TWISTED BUILDINGS: CONCEPTS AND APPROACHES

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Abstract
With the emerging of new technologies, the look for more sustainable towers appears. Through designing twisted towers, an aerodynamic and energy efficient structure can be made to reduce materials and wind loads towards it. By definition, a twisted building is one that has gradually rotating floor plates along its height. The problem here rises due to the risk of structural failure and lack of load transfer and unorganized interior function. Thus, this research aims to detect the design solutions used to execute the twisted buildings achieving stability, safety, and withstanding climatic effects. In order to accomplish the mentioned aim, the research will start with a literature review, desk research, highlighting previous readings solving the problem. Qualitative research will be conducted based on academic articles and the case study of projects such as Dubai’s Infinity Tower by SOM and the second tallest building in Saudi Arabia, the Diamond Tower in Jeddah.

Keywords
Twisted Building, Concept, Approach, Structure System, Function
1. INTRODUCTION

In architectural design, there are many non-conventional and complex shapes. However, this paper decides to go through the twisted forms for tall buildings. A research in terms of the geometric properties of twisted buildings, as well as the structural systems, the difficulties in design and construction will be tackled, in addition to presenting a number of buildings constructed or on the process of construction.

Nowadays, while valid for other styles of architecture, there are many architectural directions for contemporary and classic tall buildings. This implausible design approach has created a variety of geometric shapes, such as bent, tapered, inclined, tilted and free forms. Architects step away from traditional shapes and plain geometries, such as pyramids, boxes, tubes and cones, in order to create excellent structures.

As a result, non-orthogonal tall buildings are evolving worldwide with a growing degree of geometric variation. Employing a twisted shape in a tall building is a relatively recent approach for developers as well as engineers. The difficulty of planning, manufacturing and building superstructures of exceptional and non-conventional shapes rises with geometrical sophistication (Başarır, 2011).

Table 1 – List of twisted buildings designed until today. Source: Council on Tall Buildings and Urban Habitat.

<table>
<thead>
<tr>
<th>No.</th>
<th>Building</th>
<th>City</th>
<th>Country</th>
<th>Completion Year</th>
<th>Architectural Height (m)</th>
<th>Floor Count</th>
<th>Average Floor Rotation</th>
<th>Total Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shanghai Tower</td>
<td>Shanghai</td>
<td>China</td>
<td>2015</td>
<td>362</td>
<td>128</td>
<td>0.938°</td>
<td>120°</td>
</tr>
<tr>
<td>2</td>
<td>Lähteen Centre</td>
<td>St. Petersburg</td>
<td>Russia</td>
<td>2016 (expected)</td>
<td>462</td>
<td>86</td>
<td>1.04°</td>
<td>50°</td>
</tr>
<tr>
<td>3</td>
<td>Diamond Tower</td>
<td>Jeddah</td>
<td>Saudi Arabia</td>
<td>2019 (expected)</td>
<td>532</td>
<td>59</td>
<td>1.87°</td>
<td>360°</td>
</tr>
<tr>
<td>4</td>
<td>Ocean Heights</td>
<td>Dubai</td>
<td>United Arab Emirates</td>
<td>2010</td>
<td>310</td>
<td>83</td>
<td>0.482°</td>
<td>40°</td>
</tr>
<tr>
<td>5</td>
<td>Cayan Tower</td>
<td>Dubai</td>
<td>United Arab Emirates</td>
<td>2013</td>
<td>306</td>
<td>73</td>
<td>1.233°</td>
<td>90°</td>
</tr>
<tr>
<td>6</td>
<td>Supernova Spira</td>
<td>Mumbai</td>
<td>India</td>
<td>2017 (expected)</td>
<td>390</td>
<td>60</td>
<td>1.825°</td>
<td>146°</td>
</tr>
<tr>
<td>7</td>
<td>Evolution Tower</td>
<td>Moscow</td>
<td>Russia</td>
<td>2015</td>
<td>246</td>
<td>55</td>
<td>2.365°</td>
<td>156°</td>
</tr>
<tr>
<td>8</td>
<td>F&amp;P Tower</td>
<td>Panama City</td>
<td>Panama</td>
<td>2011</td>
<td>233</td>
<td>53</td>
<td>5.943°</td>
<td>315°</td>
</tr>
<tr>
<td>9</td>
<td>Al Majdoul Tower</td>
<td>Riyadh</td>
<td>Saudi Arabia</td>
<td>2016 (expected)</td>
<td>232</td>
<td>54</td>
<td>2.500°</td>
<td>135°</td>
</tr>
<tr>
<td>10</td>
<td>Al Tajma Tower</td>
<td>Kuwait City</td>
<td>Kuwait</td>
<td>2019</td>
<td>218</td>
<td>41</td>
<td>1.951°</td>
<td>80°</td>
</tr>
<tr>
<td>11</td>
<td>United Tower</td>
<td>Manama</td>
<td>Bahrain</td>
<td>2016 (expected)</td>
<td>200</td>
<td>47</td>
<td>3.837°</td>
<td>180°</td>
</tr>
<tr>
<td>12</td>
<td>Al Bidda Tower</td>
<td>Doha</td>
<td>Qatar</td>
<td>2009</td>
<td>197</td>
<td>44</td>
<td>3.364°</td>
<td>60°</td>
</tr>
<tr>
<td>13</td>
<td>SOCAR Tower</td>
<td>Baku</td>
<td>Azerbaijan</td>
<td>2015</td>
<td>196</td>
<td>40</td>
<td>0.505°</td>
<td>20°</td>
</tr>
<tr>
<td>14</td>
<td>Turning Tororo</td>
<td>Makro</td>
<td>Sweden</td>
<td>2005</td>
<td>190</td>
<td>57</td>
<td>1.580°</td>
<td>90°</td>
</tr>
<tr>
<td>15</td>
<td>Trump International Hotel &amp; Tower Vancouver</td>
<td>Vancouver</td>
<td>Canada</td>
<td>2016 (expected)</td>
<td>188</td>
<td>63</td>
<td>0.314°</td>
<td>180°</td>
</tr>
<tr>
<td>16</td>
<td>Generali Tower</td>
<td>Milan</td>
<td>Italy</td>
<td>2017 (expected)</td>
<td>185</td>
<td>44</td>
<td>1.127°</td>
<td>96°</td>
</tr>
<tr>
<td>17</td>
<td>Absolute World Building D</td>
<td>Mississauga</td>
<td>Canada</td>
<td>2012</td>
<td>176</td>
<td>56</td>
<td>3.732°</td>
<td>209°</td>
</tr>
<tr>
<td>18</td>
<td>Mode Hakum Spiral Tower</td>
<td>Nagoya</td>
<td>Japan</td>
<td>2008</td>
<td>170</td>
<td>38</td>
<td>3.000°</td>
<td>114°</td>
</tr>
<tr>
<td>19</td>
<td>Absolute World Building E</td>
<td>Mississauga</td>
<td>Canada</td>
<td>2012</td>
<td>158</td>
<td>50</td>
<td>4.000°</td>
<td>200°</td>
</tr>
<tr>
<td>20</td>
<td>Balcones Tower</td>
<td>London</td>
<td>United Kingdom</td>
<td>2017 (expected)</td>
<td>149</td>
<td>44</td>
<td>2.152°</td>
<td>96°</td>
</tr>
<tr>
<td>21</td>
<td>Avila Twist Tower</td>
<td>Sarajevo</td>
<td>Bosnia and Herzegovina</td>
<td>2008</td>
<td>142</td>
<td>39</td>
<td>1.539°</td>
<td>60°</td>
</tr>
<tr>
<td>22</td>
<td>The Point</td>
<td>Guayaquil</td>
<td>Ecuador</td>
<td>2014</td>
<td>137</td>
<td>36</td>
<td>5.887°</td>
<td>210°</td>
</tr>
<tr>
<td>23</td>
<td>Sitara Radio &amp; TV Centre</td>
<td>Chengdu</td>
<td>China</td>
<td>2019</td>
<td>236</td>
<td>31</td>
<td>2.902°</td>
<td>90°</td>
</tr>
<tr>
<td>24</td>
<td>Puch Tower</td>
<td>Midrand</td>
<td>South Africa</td>
<td>2018 (expected)</td>
<td>106</td>
<td>26</td>
<td>1.154°</td>
<td>30°</td>
</tr>
<tr>
<td>25</td>
<td>Xiamen Suzhou Tower</td>
<td>Xiamen</td>
<td>China</td>
<td>2016 (expected)</td>
<td>100</td>
<td>22</td>
<td>4.091°</td>
<td>90°</td>
</tr>
<tr>
<td>26</td>
<td>Grove at Grand Bay North Tower</td>
<td>Miami</td>
<td>United States of America</td>
<td>2016</td>
<td>94</td>
<td>21</td>
<td>1.845°</td>
<td>38°</td>
</tr>
<tr>
<td>27</td>
<td>Grove at Grand Bay South Tower</td>
<td>Miami</td>
<td>United States of America</td>
<td>2016</td>
<td>94</td>
<td>21</td>
<td>1.845°</td>
<td>38°</td>
</tr>
<tr>
<td>28</td>
<td>Zhao Zhu Yin Yuan</td>
<td>Taipei</td>
<td>Taiwan</td>
<td>2016 (expected)</td>
<td>93</td>
<td>21</td>
<td>4.286°</td>
<td>90°</td>
</tr>
</tbody>
</table>

After Calatrava designed the first twisted tower in 2005, it is reported that other 28 buildings following the same design approach were designed until 2018. The increased interest in green buildings as well as technological improvements lead to this trend (Urban-Hub, 2017).

This research aims to detect the design solutions used to execute the twisted buildings achieving stability, safety, and withstanding climatic effects. The objectives of the research include studying the different concepts used to design the twisted building, analyzing the structure system that can be used, and discussing the advantages of using the twisted shape in the architecture.

Thus, this research questions the possibility of using such buildings. Are the design methods effective? Are they cost-efficient? Did they damage the interior spaces or added value to it?

This research is a qualitative type of work. The theoretical study based will depend on a scientific methodology, beginning with a literature review, presenting definitions, highlighting previous readings solving the problem, approaches, and as a detailed case study, the paper will analyze such buildings as Dubai’s Infinity Tower by SOM and the Diamond Tower in Jeddah.
2. TWISTED BUILDINGS

After going through the literature, it is found that the future of skyscrapers is rethought and given a new type of development through the rotation of the structure. In order to understand these structural designs, the paper will begin to highlight the definitions of twisted buildings as follows:

2.1 Definition of twisted buildings

Shawn Ursini, author of the CTBUH study says:

“When you introduce the twist, the parameters change, it adds complexity to the project because the windows have to be manufactured and installed in a particular manner.”

This definition is mentioned in:

‘Twisting towers: Number of spiraled skyscrapers soars’ (CNN, 2016)

The twisted building consists of the rotation of floor plates or façades while it increases in height. Most of the time, the plates share an axis upon which they turn certain degrees from the floor below (CTBUH, 2016). These twists make the buildings one of the iconic volumes with their manipulation of form resulting in various view angles and effects. In the normal case of tall buildings where the plates are usually just stacked up, it utilizes the standard design of components such as structural walls and vertical columns. However, in the presence of the twist all details must be revised and rethought from the shape of the windows to the structural loads of the interior columns as well as the variable shapes of floors. All the advances in new technologies for construction and architectural computer programs as well as engineering are making this type of buildings available (Ursini, 2016). With this type of design, the building resolves the challenges of wind loads that affect tall buildings by making it more aerodynamic and reducing consumption of materials. Thus, this design will eventually spread around the world and create various iconic buildings.

2.2 Types of Twisted Buildings

After conducting an analysis of many different forms, concerning their external appearance, their facades, and their respective the techniques of construction, Dutch architect Dr. K. Vollers came up with two main classifications for twisted forms. According to Vollers, twisted structures can be classified as tordos or twisters.

A twister building has its rotation axis, a straight line along all the building height, usually located in the centre of the plan. All the structural and architectural features in a twister, such as mullions, columns and walls, twist around this axis and are not aligned with the same elements in the floors above or under it, which creates a non-orthogonal structure. Typically, in a basic twister, all the floor plans are the same, but are positioned according to a gradual rotation pattern. Buildings that have one or more twisted façades connected to a regular structural grid are called tordos. In this type of building, the walls enclosing the interiors, as well as the structural columns, are aligned; and the floor slabs are vertically repetitive. In this case, the axis of rotation is located in the façade itself, not in the centre of the building. This twisting in the façade creates at least one ending, or one corner, in the floor plan that isn’t parallel to the structure’s orthogonal grid (Vollers, 2005).
Figure 3 – Typology of Floor Plan Manipulations with Vertical Torsion Axes. Source: Vollers (2001).

There are also buildings in which each floor is distributed upwards along a curve. This curve can be either two-dimensional or three-dimensional. These buildings are known as “sliders”. If these sliders buildings also include a gradual rotation, they are called “sliding twisters”. When the building’s floors rotate along a spiral axis, it is classified as a “helical twister” (Ali & Sun Moon, 2007). The buildings known as “intersected twisters” consist of entangled volumes, while the ones that are shaped by rotating and scaling hexagonal pyramids around a 3D axis area called “tapered sliding twisters”. Another classification for the twisters is the “hybrid twisters”. The façades of these twisters usually are composed of more than one geometry that harmoniously bond with each other (Başarır, 2011).

2.3 Historical Background of Twisted buildings

Humans have been always so obsessed about reaching new heights. The erection of twisted buildings started to evolve rapidly starting from the late twentieth century and continued till today. Their construction was associated with some economic interests and urban planning issues, as well as dreams and utopias that led to intense competitions between architects to reach new heights. (Helsley & Strange, 2008).

The first generation of habitable twisted structures started to emerge in Sweden in 2005, the Turning Torso building shown in Fig. 7, was considered the first of its kind. It was designed by Calatrava. This
super scraper reached a height of 190 m, later in 2011 Frank Gehry has modified the building to what it becomes today. In 2008, another building was built, Mode Gakuen spiral tower done by Nikken Sekkei in Japan, it was planned to have 36 stories with a height of 170 m. it consists of 3 ribbons that warp the central core shown in Fig. 8. A year later in 2009, the forty-one stories Altejaria tower in middle east in Kuwait overtook the Torso and Gakuen buildings, with 218 m, the spiral tower twists 90 degrees as it rises from the ground level to the top-most occupied point (Fig 9), while in 2011, It is possible to see one of the most impressive and stunning twisting towers in Panama, F&F tower or Revolution tower, whose height reaches 170 meters. (Kayvani, 2014).

Twisted shapes have recently become common for tall buildings. This type of construction had never stopped and the competition had never come to an end. Skyscrapers kept on rising from the ground trying to touch the sky, but the last one of them that surpassed every other match was Shanghai tower in china that was completed in 2015, Fig.10. This super scraper reached a height of 632 m with more than 120 stories to be the world’s twisted tallest building so far (Xia, 2010).

2.4 Reasons to design Twisted buildings

The reasons consist of two levels; in respect to the city and in respect to itself. In terms of the city, it is responding to the decrease of used up land area and adding identity to said city by inserting an iconic sculpture altering the skyline. With respect to itself, it decreases the wind loads to offer less swaying contrary to a regular tower, yet it provides same floor area with less structure and steel. This might be a big saving but it might need more due to the production and application of an elaborate skin for the twisted façade. This twist may also respond to the thermal needs or to provide certain views for the users.

2.5 Previous Readings

2.5.1 Twist & Build: Creating Non-Orthogonal Architecture, Karel Vollers (2001): In this book the author writes about the work of architects like Frank Gher and how they prefer to approach their design as a sculptor sculpts his models in clay. Twist & Build is architect Karel Vollers’ analysis of non-orthogonal architecture. Vollers explored the perpendicular lines as well as the slanting in town planning, using illustrations and critical commentary to analyze twisted volumes.

2.5.2 The Tall Buildings Reference Books, Dave Parkers and Antony Wood (2013): This book presents a series of case studies, including the twisting Al Hamra Tower in Kuwait, as well as trends in tall buildings and different construction and engineering techniques.
2.5.3 Tall Buildings Structural Systems and Aerodynamic Form, Mehmet Halis Gunel and Huseyin Emre Ilgin (2014): In this book, the authors focus on providing the architectural and structural features that should be taken into consideration when designing and constructing a tall building.

2.6 Analysing International Similar Examples

2.5.1 F&F Tower, Panama City, Panama

The F&F Tower was designed by Pinzon Lozano & Associate Architects and was completed in 2011, after 3 years of the start of construction. According to CTBUH’s Skyscraper Center, F&F Tower, formerly known as Revolution Tower, is the 9th tallest building in Panama and Central America, with 53 floors constituting the 232.7 meters high building (CTBUH, 2016). Initially, this building was just a conceptual idea that was inspired by the geometry of a prism. The concrete structure building is known by its characteristic green glass façade. The upper 39 floors rotate 9 degrees to create a helix like form, while the first floors are parking spaces. All along its height, the building twists 360 degrees, being a major feature of the Panama skyline. The helix form allows the creating of four balconies for each level. This office building has a total area of 60,753 square meters, and 5 elevators in total. The area of the entrance lobby is seven meters high (F&F Properties).

Figure 11 - F&F Tower. Source: courtesy Ruby Diaz Mendez.
Figure 11 – F&F Green glass façade. Source: Alluring World, available at alluringworld.com/ff-tower/
Figure 11 – Floor Plan of F&F Tower. Source: Courtesy of Invest X Capital, available at www.investx.org
2.5.2 The Evolution Tower, Moscow, Russia

The tower, designed by Philipp Nikandrov, took 12 years to be completed, in 2015. At a height of 264 meters, each level rotates 3 degrees from the previous level to achieve a twist of 156 degrees clockwise. The towers crown is supported by twisted steel structure arches to provide a helipad (Nikandrov, 2016).

![Figure 11 – The Evolution Tower Crown (aerial view). Source: CTBUH Journal, 2016, Issue III.](image)

![Figure 12 – The Evolution Tower-Plan and cross-section. Source: Architectural and Structural Analysis of Selected Twisted Tall Buildings - Figure on ResearchGate.](image)

a) Structural Challenges: The twisting of the square floor plates was accomplished with the use of a vertical reinforced concrete frame. The tower has a central core and is supported by an octagonal arrangement of 8 columns and continuous beams. In addition, 4 spiraling columns placed at the corners. A raft of 3.5 meters thick supports both the core and the 12 concrete columns. The 8 circular columns start at a 2.5 meters diameter to reach 1.2 meter at the top and are placed 15 meters apart.

b) Façade: Cold-formed double-glazed units were used to form the double-curved envelope; this method is cost-effective and energy-efficient. 108 of 4.3×4.5 meters parallelogram façade panels are placed on each floor. 27 panels have 2 different sizes and variable angles from +14 to -14 degrees.

c) The crowning achievement: Two 41 meters span twisted steel arches are cantilevered from the central core and 4 smaller arch supports beneath the steel ribbons. The parapet is made of cold-bent glass and a motorized foldable top element to allow for access of Building Maintenance Unit (BMU).

d) The podium: The skylights and entrance canopies consist of spider system glazing and beam fins and vertical mullion fins from triplex glass. The triplex along with electrical heating prevents snow and ice from exterior and water condensation on the interior. In addition to an energy saving frit pattern that decreases solar radiation gain while providing proper lighting (Nikandrov, 2016).
2.7 Parameters of Analysis

Tall buildings represent a significant feature on the urban skyline. There are several approaches to designing such buildings, and from the perspective of form generation, the role of the architect is significant. A modern, innovative approach to such buildings is the twisting of facades and structures, contrasting to boxed designs commonly found. Several twisted buildings are being constructed and designed all over the world, and there are some parameters to be considered when doing so (Başarır, 2011).

Based on the preceding research, some of the deducted parameters of twisted buildings are summarized in the following table.

Table 2 – Parameters of Analysis for Twisted Buildings

<table>
<thead>
<tr>
<th>Rotation Axis</th>
<th>Rotation Degree</th>
<th>Floor Layout</th>
<th>Façade System</th>
<th>Structure System</th>
<th>Twisted Form Classification</th>
</tr>
</thead>
</table>

These parameters must be referred to when investigating twisted buildings. The following case studies justify them. For example, through using shifting columns, the Cayan Tower achieves its twisted classification.

3. RESEARCH METHODOLOGY REFLECTING THE SUGGESTED PARAMETERS

This research is based on three research methods; the inductive method, the analytical method, and the comparative analytical method. The first one was used to gather data about the selected two case studies based on consulting a variety of sources. The second was used to analyze these data, providing figures and necessary drawings and diagrams to enhance explanations. The third method was a comparative analysis between the two case studies. In this context, the study used the parameters mentioned in table 2. To analyze the case studies which were selected according to the following criteria:

- Different floor layout
- Different form classification
- Different structure solutions
- Different façade systems

3.1 Case Study 1: Cayan Tower

Location: Dubai, United Arab Emirates
Architects: Skidmore, Owings & Merrill (SOM)
Date of Opening: June 2013
Area: 111,000 m²
Height: 75 story, 307 meters.
Material: Concrete
Use: Residential

Figures 16 & 17 – Views of the Cayan Tower (source: courtesy of Tim Griffith).
3.1.1 Rotation Axis
The form of the tower follows the structural framework that rotates around an axis located at the center of the building. The floors rotate around the core which consists of a cylindrical elevator and a core used for service functions.

3.1.2 Rotation Degree
In total, the Cayan Tower has a 90-degrees twist. Each hexagonal floor plate rotates 1.2 degrees around the central axis.

![Figure 18](image1.jpg)  
**Figure 18** – Different apartment configurations layout and section (source: Courtesy Skidmore, Owings & Merrill).

![Figure 19](image2.jpg)  
**Figure 19** – Typical floor layout (source: Courtesy Skidmore, Owings & Merrill).

![Figure 20](image3.jpg)  
**Figure 20** – Rotation plan of Cayan Tower (source: courtesy of Sagan Arora).

3.1.3 Floor Layout
All floor plates in the Cayan tower have an identical form, with six different apartment configurations. The different residential configurations were designed to provide terraces for each residential unit. Although each floor is identical in area and layout as the below, the walls are shifted about 1.3 degrees from one level to another, to allow the building twist (Arora, 2019).

3.1.4 Structure System
The structure is supported mainly by a circular reinforced concrete wall at the central circular core, a reinforced concrete wall system, six squared reinforced concrete interior columns, sloping columns in the façade and four L shaped corner columns, one at each corner. The floor slabs are flat plates 230 mm thick. The façade columns slope in three different directions (Shapiro, 2013). For the best performance in the architectural, structural, and performance point of view, the columns were designed to step at each level. As the structure ascends, the columns lean either in or out, according to the twisted form, perpendicular to the slab edge. At every level, the columns, except for the corner and interior ones, shift slightly to the side.
3.1.5 Façade System

Because of the tower’s singular and formal motion, the design team wanted to remove all elements contradicting its smoothness. The turning shape of the tower reveals the structure that is protecting the interior from the sun. Yet, there is still a need to provide additional shade due to the harsh desert heat. The exterior reinforced concrete is fully clad in titanium panels and screens. Sun blinds made of titanium panels as well cover the residential balconies to further control sunlight. (Arora, 2019).
3.1.6 Twisted Form Classification
Since the tower rotates along a strait axis located at the center of the structure, the Cayan tower is classified as a Twister.

Table 3 highlights the parameters used in the analysis of ‘Cayan Tower’

<table>
<thead>
<tr>
<th>Rotation Axis</th>
<th>Rotation Degree</th>
<th>Floor Layout</th>
<th>Façade System</th>
<th>Structure System</th>
<th>Twisted Form Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Around the central core</td>
<td>Total of 90 degrees</td>
<td>All plates are similar with only small shift in walls</td>
<td>Reinforced concrete exterior clad with titanium sun blinds</td>
<td>Central circular core 6 square interior columns and 4 L shaped corner columns</td>
<td>Twister</td>
</tr>
</tbody>
</table>

3.2 Case Study 2: Shanghai Tower

Location: Shanghai, China
Architects: Marshall Strabala & Jun Xia (Gensler)
Date of Opening: November 2015
Area: 380,000 m²
Height: 121 story, 632 meters.
Material: Concrete & steel
Use: Mixed Use

3.2.1 Rotation Axis
The profound twist of the tower is due to its geometry, the structure framework has a linear rotation process from the base to the top, located at the center of the building. due to the design, this operation used various rotation angles to determine the best angle for the pattern. The structure is based on a convex equilateral triangle, rotate around a central core on a cross plan, which has variable form used for service functions (Sev, 2011).

3.2.2 Rotation Degree
The tower is the first of its kind in the world, with a curved and twisted shape that rotates 120 degrees from base to top. The unusual rotation is primarily designed to minimize wind loads on the structure. each convex equilateral triangle rotates 1 degree per floor, giving the spiraling form to the building’s exterior wrapper (Kelly, 2009).
3.2.3 Floor Layout
The tower has a height of 632 meters and 121 floors, all the floor plans have an identical form, a convex equilateral triangle, rotate around a central core, which has variable form used for service functions, vertically, it's divided into 9 zones, each zone has a different function, rises 12 to 15 floors and includes a public space enclosed by curtain walls, the ground zone is occupied by an open market that links the tower with the surrounding, while the podium zone includes shops and restaurants, The offices are in the middle zone (Ding, 2010).

3.2.4 Façade System
The horizontal radial pipe strut supports are made up of a 219-mm diameter pipe (with varying wall thicknesses but often 22 mm) that moves the lateral load from the outer façade to the inner circular building slab edge. The radial strut pipes are rigidly attached to the horizontal girt on one side, while a hinge link on the other side—at the internal slab edge steel support—allows the external façade to go up and down relative to the inner framework (Zeljic, 2011).

Fig 28 – The Rotation plan of Shanghai Tower (source: Courtesy of Gensler, available on https://www.archdaily.com)

Fig 29 – The Shanghai Tower drawings (source: Architectural and Structural Analysis of Selected Twisted Tall Buildings - Scientific Figure on ResearchGate.)

Fig 30 - Diagram of positive and negative wind cladding loads (RWDI) (source: Architectural and Structural Analysis of Selected Twisted Tall Buildings - Scientific Figure on ResearchGate.)
3.2.5 Structure System

To support the structure and its loads, the Shanghai Tower utilizes a combination of structural elements. A longitudinal reinforced concrete core situated in the middle of the building is shaped by a 30 meter by 30-meter square made up of a grid of reinforced concrete walls. The center executes the whole program. A super column framework protects the exterior of the building frame in addition to the square reinforced concrete heart. The key structural form of the building is created by four pairs of composite super columns, which are made up of steel beams encased in concrete. Additional single super columns are orthogonal to these four pairs of super columns to assist with even transition. The relations between the super columns are improved by encasing them in concrete (Kaufman, 2017).

Fig 31 - Tower curtain wall support system (CWSS) (source: Architectural and Structural Analysis of Selected Twisted Tall Buildings - Scientific Figure on ResearchGate.)

Fig 32 - Typical atrium top and bottom Curtain Wall A connections (source: Architectural and Structural Analysis of Selected Twisted Tall Buildings - Scientific Figure on ResearchGate.)

Fig 33 - Curtain wall atrium view (source: Architectural and Structural Analysis of Selected Twisted Tall Buildings)

Fig 34 - “Smooth” scheme rotational bushing detail (source: Architectural and Structural Analysis of Selected Twisted Tall Buildings - Scientific Figure on ResearchGate.)

Fig 35 – Building cut of core structure (Left). Cut of one zone incorporating floor slabs (Right) (Source: Courtesy of Kaufman, 2017 “Megatall Structures: The Shanghai Tower”.)

Fig 36 – Mega Frame (Source: Courtesy of Kaufman, 2017 “Megatall Structures: The Shanghai Tower”.)
At zone stage, a mega-frame with a double belt steel truss is visible (Left and Center). The foundation of the tower, structural concrete floor slabs, and the outer curtain wall frame and glass are all visible throughout construction (Right). Every 12-15 floors, the full floor atrium slab extends to the external curtain wall (Kaufman, 2017).

3.2.6 Twisted Form
Since the twisting of this tower is also combined with a slight curve at the central axis, the building is a slider twister.

Table 4 highlights the parameters used in the analysis of ‘Shanghai Tower’

<table>
<thead>
<tr>
<th>Rotation Axis Around the central core</th>
<th>Rotation Degree Total of 120 degrees</th>
<th>Floor Layout equilateral triangle identical form</th>
<th>Façade System Curtain wall</th>
<th>Structure System Steel column framework with reinforced concrete</th>
<th>Twisted Form Classification Slider Twister</th>
</tr>
</thead>
</table>

After analyzing the two previous projects and detecting important architectural representations for twisting towers, a comparative analysis was used between the two projects. This comparison is shown in table 5.

3.3 Comparison between the two case studies
The following table presents an analytical comparison between the case studies based on the parameters that were detected previously.
Table 5: comparative analysis between the two case studies

<table>
<thead>
<tr>
<th>Parameters of analysis</th>
<th>Cayan Tower</th>
<th>Shanghai Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Dubai, United Arab Emirates</td>
<td>Shanghai, China</td>
</tr>
<tr>
<td>Date of opening</td>
<td>2013</td>
<td>2008</td>
</tr>
<tr>
<td>Architect</td>
<td>Skidmore, Owings &amp; Merrill (SOM)</td>
<td>Marshall Strabala &amp; Jun Xia (Gensler)</td>
</tr>
<tr>
<td>Rotation Axis</td>
<td>Around the central core</td>
<td>Around the central core</td>
</tr>
<tr>
<td>Rotation Degree</td>
<td>90 degrees</td>
<td>120 degrees</td>
</tr>
<tr>
<td>Floor Layout</td>
<td>All plates are similar with only small shift in walls</td>
<td>equilateral triangle identical form</td>
</tr>
<tr>
<td>Façade System</td>
<td>Reinforced concrete exterior clad with titanium sun blinds</td>
<td>Curtain wall</td>
</tr>
</tbody>
</table>
To support and validate the research methodology, an online survey was conducted with 25 Beirut Arab University architecture students of the fifth level about the concepts and approaches of twisted buildings. The survey consisted of eight questions:

1. Do you consider twisted buildings to be the preferred approach for all future projects?
   a. Yes
   b. No
2. What do you think is the biggest challenge architects face when designing twisted buildings?
   a. structural problems
   b. functional problems
   c. environmental problems
   d. all of the above
3. What are the special architectural benefits that twisted buildings give and normal skyscraper?
   a. environmental
   b. structural
   c. functional
   d. Attractive shape
   d. all of the above
4. Do you think the twisted shape affects the functions inside the tower?
5. Do you think the inclined columns will affect the interior spaces?
6. What do you think helped to design the twisted buildings?
7. What distinguishes the twisted buildings?
8. Do you know any twisted building project?

From this table and the conducted survey, the paper may reach certain findings as follow…
4. FINDINGS

The survey yielded the following results:

For question 1 “Do you consider twisted buildings to be the preferred approach for all future projects?”:

![Pie chart showing the results of question number 1.](image)

Figure 37 – Pie chart showing the results of question number 1.

For question 2, “What do you think is the biggest challenge architects face when designing twisted buildings?”, students were given 4 choices:

![Pie chart showing the results of question number 2.](image)

Figure 38 – Pie chart showing the results of question number 2.

For question 3 “What are the special architectural benefits that twisted buildings give and normal skyscraper?”, the results were as follows:

![Pie chart showing the results of question number 3.](image)

Figure 39 – Pie chart showing the results of question number 3.
Question 4 asked whether they think the twisted shape affects the functions inside the tower:

![Pie chart](image1.png)

Figure 40 – Pie chart showing the results of question number 4.

Question 5 asked whether they think the inclined columns will affect the interior spaces:

![Pie chart](image2.png)

Figure 41 – Pie chart showing the results of question number 5.

Question 6 asked what do they think helped to design the twisted buildings:

![Pie chart](image3.png)

Figure 42 – Pie chart showing the results of question number 6.
Question 7 asked what distinguishes the twisted buildings:

Figure 43 – Pie chart showing the results of question number 7.

Finally, question 8 asked the students to mention a twisted building tower they know:

Figure 44 – Pie chart showing the results of question number 8.

5. DISCUSSION

Based on the questionnaire, 80% of the participants do not expect the twisted towers to be the main approach designers would prefer in the future; only 20% did. When it comes to design challenges, most participants (56%) believed that they lie in all three aspects: structural, functional and environmental. Only 4% believed that the main challenge is environmental, compared to 24% and 16% to structural and functional challenges respectively. Similarly, when asked about the benefits of the twisted tower design, the majority (46%) believed that they include environmental, structural, functional, and even attractiveness in the building shape. 29% believed the benefits are limited to the attractive form only, whereas 13% and 8% answered that the benefits were structural and environmental, in this order. A very small percentage (4%) answered that twisted buildings provide any functional benefit. In fact, when asked if the twisted form affected the interior functions, the majority stated that no. Only 48% believe that there are any effects of the form on function; but 68% believe that the inclined columns may affect the interior.
When asked about their opinions on what helped the advance of twisting building design, 65% of the participants answered that it is due to the development of advanced structure systems. Another remarkable answer was the BIM software, cited by 22% of the students. The remaining 13% answered that this happened due to advances in architecture and engineering techniques in general.

According to the participantS of the survey, two factor are responsible for the distinction of twisted towers: form (56%) and structure system (44%). Finally, it was asked if they knew any twisted tower. The Cayan Tower in Dubai was by far the most mentioned (by 61%), followed by the Shanghai Tower in China (17%), the Turning Torso (9%) and the Mode Gakuen Spiral Tower (4%). 9% answered that they do not know any twisted building project.

Based on the data presented on the paper, the design solutions used to execute the twisted buildings and that guarantee stability, safety and environmental compatibility, include an appropriate structure system with a degree rotation that will allow optimal environmental effects and effective load transfer. This structure system is preferably related with the rotation axis, which will also determine the form of the building.

6. CONCLUSION

The paper concludes, therefore, several factors related to the development of the twisted tower approach.

A. The execution of twisted towers allows for the opportunity to create and test new construction techniques as well as innovative materials.

B. Besides the structural changes, the economic aspect may also be a challenge for the project’s feasibility, since they are much more expensive to be built.

C. Twisted shapes are not structurally beneficial due to the static structure response, because the lateral stiffness of the twisted tower is lower than that of the straight structure. As the rate of twist rises, the lateral stiffness decreases. As the height of the structure rises, this process accelerates.

D. Due to its complexity, creating the façade system of a twisted tall structure is also a considerable challenge. This complex shape of a high-rise structure, on the other hand, is not only attractive, but also plays a significant role in the support of dynamic loads. The usage of aerodynamic twisted shapes is a good way to reduce wind stresses on structures. Breaking up the wind flow effectively blocks the wind's influence on a structure.

E. Twisters are able to combine a broad variety of textures, view angles, and ripple effects due to their design, which makes them often aerodynamic and energy-efficient. In terms of mean moments, both types can be favorable depending on wind direction. When opposed to a square plan, the rectangular plan of the skyscraper has an impact.

F. Because the twisted tower's lateral rigidity is lower than that of a straight structure, twisted structures are not structurally advantageous.

G. For architects and companies that would like to follow this approach, the aid of computer software that efficiently generate distinct forms can be of great benefit.

H. For students choosing this path in their projects It is best to practice in depth analysis due to the high risk of failure.
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- Ding, J.M, Zhao,X. and Chao, S., 2010- The Shanghai Tower , Conference on Structural Marvels, Singapore, December 13-14
- Kelly, D (2009) High Reynolds Number Tests, Shanghai Center Tower, RWDI, Guelph, ON, Canada