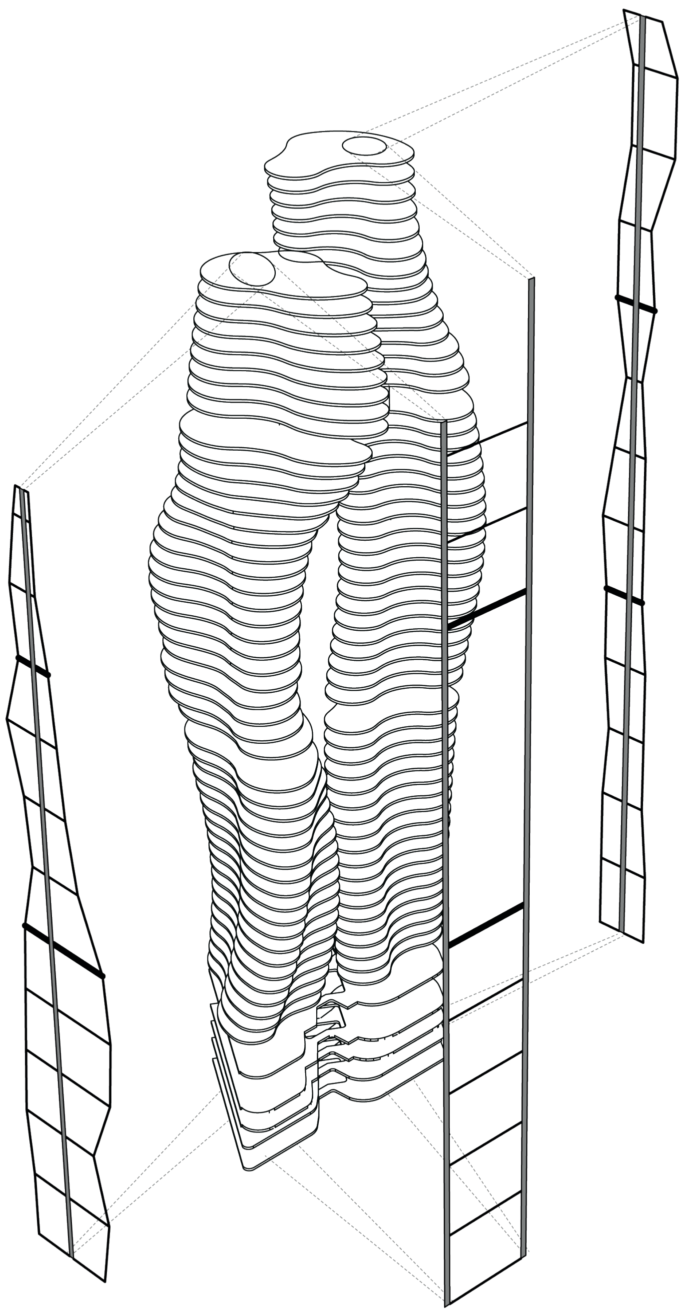
Design Collaboratory_**Advanced High Rise**

Analyses of High Rise Structures



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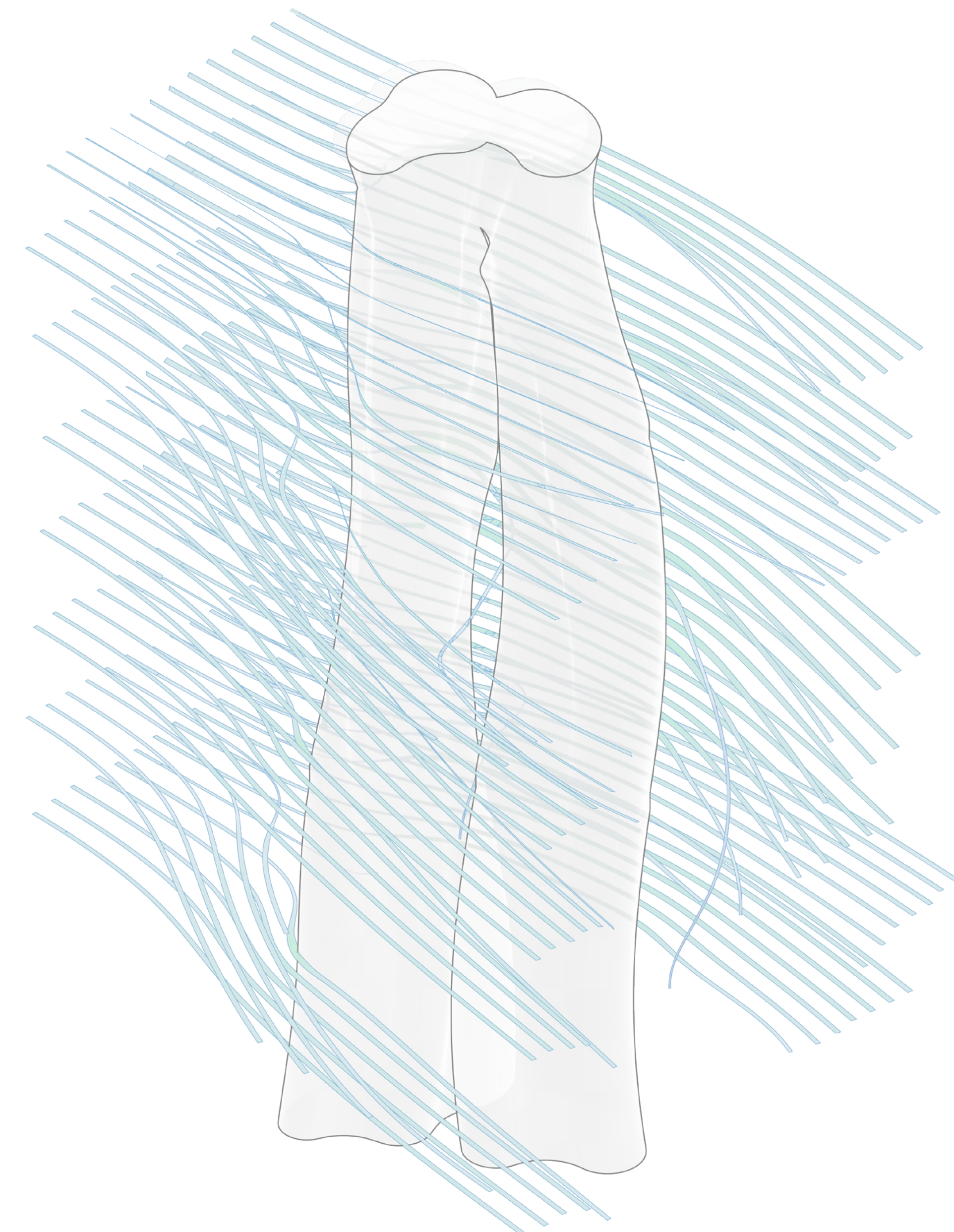

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1.0_Abstract

The design of a high rise tower involves many moving parts and is best done in collaboration with all construction disciplines. This report examines the basic steps and principles followed and discovered along the collaborative design process between Architectural and Architectural Engineering students of two high rise building systems. The report will look at physical model tests and digital model analyses. It will also follow the design of two high rise towers proposed for San Francisco, CA: The Crystal and the HOODOO. The tower design includes a study of possible lateral loading systems, a dual core and outrigger system analysis and the design of facade detail connections.

1.1

2.0_Introduction

Background

The Advanced High Rise Design Collaboratory is run in coordination with California State Polytechnic University, San Luis Obispo and the multi-disciplinary design firm Skidmore, Owings & Merrill (SOM). The 2020 interdisciplinary program included 35 students, ranging from 3rd year undergraduate to graduate level in Architecture and Architectural Engineering. Students were placed in teams of three to five and tasked to design a 700' high rise tower in San Francisco, CA.

This report will go through the varying analyses and considerations taken during the design of two of the proposed high rise towers. The studio was a 20-week session broken up into two parts. During the first 10 weeks, I took part as primary structural engineer in the concept design and form finding of The Crystal tower. In the second 10 weeks, I was brought on as the structural engineer to design a structural system for the HOODOO, a geometrically organic tower designed to respond to local wind patterns.

Process

In order to learn what is required of a high rise tower, architecturally and structurally, groups took to three primary methods of investigation. Intensive precedent cases were examined to understand what solutions other designers had found when scheming their towers. These precedent cases are only briefly mentioned in this report. After precedent cases, physical models were built to help visualize building responses and understand major building connections. These studies are summarized in this report in section 3.0. After the physical modes, digital models were run to understand simplifications and assumptions present when designing a high rise system. These studies are presented in section 4.0, providing a chronological progression of findings made during the course of this collaboration.

Tower Design

The Crystal and the HOODOO final designs are presented in sections 5.0 and 6.0, respectively. The Crystal design includes various structural systems considered as the tower's architecture evolved, as well as the final design as of week 10 of the collaboration. The HOODOO's architectural and structural features are shown and discussed, as well as the series of studies run to determine the efficacy of the chosen structural system. Additionally, section 10.0 contains the HOODOO presentation posters, summarizing the tower's structural and architectural systems, as well as the analyses run.

Student Experience

As this is a collaborative class and senior project, the findings of these studies are for educational purposes only. Sections 7.0 and 8.0 will discuss conclusions reached after the 20-week session and general experiences of the collaborative process, including the switch to a virtual platform in the second 10 weeks, due to the outbreak of Covid-19. The information is presented in chronological order, following the student process of trial and error and discussing misunderstandings that were solved through case studies or corrections that would be made next time such an experience presents itself.

Thank You

I would like to thank Professor Kevin Dong and Professor Thomas Fowler, for taking the time to not only offer this unique collaboration, but for taking so many hours and patience to teach us the basics of high rise design.

Additionally, a huge thank you to the everyone at Skidmore, Owings and Merril, who guided us in our design through several lectures and many, many hours of reviews and critiques.

A huge thank you to my architectural colleagues, who made this experience unforgettable.

3.0_Physical Studies **The Prologue**

For the first exercise of the collaborative studio, each student was tasked to design an 18" basswood structure, which would be able to maintain the weight of a standard American brick. Additionally, students were asked to ensure failure of the model within 3 lb of the standard brick, as an exercise of avoiding over designing.

This exercise was important to connecting our instinctual knowledge of structures to actual terminology. As towers were tested, students would guess failure modes and with 35 separate models, there was a very diverse array of tower typologies.

The most unexpected result of the prologue models was the strength of basswood. Of the 17 engineering students tasked with failure before an additional 3 lb, only 3 reached this goal. One tower even held 45 lbs past the brick and failed in instability of the bricks, rather than of the tower. It was a lesson in understanding the true strength of the materials we work with and the conservatism for which we inherently design.

Tower Dimensions

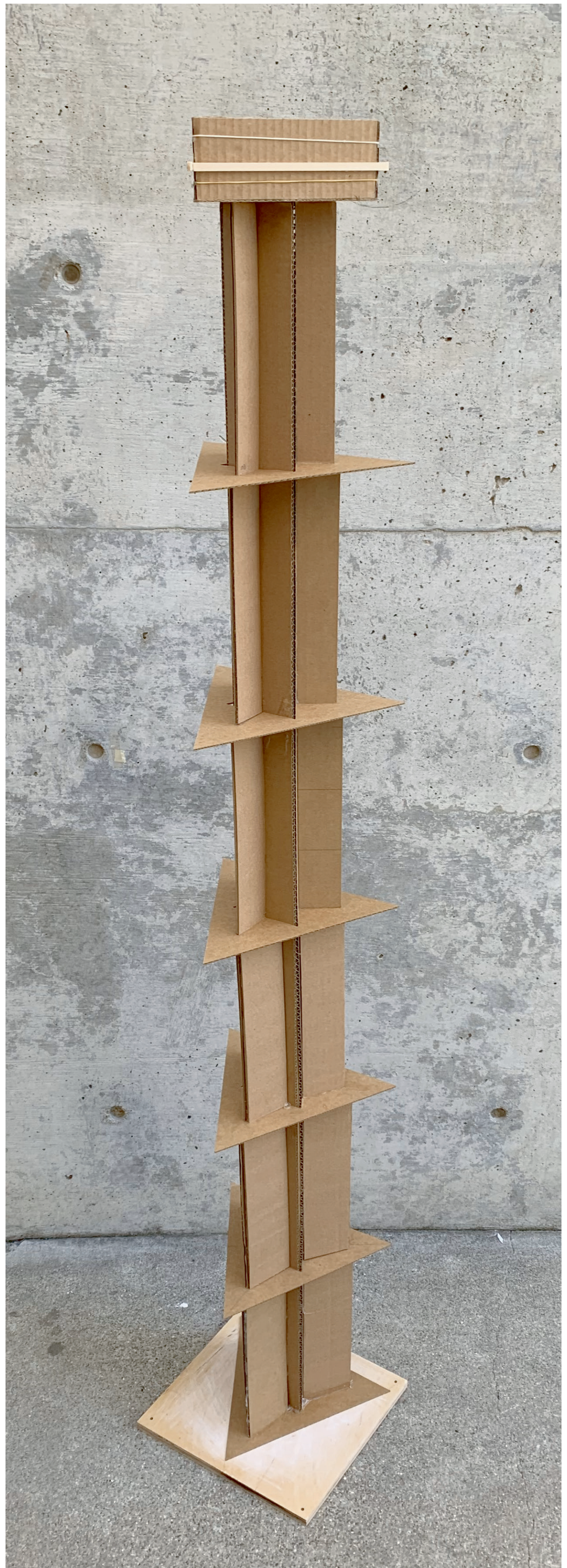
Height:	*18"*
Base:	*4"*
Aspect Ratio:	*4.5*

The Tale of the Tipsy Tower

In order to ensure failure within 3 lbs past the brick load, the structure to the right was designed with an intentional torsional irregularity. Where a third brace could have been placed along the edge of the hexagonal cylinder, it was omitted. During loading, the tower was very unstable. After placing the 2 lb weight, the tower could be heard to pop as it veered to the left, and seemed to straighten out again, presumably forming a miniature plastic hinge and gaining enough strength to twist back to the right. At the third lb weight, the tower failed after a few seconds of swaying, popping a joint as it deflected. The experience was truly a rollercoaster of emotion.

Failure Sequence

Quake and Shake



Quake and shake was an exercise in understanding high rise response in a seismic event. Teams built towers with a 12" x 12" base and 60" height. Tower were constructed from easy to find materials, such as basswood or cardboard. The towers each articulated 6 floors and the top floors were loaded with 4 lbs. All the towers were screwed down onto a shake table and taken through a frequency sweep. Towers were observed for failure modes, resonance, and seismic response.

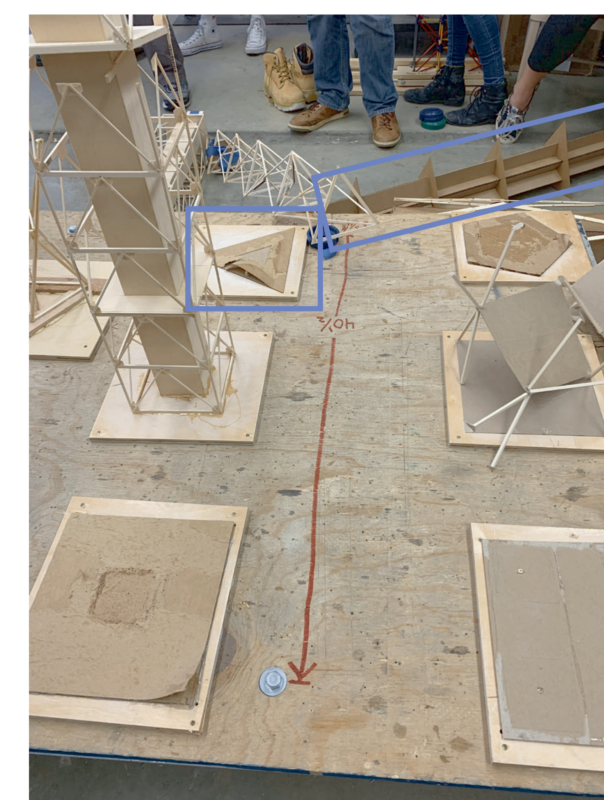
Our tower failed due to an overturning moment at the base foundation. Even though the tower was experiencing resonance, the structure above the base remained stable and intact. When the structure did fall over, it remained whole,

Tower Design

Inspired by the Burj Khalifa, our tower adopted the "Y" shaped core. The motivation behind choosing this system was an interest in understanding more about it's response under loading. The tower showed immense stiffness and strength, even under intense loading.

Tower Failure

The tower ultimately failed at the base connection. While on the shake table, it's resonance was discovered and it was shaken until the cardboard Y-shaped cores ripped away from the cardboard base. The remnants are shown in the image to the right.



4.0_Digital Studies **Core and Outriggers**

The first study of a high rise structure was an introduction to computer analysis of high rises and the assumptions that can be made during analysis.

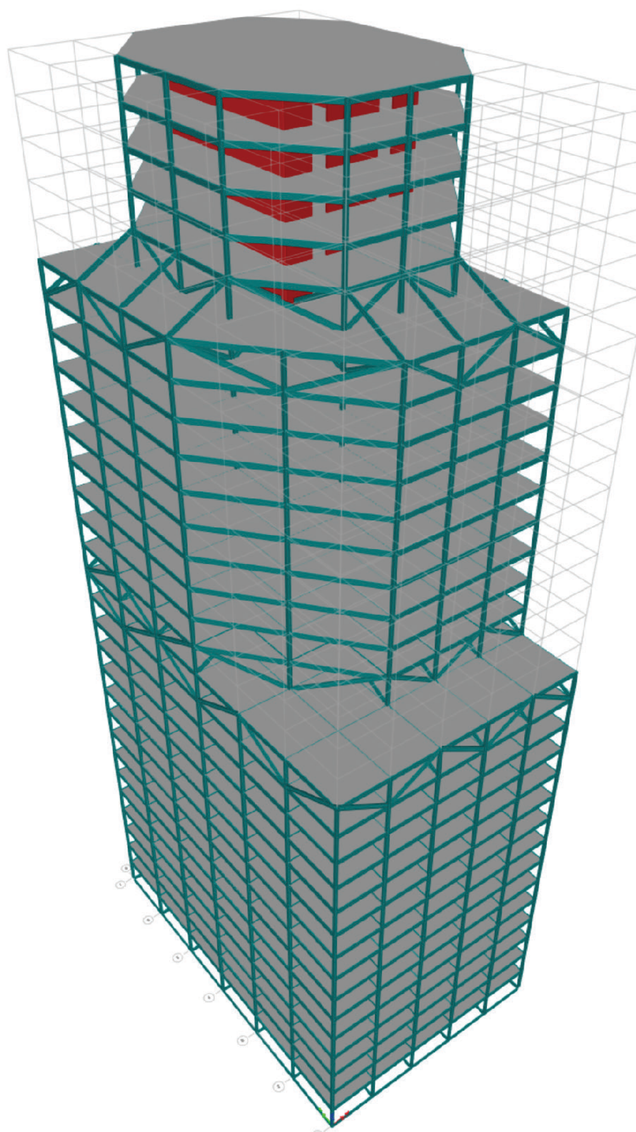
The model incorporated two story outrigger trusses and belt trusses on floors 15 - 16 and 25 - 26. These floors are also locations of changing floor plans. The outriggers are intended to help the core provide lateral support. The outrigger layout is shown on the plan. Belt trusses are "belted" around the tower, to help ensure all elements are working synchronously.

Wind loads were idealized as a three stepped profile.
28 psf
from Stories1 - 10

33.5 psf
from stories 11 - 20

39 psf
from stories 21 - 30.

These loads are applied to the building edge, as shown in the image "Wind Loading."



Building Info.

Building Geometry:
(30) 14' stories
420' story height
120 x 180 footprint

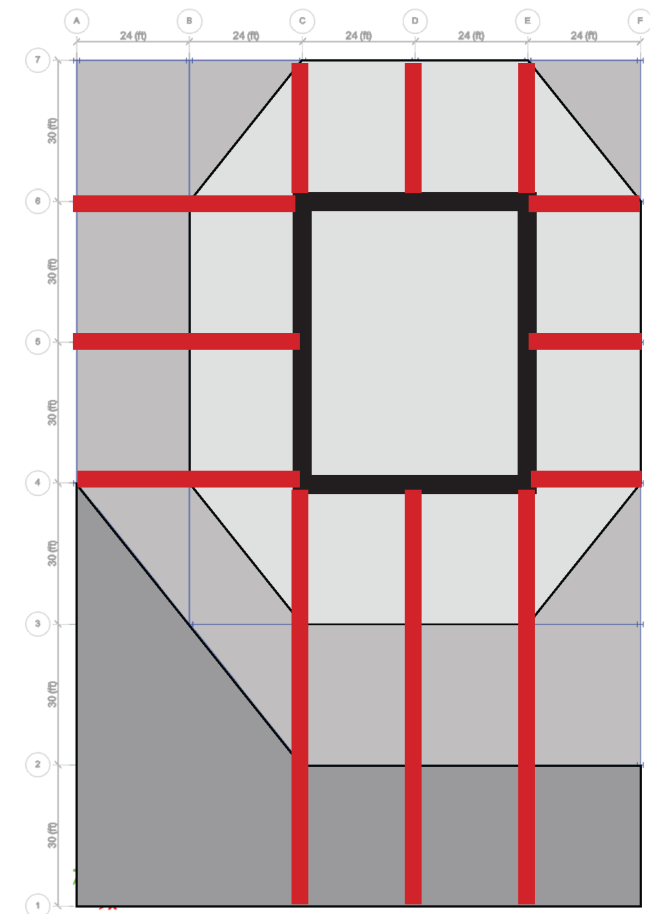
Materials:
Concrete Core
Steel Framing
Concrete Slab

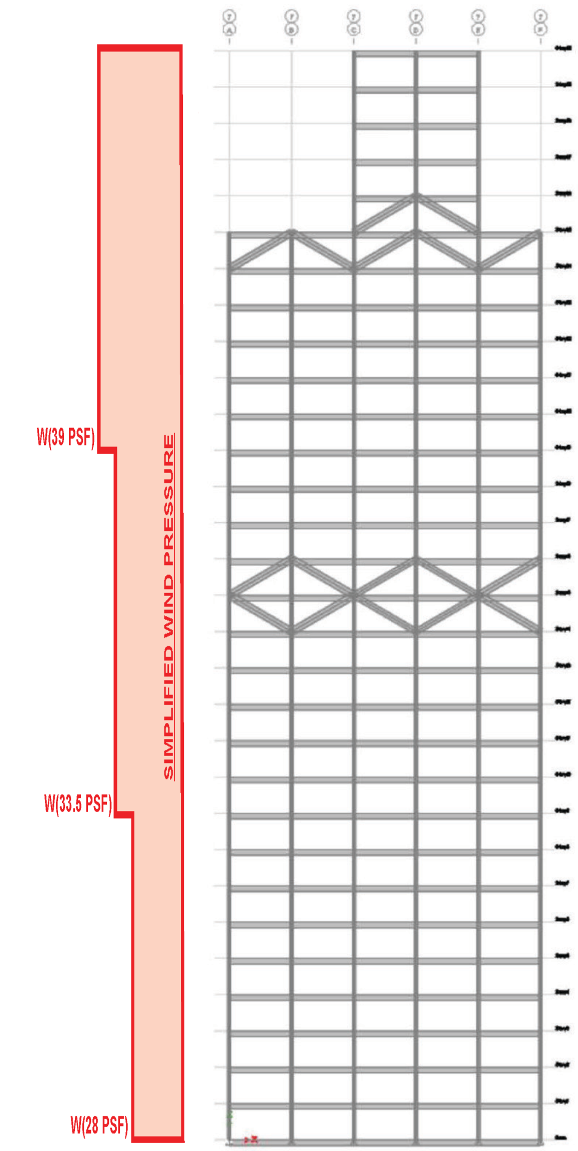
Gravity System:
Slab: 6" thick
Exterior Column: W14 x 176
Interior Column: W14 x 311
Beam: W27 x 84

Lateral System:
12" Core (48' x 60')
Trusses: W33 x 118

Building Plan

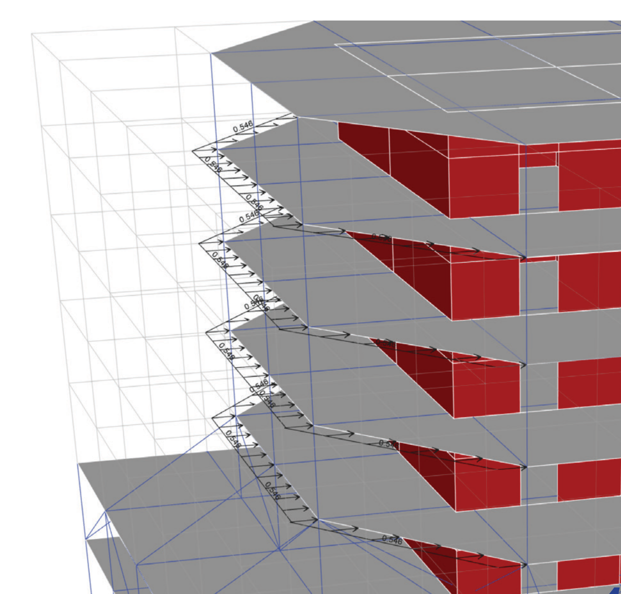
The building plan is shown below, with outriggers marked in red.

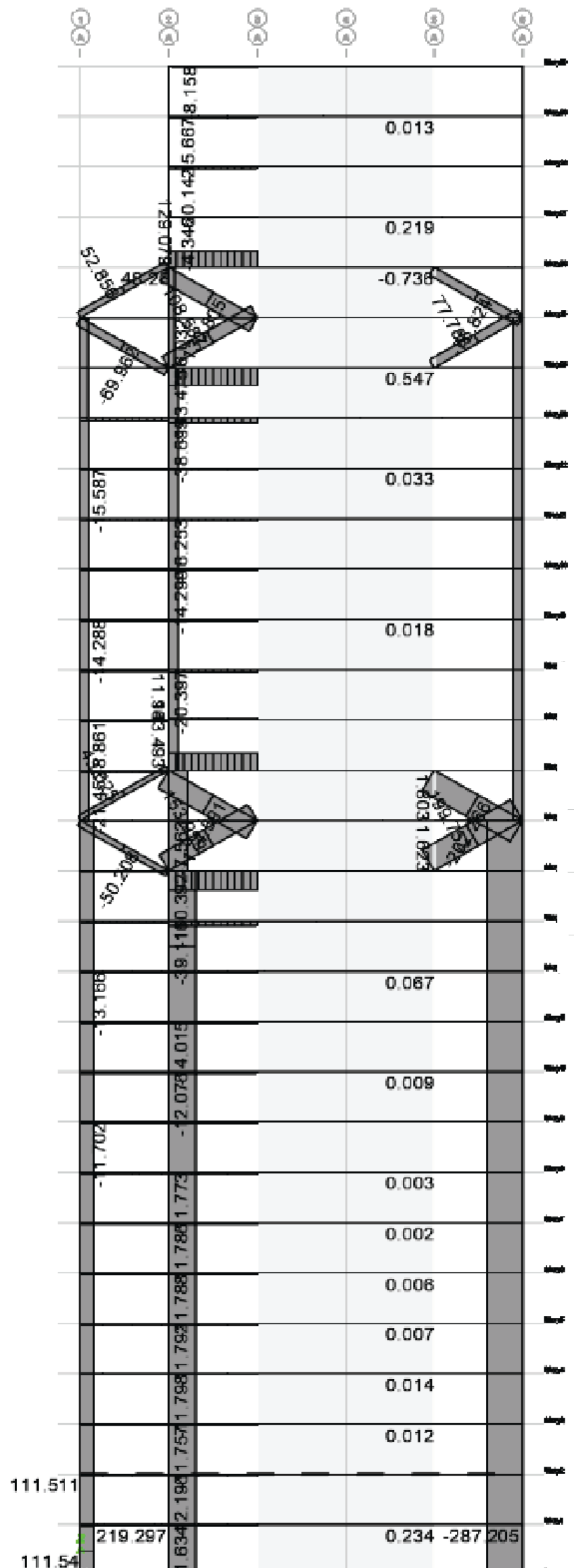




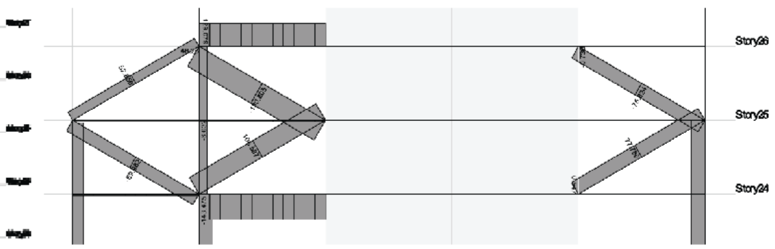
Wind Loading

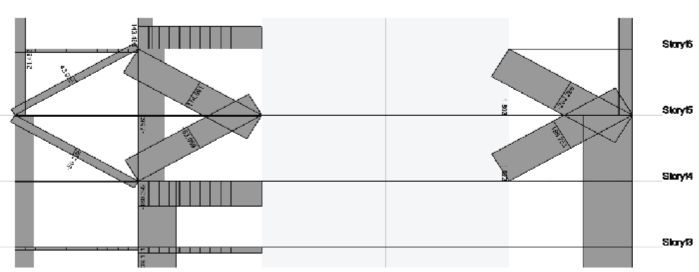
Wind loads are applied to the edge of the slab in the desired direction, eastwardly in this scenario.





Axial Loads Diagram





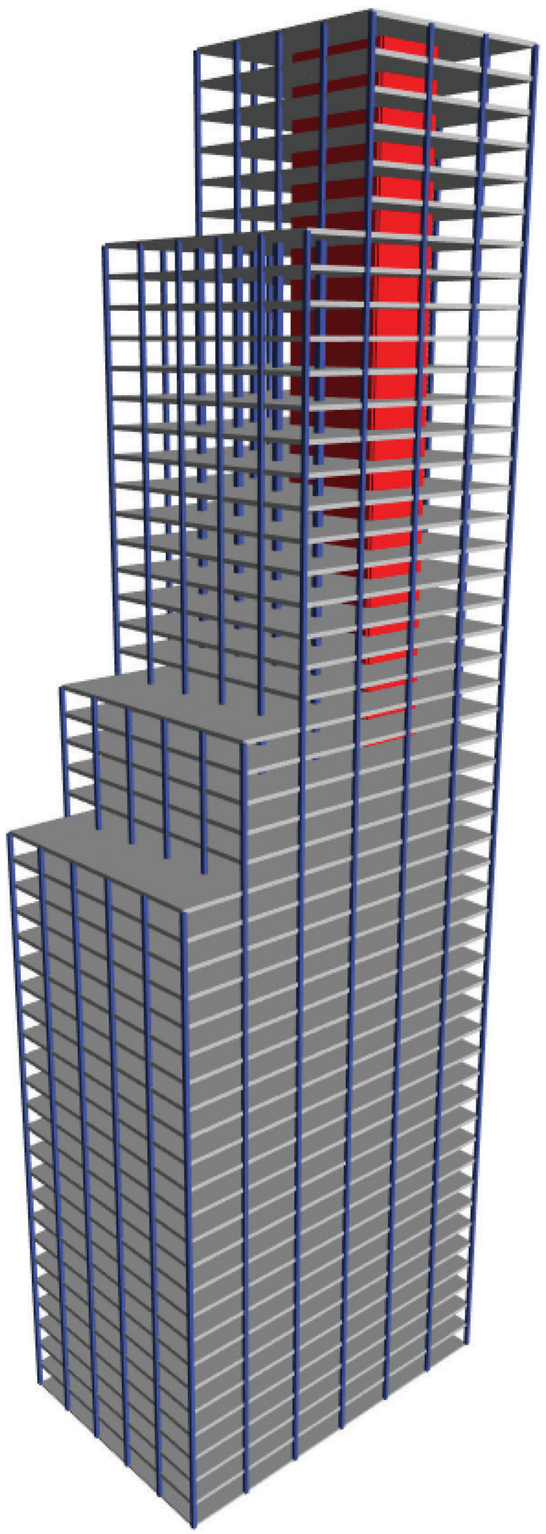
In order to get a sense of the force flow of the building above, a 2 dimensional model of the building was made*. The axial force diagram of the 2D model is shown to the left.

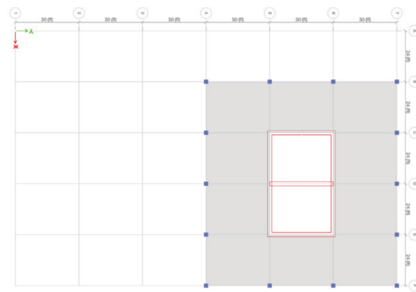
It can be seen that the column axial force jumps in magnitude once the column reaches the outriggers. This indicates that the columns are collecting force from the outriggers. Following the reasoning that this force must come from somewhere and understanding the outriggers are only connected to columns, slabs and cores, it becomes easier to understand the force flow. The slabs are unlikely to be carrying that much concentrated load, so it follows that the outriggers are helping reduce the core loads by spreading it out to the columns.

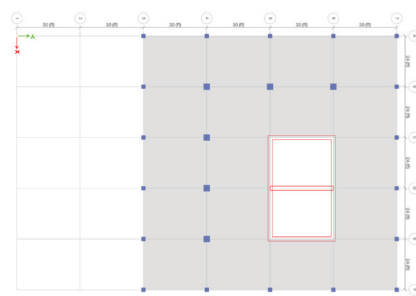
Outriggers can be thought of as arms holding ski pole columns, which help the core balance, the same way ski poles may help a person balance. The increased loading to the ski poles indicates increased balance in the core. Similarly, when a person balances with ski poles, the increased axial force the ski poles experience leads to a straightening of the user, aka, lessened deflection. It can therefore be said, outriggers help decrease core loading and would likely lessen deflections in the building as a whole. In other words, as the columns are taking loads from the core through the outriggers, the building stiffness would increase, per force = stiffness * deflection (F = Kd).

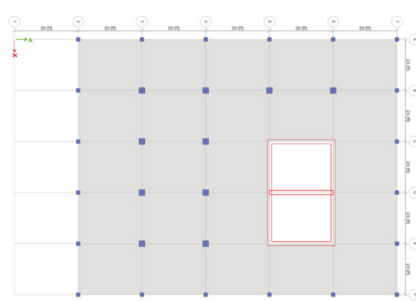
The 2D and 3D models were compared for deflection. They were found to be significantly different in magnitude but my colleagues in the collaboratory had run similar studies and found the 2D analysis to be a very good representation of the 3D results. It was later discovered that the 3D model we had used was improperly joined. It is assumed that the 2D model is an accurate representation of the force flow, as the model deflections met expected hand calculation deflections. The force flow is also in keeping with other studies.

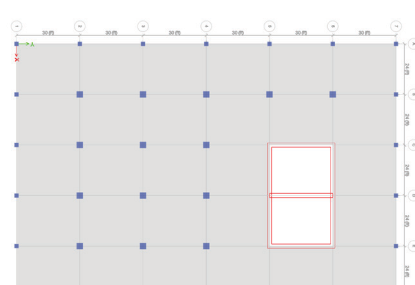
4.0_Digital Studies **Concrete Core**











Building Info.

Materials:
Concrete

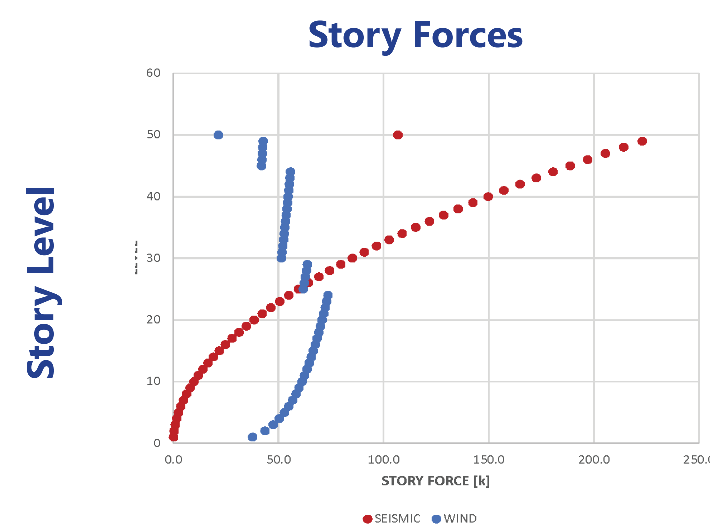
Gravity System:
Floor Plate: 12" thick
Exterior Column: 36" Sq.
Interior Column: 24" Sq.

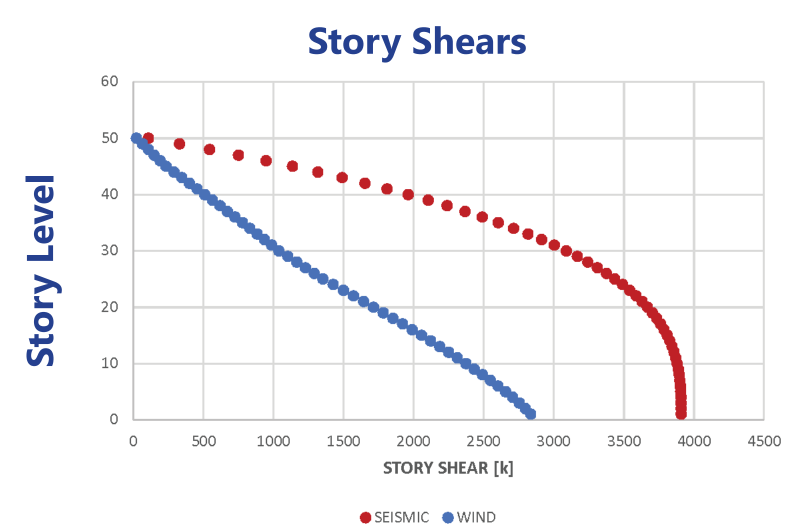
Lateral System:
24" Core (30' x 48')

Loading:
Dead Load: 160 psf
Live Load: 80 psf

The next structural system examined through the digital studies was a simple concrete core system. The concrete core functions similarly to a cantilever beam. Due to the system's simplicity, it was chosen as the model used to analyze modal analysis through mode shapes and mass modal participation.

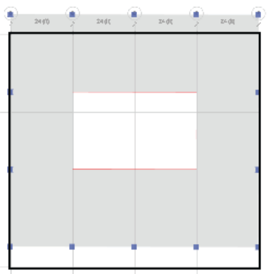
Additionally, a comparison of seismic vs wind loading was run, to try and understand what heights are governed by what system. Both the wind and seismic loading were found according to ASCE 7-16 guidelines. For high rise design, both seismic and wind forces must always be checked to determine which force will govern.



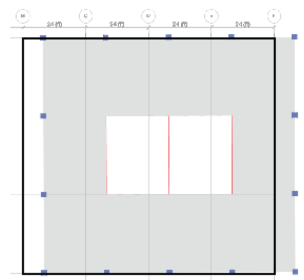


Seismic forces are shown in red and the wind forces are shown in blue. In this scenario, the seismic forces govern the base shear and the story forces roughly above 30'.

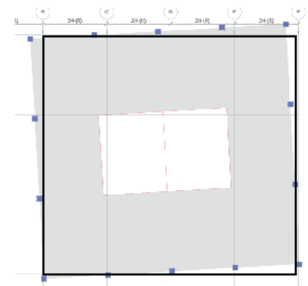
The building analyzed tapers towards the top, which helps reduce wind forces. The forces can be seen stepping down as the building floor plan steps down in size.



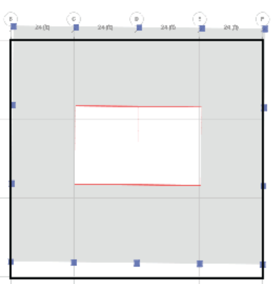
Mode Shape 1
T = 6.602 s



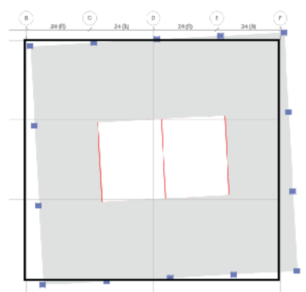
Mode Shape 2
T = 5.532 s



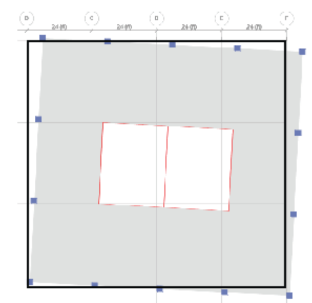
Mode Shape 3
T = 2.382 s



Mode Shape 4
T = 1.580 s



Mode Shape 5
T = 1.188 s



Mode Shape 6
T = 0.884 s

Motion	**% Mass Participation @ 6 Modes**	**% Mass Participation @ 12 Modes**	**# of Modes @ 90% Mass Participation**
Translation (X)	80.86%	89.41%	13
Translation (Y)	79.34%	90.15%	11
Rotation (Z)	86.59%	92.91%	9

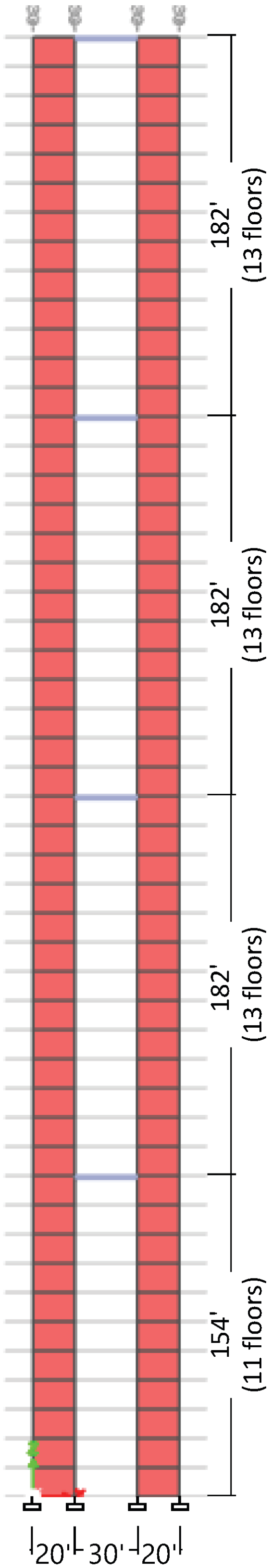
A mode shape analysis is an analysis option with 3D models. The results of a modal analysis that was run for this case study are seen to the left. The mode shape analysis can alert the user of an irregularity that can significantly impact the building expected results.

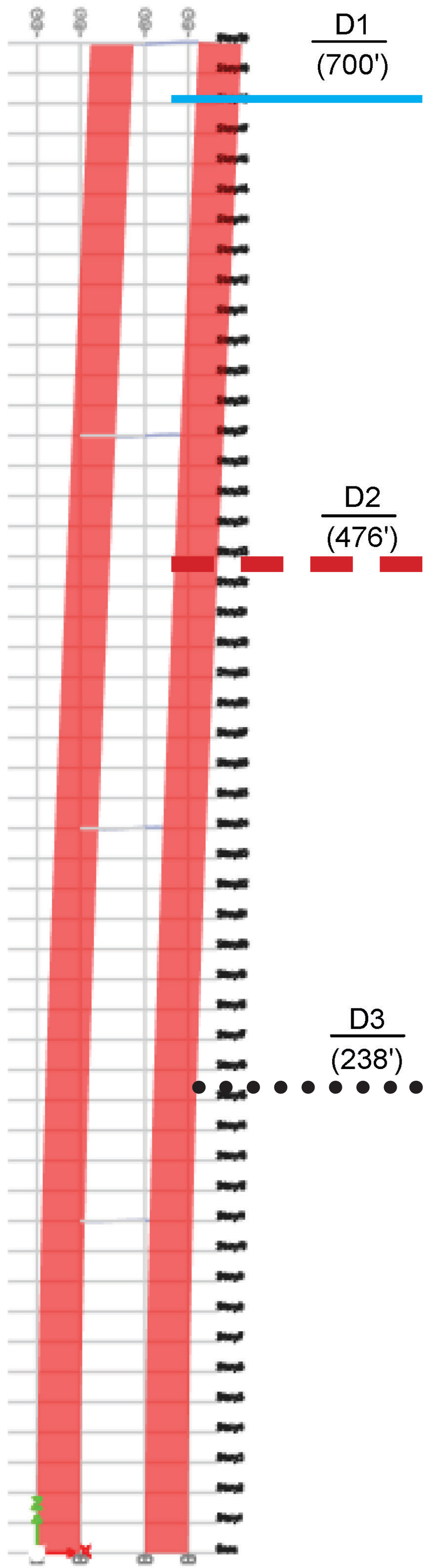
The expected modal response is seeing deflection in the two cardinal directions and rotation within the first, second and third mode shapes, respectively. Thereafter, the mode shapes are expected to become a mix of translational and rotational deformation. The expected results were found in this case study building, meaning no special measure or precautions need to be taken to correct a torsional irregularity.

Problems occur when the primary mode shape is rotational, as it can indicate that in a seismic or a heavy wind event, the building will begin to twist before it translates. Once buildings begin to rotate, the expected outcomes become difficult to prepare. For this reason, designers try to keep building deflection in the orthogonal directions as much as possible.

Aside from simply looking at the mode shapes, it is also helpful to examine the mass modal participation of each direction. This is the percentage of building mass response that is captured by the mode shape. The amount of modal participation captured by the mode shapes indicates the accuracy of those mode shapes. Typically, if 90% mass participation is met, then the number of mode shapes it took is the number of modal scenarios needed to prepare for building deflections. The less mode shapes it takes to capture the building mass, the better.

4.0_Digital Studies **Coupled Shear Wall**





The last digital study that was run was a coupled shear wall parametric study. The study examines how changes in beam frequency and beam depth affect the wall's deflection. When the walls are properly coupled, the deflection should significantly decrease. Therefore, the greater the deflection, the better the wall coupling.

As the area of the beams was increased by way of depth, the effectiveness of the increase on the deflection reduction remained linear. On the other hand, the curve began to level off as the area decreased, presumably reaching the uncoupled deflection.

Base Model Info.

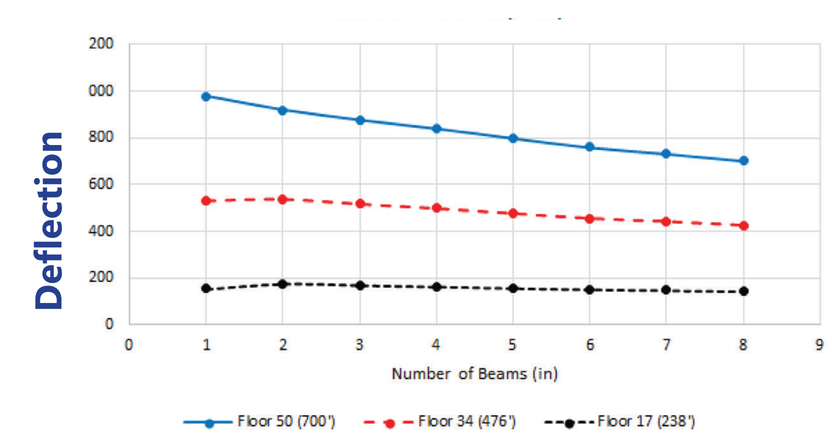
Materials:
Concrete

Members:
Beams: (4) 12″ x 18″
6″ rigid links at ends

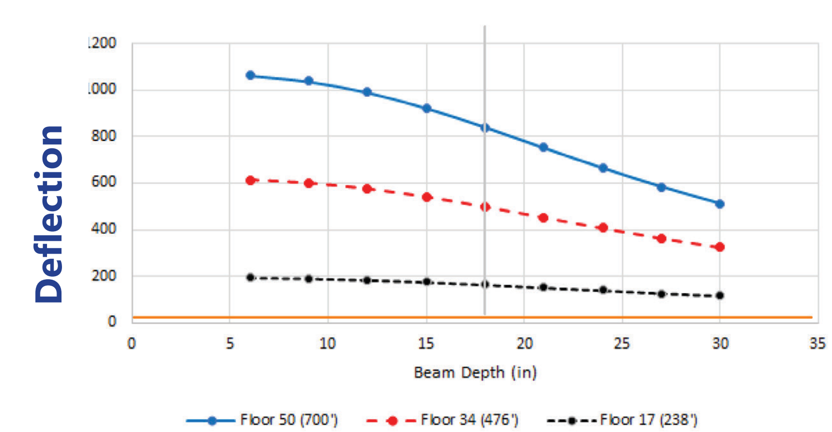
Walls: (2) 12″ thick
Walls 20′ wide
Walls 30′ apart

Loading:
No gravity loads
29.4 k/floor
14.7 k/roof

Variation in Beam Frequency



Variation in Beam Size



The beam frequency seems to have less effect on the deflection decrease. While still fairly linear, the addition of beams past the 4 beams baseline has a deflection percent difference of 4%. By comparison, the changes in beam area fluctuations averaged a 13% difference.

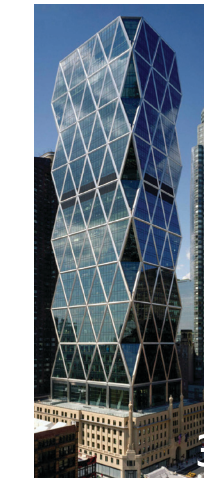
As will be shown in the HOODOO lateral studies, this is now understood to be likely associated with an increase in beam stiffness.

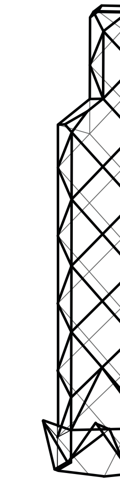
5.0_The Crystal **Structural Studies**

The Crystal is derived from the triangular and faceted nature of crystals. Through its evolution, the tower maintains a desire to grow the housing units in clusters, similar to the clustered growth of crystal unit cells. These housing unit clusters were an architectural focal point for the building and the connection between these clusters provided a challenge both architecturally and structurally.

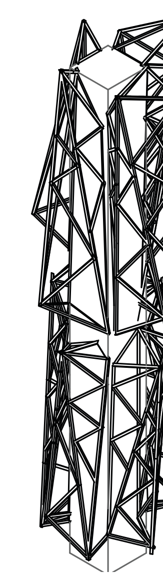
Where two clusters met, an opportunity for community space and a break in the building created a challenging structural problem. Through this architectural expression, several structural systems were proposed to express the breakdown of the facade and create a version of the hanging cluster. These structural systems are listed to the right, along with precedents referenced and models of the system. The final system chosen is a split core and diagrid system, shown below.

Diagrid Structure
The initial exploration of crystal led to the formation of a diagrid structural system. The the system would simply encase the crystaline structure. Precedents referened include the Broadgate Tower and the Heart Tower.

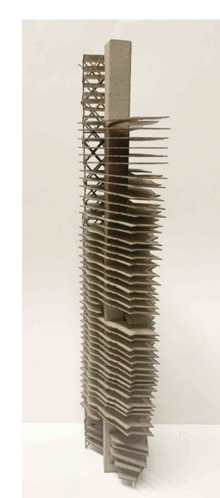


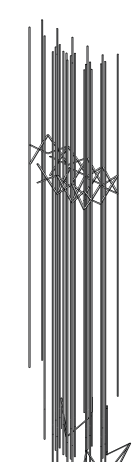


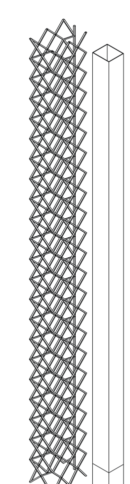
Tension Hung Modules
The option of hanging the crystal modules from the core via tension chords, similar to the New York Times building was investigated. It was ultimately abandoned due to lack of connection with the crystal core concept.



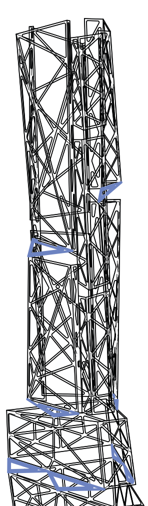
Central Core with Space Truss
The space truss is meant to carry the module gravity loads. Loads would be transfered back to the core, which would carry all gravity loading to the ground, as well as all lateral loads. The architectural difficulty behind the unusable bottom space of the trusses and the large core led to it's abandonment.

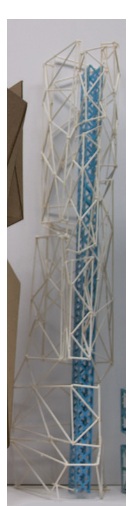


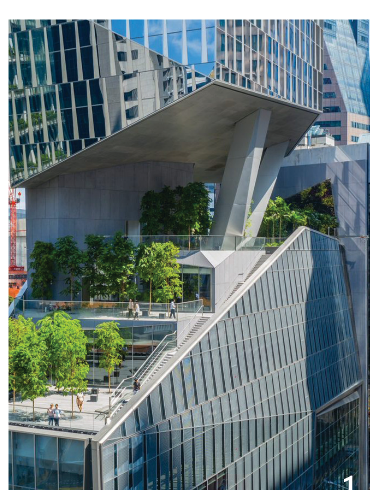




Offset Steel Core
An offset steel core was examined, for its architectural benefits of units facing the corner of Market and Van Ness. Torsional irregularity issues could not be overcome and it was opted out of.



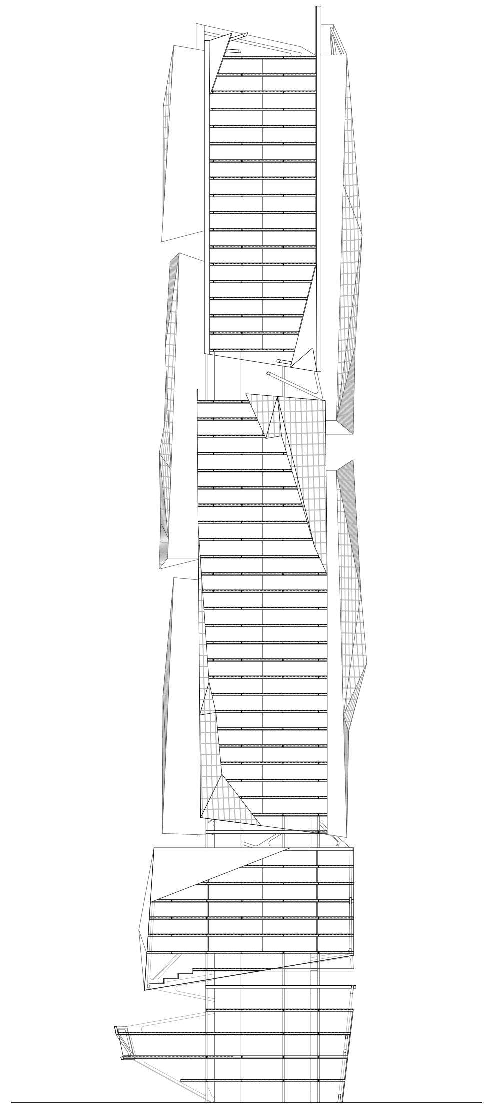




Split Core with Diagrid
A split central core around the central building atrium serves as the primary lateral stiffness element, with outriggers and belt trusses helping tie together the external diagrid and the two cores. The diagrid is expressed at architectural gaps with a similar external expression as the Robinson Tower.

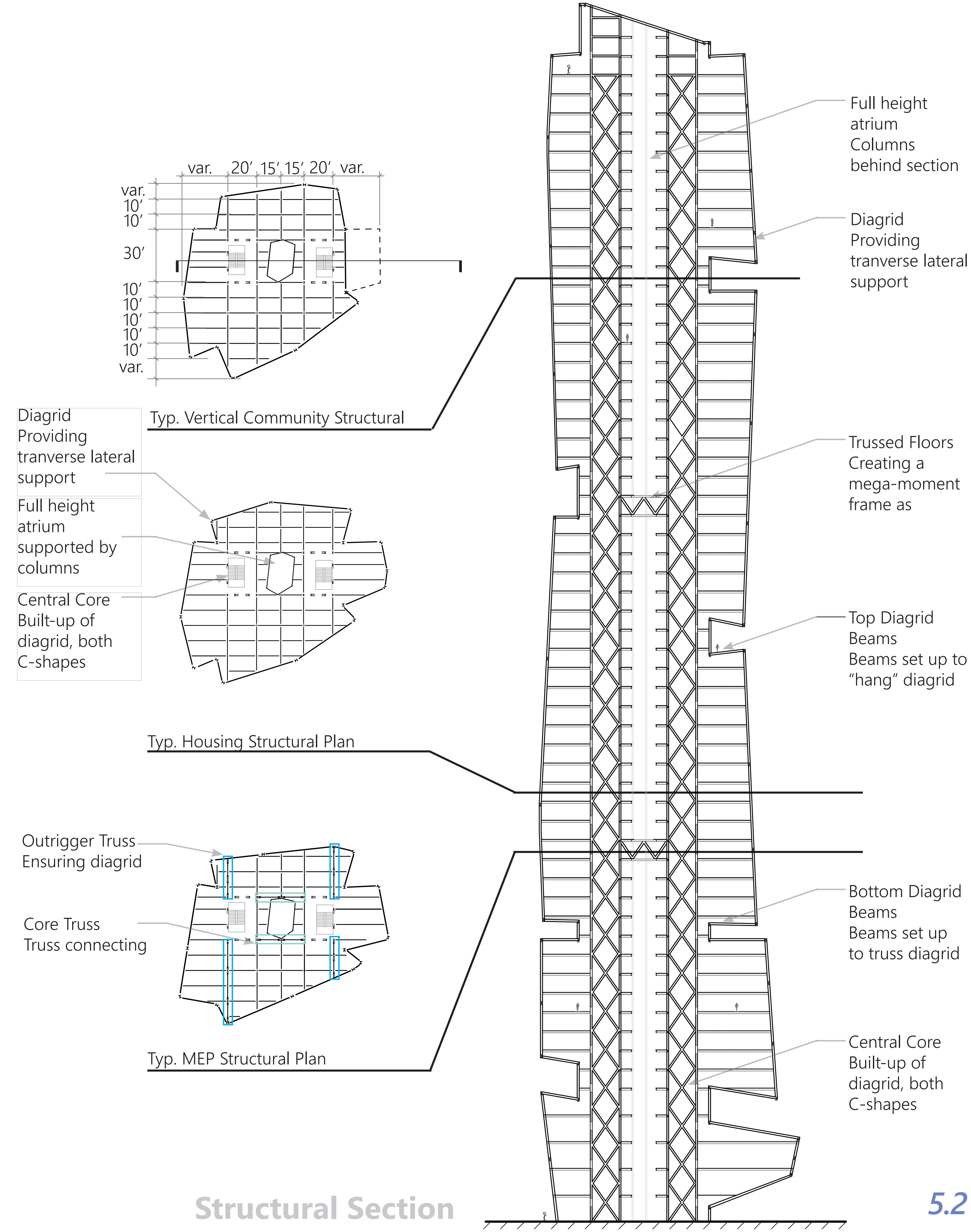
5.0_The Crystal **Structural Studies**

Physical Model



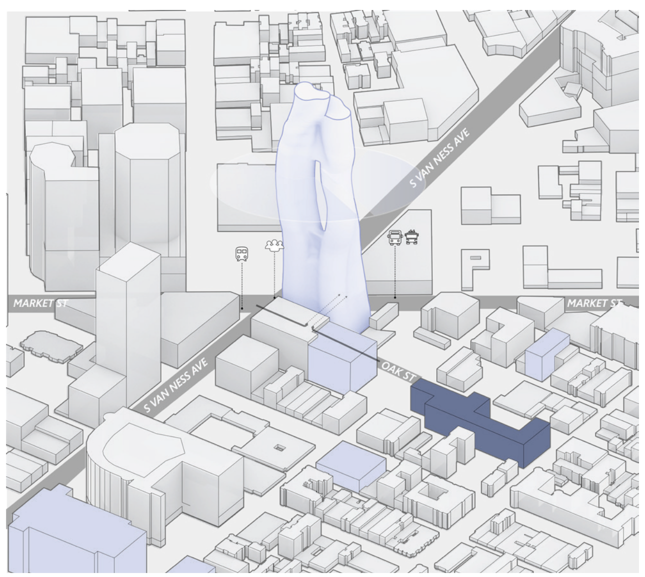
Architectural Elevation

The final iteration of the Crystal consists of a split core system with an exterior diagrid. The split cores are the main lateral force resisting system. They are joined in the longitudinal direction to each other at approximately 1/3 and 2/3 building height by outrigger trusses. In the transverse direction, these outriggers trusses connect the cores to the exterior diagrid for additional stiffness. The diagrid is continuous despite facade opening. Diagrid members through facade openings are incorporated into the community space focal points.



Structural Section

6.0_the HOODOO **Building Information**



The HOODOO tower is a 700', residential tower, inspired by the wind erosion of the hoodoo (shown below). It's unique geometry is achieved through a series of pulling and rotating of building sections. It is located on the corner of Market St and Van Ness Blvd in San Francisco, CA.

I joined the HOODOO team for the second 10 week period. The building form had been designed to the level seen in the render to the right. I was familiar with the project concept from previous reviews, but I did not have an understanding of the tower tectonics or exact geometries. The previous engineer had been working on a shear wall solution, which was very restricted by the limited continuous vertical locations of the tower and in turn caused challenges in the space design of housing layouts

Building Numbers:

Height
700'

Girth
100' x 100'

Floor to Floor Height
12'

\# Tower Floors
50

Podium Height
85'

Podium Floor Height
21.1'

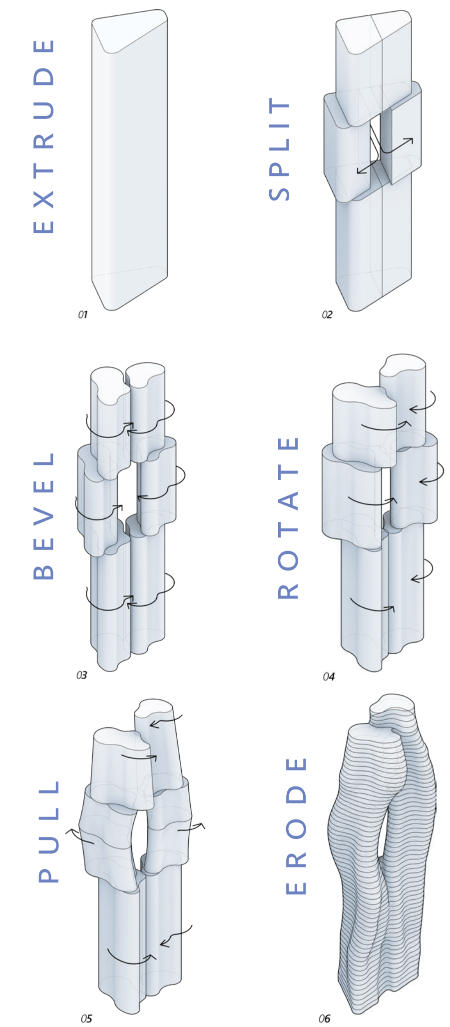
\# Housing Floors
46

Housing Units/Floor
10

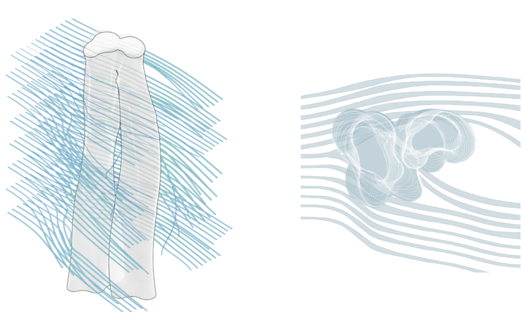
Typ. Unit Sq Ft
1,200

Core size on each floor (avg)
2,400

Vertial Communicty Space Sq Ft
4,740



PROCESS



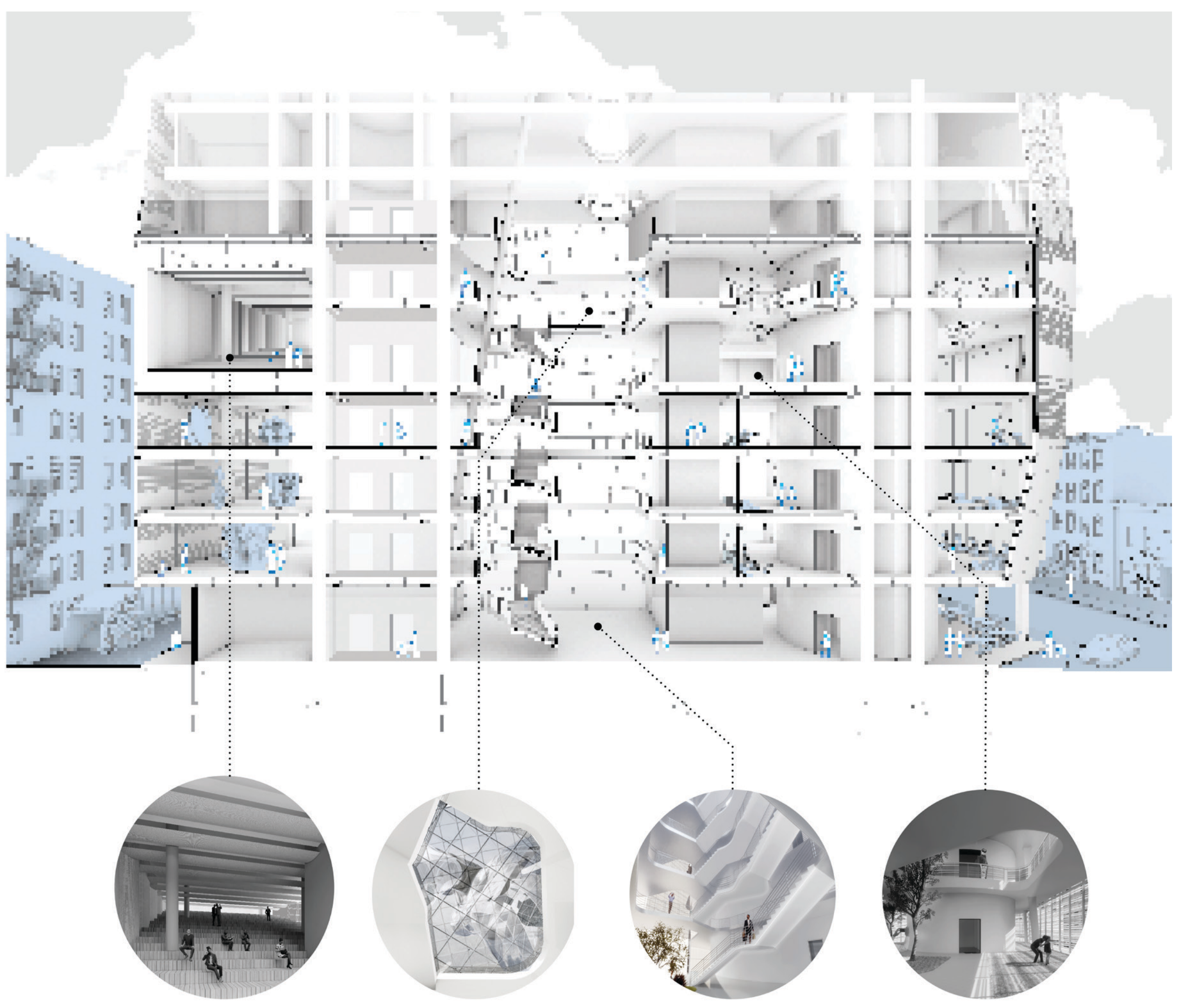
WIND STUDY

6.0_the HOODOO **Architecture**

The Hoodoo is eponymously named and conceptualized by the wind erosion of the hoodoo rock formation. The tower's shape responds to existing wind patterns and minimizes the influence of lateral forces. The central void stresses the concept of wind and creates a vertical community space.

Podium Level

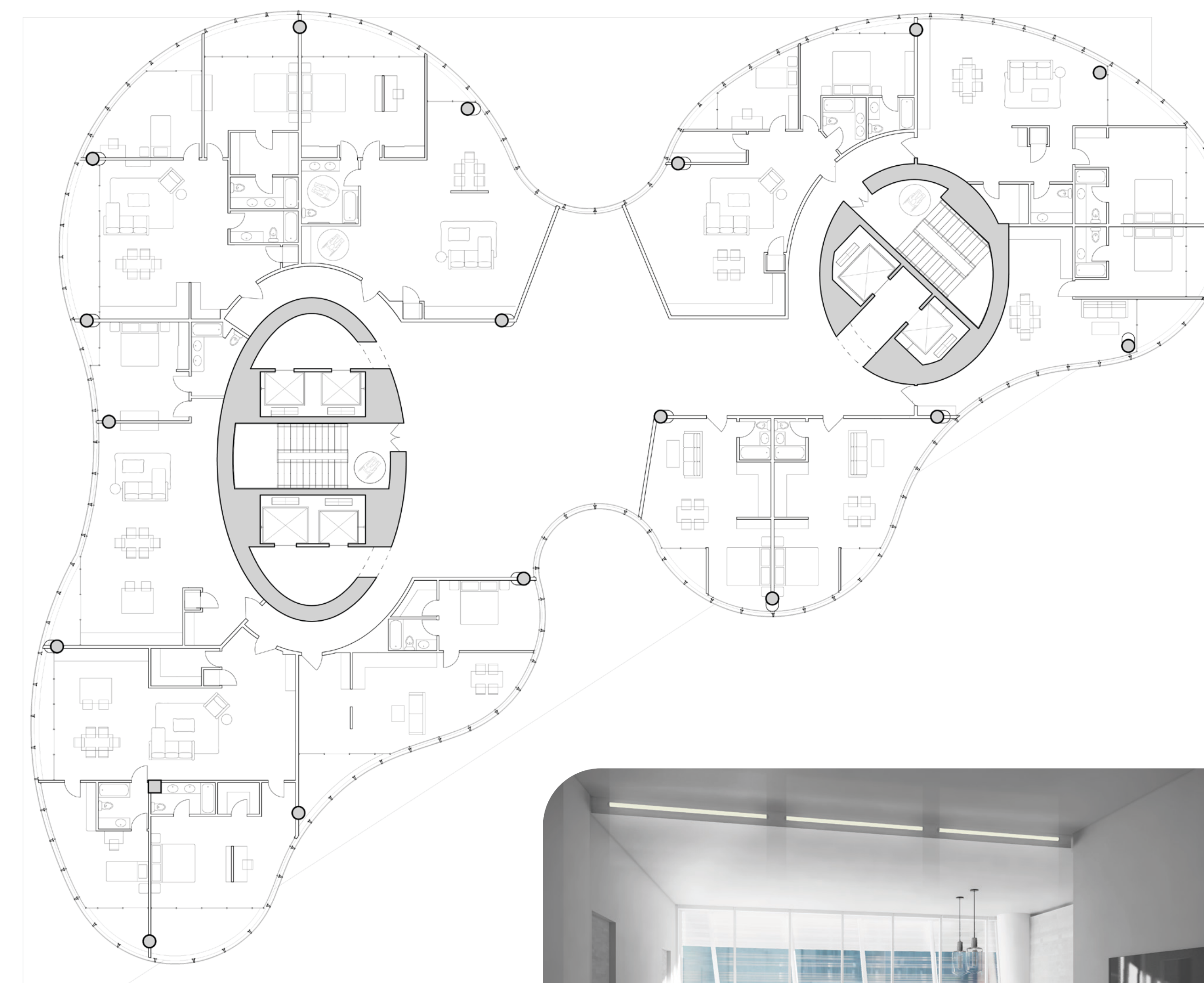
We designed the podium to address the intersection of two major streets of SF with an open space on the first floor. The podium atrium/garden connects Market and Oak street with an indoor space and provides an entrance to the towers for residents. The transparency of the atrium provides a view to the eroded towers, as well as the city, giving visitors a sense of place.



Podium Level Section

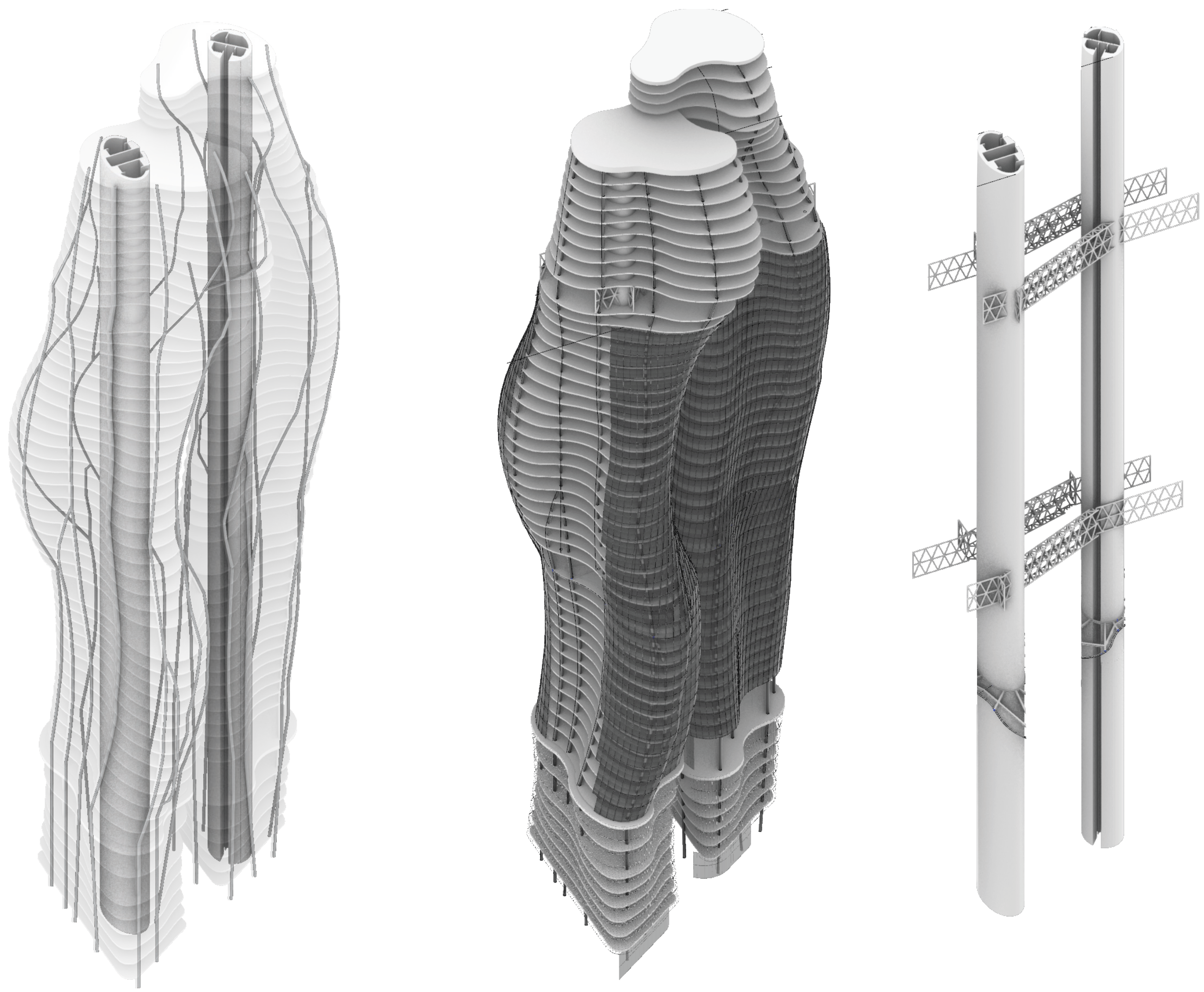
Housing Level & Housing Unit

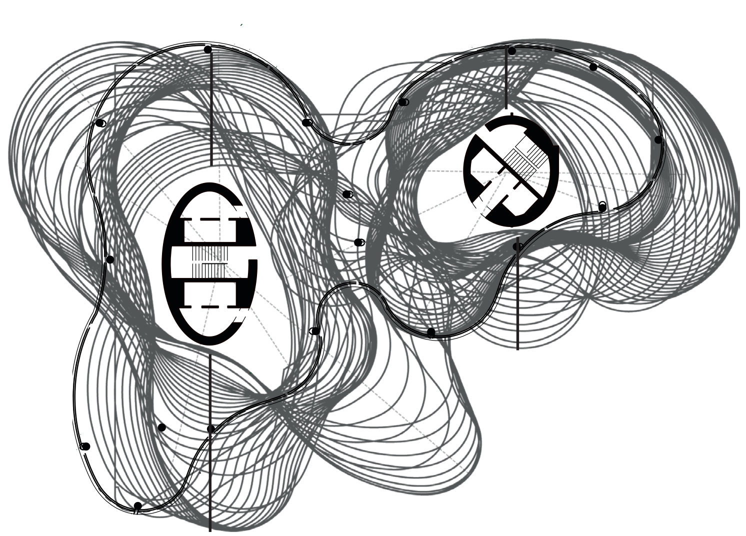
The Housing Unit is a segment of a floor plate. This provides every room of a unit with a lot of daylight. Semi-closed balconies exist in most units.



Typ. Housing Layout

6.0_the HOODOO **Structural System**

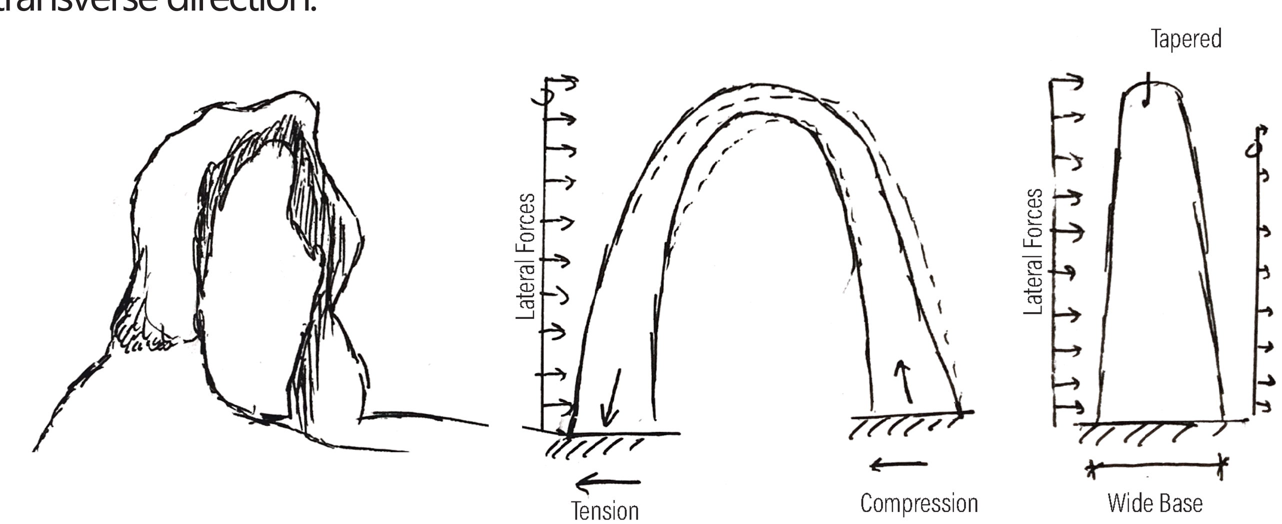




As I wanted the structure and architecture to become one, the first step to designing the new structural was understanding the concept and exploring inspirational forms from the geological arch formation. The arch forms a force couple in the legs in the longitudinal direction and is tapered in the transverse direction withstand lateral loading.

This arch-like structure is achieved through the placement of a core in each tower and outriggers to join the tower and created the tension-compression couple. The most difficult architectural work around was finding a way to carry loads to the ground. The floor plate edges were modeled as a wire frame and locations where a strictly vertical transfer of forces was available were discovered. The cores were designed to be elliptical for ease of analysis and made as large as possible within the space.

Straight columns were not feasible, as the plans rotate too much to have non-centralized vertical elements. Therefore, the columns that were design to be canted, to follow along the building exterior and accentuate the building's organic shape. Columns are directed along the YZ plane above and below the core's maximum transverse width in plan, as they are used as outriggers to stiffen the transverse direction.

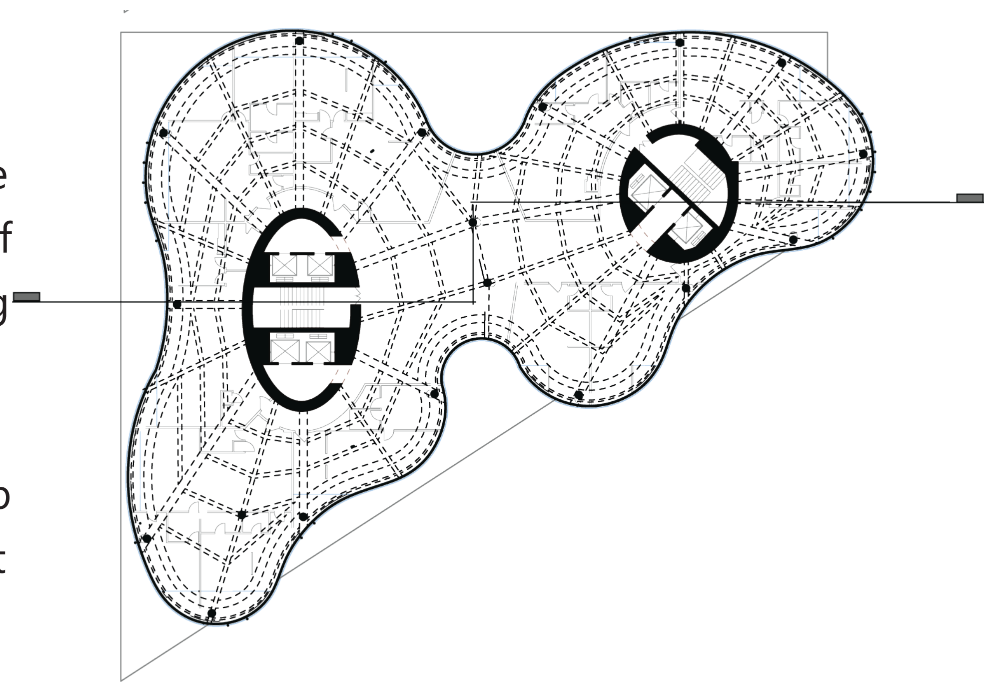


6.0_the HOODOO **Gravity System**

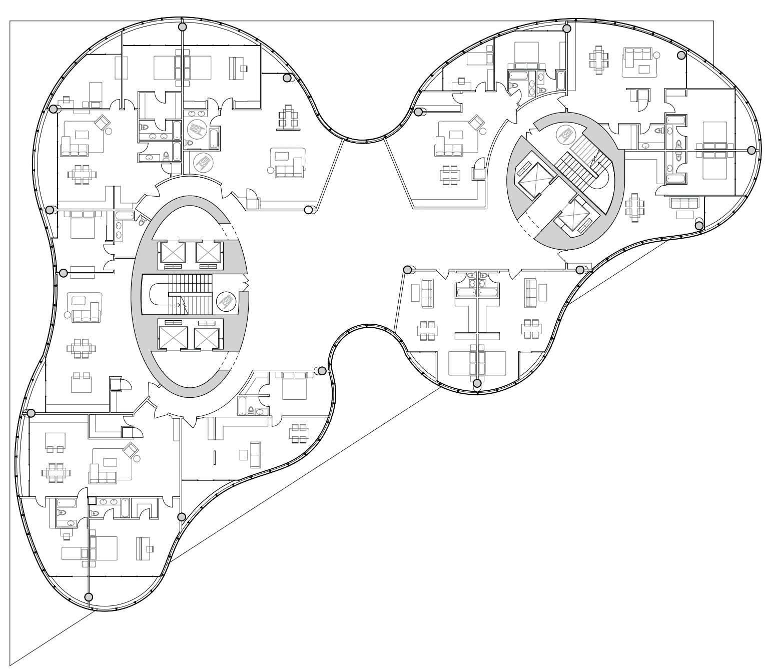
The gravity system is composed a 5″ steel composite decking, with joists and beams expanding radially from the cores. With the exception of a W6 edge beam providing an anchorage point for the facade and the major edge beam, which follow the slab edge, all beams are straight members.

Beams are W 14 x 283. No beams span a distance greater than 50′ without framing into a column. Canted columns are all W 14 x 873.

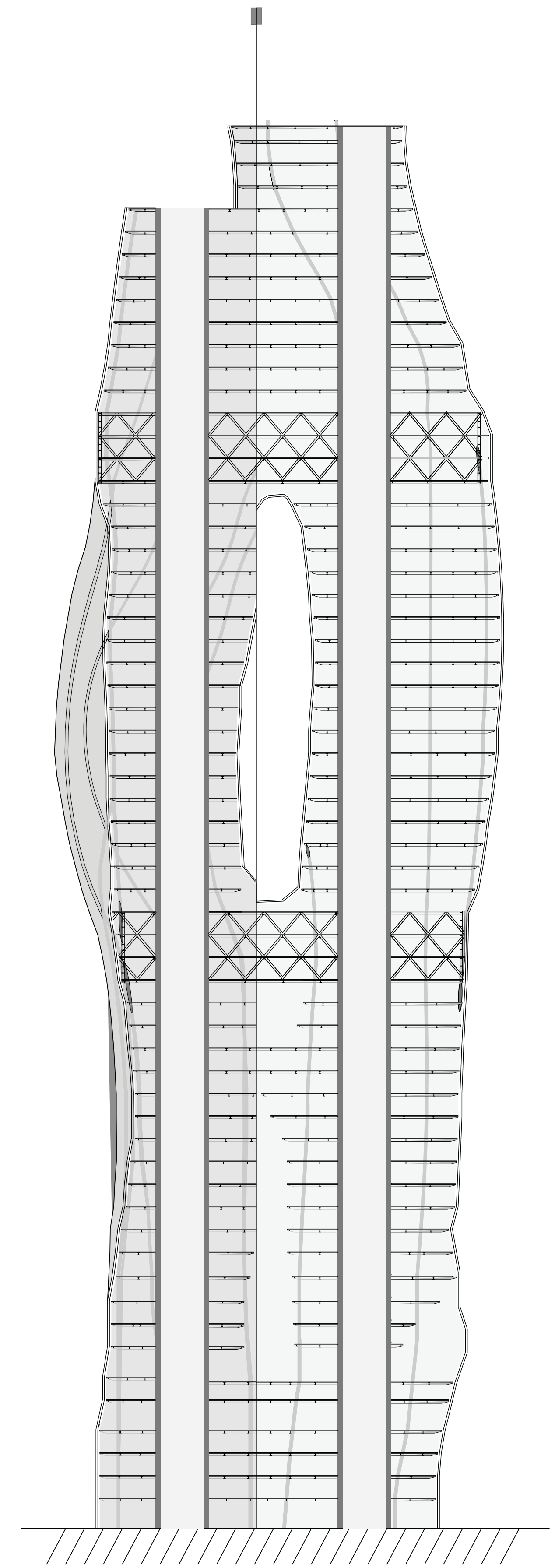
Columns follow the floor plate rotation pattern and align with partition walls. Beams follow the columns and are framed where necessary.

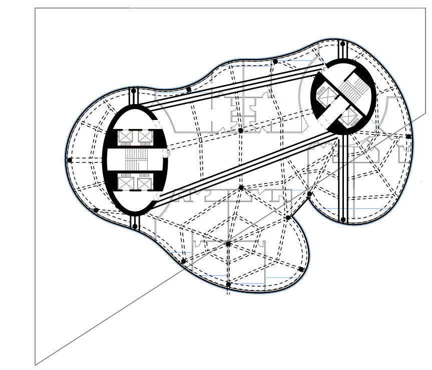


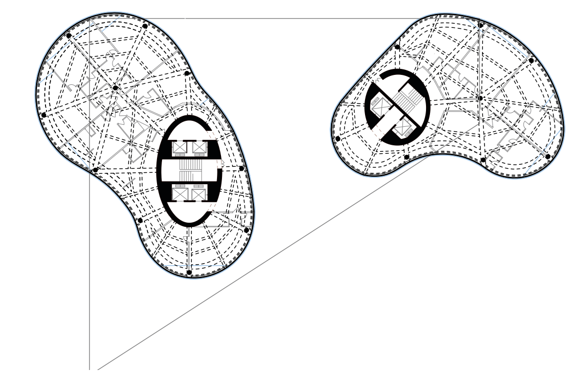
Strcutural Framing Floor Plan

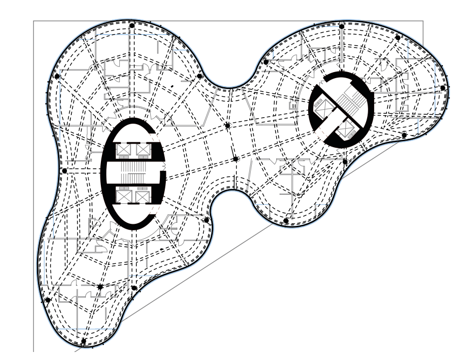


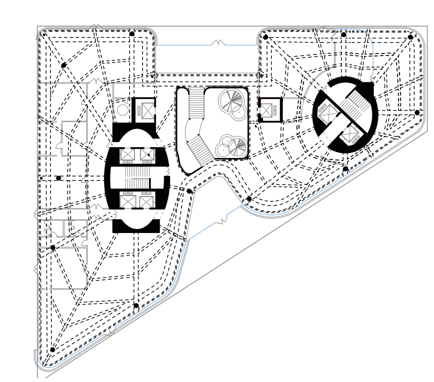
Architecture Housing Floor Plan









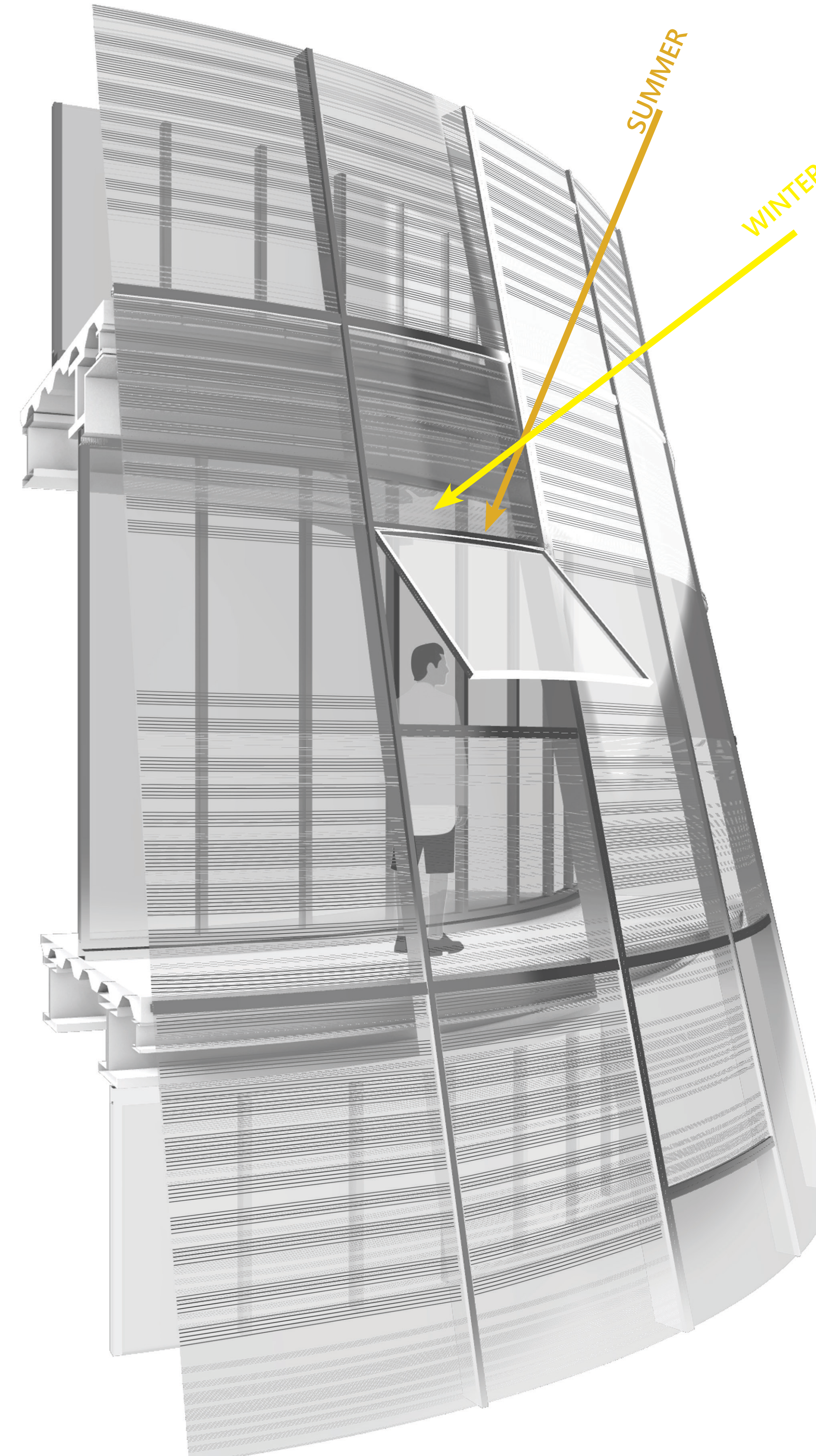


The facade concepts for the HOODOOO tower is a double skin envelope, with a glass curtain wall along exterior, covering the slab edges, and a window wall running from slab to slab, which moves in plan to create patio spaces. The curtain wall includes an operable window, opening to allow fresh air, for occupants, while still protecting them from the high wind speeds and cold, foggy mornings.

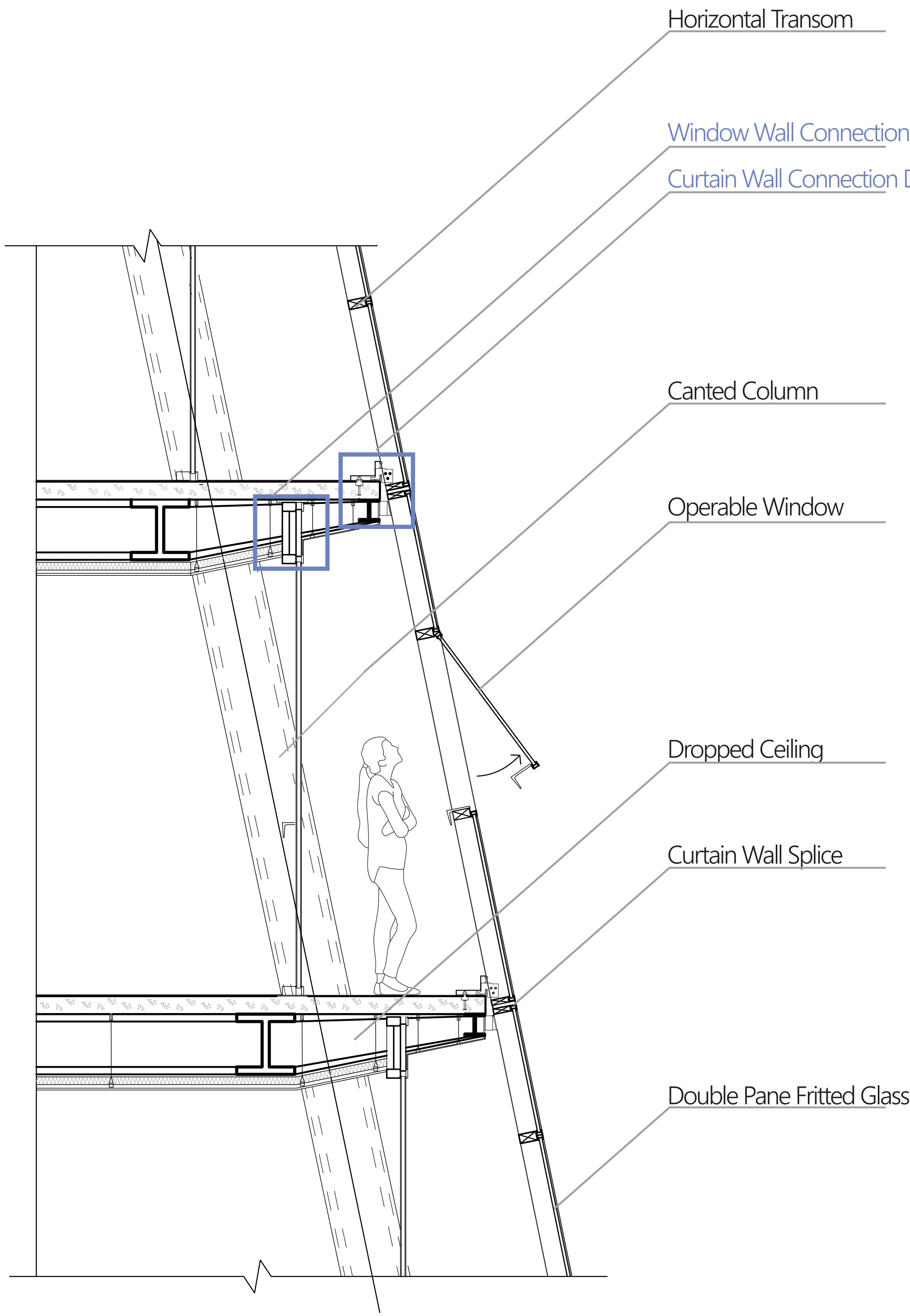
The curtain wall employs the use of frit as sunlight and heat protection. The frit is designed to block most direct summer sun angles and to filter winter sun angles. When seen on the tower as whole, the frit evokes of a sense an eroded tower.

Facade Plan and Elevation

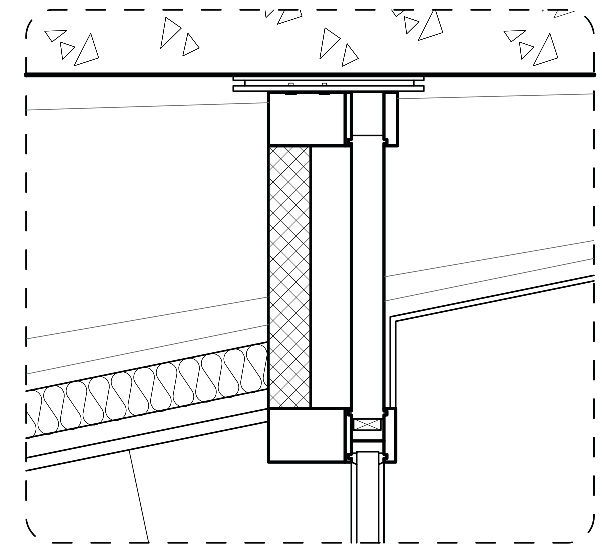
Structurally, the both the window wall and curtain wall span 1 floor at a time. The bottom connection for both are bearing connections, which have built in systems to allow for construction tolerances. The top connections accommodate deflections in all three cardinal directions, to allow the building expected story drift. Both can be seen on the next page.

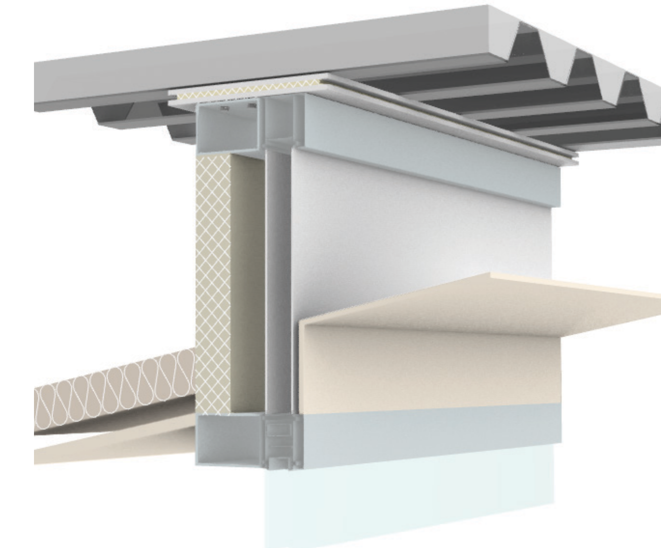


6.0_the HOODOO **Performative Envelope**

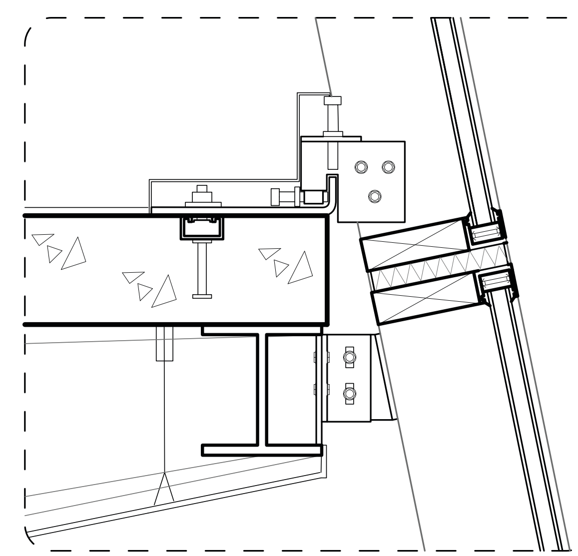


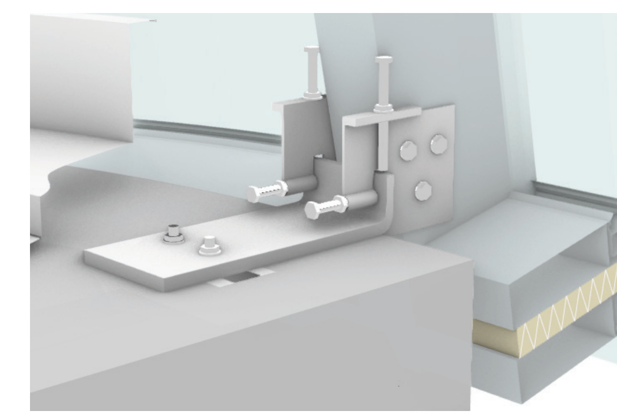
Facade Section

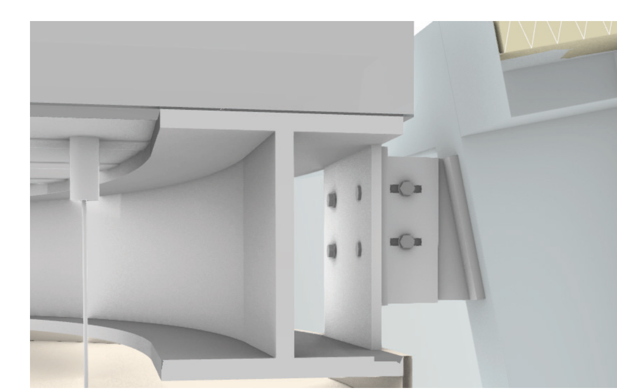




Window Wall Movable Connection Detail
The top window wall connection allows for inter story drift via slotted holes in the top mullion channel and the bottom flat plate. The two flat plates are rubber padded on the interior and connected via bolts which allow for vertical movement.







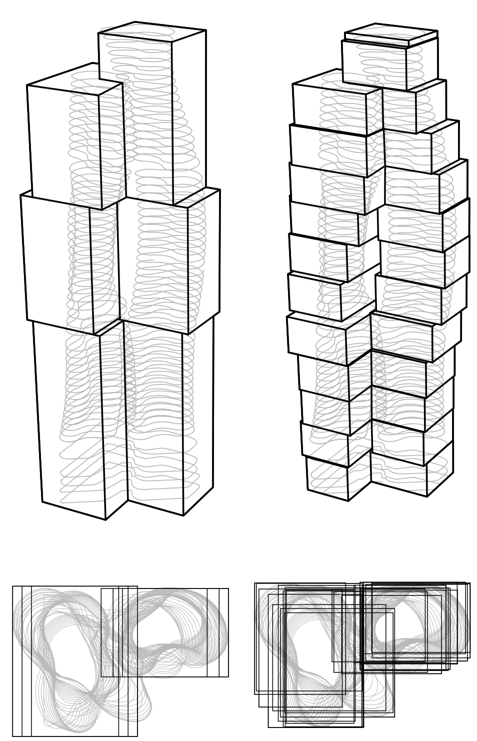
Curtain Wall Connection Detail
The top bearing connection has adjustable bolts, which allow for construction tolerances. This bearing connection is covered with a metal plate, creating a 6" curb on unit balconies. The bottom connection utilizes four bolted angles and plates to provide six slotted bolt holes, two in each direction of possible movement.

6.0_the HOODOO **Analysis Methods**

The HOODOO structural cores and canted columns were analyzed using RISA 2D and ETABS. The 2 dimensional RISA studies used user inputted sections to analyze deflection control in the longitudinal and transverse directions. The deflection limits were set out by the Canadian building code as H/500. The 3 dimensional ETABS study used similar assumptions to analyze torsional issues and modal diagrams. Exact core section properties were found using Rhino 6 software.

Model Properties

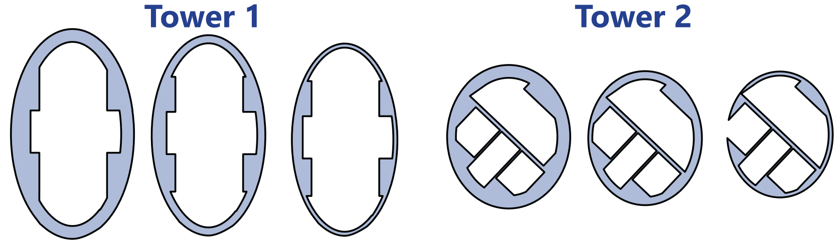
Columns were set to W14x873, beams were set to W14x283. Cores were varied by 1′, 2′ and 3′ thickness, using a user defined section, with manually entered areas and moments of inertia. Outriggers were analyzed by varying the area and moment of inertia of section sets and designing the outrigger using the results. Within the 3 dimensional model, rectangular walls that closely matched elliptical core area and moment of inertia were used as the tower cores. The 5″ slab floor plates were estimated at every 5 stories (60′) for model simplification.



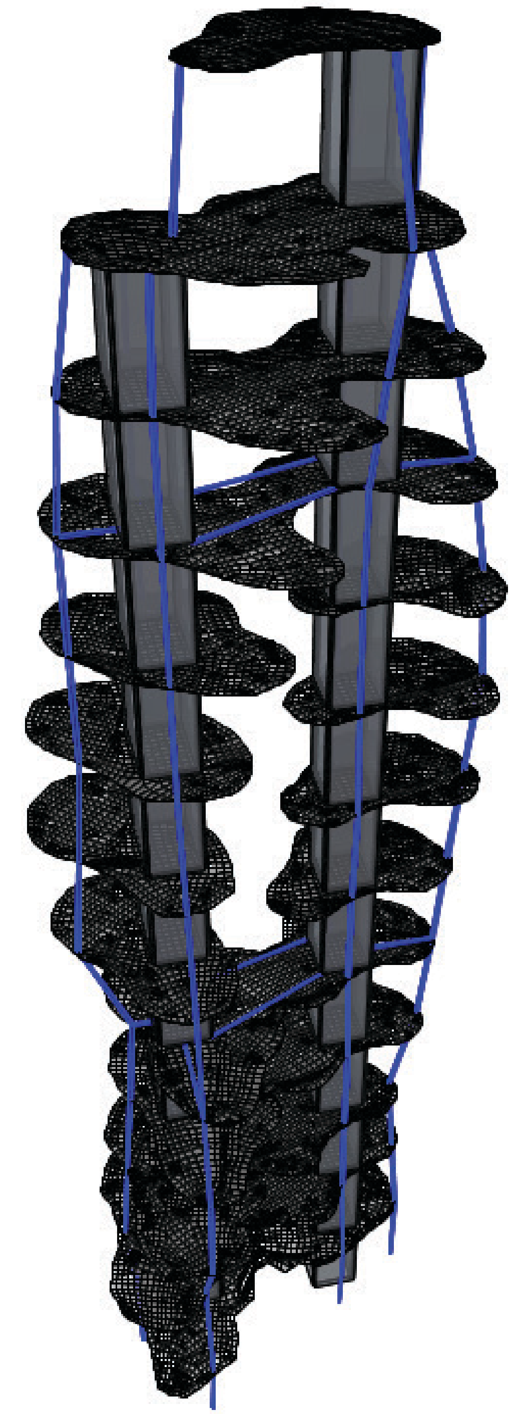
Wind Loading Diagram

Model Loading

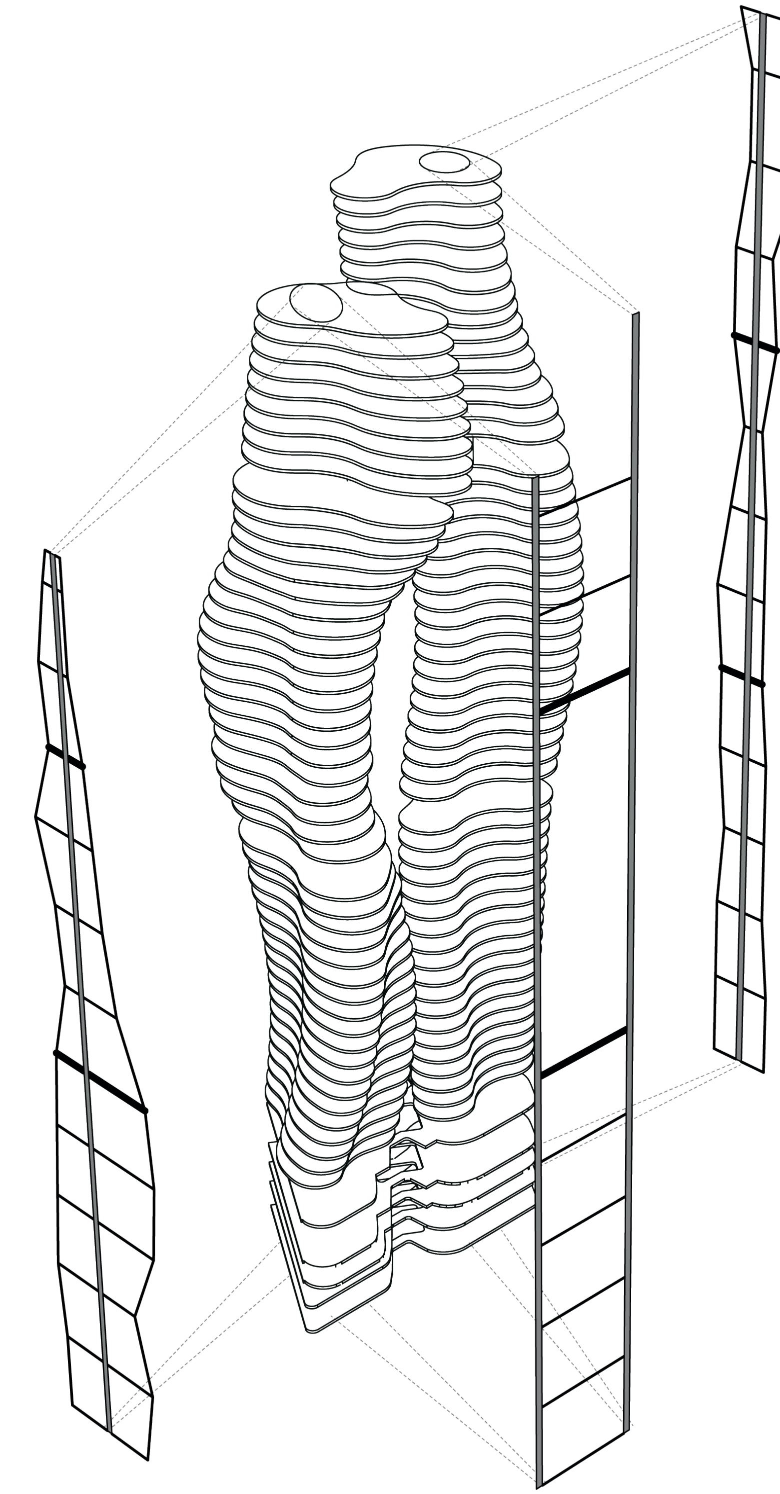
The building's shape could not be taken into account for the wind loading. Instead, the area extrusions seen in the loading diagram were used to estimate a wind force, using the ASCE 7-16 directional method.



Core Shape Variation

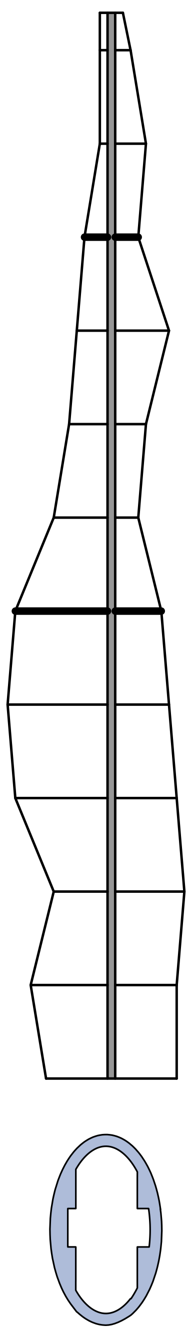


3D Model



2D models

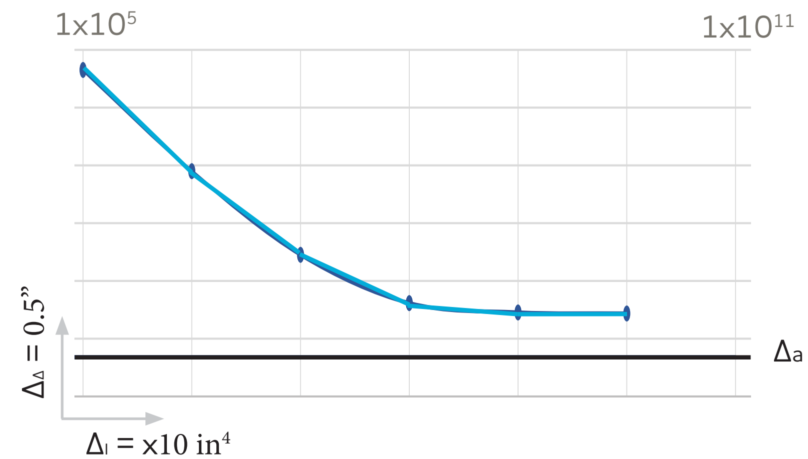
6.0_the HOODOO **Tower 1 Analysis**



Core = 3'

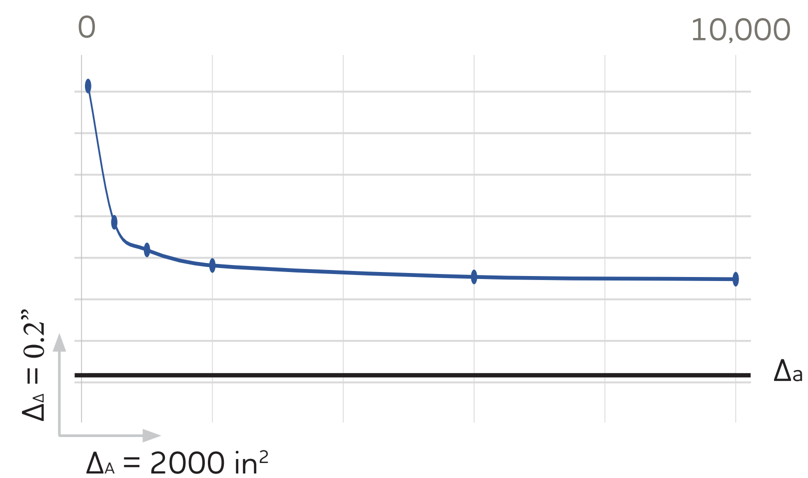
$I_x = 2.036 \times 10^9\ in^4$
$A = 66{,}398\ in^2$

Outrigger Moment of Inertia

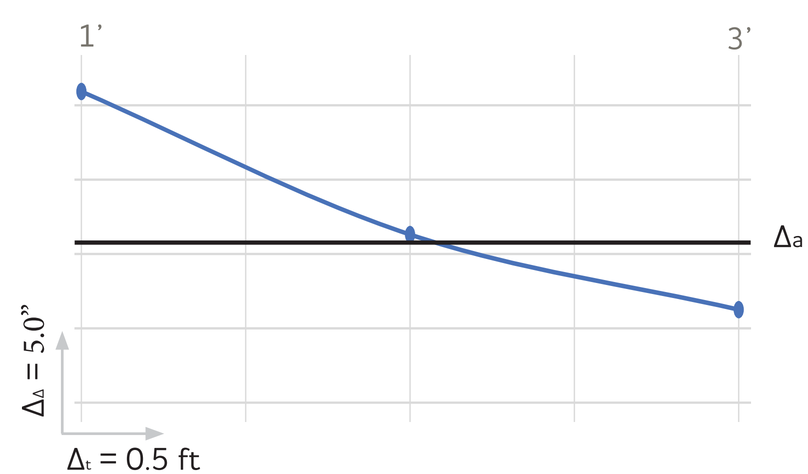


Outrigger Area

Deflection (in)



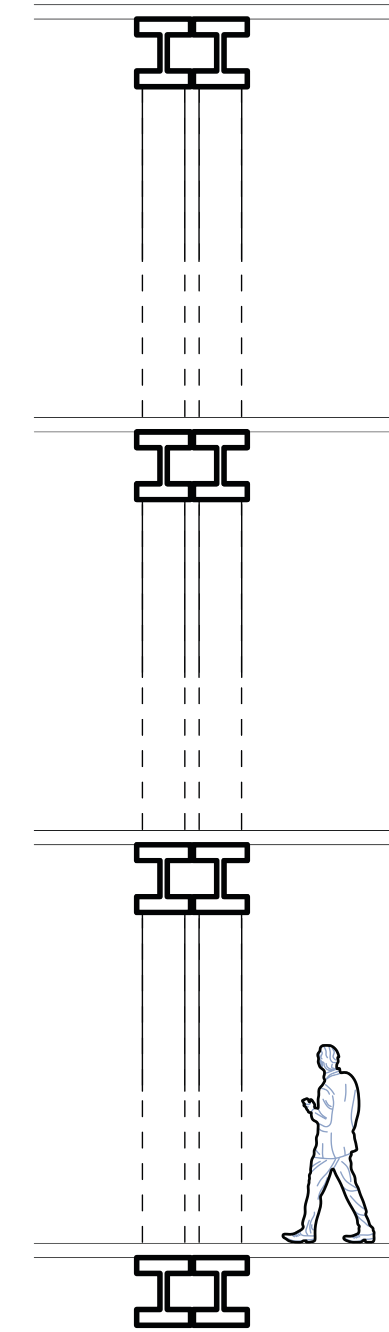
Core Thickness



The first tower analyzed was Tower 1. The tower was analyzed for deflection criteria and served as a parametric study to understand the effect of outrigger and core section changes on the tower deflection. Variations were made to all elements of the model, to understand what effect they had on the model stiffness. It was found that only changing the core and outriggers offered significant changes to the stiffness.

Initially, I believed that only changing the core size had any effect on the stiffness of the tower. I had changed the outrigger sizings and seen little success in reducing the stiffness. After encouragement from my advisor, I continued to increase the outrigger stiffness, until I reached a stiffness that did have a significant impact on the tower stiffness.

As it turns out, outriggers are only effective when their relative stiffness is comparable to the stiffness of the element they are restricting. This is in keeping with the results found in the coupled shear digital study. Even then, they have to be carefully designed, as their effectiveness diminishes exponentially once they have restricted the element. This can be seen in the beam parametric studies to the left. As the area and moment of inertia continued to increase, the deflection reduction stagnated. Increasing the core stiffness also began to stagnate, but this stagnation occured long after the architecturally allowable core thickness was surpassed.



Outriggers

W 14 x 873

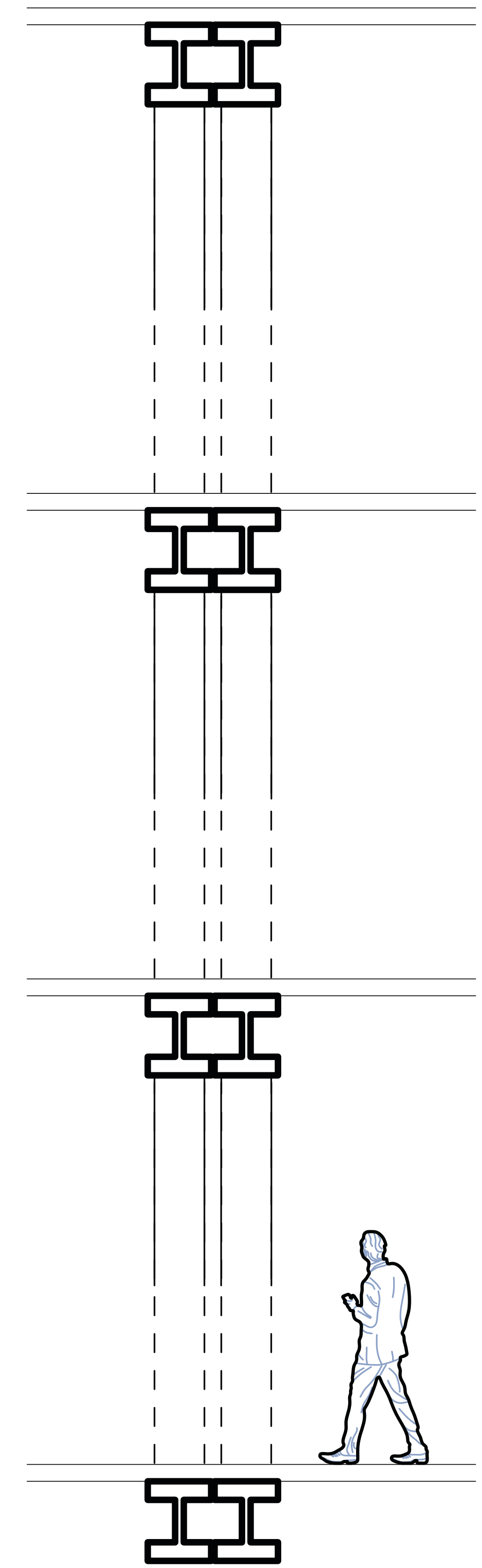
$I_x = 1.201 \times 10^7\ in^4$
$A = 2{,}046\ in^2$

6.0_the HOODOO **Outrigger Design**

Once an appropriate deflection had been met, it became time to devise an outrigger system which could achieve the high stiffness required. In the parametric studies, the moment of inertia was shown to have a larger effect on the deflection decrease. Because of this, I chose to use my moment of inertia to control my outrigger design.

Given the parallel axis theorem, the most effective way to increase the outrigger moment of inertia was by increasing the distance or the area of the shapes. The distance was increased by increasing the outriggers from two stories to three stories. The section shape chosen was a W14 x 873. Although still incredibly heavy, this shape had an area comprable only to the W 36x 802+, while retaining a smaller section size.

Through a system of trial and error via Matlab code, I was able to find an outrigger configeration which, although a goliath, could be feasible. Two W14 x 873 beams at each floor of the three story system, as pictured to scale to the right.

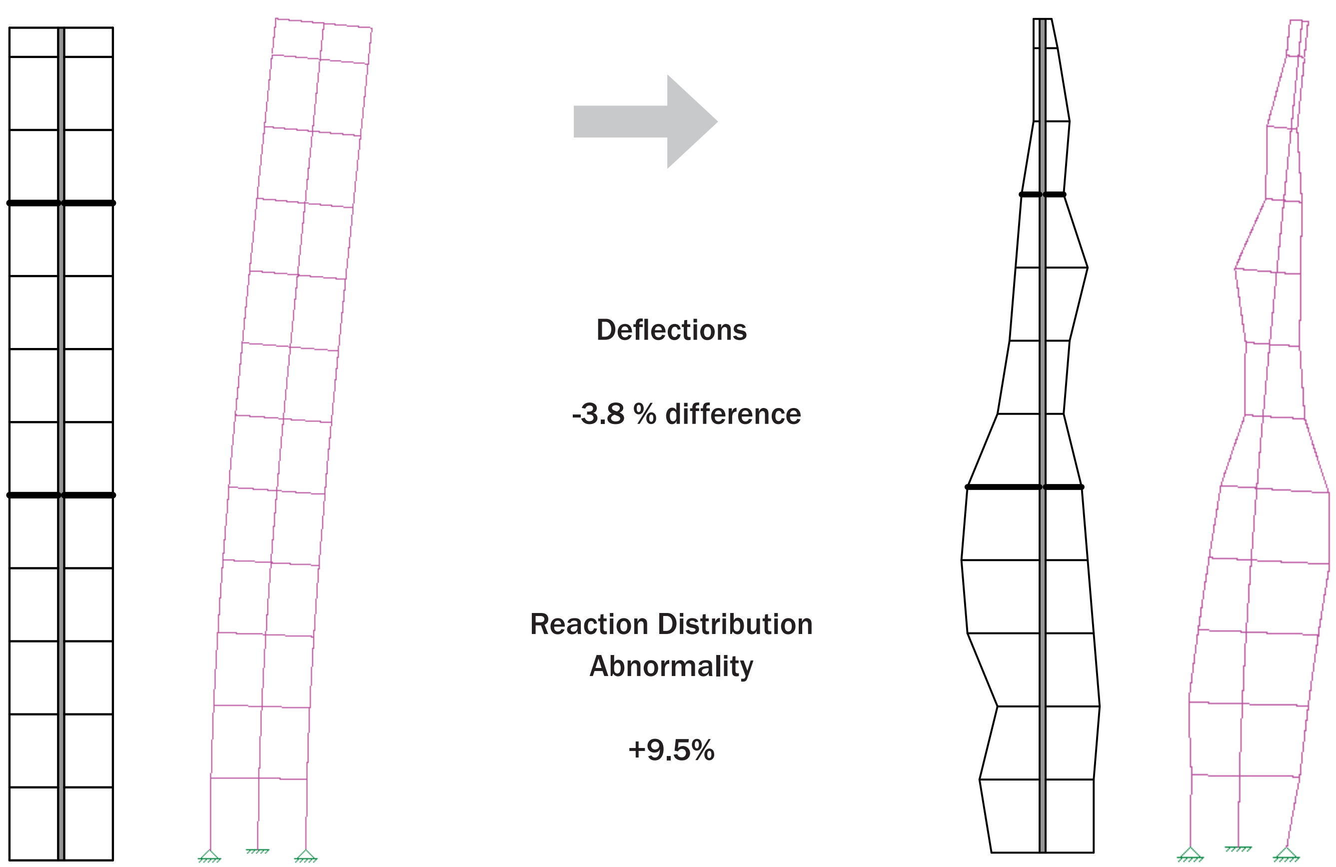


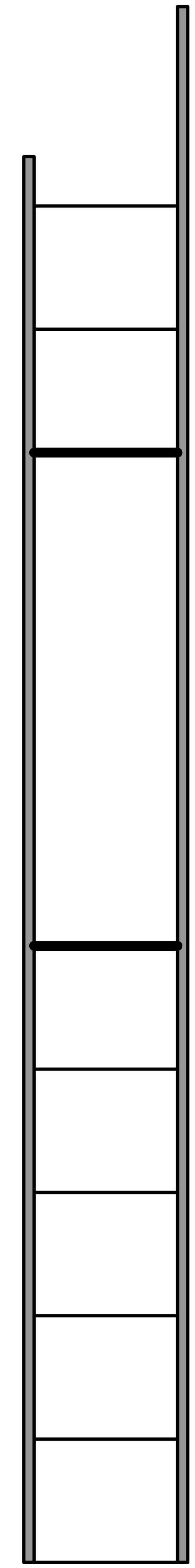
Outrigger Diagram

6.0_the HOODOO **Analysis**

Alongside the core studies, canted column studies were run to determine the effect the cant may have on the structure. In order to understand these effects, the towers were run as averaged vertical columns and as canted columns. It seemed the largest factor contributing to the stiffness was the aspect ratio, or more specifically, the base width.

When the averaged model had the same base width as the canted column, the deflections were within 5% for both tower 1 and tower 2. In tower 1, the deflections were actually slightly improved thanks to the cant. However, introducing the cant did lead to an abnormal distribution of forces. In the averaged model, the columns created a perfect force couple, with matching tension and compression axial forces. In the canted model, the core began to take some of the compressive loads, and the base reactions of the columns did not match.





After the first tower was designed, a model was run to confirm the expected stiffness in the longitudinal direction. The model was run assuming the same properties, with a 3′ width core for tower 1 and tower 2 and the chosen outrigger design. The results were conclusive, showing that the tower meets deflection criteria in the longitudinal direction.

In order to understand the contribution of the outrigger, as compared to the use of beams, the individual tower stiffness was compared to the joint tower stiffness. Individually, both towers deflected about 30″. Once joined, the structure deflected a little less than 10″. This would indicate that joining the towers through outriggers increase the joint stiffness to three times that of the individual core stiffness.

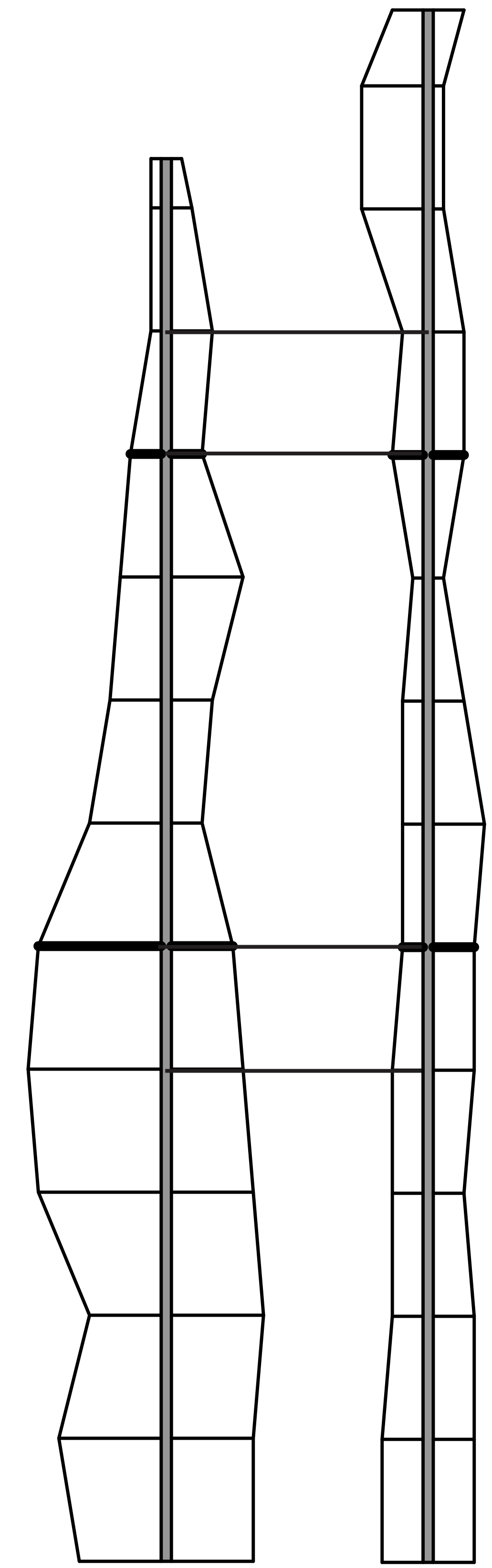
The next step in the analysis was to examine Tower 2. Tower 2 has an aspect ratio of about 10 and a maximum core width of 35'. When run by itself, the tower did not meet the deflection criteria.

The next study run was with both tower cores linked through pinned rigid links, shown to the right. This is to account for stiffness that tower 1 would contribute to tower 2 through their slab and beam connections. Tower 2 again did not meet the deflection criteria required.

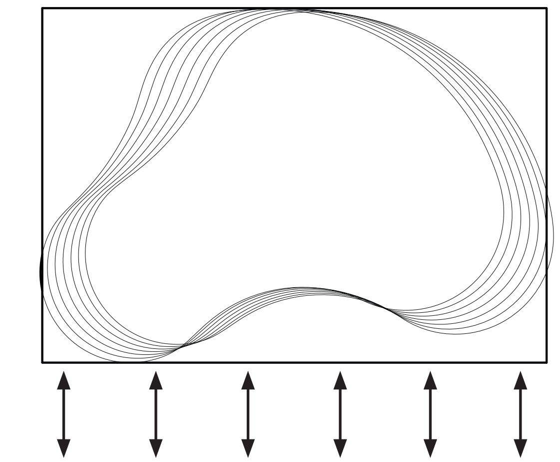
It was found it would require either a 65% decrease in loading or a 300% increase in the tower core stiffness. The tower loading is based on conservative code-based loads and an extruded surface estimation. As the tower design goal is wind interaction, it is very likely that the tower loading would if proper wind studies were run. Unfortunately, due to the Covid-19 pandemic, we were unable to test the tower in the wind tunnel. A paper in the International Journal of Science, Engineering and Technology Research[5] seems to indicate that the shape effect from a square to an ellipse may decrease wind forces up to 70%. Although the circular shape did not see the same decrease, our tower rotates as it rises, likely causing disruptions of the wind loads.

Furthermore, the cores were chosen as idealised ellipses, due to concerns of dealing with a complex shape. If I had more time on this project, I would look into using the full area of the second tower to create a responsive core. A 3' core as marked in the picture to the right would meet the 300% increase in stiffness criteria.

I believe that if this tower were analyzed further, the deflection failure could be solved through a combination of in-depth wind analysis and a full use of available area for the core.

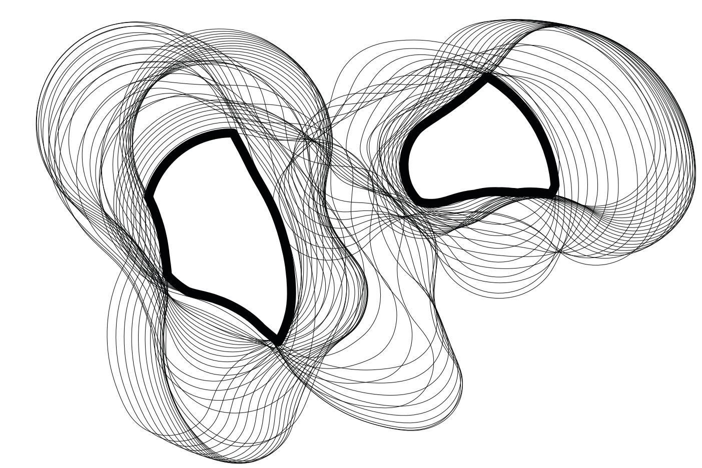


Load Correction



65% Decrease in Tower 2 Loading

Stiffness Increase



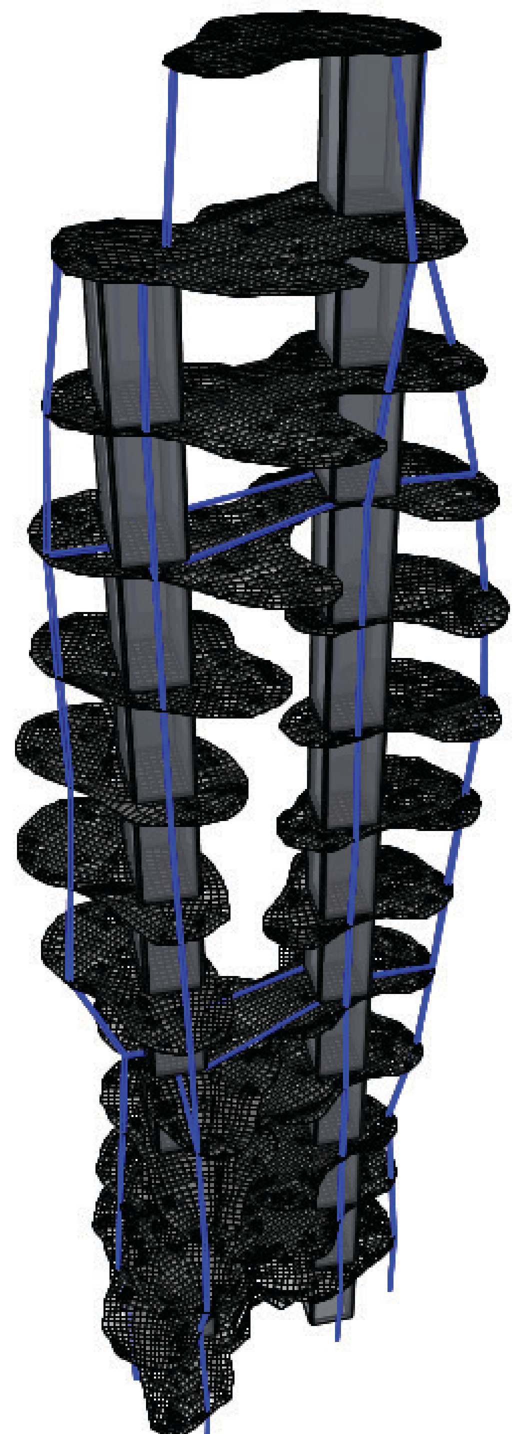
300% Increase in Tower 2 stiffness

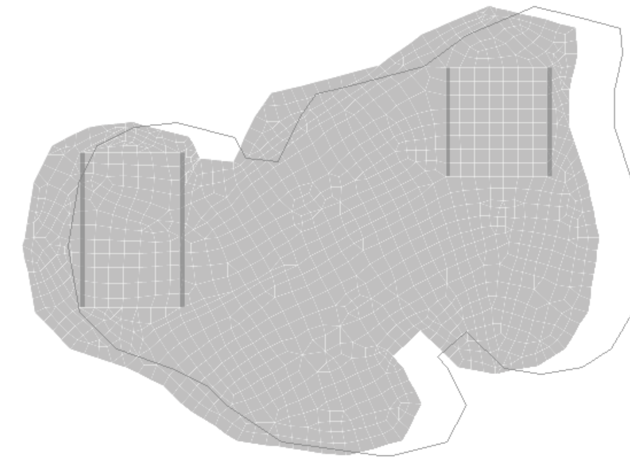
6.0_the HOODOO **3D Analysis**

The 3 dimensional analysis was run to understand what torisonal issues the tower might experience. An ETABS model was run and examined for expected deformations within the first three mode shapes and for anything irregular within the deflected shapes. For ease of analysis, the loads were applied to the center of mass of each slab.

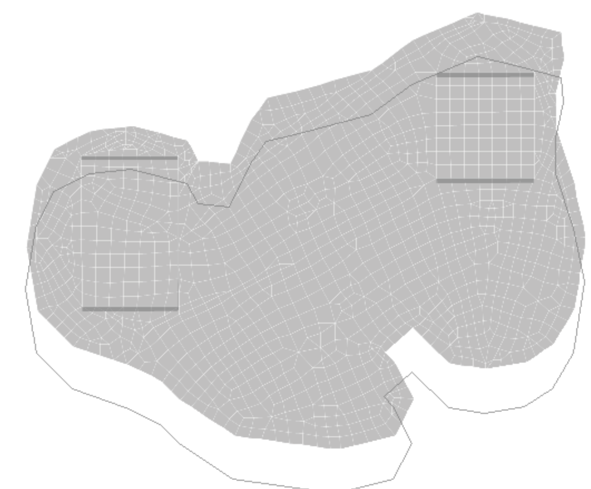
The results were as expected, with the first mode experiencing displacement in the x direction, the second in the y, and the third in rotation. Additionally, when the x and y loaded deflected shapes are examined, there is no distinguishable torsion visible.

This result makes sense, as the tower cores were built according to available space. In other words, the larger core, with greater stiffness, is also in the larger tower, with greater mass. The relative stiffness and mass are about equal, given that the shapes were designed to match their respective tower.

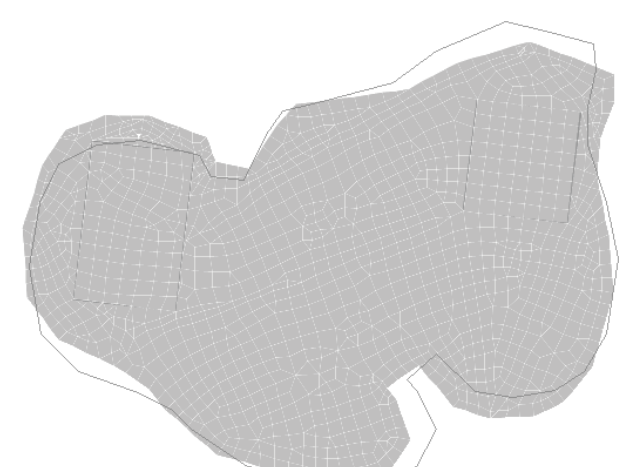




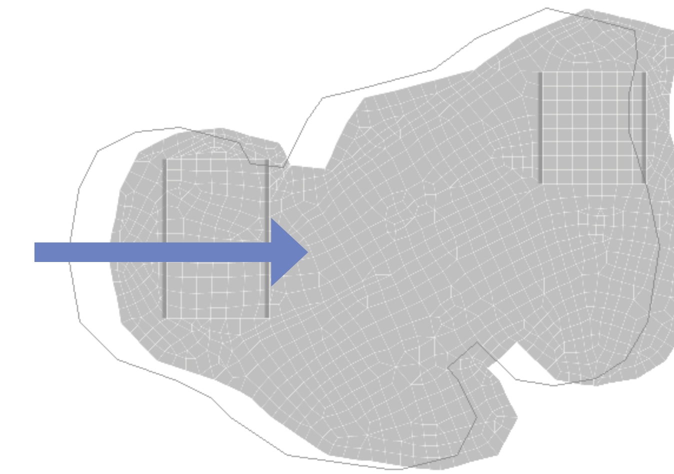
FIRST MODE SHAPE: T = 6.77 s



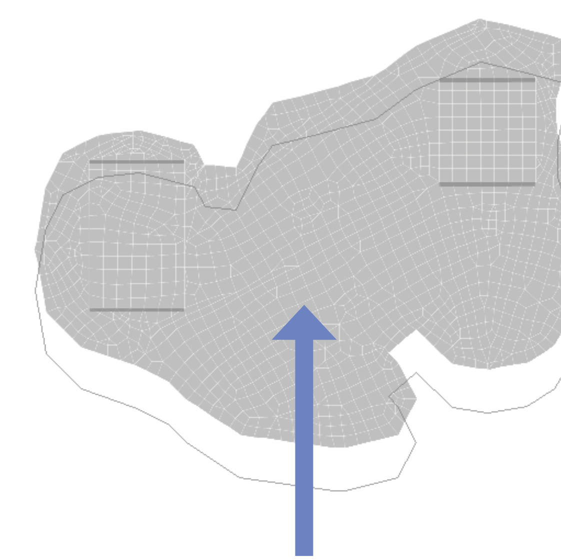
SECOND MODE SHAPE: T = 5.34 s



THIRD MODE SHAPE: T = 1.25 s



DEFLECTED SHAPE ALONG X



DEFLECTED SHAPE ALONG Y

7.0_Conclusion

This design collaboratory has been an incredible learning experience. I used to think that high rise design would be complex for an undergraduate to complete. After two quarters of studies, models, and discussion, I feel I have become proficient in designing a proposed structural system. I've come to believe that the not-so-secret big secret about structural engineering is everything you design can be boiled down to the basics: mechanics of materials, force flow, and deflections. Even within high rise design, we focused on the mechanics of materials, with section properties of members, forces, moments and shear and axial force diagrams,and deflections. This studio has fostered my instinctive ability to apply those concepts. I believe the more I practice, the more that instinct will grow and I can't wait to continue developing it.

7.1

8.0_Student Experience

This studio experienced a unique journey, but me and my colleagues, in particular, have faced major twists in the road. Halfway through our studio, the response to the Covid-19 pandemic escalated to a stay-in-place order being issued for all of California. Events transpired so quickly, that we did not know our final in-person class was just that. Over spring break, the world went into quarantine. Not only did virtual learning become the new norm, but The Crystal team was disbanded, as our colleague had to leave for personal reasons, and we found ourselves merging with the HOODOO, who had also lost a member.

Despite all this, I think it was a great learning experience and I don't believe the quality of experience was diminished by the virtual setting. We were able to meet with professionals from SOM and have virtual reviews far more often than before. We were able to annotate posters on the screen as we spoke, which turned out to be a major benefit to the review process. We would meet three to four times a week via zoom, and group chats and texting allowed for at least some of the student community to continue. I, personally, was able to focus better on my work when commute times were cut out, although it was not as positive for my physical health, sitting in a chair for upwards of 12 hours a day.

Part of why my experience in the second quarter was so positive is that the Crystal group had major collaboration issues. Despite the three of us getting along as individuals, our work and communication styles were vastly different. It made the collaboration very frustrating and the studio very unlikable. By contrast, despite the lack of face to face contact, the remaining HOODOO team embraced us and we merged seamlessly. It was an amazing opportunity, getting to collaborate with them and having such a high level of communication and back and forth.

I believe that while in person contact is missed, we should consider incorporating technologies like zoom even when the pandemic ends. It would allow us to create more connections than we could've thought and would make distance meaningless when it comes to professional and personal contacts.


8.1

9.0_References

1. Image of the Robinson Tower. “A Gravity-defying tower aimed at ‘sustainable urbanism’ has opened in Singapore.’, CNN Style. 2020 Cable New Network. 08/02/2019. 06/06/2020. https://www.cnn.com/style/article/singapore-sustainable-tower-building-scli-intl/index.html

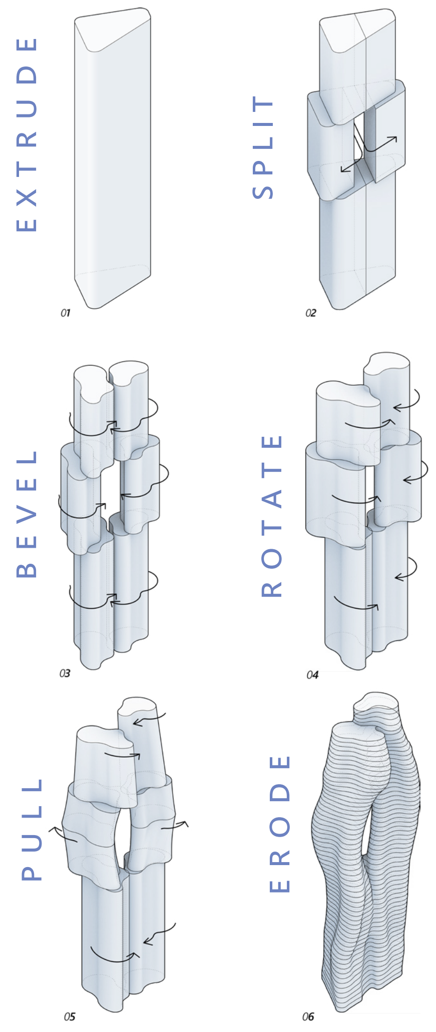
2. Image of the Broadgate Tower. “The Broadgate Tower Run Up - London 2017.” Good Run Guide. 2020 Good Run Guide Ltd. n.d.. 06/06/2020. https://www.goodrunguide.co.uk/RaceDetails.asp?RaceID=14469

3. Image of Hearst Tower. “Hearst Tower.” The Skyscraper Center. 2020 Council on Tall Buildings and Urban Habitat. n.d.. 06/06/2020. http://www.skyscrapercenter.com/building/hearst-tower/2245

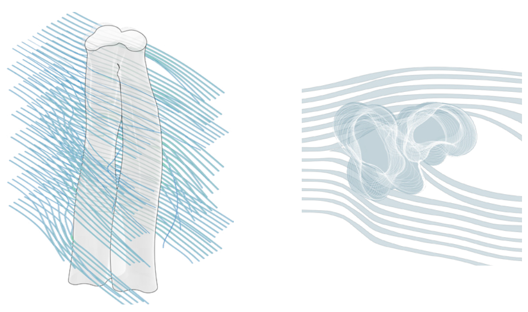
4. Image of the New York Times Tower. “What is the physical address for the New York Times office?.” Quora. n.p.. 11/21/2019. 06/06/2020. https://www.quora.com/What-is-the-physical-address-for-the-New-York-Times-office

5. Wakchaure, Professor M. R., Sayali Gawali. “Effects of Shape on Wind Forces of High Rise Buildings Using Gust Factor Approach.” International Journal of Science, Engineering and Technology Research (IJSETR), Volume 4, Issue 8, August 2015. 6/6/2020. http://ijsetr.org/wp-content/uploads/2015/08/IJSETR-VOL-4-ISSUE-8-2979-2987.pdf

the_HOODOO

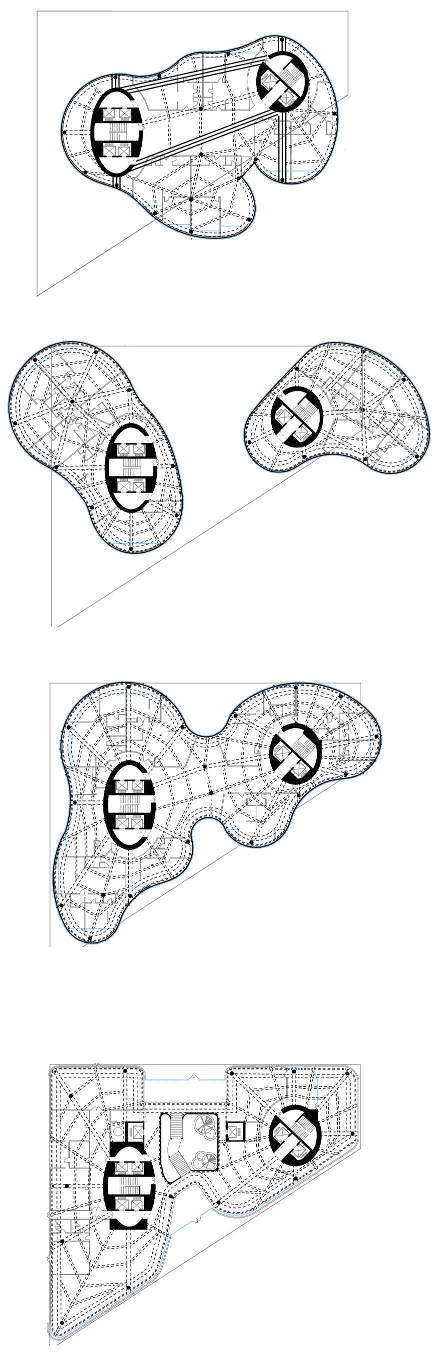


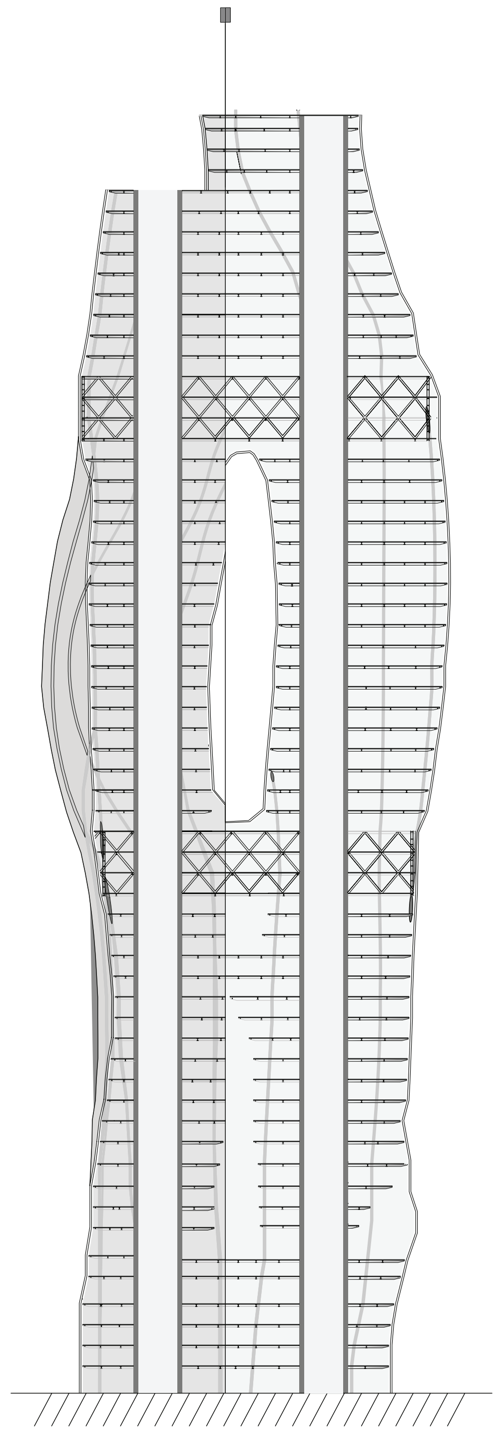
PROCESS



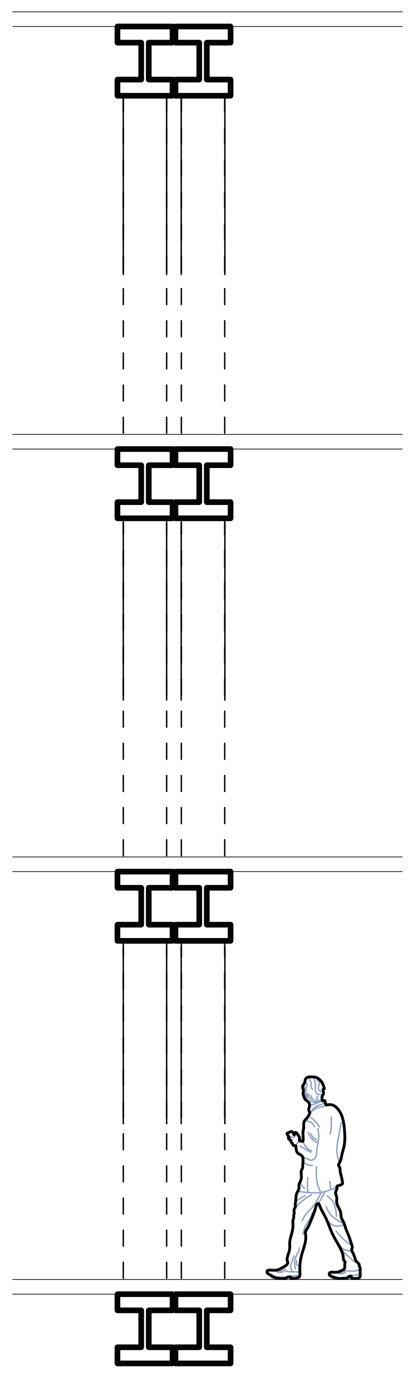
WIND STUDY

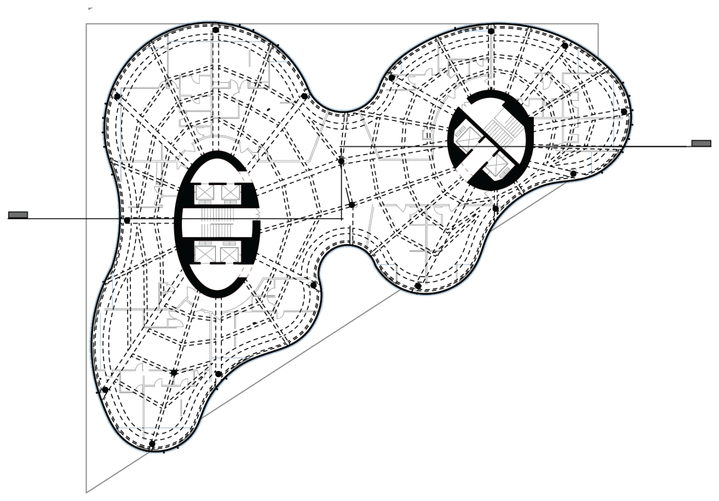
GRAVITY SYSTEM



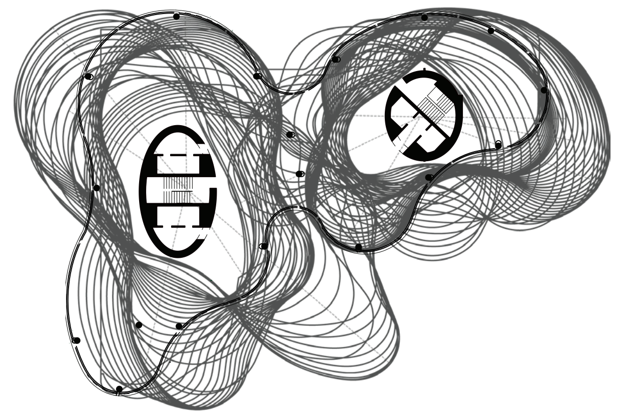


OUTRIGGER SYSTEM

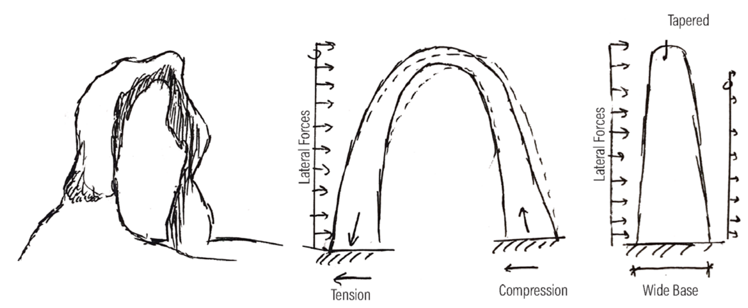




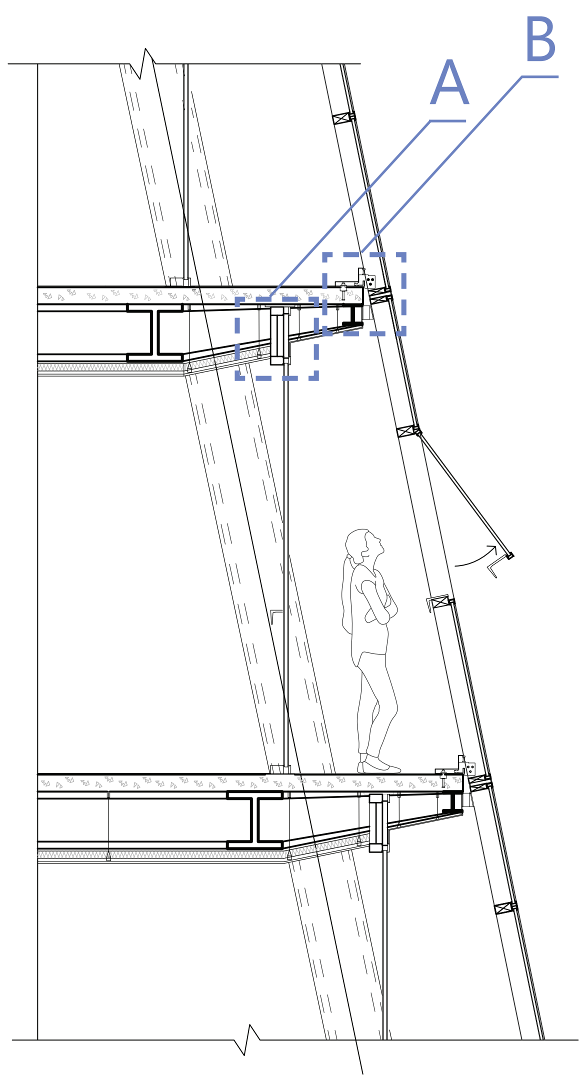
TYP. HOUSING PLAN

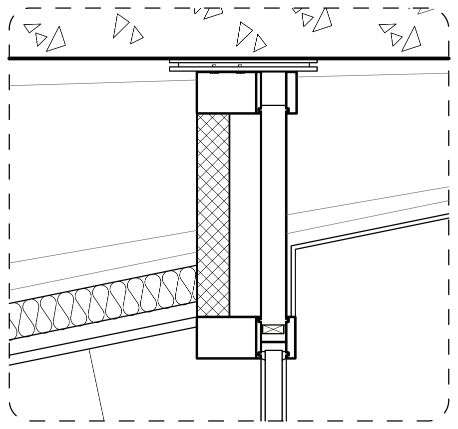


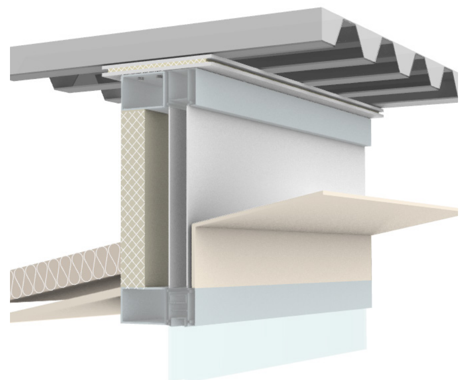
OVERLAY OF FLOOR



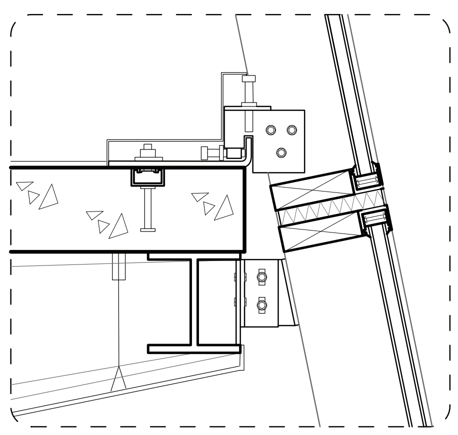
STRUCTURAL CONCEPT

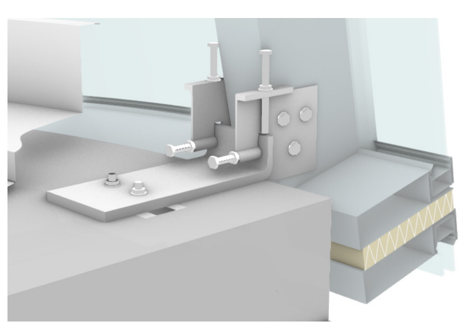


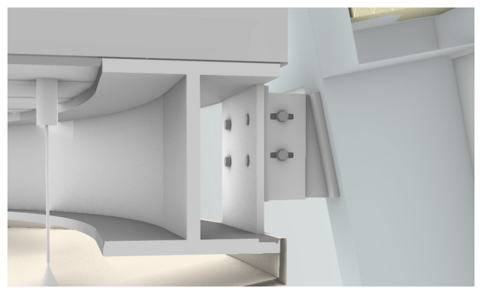




DETAIL A

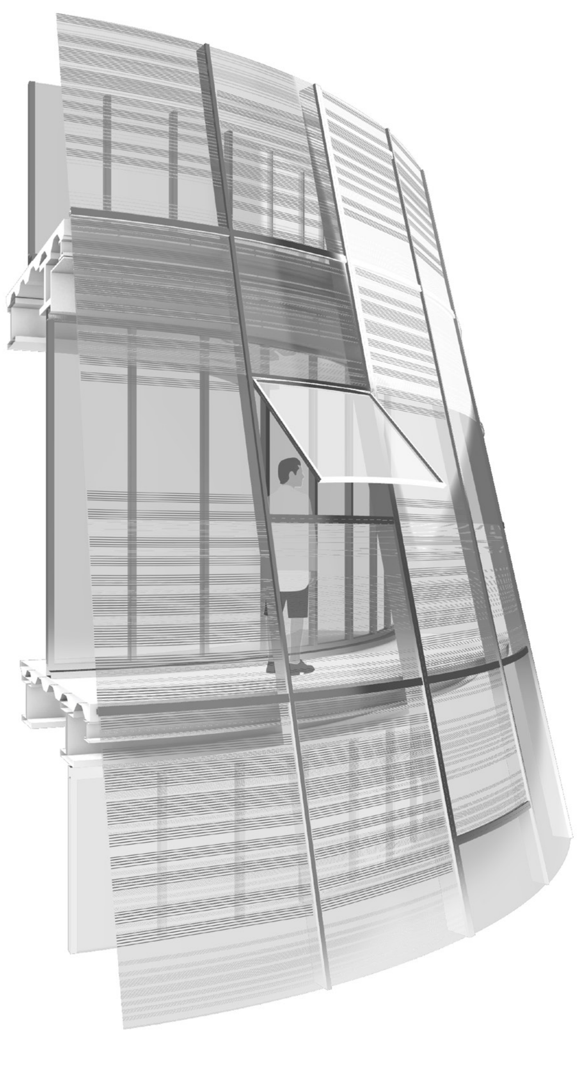


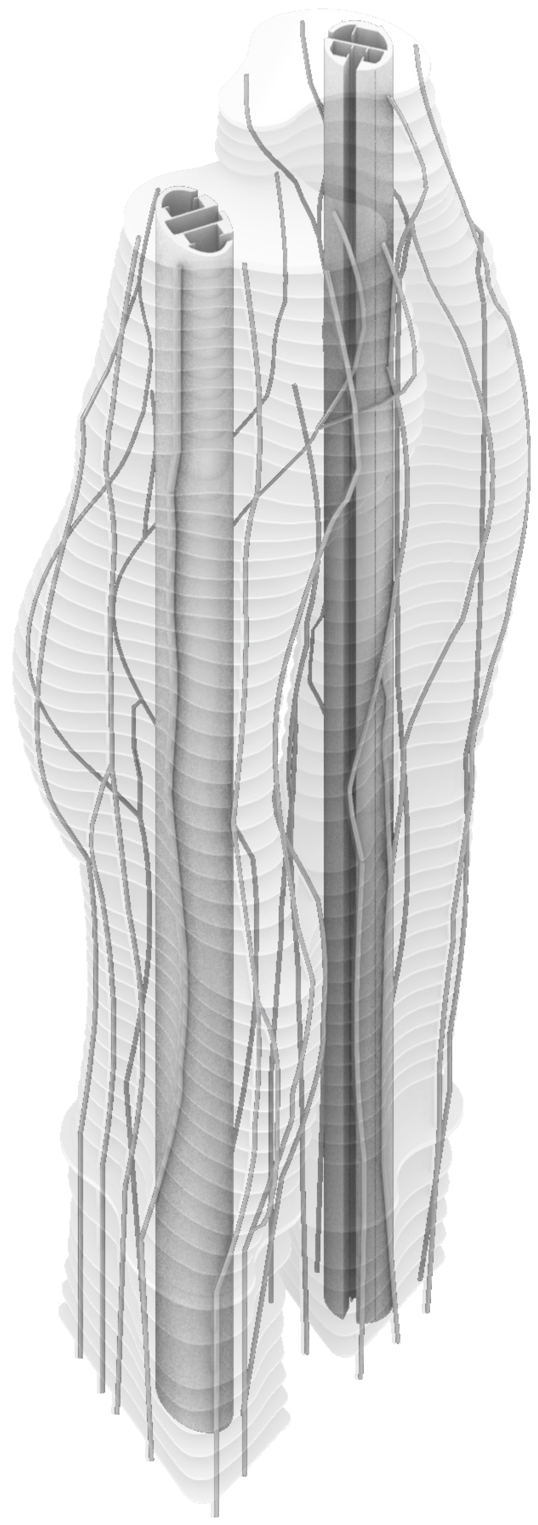


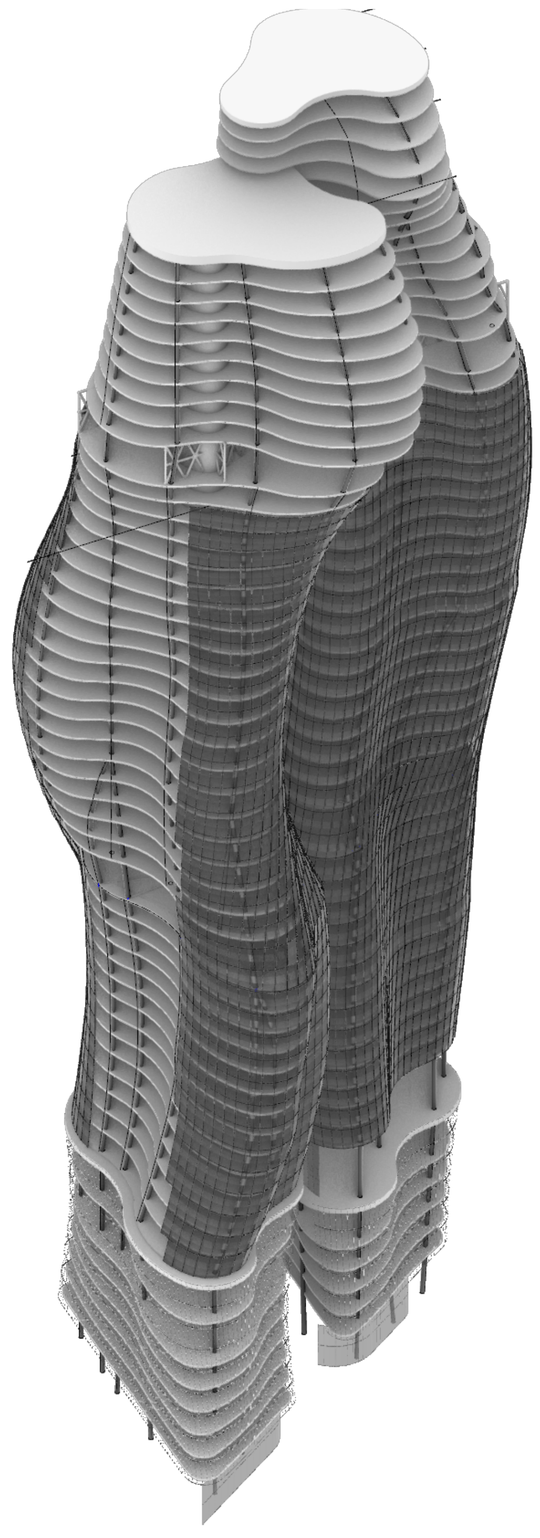


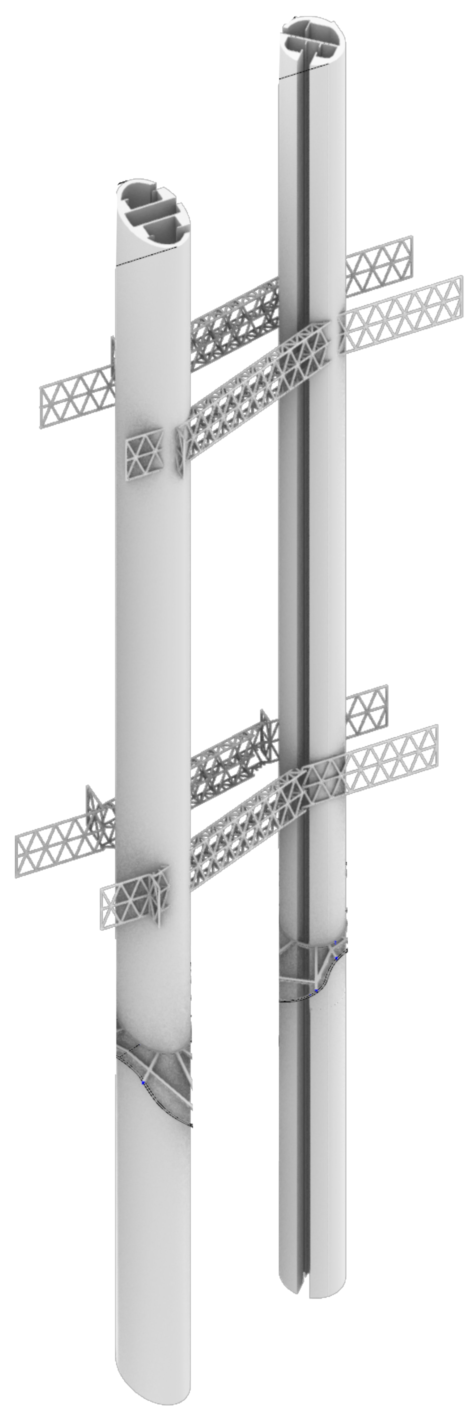
DETAIL B

PERFORMATIVE ENVELOPE



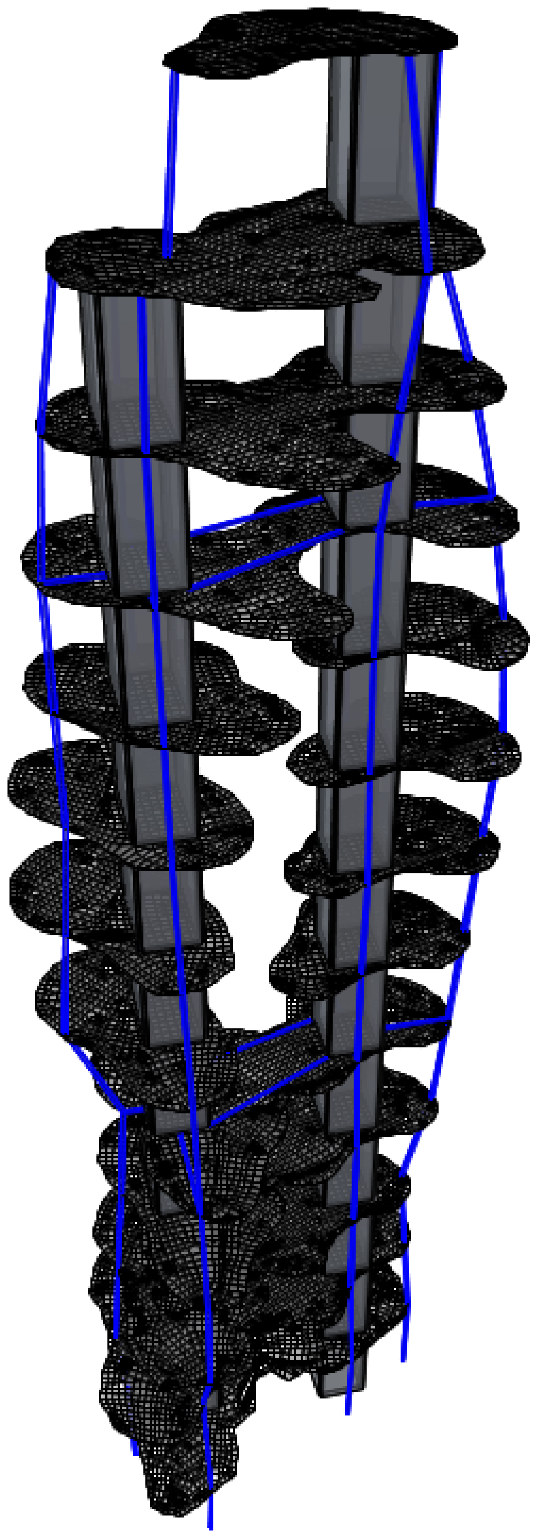


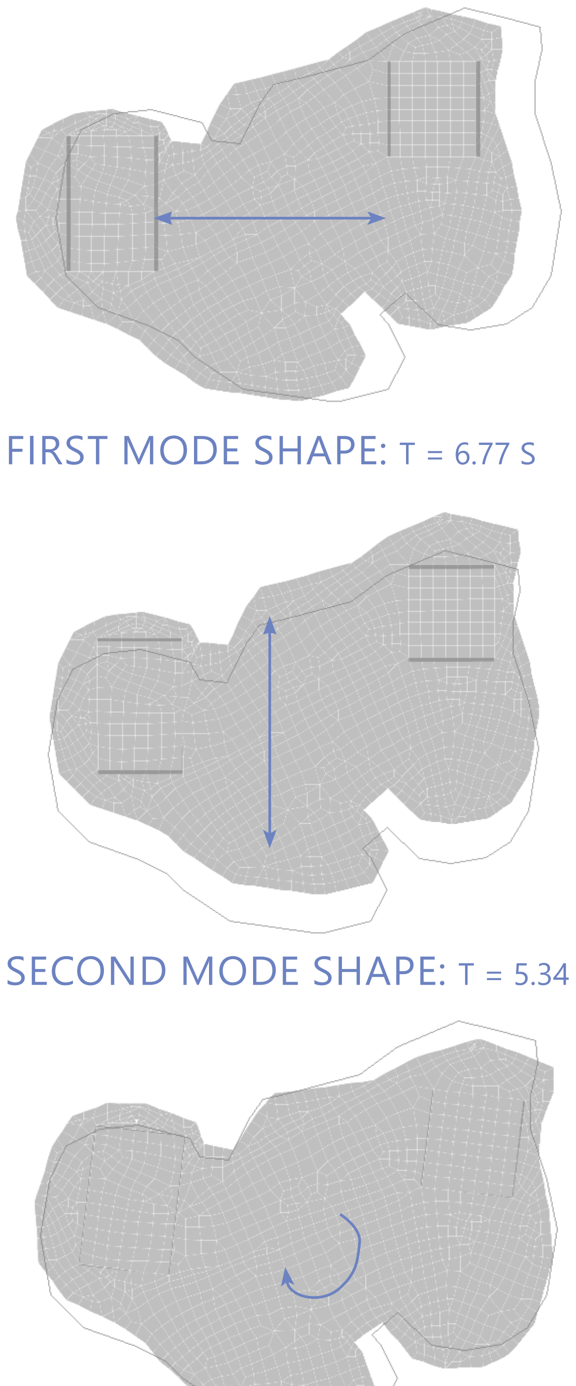




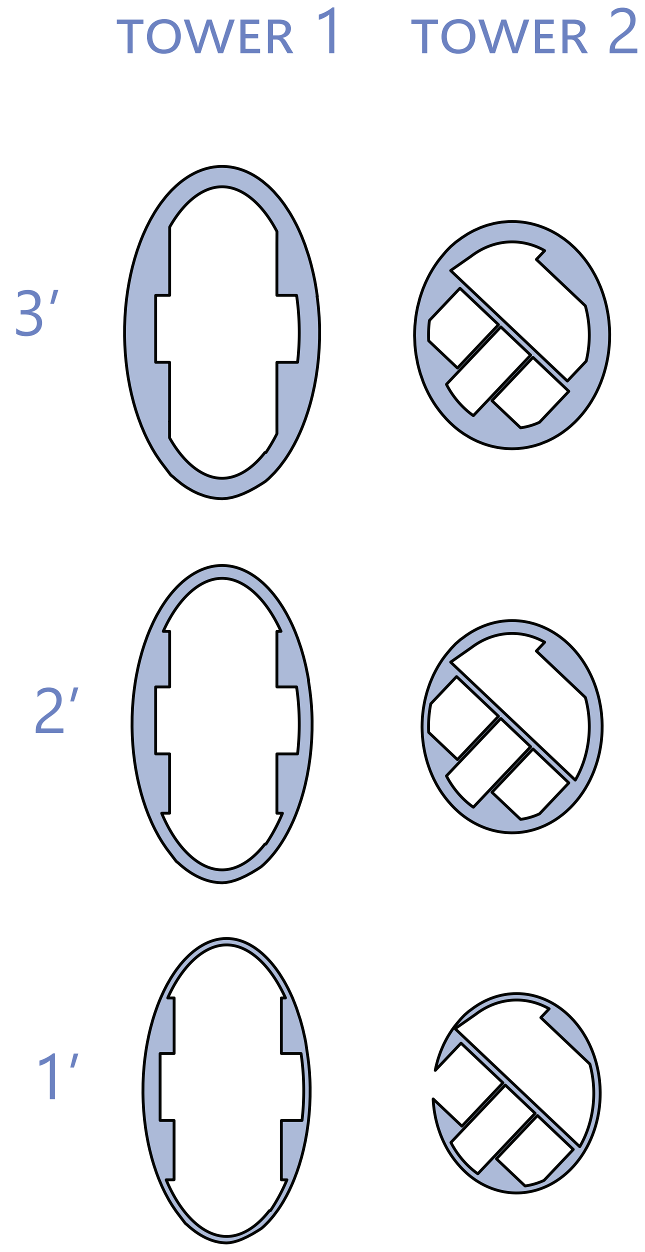
the_HOODOO
Structural Analysis

3-DIMENSIONAL ANALYSIS

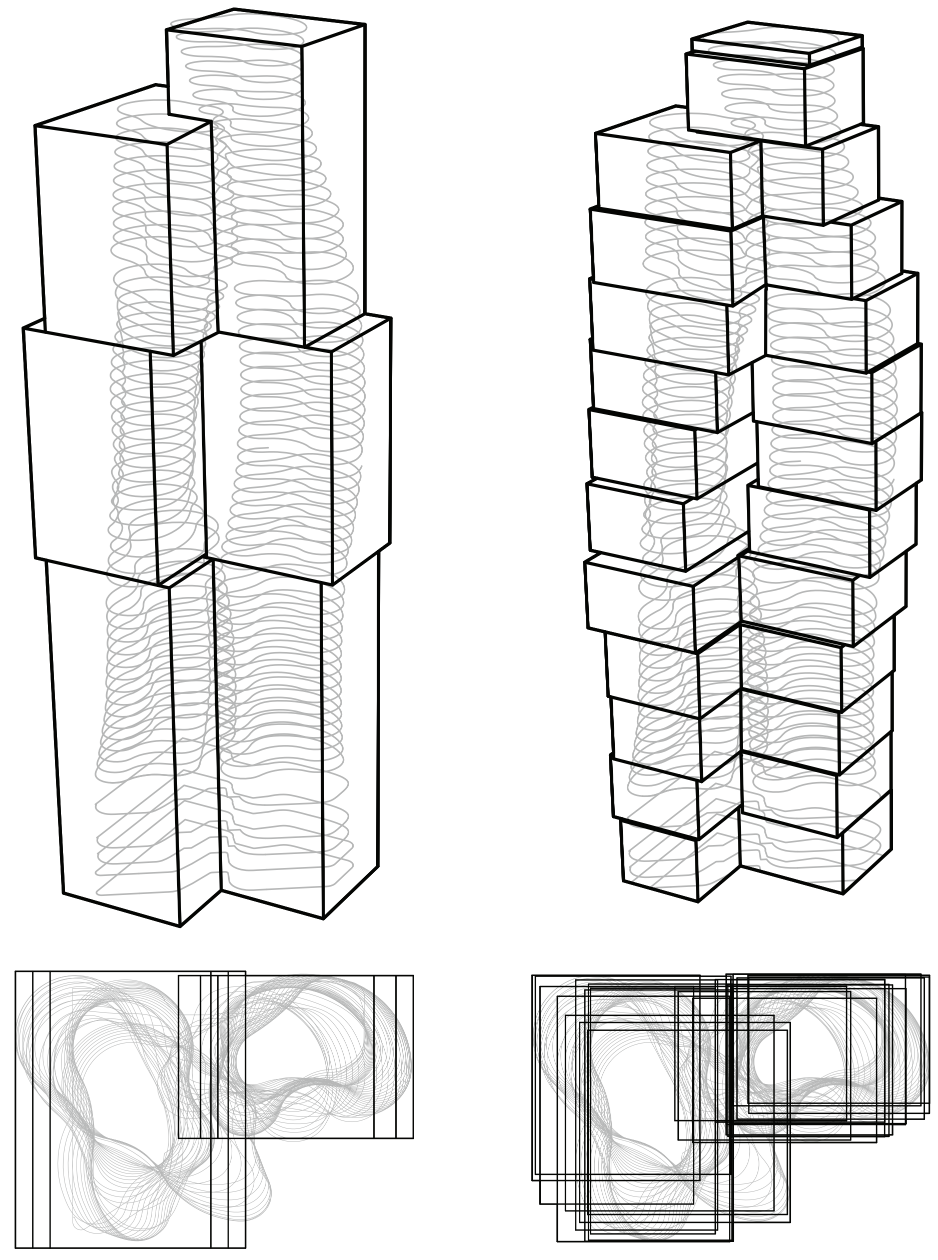




ANALYSIS INPUTS

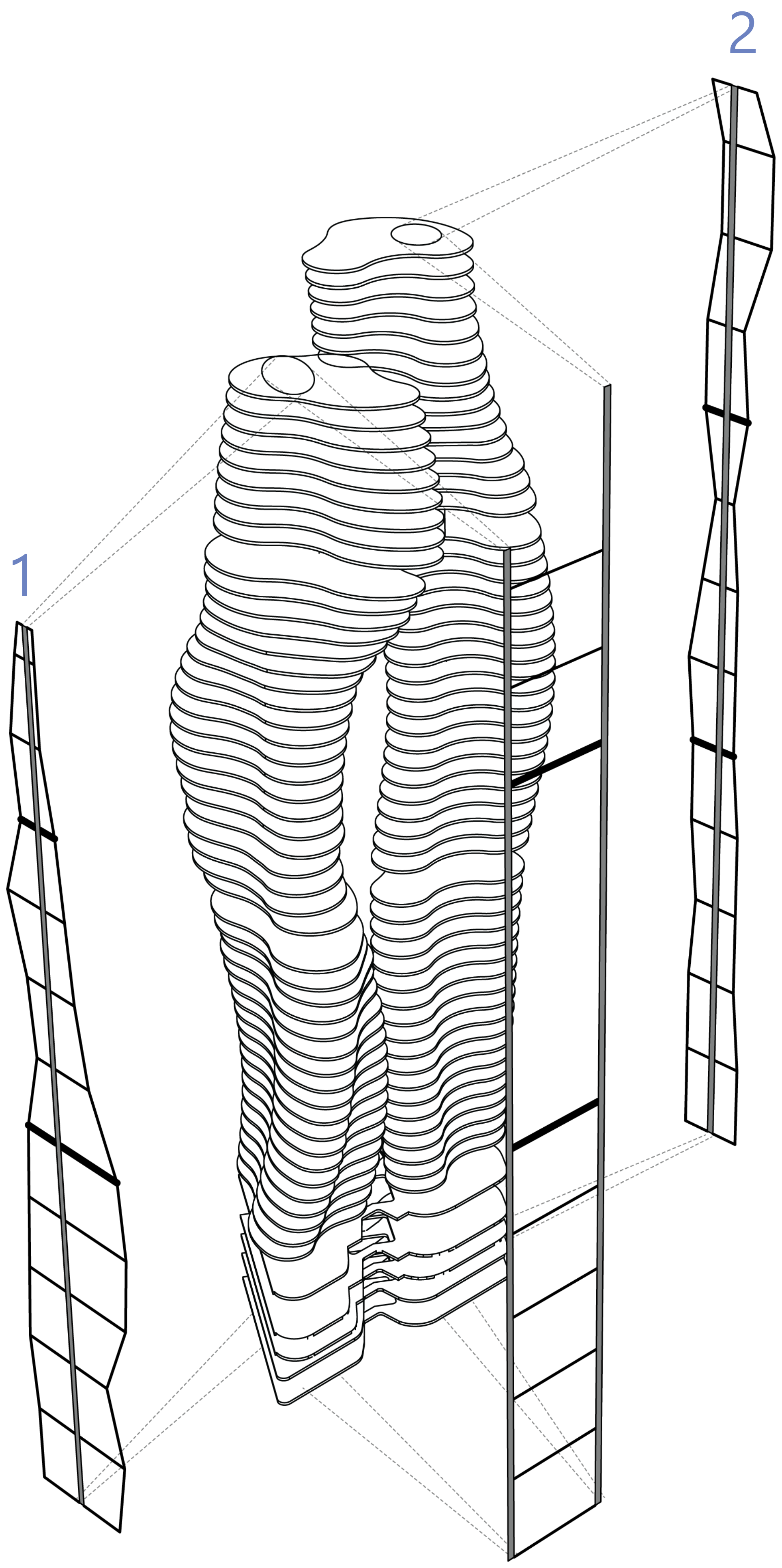


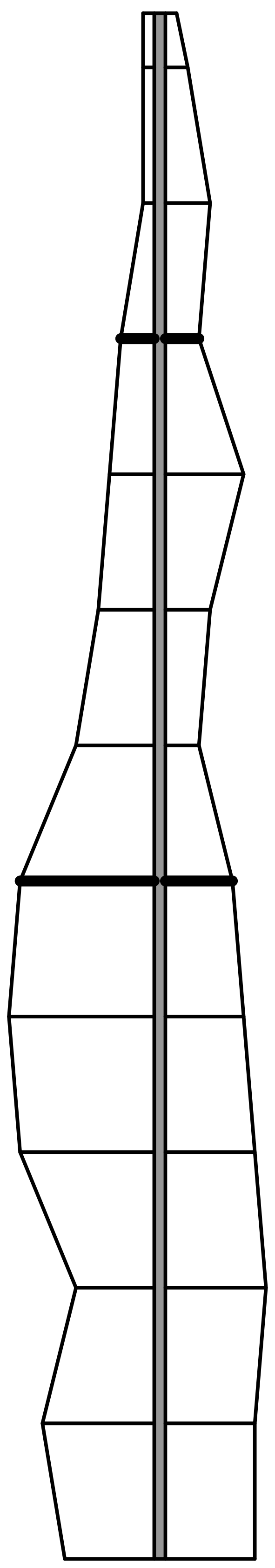
CORE VARIATIONS

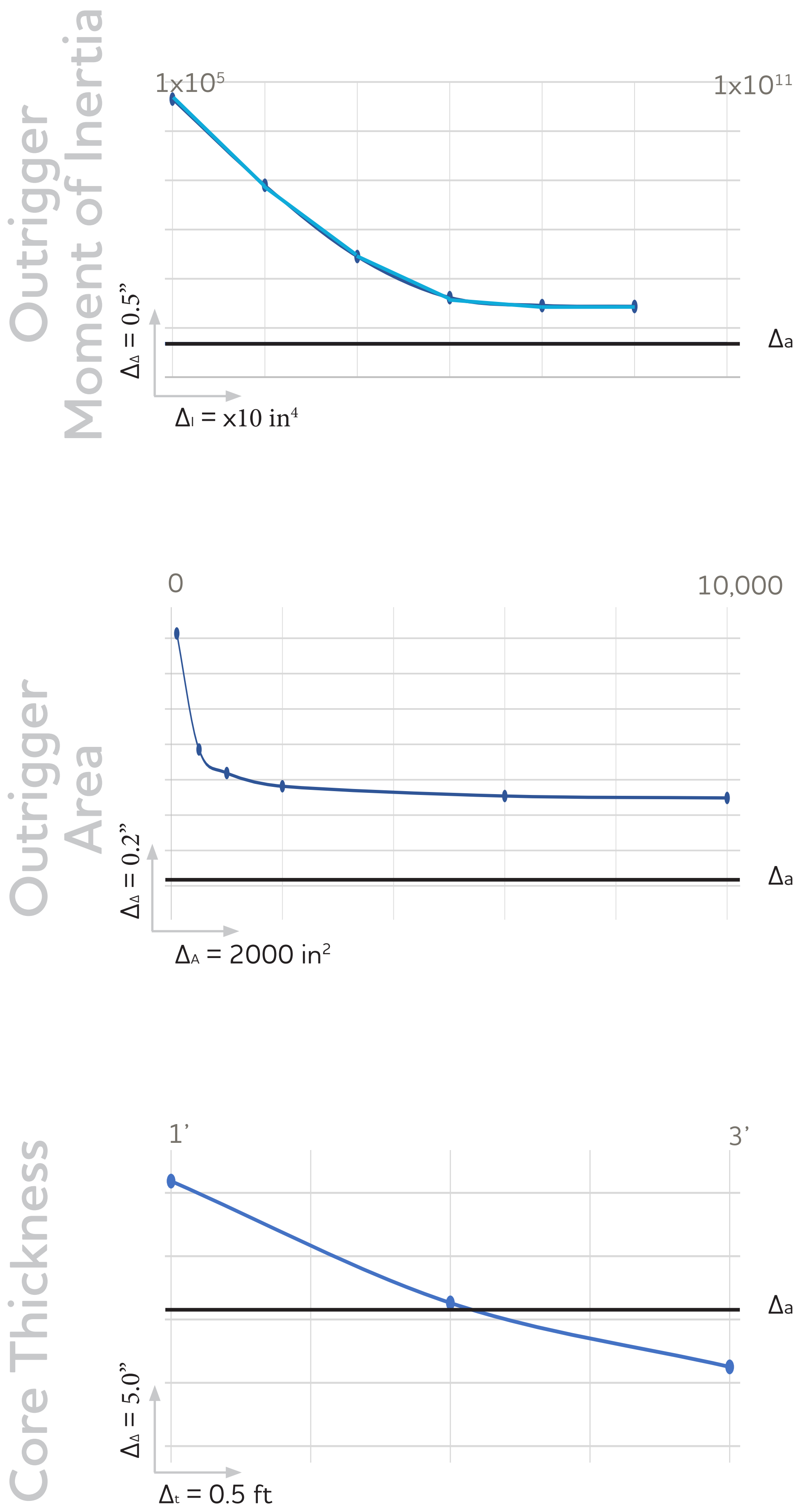


WIND LOADING EXTRUSIONS

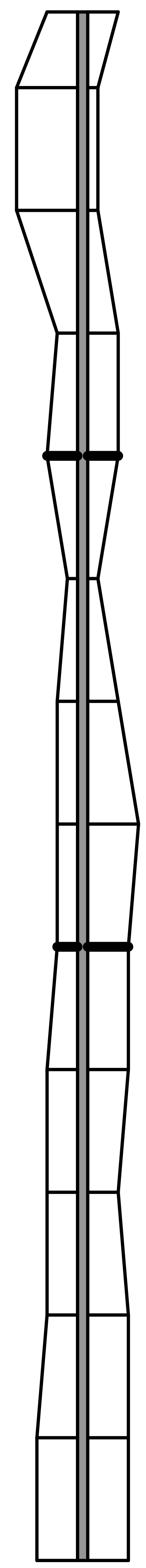
2-DIMENSIONAL ANALYSIS



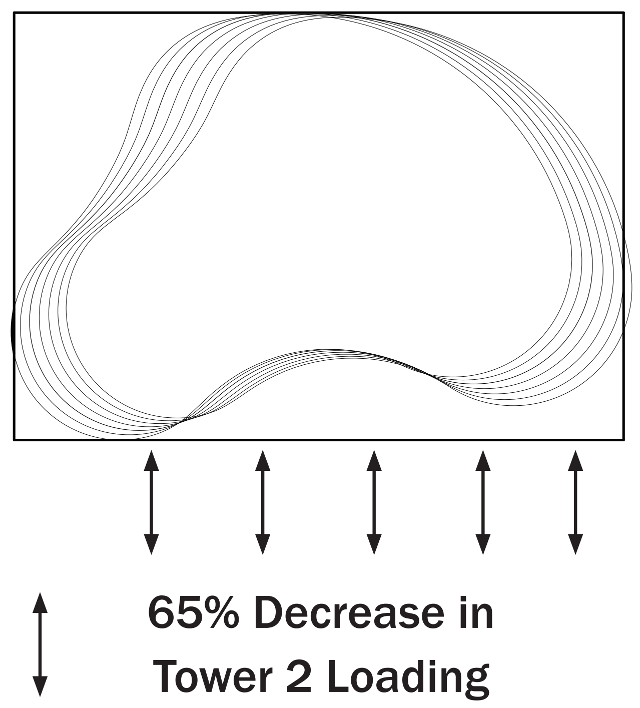




TOWER 1: PARAMETRIC ANALYSIS

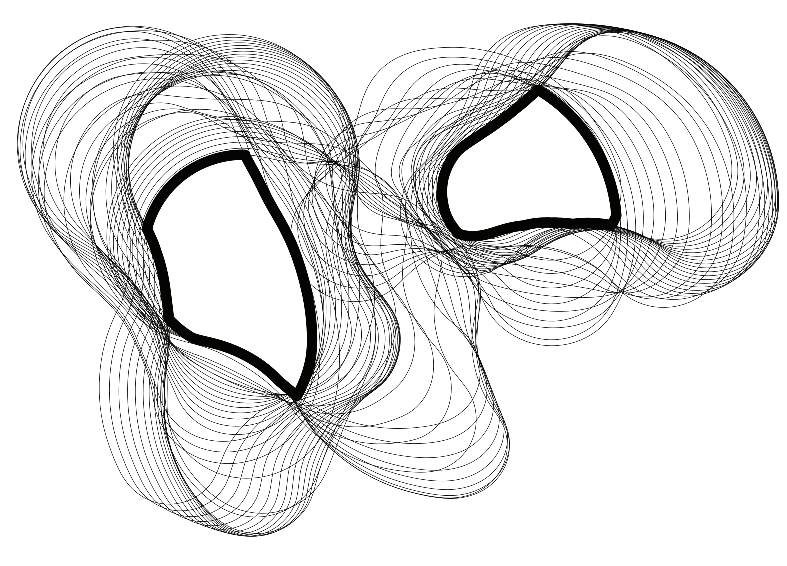


Load Correction



65% Decrease in Tower 2 Loading

Stiffness Increase



300% Increase in Tower 2 stiffness

TOWER 2: SOLUTIONS