Conceptual Design of a Building with Movable Parts

by

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Abstract

Although we live in a Dynamic Universe filled with movement, the design methodology that has been given to Architecture is clearly static: buildings look the same all the time. As an approach to "Dynamic Architecture", the design of a building with a changing geometry is examined in an attempt to explore factors that affect the design of this type of building. The proposed building is 200 m in height and follows the shape of a "T", it has a movable structure on its top that can rotate 360 degrees. Because of the changing geometry of the building due to the rotation of the upper part, two assumptions can be made in the structural analysis: a. that the changing geometry drastically changes the dynamic behavior of the building, or b. that this changing geometry doesn't affect at all the dynamic behavior. Since the movement will be slow, the structural analysis can be quasi-static. The cantilevered structure acts as a concentrated mass on the top of the building which is an important factor to consider against seismic loads. The design of the connection of the movable structure to the building is a critical aspect so it can move but at the same time be fixed to the building. A correct assumption of the modeling of this connection is critical in the structural analysis. Due to the rotation of the upper part, special emphasis has to be made in the torsional effects of the whole structure.

Thesis supervisor: Jerome J. Connor
Title: Professor of Civil and Environmental Engineering

“Nevertheless, it moves.”

Galileo

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Getting my admission into MIT has been not only a dream but also one of the major challenges of my life. My studies and life while at MIT have been one of the most defiant experiences both intellectually and emotionally. Nevertheless the hardest a situation could be, I always kept in my mind this quote by George Bernard Shaw to get the strength I needed to keep on going:

"People are always blaming their circumstances for what they are. I don't believe in circumstances. The people who get on in this world are the people who get up and look for the circumstances they want, and if they can't find them, make them. People see things; and say, "Why?" But I dream things that never were; and I say, "Why not?"

Table of Contents

1. The inspiration for an idea. 11
   1.2. Dynamic Architecture 12
   1.3. Examples of Dynamic Architecture 13
   1.4. Present of Dynamic Architecture 15
   1.5. Technical Aspects of the building 16
2. Architectural Design 21
   2.1. Fundamentals of design 21
   2.2. Roller bearing for the rotational cantilevered structure 21
   2.3. Building dimensions 22
      2.3.1. Floor plan 22
      2.3.2. Rotational cantilevered structure plans 23
      2.3.3. Elevation view of the building 25
      2.4. Technical issues inherent to this design 26
3. Structural analysis and implications 27
   3.1. Problems generated by having a mass in the top 27
   3.2. Assumptions for the response of the rotational structure 27
      3.2.1. First assumption 27
      3.2.2. Second assumption 28
   3.3. Preliminary member sizing 28
   3.4. Bracings for the building 30
   3.5. Model idealization with lumped masses 32
      3.5.1. Preliminary Mass Calculation per floor 34
   3.6. Dynamic analysis of the building with different positions of the rotational structure 36
      3.6.2. Results for the building with the top structure rotated 22.5 degrees 41
      3.6.3. Results for the building with the top structure rotated 45 degrees 42
      3.6.4. Results for the building with the top structure rotated 67.5 degrees 43
      3.6.5. Results for the building with the top structure rotated 90 degrees 44
      3.6.6. Results for the building without the top structure 45
      3.6.7. Dynamic Analysis Results Comparison 46
   3.7. Static load pattern in the roller bearing of the rotational structure 47
   3.8. Excitation of the rotational mode 48
4. Conclusions 54
5. References 55
Appendix 1. Patent publication by David Fisher. 56
Appendix 2. Stiffness calibration 61
Appendix 3. Values for the periodic excitation function inserted in SAP2000 63

List of Figures

Figure 1. Sketch of the original “T” Building Idea by the author, made in June 1998. ... 11
Figure 2. Vitrubian Man by Leonardo Da Vinci [1]. 12
Figure 3. CN Tower[2] in Toronto, Canada (left). WTC[3] Mexico City (right)............. 14
Figure 4. George P. Coleman Bridge[4]. 15
Figure 5. Rotating tower concept for Dubai by David Fisher[5]. 16
Figure 6. Tower crane by the company Liebherr, Germany. 17
Figure 7. Roller bearing by the company Liebherr, Germany[6]. 18
Figure 8. Piling of three roller bearings recently manufactured by Liebherr, Germany[6]. 18
Figure 9. 3D view with cut of a roller bearing with external teeth by Liebherr, Germany[6]. 19
Figure 10. Cross section of a roller bearing with external teeth by Liebherr, Germany[6]. 19
Figure 11. Slewing gearbox manufactured by Liebherr, Germany[6]. 20
Figure 12. Floor plan of the building, showing the concrete elevator and services core, as well as the beams that form the structure floor. 22
Figure 13. Side view and floor plan projections for the last three rotational floors of the “T” Tower Concept. 23
Figure 14. Isolated view of the rotational cantilevered structure..................................... 24
Figure 15. Elevation view of the building with its measures... 25
Figure 16. View of the rotational structure isolated from the rest of the building. The supports are modeled as pinned since the structure rests on a roller bearing to allow for rotation. 28
Figure 17. Static analysis of a floor plan made in RISA 3D for a preliminary sizing of steel members.. 29
Figure 18. Building with bracings (left) and without bracings (right)............................. 30
Figure 19. Idealized model of the building consisting of a 20 DOF model...................... 33
Figure 20. Isometric and top view of the building. Rotational part parallel to the front façade of the building.. 37
Figure 21. First mode of the structure without rotation. 38
Figure 22. Second mode of the structure 39
Figure 23. Third mode of the structure. 40
Figure 24. Isometric and top view of the building rotated 22.5 degrees from its original position... 41
Figure 25. Isometric and top view of the building with the top structure rotated 45 degrees from its original position. 42
Figure 26. Isometric and top view of the building rotated 67.5 degrees from its original position... 43
Figure 27. Isometric and top view of the building rotated 90 degrees from its original position... 44
Figure 28. View of the building without the rotational structure on the top. 45

Figure 29. Top view of the cantilever, the green supports show concentrated loads on the roller bearing. The arrows show the supports that carry the bigger load according to this configuration. 47
Figure 30. Representation of the load pattern of any node representing the roller bearing, depending on the rotation of the structure. 48
Figure 31. View of the structure modeled in SAP2000. The arrows indicate the joints were the periodic loads were applied. 49
Figure 32. Top view of the building indicating Joint 1 (the joint at one extreme of the cantilever) and joint 2 (the joint close to the structure of the building. 49
Figure 33. Plot of the unitary periodic excitation. 51
Figure 34. Input of the values for the sinusoidal function in SAP2000. 51
Figure 35. Input of the Time History Case Data in SAP2000, as can be seen the value of in our function can be introduced in the Scale Factor lot in the program. 52
Figure 36. Displacement of joint 1 due to the periodic excitation in that same joint. 53
Figure 37. Displacement of joint 1 due to an excitation in joint 2. 53

List of tables

Table 1. Period of the structure with bracings 31
Table 2. Period of the structure without bracings. 31
Table 3. Mode and period values for the building with the top structure rotated 0 degrees. 37
Table 4. Mode and period values for the building with the top structure rotated 22.5 degrees. 41
Table 5. Mode and period values for the building with the top structure rotated 45 degrees. 42
Table 6. Mode and period values for the building with the top structure rotated 67.5 degrees. 43
Table 7. Mode and period values for the building with the top structure rotated 90 degrees. 44
Table 8. Mode and period values for the building without the top structure. 45
Table 9. Period values of the structure depending on its rotational configuration. 46
Table 10. Load pattern in a particular node depending on the rotation of the structure. .. 47

1. The inspiration for an idea.

In June 1998 while watching the construction of a 20 story building in Mexico City, a tower crane was rotating making its path to put some materials on the top. My insight in building an innovative piece of Architecture made me imagine immediately a skyscraper whose top part would rotate such as this tower crane, generating in the moment what I called "Dynamic Building" (Figure 1). This event left me thinking at the moment why nobody had designed a building in which the structure itself changed its appearance in time?

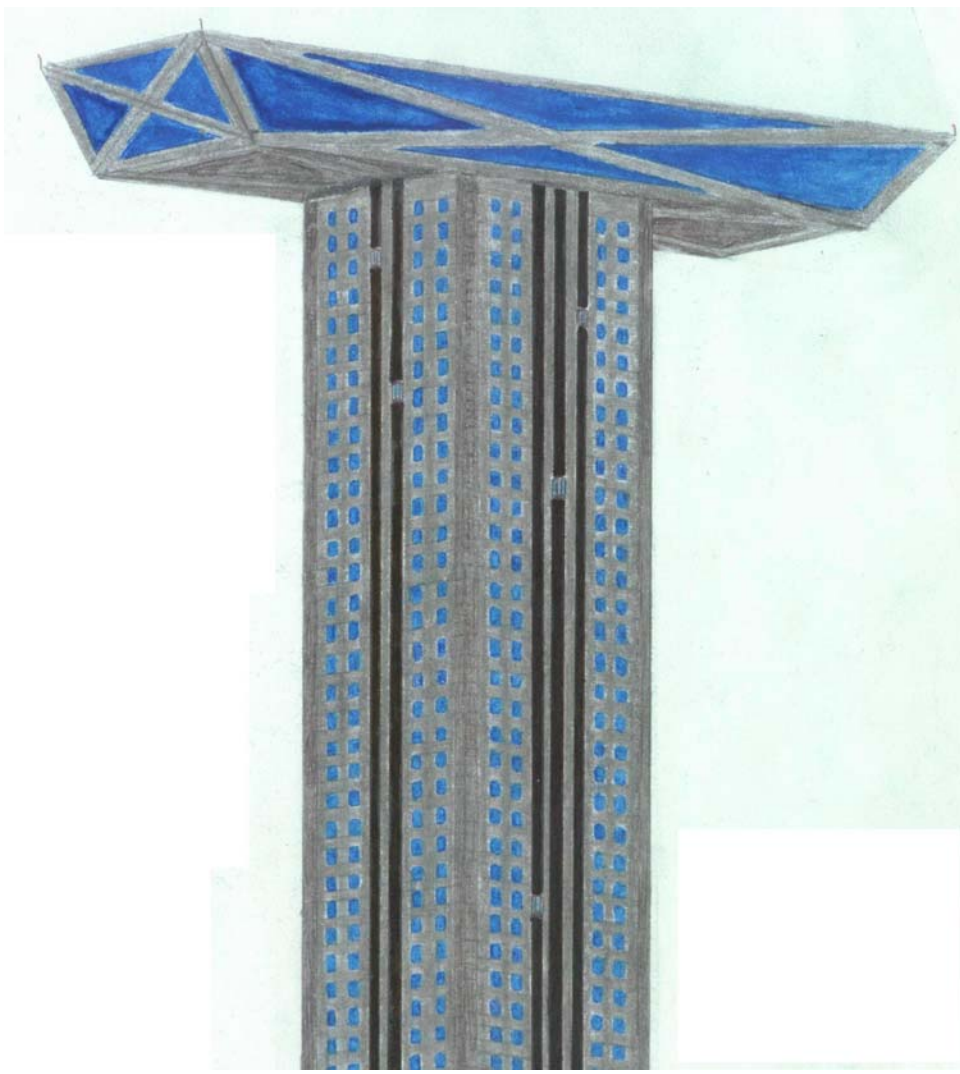

Figure 1. Sketch of the original "T" Building Idea by the author, made in June 1998.

The tower's top part would be cantilevered to each side of the building just like the tower cranes with inherent movement. This building resembles immediately the "Vitruvian Man" by Leonardo Da Vinci with its extended arms (Figure 2). The design features try to follow the human proportions as close as possible.

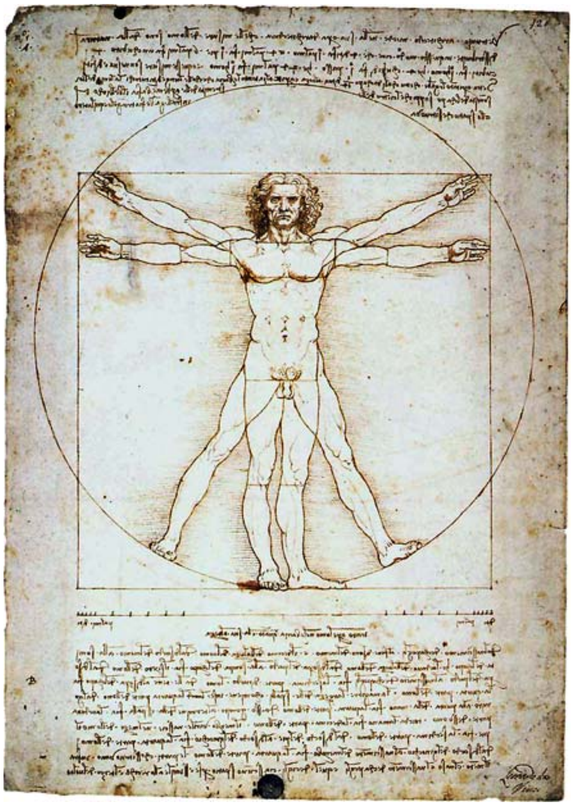

Figure 2. Vitrubian Man by Leonardo Da Vinci [1].

1.2. Dynamic Architecture

Dynamics is a branch of mechanics that is concerned with the effect of forces on the movement of objects. Nowadays architecture is seen as something static, since buildings remain on the same place and their configuration doesn't change at all. The concept of movement in a building is known now as Dynamic Architecture. Dynamic Architecture buildings modify their shape constantly; living in a dynamic Universe it makes sense that the future in building design will follow this example.

Buildings that follow a Dynamic Architecture modify their shape constantly. This creates a visual attraction immediately caught by the human eye, which focuses its attention in movement while being surrounded in a static environment.

Dynamic Architecture involves the fourth dimension: time. Change and adaptability to a changing environment will be premises to follow in this type of design. Looking towards the future makes sense that buildings following a dynamic approach will shape the cities. Cities having a dynamic approach will change the skyline in an innovative and unusual way.

1.3. Examples of Dynamic Architecture

In the world there are some structures that change their configuration. Some floors in the top of landmark buildings rotate but this is done within the structure of the building, no movement can be seen from the exterior of the structure. This has been done mainly as tourist attractions in which rotating restaurants that have a 360 degree view of a city gather a lot of attention (examples of these are the rotating restaurant in the top of the CN Tower in Canada, or the one in the top cylinder of the World Trade Center Building in Mexico City (Figure 3)).

Figure 3. CN Tower[2] in Toronto, Canada (left). WTC[3] Mexico City (right).

But in the case of bridges, rotation follows functionality. Sometimes these structures have to rotate to allow a path for ships due to their low clearance. Bridges are the closest example to what the "T" Tower will look like structurally, since bridges are usually cantilevered from the center pylon and follow the most optimal structural shape (Figure 4).

Figure 4. George P. Coleman Bridge [4].

1.4. Present of Dynamic Architecture

The most recent work made in the field of “Dynamic Architecture” appeared in the news in March 2007. It is the work of the Italian Architect David Fisher that proposes an apartment building in Dubai in which every floor rotates from a central core (Figure 5). Each floor consists of a separate module that the owner can rotate at will or follow a particular configuration in synchronization with the whole building.

He was just awarded a patent publication for rotatable building structures [12] (see Appendix 1). Although the mechanisms he uses for rotation are a common standard in the machinery industry and simply adapted to the bigger scale of buildings; clearly there is no innovation in his patent and he cannot claim this “invention” as “unique”.

Figure 5. Rotating tower concept for Dubai by David Fisher[5].

1.5. Technical Aspects of the building

Technically, the concept itself is not complicated, it would imply designing a magnified structure of existing mechanisms such as tower cranes, and building bigger bearings. The technical knowledge for building this type of structure is readily available since it is a technology that has been proven to work in construction machinery for many years: most of the cranes follow this principle since they need to allow rotation of the structure, electricity and plumbing for hydraulic cylinders have to pass through it so the operator can make the machinery work.

The design concept is simple, a 200 m tall skyscraper that follows the shape of the letter “T”, the top is cantilevered to each side of the building (similar concept to tower crane (Figure 6)) while sitting on a roller bearing (Figures 7 to 10) that will allow it to rotate at a maximum speed of one complete turn per hour.

Figure 6. Tower crane by the company Liebherr, Germany.

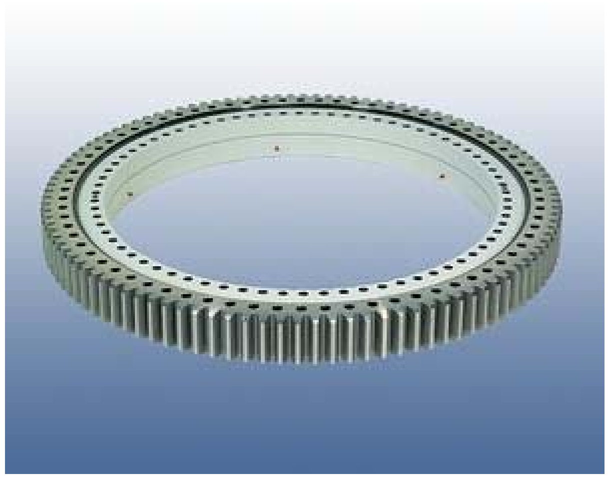

Figure 7. Roller bearing by the company Liebherr, Germany[6].

Figure 8. Piling of three roller bearings recently manufactured by Liebherr, Germany[6].

Figure 9. 3D view with cut of a roller bearing with external teeth by Liebherr, Germany[6].

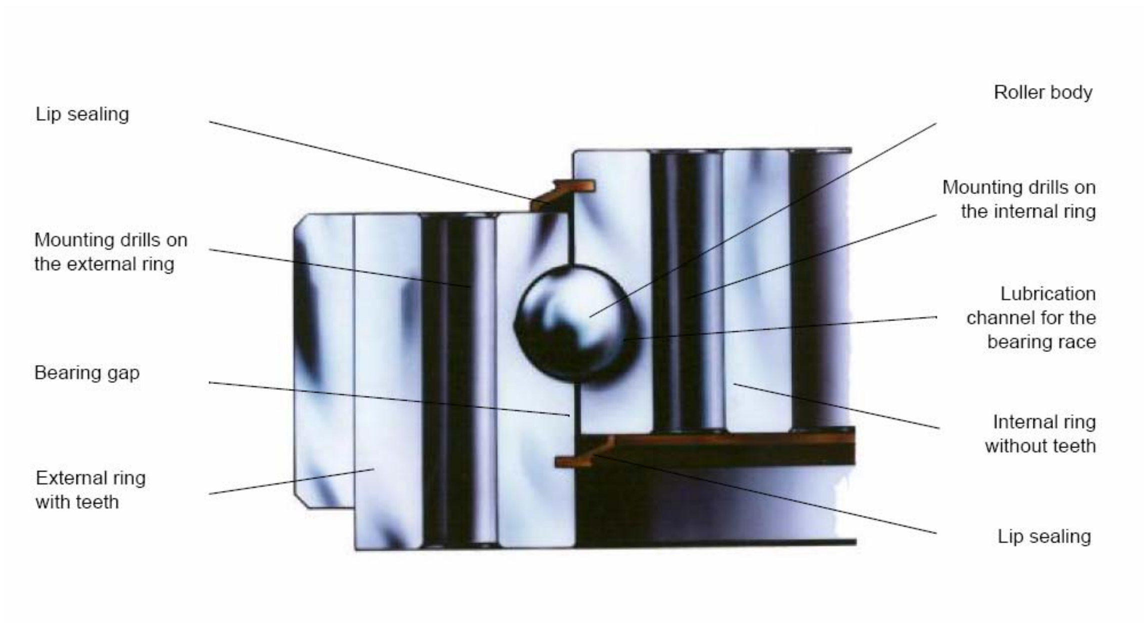

Figure 10. Cross section of a roller bearing with external teeth by Liebherr, Germany[6].

Figure 11. Slewing gearbox manufactured by Liebherr, Germany[6].

A slewing gearbox (Figure 11) will be the power source of movement for the roller bearings of the structure. The German company Liebherr [6] produces some of them with high standards in quality.

2. Architectural Design

2.1. Fundamentals of design

The first architectural model was focused on symmetry, since this would facilitate structural efficiency. A concrete core that includes the stairs, elevators, restrooms as well as service pipes would be accommodated in the center in the most symmetrical and architecturally efficient manner. When reaching the top, only four elevators continue its path across the rotating structure, and from the inside diameter of the roller bearing. The top cantilevered structure will sit on a roller bearing to allow for rotation.

2.2. Roller bearing for the rotational cantilevered structure

A bearing is a device to permit constrained relative motion between two parts, typically rotation or linear movement [7].

For architectural and structural reasons, the gear must be 16.2 m diameter, since it must rest on the elevator and services core of the building. The mass of the rotating last three floors will be supported on this bearing and loads will be transmitted to the ground through the concrete core.

The German company Liebherr produces some of the biggest roller bearings in the world, mainly because it is a company focused on the design of heavy construction machinery. Their manufacturing range covers bearings up to 6 m diameter with individual weights of up to 17,000 kg [6].

According to this company, dimensions and special designs can also be provided to customers' requirements [6].

The rotation can be programmed to follow the path of the sun, solar panels will be installed in the roof of the rotational part of the building. So, although the rotation would be even slower, this will translate into efficiency in the design of the building by making it more sustainable.

2.3. Building dimensions

2.3.1. Floor plan

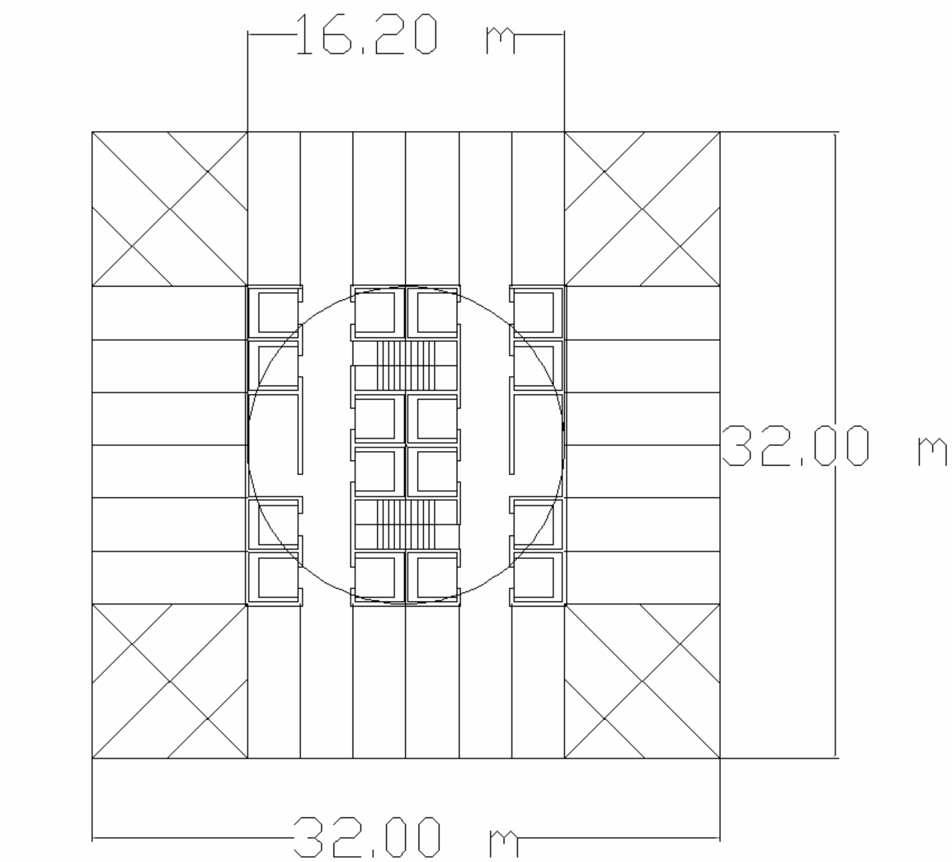

Figure 12. Floor plan of the building, showing the concrete elevator and services core, as well as the beams that form the structure floor.

The 32 x 32 m floor plan comprises 1024 m^2 of space. From which the core occupies 16.2 x 16.2 m, or 262.44 m^2. This means that the available space for office use will be of 761.56 m^2.

The core is composed of 16 elevators that will give service to different floors according to demand, two emergency stairs, and two restrooms (one for men and one for women, each one of them with six toilets). Electricity and telephone cables could make their way through one of the elevator cores or use some space in the stairs.

2.3.2. Rotational cantilevered structure plans

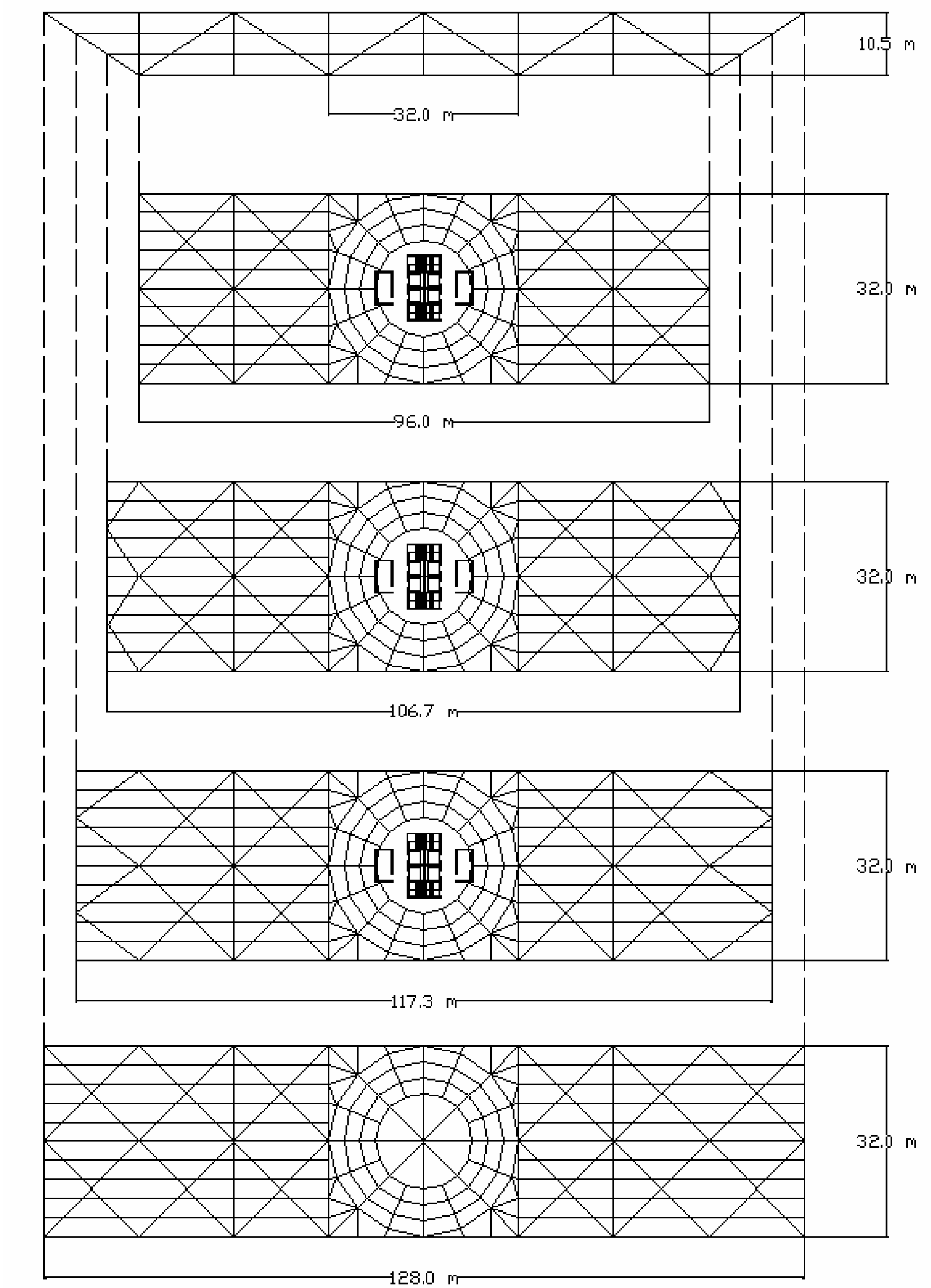

Figure 13. Side view and floor plan projections for the last three rotational floors of the "T" Tower Concept.

The last rotational three floors can be given any use, from restaurants, clubs, auditoriums with a 360 degree view of the city or offices for executives. The core is clearly reduced for these last floors, only four elevators, the emergency stairs and restrooms will make their way through the roller bearing.

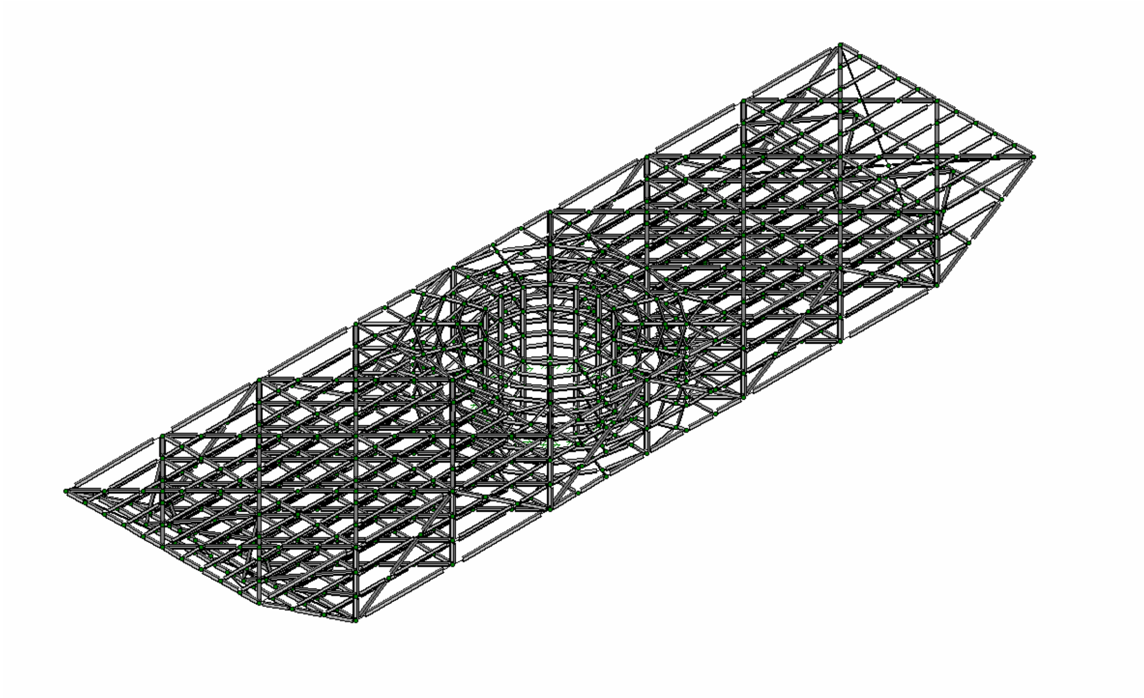

Figure 14. Isolated view of the rotational cantilevered structure.

2.3.3. Elevation view of the building

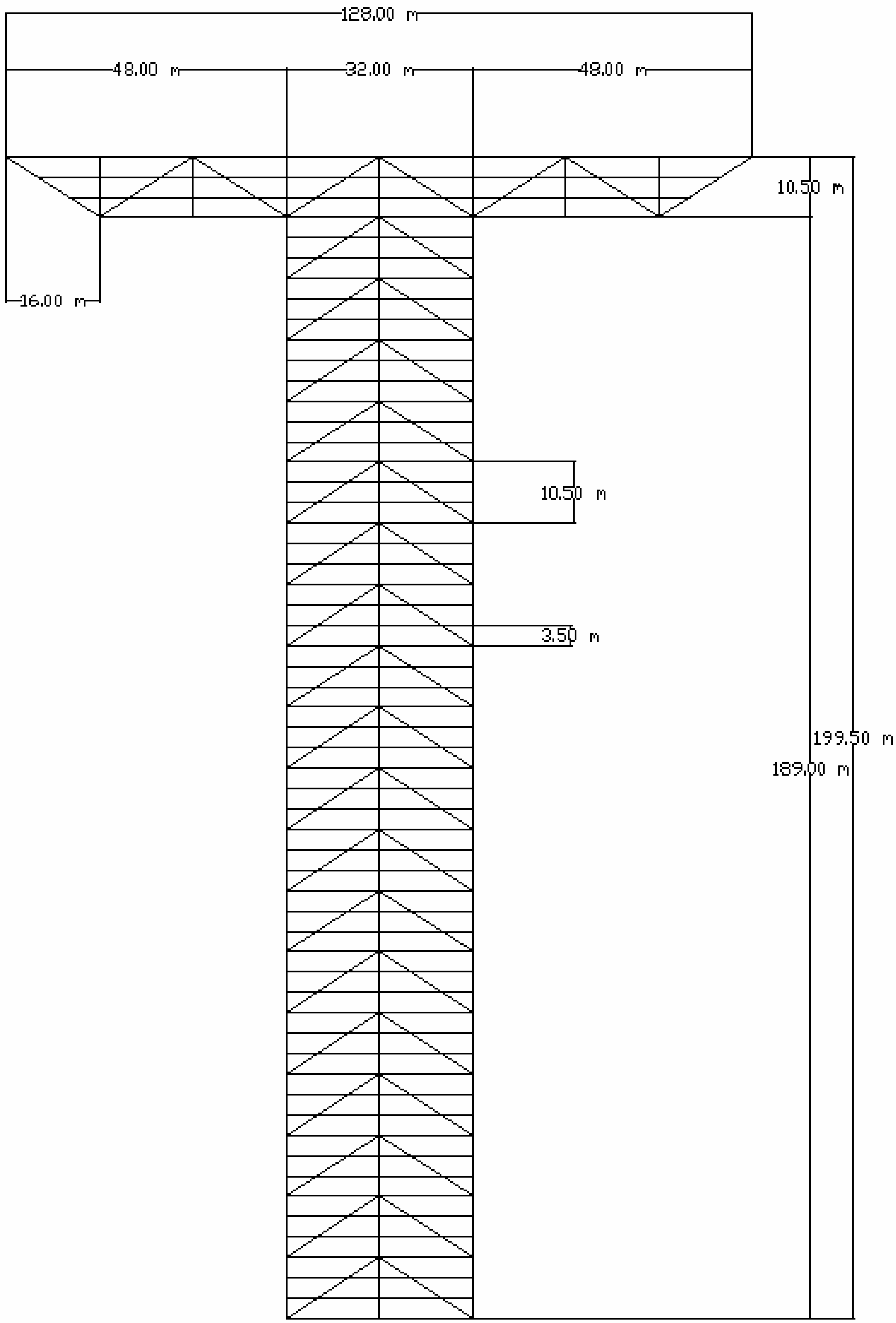

Figure 15. Elevation view of the building with its measures.

The building is comprised of 57 floors, each with a height of 3.5 m suitable for office use. This gives a total height to the building of 199.5 m. The rotational part of the building starts at a height of 189 m. The rotational structure is cantilevered to each side of the building by 48 m, which clearly overhangs the width of the floor plan of 32 m. Concentric braced frames, also known as “K” bracings are installed every 3 floors, or 10.5 m height.

2.4. Technical issues inherent to this design

This design implies some technical issues. Some of them are described below:

Since the top part will will be seated on bearings, the structure of the building has to be able to withstand the changing forces due to the rotation.

The rotating structure acts as a huge mass on the top of the building, this makes the structure behave as an inverted pendulum which works in detriment rather than in benefit of the overall structure.

Certain unbalanced loadings in the rotating part of the structure generate torsion on it. Some critical load cases have to be analyzed for safety. An example of this could be a concentration of people in just one side of the cantilever due to a particular event.

3. Structural analysis and implications

3.1. Problems generated by having a mass in the top

The characteristic feature of a cantilevered rotational structure in the top of the building implies some considerations in the structural design. Having this rotational part in the top of the building decreases the structural efficiency, the massive weight makes the building act as an inverted pendulum and reduces the effective stiffness of the system [8].

The rotation of the structure will be very slow, allowing for a quasi-static approach in the analysis. A whole different approach would be used if the rotation was faster, but for human comfort a fast rotation is neither feasible or desirable (it could produce dizziness in the occupants). Besides, visually speaking, a structure that rotates very fast would be scary for people just by seeing it from outside (it could not rotate as a radar, for example).

In the program RISA 3D [9], the base of the rotational structure was modeled using pinned supports, since the bearings would restrain the vertical and horizontal movements, though they are not able to carry bending moments. The top three floors of the structure act as a concentrated mass. There are two assumptions that will be proved in the structural analysis:

3.2. Assumptions for the response of the rotational structure

3.2.1. First assumption

The rotation of the top part will significantly change the period of the structure, because of the changing orientation of the elements. The moment of inertia is included in the stiffness of the elements, and the moment of inertia is dependant on the orientation of the element. Then the orientation of the rotational part will be critical aspect to consider in case an earthquake hits the building, since forces in elements could be amplified.

3.2.2. Second assumption

Since the top mass is supported in bearings, the orientation is not critical since all the mass could act as if it were lumped in the centroid. Then, the orientation of this structure will not change the period of the whole building. In case an earthquake hits the building, the response of the building will not vary significantly.

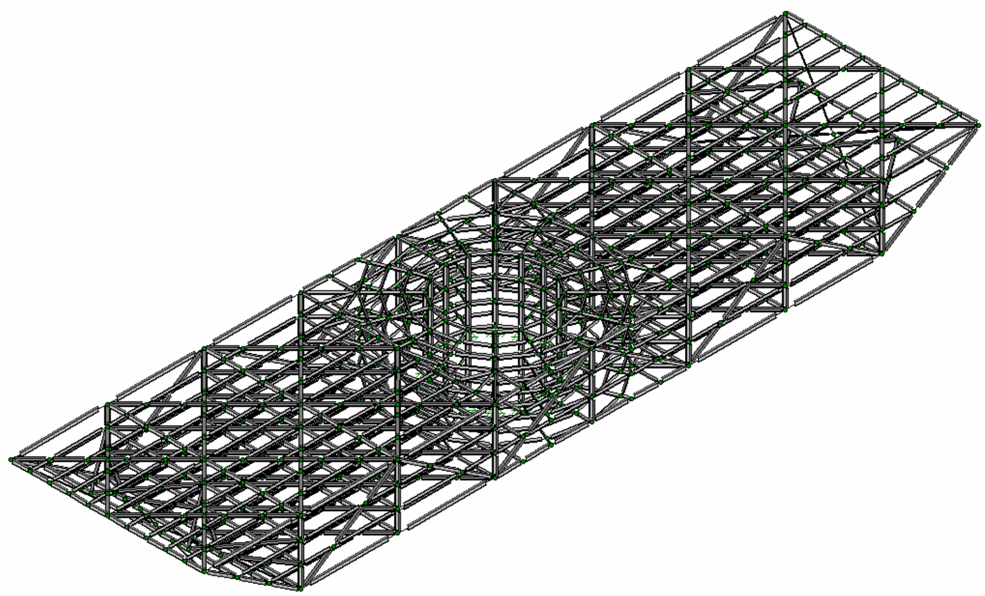

Figure 16. View of the rotational structure isolated from the rest of the building. The supports are modeled as pinned since the structure rests on a roller bearing to allow for rotation.

3.3. Preliminary member sizing

The process of the analysis involved a simple static analysis for dead and live loads, just to get an idea of the sizing of the members. These members were then revised for a dynamic approach using a simplified model.

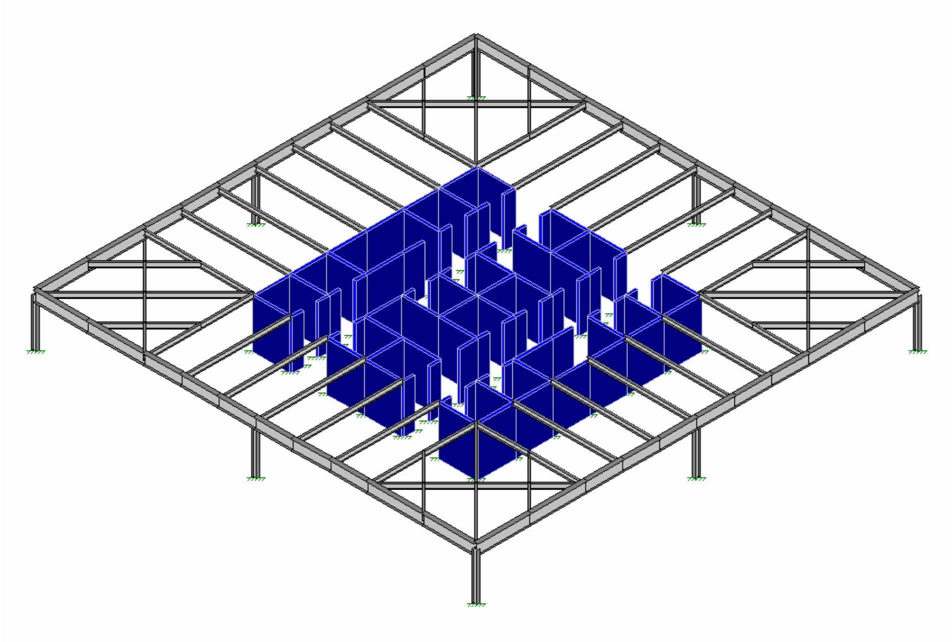

Figure 17. Static analysis of a floor plan made in RISA 3D for a preliminary sizing of steel members.

Doing a static analysis in RISA 3D, and applying a load of 4.8 kN/m^2 on the slabs (considering dead and live loads), a preliminary column size of W14x176 was obtained with a moment of inertia of 8.9×10^{-4} m^4.

3.4. Bracings for the building

To give lateral stability to the structure and to increase its stiffness, concentric braced frames were added to the structure every three floors. The architectural design considers the structure as part of the scheme, believing that when the structure is clearly integrated on the architecture itself, it creates more appealing and interesting works. Bracing that is shown in the structure can be seen in works such as the Bank of China, in Hong Kong, and the John Hancock Center of Chicago.

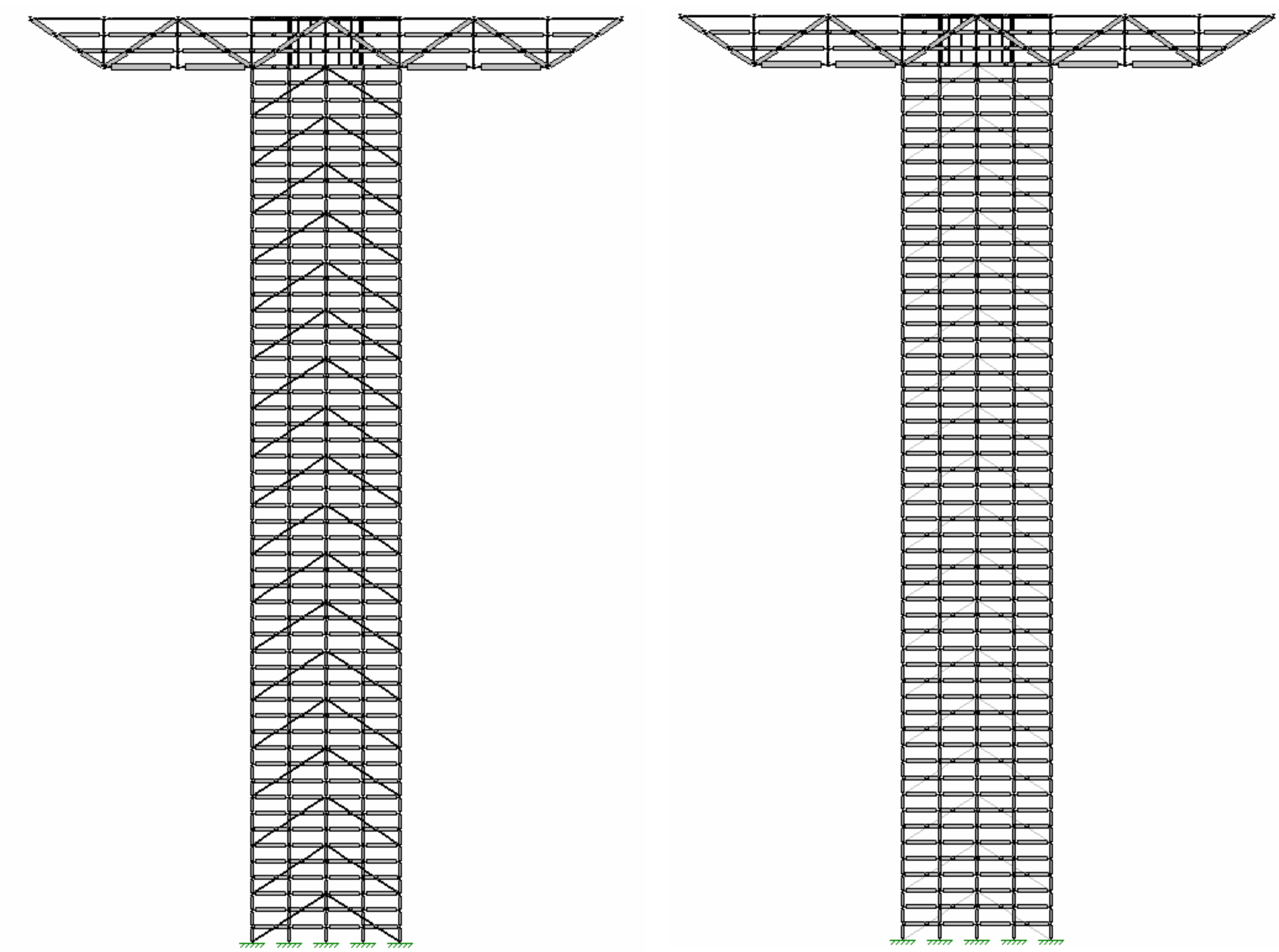

Figure 18. Building with bracings (left) and without bracings (right).

As can be seen from the comparison of tables 1 and 2, the bracings significantly increase the stiffness of the system and reduce its period, which is something we desire for this structure. We don't want it to move excessively especially having such a concentrated mass in the top.

Mode	Period (s)
1	4.661
2	4.599
3	3.333
4	1.034
5	1.015
6	0.622
7	0.540
8	0.482
9	0.440

Table 1. Period of the structure with bracings

Mode	Period (s)
1	7.766
2	7.023
3	6.027
4	3.411
5	1.567
6	1.274
7	1.023
8	0.783
9	0.656

Table 2. Period of the structure without bracings.

3.5. Model idealization with lumped masses

Usually a structural analysis should begin with an idealized model to get some insight on the behavior. For this thesis, a computer model was generated first and some members sizes were set in an iteration process.

A simplified model (Figure 19) with 20 lumped masses every three floors was done to verify the sizing of the members, based on a stiffness distribution that produces a linear profile for the fundamental mode (Connor, Structural Motion Control [8]) (see Appendix 2 for values).

The slab of every floor acts as a diaphragm, so we can consider the flexural rigidity of the beams as infinite (Chopra, Dynamics of Structures [8]); the stiffness contribution of the columns for each frame of the building is:

$$k_{columns} = \sum_{columns} \frac{12EI_c}{h^3}$$

Also, the stiffness contribution of the bracing (Connor, Structural Motion Control [8]) is

$$k_{bracings} = \sum_{bracings} \frac{A_d E_d \sin 2\theta \cos\theta}{h_{bracing}}$$

Hence, the total stiffness every three floors will be given by:

$$k_{total} = k_{columns} + k_{bracings}$$

A maximum lateral deflection of H/500 over a 100 year return period [11] was given, then:

$$\gamma^* = \frac{H}{500} = \frac{200m}{500} = 0.40m$$

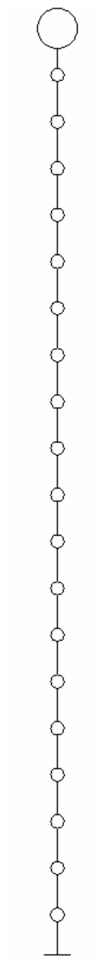

Figure 19. Idealized model of the building consisting of a 20 DOF model.

3.5.1. Preliminary Mass Calculation per floor

Concrete slabs = 32m x 32m x 0.1m x 2400kg/m^3 =	245,760 kg
Equipment = 32m x 32m x 100kg/m^2 =	102,400 kg
Mass of steel structure =	40,683 kg
Total =	388,843 kg

Since the masses will be lumped every three floors:
Lumped masses = 388,843 kg x 3 = 1,166,529 kg

For the rotational structure, the weight of the steel structure for the four floors is,

Mass of steel structure =	969,311 kg

The cantilever mass is equal to another floor spanning to each side of the building, so the former values will be multiplied by a factor of 3 to get a rough estimate:

Concrete slabs = 3 x 32m x 32m x 0.1m x 2400kg/m^3 =	737,280 kg
Equipment = 3 x 32m x 32m x 100kg/m^2 =	307,200 kg
Mass of steel structure per floor=	242,327 kg
Total =	1,675,650 kg
Cantilever lumped mass = Total x 4 =	6,702,600 kg

These values were inserted in a matrix (Appendix 2) to gain some insight on the stiffness distribution along the building.

To verify the stiffness, the values for the period of the structure obtained from the computer analysis were plugged in the equations for an optimal stiffness calibration [8], these calculations are made as follow:

Building without bracings

$T = 7.76s$

$k = w^2 k'$

$$w = \frac{2\pi}{T} = \frac{2\pi}{7.76} = 0.81 rad/s$$

$k' = 355{,}692{,}510 N \cdot s^2 / m$ (see Appendix 2)

$$k = (0.81 rad/s)^2 (355692510 N \cdot s^2/m) = 23{,}120{,}013 N/m$$

The stiffness for our 12 columns whose moment of inertia was obtained in the computer analysis is:

$$k_{columns} = 12\left(\frac{12EI}{h^3}\right) = \frac{(12)(12)(2.1x10^{11} N/m^2)(0.00089073 m^4)}{(10.5m)^3} = 23{,}268{,}048 N/m$$

which is a similar number obtained from the stiffness distribution.

Building with bracings

$T = 4.66s$

$k = w^2 k'$

$$w = \frac{2\pi}{T} = \frac{2\pi}{4.66s} = 1.35 rad/s$$

$k' = 355{,}692{,}510 N \cdot s^2 / m$ (see Appendix 2)

$$k = (1.35 rad/s)^2 (355692510 N \cdot s^2/m) = 648{,}249{,}599 N/m$$

$$A_{bracings} = \frac{h}{2Ed \sin 2\theta \cos\theta}\left(k_T - k_{columns}\right)$$

$$A_{bracings} = \frac{10.5m}{2(2.1x10^{11}N/m^2)\sin(2x33.27)\cos(33.27)}\left(648{,}249{,}599N/m - 23{,}268{,}048N/m\right)$$

$$A_{bracings} = 0.03943m^2$$

$$A_{bracings} = 394.3cm^2$$

this would correspond to a W12x120 shape with an area of 398.7 cm^2, which is six times bigger than the one used in the program of W10x33 with an area of 64.5 cm^2. Although in the computer model all bracings have the same shape, ideally the stiffness of the member would change from floor to floor but for constructability reasons this might not be economical.

These results demonstrate how powerful and how much insight one can obtain by simplifying structural models.

3.6. Dynamic analysis of the building with different positions of the rotational structure

As a way to prove the assumptions made earlier in this chapter (Section 3.2.1 and 3.2.2), several dynamic analysis of the building with its top cantilevered structure in different rotation configurations were performed.

3.6.1. Results for the building with the rotational structure in the original position.

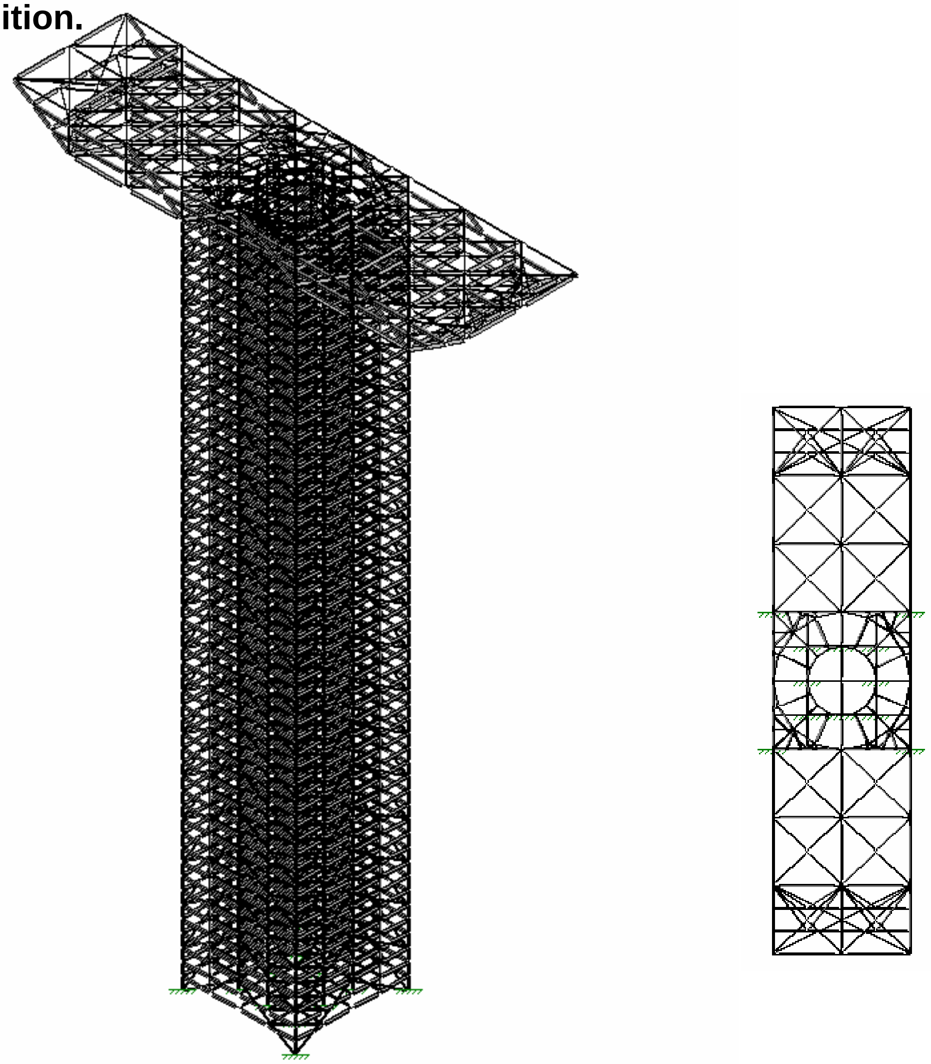

Figure 20. Isometric and top view of the building. Rotational part parallel to the front façade of the building.

Mode	Period (s)
1	4.661
2	4.599
3	3.333
4	1.034
5	1.015
6	0.622
7	0.540
8	0.482
9	0.440

Table 3. Mode and period values for the building with the top structure rotated 0 degrees.

A representation of the first three modes of the building can be seen from Figure 21 to Figure 23. For the buildings whose top part is rotated, the mode shapes follow the same pattern.

3.6.1.1. First mode

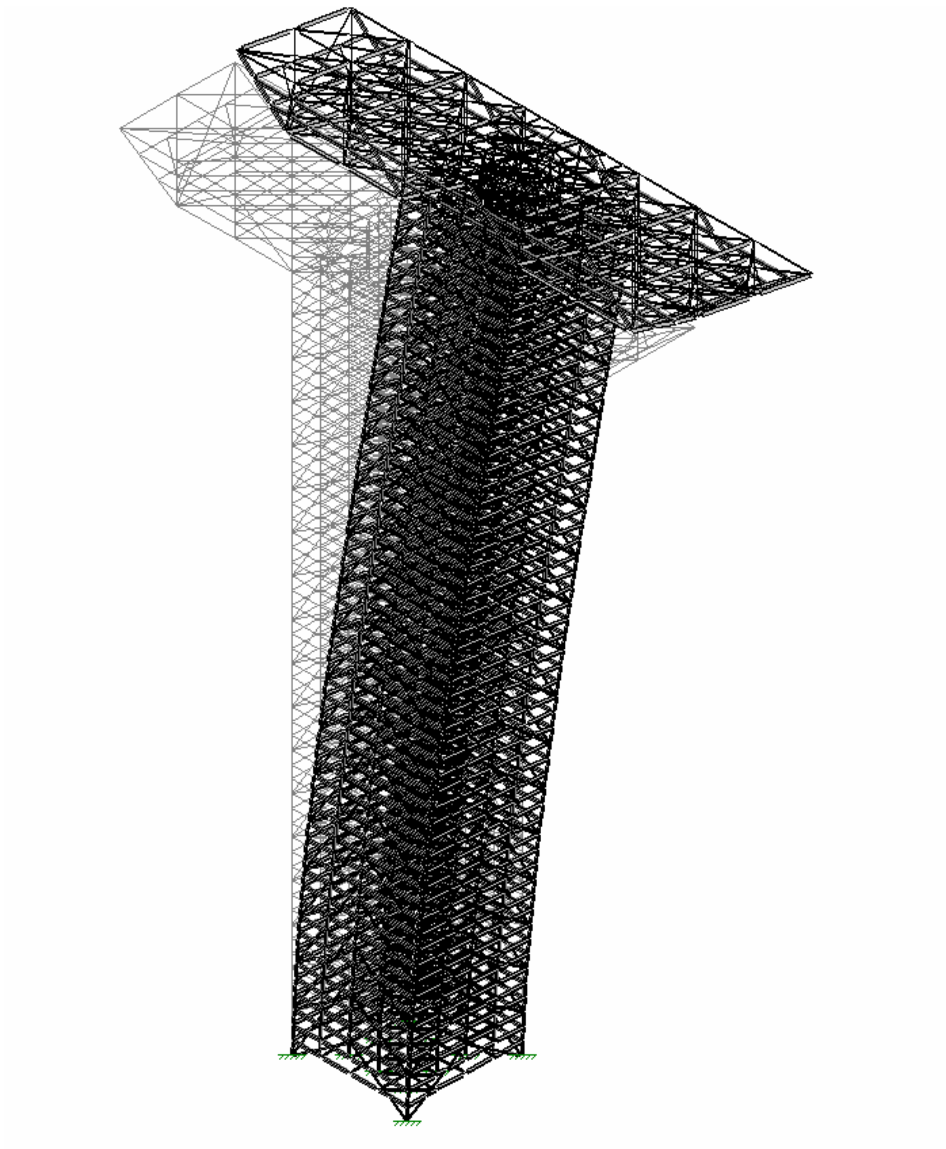

Figure 21. First mode of the structure without rotation.

For first mode, the period is 4.661 seconds, the tower sways front and back.

3.6.1.2. Second mode

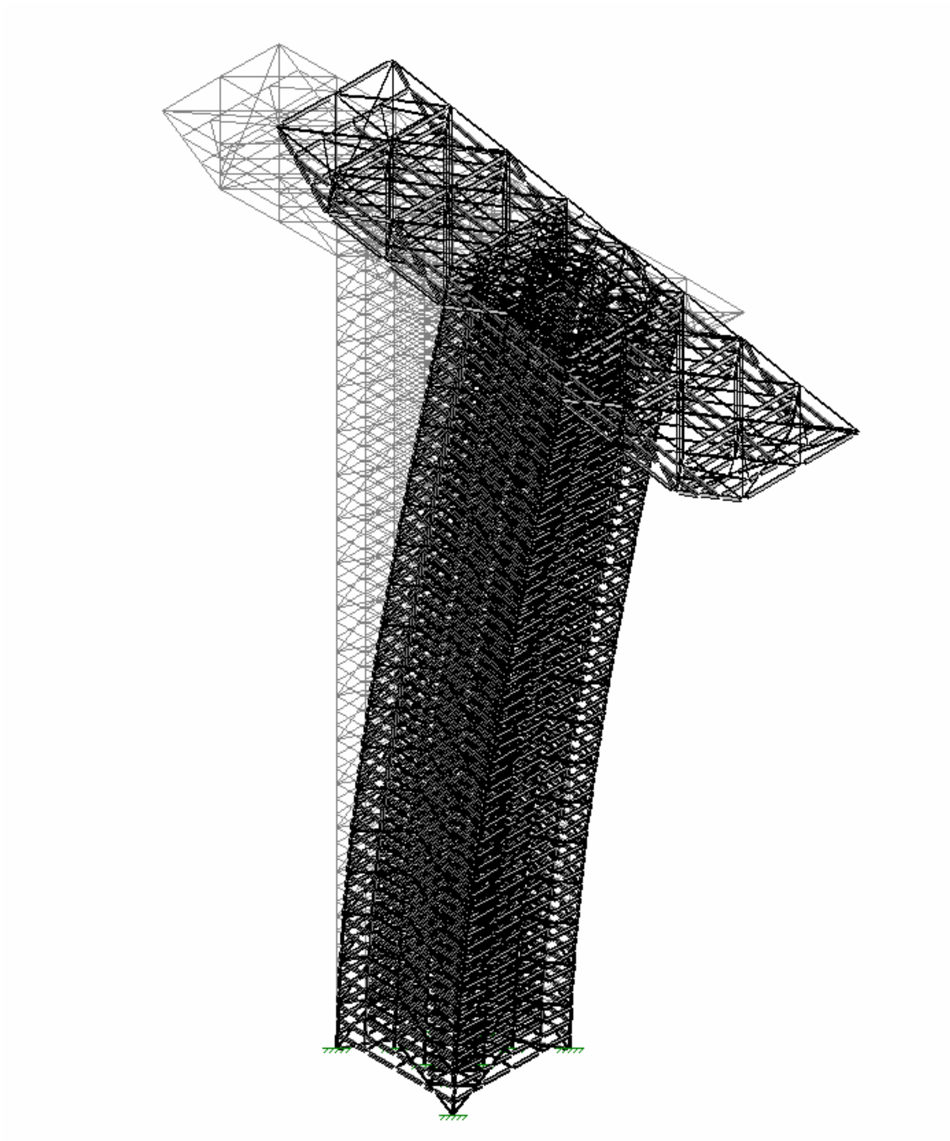

Figure 22. Second mode of the structure

For the second mode, the period of the structure is 4.599 seconds, similar to the first mode but the tower sways from left to right.

3.6.1.3. Third mode

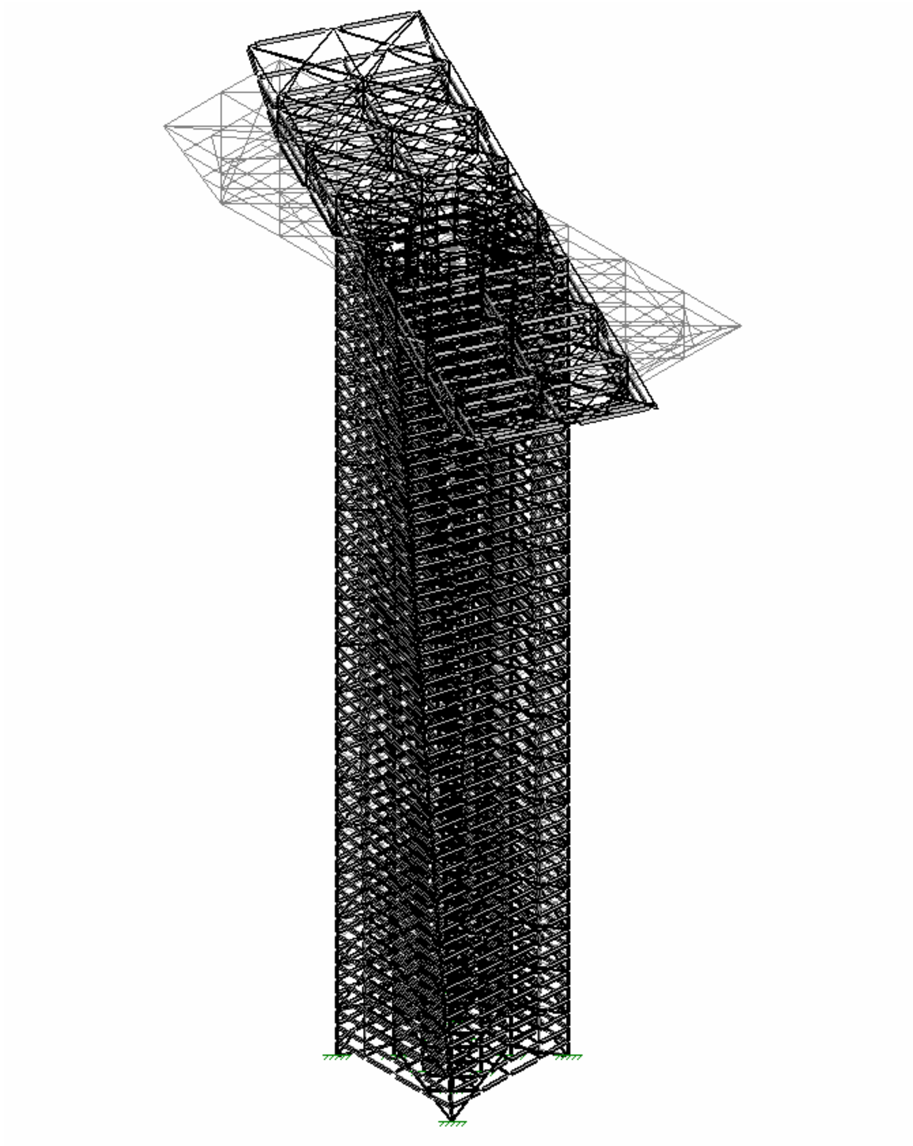

Figure 23. Third mode of the structure.

For the third mode, the period of the structure is 3.33 seconds, it is a torsional mode twisting around the vertical axis of the structure.

3.6.2. Results for the building with the top structure rotated 22.5 degrees

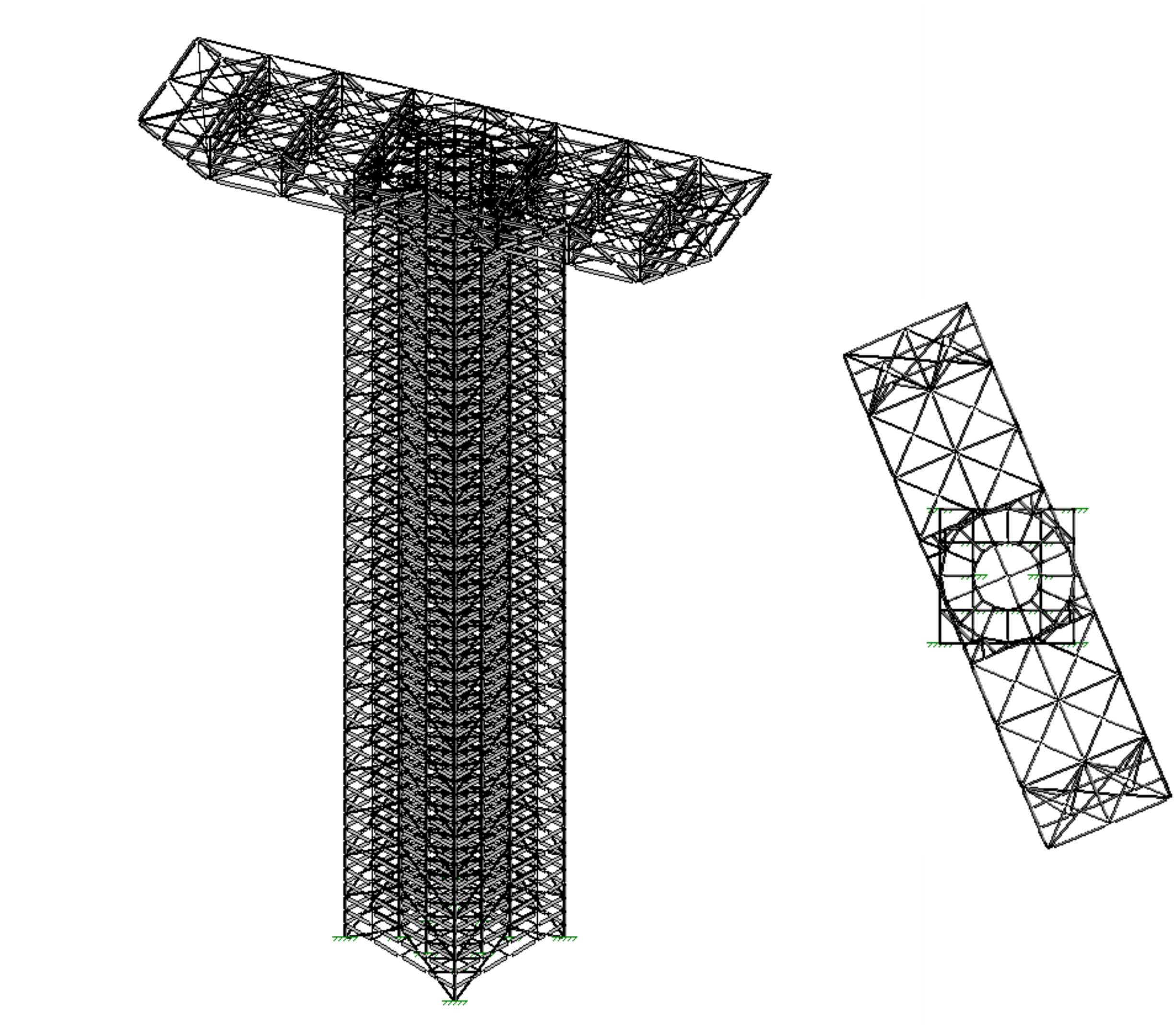

Figure 24. Isometric and top view of the building rotated 22.5 degrees from its original position.

Mode	Period (s)
1	4.751
2	4.667
3	3.348
4	1.061
5	0.994
6	0.622
7	0.555
8	0.477
9	0.448

Table 4. Mode and period values for the building with the top structure rotated 22.5 degrees.

3.6.3. Results for the building with the top structure rotated 45 degrees

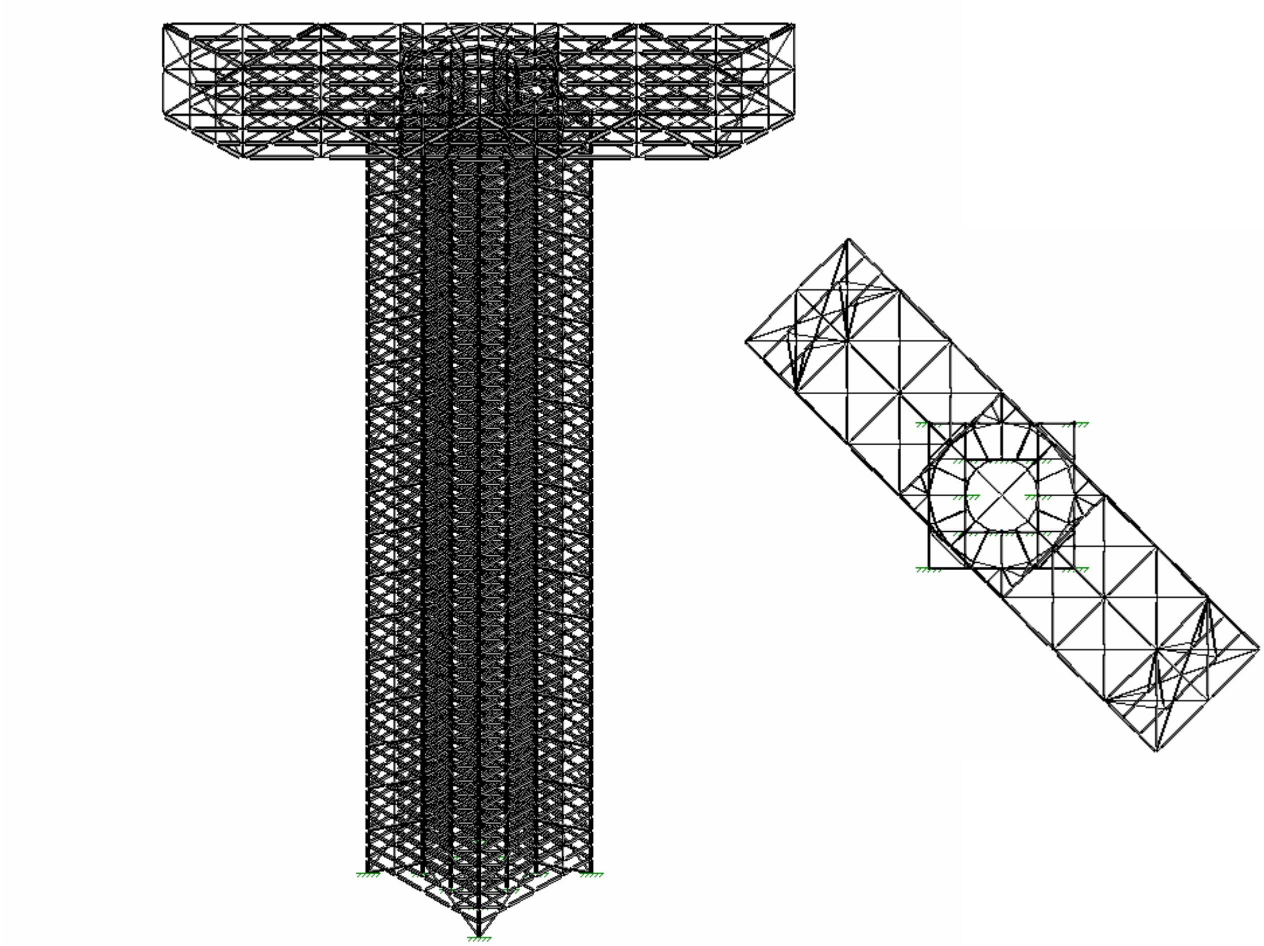

Figure 25. Isometric and top view of the building with the top structure rotated 45 degrees from its original position.

Mode	Period (s)
1	4.769
2	4.648
3	3.348
4	1.087
5	0.966
6	0.622
7	0.573
8	0.465
9	0.448

Table 5. Mode and period values for the building with the top structure rotated 45 degrees.

3.6.4. Results for the building with the top structure rotated 67.5 degrees

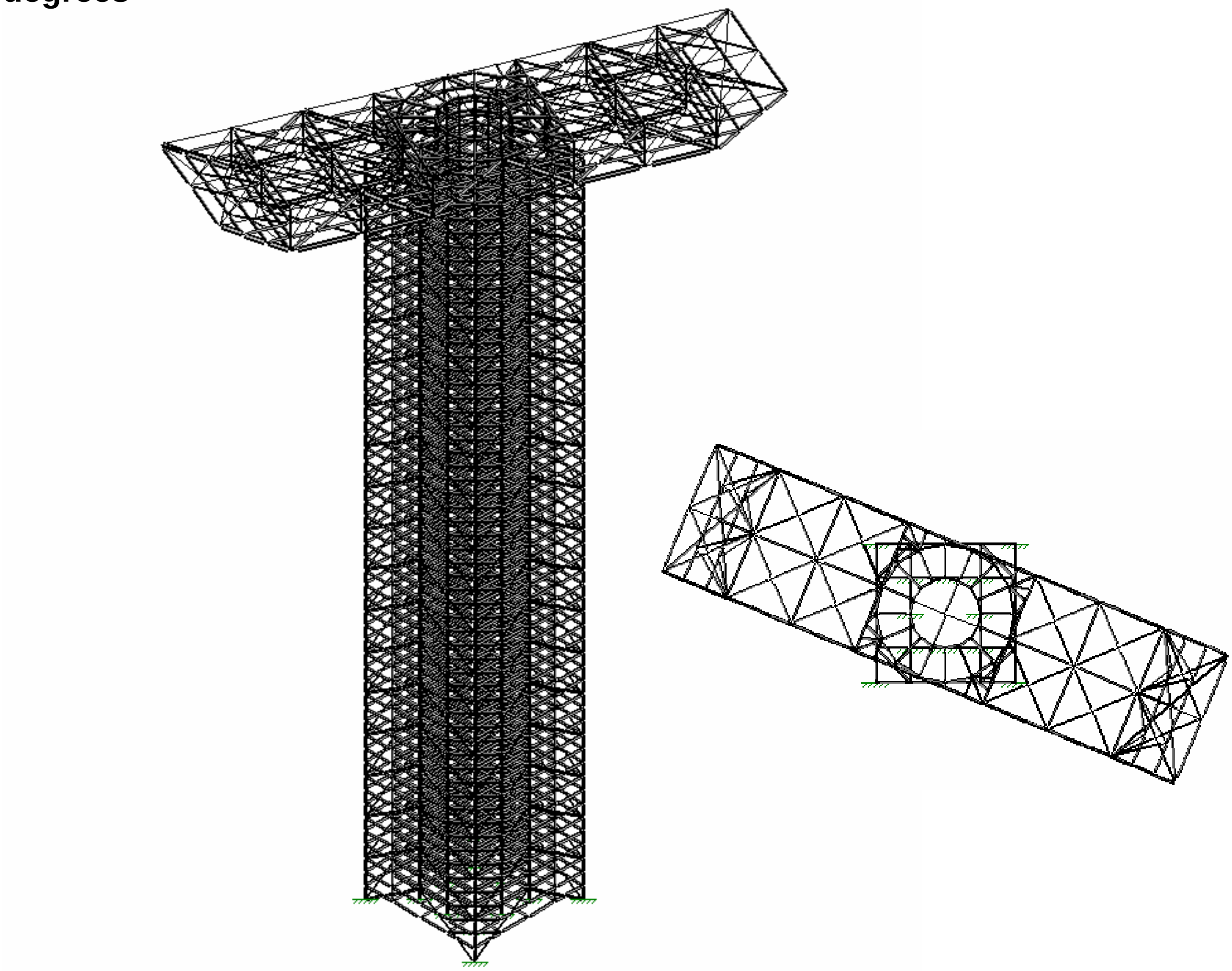

Figure 26. Isometric and top view of the building rotated 67.5 degrees from its original position.

Mode	Period (s)
1	4.786
2	4.636
3	3.369
4	1.107
5	0.949
6	0.631
7	0.594
8	0.464
9	0.459

Table 6. Mode and period values for the building with the top structure rotated 67.5 degrees.

3.6.5. Results for the building with the top structure rotated 90 degrees

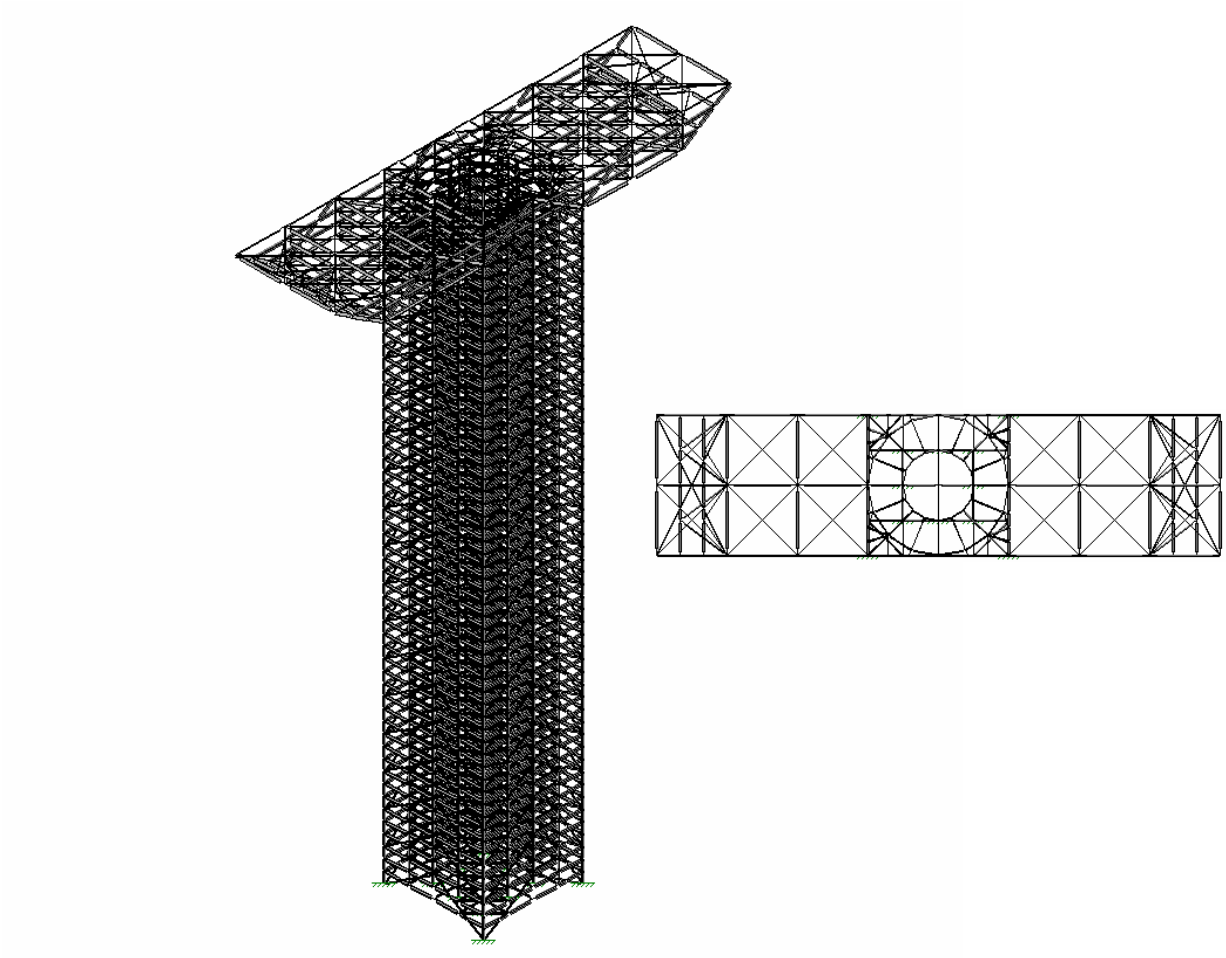

Figure 27. Isometric and top view of the building rotated 90 degrees from its original position.

Mode	Period (s)
1	4.706
2	4.548
3	3.333
4	1.106
5	0.935
6	0.622
7	0.582
8	0.440
9	0.438

Table 7. Mode and period values for the building with the top structure rotated 90 degrees.

3.6.6. Results for the building without the top structure

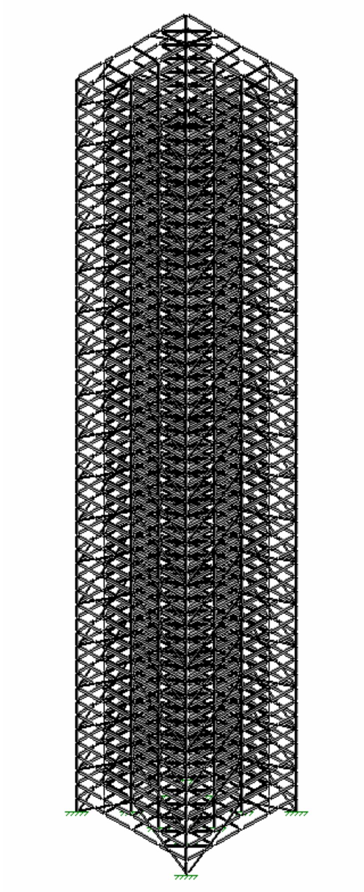

Figure 28. View of the building without the rotational structure on the top.

Removing the mass at the top, reduces the period since this factor is directly proportional to the mass.

$$T = 2\pi\sqrt{\frac{m}{k}}$$

Mode	Period (s)
1	2.840
2	2.745
3	1.279
4	0.785
5	0.721
6	0.426
7	0.388
8	0.351
9	0.311

Table 8. Mode and period values for the building without the top structure.

3.6.7. Dynamic Analysis Results Comparison

Mode	Period of the structure according to its rotation (seconds)				
	0°	22.5°	45°	67.5°	90°
1	4.661	4.751	4.769	4.786	4.706
2	4.599	4.667	4.648	4.636	4.548
3	3.333	3.348	3.348	3.369	3.333
4	1.034	1.061	1.087	1.107	1.106
5	1.015	0.994	0.966	0.949	0.935
6	0.622	0.622	0.622	0.631	0.622
7	0.540	0.555	0.573	0.594	0.582
8	0.482	0.477	0.465	0.464	0.440
9	0.440	0.448	0.448	0.459	0.438

Table 9. Period values of the structure depending on its rotational configuration.

As a rule of thumb, the period of the structure for the first mode can be said to be the number of stories of the building divided by 10. Since we have 59 stories, we would expect the period of the building to have a value of around 5 or 6 seconds. The periods obtained for the first mode are close to the value of 5 seconds.

It can be seen from the different analysis (Table 9), that the rotation of the top part of the structure does not affect considerably the period of the building. For example, for the first mode, the difference between a zero degree rotation (original position) to a rotation of 67.5 degrees only brings a difference in the period of 0.125 s, which is almost imperceptible. The other modes fall in this category of values, in which the differences are valued in decimals.

This means that the second assumption mentioned earlier in this chapter will be the valid criteria for the design of this building. The orientation of the top structure is not a critical factor in the design of the structure for the dynamic analysis; this is due to the nature of the connection of the rotational structure to the building. If the structure were rigidly connected to the building the stiffness would change and hence the period. The roller bearing on which the top structure is supported does not change the stiffness of the building.

3.7. Static load pattern in the roller bearing of the rotational structure

Table 10 presents (just with loads of the self weight of steel structure) the load pattern that is followed on the nodes marked with the arrows (Figure 29) every time that this structure rotates 22.5 degrees.

Rotation (degrees)	Load (N)
0.0	810375
22.5	575239
45.0	450730
67.5	637885
90.0	615195
112.5	637768
135.0	450720
157.5	575670
180.0	811748
202.5	575239
225.0	450730
247.5	637885
270.0	615195
292.5	637768
315.0	450720
337.5	575670
360.0	811748

Table 10. Load pattern in a particular node depending on the rotation of the structure.

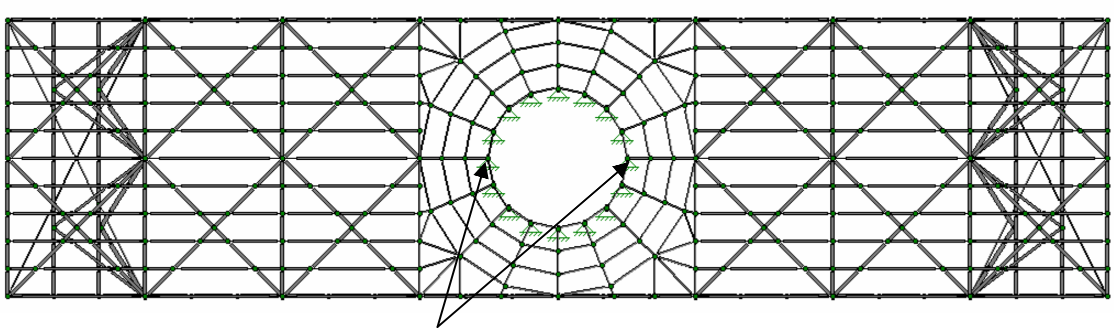

Figure 29. Top view of the cantilever, the green supports show concentrated loads on the roller bearing. The arrows show the supports that carry the bigger load according to this configuration.

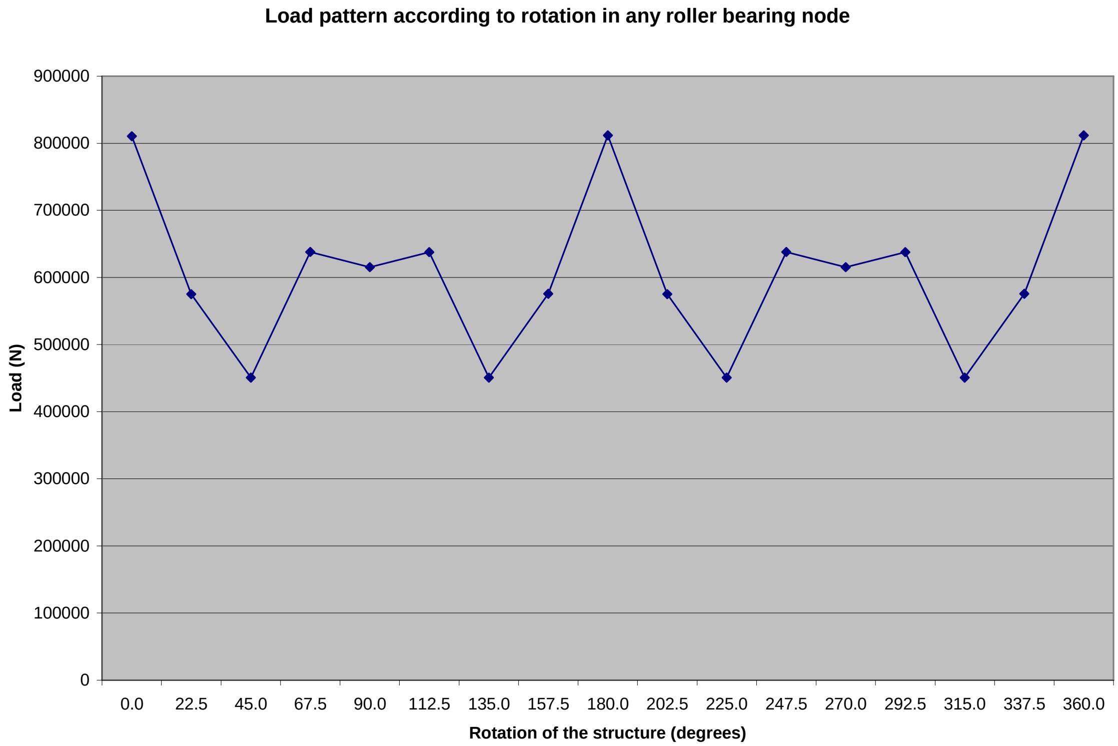

Figure 30. Representation of the load pattern of any node representing the roller bearing, depending on the rotation of the structure.

The pattern is repeated every 180 degrees, being the peak a load of 810,375 N. So in the case of static loads, this rotation does affect how loads are distributed in the structure. And the peak load will be the design load for every point in the rotation. For all the static loads, peaks will be the design patterns. So the function for the maximum static load would take a sinusoidal form in the way: $p = 810{,}375\sin(\pi t)$

3.8. Excitation of the rotational mode

The particular geometry of this tower involves some particular problems in the case of a seismic event. As seen before, the first and second modes (a period of 4.66 s and 4.59 s respectively) are very close to the rotational mode (period of 3.33 s), a difference of only 1.33 s. If a particular loading was concentrated in one extreme of the cantilever of the rotational structure (an office layout that might be heavy, a concentration of people due to an event, etc.), a coupling of the translational and rotational modes can occur which is very undesirable.

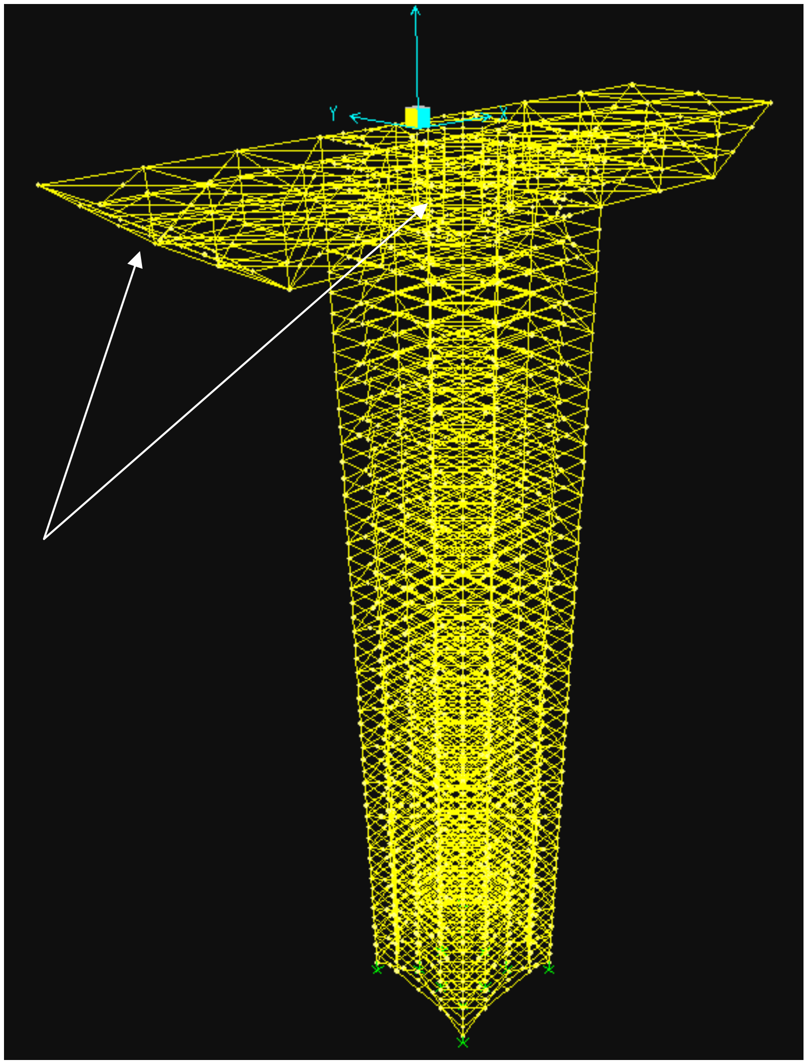

Figure 31. View of the structure modeled in SAP2000. The arrows indicate the joints were the periodic loads were applied.

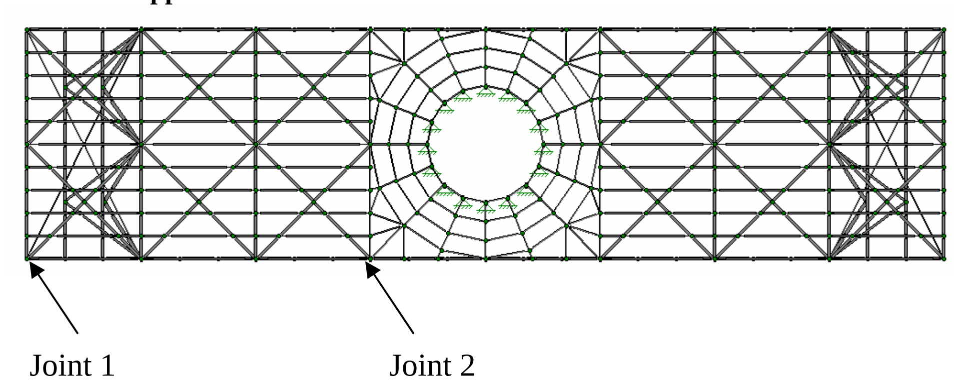

Figure 32. Top view of the building indicating Joint 1 (the joint at one extreme of the cantilever) and joint 2 (the joint close to the structure of the building.

To prove this particular effect, a simplification with a sinusoidal loading was made.

$$p = \hat{p} \sin w(t)$$

The period of the loading will be a number between the translational and rotational mode. Hence, we have:

Period of translational modes	4.66 s
Period of rotational mode	3.33 s
Δ	1.33 s

Dividing the difference over 2, and either adding this number to the rotational mode or subtracting it from the translational mode we get the period for the excitation we want.

Period of sinusoidal function = 3.33 + (1.33/2) = 3.995 s $\approx$ 4.00 s

$$w = \frac{2\pi}{T} = \frac{2\pi}{4s} = 1.57 rad / s$$

An Excel table was made (Appendix 3) to plot this sinusoidal loading function (Figure 33).

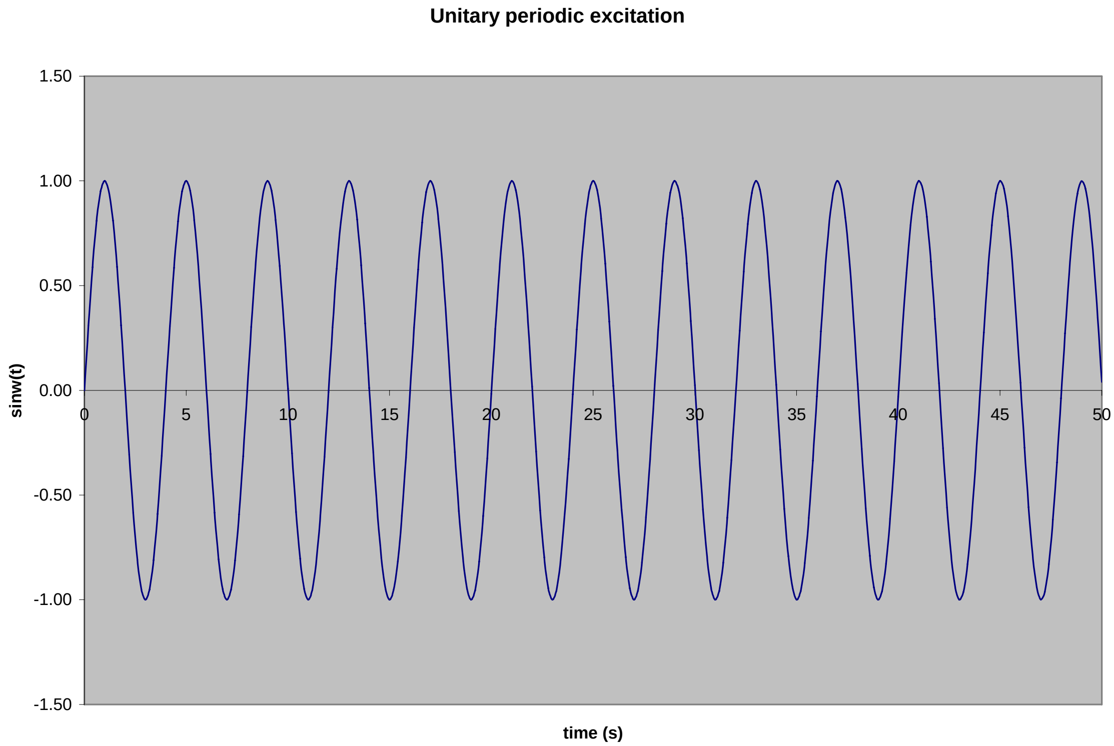

Figure 33. Plot of the unitary periodic excitation.

The values for the sinusoidal function were introduced in the program SAP2000 (Figure 34) to get a time history analysis of the building (for which the program RISA 3D was not suitable).

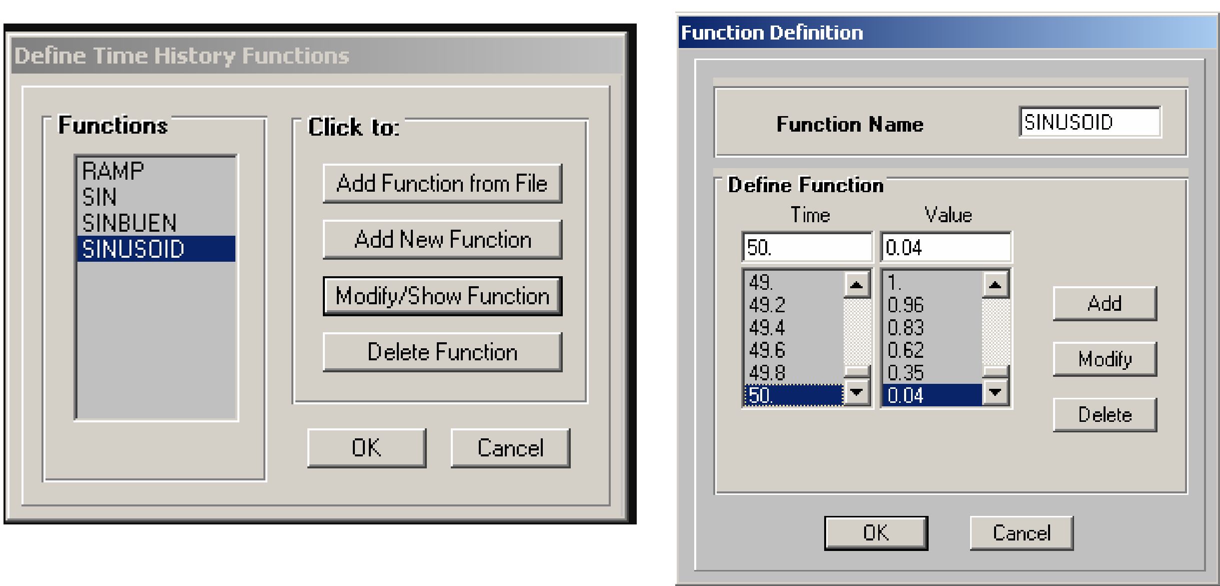

Figure 34. Input of the values for the sinusoidal function in SAP2000.

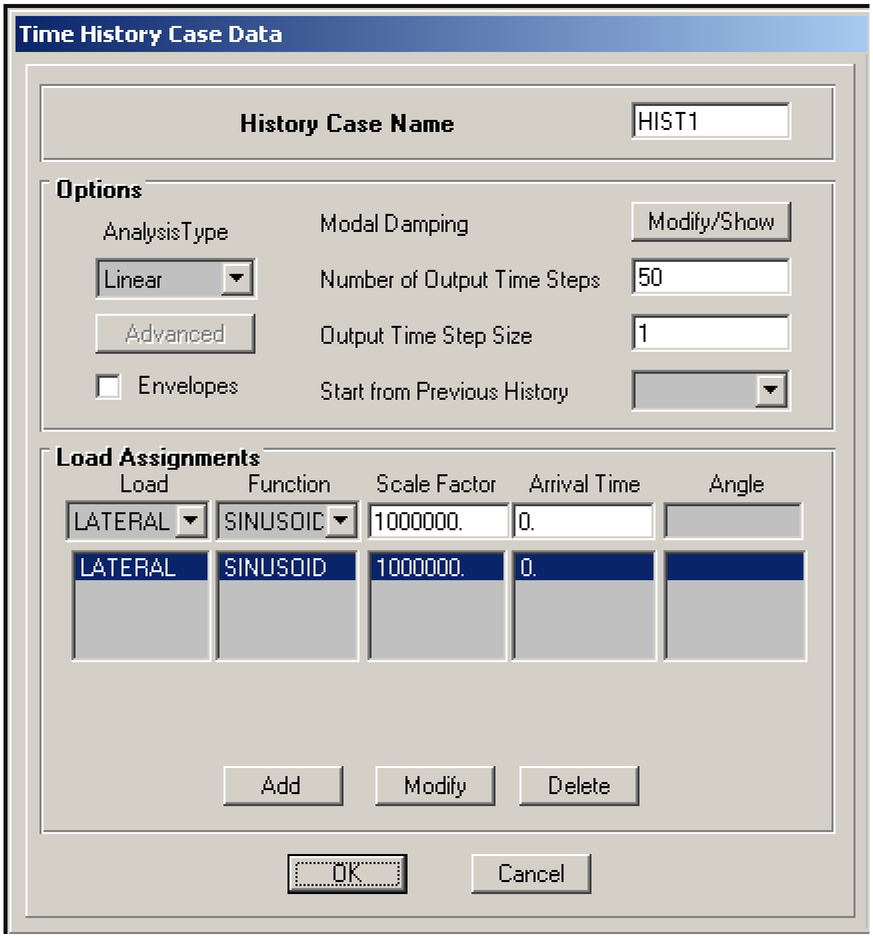

Figure 35. Input of the Time History Case Data in SAP2000, as can be seen the value of   in our function can be introduced in the Scale Factor lot in the program.

Applying this periodic excitation force in one extreme of the cantilever we can plot the displacement in time of a particular node. As can be seen in Figure 36 this force excites the rotational mode which generates a maximum displacement of 0.83 m.

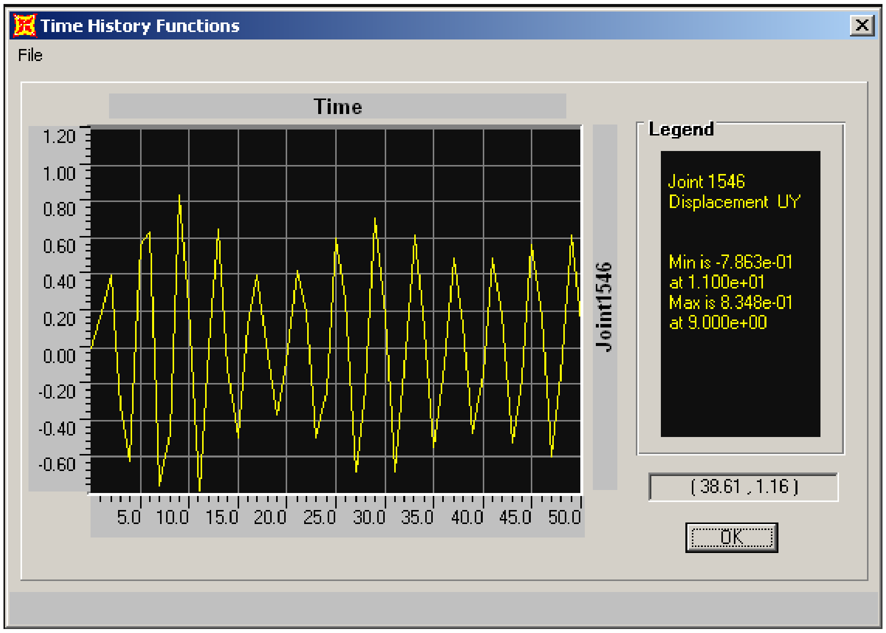

Figure 36. Displacement of joint 1 due to the periodic excitation in that same joint.

Though when we apply the same loading in a point close to where the cantilever begins, the rotational mode is not excited, a maximum displacement of 0.25 m is achieved at the beginning of the response but then the response decreases considerably, though it continues being periodic due to the loading pattern (Figure 37).

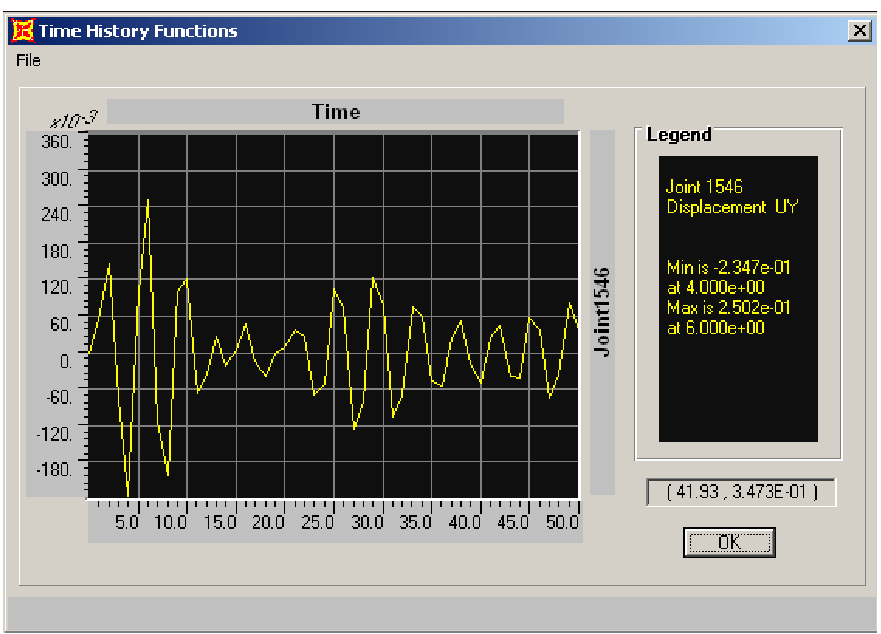

Figure 37. Displacement of joint 1 due to an excitation in joint 2.

4. Conclusions

The design of dynamic buildings faces many challenges due to the changing geometries of the structure. This thesis addresses some of the most critical aspects that have to be considered in the design of this type of structures.

Even though the cantilevered structure at the top decreases the structural efficiency, it is an interesting piece of Architecture that undoubtedly catches the human attention. It was demonstrated that the rotation of the top structure doesn't change the stiffness of the whole building, maintaining a similar dynamic behavior and simplifying the design considerations from a seismic approach.

The design has some challenges, such as assessing the most appropriate distributions, whether in stiffness or damping, that would avoid a coupling of translational and rotational modes.

An interesting design strategy would be the implementation of a tuned mass damper, acknowledging that we have an enormous cantilever to each side of the building. The range of displacement of the mass for this tuned mass damper would be so big that it could effectively counter balance the motion of the building using a small mass.

5. References

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[12] Fisher, David H., Rotatable Building Structure, United States Patent Application Publication No. US 2006 / 0230691 A1, October 19, 2006

Appendix 1. Patent publication by David Fisher.

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(43) Pub. Date: Oct. 19, 2006

Fisher

(54) ROTATABLE BUILDING STRUCTURE

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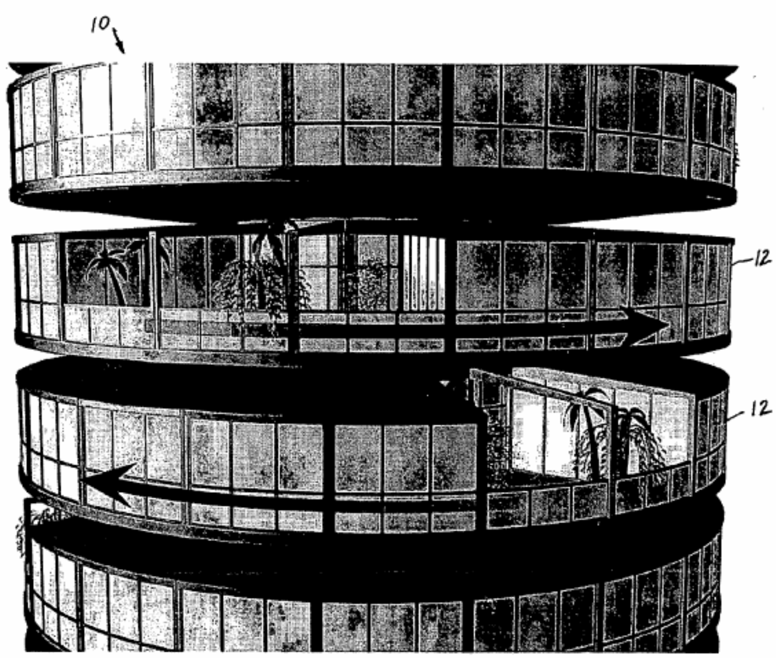
(57) ABSTRACT

A rotatable building structure contains a vertical central core for supporting suspended floor units surrounding the core. An annular platform extends from the core at corresponding floor units for providing accessibility to and from the central core. The floor units contain a drive mechanism for rotational displacement. A wind tool deployable from the floor unit provides alternative wind power assist for rotating the floor units.



ROTATABLE BUILDING STRUCTURE

CROSS-REFERENCE TO DISCLOSURE DOCUMENT

[0001] A disclosure document entitled Building with Independently Rotatable Suspended Floor Structure (Turning Tower) filed Dec. 2, 2004 as Disclosure Document No. 565968 is referred to herein and incorporated by reference.

CONTEXT OF THE INVENTION

[0002] 1. Field of the Invention

[0003] This invention relates to static structures and especially to a structure mounted for in situ repositioning.

[0004] In particular, the structure of this invention concerns a building having floor units that are rotatable about a vertical axis.

[0005] 2. Background Information

[0006] The ability of an apartment to command a desirable view is a recognizable factor in determining the salability and economic value of the apartment. However, most buildings have only a limited number of apartments with highly desirable exposures. A solution to this problem is to provide a changeable environment by in situ repositioning of the building. Typically, repositionable building structures were designed with an outer casing rotatably mounted on a spindle; the structures were used principally for observation towers, amusement devices, and/or restaurants for providing patrons with changeable views and not for apartment, hotel and similar dwellings; examples of such structures are shown in U.S. Pat. Nos. 3,905,166, 6,742,308, and 841,468.

[0007] A limitation of these structures is that they are not intended primarily for use as multi-story apartment buildings or hotels or for providing selective 360° viewing capability. Another shortcoming is that lack of floor independence decreases load stability.

BRIEF SUMMARY OF THE INVENTION

[0008] Briefly, the nature of this invention involves a building structure having a vertically disposed central core with plural horizontal floor units suspended from and surrounding the core at incremental heights for transferring balanced vertical loading through the core. An annular platform extending horizontally from the core, in correspondence with the floor units, provides a corridor for accessing the central core. The floor units are independently displaceable about the core, for example, by motor-power actuation, wind-power, electro-magnetic energy, or other drive force.

[0009] In view of the foregoing, it should be apparent that the present invention overcomes the limitations of the prior art and provides an improved rotatable building structure.

[0010] Having thus summarized the invention, it will be seen that it is an object thereof to provide a rotatable building structure of the general character described herein which is not subject to any of the aforementioned limitations.

[0011] Another object of this invention is to provide a rotatable building structure suitable for high-rise or low-rise buildings.

[0012] A further object of this invention is to provide a rotatable building structure with independently rotatable suspended floor units that provide improved seismic stability.

[0013] A still further object of this invention is to provide a rotatable building structure wherein the configuration of the floor units can optionally be varied in shape such that the profile of the building will continually change during rotation of the floor units.

[0014] Still another object of this invention is to provide a rotatable building structure including a stationary platform providing an accessway from the floor unit to the central core.

[0015] Yet another object of this invention is to provide a rotatable building structure having single or multiple vertical cores for supporting the floor units.

[0016] Still yet another object of this invention is to provide a rotatable building structure wherein displacement of the floor units are computer-controlled and actuatable on command.

[0017] Yet still a further object of this invention is to provide a rotatable building structure having prefabricated furnished floor units to facilitate erection and onsite installation.

[0018] Yet still another object of this invention is to provide a rotatable building structure with aerodynamically designed floor units that can be repositioned to reduce wind load, as in a hurricane.

[0019] Other objects of this invention will in part be apparent and in part will be pointed out hereinafter.

[0020] With these ends in view, the invention finds embodiment in certain combinations of elements and arrangements of parts by which the aforementioned objects and certain other objects are hereinafter attained, as more fully described with reference to the accompanying drawings and the scope of which is more particularly pointed out and indicated in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] In the accompanying drawings, in which are shown an exemplary embodiments of the invention:

[0022] **FIG. 1** is a perspective new illustrating a portion of a multi-story building in accordance with this invention having independently rotatable floor units surrounding a central core;

[0023] **FIG. 2** is a plan view of the rotatable building structure of this invention showing a central core, a platform projecting from the central core and the floor units;

[0024] **FIG. 3** is a perspective view of the rotatable building structure of this invention showing a floor unit suspended from the central core;

[0025] **FIG. 4** is a perspective view of the rotatable building structure of this invention detailing the attachment of the floor unit to a respective upper and a lower rail for supporting the floor unit;

[0026] **FIG. 5** is a sectional view of the rotatable building structure of this invention taken substantially along lines

5—5 of **FIG. 4** showing in detail the central core, the platform, the upper rail, the lower rail, and a motor drive for displacing the floor unit;

[0027] **FIG. 6** is an elevational view of an alternate embodiment of the rotatable building structure of this invention showing a floor unit with a wind tool in operational position for providing wind-power assist during rotational displacement of the floor unit around the central core;

[0028] **FIG. 7** is a schematic illustration of an alternate embodiment of the rotatable building structure of this invention showing a platform with a track for supporting a floor unit; and

[0029] **FIG. 8** is an elevational view of the rotatable building structure of this invention showing a variable building profile formed by a plurality of floor units mounted along a horizontal plane asymmetrically with respect to the central core.

DETAILED DESCRIPTION OF THE INVENTION

[0030] With specific reference now to the figures in detail, it is stressed that the particulars shown are by way of example and for the purposes of illustrative discussion of the preferred embodiments of the present invention only and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the invention. In this regard, no attempt has been made to show aspects of the invention in more detail than is necessary for a fundamental understanding of the invention, the description taken together with the drawings should make it apparent to those skilled in the art how the several forms of the invention may be embodied in practice.

[0031] Referring now in detail to **FIG. 1** of the drawings, there is shown a portion of a multi-level rotatable building structure **10** having an independently rotatable suspended floor unit **12**. It should be understood that the structure of this invention encompasses application to high-rise and/or low-rise buildings. The arrows are intended to show that each of several floor units **12** can rotate in opposite circular directions or optionally can rotate in the same circular direction. The floor units can also operate at different speeds.

[0032] Referring next to **FIG. 2**, there is shown in plan view of a central core **14**, preferably cylindrical in shape, and constructed of reinforced concrete, structural steel or equivalent materials. A platform **22** is attached to or formed integrally with the central core **14**. The core **14** is designed to support the total live and dead load of the floor units **12**. The floor units **12** surround the core **14** and provide for balanced load transfer to the core **14**. The floor units **12** can be nonuniform shapes and/or mounted asymmetrically with respect to the central core **14**, as for example, is shown in **FIG. 8**, with a counterweight applied to achieve balanced loading. It should be noted that this later arrangement of floor units **12** will provide a variable building profile during rotation. As will be further noted, the floor units **12** can be connected along a horizontal plane to form floor levels at incremental vertical heights along the central core **14** and are supported in cantilever fashion from the central core **14**. In the event of seismic loading, the free ends of the respective floor units **12** may be subjected to movement without resulting in stress fracture, as may be the case if the separate floor levels were interconnected.

[0033] The mechanical/electrical components such as an elevator shaft **16**, an emergency stairway **18**; HVAC, water supply systems, trash disposal, electrical power cables, and utilities, such as, telephone, computer, television, jointly designated **20**, are housed within the central core **14**. It should also be noted that the core **14** has an opening (not shown) to provide a passageway from the platform **22** to the interior of the core **14**, for example, for occupants to access the elevator shaft **16**.

[0034] As further noted in **FIG. 3**, in this preferred embodiment, the floor unit **12** is substantially a wedge-shaped, open-frame segment that is preferably fabricated of structural steel, aluminum, a combination of the above, however, other materials may be suitably utilized. A plurality of connected floor units **12** are designed to encircle the core **14** to provide a circular periphery. A roof member **21** and a floor member **23** are secured to the frame segment to form an enclosure. Note that a portion of the floor member **23** as shown in **FIG. 3** has been displaced to better illustrate the connection to the core **14**. The floor unit **12** also has a peripheral exterior curved boundary wall **24**, preferably made of a transparent material, for providing maximum visibility from within the floor unit **12** and an interior boundary wall (not shown) adjacent the platform **22** with an occupant passageway through the interior boundary wall for accessing the platform **22**.

[0035] Concerning next the securement of the floor units **20** to the central core **14**, there is provided an upper rail **26** and a lower rail **28**, as shown in **FIGS. 3, 4** and **5**, designed for supporting the floor unit **12**. With regard to rotational displacement of the floor unit **12**, a roller bearing **30** is mounted to a distal end of an arm **27** extending from the roof member **21**. The roller bearing **30** is adapted to ride within a raceway **32** defined by the upper rail **26**. A safety lock **34**, also extending from the arm **27**, is positionable below the raceway **32** for securing the roller bearing **30** in the raceway **32**. Another raceway **36** is defined in the lower rail **28** and is adapted to accommodating a drive wheel **38**. The drive wheel **38** is actuated by an electric motor **40** mechanically linked to the drive wheel **38** by a beveled gear arrangement **42** or by other drive force. The gear ratio can be designed to the operating specifications. The motor drive **40** can also be computer operated by command at selected speeds and directions for displacing the floor unit **12** in either a clockwise or counterclockwise direction.

[0036] Although the floor unit **12** has been described as defining a circular periphery surrounding the core **14**, alternative floor unit configurations e.g. square, ellipsoid, or non-symmetric shapes are within the scope of this invention, and will provide a continually changeable building profile during displacement. It should also be noted that the radial dimension of the floor units **12** can be varied, for example, from floor level to floor level, so as to create a variable building profile. Additionally, the exterior boundary wall **24** can be aerodynamically designed and selectively positionable for reducing wind load, especially during hurricanes.

[0037] It is also within the scope of this invention to employ prefabricated floor units **12**, with the respective unit containing factory-furnished interiors of an apartment, a hotel room, an office space, such as partition walls, floors, mechanical equipment, HVAC, plumbing connections, electrical connections, and the like.

[0038] In an alternate embodiment, wherein the same reference numerals have been used for designating corresponding parts of the previously described embodiment with the suffix "a", a floor unit **12***a* is connected to a central core **14***a* in a manner as described herein (see **FIG. 6**). In this embodiment, a wind tool **46** is shown deployed for providing a wind-power assist to the previously discussed motor drive. The wind tool **46** is comprised of a planar vane **48** hingedly connected to a spindle **50** mounted to a peripheral wall **24***a* of the floor unit **12***a*. The vane **48** can be remotely and/or directly actuated for deployment to an operational mode from a retracted mode housed within the floor unit **12***a*. A bar **52** provides a rotational limit stop to prevent further rotation of the vane **48** when in the fully deployed position. The wind tool **46** can alternatively be used for electrical power generation, for example, for recharging a backup battery system.

[0039] In a further alternate embodiment as shown in **FIG. 7** wherein the same reference numerals have been used for designating corresponding parts of the previously described embodiment with the suffix "b", a floor unit **12***b* is connected to a central core **14***b* by a tension cable or steel strut **26***b*. A slidable anchor bearing **30***b* is attached at a distal end of the strut **26***b*. The anchor bearing **30***b* is contained within a slot **32***b*. The slot **32***b* extends on a horizontal plane, around the circumference of the central core **14***b*. The strut **26***b* is designed to support the floor unit **12***b*. A modified platform **22***b* projects under a portion of the floor unit **26***b* to provide additional support thereto and further includes a roller bearing **38***b* mounted in a track (not shown) or equivalent slide means for permitting displacement of the floor unit **26***b* along the platform **22***b*.

[0040] It should further be apparent that since the independent floor units **12** at each floor level are each separated, for example, as noted in **FIG. 1**, any seismic force transmitted through the central core **14** would tend to be absorbed, in contrast to conventionally interconnected floors, and thus less likely to be subject the floor units **12** to stress failure. Also the aerodynamically designed and repositionable boundary wall **24** of the floor units **12** and the opening spacing between respective horizontal levels of floor units **12**, substantially reduce the wind load applied as compared to a conventional vertical wall structure.

[0041] It should thus be seen that there is provided a rotatable building structure which achieves the various objects of this invention and which is well adapted to meet conditions of practical use.

[0042] Since various possible embodiments might be made of the present invention or modifications might be made to the exemplary embodiments above set forth, it is to be understood that all materials shown and described in the accompanying drawings are to be interpreted as illustrative and not in a limiting sense.

Having thus described the invention, there is claimed as new and desired to be secured by Letters Patent:

1. A rotatable building structure comprising at least one central core, at least one floor unit attachable to said central core, said floor unit being adapted for rotatable displacement about the central core, an annular platform extending horizontally from the central core, said platform being accessible from the floor unit for providing passage to the central core.

2. A rotatable building structure as claimed in claim 1 wherein a plurality of floor units define a circular periphery about the central core.

3. A rotatable building structure as claimed in claim 2 comprising multiple levels of floor units, each level of floor units being independently displaceable.

4. A rotatable building structure as claimed in claim 1 wherein the annular platform provides accessibility to the floor units from the central core.

5. A rotatable building structure as claimed in claim 3 wherein the multiple levels of floor units are structurally separated for withstanding seismic loading.

6. A rotatable building structure as claimed in claim 1 wherein the central core includes an upper and a lower rail, said rails being adapted to suspendedly accommodate the floor unit, the floor unit further being displaceable along said rails.

7. A rotatable building structure as claimed in claim 1 wherein the floor units define a noncircular periphery about the central core for providing a changeable profile during rotational displacement.

8. A rotatable building structure as claimed in claim 1 wherein the floor units are rotatably displaceable by a drive-force.

9. A rotatable building structure as claimed in claim 1 wherein the floor units include a deployable wind vane for providing an auxiliary power source.

10. A rotatable building structure as claimed in claim 1 including multiple vertical cores.

11. A rotatable building structure comprising at least one vertical core, a plurality of floor units suspended from and surrounding the vertical core, said floor units being positionable at vertical increments along the core corresponding to floor levels, an annular platform fixedly connected to the vertical core, said platform corresponding to the respective floor units and being accessible from the floor units, said core further having a passageway from the platform to the interior of the core.

12. A rotatable building structure as claimed in claim 11 wherein the interior of the core contains at least one of an elevator shaft and a stairway.

13. A rotatable building structure as claimed in claim 12 wherein the floor units are suspended from at least one rail member mounted to the core and includes a roller bearing for cooperative interaction with the rail member for rotational displacement of the floor unit.

14. A rotatable building structure as claimed in claim 13 wherein the floor unit includes a drive mechanism for displacing the floor unit with respect to the core.

15. A rotatable building structure as claimed in claim 11 further including a wind tool deployable from the floor unit for providing a wind generated force.

16. A rotatable building structure as claimed in claim 11 wherein the platform extends below and partially supports the floor units.

17. A rotatable building structure as claimed in claim 16 wherein the interface between the platform and the floor unit includes slide means for permitting displacement of the floor unit along the platform.

18. A rotatable building structure as claimed in claim 11 wherein the floor units are connected along a horizontal plane with respect to the central core at selected heights along the central core.

19. A rotatable building structure as claimed in claim 11 wherein the floor units are mounted asymmetrically along a horizontal plane with respect to the central core.

20. A rotatable building structure as claimed in claim 11 wherein the floor units define a peripheral boundary wall, said wall being aerodynamically designed and selectively repositionable for reducing the effect of wind loads.

* * * * *

Appendix 2. Stiffness calibration

mass matrix	1166529	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	1166529	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	1166529	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	1166529	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	1166529	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	1166529	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	1166529	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	1166529	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	1166529	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	1166529	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	1166529	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	1166529	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	1166529	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	1166529	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1166529	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1166529	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1166529	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1166529	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1166529	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6702600

s matrix	0.05	-0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0.05	-0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0.05	-0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0.05	-0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0.05	-0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0.05	-0.05	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0.05	-0.05	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0.05	-0.05	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0.05	-0.05	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0.05	-0.05	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0.05	-0.05	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0.05	-0.05	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0.05	-0.05	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	-0.05	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	-0.05	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	-0.05	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	-0.05	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	-0.05	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	-0.05
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05

s matrix inv	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	0	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	0	0	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	0	0	0	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	0	0	0	0	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	20	20	20
	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	20	20
	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	20
	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20
	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20
	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20
	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20

sinv*mass	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	0	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	0	0	0	0	0	23330580	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23330580	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23330580	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23330580	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23330580	23330580	134052000
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23330580	134052000
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	134052000

Φ		k'	
	0.05		355692510
	0.10		354525981
	0.15		352192923
	0.20		348693336
	0.25		344027220
	0.30		338194575
	0.35		331195401
	0.40		323029698
	0.45		313697466
	0.50		303198705
	0.55		291533415
	0.60		278701596
	0.65		264703248
	0.70		249538371
	0.75		233206965
	0.80		215709030
	0.85		197044566
	0.90		177213573
	0.95		156216051
	1.00		134052000

Appendix 3. Values for the periodic excitation function inserted in SAP2000

t (s)	sin(wt)
0	0.00
0.2	0.31
0.4	0.59
0.6	0.81
0.8	0.95
1	1.00
1.2	0.95
1.4	0.81
1.6	0.59
1.8	0.31
2	0.00
2.2	-0.31
2.4	-0.59
2.6	-0.81
2.8	-0.95
3	-1.00
3.2	-0.95
3.4	-0.81
3.6	-0.59
3.8	-0.31
4	0.00
4.2	0.31
4.4	0.58
4.6	0.81
4.8	0.95
5	1.00
5.2	0.95
5.4	0.81
5.6	0.59
5.8	0.31
6	0.00
6.2	-0.30
6.4	-0.58
6.6	-0.81
6.8	-0.95
7	-1.00
7.2	-0.95
7.4	-0.81
7.6	-0.59
7.8	-0.31
8	-0.01
8.2	0.30
8.4	0.58
8.6	0.80
8.8	0.95
9	1.00
9.2	0.95
9.4	0.81
9.6	0.59
9.8	0.32

t (s)	sin(wt)
10	0.01
10.2	-0.30
10.4	-0.58
10.6	-0.80
10.8	-0.95
11	-1.00
11.2	-0.95
11.4	-0.81
11.6	-0.60
11.8	-0.32
12	-0.01
12.2	0.30
12.4	0.58
12.6	0.80
12.8	0.95
13	1.00
13.2	0.95
13.4	0.82
13.6	0.60
13.8	0.32
14	0.01
14.2	-0.30
14.4	-0.58
14.6	-0.80
14.8	-0.95
15	-1.00
15.2	-0.95
15.4	-0.82
15.6	-0.60
15.8	-0.32
16	-0.01
16.2	0.30
16.4	0.58
16.6	0.80
16.8	0.95
17	1.00
17.2	0.96
17.4	0.82
17.6	0.60
17.8	0.32
18	0.01
18.2	-0.30
18.4	-0.58
18.6	-0.80
18.8	-0.95
19	-1.00
19.2	-0.96
19.4	-0.82
19.6	-0.60
19.8	-0.32

t (s)	sin(wt)
20	-0.02
20.2	0.29
20.4	0.57
20.6	0.80
20.8	0.95
21	1.00
21.2	0.96
21.4	0.82
21.6	0.60
21.8	0.33
22	0.02
22.2	-0.29
22.4	-0.57
22.6	-0.80
22.8	-0.95
23	-1.00
23.2	-0.96
23.4	-0.82
23.6	-0.60
23.8	-0.33
24	-0.02
24.2	0.29
24.4	0.57
24.6	0.80
24.8	0.94
25	1.00
25.2	0.96
25.4	0.82
25.6	0.60
25.8	0.33
26	0.02
26.2	-0.29
26.4	-0.57
26.6	-0.80
26.8	-0.94
27	-1.00
27.2	-0.96
27.4	-0.82
27.6	-0.61
27.8	-0.33
28	-0.02
28.2	0.29
28.4	0.57
28.6	0.80
28.8	0.94
29	1.00
29.2	0.96
29.4	0.82
29.6	0.61
29.8	0.33

t (s)	sin(wt)
30	0.02
30.2	-0.29
30.4	-0.57
30.6	-0.79
30.8	-0.94
31	-1.00
31.2	-0.96
31.4	-0.82
31.6	-0.61
31.8	-0.33
32	-0.03
32.2	0.28
32.4	0.57
32.6	0.79
32.8	0.94
33	1.00
33.2	0.96
33.4	0.82
33.6	0.61
33.8	0.33
34	0.03
34.2	-0.28
34.4	-0.57
34.6	-0.79
34.8	-0.94
35	-1.00
35.2	-0.96
35.4	-0.83
35.6	-0.61
35.8	-0.34
36	-0.03
36.2	0.28
36.4	0.56
36.6	0.79
36.8	0.94
37	1.00
37.2	0.96
37.4	0.83
37.6	0.61
37.8	0.34
38	0.03
38.2	-0.28
38.4	-0.56
38.6	-0.79
38.8	-0.94
39	-1.00
39.2	-0.96
39.4	-0.83
39.6	-0.61
39.8	-0.34

t (s)	sin(wt)
40	-0.03
40.2	0.28
40.4	0.56
40.6	0.79
40.8	0.94
41	1.00
41.2	0.96
41.4	0.83
41.6	0.61
41.8	0.34
42	0.03
42.2	-0.28
42.4	-0.56
42.6	-0.79
42.8	-0.94
43	-1.00
43.2	-0.96
43.4	-0.83
43.6	-0.62
43.8	-0.34
44	-0.04
44.2	0.28
44.4	0.56
44.6	0.79
44.8	0.94
45	1.00
45.2	0.96
45.4	0.83
45.6	0.62
45.8	0.34
46	0.04
46.2	-0.27
46.4	-0.56
46.6	-0.79
46.8	-0.94
47	-1.00
47.2	-0.96
47.4	-0.83
47.6	-0.62
47.8	-0.34
48	-0.04
48.2	0.27
48.4	0.56
48.6	0.79
48.8	0.94
49	1.00
49.2	0.96
49.4	0.83
49.6	0.62
49.8	0.35
50	0.04