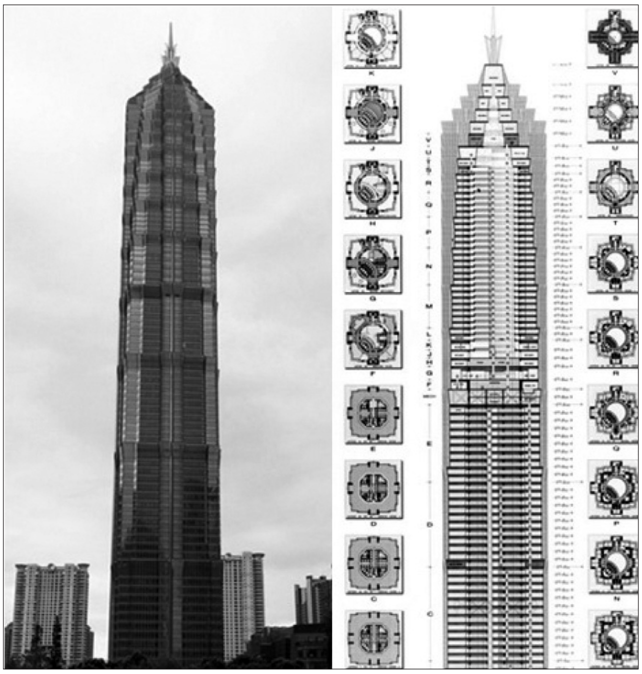

Fig. 22. *Jin Mao Tower, Shanghai, 1999*

The other remarkable examples of regional high-rises can be stated as the National Bank of Jeddah in Saudi Arabia, Taipei 101 Tower in Taipei, Burj Al Arab and Burj Khalifa in Dubai and Aldar Tower in Abu Dhabi.

3. Structural Design Considerations in Non-Orthogonal High-Rise Buildings

The significance of the structural system for a high-rise building can be seen by the fact that structural cost increases with height, primarily due to the drastic increase in the quantity of structural material required to resist heavy gravity loads and more importantly lateral loads. Such costs can constitute up to 30 % of the building's total construction cost (Almusharaf and Elnimeiri, 2010). For a viable design solution to be realized, structure must assume its rightful place during the architectural form conceptualization process.

The primary task for a structural system is to provide the required equilibrium, stability, strength, stiffness, ductility, occupant comfort and constructability to ensure a robust structure. Of course, the structure also has to be care- fully designed to fit well within the enthusiasm of the architect. For example a structural form that is architecturally exposed to the outside can act as horizontal/vertical shading devices, or it can shape atriums for the use of solar/wind spaces. It can also interact with the installation of wind turbines by providing and supporting the openings needed for the wind to pass through, such as in the case of Pearl River Tower in Guangzhou.

According to Halvorson (1988), design principles of an efficient high-rise building structure is as follows:

- It must resist the overturning forces due to lateral forces on vertical elements,
- It must channel gravity loads to those vertical elements resisting overturning forces.
- It must resist lateral forces with members axially loaded in compression rather than tension or bending.
- The structural systems, which are widely employed in non-orthogonal high-rise buildings are as follows:

3.1. Tubular Systems

Tubular systems, which was developed by Fazlur R. Khan in 1960s, have been employed in a number of high-rise buildings in the past, for being an efficient framing systems. A tube is described as a structural system in which the perimeter of the building is consisted by closely spaced vertical columns interconnected by spandrel beams or bracing members, acting as a cantilever structure. It resists the horizontal forces caused by wind or earthquake, and provides lateral support to all vertical supporting members against buckling (Özgen, 1989).

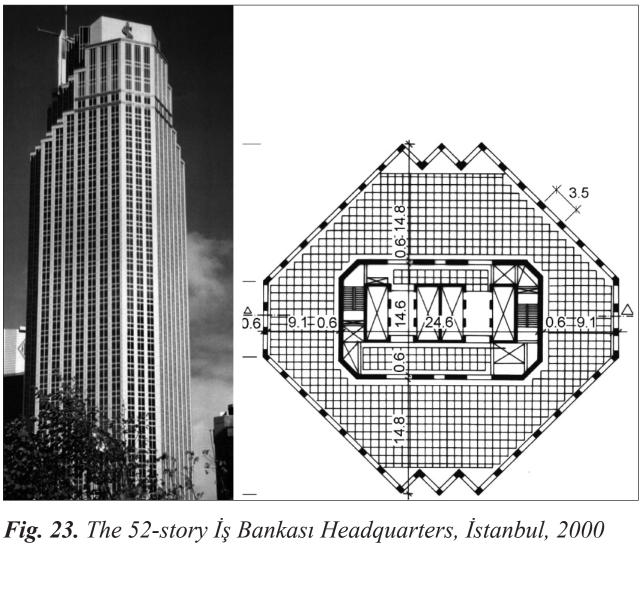

Fig. 23. *The 52-story İş Bankası Headquarters, İstanbul, 2000*

The tubular concept was further enhanced for increasing efficiency, thus introducing new architectural forms as well (Taranath, 1997). Bundled tubes and braced tube systems are the result of these advancements. By employing a bundled tube, which is a cluster of individual tubes connected together to act as a single tube, the structural efficiency of the structure can be increased. A few non-orthogonal buildings could have been realized in the past, such as the 60 State Street Building in Boston (1977). One of these non-orthogonal applications is the 52-story Is Bankasi HQ Building in Istanbul, constructed in 2000 (Fig. 23) (Sev, 2001). A bundled tube system offers great freedom in the overall design of high-rise buildings by creating a variety of existing forms.

For super tall buildings, framed tube systems are not efficient since the size of the frame members are controlled by bending, resulting in large sizes. In addition, the cantilever behaviour of the structure is undermined and shear lag is increased in the columns. Supporting the tube by bracing members can partially solve this problem by stiffening the widely spaced columns by diagonal braces. This system also has a structural expression of the façade, as well as providing large windows and openings. The John Hancock Center in Chicago (1969) is a typical example of this concept (Fig. 1). However the imperative for vertical and lateral structural members in a braced tube restrains the architect to design non-orthogonal forms. In order to overcome this restraints, the latest trend in the design of non-orthogonal high-rise buildings is to eliminate the lateral and vertical members, thus introducing the diagrid system for high-rise buildings.

3.2. Diagrid System

One of the latest developments in the structural technologies is the diagrid system, which is a very efficiency system for super high-rise buildings, especially with non-orthogonal and complex forms (Moon, *et al.*, 2007). This system is an enhanced variation of braced tubes; the difference between the two systems is that; vertical elements of the braced tubes on the perimeter are almost eliminated, in order to achieve more stability. In this case the vertical and lateral loads are resisted by diagonal members. This is possible due to their triangulated configuration in a distributive manner. Despite other structural systems for super high-rise buildings, diagrid system has a great potential for being aesthetically attractive in addition to structural efficiency. Also by the elimination of vertical members, unobstructed views can be provided for the occupants. A stiff core is not always necessary for lateral stiffness, since the diagonal members can resist both lateral and vertical forces.

A diagrid can be constructed by both steel or reinforced concrete. Swiss Re Tower in London (2004), Guangzhou International Finance Center in Guangzhou (2010), O-14 Building in Dubai (2010), Capital Gate in Abu Dhabi (2011), Phare Tower in Paris (on construction), Aspire Tower in Doha (2007), Aldar Tower in Abu Dhabi (2010) and the Bow in Calgary (2012), are all non-orthogonal high-rise buildings supported by diagrid systems (Sev and Eren, 2010) (Fig. 24–26).

Fig. 24. *Guangzhou Int. Finance Center, 2010*

Fig. 25. *O-14 Building, Dubai, 2010*

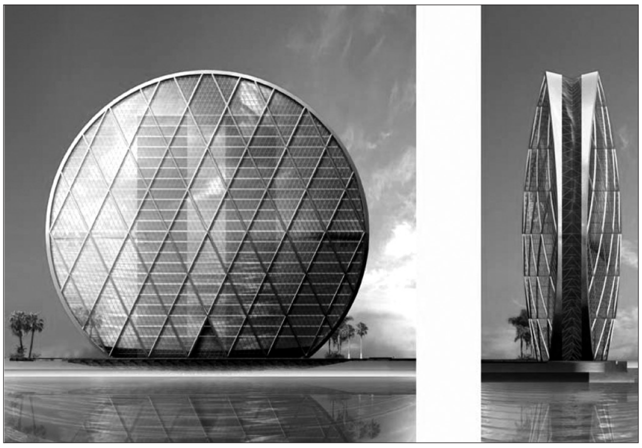

Fig. 26. *Aldar Tower, Abu Dhabi, 2010*

3.3. Mega Frames with Core and Outriggers

In super high-rise buildings, tubular systems are not efficient due to the huge weight of the structure, thus causing the building collapse. For this reason mega frames or super frames consisting of large columns will be beneficial. These columns are located on the perimeter or corners of the building, and sometimes can also be linked with multi-storey trusses, in addition to the perimeter beams. However, this mega frame can not alone be efficient enough to withstand the lateral loads, thus necessitating a central core of braced frames (in steel construction) or shear walls (in reinforced concrete construction), which is linked to the mega columns with outriggers. The links between the two elements are the outriggers, either trusses or girders.

Outriggers have been used by sailing ships in the past, to help resist the wind loads, making the tall and slender masts stable and strong. The mast of the ship can be resembled to the core in a high-rise building with outriggers acting as the spreaders and the exterior columns like the stay (Ali and Moon, 2007; Taranath, 1997). Architectural advantages of mega frame with core-and-outrigger systems are that, the exterior column spacing can easily meet aesthetic and functional requirements. For super high-rise buildings, connecting the outriggers with exterior megacolumns opens up the façade system for flexible aesthetic and architectural articulation thereby overcoming a principal drawback of closed-form tubular systems. In addition, outrigger systems have a great height potential up to 150 stories and possibly more. Today most of the super high-rise buildings taller than 70 stories are supported by mega frames with core and outrigger systems. The most remarkable examples, which are constructed are the Jin Mao Tower in Shanghai (1999), Petronas Towers in Kuala Lumpur (1997), Taipei 101 in Taipei (2004), Shanghai World Financial Center in Shanghai (2008) and the very recently constructed Shanghai Tower in Shanghai (Fig. 27–28).

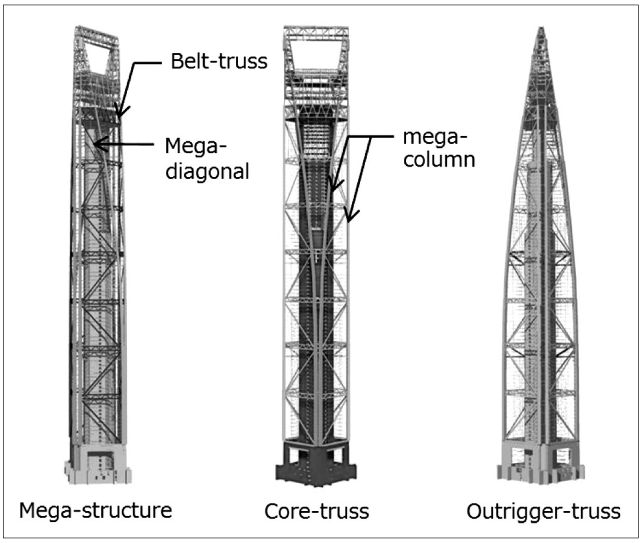

Fig. 27. *The structural scheme of Shanghai World Financial Center, Shanghai, 2008 (Shanghai WFC, 2010)*

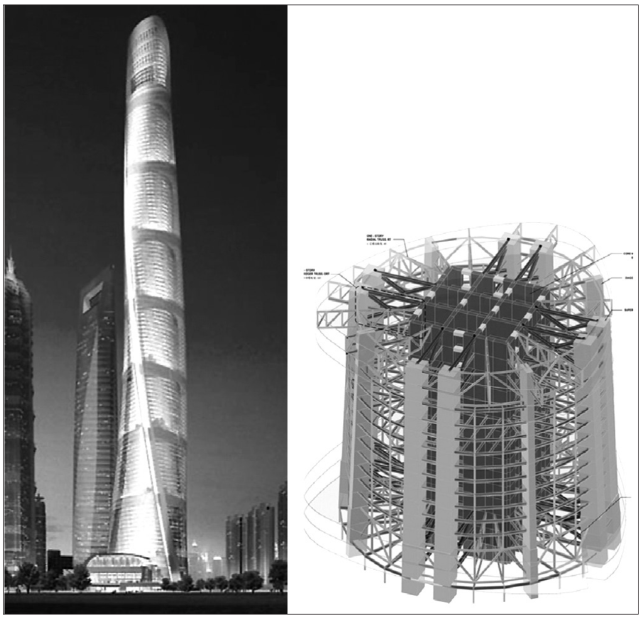

Fig. 28. *Shanghai Tower in Shanghai, and the structural scheme, 2014 (Xia, et al., 2010)*

3.4. Buttressed Core System

The buttressed core is a very new structural system developed by the close relationship of structural engineers with the architects of the world's tallest building, Burj

Khalifa. Bill Baker and his associates at SOM designed a large concrete core acting as a solid tube in order to significantly contribute to lateral stiffness (Fig. 29).

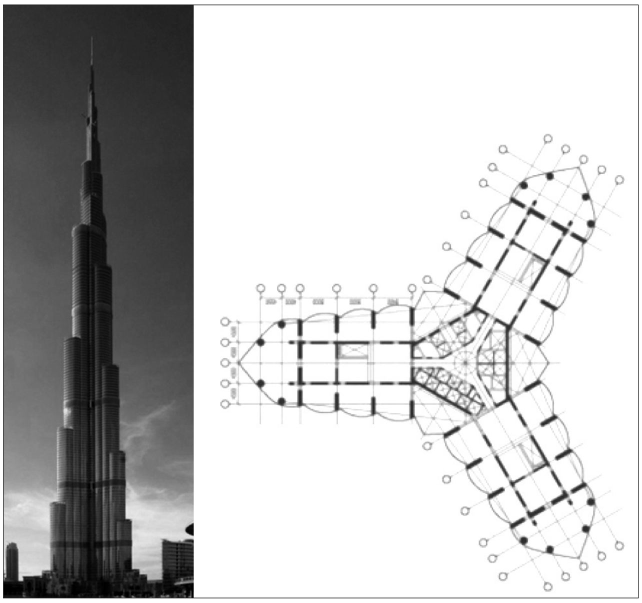

Fig. 29. *Burj Khalifa, 2010, and the plan shape of the tower, Dubai*

As a residential tower, the Burj Khalifa required floor plates with shallow lease spans in the living spaces. It also required a wide footprint to provide sufficient stability to resist high wind loads. The Y-shaped arrangement of reinforced concrete shear walls around the central hexagonal reinforced concrete core satisfied both of these requirements (Baker, *et al.*, 2007). This concept was also employed in the 610 m tall Chicago Spire Tower project (unbuilt) designed by Santiago Calatrava and engineered by SOM in Chicago. This system is then reconfigured for the Kingdom Tower (Jeddah), which is currently under construction.

4. Framework for Integration of Architectural and Structural Design

By the advent of developments in structural systems and façade construction, as well as the innovations in digital technologies, architects can now design any buildings with unconventional, non-orthogonal and irregular forms. From the view point of current structural design practice, today's irregular and non-orthogonal high-rise building forms require more complicated and integrated system design, analysis and construction. On the other hand, they may offer better performance in response to dynamic loads such as wind and earthquake forces. Unlike conventional and box-formed buildings, any irregularity in the form of a high-rise building impacts the aerodynamic properties positively, thus preventing wind from forming organized vortexes, which may cause serious vibration problems (Aminmansour & Moon, 2010). Integration of architectural design with engineering strategies beginning with the initial design stages is very important, in order to produce better performance high-rise buildings. For example the collapsed World Trade Center Twin Towers required viscoelastic dampers to be installed to mitigate motion, after the structural design process, while the recently constructed Burj Khalifa, which is taller than World Trade Center TT, could be built without any damping devices. Because the irregularity of the overall form and non-orthogonal plan shape helped the architectural design to be aerodynamic, thus confusing the wind and decreasing the lateral loads on the structural system (Baker, *et al.*, 2007).

In the context of current high-rise building design practice, issues related with the structural system are generally dealt with after the architectural form is articulated. Such an approach requires that the form undergo a rigorous after-the-fact rationalization process, which necessarily limits the structural design's role on solving the problem rather than integrating the structural system and solution into the architectural design concept (Almusharaf and Elnimeiri, 2010). While such an approach may enable a building to stand upright, it will not provide solutions that will satisfy the architect's enthusiasm and perform fully in the conceptual, formal, technical and financial manner (Kloft, 2005).

Today wind tunnel tests are imperative not only for structural analysis, but also for revisions in the architectural design as well. These analyses offer the structural engineer the opportunity to provide enough provision about the building's response to wind. Also the architects can obtain information from these analyses and revise the shape and form of the building, to reduce the impact of wind on the building. A successful example of integration of engineering and architectural design of the high-rise building is the Taipei 101 in Taiwan, for having a pendulum inside the building, to act as a damping device, and this device is exposed in the atrium of the building as an attractive element for occupants and visitors (Fig. 30).

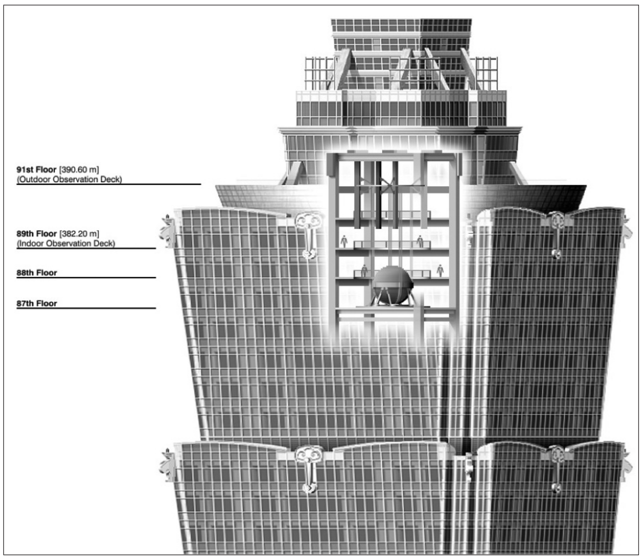

Fig. 30. *The pendulum of the Taipei as the damping device*

Integration of structural with architectural design is not only significant from the structural, aesthetic and economic point of view, but also from the point of constructability. In a non-orthogonal high-rise building, the construction of the façade system and elements is also a challenging issue. As buildings' form becomes irregular, the integration of structural system and façade elements becomes more critical. One efficient approach is to possibly standardize façade modules, while designing more adaptable connection elements, as in the case of many high-rise buildings supported by diagrid structures. For example, the greatest challenge in the construction of Swiss Re Tower in London was the integration of cladding panels with the non-orthogonal, diagrid structure. Schimidlin, a Swiss company, who worked on many buildings' cladding systems in Europe, created their own detailing computer software for the design of cladding panels of Swiss Re, bridging spreadsheets and production lines. Schimidlin also wrote their own special software linking the 3D model directly to the CNC machines on the production line (Abel, 2004).

According to Thurnauer (2006), buildings are governed by good detailing practices such as material limitations, weather and water resistance, construction tolerances and feasible construction sequencing. However, the form generation process heavily depends on the limitations of structural configuration and material properties. The works of Classical Architecture era shows this structural influence on the form generation in the design, very clearly. Two dimensional graphical methods have been used from ancient times to find appropriate form and structural considerations at the same time. Although very simple, this method is extremely powerful for structural analysis. However, today this method can be poor, since the designers' capabilities to create new forms have soared, thus imaging more complex configurations. Also there are a number of attempts to capture design motives from the nature and apply them to architectural and structural design. Natural structures are very remarkable examples of efficiency. Technology transfer helps the designers to capture these natural forms, organisms and functions, and analyze them in order to utilize it in an architectural object or design process.

The Information Technologies (IT) changed the practice of architectural design process, and helped the designers to enhance their imagination to introduce new and more complex shapes. Today there are a number of software programs that help the architects and engineers to design and analyze irregular building shapes. These programs help the designers to easily generate complicated forms in 3D models at all levels of familiarity with digital modelling. They also help them efficiently explore design variations with very few manual operations and provide mechanisms to store design knowledge in digital formats (Bldgsim, 2008).

Today, the latest trend in the design of high-rise buildings, whether it has a non-orthogonal form or not, is to use digital tools in the early design phase, preferentially in order to provide an interaction between the architectural and structural design. The convergence of the generative and analytical tools for use in the early phases of the design offers many opportunities for creating forms beyond traditional approaches. If these tools help the designers investigate both the architectural and structural design alternatives concurrently, the task of iconic high-rise buildings with highest efficiency will be achieved.

To evolve iconic high-rise buildings with unconventional, out-of-box and non-orthogonal forms, a methodology, which considers architectural design preferences and structural design considerations together, also providing interaction between them, will help designers to analyze the design alternatives in every design stage (Fig. 31) by using digital design tools. This methodology

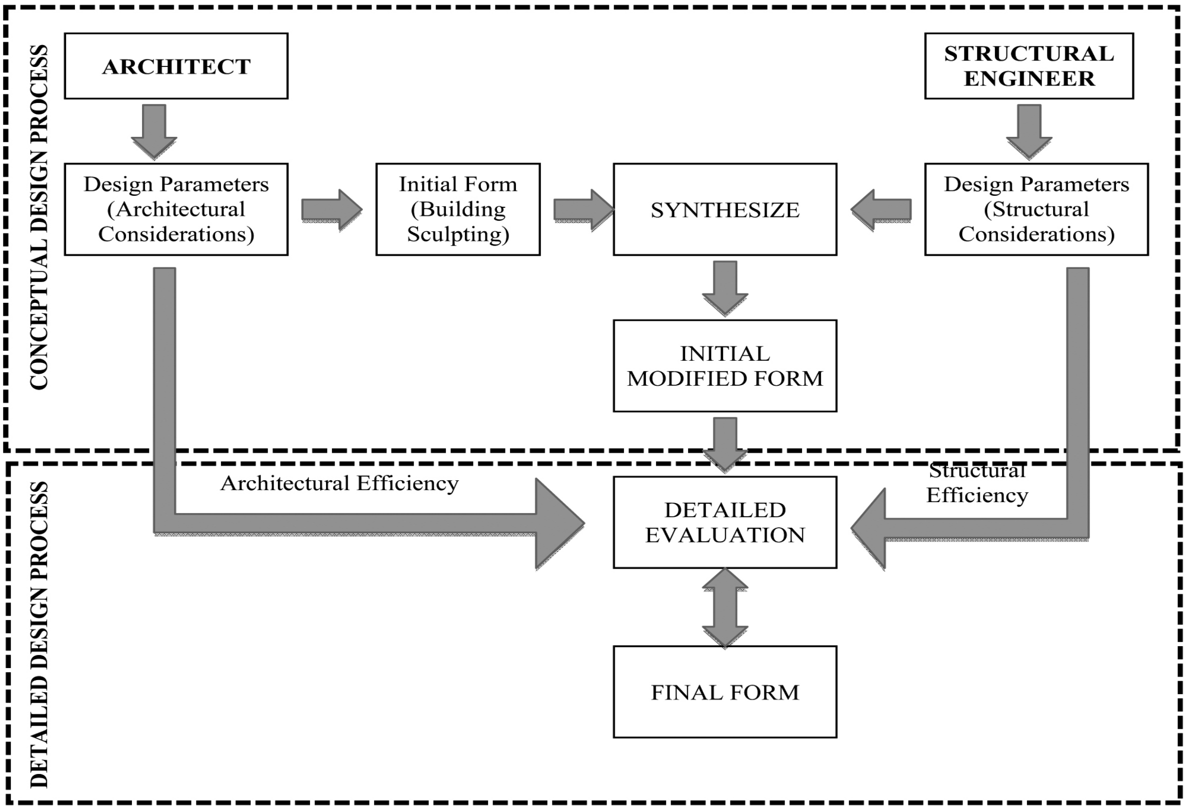

Fig. 31. Framework for the integration of architectural and structural design process in non-orthogonal high-rise buildings

consists of two phases; (i) Conceptual Design Process (CDP), and (ii) Detailed Design Process (DDP). In the CDP, by integrally synthesizing the design parapeters resulting from the architectural and structural considerations, initial modified form is put forward. In this stage, structure is of paramount importance, since it greatly affects the architectural form and efficiency of the floor plates. It is essential that, structurally sensitive architectural forms can only be achieved by an integrated design process with architects and engineers creativity. Structural issues must be carefully and diligently dealed with other design considerations in this early process, and the alternatives must be evaluated from architectural and structural design criteria in order to achieve a detailed design in the DDP. In this second stage of decision making, the former architectural form development is critical and has a significant implication on the final design. Placing less emphasis on structural design in CDP frequently yields inefficient design solutions that typically lead to problematic and costly construction process. Utilizing generative and analytical design tools supports the design activities in both processes and enables the integration of architectural and structural designs. By the help of this methodology, architectural planning considerations will adhere to basic structural principles in an efficient and aesthetically satisfied manner, as well.

5. Conclusion

The recent trend in high-rise building design all over the world is to design and build increasingly taller and complex-shaped, non-orthogonal structures. These buildings face many architectural and structural design challenges due to their extreme height and unconventional geometric forms. In the traditional design process, architects usually make analog sketches for the overall form of the building, then the process is passed on the structural engineering, making amalysis and synethesis on the selected architectural and structural form. Due to this inefficient design process, many delays could occur in the finalization of the project. However, with the advent of advances in the digital design methods, today architectural and structural design processed can be driven simultanously. Today, the age of interaction between the architect and the engineer is even more intricately interwoven by virtue of a combination of factors, ranging from new digital tools to highly advanced technological means and methods. The integration of architectural and structural design has many benefits, such as providing the ultimate efficiency in structural design, as well as creating the any iconic form that the architect imagined. By following the steps in the proposed framework designers will take the benefit of this integration to the utmost.

References

Abel, C., 2004. Architecure, Technology and Process, Burlington: Arhitectural Press.

Ali, M. M., Moon, K. S. 2007. Structural developments in tall buildings: current trends and future prospects. Architectural Science Review, 50(3), 205–223. http://dx.doi.org/10.3763/asre.2007.5027

Almusharaf, A., Elnimeiri, M. 2010. A performance-based design approach for early tall building form development. 5th International Conference Proceedings of the Arab Society for Computer Aided Architectural Design (ASCAAD 2010), Morocco, 19–21 October 2010, 39–50.

Aminmansour, A., Moon, K. S. Integrated design and construction of tall buildings. Journal of Architectural Engineering, June 2010, 47–53. http://dx.doi.org/10.1061/(ASCE)1076-0431(2010)16:2(47)

Baker, W. F., Korista, D. S., Novak, L. C. 2007. Burj Dubai: engineering the world's tallest building. The Structural System of Tall and Special Buildings, 16, 361–375. http://dx.doi.org/10.1002/tal.418

Bldgsim, 2008. Parametric Design Tool based on Rhino, Tools for better and more Sustainable Building Design. Available at: http://bldgsim.wordpress.com/2008/10/09/parametric-design-tool-based-on-rhino/ (accessed 01 April 2014).

Crespo, A. A. 2007. Conceptual design of a building with movable parts. Master of Civil and Environmental Engineering Thesis, Massachusetts Institute of Technology, Massachusetts.

Ferro, C. 2005. Malmö reaches for the sky. Available at: http://www.sweden.se/templates/cs/Article_12964.aspx (accessed 30.September.2005).

Halvorson, R. A. 2008. Structural design innovation: Russia Tower and other tall collaborations. CTBUH 8th Congress: Why Tall? Green, Safety and Humanity, 10–11 October 2011, Seoul.

Ilgın, H. E., Günel, M. H. 2007. The role of aerodynamic modificiations in the form of tall buildings against wind excitations, METU JFA, 24 (2), 17–25.

Kloft, H., 2005. Non-standard structural design for non-standard architecture, in B. Kolarevic, Performative Architecture: Beyond Instrumentality, London: Spon Press.

Lee, J., 2011. The role of aerodynamic modifications of the shapes of tall buildings, MSc Thesis, Massachusetts Instititute of Technology, Massachusetts.

Moon, K. S., Connor, J. J., Fernandez, J. E. 2007. Diagrid structural systems for tall buildings: characteristic and methodology for preliminary design. The Structural Design of Tall and Special Buildings, 16(2), 205–230. http://dx.doi.org/10.1002/tal.311

Ozgen, A. 1989. Çok katlı yapıların gelişimi ve son aşama: tübüler sistemler (The historical development of multi-storey buildings and the last phase: tubular Systems), Yapı, 89, Yapı Endüstri Merkezi, 47–53.

Puerto De Europa Towers, 2010. Available at: http://architecturerevived.blogspot.com.tr/2010/02/puerta-de-europa-towers-madrid-spain.html (accessed 22.February. 2010).

Sev, A. 2001. Türkiye'de ve Dünyadaki Yüksek Binaların Mimari Tasarım ve Taşıyıcı Sistem Açısından Analizi (The Analysis of Tall Buildings According to Architectural Design and Structural Systems in Turkey and at Abroad). Doctoral Dissertation, Mimar Sinan University, Institute of Science and Technology, Istanbul.

Sev, A., Başarır, B. 2011. A recent trends in tall building design. E-Journal of New World Sciences Academy (NWSA), Engineering Sciences, 2011, 6(4), 1603–1619.

Sev, A., Eren, Ö. Diagrid structures as a sustainable strategy for tall buildings, Proceedings of International Sustainable Buildings Symposium, 26–28 May 2010, Ankara, 232–237.

Shanghai WFC, 2012. Available at: http://www4.kke.co.jp/stde/en/consulting/highrise_bldg.html (accessed 01.April.2014).

Taranath, B. S., 1997. Steel, Concrete and Composite Design of Tall Buildings. New York: McGraw-Hill, Inc.

Thurnauer, M. 2006. From Design to Fabrication: Precast Concrete with FormZ, FormZ Joint Study Report, 74–76.

Transamerica Pyramid, 2010. Available at: http://en.wikipedia.org/wiki/Transamerica_Pyramid (accessed 16.01.2010).

Vollers, K. J. 2005. High-rise buildings with twisted façades. CTBUH Proceedings of CTBUH (Council on Tall Buildings and Urban Habitat) 7 World Congress: Renewing the Urban Landscape, New York, 16–19 October. Available at: http://technicalpapers.ctbuh.org (accessed 01.MArch.2014).

Voller, K. J. 2008. Morhological scheme of second-generation non-orthogonal high-rises, CTBUH 8th World Congress, Tall and Green: Typology for a Sustainable Urban Future, 3–5 March, Dubai, Available at: http://technicalpapers.ctbuh.org (accessed 01.March.2014).

Xia, J., Poon, D., Mass, D. 2010. Case study: Shanghai Tower. CTBUH Journal, 2010 Issue II, 12–18.

Received 2014 05 07

Accepted after revision 2014 05 30

Ayşin SEV – Assoc. Prof. Dr., Mimar Sinan Fine Arts Uni., Faculty of Architecture, Builidng Technology Department.
Main research area: High-rise buildings, sustainable design, energy efficient design, structural sytsems of tall buildings,
Address: Meclis-i Mebusan Cad. Findikli, 34427, Istanbul, Turkey.
Tel.: +90 212 2521600
E-mail: aysinsev@yahoo.com

Fazilet TUĞRUL – Architect, Res. Asst., Gebze Institute of Technology, Architecture Department.
Main research area: Tall buildings, building technologies.
Address: Çayırova Yerleşkesi, 41420, Çayırova, Kocaeli, Turkey.
Tel.: +90 262 6051000
E-mail: mimfazilettugrul@hotmail.com