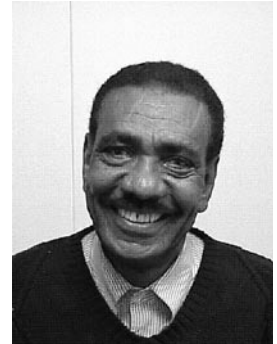


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Dubai Tower 29, Structure and Form

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Biography

Dr. Mahjoub M. Elnimeiri holds a BSc. In Civil Engineering (with Honors) from the University of Khartoum, a D.I.C. and M. Sc. in Structural Engineering from London University at Imperial College, London, England, and Ph.D. in Structural Engineering and Structural Mechanics from Northwestern University, in Evanston, Illinois USA (1974).

Since then he has been involved in the practice of structural and architectural work of buildings in Chicago, USA and overseas. He is very active and well known, in the professional and academic communities. He has been speaker in many conferences and conventions. His expertise is in the areas of structural analysis, design and construction of buildings, and in particular tall buildings, and in the application of computer technology. His publications are directly related to these areas, and he is a recipient of the “State of The Art Award” of the American Society of Civil Engineers for the year 1989. He is a member of a number of professional societies, and also a member of the steering group of CTBUH.

Dr Elnimeiri is Chairman of CDCi Engineers international, Chicago, Illinois, USA. CDCi is a progressive and at the cutting edge of technology. The practice includes structural analysis, design and consulting to construction issues of very special buildings, primarily tall buildings.

Dr Elnimeiri is also a full professor, and Director of the PhD Program, at the college of Architecture at Illinois Institute of technology, Chicago, Illinois, USA.

Dubai Tower 29, Structure and Form

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Abstract

Dubai is rapidly emerging as the center of urban real state development world-wide, and for many good reasons, the least of which is its desire and passion to be the city of the 21st century. The challenge for the architect is overwhelming. Not only he has to be original, but he has to dig deep into his creative mind to pursue a unique and exciting (iconic) building. On the other hand, the challenge for the engineer is two folds: (1) to preserve the architectural vision, (2) to maintain the structural integrity. In this paper, the author will briefly introduce the Dubai Towers project, but will then focus the attention towards tower 29, the tallest (550 M) and by far the most dramatic. The author will present the architectural design ideas that led to the creation of Tower 29. He will then introduce the innovative structural design concepts and the collaborative process that help shape its inception. Tower 29, with the exception of the elevator core, exhibits three independent geometric movements which define its spectacular form: Plan offsetting (morphing), taper and 90-degree twist. The exterior structure is a structural steel tube consists of paired eight mega composite columns located at the corners of the octagonal plan, working in conjunction with continuous ribbons of sloped columns. Beyond the roof, at elevation 450 meters, the exterior structure of the tower opens up in spectacular blossoming flower-like vertical ribbons, to shape the spire. The spire rises 100 meters above the roof. Except for the observatory space, the spire is partially open to the outside where wind turbine(s) are housed. The spire framing system picks up where the exterior braced tube ends. However, both systems blend with each other to preserve the continuity of the structure and the form. The structural system does not simply follow the form, but derives it in a logical and harmonious way. The paper also gives a brief but very favorable assessment of the sustainable/green features of Tower 29.

Keywords: Structure, architecture, ultra tall, form, twist, morphing

Architecture

The Dubai Towers are a group of four sculptural structures, evoking the image of candle flames. They are the centerpiece of the Lagoons development in Dubai. See Figure 1. The towers range in height from 360 m to 550m, and together contain approximately 7 million square feet. Tower 29, the tallest, is an 88-story office building with 2.9 million SF.

The setting is a lushly landscaped urban environment that includes parks, an entertainment-oriented marina space, and a grand vehicular arrival court. See Figure 2.

The project explores the ramifications of applying a series of transformations to octagonally shaped towers. First, each tower leans away from vertical according to a sinuous curve that establishes the center of each floor, forming a spine shape not unlike that of the human backbone.

The towers also taper by applying a reduction in floor diameter as the height increases based on a mathematical curve. Finally, the towers twist as a result of rotating each floor in relation to the one below it by a constant factor. Each tower has a unique form yet has a relationship to the whole composition.



Figure 1. Dubai Towers



Figure 2. Dubai Towers, Site Plans

The result is an unprecedented group of structures with a whole new set of considerations with respect to gravity, wind load, fabrication, and construction.

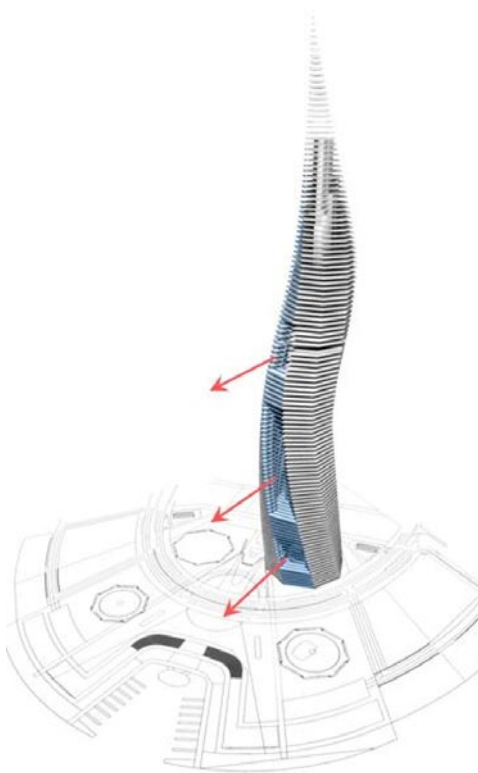


Figure 3-1. Tower 29, Atriums

Tower 29 has three major atriums, strategically located, to maximize access to daylight, while creating extremely exciting inner spaces. The vertical continuity of the atrium is integrated by partial floors that house green areas. See Figure 3-1 and 3-2.

The Elevator system of Dubai tower 29 consist of 5 elevator zones with express shuttles to the sky lobby (located in level 45 to level 47). Within the first 3 zone, each elevator zone has 8 double deck elevators, 1st zone serving 10 floors (level 3 - level 12), 2nd zone serving 17 floors (level 14 - level 31), and 3rd zone serving 11 floors (level 32 - level 43).



Figure 3-2. Tower 29, Atriums

6 double deck express shuttles are placed in the center of the core. These shuttles are serving large amount of office space at the upper portion of the building. They stop only at the ground lobby and the sky lobby. See Figure 4.

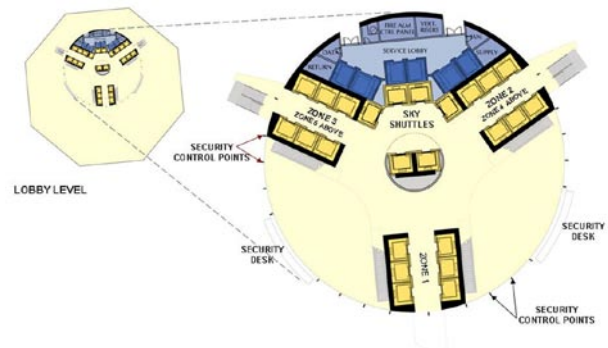


Figure 4. Elevator Core at Lobby

The 4th and 5th elevator zone are located above the Sky lobby and required to transfer elevators from express shuttle at sky lobby (level 46 - 47). Both zone consist of 6 double deck elevators, the 4th zone serving 12 floors (level 48 - level 60), and the 5th zone serving 25 floors (level 61 - level 86). In the 5th zone, 4 of passenger elevators are dropped at level 83 due to the reduced floor plate.

The building also has 6 freight elevators. 3 of them are dropped at level 62 and 2 of them are dropped at level 83 to match with the reduced floor plate at the upper portion of the building. The remaining freight elevator runs all the way to the top of the building and stops every floor serves as fireman's elevator of the tower.

There is one express shuttle dedicated to the observatory

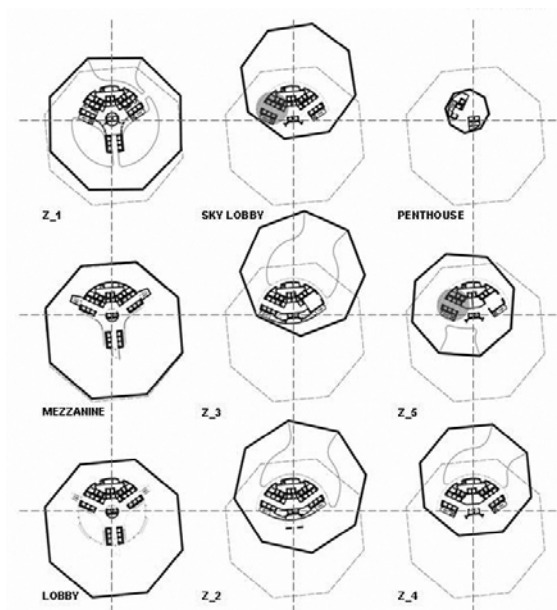


Figure 5. Elevator Core/ Plan Layout

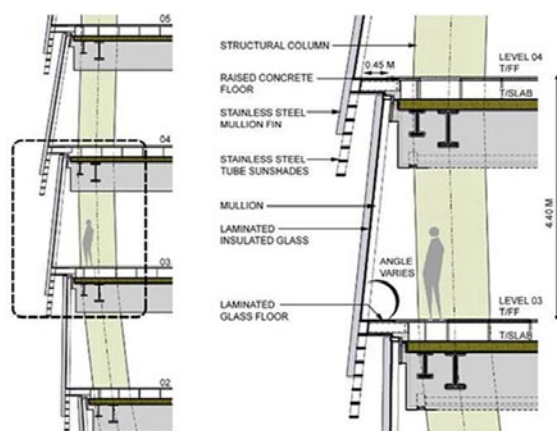


Figure 6. Tower 29, Typical Façade (courtesy of W.Sobek, NY)

and it starts at the P3 level and stops at the sky lobby. Passengers are required to transfer to another elevator that takes them directly to the observatory (level 88). See Figure 5.

The façade is a multilayered curtain wall system featuring shading elements and sophisticated energy efficient glass panels. See Figure 6.

Structure architecture interaction

It took the author a few extensive sessions with the architect to be able to understand and appreciate the architectural idea. Hence, the structural concept began to develop and fit naturally for most of the parts, and the elements of the structure began to emerge and claim their place within the architecture.

Understandably, there were a few wrinkles that had to be ironed out. During that period, we built an architectural physical model (see Figure 7-1). We made every effort to produce a model that represented the tower as close as possible.

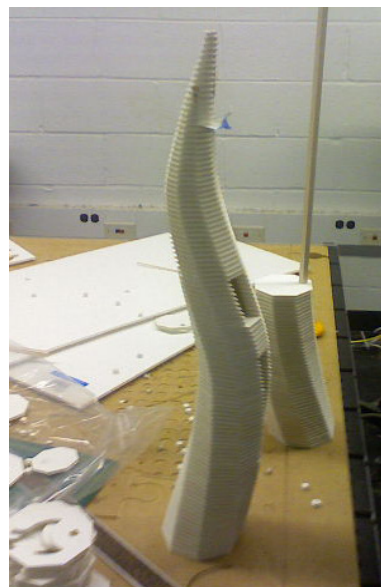


Figure 7-1 Tower 29 Physical Model, Architectural

The result was a model that was useful and very informative. It expressed clearly the pluses and minuses of the form and helped enrich the dialogue between the architect and the engineer. Few of the issues addressed can be highlighted here.

The locations of the atriums and the extent of their depth and height were revisited. From a structural viewpoint, the ideal location of the cavity would be near the exterior wall in order to reduce the overturning moment due to gravity loads. It is also preferable to reduce the size of the openings, so that reasonable bracing system for the exterior frame was provided.

The physical model, by standing upright, confirmed the belief that the building will be firmly touching the ground without any serious concerns of uplift. However, visually,

the form as built lacked the mathematical purity. Subsequently, a structural physical model was built to express visually the proposed structural system. See Figure 7-2.

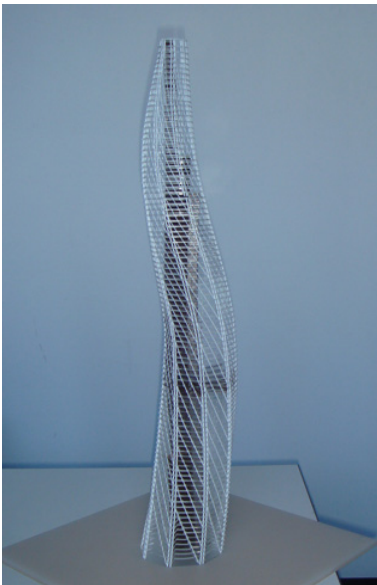
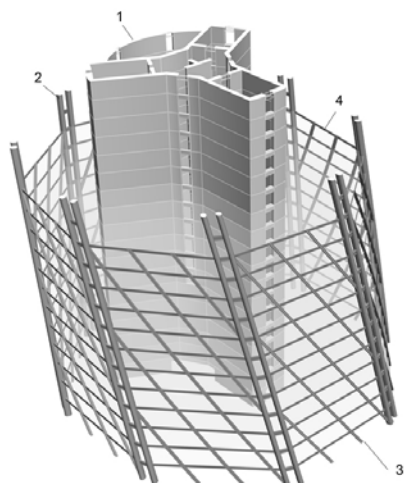


Figure 7-2 Tower 29 Physical Model, Structural

Both models and their components are built to scale. The models proved to be of great value in confirming that the tower will be stable and will transfer dead loads to the foundations without concerns of any noticeable uplift.

Structure: description of the system



- 1 Shear Wall
- 2 Paired-Mega Column
 - at upper levels
 - at lower level
- 3 Sloped Columns
- 4 Spandrel Beams

Figure 8. Typical Elements of the Structural System

The overall structural system that resist both lateral and gravity loads is a composite structural system (see Figure 8) which consists of the following:

1. Exterior braced tube
2. Core shear wall
3. Outriggers
4. Interior columns
5. Floor framing
6. Bracing of the exterior tube at atriums
7. The Crown (Spire) Skeleton

1. Exterior Braced Tube

The exterior tube consists of paired eight mega columns located at the corners of the octagonal plan, working in conjunction with continuous ribbons of sloped columns.

The Tower, with the exception of the core shear wall, exhibits three independent geometric movements (see Figure 9-1 and 9-2):

- a. The octagonal floor plans are reduced as the building rises, non-linearly. The reduction starts slow but increases rapidly towards the top most occupied floor.
- b. The floor plans are subjected to a linear clockwise twist, starting from the ground floor. This resulted in that every floor is rotated clockwise 0.74 degrees, leading to a 90 degree twist at the top of the spire.
- c. The floor plans morph horizontally out of the geometric center, in a dramatic, quasi-spiral fashion, leading to a vertical profile that can be represented by a stretched S curve.

The mega columns will be of structural steel open built up I-sections, enclosed compositely with high strength reinforced concrete. The composite column sizes will vary from an elliptic profile at the base of 1000 mm by 1500 mm to a circular geometry of 60 mm diameter. The paired column is moment connected every floor to preserve continuity, and maintain its behavior as one column.

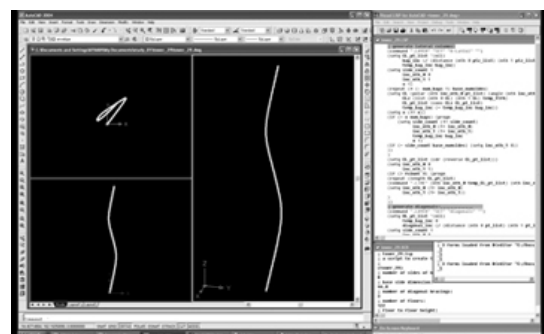


Figure 9-1. Form Generative Tool

The diagonal bracing, which will be termed here a sloped column system, is a one way upward projecting and twisting in a clock-wise continuous ribbon-like configuration. These sloped columns will be spaced vertically at every 4 floors. The slope of these columns

starts at the base is 60 degrees to the horizontal. Because of the structural requirement that the sloped column is to meet the mega column at the floor level, every 12 floors, and because of the taper to the floor plan, the slope of its angle keeps increasing with height. In addition the system will provide support to the spandrel beams at each floor. The sloped column system will be of structural steel wide flange sections.

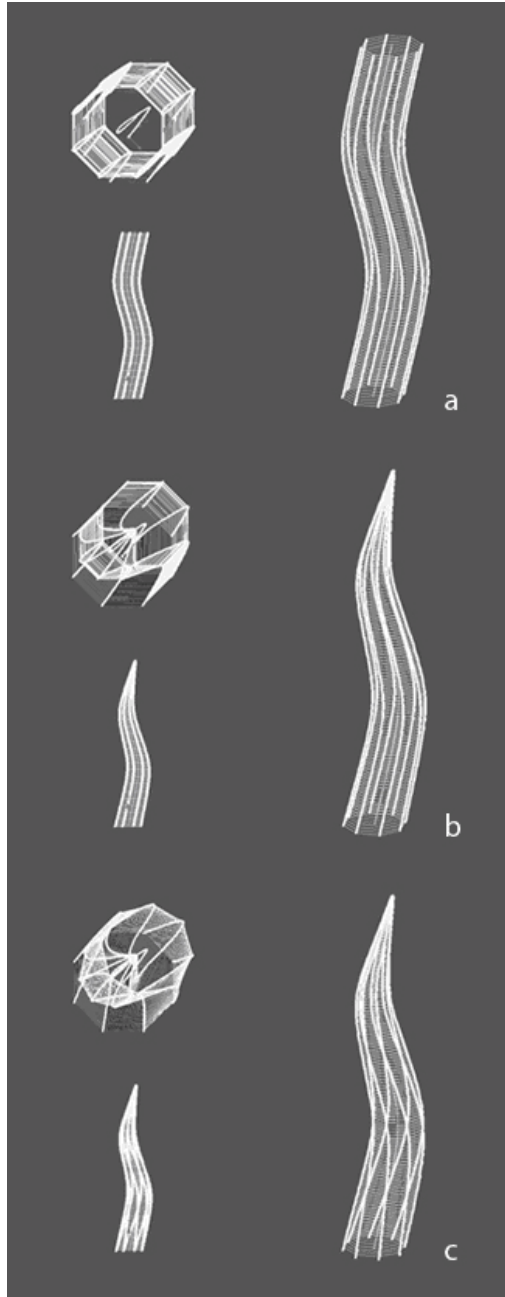


Figure 9-2. Form Generation Process

2. Core shear wall

The core shear wall (see Figure 8) will be of reinforced concrete, and it will be built around the elevator core and will be part of its wall system. The structural wall will vary in thickness from 900 mm at the base to 300 mm at the top. Some filler walls will remain

of a constant thickness.

The Wall will maintain a straight and vertical profile all through. However, some parts of the wall will drop as the elevator banks drop off. At openings the shear wall will maintain continuity through a link of a minimum depth of 1200 mm.

3. Outriggers

There will be two structural steel outrigger systems located at the 38 to 42 floor and at the 63 floor.

The outrigger at the 63 floor will be integrated within the mechanical floor. The outrigger at levels 38 to 42 will take the shape of a Japanese fan. It takes a spiral form visible at the atrium space, (see Figure 10). These outriggers will provide coupling between the shear wall and the exterior tube.

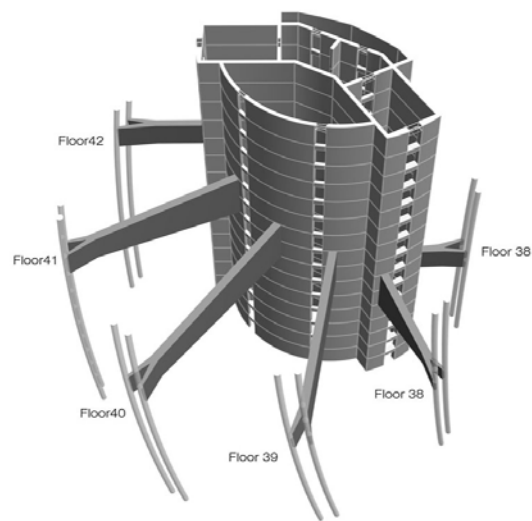


Figure 10. Outriggers at Floors 38-42

5. Interior columns

The interior columns will be simply supported structural steel, gravity load carrying system only. The columns may stay vertical between the floors but will follow the overall twisting profile of the tower, (see Figure 11). The columns will be arranged in such way to be able to support the floors around atrium cavities.

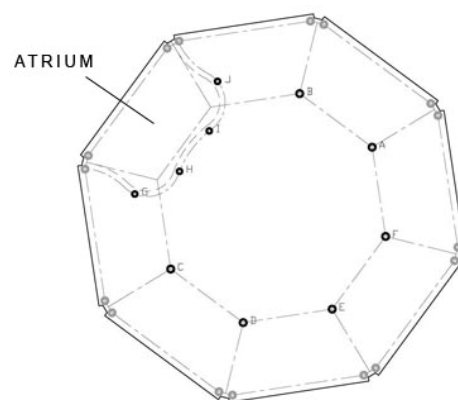


Figure 11 Interior Columns Location Plan

5. Floor framing

Except at the mechanical and other special floors, the floor framing system will consist of a standard composite structural steel framing and normal weight concrete slab over a light gauge metal deck. Special effort will be made in the arrangement and spacing of the interior columns to limit the floor framing overall depth to an acceptable dimension as dictated by the floor to floor targeted dimension.

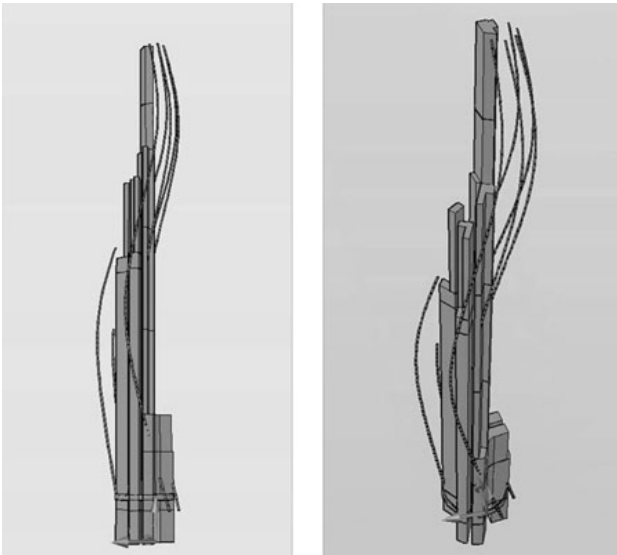


Figure 12 Interior Columns Generation

6. Bracing of the Exterior Tube at Atriums

Because of the cavities at atriums span many floors, the exterior tube has to be well braced, with structure integrated with the floor framing and the shear wall.

7. The Crown (Spire) skeleton

Beyond the roof, at elevation 450 meters, the exterior structure of the tower opens up in spectacular blossoming flower-like vertical ribbons, to shape the spire.

The Crown (spire) rises 100 meters above the roof. Except for the observatory space, the spire is partially open to the outside. The spire framing system picks up where the exterior braced tube ends. However, both systems blend with each other to preserve the continuity of the structure and the form. The spire vertical elements will terminate in a spiral way, leaving only one ribbon to reach the set height of 550 meters. The lower portion of the spire will be braced by a series of floating rings. However, at the upper portion the vertical ribbons will be self-stiffened, (see Figures 12-1, 12-2).

Significant amount of time was dedicated to the crown (spire). Being of a height over 100 meter, many possibilities were available along with major challenges. At this time, many design decision still remain open.

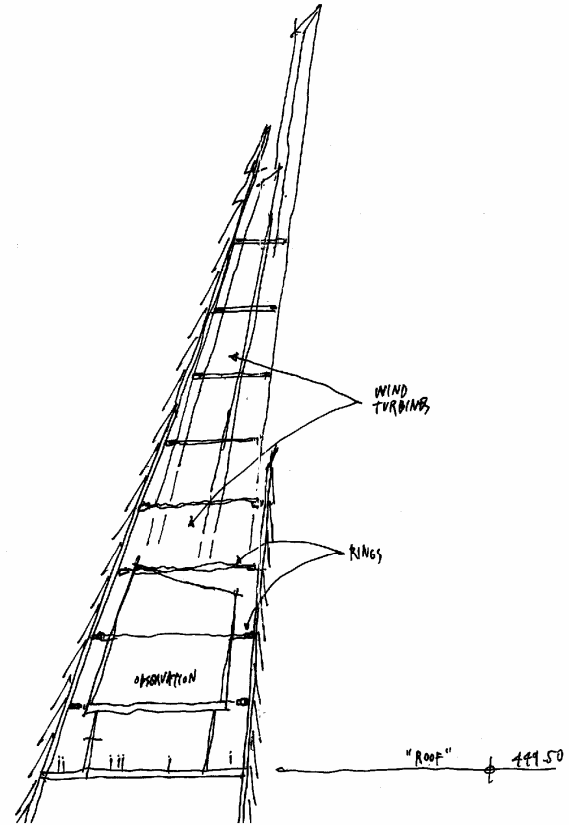


Figure 12-1. The Crown Architect's Sketch

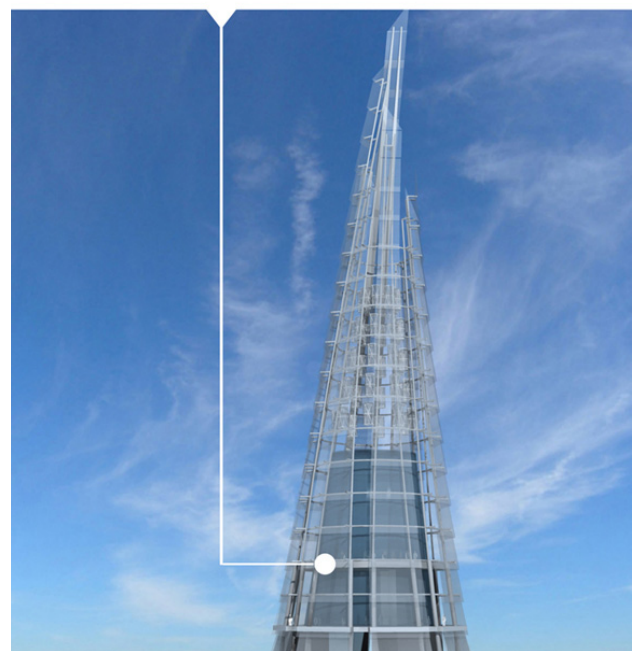
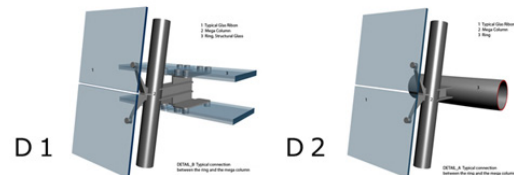


Figure 12-2. The Crown

Structural Design Approach

The following buildings codes and Standards are utilized:

Dubai Municipality Requirements

IBC 2003

BS 6399-1

ASCE7 2002

UBC 1997 for seismic static loading requirements

For such an ultra tall building of complex geometric form, extensive and comprehensive layered analyses will be performed; with two objectives in mind:

1. To preserve the architectural visionary form.
2. To maintain the structural integrity, its efficiency, and the constructability of the Tower.

The following structural analyses conducted are conducted:

Preliminary Linear Static Analysis:

The structure will be subjected to the appropriate static dead, live, wind and seismic loads separately and in combinations, with the intent to satisfy the strength and drift criteria.

Preliminary Special Analysis:

Different scenarios of Construction sequencing will be studied, and the associated differential vertical shortenings will be assessed and corrected.

Preliminary Dynamic Analysis:

Free vibration analysis will be conducted to evaluate the fundamental periods, to develop a good feel of the dynamic response of the tower, and to provide the needed information for the Wind Tunnel Testing.

Further studies and analyses will be conducted all through the design process. Such analysis will include Redundancy/progressive collapse, and nonlinear.

Special attention will be given to the dynamic response to wind. In conjunction with the wind tunnel results decisions will be made in reference to auxiliary damping needs.

Applied Loads

The total dead load on floor is assumed 5.7kPa and live load is 2.4kPa that can be reduced down to 1.2kPa per code.

Static wind load is defined based on ASCE7-2002. The wind pressure is conservatively increased by considering the potential dynamic effects due to the unique geometry of the tower. Thus, this profile shows 1.44kPa (30psf) at the ground, 3.35kPa (70psf) at elevation 440m and 3.59kPa (75psf). See Figure 13.

Preliminary Structural analysis

For the schematic investigation and design of the structure of this super tall tower, static structural analysis was conducted utilizing ETABS ver.9, well-validated

commercial finite element analysis software that is specialized in analysis for tall building structures. All members in exterior steel tube structure including the mega columns, the sloped columns, and the spandrel beams are defined with beam elements, while the shear walls are defined with shell elements. The floors are defined only as diaphragm for analysis for lateral system. Plate elements with atrium openings are assigned to floor in order distribute load in analysis under gravity loads. Later, actual slabs are tested to validate the assumption of the rigid diaphragm and to investigate further concerns about shear stresses on the slabs due to torsion.

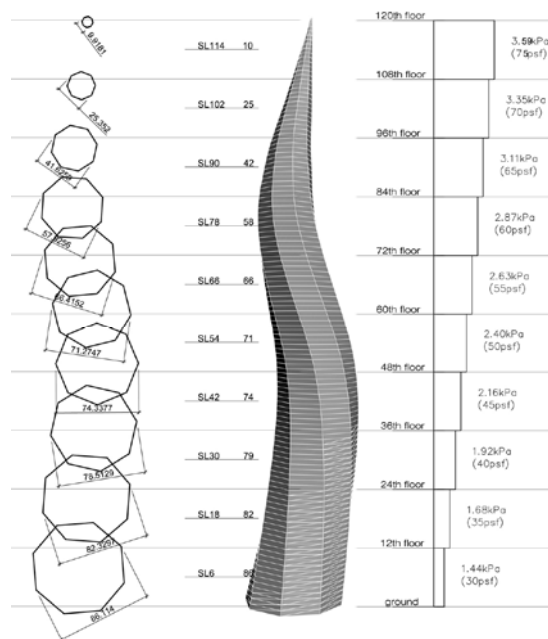


Figure 13 Static Wind Load Diagram

Based on this schematic structural analysis, the thickness of the concrete shear walls are determined to be 1000mm at the base and 300mm at the top of the wall. (The thickness at the top was revised to 600mm due to architectural change of shear wall shape.) The sizes of steel mega columns are chosen to vary from 5800cm² at the base to 1280cm² at the top, while those of the sloped columns are about one third of that of the mega columns. In this analysis the members of the exterior tube structure are assumed steel in the analysis though composite members will be used as mentioned earlier in the description.

A sequence of analyses were conducted to evaluate the contribution of the shear wall alone, the exterior frame alone, combined contribution, and then add the outriggers and evaluate the response of the total system.

The results were very good and as anticipated. To give a brief summary for the drift ratio (See Figure 14):

Shear wall alone	225
Exterior frame alone	235
Combined Exterior frame and shear wall	518
Total system with outriggers	557

The above results are essentially saying that the exterior frame and the shear wall have almost equal lateral stiffness. The outriggers enhanced the overall stiffness by about 8%

This is good considering that the outriggers are also significantly contributing in redistributing some of the exterior frame gravity loads to the shear wall.

Dynamic analysis was conducted in order to investigate the free vibration mode of the tower 29. The results show that the first mode has 6.5 seconds period in the least laterally stiff direction. The crown (spire) of the tower is not included in the natural vibration analysis because the discontinuity of the stiffness where the shear wall ends may cause a local vibration of a frequency lower than the global first mode.

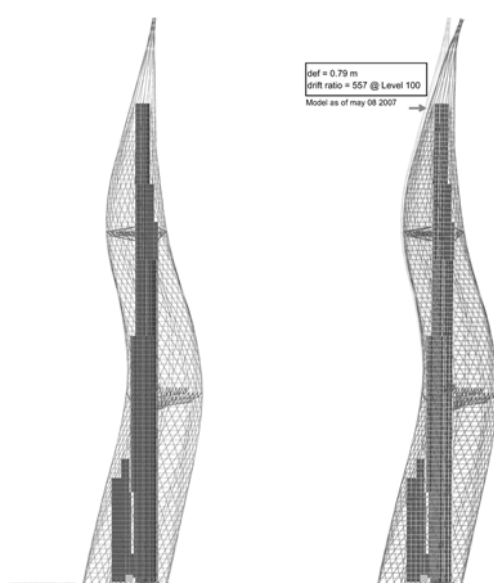


Figure 14 Left) Initial State, Right) Deformed State

Focused Studies

Localized analyses were deemed necessary to support and provide credibility to the assumption made in the above-mentioned overall linear analysis.

Sloped column orientation

The orientation, tilt and density of the sloped columns have occupied close attention; many different configurations were looked at visually and complimented with numerous structural analyses. The studies have confirmed that the sloped columns should maintain the same orientation with the mega columns i.e. follow the twist direction of the tower. This is the natural orientation envisioned by the architect because it works with the twisted form and it does enhance greatly its character.

Although a linear structural analysis shows that if the sloped columns were oriented in the opposite direction to the twist, there will be a noticeable increase of stiffness by around 20 percent, we believe that upcoming advanced studies will show the great potential of the orientation that follow that twist.

Effectiveness of outriggers

One are of concern was how effective these outriggers are and even whether or not they are necessary. A parametric study was conducted. See Figure 15. It clearly shows that the outriggers are not only necessary but they contribute well to the overall stiffness of system, regardless the shear wall is located concentrically or eccentrically. Another discovery made was that although outriggers are traditionally utilized to enhance resistance of overturning due to wind, these outriggers designed in Tower 29 help redistribute gravity loads between exterior structure and the shear wall.

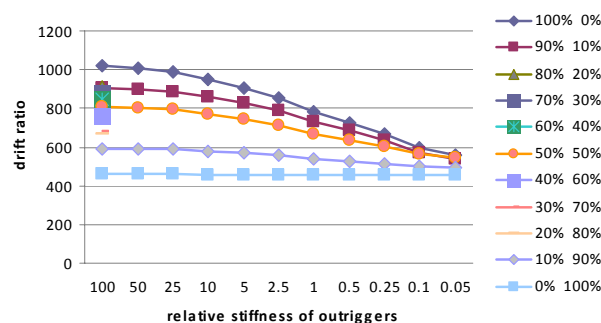


Figure 15 Effectiveness of outriggers

Effect of twist on slab due to shear stresses

A study with a simple building model was conducted in order to investigate the shear stress within the floor slab and at the interfaces to exterior frame and shear wall. The model used in this study has 20m x 20m square plan and 100m height. The floor with 160mm thick slab is located only every 10m. The shear wall with 8mx8m square plan is assumed to have 400mm constant thickness. Four columns at the exterior lateral system are properly braced.

The findings of this study are following:

1. The results of shear forces in the shear wall indicate that most of the torsion in the shear wall is developed at the top floor. It increases a little more to reach the constant value after two floors down.
2. Accordingly, the forces in brace members reduce and reach the constant magnitude after the third floor from the top.
3. At the base, 65% of the external torsion is resisted by the shear wall, and 85 % of it is transferred to the shear wall at the first two floors.

Three points must be remarked from these analysis results:

1. The in progress study shows that, with typical stiffness in the slabs (as the case in Tower 29), the torsional moment is distributed between exterior structure and core structure quickly within a few floors through slabs. This means that the floors below the one on which torsional moment is applied show rigid rotation and develop only negligible shear to satisfy compatibility.
2. Stress in the floor slabs due to building torsion, which transfer external torsional moment to the shear

wall, is relatively small compared with stress due to floor bending.

3. With a further investigation that includes the complete model of Tower 29, it will be verified that there will be no concern of shear fracture of floor slabs due to building torsion at the interface between the slab and the shear wall.

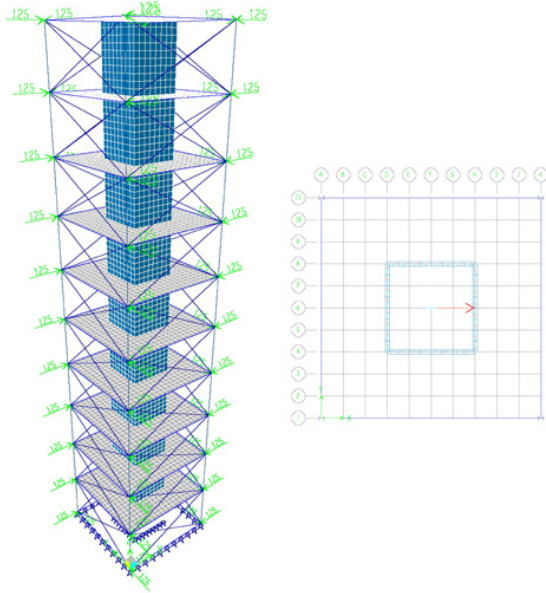


Figure 16. Unstressed Model

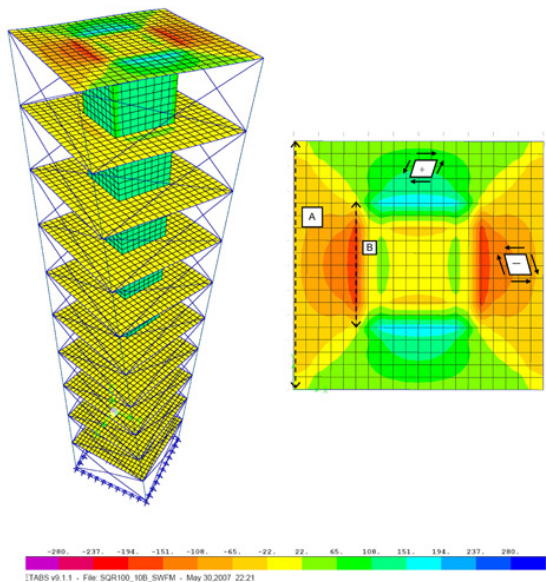


Figure 17. Stressed Model

Sustainability

Although the main focus of this paper is on the structure and its relationship to the form, it is appropriate to briefly address the potential of the Tower to provide a sustainable/green building. Few areas can be given below:

1. Energy saving strategies:

The proposed façade with the integrated elements offers significant reduction of the cooling load and hence of the cooling energy required. The well located multi story atriums offer deep penetration of day light while preserving a minimum surface to volume ratio

2. Form Contribution:

The plan- offsetting (morphing) will have a positive effect when the direction of the morphing causes the facade to tilt away from the sun.

3. The Crown Contribution:

It is expected that significant amount of reliable and steady source of clean electrical energy will be produced from the wind turbine(s) housed there. That is because the turbines are located very high above the ground, where the air flow, most of the time, is abundant and steady.

Conclusions

The extensive structural preliminary analysis conducted by CDCI, as summarized above, shows that Tower 29 does not only possess an iconic form, but it responds favorably both structurally and environmentally. The collaborative effort between the architect and the engineer yielded a structure that blend very well with the form and enables it to express itself in a magnificent way. The preliminary structural member sizing also indicates that the structure has maintained a good level of efficiency. Perhaps the innovation in the structural system stems from the fact that the structure capitalized in the potential of the form to yield an efficient structure. The process was not an easy one, but went through many complex steps that include visualization, model building, both physical and digital, and many simulations. But, in the end it is the creative endeavor between the architect and the engineer that led to the successful outcome.

However, further special studies and analyses will be conducted to tap into the potential of the system to provide damping among others.

Through the structural investigative process, it also became evident that the form has a great potential to provide a sustainable building.

Acknowledgement

It is not possible to achieve any meaningful work without the involvement and the collaboration of many. It give the author great pleasure to thank Architect Jay Thomson of TVS for his patience, kindness and incredible knowledge. It was truly an enjoyable collaborative experience. My thanks also extend to his group. To name a few: Reeti Samboria, Jorge Basan and Howard Chen. The author gives to acknowledge his own team within CDCI for their high quality performances: Dr. Hiroki Tamai, Ayman Almusharaf, and Dr. Hyeong-Il Kim. Special recognition to Mr. Ray Clark for his energy analysis.