Title:	**Structural Challenges of Twisting Towers**
Authors:	Vincent DeSimone, Chairman, DeSimone Consulting Engineers Luis Ramirez, Senior Associate, DeSimone Consulting Engineers Abdul Mohammad, Project Manager, DeSimone Consulting Engineers
Subjects:	Building Case Study Building Materials/Products Structural Engineering
Keywords:	Belt Wall Composite Concrete Form Outriggers Structural Engineering
Publication Date:	2015
Original Publication:	Global Interchanges: Resurgence of the Skyscraper City
Paper Type:	1. Book chapter/Part chapter 2. Journal paper 3. **Conference proceeding** 4. Unpublished conference paper 5. Magazine article 6. Unpublished

Structural Challenges of Twisting Towers

Vincent DeSimone
Chairman

DeSimone Consulting Engineers,PLLC,
Miami, USA

Vincent J. DeSimone, the founder and chairman of DeSimone Consulting Engineers, is noted for his solutions to special structural problems. He is an innovative practitioner who emphasizes optimization and efficiency. Some of his projects include One Thousand Museum, Grove at Grand Bay, Four Seasons Hotel & Tower, Miami, The Cosmopolitan of Las Vegas, and Atlantis in Bahamas. Mr. DeSimone received his Bachelor of Science in Civil Engineering from Manhattan College and was awarded an Honorary Ph.D. for his 50 years of engineering contribution. In addition to his significant professional accomplishments, Mr. DeSimone continues to serve as an industry leader.

Luis Ramirez
Senior Associate

DeSimone Consulting Engineers,PLLC,
Miami, USA

Luis Ramirez joined DeSimone's Miami office in 2005 and is currently a Senior Associate. His experience includes high-rise structures, mixed-use, resorts, and healthcare projects. His technical expertise is matched by his ability to communicate within the design team to facilitate solutions that enable production of high quality construction documents. Luis' projects include One Thousand Museum, Grove at Grand Bay, Faena Arts Center, and the expansion of Seminole Hard Rock Hotel & Casino in Tampa. Luis received his Bachelor and Masters of Science degrees in Civil Engineering from Manhattan College.

Abdul Mohammad
Project Manager

DeSimone Consulting Engineers,PLLC,
Miami, USA

Abdul Mohammad joined DeSimone's Miami office in 2006 and is currently a Project Manager. His experience includes high-rise structures, mixed-use, hotels, and residential projects. Abdul' projects include One Thousand Museum, Grove at Grand Bay, The Mint, Eden Roc Hotel and The Glass. Abdul received his Bachelor of Engineering degree in Civil Engineering from Osmania University and Master of Science in Civil Engineering from Florida International University.

Abstract

This paper investigates challenges of designing buildings to accommodate challenging twisting architecture. The foremost challenge is to resist the torsion generated due to twisting geometry Grove at Grand Bay feature two towers rising 20 stories while rotating a total of 38 degrees. The true twisting nature of the columns posed a number of structural challenges that demanded innovative solutions. The horizontal component of the gravity load in the columns is resolved in the slabs then transferring it to core shear walls, which are the only consistently vertical structural elements in the building. To minimize the torsion on the building a "hat truss" was introduced at the roof. The hat truss collects superimposed dead load and live load delivering the "suspended" loads directly to the core as a vertical load component. The torsion caused by the remaining gravity load is resisted by a composite concrete shear wall and link beam system.

Keywords: Belt Wall; Composite; Concrete; Form; Outriggers; Structural Engineering

Introduction

In today's competitive residential marketplace, structural engineers and architects are increasingly challenged to create projects that stand out from other contemporary designs while offering developers an edge in attracting buyers at premium prices. This is perhaps even more important for building sites that cannot alone demand high sales prices with an oceanfront location. South Florida is in the midst of a development boom and the competition between developers is greater now than ever. With virtually all of the major beachfront sites in Miami-Dade spoken for, developers are now pursuing urban sites that must allure buyers with something other than a view of the ocean. For the most part, this means striking and exceptional architectural designs coupled with a plethora of luxurious amenities.

Enhanced computer modeling capability is now a commonplace in our profession enabling architects to formulate three-dimensional images that often appear to defy gravity. For structural engineers, the challenge is to capture the architect's vision and introduce a compatible structure to achieve the, "How did they do that look?" which makes these extreme designs viable in the real world.

The Grove at Grand Bay, the first truly twisting buildings in the United States, is used here as a case study in defying structural conventions.

The Grove at Grand Bay is an iconic residential project located at the former site of the Grand Bay Hotel in Miami, Florida. Bjarke Ingels Group's (BIG) residential tower designs are part of The Terra Group's greater Coconut Grove development, which includes the transformation of the waterfront

Figure 1. Project Rendering (Source: Bjark Ingel Group)

area with the realization of a mid-rise residential living program designed by OMA. The Grove at Grand Bay features two similar towers rising 22 stories above a lushly landscaped on a two-story podium. The two towers are low density with only 98 spacious custom homes combined in the two towers featuring 12-foot high ceilings and 14-foot deep balconies. In order to capture the full panoramic views of Biscayne Bay and the Miami skyline from both buildings, the architect rotated the buildings incrementally along the height for a total rotation of 38 degrees (See Figures 1 and 2). The twisting of the buildings also allows them to be side by side, as opposed to front to back, at the upper floors. This permits premium views for the most expensive units in the towers.

Site constraints required a square footprint for the lower levels of the south tower. The floor plate increases in length as the building twists maximizing the sellable area. The north tower footprint remains a constant rectangle throughout its height. When completed, these towers will be the first LEED Gold Certified high-rise residential buildings in Miami-Dade County.

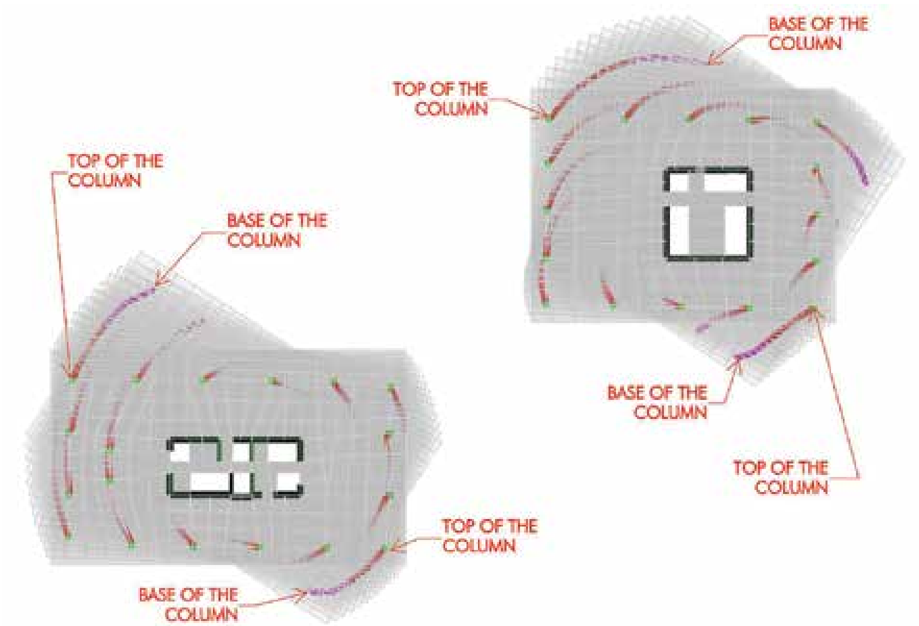

Figure 3. Sloping Columns (Source: DeSimone Consulting Engineers, PLLC)

Structural Engineering Challenges

In residential buildings, it is ideal to have the columns at the same location at each floor. This is to try to limit the number of different units throughout the building. The common practice is to design an efficient floor plate and repeat it for most of the building height saving a few upper floors for special penthouse units. This was not possible in the Grove at Grand Bay.


Figure 1. Structural Revit Model (Source: DeSimone Consulting Engineers, PLLC)

The Grove at Grand Bay floor plates rotate by approximately three degrees in plan relative to the floor below until the upper five floors that are vertically stacked. All of the columns follow the slab rotation such that they slope in two planes (See Figure 3). This sloping geometry creates horizontal forces at each level that are components of the axial load in the column. With all columns sloping in the same general direction, the forces of gravity create a twisting force that unrestrained would cause the building to come spinning down to the ground. Structural stability is provided when the horizontal component of the gravity load in the columns is resolved into the floor slabs and then to the central core shear walls, which are the only consistently vertical structural elements in the building.

The foremost challenge was to find a cost-effective solution to resist the large torsional forces while at the same time impose minimal impact on the unit layouts. The architectural design called for open, spacious, and unobstructed floorplans. To accomplish this with the true twisting nature of the building, a fresh, innovative approach was necessary. Initial studies of the central core composition were conducted utilizing conventionally reinforced concrete shear walls. The magnitude of the combined horizontal shear force from the building self-weight and the lateral wind loads required heavily reinforced concrete shear walls of up to 6 feet thick (See Tables 1 and 2). This core wall thickness was predictably met with a large cry of resistance from the architect and developer. However, it was a solution and the next task was to refine this solution.

Figure 4. Aerial view of composite shear wall cores (Source: DeSimone Consulting Engineers, PLLC)

Figure 5. View of the steel plates within composite core (Source: DeSimone Consulting Engineers, PLLC)

In order to regain valuable sellable real estate, a composite concrete shear wall and link beam system was introduced. The composite action between steel and concrete allowed a substantial wall thickness reduction to 30 inches (See Figures 4 and 5).

This solution included the use of 12,000 psi concrete in the walls and columns from the pile caps up through the 10th floor. Concrete strength was incremented down to 10,000 and then to 8,000 psi in the upper levels. Concrete produced with South Florida sourced aggregate will not provide the full modulus of elasticity specified in the ACI code. The actual values for 12,000 psi concrete are approximately 80 percent of the ACI code value. This reduction was detrimental to the building performance. Use of granite aggregate imported from Nova Scotia was required. Oddly enough, the Nova Scotia granite aggregate was less expensive than granite aggregate sourced from the Carolinas due to transportation costs – it arrived via barge rather than the costlier truck and rail.

Internal steel plates with thicknesses of up to 3.75 inches were required to achieve the overall reduced wall thickness. Rolled steel sections replaced traditional reinforcing steel in the boundary element zones. The steel plates extend vertically from the pile caps for 10 floors for the full perimeter of the central core. Steel plates in the short walls at the end of the cores continued up to the 15th floor with conventional reinforcing steel continuing up to the roof levels. The initial concept for the internal plate connections was to employ a bolted connection between plates as well as onto boundary elements. In the end, the contractor chose to stitch the plates together with welded connections.

The economic gain of the wall thickness reduction compared to the steel plate cost was great. The area gained back per floor was 850 square feet totaling approximately 16,150 square feet for both towers. Since there are no internal circulation corridors with the private elevator configuration, each square foot of area around the core perimeter was returned into the sellable area tabulation. Based on an average selling price of $1,200 per square foot, this translates

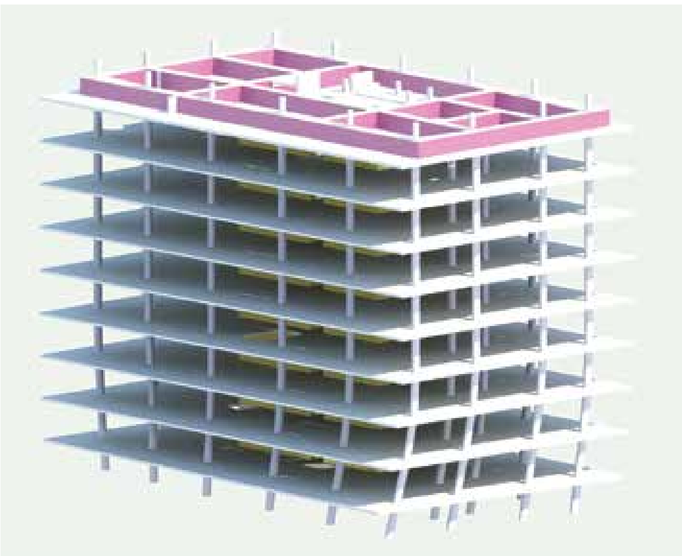

Figure 6. Revit model with Roof Girder system (Source: DeSimone Consulting Engineers, PLLC)

Figure 7. Roof girders highlighted (Source: DeSimone Consulting Engineers, PLLC)

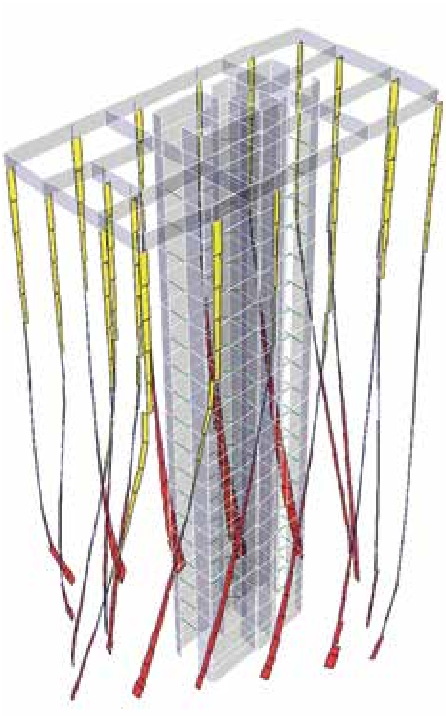

Figure 8. Yellow depicts the tension in the upper columns (Source: DeSimone Consulting Engineers, PLLC)

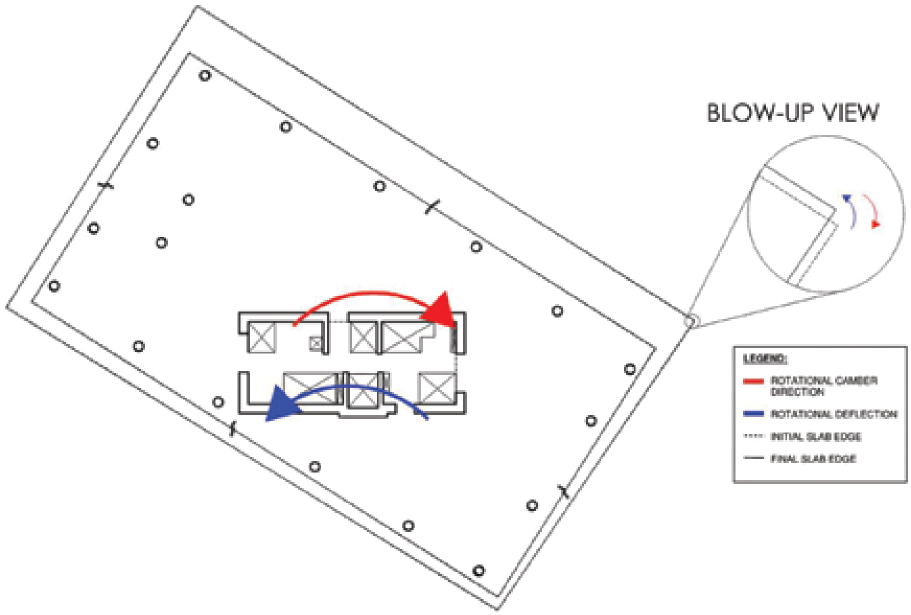

Figure 9. Rotational Camber (Source: DeSimone Consulting Engineers, PLLC)

into a sales volume increase of $19.4 million. The premium for using composite walls was approximately $6 million, which does not include the savings in conventional reinforcement that was replaced by the steel plates and W-sections. Therefore, the net gain of $13.4 million was well received.

Can the Torsion be Reduced?

Use of the internal steel plates, however, was not the complete solution. The composite structure could not take all of the superimposed loads into the core walls. There was too much torsional load to resist with a core wall limited in thickness and a reasonable quantity of steel plate reinforcing. If the superimposed gravity load could be reduced from being conventionally gathered at the columns, then there would be a way to reduce the torsional force in the core.

A roof truss system was envisaged that would be supported from the central core reaching out to connect with the top of the tower columns. With load collected in this manner, it would transfer to the core as a concentric load. A series of girders were introduced to the roof level framing. These girders cantilever from the central core and connect to the perimeter columns (See Figures 6 & 7). The girders relieve large portions of the superimposed dead load and live load from the columns. This approach causes the uppermost nine levels of columns to have a net tension force once the girders are installed (See Figure 8). The "suspended" loads are transferred directly to the core as a vertical load component. The girders were initially designed using built-up plate girders consisting of ASTM A514 90 ksi steel welded plates. After discussion with potential contractors, it was suggested that bonded post-tensioned concrete girders should be considered. With the use of post-tensioning, the girder dimensions were minimized to 4 feet wide by 7 feet deep. The more heavily loaded girders required as many as 114, 5/8-inch diameter high strength bonded post-tensioned cables. This alternate load path reduced torsional forces in the core by approximately 30 percent. It should be noted that the magnitude of the resulting shear forces in the tower cores, due to the building self-weight, were considerably higher than those caused by the 700-year return period hurricane wind loads.

Arresting Movement

Building movement was yet another challenge to address, especially before the roof girder system was installed and loaded. A conventional linear analysis was performed and it was determined that there was considerable horizontal displacement of the floors with respect to one another due to self-weight alone. Therefore, an extensive analysis was conducted to determine accurate building movements using a nonlinear construction sequence approach found in the ETABS software. The relative movement between floors has much to do with the enclosing glazing system. The glazing system had to accommodate relatively small rotational movement about the vertical axis due to the initial loads and to the long-term effects of concrete creep. The issue is particularly pronounced at the corners of the building where the glazing units meet. A special closure piece was developed by the window manufacturer for the corner joints.

To compensate for the rotational displacement, tower floor plates are cambered rotationally as much as a half-inch (See Figure 9) relative to the floor below for 75% movement due to the building self-weight. This allows the tower to settle back to the design coordinates just before the hat truss reaches design strength. Use of steel plates for strength in the lower levels also helped to control the building rotation due to long-term concrete creep.

Geotechnical Issues

Based on the geotechnical studies, it was determined that due to existing subsurface conditions at the site, traditional shallow foundations would not have the capacity to support the heavily loaded 22-story towers. Various ground improvement techniques were studied, such as vibro-compaction and vibro-replacement (also referred to as stone columns) to densify the subsurface soil. However, preliminary cost analysis indicated that shallow foundations made possible by ground improvement are not as cost-effective as relatively high capacity pile foundations with small pile caps. In the South Florida area, pressure-injected auger-cast piles have proven to be the most cost-

Figure 10. North tower core pile cap being laid out (Source: DeSimone Consulting Engineers, PLLC)

effective foundation solutions for medium to high-rise structures when compared against shallow foundations or drilled shafts. Based on the structural loading and the subsurface conditions at the site, medium length auger-cast piles were selected for the towers consisting of 30-inch diameter units, ranging in length from 50 to 80 feet, and with an 800-ton compression capacity. The torsional force in the core walls had to be resolved at the foundation level. While these were significant forces, the governing load case was gravity and overturning moment.

Dewatering of the site was known to be a challenge upfront. The design team was tasked to minimize the depth of tower foundations. The central core of each tower is founded on a 7′-6″ thick concrete mat supported on 80 auger-cast piles (See Figure 10). In order to achieve this thickness, grade 100 ksi reinforcement was used for the top and bottom reinforcing mats. Additionally, a series of vertical reinforcing cages were distributed through the pile cap to resist the vertical shear.

The 3-story podium was initially supported on 16-inch diameter pile groups. As another cost-saving measure, a single larger 30-inch diameter pile with a cap poured monolithically with the basement slab was introduced. This reduced the cost of excavation and dewatering.

As is common in many of the coastal areas of Florida, this site is subject to flooding during tropical storm events. Portions of this site are located in a FEMA designated AE-12 flood zone. For insurance requirements, the entire basement slab was designed to a design flood elevation of +13.0 NGVD. This floodwater elevation generates a design uplift pressure of 710 pounds per square foot. To withstand this tremendous uplift pressure, a 15-inch thick post-tensioned hydrostatic slab was employed. This system was selected by the contractor as a way to reduce cost. It should be noted that this was the first time a post-tensioned hydrostatic basement slab was used in South Florida. There were several construction challenges related to the particular site conditions and logistical constraints.

Architectural Challenges

Sloping columns take up more space on a floor plan as compared to vertical columns. Rather than to trying to enclose the columns with vertical walls, the architect chose to make them an architectural feature within the units (See Figures 11 and 12). This is obviously a challenge when trying to furnish a residential unit, but one that unit owners have chosen to embrace. They do present a dramatic look within the units that is visible from the surrounding neighborhood as well.

To allow for maximum flexibility of the unit layouts, column-free interior spaces were provided. Resulting spans between the central core and perimeter columns ranged from 30 to 42 feet and balconies cantilevered up to 16 feet (See Figure 13). The columns were spaced along the perimeter of the building at approximately 35 feet on center and were typically 30 inches in diameter. An unconventional slab scheme was proposed consisting of an 8-foot wide, 16-inch

Figure 11. The architect has made the columns an architectural feature (Source: Bjark Ingel Group)

Figure 13. Large cantilevers allowing for outdoor living space (Source: DeSimone Consulting Engineers, PLLC)

thickened slab around the core to allow a 10-inch thick post-tensioned slab to span the remaining distance to the perimeter. This provided 12-foot clear floor to ceiling dimensions in the living spaces. This same scheme had successfully been used a few years earlier on the Four Seasons Miami Tower, which is currently the tallest building in Florida, standing at 789 feet.

The mechanical systems of the buildings were also a challenge. For one, the rotating floor plates cause slight variations in the unit types throughout the building. To maintain an efficient vertical distribution system, vertical shafts were located within or immediately adjacent to the central core, which avoided complicated and expensive offsetting of risers. Given the large loads in the central core and extent of internal steel plates, the structural engineer challenged the MEP engineers to limit the number of horizontal penetrations through the shear walls.

The podium posed its own challenges as well. The landscape architect envisioned a lush garden retreat with large native trees typical of the Coconut Grove area (See Figure 14). The podium slab was designed to accommodate 5 feet of soil. In the areas where fill depths of up to 8 feet were required, a lightweight expanded polystyrene fill was specified below the 5 feet of soil to reduce the load on the slabs.

Cost Conclusions

The South Florida residential market is currently leading the construction boom in the United States. As such, construction

Figure 12. Embracing the columns with the furniture layout (Source: Bjark Ingel Group)

costs have escalated in the last few years. The structural cost of a "typical" condominium in Miami in 2014-2015 is expected to range from $40 to $45 per square foot of built horizontal area. Compare this cost to the low $30's per square foot just two years ago in early 2013.

There are many buildings being designed and constructed in the South Florida region in this latest development wave. It is a very competitive environment for the developers who are all trying to attract the same type of buyer. In such a competitive environment, cookie-cutter architecture is unlikely to sell at desirable prices and developers are demanding their architects to create more technically challenging and unique designs. These designs are often coupled with unique and luxurious amenities in order to appeal to wealthy buyers from all over the world. At the Grove at Grand Bay just of portion of the amenities will comprise: five pools for all residents, including two on the rooftop (which created yet another specific engineering challenge); 1,700-square-foot wellness spa with private treatment rooms; children's playground and play area; residents' lounge; club room; curator-maintained art gallery; private elevator to each unit; as well as extensive support personnel: a full-time concierge; butler staff; and a private chef who creates a weekly menu, and whom is available for catered events.

However, there is a limit of what the market will pay and how much a developer is willing to spend. With the structural ingenuity used in the design of the Grove at Grand Bay, the premium for a twisting architectural design was limited to an additional 18% above traditional construction. It required a focused effort on behalf of the entire design and ownership team. Without extraordinary interdisciplinary work between the engineers, architects, and developers, the project would not be a success.

Figure 14. The lush landscaping creating a grove within "The Grove" (Source: Bjark Ingel Group)

The market responded to the project with great enthusiasm. The project quickly sold out in pre-construction sales. This happened despite the fact that 50 percent cash deposits were required at ground breaking with incremental additional cash deposits at subsequent construction milestones. The project is now topped off and is scheduled to be turned over to the developer in the fourth quarter of 2015 (See Figure 15).

The Details

Developer: Terra Group
Design Architect: Bjarke Ingels Group (BIG)
Executive Architect: Nichols Brosch Wurst Wolfe Architecture
Structural Engineer: DeSimone Consulting Engineers
Landscape Architect: Raymond Jungles Inc.
M/E/P Engineers: Hufsey Nicolaides Garcia Suarez, Associates, Inc.
Wind Engineering: RWDI Consulting Engineers
Geotechnical Engineering: Langan Engineering & Environmental Services, Inc.
Construction Manager: Facchina Construction of Florida

Figure 15. Final touches of the buildings (Source: DeSimone Consulting Engineers, PLLC)

Design Parameters

The gravity load resisting system is comprised of the post-tensioned reinforced concrete structural slab, which is poured monolithically with the shear walls and columns, and lastly transferred to the foundations. In general, the thickness of the slabs range between 10 inches and 12 inches, with concrete strengths not exceeding 12 ksi. Shear loads in the central core are higher than average due to the twisting geometry of the building.

The lateral load resisting system for the tower is comprised of a composite shear wall core. Shear wall and column concrete strength range from 8ksi to 12 ksi utilizing reinforcement steel as high as grade 75 #11 reinforcing bars and grade 50 steel plates.

Wind loads were found to govern the design of the building over earthquake loads as is typical in South Florida. Wind engineering services and loads were provided by RWDI.

The foundation system consists of two 7'-6" thick concrete mats comprised of more than 2,700 cubic yards of concrete supported 160, 30-inch diameter auger-cast piles. The top and bottom reinforcement within the mat is comprised of up to eight layers (four running in each direction) of grade 100 #11 reinforcing bars.