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Twisted, Tapered, Tilted (Leaning) Towers: Structural Complexities & Advantages

Marionne James

M-Arch Sustainable Tall Buildings,
University of Nottingham, UK

***Abstract:** Recent decades have seen the rise of non-conventional, non-orthogonal high-rise buildings coming up in many parts of the world. The modern digital design capabilities and construction methods have aided in the design of highly complex geometrical structures, which are materialised using cutting edge technologies, materials and efficient building practises. This paper examines the structural complexities and relative advantages of the three main categories of non-conventional geometric forms namely Twisted, Tapered and Tilted towers.*

The author thankfully acknowledges the reliance on the studies and observations of experts referred to here in.

***Keywords:** Structural complexities, Twisted towers, Tapered Towers, Tilted towers, Tall Buildings.*

I. INTRODUCTION

Human effort to construct high-rise buildings that reach out to the skies began in the 19th century. Until the latter half of the 20th century architectural and structural features of such high-rise buildings had remained almost the same with the prismatic box-type structure being the predominant form. Architects started breaking out of this more than century old trend/convention during the later decades of the 20th century. Since then there has been a flurry of non-conventional high-rise buildings. Now, economic centres and urban metropolises are vying with each other to raise non-conventional non-orthogonal high-rise iconic structures that will give those locales a better visibility, an added attraction and a collective ego-boosting.

Though, earlier itself there had been proposals for construction of off-beat high-rise structures by eminent architects like Frank Lloyd Wright, Frank Gehry, et al., those projects had not materialised because of the inability to give structural form to such complex architectural designs. However, with the advent of the digital design capabilities and construction methods there has been a giant leap in this regard. Innovative and highly sophisticated digital design tools lends immense capabilities to architects and structural engineers to design highly complex geometrical structures which can be materialised making use of cutting edge technologies, traditional as well as specially developed building materials and highly efficient building practices.

Sev and Tagrul (2014) classifies the non-conventional, non-orthogonal forms of high-rise structures into four primary categories based on their geometrical forms: (i) Pyramidal; (ii) Leaning; (iii) Twisted; and (iv) Free Forms. They further sub-classify Free Forms based on the design inspiration into aerodynamic forms, regional forms and dynamic forms. This essay examines the structural complexities and advantages of Twisted, Tapered, and Tilted Towers (3 T types)

A. TAPERED TOWERS

The '*Pyramidal*' category under the above referred classification is also known as 'Tapered' because of their morphological characteristic. These structures as the name suggests taper as it goes up. It may not end in a pointed vertex in all cases. John Hancock Centre in Chicago (1969) is considered to be the first modern high-rise 'Tapered' building. It is rectangular in plan and tapers upwards. It does not have a pointed top; instead it is truncated at the top and so it has a flat top. This building with a height of 344 meters is having a braced-tube structure with large fully exposed X-braces on the facade.

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(Photo Source: CTBUH database- Skyscrapercenter.com)

Figure 1: (Left-Right) John Hancock Centre in Chicago, Transamerica Pyramid in San Francisco, Al Faisaliah Center in Riyadh, The Shard in London

Architect William Pereira's Transamerica Pyramid (1972) in San Francisco is another Tapered Tower 260 meter tall with 48 storeys .Another prominent example of a Tapered Tower is the Al Faisaliah Centre (2000) in Riyadh.

The 'London bridge tower', commonly referred to as 'the Shard', by Italian architect Renzo Piano which was completed in 2012 is an excellent example of a Tapered Tower. The 72-storey, 309.6 meters building with a needle-point structure is considered to be the tallest building in Western Europe at present. It is a mixed-use tower with office space, 5-star hotel, restaurants and residences.

(Source: CTBUH Database-www.skyscrapercenter.com)

Figure 2: (Left-Right)-Capital Gate Building in Abu Dhabi and The Gate of Europe, Madrid, Spain

B. LEANING TOWERS (TILTED TOWERS)

This terminology brings home to any reader the classical case of the Leaning Tower of Pisa where the characteristic phenomenon was accidental ie. the tilt was caused by differential settlement. By common sense explanation a leaning tower is one which stands tilted ie. at an angle not perpendicular to the base. This category is also known as Tilted Towers.

The Capital Gate Building (2011) in Abu Dhabi and the Gate of Europe (KIO Towers) in Madrid, Spain are the prominent examples of Leaning high-rise buildings. Capital Gate Building has a height of 160 meters with 35-storeys and has a curved shape which leans 18 degrees to the west. KIO Towers designed by Philip Johnson and John Burgee consists of two towers each with a height of 115 meters and they tilt 15 degrees towards each other. These buildings have vertical reinforced core surrounded by horizontal, vertical and diagonal steel structures.

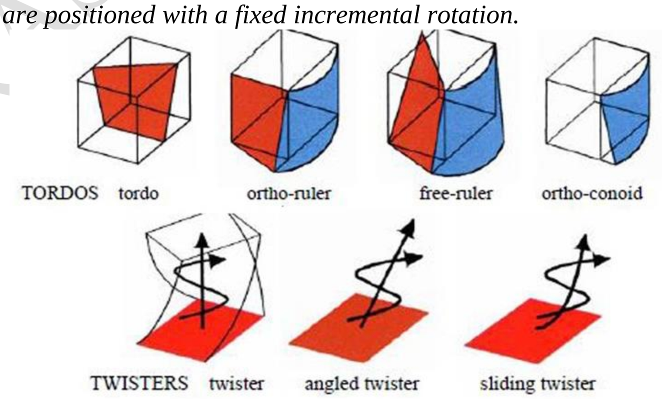
C. TWISTED TOWERS

Recent decades have seen many high-rise buildings with twisted structures. Most of these have achieved iconic status and have become notable landmarks bringing fame to their locality.

A high-rise structure where its form is the result of a combination of twisted facades is termed as Twisted Tower. Sev and Tugrul (2014) explains: "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 facades will also be repeated."

Vollers (2005) had classified buildings with twisted surfaces into Tordos and Twisters. A Tordo is a building with one or more twisted facades connected to an orthogonal superstructure. The floors are basically repeated in vertical direction with interior walls and columns aligned. The rotation axis of the twisted surface usually lies in the facade. All elements in a Tordo's twisted facade are different - in upright and in horizontal direction.

A Twister is a building with floors that lie horizontally rotated around a vertical axis. This axis usually lies in the centre of the floor plan. Often there is a cylindrical core, around which floor-wings lie. 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; they are positioned with a fixed incremental rotation.



(Source: "Morphological scheme of Second Generation Non-Orthogonal High Rises" by Vollers, K.)

Figure 3: Tordos (Above) and Twisters (Below)

Turning Torso in Malmo, Sweden designed by Santiago Calatrava is the first twisted high-rise building in the world. It was officially opened on 27th August 2005. Inspiration for this design came from the motion of the human body. This building which became an iconic landmark in no time, is 190 meters (623 feet) tall with 54 storey and having a twist of 90 degrees from ground to the top. The floors are having an irregular pentagonal shape and they are arranged rotating around a vertical concrete core that is supported by an exterior steel framework. The steel exoskeleton is formed from a lone steel column standing at the apex of the building's walls and it rotates with the building.

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(Source: CTBUH Database-www.skyscrapercenter.com)

Figure 4: Turning Torso in Malmo, Spain (Left) Absolute World Tower in Ontario (Center) and Cayan Tower in Dubai (Right)

Absolute World Tower in Mississauga, Ontario, Canada is a residential twisted twin tower complex. The first tower is 179 meters tall and the other 161 meters. These towers twist 209 degrees from the base to the top. It is also known by the nickname "The Marilyn Monroe Tower" due to its curvaceous, hourglass figure.

Cayan Tower (2013), Dubai, the world's tallest twisted tower designed by Skidmore Owings and Merrill LLP (SOM) has a height of 1010 ft. It is a 75-storey building which houses 495 apartments. Mode Gauken Spiral Tower in Nagoya, Al Bidda Tower in Doha, and Shanghai Tower in Shanghai are among the other prominent twisted towers in the world.

II. STRUCTURAL COMPLEXITIES OF TAPERED, TILTED AND TWISTED BUILDINGS

Advanced digital tools for design and analysis have enabled architects and engineers to design unusual high-rise structures with complex geometries. When designing such non-prismatic towers the basic challenge that comes up is the question of dealing with the shifting floor plate. In structures where footplates tilt, taper or twist, each floor will mostly be unique. As such the program will have to be specially arranged to deliver repetition and consistency for the program elements that need it.

Traditionally, the design process in the case of conventional box-type structures involved architectural designs followed by structural design. This in most cases involved a lot of delay. In the case of modern complex structures, because of the availability of advanced digital design tools, almost simultaneous consideration of architectural and structural design issues and parameters at the conceptual design process level itself is possible and this helps in unleashing the conceptualisation capabilities of the architect and the efficiency of the structural designer.

A. TAPERED TOWERS

The structural complexity of tapered towers as compared to box-type, prismatic structures is not that large as in the case of tilted and twisted types. However, the basic morphology of the structure may not always permit a simple stacking of features and facilities as in the case of conventional box-type structures.

John Hancock Centre considered to be the first modern high-rise Pyramidal building shows a major departure from the then prevailing design approach. Earlier to this, though the structural potential of diagonals were recognized, they were not accepted on the ground that they obstructed the outside view. Therefore, diagonals were mostly embedded in the building cores in the interior of the building. In the case of John Hancock Centre fully exposed diagonals (X braces) were used on the entire exterior surfaces of this 100-storey tall building. This not only contributed to their structural effectiveness but also created a varied aesthetic appeal. As there is no variation in the structure, the continuity of the shaft is not interrupted visually. All of the exposed details of the building are held together by the X-bracing. As a fully integrated expression of form and structure, the braced-tube structure maintains its character of strength and performance. (Sev, 2001).

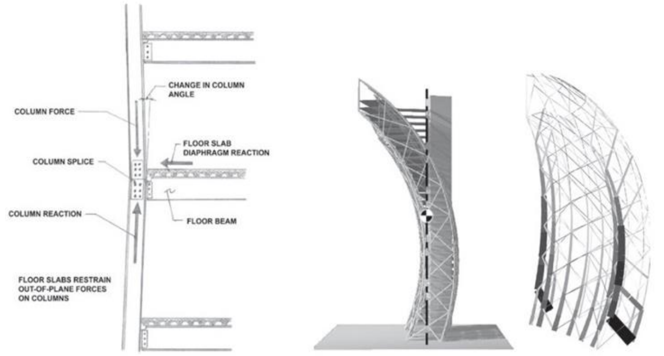
B. TILTED TOWERS

D. Scott et al (2007) have described the issues and tools that could be used to solve the design hurdles of the Tapered, Tilted and Twisted high-rise buildings. According to them, repetitive floor plates could be created within a tilted tower if the elevator and service core lean with the tower. Though leaning elevators are available, the cost is very high and so the decision mostly goes in favour of vertical cores and therefore limits the lean of a tower to fall within its own plan foot-print at the ground level. The effect of overturning moment caused by gravity is the main structural concern faced by a leaning tower. Such deflection in the direction of the lean will be accentuated by wind deflection also.

These authors have suggested some structural steps that can result in giving the appearance of a leaning tower while keeping the overturning forces to the minimum.

- ✓ Design the tower in such a way that the overall centre of mass of the building is directly over the base where it meets the ground. In such a case there won't be any need to have additional loads on the foundations.
- ✓ Another method is to have the loads as near to the vertical as possible whereby these additional loads get minimized. Various methods like transferring out of inclined columns, use of cantilevers in place of inclined columns, etc. can be resorted to achieve this.
- ✓ A third approach is to go in for a symmetric structure, as such structures will remain balanced over their base and so there won't be any need for any additional loads on the foundations. In such cases, if inclined columns are used, the additional horizontal forces generated by inclined columns are balanced by equal and opposite forces from the symmetrically opposing columns. Because of this there won't be any additional load on the lateral system. Even in cases where the symmetry is not perfect, the variations can be balanced by various methods like varying the density of the building, or by shifting the columns.

Tilted Towers on soft ground requires a uniform foundation to avoid differential foundation settlements magnifying the intended tilt of the building.

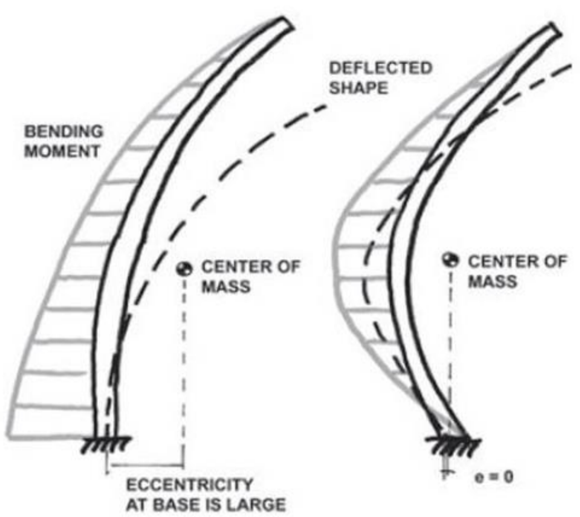


(Source: The effects of Complex Geometry on Tall Towers, Scott, et al.)

Figure 5: Lateral restraint of columns that kink at floor slabs (Left), and Side elevation of Milan Fiera showing center of mass and force plot (Right)

Milan Fiera, a 22-storey tower designed by Libeskind, is formed as a section of a spherical shell, with the centre of mass of the tower precisely over the base. Structural steel diagrid system has been used in this tower to resist overturning and wind loads.

Scott et al (2007) cites the example of the Songdo Northeast Asia Trade Tower to illustrate the use of a mixture of the above methods to design a structurally stable and visually appealing leaning tower. The floor-plates of this tower varies from trapezoid at the base to a reversed triangle at the top. There are also six-sided floor-plates in between. Two sides of the tower, ie. the front and the rear side, are curved and sloping. The variation in the average offset along the height of the tower results in creating the feeling that the tower is leaning forward.



(Source: The effects of Complex Geometry on Tall Towers, Scott, et al.)

Figure 6: Minimising bending moments by centering mass over centroid of base

The variation in the shape from base to top helps in the centroid of the floor masses aligning closely and so overturning moments due to gravity loads on the core and foundation are very low.

C. TWISTED TOWERS

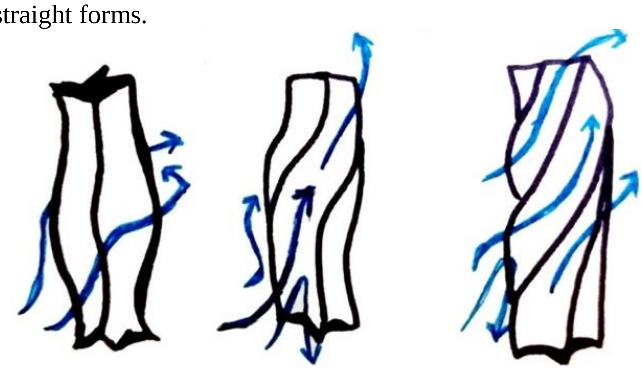
Twisted Towers are the result of successful tackling of complex architectural and structural issues. The core, even in twisted towers, are mostly vertical only, due to practical reasons. But the relationship of this vertical core with the exterior of the building undergoes changes at every level. This can pose challenges to optimal space utilization. One approach in this regard is to keep the core circular and to have a ring corridor. In order to avoid large structural demands on the building core that can result from the twisted nature of the tower the structural column grid needs to be designed with much care.

Torsion on the core will be a problem faced by twisted towers if the columns in them follow the form. According to *Scott et al (2007):*

To maximize torsional stiffness and strength, it is desirable to maximize the area inside the core. For a steel building an external bracing system is desirable. As the torsional force is proportional to the load on the inclined columns, it can be beneficial to vary the rate of twist with height.

Another way to approach this problem is to release the columns from the twisting shape of the building, or to add counter rotating columns to balance the torsional force. An extension to this method is to constrain all the columns to move on radial gridlines, so that for a symmetric form all the horizontal forces cancel each other overall.

Ali and Moon (2007) observes that in general twisted forms are effective in reducing vortex-shedding-induced dynamic response of tall buildings by disturbing vortex shedding. In terms of static response, twisted forms are not beneficial. If solid sections are considered, the moment of inertia of a square plan is the same regardless of its twisted angle. Thus the displacements due to bending are the same as well. However, if the building type frames are considered, the lateral stiffness of the twisted forms is not as large as that of straight forms.



(Source: Author)

Figure 7: Different twists directing wind around them.

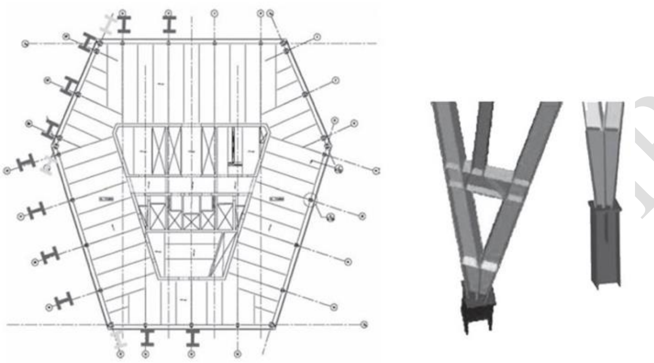
III. CONSTRUCTABILITY OF BUILDINGS WITH COMPLEX GEOMETRY

Though modern fabrication and production techniques are being adopted in the construction of all high–rise buildings, construction process always throws up too many challenges at various stages of its execution. The construction of Tilting and

Twisting high-rises always faces additional problems and challenges. Scott et al (2007) explains this:

"If the dead loads of a tower cause lateral deflections or twist, and the tower is made of concrete, then there can be significant complexities involved in both determining and dealing with the creep of a tower with time. Tower designers are used to dealing with differential creep and shrinkage deflections between highly stressed columns and lightly stressed cores in reinforced concrete structures and composite structures. But when the long-term deflections include lateral or twisting movements, these are particularly difficult to predict owing to their dependence on concrete mix designs and construction staging. Other than the need to accommodate these deflections in the internal partition walls and facade joints, a designer may reasonably conclude that the tolerance in predicting them is not important from a visual perspective – if the tower is leaning, there is often no point of reference from which to visually measure the tower's deflected shape."

The adoption of such strategies/approaches is well evidenced in the case of Songdo Northeast Asia Trade Tower. The columns framing the corners of the building pick up loads from the columns of the facade that intersect these corners. Many columns that carry the load of more than sixty storeys are joined together. By orienting the steel sections in such a manner that the web plates are coplanar, such connections have been made very simple.



(Source: The Effects of Complex Geometry on Tall Towers- Scott et al.)

Figure 8: Orientation of multiple rotated columns and their intersection at Songdo Northeast Asia Trade Tower

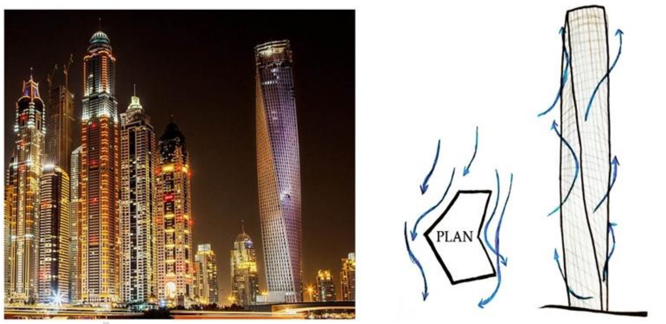
IV. ADVANTAGES OF TALL BUILDINGS WITH COMPLEX GEOMETRIES

The use of advanced digital/computational tools, adoption of cutting edge technology and use of specialized building materials - all these are enabling the design and construction of high-rise structures, the forms and sizes of which existed only in the realm of dreams a few decades back. Many of such modern high-rises are having complex forms and structures and they have in no time become iconic landmarks. Such tapered, tilted, twisted and free form high-rises with unique features are becoming the pride of communities, localities and countries. They are being flaunted as the sign of economic might, used as an instrument to attract foreign investment, highlighted as a tourist attraction and exalted as an object boosting collective vanity. A giant structure, having an unusual form aesthetically crafted, definitely contributes positively to the mind-set of the users as also the community around. Impact of such structures on the overall economy of the locality is also immense.

The twisted towers are effective in reducing vortex-shedding-induced dynamic response of tall buildings by disturbing vortex shedding.

The Cayan Tower structure rotates a full 90 degrees from the base to the top and this design feature allows residents in the lower floors of the tower to have a full view of the waterfront promenade of Dubai Marina while the residents of the upper floors faces the Persian Gulf. Because of its twist, when viewed from one angle the silhouette of the tower has a hour-glass shaped appearance while from another angle the middle floors appear to bend outward.

An important advantage of the characteristic twist of the Cayan Tower is that it reduces the wind force on the tower.



(Source: Author)

Figure 9: Cayan Tower, Dubai (Source: SOM), Confusing the wind around the tower

Gideon Fink Shapiro (2013) in his article in the 'Architect' mentions that measurements were carried out during various stages of its construction and afterwards to assess the structure's movements. Wind Tunnel tests predicted that the tower's twisting profile would scatter the flow of wind around it, thus reducing the structure's sway during storms. As per William Baker, SOM's structural engineering partner, "*the wind performance of Cayan Tower will be at least as good as that of a comparably high, non-twisting tower*".

Irrespective of the complex geometry, tall buildings have the potential to reap benefits from wind. Judicious use of natural ventilation and carefully designed system for the usage of wind and shade conditions to improve comfort in outdoor areas like balconies, terraces and open spaces adjacent to the towers are possibilities. The potential for generating electricity using wind turbines is very bright in tall buildings because of the higher wind speeds at the heights of such buildings.

V. CONCLUSION

Towers with complex geometry have come up in many countries around the world and many more are in various stages of planning and execution. Such towers vary in form from the tapered to the tilted, to the twisted and then to the free form ones. Because of their uncommon shapes and huge volumes they immediately attract the attention of the onlooker and gives visibility to the location and surroundings. Most of them achieve iconic status in short time. Various examples of the tapered, tilted and twisted towers examined in the essay

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are well known ones, which are inspiring architects to excel in designing such complex structures.

Their quest for unconventional geometry and extreme height pauses many architectural and structural challenges. These complexities throw up many challenges in construction also. The integration of architectural design process and the structural design process, resulting from the advances in digital design skills available today, are helping in exactly materialising the fruits of architects' imagination.

Even with the complexities and the challenges that they pause in conceptualising and executing these types of off-beat forms, they do have various advantages depending upon their individual features, especially in countering the effects of wind, and facilitating better view of the surroundings. The overall advantages that accrue from aesthetic, cultural and economic view-points needs no special mention.

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