the ALOE | Senior Project Report

ARCE 415 | Interdisciplinary Capstone Project: 2020 Skyscraper Collaboratory

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Abstract

The authors of this document are architectural engineering (ARCE) undergraduate students from California Polytechnic State University, San Luis Obispo (Cal Poly). They joined the 2020 Skyscraper Collaboratory as part of the ARCE course 415: Interdisciplinary Capstone Project. This course emphasizes the analysis and evaluation of interdisciplinary challenges associated with integrating the design and construction processes to deliver a project with respect to the design, quality, and performance expectations for a client or presented criteria. The course was taught in collaboration with industry partners and associates from the global architectural, urban planning, and engineering firm Skidmore, Owings & Merrill (SOM). Instruction took place over the span of twenty weeks to educate students about high-rise residential building design in an interdisciplinary and integrated design studio.

This report details the students' design approach for the architectural typology of rotation. The document focuses on architectural design process, structural analysis, and project impacts. More specifically, this report examines the development of building form, inherent torsion due to rotation, and contextual outcomes of tall buildings.

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1.0.0 Introduction

As part of an extended 20-week comprehensive building design studio, a team of architectural engineering (ARCE) students worked closely with assigned third year architecture (ARCH) students to develop a skyscraper for a chosen architectural typology. The studio consisted of ten teams with three to five students per team. Each team must address their selected typology and the built environment by studying topics relating to structural systems, siting, massing, adjacency, materiality, occupancy, natural ventilation, day lighting, computer generation and modeling, and constructability. A curation of their developments was then submitted to the Council of Tall Buildings and Urban Habitat (CTBUH) 2020 International Student Tall Building Design Competition and Association of Collegiate Schools of Architecture (ACSA) 2020 Steel Competition.

This report presents project deliverables and commentary from the perspective of the ARCE students.

1.1.0 Background

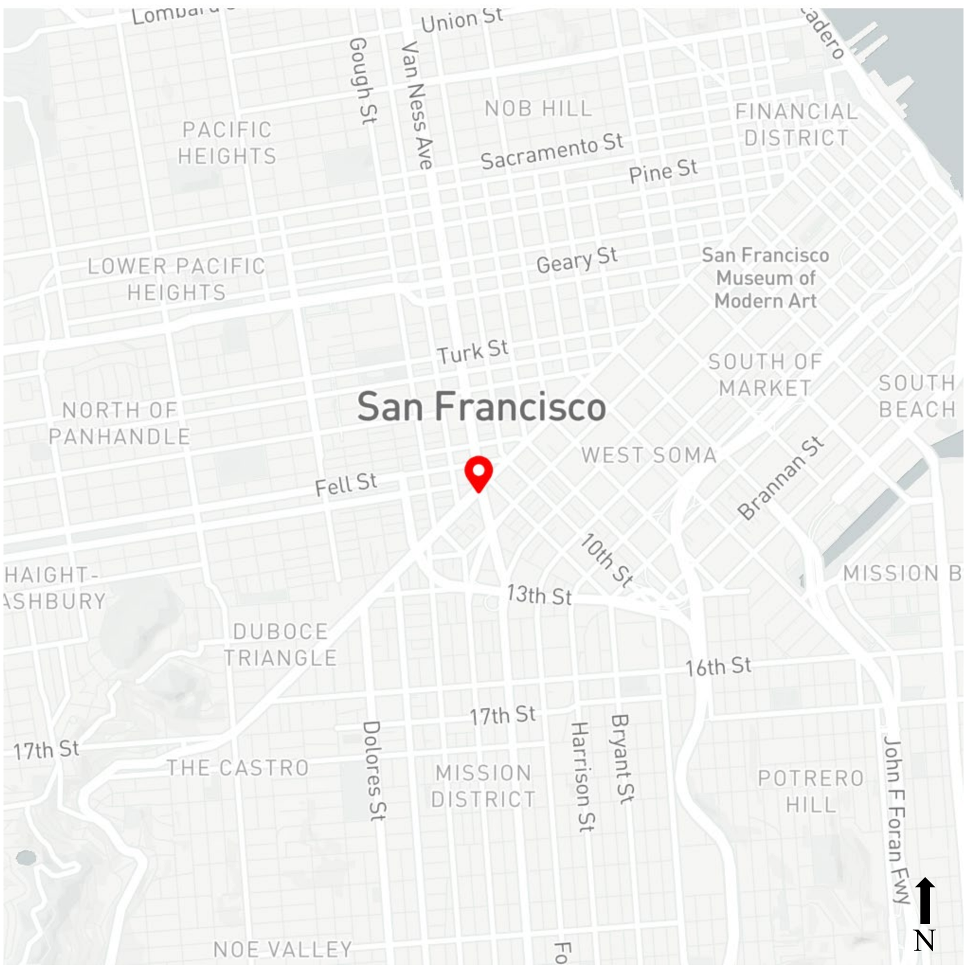


Figure 1: Site Vicinity

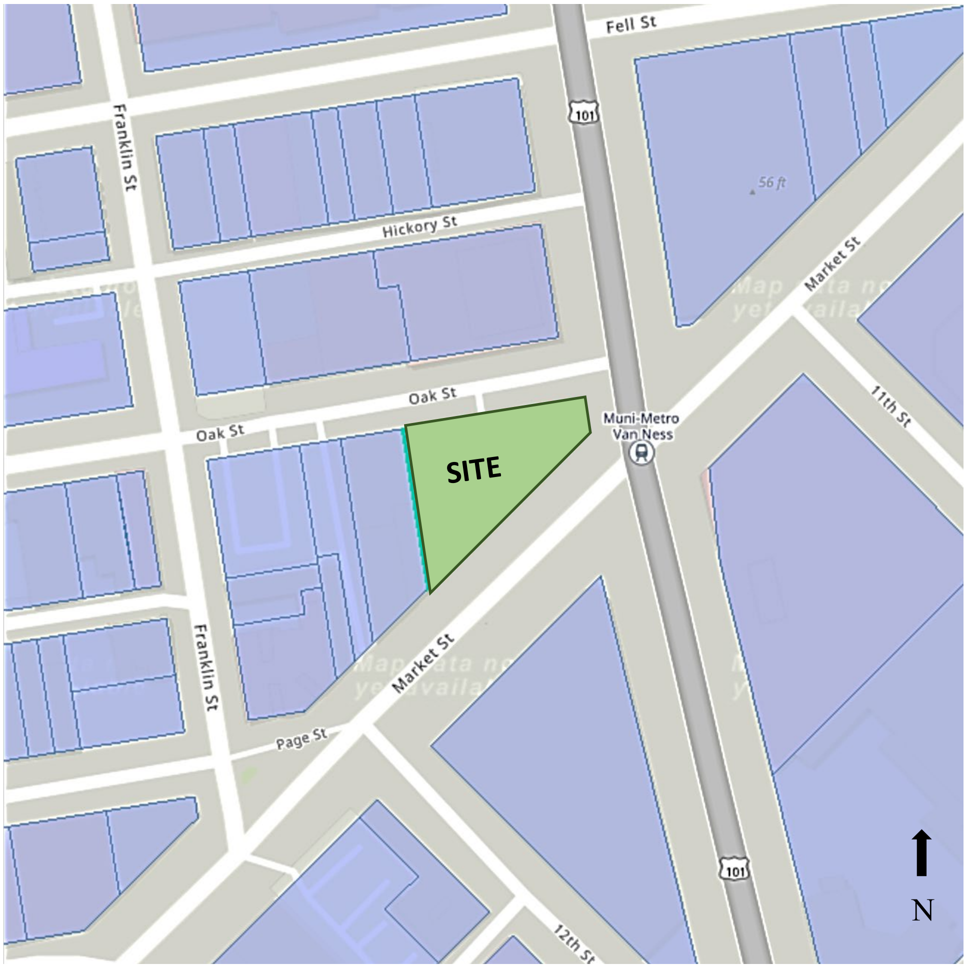


Figure 2: Parcel Map

The site is located at 1 Oak Street, San Francisco, California 94117, United States. The project is situated at the intersection of the major thoroughfares: Market Street and South Van Ness Avenue. It is a grouping of five city parcels in the shape of an irregular trapezoid. The site dimensions are approximately 175’ x 45’ x 210 ’x 165’ with an area of 14,400 square feet.

The location is significant because it lies within an area city planners call “the Hub.” The Hub is a confluence of three influential neighborhoods: Hayes Valley, Civic Center, and South of Market. This intersection is surrounded by prominent fine arts establishments, government buildings, tech magnates, and transportation throughways and stations.

1.2.0 Project Overview

The following building narrative was developed for the intent of architectural communication and has been included in true spirit of the studio. It has been taken exactly as written for the CTBUH 2020 International Student Tall Building Design Competition.

> The ALOE team’s tower design concept imitates the form and intent behind the rotating pattern of the aloe plant. Similar to how the aloe rotates outwardly to efficiently maximize sunlight exposure for its surface area to ensure survival, the form of the tower

uses this same rotational concept to increase inhabitants' access to sunlight. This also provided opportunities to tune the tower's rotation to the sun patterns of the site, overlooked views of San Francisco, and vertical community spaces.

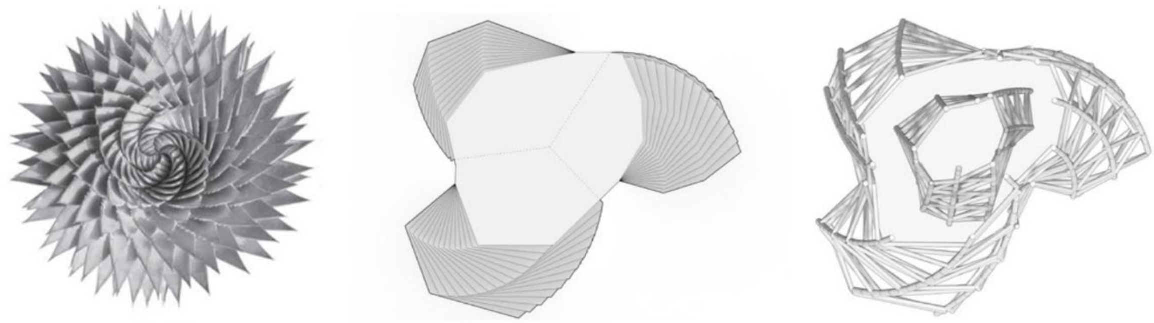


Figure 3: Condensed Evolution

Building Statistics

Building Height	725' (221m)
Stories	50
Building Program	300 Residential Units, 2 Fine Arts Spaces, 5 Community Levels
Typical Floor Height	12.5'
Average Floor Area	18,000 sf
Gravity System	Canted Columns, Wide-Flange Beams, Truss Girders
Lateral System	Dual Mega Brace Frames/Concrete Core

Table 1: Building Statistics

Project Concept

Set at the intersection of Market and Van Ness, the building contributes significant foot traffic to the area due to its proximity to the MUNI station and other transportation infrastructure. The rotational form emulates the dynamism of urban life and fosters a connection to the theatrical and artistic districts of San Francisco.

Project Structure

The primary gravity system is defined by canted columns expressed outwardly as the building exoskeleton and internally as bounding elements for the atrium endoskeleton. The slope of the columns accentuates the building's form, emulating the aloe leaves, and is a monument to architectural and structural integration. The structurally and architecturally optimized braces encasing the entirety of the three lobes act in unison to resist torsion of the Y-core and supplement its overall stiffness.

Project Program

300 housing units rest atop a podium programmed by its relation to the adjacent theater district, and features multiple indoor performance spaces, an outdoor performance space, individual and group practice spaces, and studios. The tower is composed of three sub-towers described as "pods", and their rotational wrapping creates voids relative to the core. Units are radially arrayed about the resultant atrium, which is interrupted every

eight floors by a community level. The housing options vary between one- or two-bedroom units, and all feature exterior balcony space and atrium access.

Team Members

The project team is composed of four undergraduate students from Cal Poly:

Faisl Alabdali – Third year architecture student
Moriah Haley – Third year architecture student
Lilliann Lai – Fourth year architectural engineering student
Tony Nguyen – Fourth year architectural engineering student

2.0.0 Design Process

With the selected architectural typology of rotation, the ALOE team devoted nearly twenty weeks (two academic quarters) to implement rotation and deliver a tower that effectively met the design parameters. This section details the journey from concept to final design.

2.1.0 Precedent Studies

Utilization of architectural and structural precedent studies are vital for problem solving throughout the design process. Initially, the studio class was provided with approximately fifty precedents to study by SOM and their professors. For this project, the team studied precedents that correlated not only to rotation, but also vertical community, tectonics, urban placemaking, function, and performative envelopes.

After careful investigation of the provided precedents, it was necessary for the ALOE team to perform additional research and find buildings that more closely related to rotational tectonics. From their research, the Agora Tower and the Grove at Grand Bay were twisting towers that were identified as acceptable examples to study.

Figure 4: Agora Tower

Figure 5: Agora Tower Structure

The Agora Tower is 20-story residential building located in Taipei that was designed by architect Vincent Callebaut and the structure was collaboratively designed by Bollinger-Grohmann and King-Le Chang & Associates.

The design intent was to resemble the double helix structure of DNA, with two helicoidal towers twisting around a fixed central core. The central core is a braced tube comprised of steel members. At the top of the building are outriggers bound by mega columns that follow the rotation of the floors and stabilize the structure. To provide columnless interiors, the engineers utilized Vierendeel trusses on odd numbered floors. Due to site seismicity and building geometry, the engineers also chose to use single-stage friction pendulum bearing base isolators.

Figure 6: Grove at Grand Bay

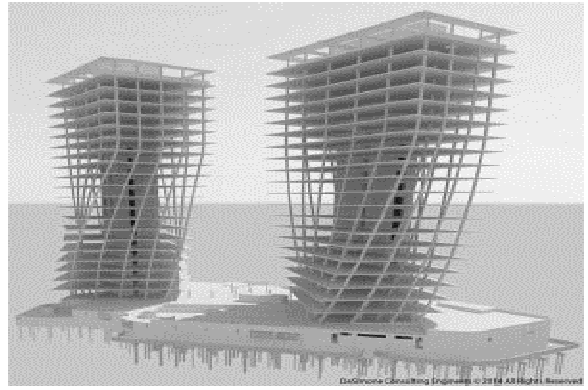


Figure 9: Grove at Grand Bay Structural Revit Model

The Grove at Grand Bay is two 21-story apartment buildings in Miami designed by architecture firm Bjarke Ingels Group and engineered by DeSimone Consulting Engineers. Each building has a composite thirty-inch composite core and floor plates incrementally rotated by roughly two degrees.

According to the engineers, the twisting nature of the columns presented several structural challenges that required innovative solutions. The main issue resisting torsion produced in the tower core due to the canted column geometry. The gravity load's horizontal component in the columns is resolved in the post-tensioned slabs by transferring the load to the interior core shear walls, which are the only consistently vertical structural elements. Furthermore, the magnitude of the combined horizontal shear force from the building self-weight and the wind loads would require conventionally reinforced concrete shear walls to be six feet thick. To recover rentable space, a composite concrete shear wall was utilized that allowed a substantial wall thickness reduction to 30 inches. Traditional reinforcing steel in the boundary element zones were also replaced with rolled steel sections.

Although the Agora Tower and Grove at Grand Bay are exceptional precedents as twisting towers, they are less than half the height of a structure that would typically be coined as a high-rise. Therefore, the ALOE team dissected the Leeza SOHO and Absolute Towers as well because they are tall buildings that implement incremental rotations and undulations.

Figure 10: Leeza SOHO

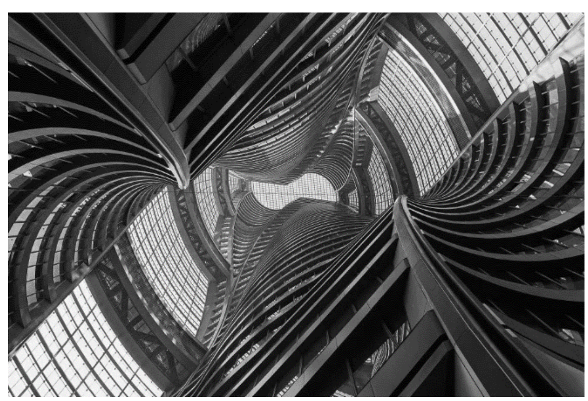


Figure 11: Leeza SOHO Atrium

The Leeza SOHO is a 46-story business, residential, and transportation hub located in Beijing. The building was designed by Zaha Hadid Architects and engineered by Bollinger-Grohmann. Essentially, the Leeza SOHO is composed of two towers tied together with four belt trusses to create a symbiotic whole, unified building. Much like the Grove at Grand Bay, there are canted columns that create substantial horizontal thrust, which is transferred in the slabs to the concrete cores. It is especially unique because of the large, full height atrium that slowly rotates a peanut-like shape from the podium level to rooftop to generate interior undulations.

Figure 12: Absolute World Towers D & E

Figure 13: Poly International Plaza

In addition to the Leeza SOHO, the Absolute Towers D and E in Mississauga have their own twist compared to a conventional high-rise. The architects on the project was MAD Architects and the structural engineer was Sigmund Soudack & Associates.

The two towers are a part of a larger complex called Absolute World. Towers D and E are fifty-six and fifty stories tall, respectively. Each tower features elliptical floor plates revolving around a central concrete core. Rather than canted columns like in the previous precedents, the Absolute Towers make use of columns that resemble shortened shear walls with varying lengths that depend on the intensity of rotation.

The final precedent the team chose to study was the Poly International Plaza by SOM, a 31-story commercial office building in Beijing. Much like some of the other precedents, the Poly International Plaza utilizes a dual structural system, and in this case this system consists of a central concrete core and exterior steel bracing. It was crucial to study the Poly International Plaza because it expresses structure as architecture, which was a vital part of the ALOE team's integrative studio. From their study, the team found that SOM's use of a dual structural system allows for a columnless interior filled with daylight and interstitial space that acts as a thermal barrier.

Ultimately, the team's dissection of precedents informed them that buildings that follow the architectural typology of rotation would essentially require a central core with boundary elements that help resist torsion. These fundamental structural components would then assist the team in their iterative design process.

2.2.0 Building Form Development

Concurrent to the precedent studies, the ALOE team was creating rudimentary massing models that implemented the architectural typology of rotation. Initial massing iterations were more abstract and sculptural, where the team explored proportions, dynamic form, and magnitude of rotation. These iterative models informed the team's decisions regarding the architectural and structural consequences of rotation. Physical and digital model making was incredibly helpful in developing the form and understanding moments that required more attention and tuning. The final form was a tower composed of three sub-towers that rotate relative to a central concrete core.

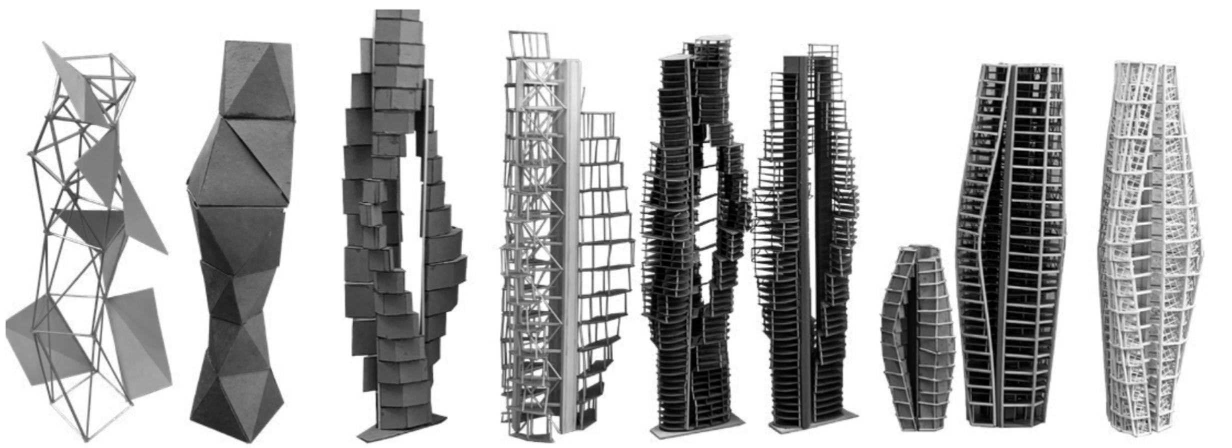


Figure 14: Physical Morphology

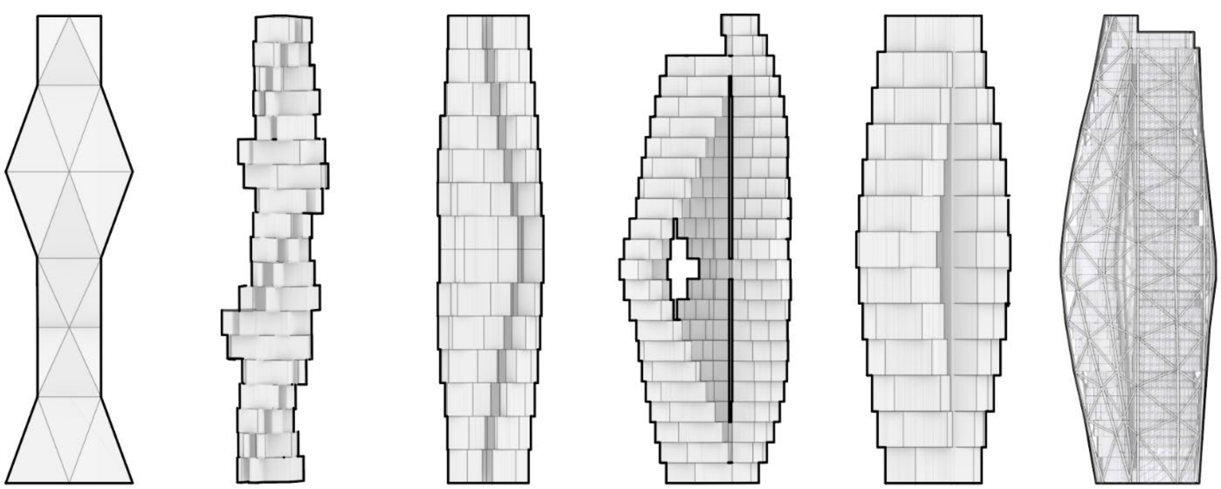


Figure 45: Digital Morphology

With the general form of the tower developed, the process of refining the final solution required having an accurate digital model that allowed for easy modifications with exploring different options and iterations. One of the key decisions was agreeing to change the bracing configuration in terms of brace angle, density, and pattern. This was a notable milestone in us being able to proceed with developing the performative envelope and overall building narrative. In addition,

other milestones included a coherent effort to layout housing units, community floors, and the podium program, and using some structural demand to inform and accommodate community floor placement.

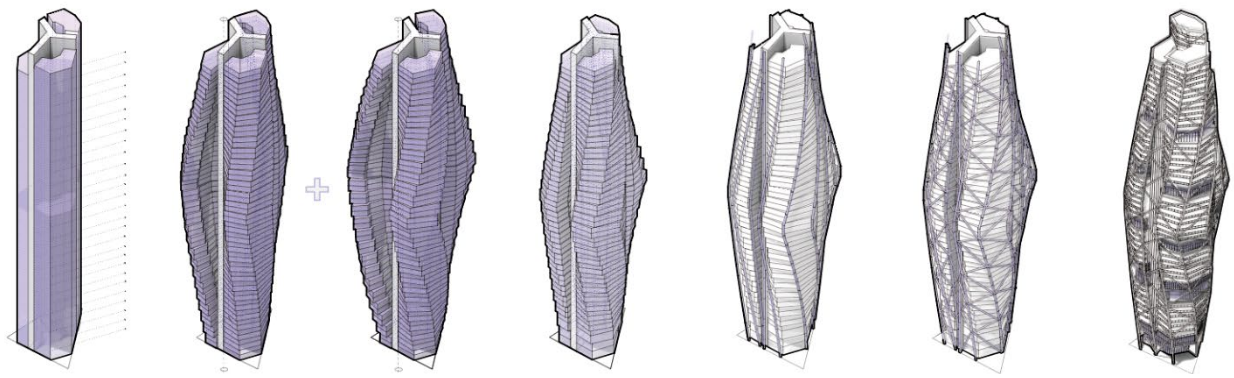


Figure 56: Model Evolution and Refinement

2.3.0 Structural Design Challenges

The process of structural design presented multiple technical and logistical challenges. Preliminary physical models made the lack of continuous load path painfully apparent, and later digital models demanded engineering judgement and evaluation for reasonability. The major structural complications are as follows:

1. Continuous Load Path
2. Unification of Three Sub-Towers
3. Torsional Issues

There was a point in this process where the resulting proposed systems and identified structural limitations began to inform future architectural changes. These moments signaled the evolution of architectural and structural coordination into an integrated collaboration.

The following sections provide narrative to process of structural design challenge resolutions. Analysis and technical references done in conjunction with this narrative are described in Section 3.0.0.

2.3.1 Continuous Load Path

An incomplete and discontinuous gravity system was an initial structural design challenge. Rapidly evolving architectural forms pressured for rushed structural development to achieve radical dynamic expressions. The structural solutions presented in the preliminary stages were regularly underdeveloped or impossible. However, moments of occasional stagnation in design form changes allowed structural tectonics progress to catch up to the architectural design.

In the case of developing continuous load path, early models featured three arbitrarily shaped masses stacked and rotated outwards and back inwards. The point of inflection occurred at building mid-height. While this mass was appealing for its slenderness and sizable gap between the towers, only one column could be driven such that it penetrated each floor of the mass. All other possible columns were offset by as much as 6' (2m).

The attempts to resolve gravity forces using normal columns were not elegant. The initial goal was to increase the overlapping floor area from 0% to a minimum of 36%. This was unlikely. By way of superimposing the forms of a tower with more rotation with that of a form with a more conservative rotation, more overlapping floor area was achieved. This superposition method allowed for the sweeping curves desired by the design to have a means of being structurally feasible. Columns were forced into these overlapping areas without any respect to architectural placemaking or even structural rational.

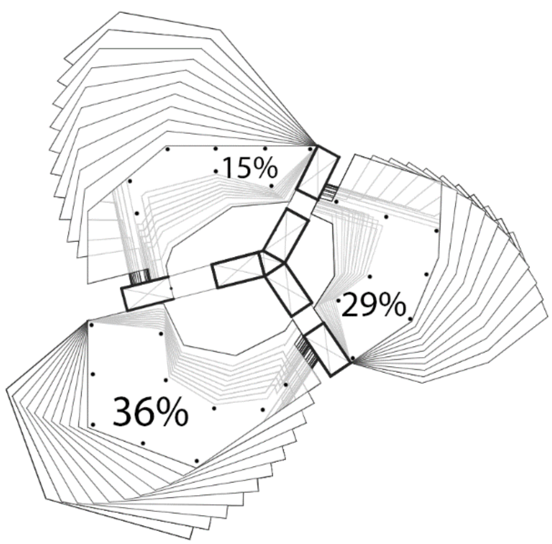


Figure 17: Overlapping Floor Areas

A major design concern was having columns expressed on each floor at a different location relative to building units. This architectural problem informed a structural solution, and so to simplify architectural plans was to simplify structural plans. The structural system needed to reflect the architecture and the solution was to understand the idea of canted columns.

A return to statics and material mechanics was needed to analyze and design canted columns. The resultant forces of loading the canted column was reduced to its components. Any thrust due to the incline of typically 10 degrees was meant to be resolved through other framing elements and throughout the highly indeterminate structure. Surely, if every element had sufficient connectivity, any amount of eccentric loading and thrust could be resolved. This assumption was perhaps overly welcomed, and by sheer luck did future structural issues demand revisited attention for a more thoughtful means of horizontal force resolution.

2.3.2 Unification

The major structural consequence of a rotational typography was irregularity. This presented itself as large openings in the floor diaphragm. These floor openings were the result of the three masses rotated away and back into the core, and while the visual affect and resultant atrium was desirable, the same could not be said for the structural effects.

The floor diaphragm was comprehensive in its ability to satisfy almost each horizontal structural irregularity type identified in the ASCE 7-16. Torsional irregularities, reentrant corners, diaphragm discontinuities, and nonparallel systems could be identified by inspection. These were mostly unnegotiable, apart from the diaphragm discontinuities.

At the time of development, the only system tying the three sub towers together to ensure the masses acted together were the floor diaphragms. The concern was that large diaphragm openings meant most of the mass of the units only had some capacity to tie back to the core. When subjected to lateral loading conditions, the tower could effectively tear itself apart as stress concentrated at corners.

A gesture of a solution was proposed in which the walkways connecting the main housing mass to the core was thickened and widened to reflect the flow of people navigating to their apartments and the flow of forces navigating to the core. However, there was doubt in this rather minimal solution in mitigating the independent movements of the towers.

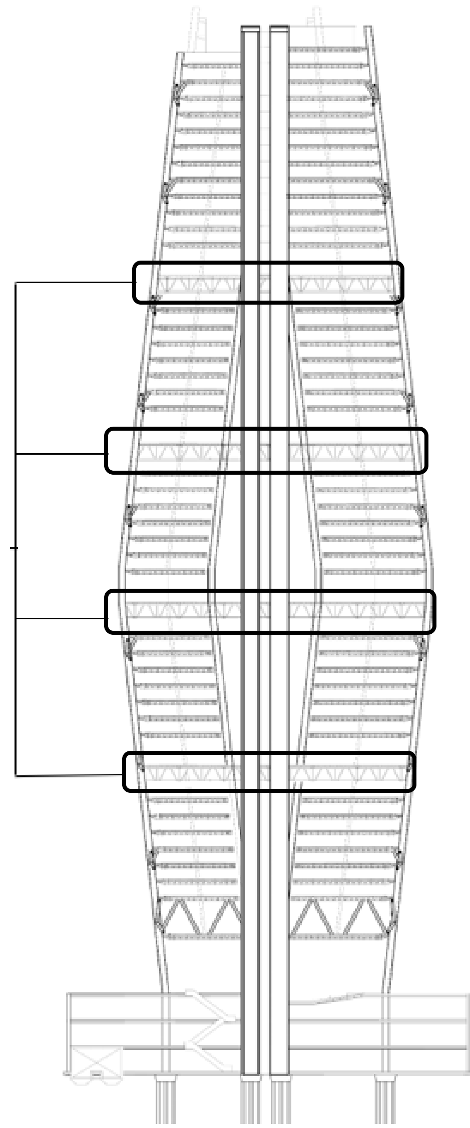


Figure 18: Section with Continuous Floors

This was an instance where structural perspectives and approaches to architectural expression cultivated an innovative approach to design and problem solving. Solutions for one discipline occasionally provided interesting and unknowingly desirable consequences for the other. In one instance, the programmatic need to provide community and mechanical levels required more floor area in each story. This resulted in removing the voids in the slab at intermittent elevations along the building height to interrupt the atrium. These “bands” of mechanical levels under community levels offered continuous and stiffer floor slabs, as building height was not of much concern at the mechanical level and the community level was two stories tall. Structurally, this was an opportunity to provide two stories of continuous, less-irregular diaphragms to be designed as rigid links connecting the three towers more frequently along the height of the tower.

2.3.3 Torsional Issues

By inspection, torsional effects were expected of the ALOE. Torsional effects can amplify a building's response to excitations, and second order effects become of concern. As described by Crisafulli et al., torsion can be due to ununiform mass distribution, asymmetric stiffness or strength, or unequal lateral displacement demand between elements of the structure (2004).

A notable avenue of possible additional study was to investigate the strength eccentricity to torsional effects. Though the work of Paulay and Crisafulli et al. were focused on seismic design of torsional effects, with focus that the eccentricity of strength was a major parameter to torsion. Crisafulli et al. proposed a procedure to consider torsional effects design based on force, noting the reduction of the system ductility and an overall consideration to how buildings subjected to larger earthquakes depend on inelastic response. However, time and technical limitations make this exercise a mode of lost opportunity.

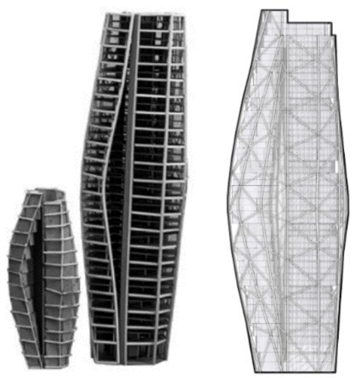


Figure 19: Bracing Configurations, (a) Left, (b) Right

The shape of the concrete core was nonnegotiable. With a given shape inherently riddled with torsional issues, a secondary lateral-force resisting system was required. Note in Figure 19 (a) the horizontal members, and (b) the diagonal braces. The original intention was for the canted columns to part of an irregular moment frame-like system. As design form began to seek more dramatic rotational forms, brace frames seemed to become a more interesting structural system. This led to the development of the system displayed in Figure 19 (b) herein referred to as the exoskeleton.

The exoskeleton encases the entirety of the tower to force a relationship between the three sub-towers. This warped braced tube-like system would supplement the concrete core and increase the torsional stiffness. An additional endoskeleton along the perimeter of three atriums within the structure. The atriums are the void spaces that are the resultant of the three towers rotating away from the core. The decision to provide additional bracing had more relation to providing architectural coherency between the building interior and exterior. The decision to consider the stiffness contribution of the endoskeleton was based less on structurally and analytically informed decisions, and more on doubt of the system overall.

The first and foremost purpose of the exoskeleton was to provide lateral stiffness to mostly mitigate torsional oscillation shapes. Sarkisian, in Designing Tall Buildings, notes that structural systems should be multifunctional. A healthy side effect of the exoskeleton system was the potential for its use as a performative envelop component to reduce direct sunlight into the units. Though the bracing pattern was an opportunity to practice shape optimization in developing a Michell truss, the angles and frequency of bracing was more dependent on existing architectural massing and with an intent to accentuate dynamic forms.

The analysis and design process of these braces are elaborated on in Section 3.0.0.

3.0.0 Analysis

A characteristic of tall buildings is their long periods, with period length, expressed in seconds, often estimated to be ten percent of the building height. With a structure of this slenderness and flexibility, dynamic response to the effects of wind were expected. Excitation of the dynamic responses of the structure would arise through wind-inducing movements, such as transverse oscillation, oscillation due to wind force coupled with structure deformation (bending and torsion), gusts, vortex shedding, or even other excitations imparted by neighboring buildings. These dynamic forces could produce amplified affects when resonance is met.

To understand a structure's dynamic behavior and properties under excitations, modal analysis was used as the main analysis method. This was used to evaluate building behavior and inform structural design decisions. A deeper understanding of the effects of flexural stiffness, axial stiffness, and slenderness could be achieved by students willing to reach beyond observation requirements through investigations of the structure's dynamics properties under forced excitations in parametric studies.

The following list described the three major types of studies done to develop the ALOE tower:

- Experimental "Big Box Building" Studies
- Core Studies
- Brace Studies

The following analysis narrative includes commentary on studies and may cite additional readings or research. Additional readings or research was done at student digression, and there was a divergence in degrees of self-research between the two students. The decision to seek additional literature through research or readings was dependent on the individual student. Student choice on this matter depended on how much the student considered additional study necessary to understanding design decisions, or if meeting base classroom requirements of no additional research was sufficient.

3.1.0 Experimental Big Box Building Studies

Throughout the twenty-week studio experience, the engineering students were tasked with parametric studies to investigate structural system responses, behaviors, and influencing factors. Initial studies provided students the opportunity to learn structural analysis software such as ETABS and RISA 2D if they had not previously learned them in another class.

The second quarter of the class focused on the studying simplified "Big Box Buildings" in RISA 2D. These buildings were 180'x120'x700'. This was a lesson for students on how to simplify large, complex structures into easily manageable and quick parametric studies. Though many parametric studies were done to give students a sense of the structural systems and their performance, two have been selected to acknowledge the preliminary structural development used to inform tower-specific designs.

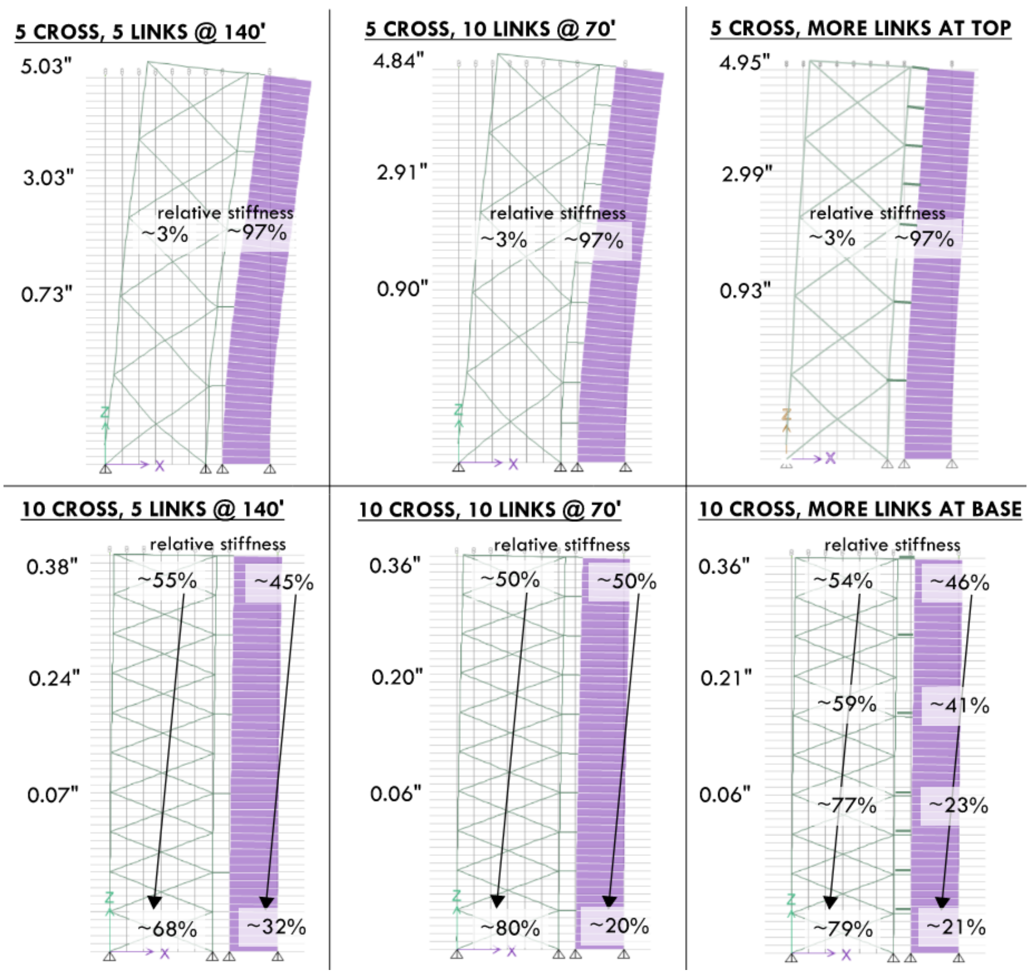


Figure 20: Dual System Study

The study in Figure 20 focused on a dual system of a concrete core and a brace frame. Different iterations of brace density and frequency of rigid links affected the relative stiffness of the systems. From the study, the team learned that with more frequent linking, the relative stiffness of each system varied depending on building height, and therefore, aspect ratio of the shear wall to brace frame

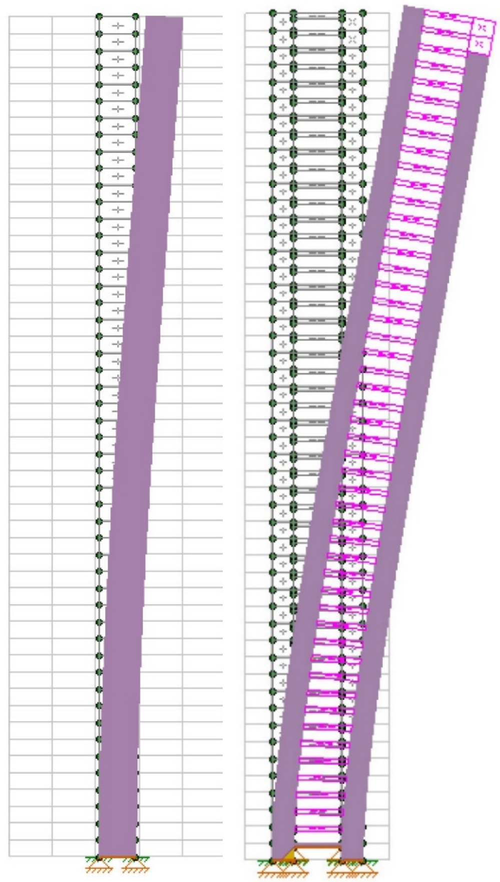


Figure 21: Coupling Beam Study

In Figure 21, the team studied the effects of coupling a dual concrete core system. The purpose of the study was to investigate the span to depth of ratio of coupling beams. However, this was more of exercise in studying the effects of using plates and wall panels in RISA 2D because the use of those elements is not commonly taught.

With a familiarity in structural systems and software to inform future studies, analysis and design work began on the ALOE's core and braces.

3.2.0 Core Studies

A concrete core system was a guaranteed lateral-load resisting system in the tower owing to programmatic needs for elevators and stairs. Due to the rotation of the three sub-towers, a familiar shape partially reminiscent of the core of the Burj Khalifa's core emerged. The plan dimensions of this Y-shaped core were non-negotiable, with the exception to shear wall thickness. The projection lengths were 50', 50', and 68' long, with perpendicular 10' wide, as shown in Figure 22.

3.2.1 Preliminary Core Study

Initially, one student was using modal analysis as a means of determining how reasonable the resulting mode shapes and periods were. For a student to believe an underdeveloped engineering judgement did not need to be supplemented by additional reading or study was to be remarkably, impressively, and arrogantly foolish. Mode shapes that went awry or periods being impressively long were typically good indicators that some part of the modeling process may have been amiss. Element connectivity or assumed boundary conditions were common issues in the structural models, and often it was easier to completely restart a model than to troubleshoot someone else's chaotic modeling attempt.

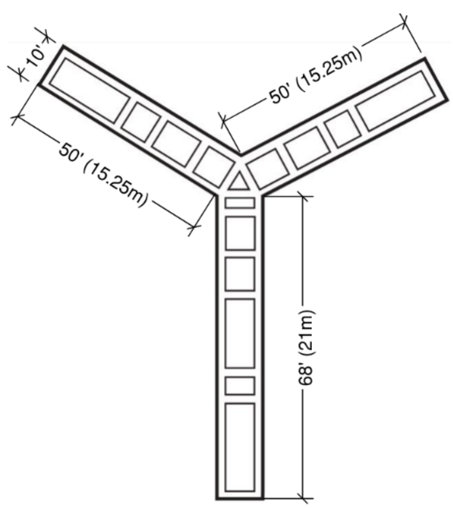


Figure 22: ALOE Core Dimensions

Another means of evaluating validity of modal analysis was to compare modeling results to known ones. In simplifying the ALOE's irregular Y core into a regular one, the resulting mode shapes identified from ETABS output matched those presented in *Some Concepts in Earthquake Behavior of Buildings* (Murty et al., 2012). Though the modeling dimensions and height differed, the overall trends matched those observed from the work of Murty et al for only the first three mode shapes. The special oscillations referred to as "Opening-closing" and "Dog Tail wagging" in the fourth and fifth mode respectively were shown to be torsion with points of inflection at mid height and third height. The sixth mode was a purely translational one.

Note the first three mode shapes of the student-investigated shape match the first three shapes of the study done by Murty et al.

This indicated a structural analysis avenue worth exploring – why were only first three mode shapes were replica in the student students? As comprehensive as the structural analysis would be if students were to indulge in every side-quest of the overarching story line that was the development of the high rise, technology and time limitations demanded compromises in understanding.

The decision was made that the first three mode shapes matching were enough validation to proceed with the structure modeling. Mode shapes and their associating natural frequency are dependent on only mass and stiffness. It could be possible that the student study and that of Murty et al. were of different story heights.

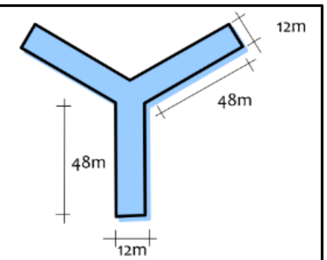
Mode	
1	*Torsional (0.87s)*
2	Y translation (0.85s)
3	X translation (0.84s)
4	*Opening-closing (0.47s)*
5	*Dog Tail wagging (0.47s)*
6	2nd torsional (0.27s)
7	2nd Y translation (0.27s)
8	2nd X translation (0.27s)
9	2nd dog tail wagging (0.24s)
10	2nd opening-closing (0.24s)

Figure 23: Modal Shapes of Regular Y Core from Murty et Al.

Student Investigated 20'(12m) x 158'(48m) Y Core Modal Direction Factors at 30 Stories Tall					
Mode	**T (s)**	**UX**	**UY**	**RZ**	**Shape**
1	3.178	0	0	1	Torsion
2	2.396	0.528	0.477	0	Translation
3	2.395	0.472	0.528	0	Translation
4	1.025	0	0	1	Torsion
5	0.582	0	0	1	Torsion
6	0.516	0.643	0.57	0	Translation

Table 2: Modal Shapes of Regular Y Core from Student Work

3.2.2 Building Core Study

The core studies shown in Figure 25 are all done with constant shear wall stiffness, connectivity, and height (700').

The Y-core only shape was the first to be analyzed to identify problematic mode shapes. With the understanding that mode shapes refer to what major deformation the building would have a tendency to want to assume under resonance due to dynamic excitations, determining torsional or mixed mode shapes informed design decisions.

Rotational mode shapes emerged at the second, fourth, and sixth mode. The performance of torsional motions is known to be poor and would induce large stress concentrations at the reentrant corners of the core projections. It was ideal to push the torsional moment to be the third

and sixth mode shape, as the higher the mode shape, the higher the energy required to withdraw the modal behavior.

Taking precedent from the Burj Khalifa, a simplified model of the core was replicated in Figure 25 (b). The mode shapes and overall stiffness were ideal, but this system was not appropriate for the ALOE given the height and circulation needs of the building. Two components of the Burj's core plan were identified that mitigated torsional issues:

1. "Hammer Head" Walls Figure 24 (c)
2. Hexagonal Torsional Knuckle Figure 25 (d)

<u>1. Hammer Head Walls</u>

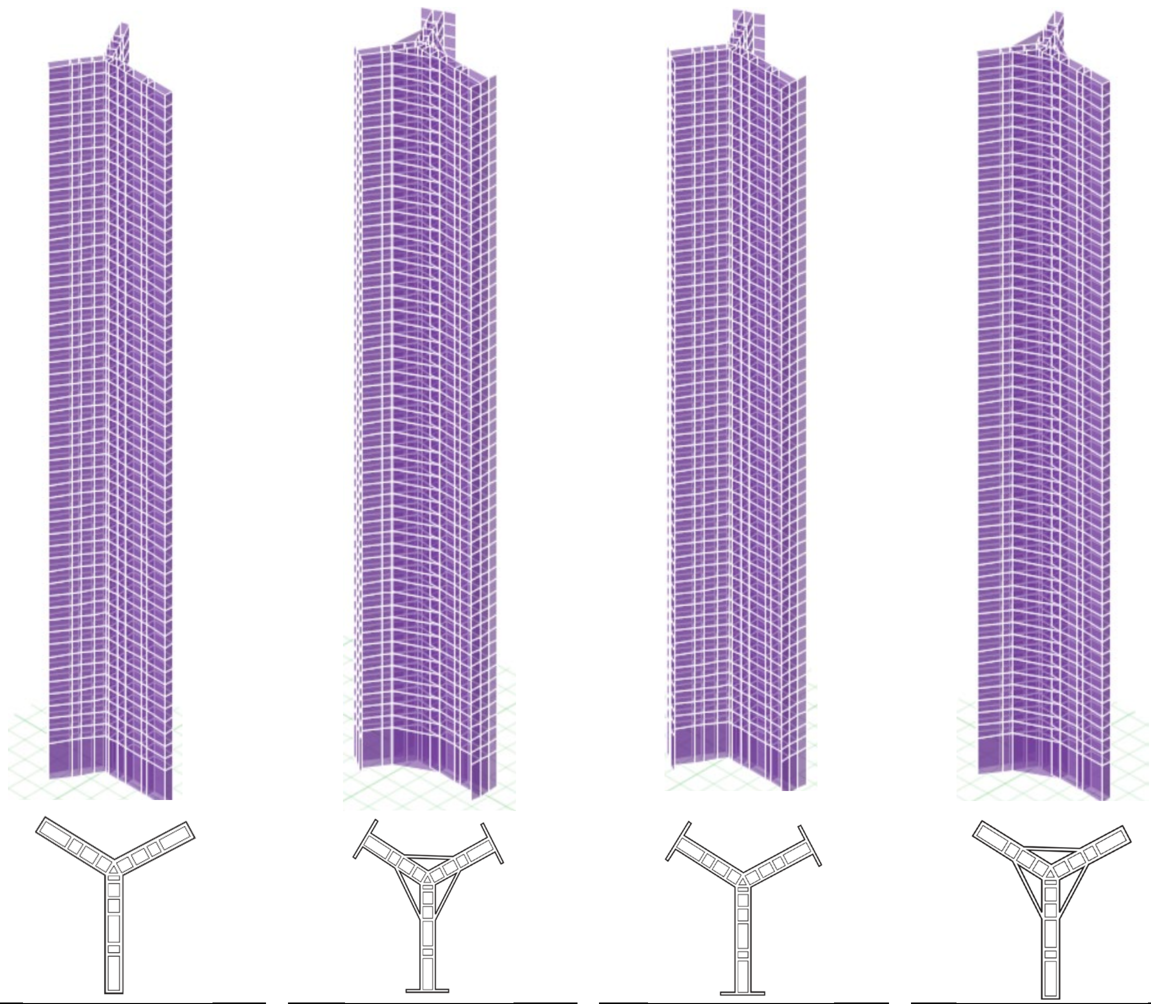
When evaluated independently, the hammer head wall system (Figure 24 (c)) provided more overall stiffness than the torsional knuckle. The perpendicular end walls seemed to provide the majority of the system stiffness, as the building period with only the hammer head walls was notably lower than the system with only the torsional knuckle. Building stiffness was not a major concern due to the concrete core itself already fulfilling expected stiffness and design deflection criteria. The main criteria for informing design decisions rested in the modal participation factors. Torsion occurred at mode shape 3, and a mixed torsional and translational shapes occurred in the fifth and sixth mode.

<u>2. Hexagonal Torsional Knuckle</u>

The torsional knuckle system (Figure 25 (d) proved to be more flexible than hammer head wall system, and it was assumed that the further the walls from the central work point of the Y projections, the stiffer the shape became. The mode shapes in this system had more pure rotation at only the third and sixth modes.

Figure 24

(a) Baseline Y- Core *(b) Hammer Head Walls & Hexagonal Knuckle* *(c) Hammer Head Walls* *(d) Hexagonal Knuckle*



Period	5.67 s
Mode 1	X
Mode 2	↻
Mode 3	Y
Mode 4	↻
Mode 5	X
Mode 6	↻

Table 3: Baseline Core

Period	4.63 s
Mode 1	X
Mode 2	Y
Mode 3	↻
Mode 4	X
Mode 5	Y
Mode 6	↻

Table 4: Baseline with Hammer Head Wall and Hexagonal Knuckle

Period	4.60 s
Mode 1	X
Mode 2	Y
Mode 3	↻
Mode 4	X
Mode 5	.7Y/.3↻
Mode 6	.3Y/.7↻

Table 5: Baseline with Hammer Head Wall

Period	5.30 s
Mode 1	X
Mode 2	Y
Mode 3	↻
Mode 4	X
Mode 5	Y
Mode 6	↻

Table 6: Baseline with Hexagonal Knuckle

When considered with architectural plans, it was immediately apparent that the hexagonal knuckle walls were not feasible due to programming. The exoskeleton brace mentioned previously was decided to act as an equivalent of those walls. The matter was to then determine the relative stiffness contribution of the walls.

Where stiffness is the inverse of deflection, an estimated relative deflection of the system could be determined by evaluating each system independently, or by observing internal shear stresses of each system.

The following section describes the translation of the hexagonal knuckle stiffness into an equivalent bracing system.

3.3.0 Brace Studies

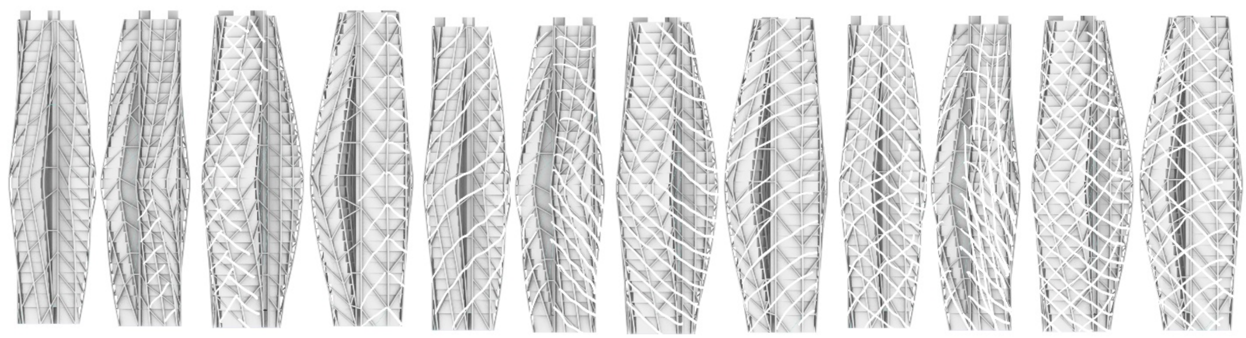


Figure 25: Conceptual Brace Sketches

In conjunction with the core investigations, the team performed brace studies. These studies analyzed the resistance of hollow steel braces to torsion caused by the Y-core. It was imperative to design an appropriate brace configuration that not only performed well structurally, but also architecturally because of the desire to showcase the structure as architecture.

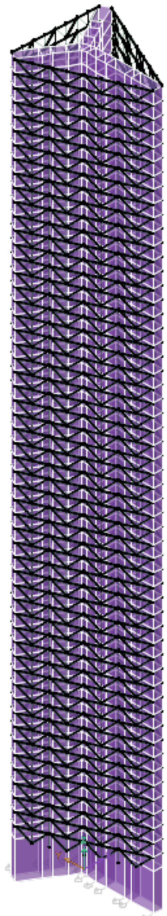


Figure 26: Floor Depth Link Trusses

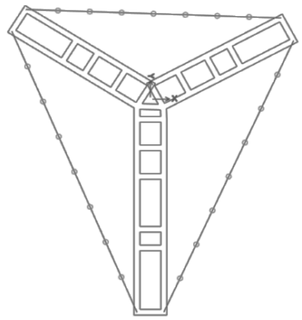


Figure 27: Floor Depth Link Trusses - Plan View

Period	4.12 s
Mode 1	X
Mode 2	↻
Mode 3	Y
Mode 4	↻
Mode 5	.25X/.75↻
Mode 6	.75X/.25↻

Table 7: Floor Depth Link Trusses Modal Analysis Results

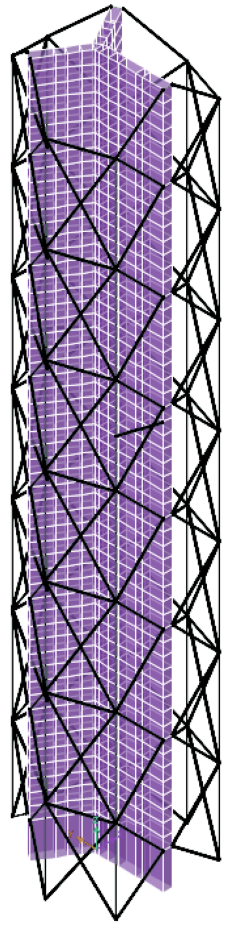


Figure 28: Perpendicular Mega Braces

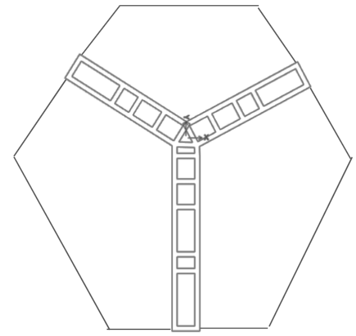


Figure 29: Perpendicular Mega Braces - Plan View

Period	3.93 s
Mode 1	X
Mode 2	Y
Mode 3	↻
Mode 4	X
Mode 5	Y
Mode 6	↻

Table 8: Mega Brace Modal Analysis Results

As part of the brace studies, results from Figure 24, the standalone Y-core, are set as the standard. In Figure 26, floor depth trusses link and restrain the ends of the core legs to resist torsion. Although the period was reduced, this iteration unexpectedly aggravated the torsion in higher modes.

The model in Figure 28 employs mega braces that are perpendicular to the core wall ends. The intent of the perpendicular braces was to serve as the hammerhead walls performed during the core studies. Compared to the baseline and hammerhead models, the mega braces sufficiently restrict torsion from occurring in the typical translational modes.

The last brace study in Figure 30 was a quick exploration analyzed in RISA 2D. The purpose of this study was to create a brace configuration that relates more to the architectural narrative. Therefore, the team compared typical x-bracing to a scheme that follows the rule of thirds. By following the rule of thirds, braces create a leaf-like shape that are similar to the aloe concept. In this model, the trusses are pinned and a 100-kip point load is applied at the ends. The top brace configuration deflects by 134” while the bottom configuration deflects 127”. In other words, the bracing scheme that follows the rule of thirds is approximately 5% stiffer.

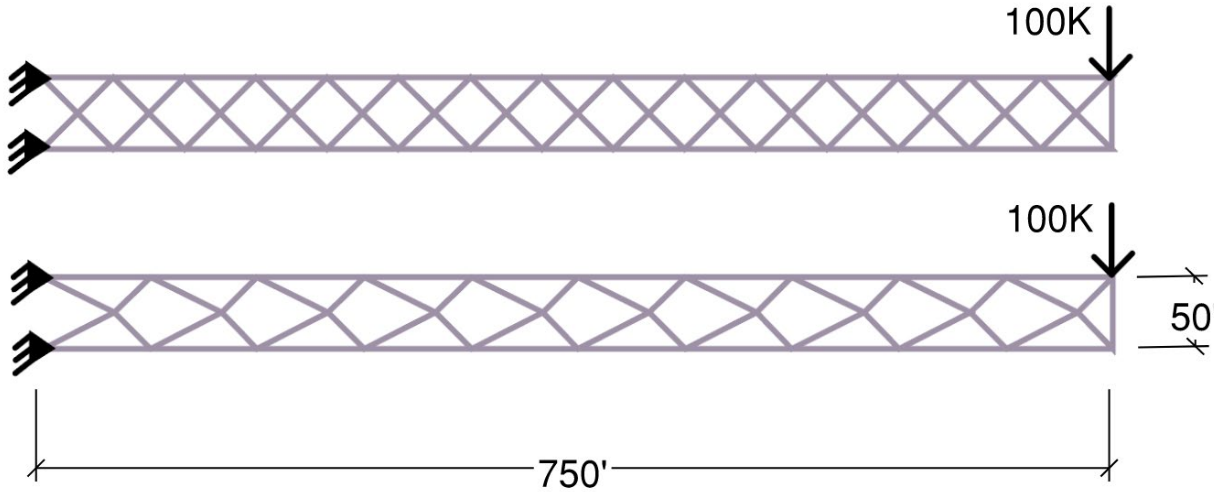


Figure 30: Brace Configuration Study

3.4.0 Dual System Incorporation

Ultimately, the ALOE team hybridized the core and brace studies. The ALOE utilizes stiffened interior and exterior braces that provide torsional resistance like the hammerhead walls and hexagonal torsional knuckle.

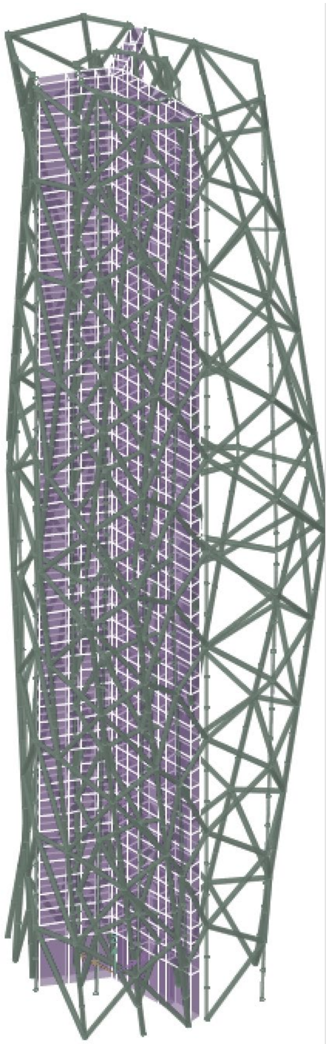


Figure 31: Final Analysis Model

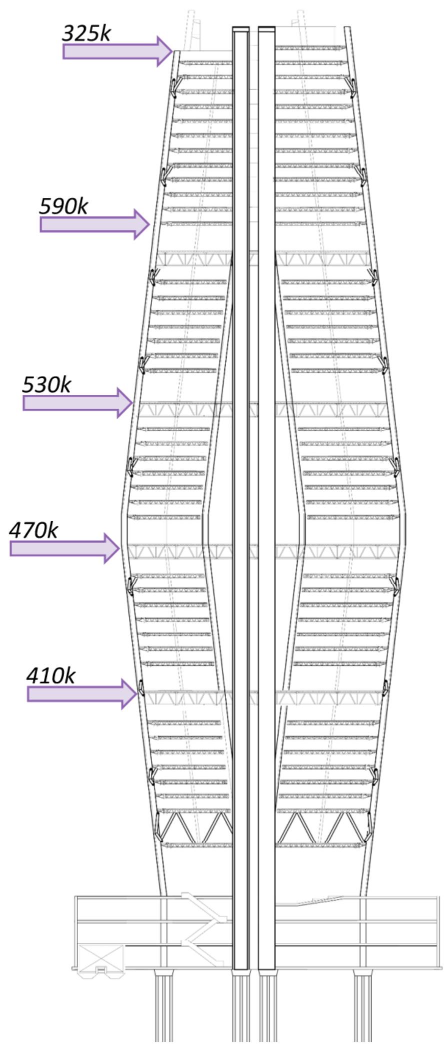


Figure 32: Wind Loading

Wind Analysis Results	
Δ_{allow}	17.40”
Δ_{allow}	h/500
Δ_{actual}	16.10”
Δ_{actual}	h/463
Modal Analysis Results	
Period	5.47 s
Mode 1	X
Mode 2	Y
Mode 3	↻
Mode 4	X
Mode 5	Y
Mode 6	↻

Table 9: Final Analysis Results

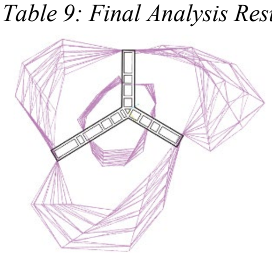


Figure 33: Superimposed Lateral System Plan View

The final analysis model uses 10 ksi strength, 12-inch shear walls for the core. The endo and exoskeletons are comprised of 36” diameter steel tubes that are 2” thick. For computational modeling purposes, the diaphragms are modeled as semi-rigid joint diaphragms at every level.

For lateral loading, the team calculated the wind pressures using ASCE 7-16, Chapter 26 and simplified them to five-point loads. Then the team assumed a service gravity load of 120 psf and simplified them to point mass loads at a predetermined center of mass on every level

The allowable drift was calculated using h/500, which is an equation that can be found in Mark Sarkisian's *Designing Tall Buildings*. At a height of 725', the allowable drift for the ALOE is 17.4". From our analysis, the actual deflection came to be 16.1" or can be equated to h/463, which is within an acceptable range. Finally, the modal analysis demonstrated that the ALOE's period is 5.47 seconds and the fundamental modes are translation, translation, rotation. As a result, of the team's unified dual lateral structural system successfully resolves discontinuous load paths and torsion.

4.0.0 Framing and Detailing

In addition to designing the lateral structural system, the team also investigated potential framing layouts and details.

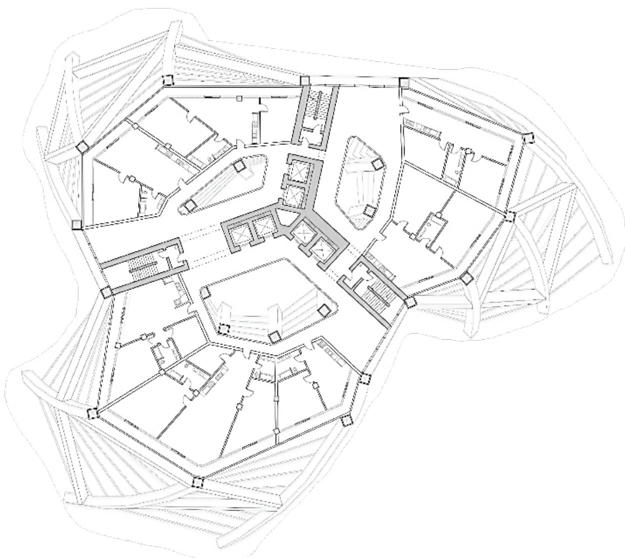


Figure 34: Unit Layout

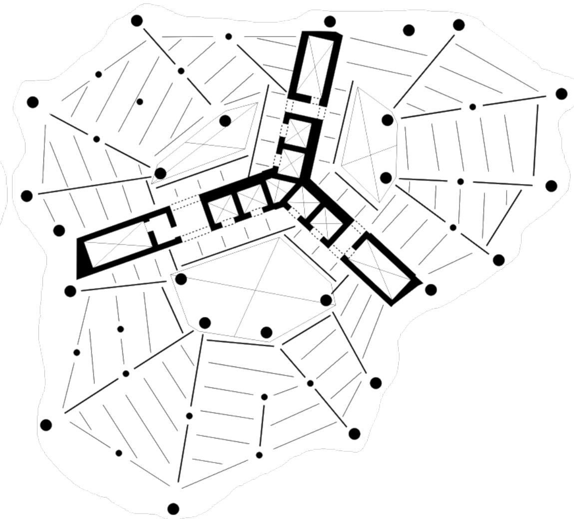


Figure 35: Framing Layout

Figure 34 is a typical architectural unit layout that was utilized in designing the gravity framing. Due to the ALOE's unique building shape, team attempted to merge structural efficiency with design intent of rotation as seen in Figure 35.

The gravity system is composed of 22" deep composite open web joists as girders and W18x55 composite beams. Members were conservatively designed to span the max length of 40 feet. Furthermore, the columns were sized to be 36"x4" hollow steel tubes.

In addition to structural detailing there was an extra emphasis of detailing for the building envelope during the second stretch of the course. Luckily, our exoskeleton provides shading to the unit balconies, so the team did not have worry about detailing louvres or special curtain walls. Instead, the team designed simple window wall connections with slotted clips that take into account inter-story drift and lateral wind loads.

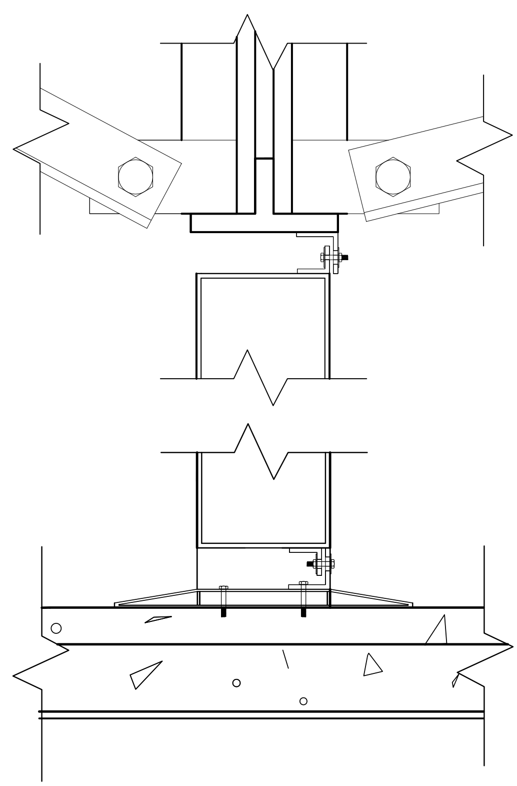


Figure 36: Window Wall Detailing

The drawn details for the ALOE tower exoskeleton were overall underdeveloped, but important to informing students how elements would connect to transfer forces. Considerations to column size, shape, connection, and geometry were demanded once details showed the lack of common work point between converging elements.

Figure 37 shows a performative envelope section, and it is worthwhile to note that every node within this structure is unique in its angles, eccentricities, and irregularities. Figures 39-41 conveys a built-up node section with steel plates within the node to help transfer forces that may accumulate in this point

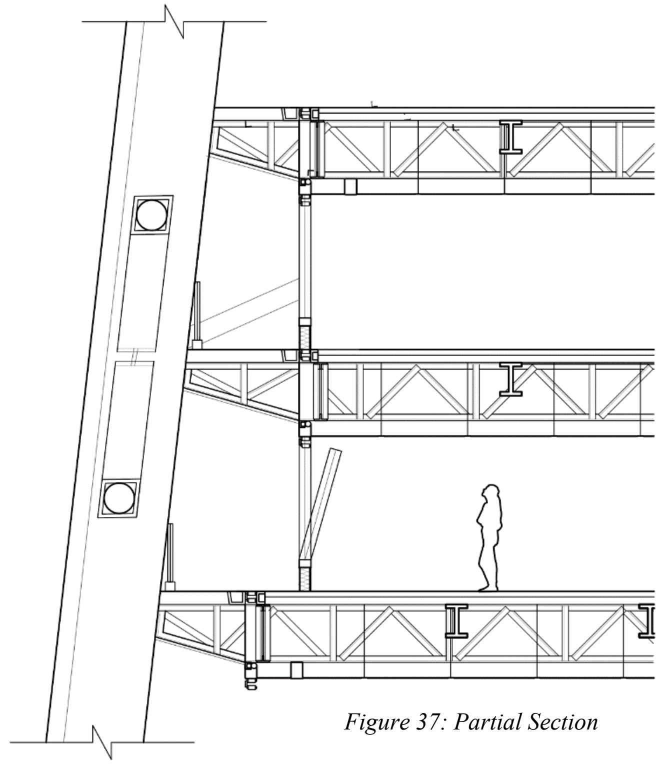


Figure 37: Partial Section

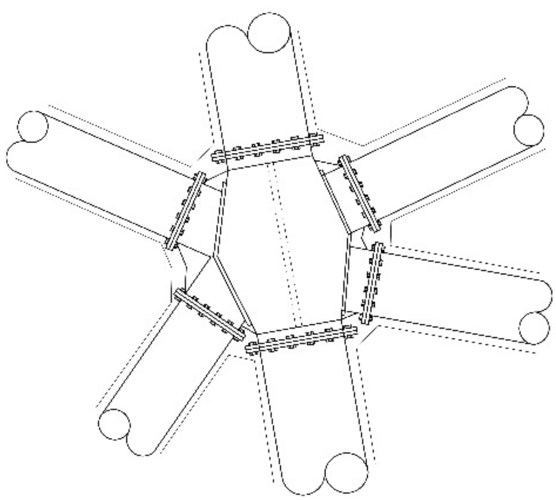


Figure 39: Brace Node Elevation

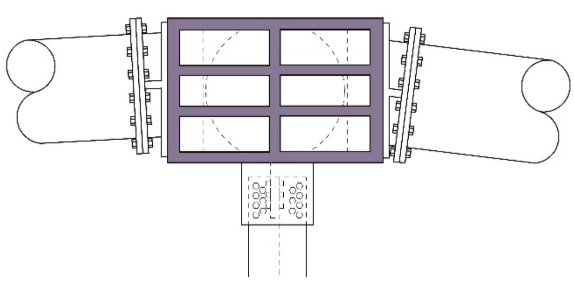


Figure 40: Brace Node Plan

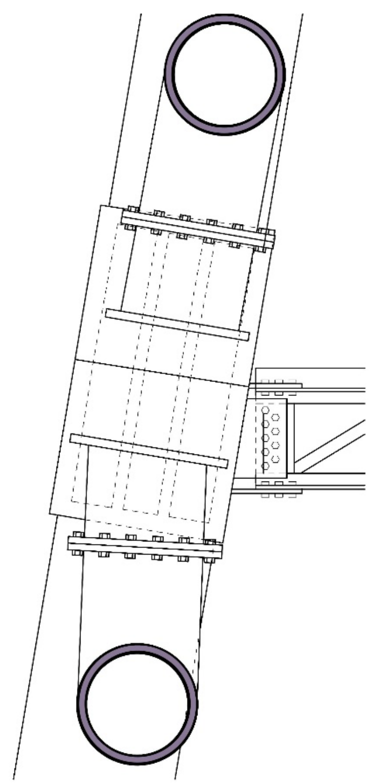


Figure 41: Brace Node Section

5.0.0 Special Considerations

As part of their studies, it is necessary for students to understand the impacts of their engineering solutions. In the case of this project, the ALOE team contextually recognized how much influence their project has on a global scale, societal and cultural level, environmental effects, and economic outcomes.

5.1.0 Global

Historically, populations across the globe are moving away from rural areas to urban centers such as the San Francisco Bay Area. However, with large influxes of new residents, cities worldwide face major housing shortages. Cities are also often confronted with exorbitant land value and limited development space to expand horizontally and sprawl out. Furthermore, urban sprawl is associated with several negative effects on the environment, public health, safety, and social capital. Therefore, by building vertically with high-rises, cities can effectively address all the previously outlined issues that afflict cities today. The ALOE residential tower specifically tackles these global issues by adding 300 units to the market that can house approximately 300 to 1200 individuals. Although the ALOE can only accommodate a small number of people relative to the population of nearly eight million in the San Francisco Bay Area, it is a step towards the right direction in increasing housing availability for an urban center that is already strained.

5.2.0 Societal and Cultural

When developing a project, it is crucial to consider the site's context to the built environment and spatial surroundings. Construction of a new high-rise in historically mid-rise neighborhoods can have major implications to the collective community the high-rise is located. Nevertheless, the rise of tall buildings in The Hub area is already becoming a common occurrence with the existing Bank of America Computer Center, California Automobile Association Building, and 1500 Mission. There is also the construction of a new a 36-story mixed use building at 98 Franklin by SOM, which is adjacent to the 1 Oak Street site. Furthermore, the ALOE brings spatial justice and urban placemaking to The Hub by incorporating multipurpose fine arts spaces at the podium level and publicly accessible vertical community levels.

5.3.0 Environmental

Building construction and operations can have extensive direct and indirect impacts on the environment. The construction of skyscrapers inherently creates substantial carbon emissions, but it is becoming more common for designers and developers to pursue green building certifications such as LEED, BEEAM, and Green Globes. Many new buildings are also attempting to become carbon neutral or even carbon negative. While there was not a large emphasis on environmental concerns during the design process of the ALOE, considerations

were made to optimize site potential, optimize building space and material use, and enhance indoor environmental quality. In terms of site potential, having a conveniently located residential building next to public transportation significantly reduces energy use and the dependency for carbon producing automobiles. To optimize building space and material use, studies were done to select efficient structural steel members and reduce concrete wall sizing. For the enhancement of indoor environmental quality, recessed operable window wall systems create deep balconies spaces that produce brise soleil-like shading and reduce solar heat gain. This in turn diminishes the need to for air conditioning and allows for natural ventilation.

5.4.0 Economic

In a market with already excessive housing costs, the most effective method to reduce the financial burden is to simply build significant volumes of equitable housing in high-rises. Building additional residential high-rises would not only eases the current housing market, but also promotes future economic growth. Furthermore, a multitude of employment opportunities would be created through the design and construction of the ALOE. In addition, material manufacturers would benefit from the construction of the house with the purchase of materials. During the construction phase, the project would create jobs for local laborers and inspectors. When repairs or maintenance are required, local workers will once again be employed.

6.0.0 Conclusion

6.1.0 Lessons Learned

The following sections summarize lessons learned by Lilliann Lai and Tony Nguyen.

6.1.1.1 Lilliann Lai

My lessons learned are categorized as the following:

A. Academic
B. Social

Though these matters are not mutually exclusive, they can be organized as so. Academic lessons learned encompasses technical learning, understandings, and revelations regarding software, analysis, design, methods, techniques, or related topics. Social lessons include conflict resolution, reliability, organization, communication, and related topics.

Academic

The four main academic lessons I learned are as follows:

1. I know more than I think I do.
2. I know less than I think I do.
3. Observation is not understanding.
4. Learn for knowledge's sake.

1. <u>I know more than I think I do.</u>

I found myself realizing I knew more than I had thought. This class was an exercise in gaining confidence in my abilities. I found that my education had equipped me with the proper tools to navigate this unfamiliar academic terrain. The matter was finding the confidence to use what I knew in ways I was not used to. This could be referred to as a sort of structural mechanics gymnastics. My major takeaway was realizing that most of the work done could be distilled to material mechanics. Topics such as moment of inertia, combined stresses, plastic bending, or beam deflection emerged behind a façade of intimidation. Problem solving different, atypical, or new situations with the skills I have was a valuable lesson.

2. <u>I know less than I think I do.</u>

At the same time, I found that I also knew a lot less than I thought. I was aware that what I had learned had only begun graze the surface of structural engineering, but I had no sense of the breadth and depth of what I did not know. The exposure to building frame types, lateral force resisting systems, structural optimization, and even structural analysis software were all learning opportunities. I was at a point in which I did not know enough to even begin asking questions, and that realization was where I embraced the true spirit

of a more independent learning endeavor. Sometimes there were assumptions that I should not have made in considering a situation, and other times there were assumptions I should have made to be able to solve a problem. Understanding my limitations in abilities and being able to identify what I need to research or learn to solve a problem, was a valuable lesson.

3. Observation is not understanding.

I approached this class as an opportunity for independent study – and as a fourth-year architectural engineering student should strive for in their senior project class. The class sessions and interactions with Professor Kevin Dong were most valuable when I put in my own work to reach him "halfway there". Coming to class with the bare minimum, or with even less than that, was a waste of both of our time.

The initial structural modeling and practice exercises could be distilled as the following:

- Observation
- Validation
- Analysis
- Presentation/Design

Early in the quarter, my work was limited to just a model of my structure, running an analysis, pulling the raw data from ETABS, and displaying the information on a nicely formatted sheet. I was naïve, and without realizing, I was expecting my professor to commit all the learning labor. I eventually learned that the process of learning was first making an observation, validating how reasonable the data was, analyzing the information for its meaning, and a design. Anyone can make a model and run it to provide an observation. A child can observe a mode shape. An engineering should be able to explain what the mode shape means, the consequences of a mode shape, or why it is good or bad. Needing to present or design with information for a study demanded a deeper or more true understanding of the situation, and I believe it is this translation from analysis to communication where the most learning occurred.

4. Learn for knowledge's sake.

The conscious decision to satisfy academic requirements that exist only to attempt to quantify learning is a shame. The motivation in this class is for the sake of gaining more knowledge and skills, and the beauty of this class was the opportunity to work with ambitious structures to experiment and safely fail.

Social

After multiple experiences in interdisciplinary projects, I feel that I have been exposed to a decent amount of social lessons. The most notable ones listed above do not mean other lessons were not as important, but rather lessons I have already learned and lost the ability to differentiate as new lessons learned.

The three main social lessons I learned are as follows:

1. The importance of reliability and trust cannot be overstated.
2. Organization can be the limiting factor.
3. Establish expectations and boundaries.

The lessons learned here were just as important as the academic ones listed before. Without these, the integration of disciplines could have never been executed.

1. <u>The importance of reliability and trust cannot be overstated.</u>

In brief, fostering trust between group members allowed for work to be efficiency delegated and executed. Tobi Lütke in "Powering a team with a 'Trust Batter'" is a good reference in elaborating how interactions and performance the current state of dynamics and affairs in a group. The repercussions of a low trust battery rating were outstandingly incapacitating. Low morale, resentment, and stress were just some symptoms of a greater illness of the group. Our team was lucky to have overall good chemistry, dynamics, and reliability. Technical skills such as model making or using Rhino 3D could be taught. Developing trust was a matter of personal integrity and care.

2. <u>Organization can be the limiting factor.</u>

Being in a physical room was enabled disorganization. The consequences of misplaced papers, digital models, or poor scheduling were never real with students working in the same room for sometimes half a day or more. The importance of organization did not manifest until remote learning in Spring 2020 due to COVID-19. Accountability was more difficult because there was no daily interaction and transparency in work progress and tasks. Disorganization and confusion over what and where the most updated digital model existed slowed work progress down considerably, and for whatever reason, an online drive was not incorporated into our workflow until about 75% into the quarter. Until then, searching for files, accidentally using outdated files, or general confusion over what was to be done hindered out productivity.

3. <u>Establish expectations and boundaries.</u>

For the architecture students, the commitment and investment into the high-rise studio was a given. For the architectural engineering students, the same could not be said. The level of priority each group member would have in prioritizing this class was something that should have been discussed early on in the progress to reduce any abrasion or friction. To expect each student to prioritize this class was to welcome disappointment and frustration. A communication about the boundaries of what a student was willing to commitment, when they would, and to what quality, was a lesson I learned needed to be determined at the beginning of the project and intermittently throughout the process as circumstances change.

6.1.2 Tony Nguyen

6.1.2.1 Academic Takeaways

Compared to my other classes, this interdisciplinary studio was where I did most learning, I have ever done in such a short amount of time. It was especially helpful to gain perspective from the architecture students to understand their outlook and process in developing our project. The most important things I took away from this experience was research and presentation.

To kickstart any project, it is necessary for students do their research. That is because utilization of architectural and structural precedent studies is vital for problem solving throughout the design process. The purpose of precedents is to give students inspiration and viable solutions the challenges they face. Most of the time, precedent studies provide students with the opportunity to learn something they have never came across in an academic setting.

Something I learned from our advisors and architecture mates is properly presenting learned information. My initial assignment submissions in the twenty-week course, were highly technical and hard to digest. Over time, I learned that it is important to consider your audience and their time when presenting them with information. They do not want to see pages and pages numbers depicted on graphs and charts. Basically, it is vital for the presenter to the distill their findings in a way that is easy to understand across the board. One of the best ways to present new information is graphically by physically pointing at what you are talking about, rather than numbers or passages of text.

6.1.2.2 Potential Improvements

If given the opportunity and time to make changes and further develop our project, there would be a boundless amount of potential improvements I would like to make with the team. However, just to name a few, I would like to further investigate the special considerations, and create a full computational model in ETABS, and increase the structural efficiency by optimizing our structure.

The special considerations are topics that students are typically required for students to answer as part of Accreditation Board for Engineering and Technology's Accreditation Criterion 3, Student Outcomes (h) that were technically not required to be a part of this report. Nevertheless, I thought it was imperative we address them anyway because I strongly believe students should have those considerations in mind when developing their projects and engineering solutions. Students should also be able to address realistic constraints such as political, ethical, health and safety, manufacturability, and sustainability because that is what engineers must do in the real-world. Having students consider all these aspects would result in a more well thought contextual solutions. It is just unfortunate these concerns were not brought up until the end during our class reflections.

As for future technical improvements, I would have liked to create a full-fledged ETABS model of our project. Unlike most of my classmates, this capstone course was the first time I was given the chance to use ETABS. There was a huge learning curve, but I luckily had Lilliann to teach

me along the way. However, due to how the class was structured to simply complex building problems, the team never took a truly in depth look at our building behavior. For example, we simplified loading and the diaphragms to such an extent that we do not know how the building would respond to its own self weight. After reviewing our precedents and learning how they tackled their structural issues, it would be interesting to do a comprehensive investigation of the ALOE.

Finally, if we were to do an in-depth analysis of our building, it would be great to see if we could structurally optimize it as well. During our iterative parametric studies, we ended up with rather large member sizes like the 36” diameter exoskeletal braces. Firstly, we would do additional iterative studies by varying the member sizes ourselves. Then we would apply what we learned from SOM an optimization lecture about optimization software created by professor Glaucio H. Paulino from Georgia Tech. I believe the ALOE would be suitable for optimization studies because the interior and exterior bracing configurations already imply a need for it.

6.2.0 Reflections

6.2.1 Lilliann Lai

I took this class to get a lot out of it. And I did – both academically and inter- and intra-personally. I preface this section with a forewarning of this exhaustive and long-drawn reflection. Reflections can be cathartic. I have categorized my reflection as the following topics:

1. Modals of Lost Opportunity
2. Personal Reflection

Modals of lost opportunity, a term from English grammar in referring to past tense with perfect simple infinite or perfect continuous infinitive, outlines the "could have, would have, and should have" moments of this studio. Personal reflection outlines growth, observations, and introspection that came from this experience

Modals of Lost Opportunity

Major time, technology, and competency limitations prevented exploration in topics that would arise from the structural process or my own self-study. I understand that even one component of the structure, such as the performative envelope, could be its own ten-week course. I would regularly find myself on tangents reading papers, literature, or studies, but never able to pursue them deeply enough to retain or understand anything appreciable.

The following are topics I wish I could have, would have, and should have studied and practiced had I had the resources to do so. I hope for any future student seeking resources, they find this section useful in providing some base resources.

<u>More Dissection of Precedent</u>

Though the initial fifty precedents were helpful, maintaining the regular interest in finding existing structures was useful. Mark Sarkisian's *Designing Tall Buildings* provided good introductions to the considerations to designing the ALOE. Additionally, reading I would recommend for the very first steps of this project would be "A Study on Innovation in Technology and Design Variation for Super Tall Buildings" Kim & Shin (2011). A better understanding of the interaction of the architectural form and structural innovations would have better informed me in the design process.

In the context of looking specifically at buildings within the same typographical category as rotation, "Architectural and Structural Analysis of Selected Twisted Tall Buildings" by Golasz-Szolomicka & Szolomicki (2018) provided a good introduction into twisting towers. I also wish I had more time to reference and explore the towers listed in that paper, as well as the references for "Key Technologies for Super Tall Building Construction: Lotte World Tower" by Kim & Lee (2016).

Structural System Selection

It felt like the structural system was selected based off aesthetics and less on what is appropriate for a building of this given height, plan dimension, and use. Fazlur Khan's classification of tall building structural systems separated steel systems from concrete systems. The ALOE featured a dual system between both a concrete core and a steel system. With reference to Ali & Moon's tables which include composite structures with respect to the exterior and interior systems, it may seem that the structure was wildly over engineering and inefficient (2018).

Relative Stiffness of Components

The attempts to determine relative stiffness of the hexagonal knuckle to a brace frame configuration were weak. More time to develop this method and renew material mechanics knowledge would have made this endeavor more fruitful. The brace study for the ALOE was less technical based and more "guess and check".

Nonlinear Exercise for Torsional Buildings

In reference to:

- "Earthquake Behavior of Buildings" by Murty et al. (2012)
- "Consideration of Torsional effects in the Displacement Control of Ductile Buildings" by Crisafulli et al. (2004)
- "Seismic Design for Torsional response of Ductile Buildings" by Paulay (1996)
- "Earthquake Response of Irregularly Shaped Buildings" by Penzien

It seemed like an interesting exercise to consider what a proposed design procedure is when considering corrective eccentricities, torsional response of ductile buildings, and the beginnings of nonlinear considerations of design. I list these mainly as resources that I wish I took the time to truly digest. This "could have, would have, should have" proposal was only because I had read about this topic in the aforementioned readings, and it opened my mind to other avenues of analysis I had not even considered.

Wind Comfort Criteria

My understanding of wind loading was superficial at best. I would have benefited more had I taken the time to understanding wind loading, and the comfort criteria associated. A resource I found useful was "Wind Loading on Tall Buildings" by Ngo et al., (2007), which elaborates on the advanced aspects to determine design wind loads and how these forces interact with the building, its occupants, and itself. A lot of emphasis in this studio was focused on meeting deflection criteria for wind overall, but much less so on determining accelerations of stories and comparing that to human perception levels.

Brace Optimization

For lack of a better term, I considered the exoskeleton to be a highly irregular diagrid system. Not much was negotiable in terms of the bracing though, as an extremely expressive structure is subject to extremely critical reviews of its aesthetic appeal. With precedents such as Poly

International Tower or the Gherkin, I wish I had made more of an effort to examine these buildings. I also wish I did have the time an opportunity for brace optimization, but my coding skills would have been the downfall. To be frank, the exo and endoskeleton seem grossly overengineered, and a full study of element forces should be the first thing I address if I were to revisit this project.

I focused more on researching diagrid nodes, and the benefits of concrete filled tubes to built up members, or the type of node fabrication that can occur. If I could do this over, I would be much more confident and insistent on pushing my learning from literature over that of amateur engineering judgement of my partner. The following are resources that I did have the time to study, but wish I had the opportunity to implement and practice.

- *Diagrid Structures, Systems, Connections, and Details* Terri Meyer Boake (2014)
- *Complex Steel Structures, Non-Orthogonal Geometry in Building with Steel* by Terri Meyer Boake (2017)

I also wish I had studied more about concrete-filled steel tubes. My partner threw the term around liberally, solved problems magically by specifying them, but took little effort to understand them. They come with many benefits such as better material interaction, properties, and construction efficiency, but at the expense of expensive welding and high worker risk.

An additional resource to helping understand a diagrid system overall, which would have been a good document to perform my own study as an exercise to replicate and understand the content was "Comparative Study of Different Shapes of Diagrid Structure System with Conventional System using Response Spectrum Analysis" by Akhand & Vyas, (2019).

Introduction to Dampening Systems

I thought it would have been neat to gain a little more exposure to systems such as dampers or base isolators.

Personal Reflection

I took this class to get a lot out of it. And I did – both academically and inter- and intra-personally. I preface this section with a forewarning of this exhaustive and long-drawn reflection. Reflections can be cathartic.

This High-Rise studio was offered for ARCE students in winter 2019 as ARCE 460 and in spring 2020 as ARCE 415 as a senior project. I had finished my senior project in fall 2019 in hopes of having my last few quarters as a senior be less strenuous. However, I saw the opportunity for high-rise and interdisciplinary collaboration, and I decided to do it "just for kicks". Having had a quarter of leadership in my senior project, I was looking for a retirement of sorts. I discussed with my ARCE partner, and we agreed on him telling me what and when to do work. This was not the case, and the ensuing 20 weeks were relentlessly demanding of personal development and growth. The following are notable topics worth reflecting on:

- Diplomatic Communication

- Studio/Lab Culture
- Detachment and Disinvestment in a project
- Tepidity with Slights

The learning opportunities in this lab were why I enrolled. It seemed to be a once-in-a-lifetime opportunity, and truly I am glad for the academic and personal growth because of this interdisciplinary experience. If this studio was run as an office as much as Professor Kevin and Professor Tom said, then I am glad to have chosen this career path. I am also thankful that my previous multidisciplinary project experiences allowed me to adjust to the learning curve and distill different types of lessons. Organization, scheduling, and project-focused communications were skills I had developed and felt like helped the team in adjusting to the sudden momentum of the studio. This allowed me to focus more in other tiers of development.

Diplomatic communication, on the other hand, was something I had yet to learn because of the informality of these situations, and the usual friendship between group members. When the boundaries between doing favors and doing too much blurred, finding the balance of a professional and friendly communication style was difficult. When communicating with friends, there is an added level of considerations and design in how a dialogue is developed. Sometimes I wish I did have the ability to do all the work myself to avoid uncomfortable conversations, but it is not reasonable and does a disservice to myself and my peers. Facing these abrasive moments full of friction was undesirable, but necessary way of navigating these types of dynamics and communication. Maintaining professionalism from the beginning is the way to go, and I wish I learned more in this way.

Studio and Lab culture I learned to be even more important than I previously thought. There is a sense of comradery between students who stay up late into the night, and a collective effort in problem solving was something I truly missed once the quarter moved to an online platform. This studio experience helped me realize that I don't need to have a question to ask to constructively interact with my peers – the invitation of others to speak about what they are working on helps everyone involved. They learn to better communicate and understand the concept, and you learn more about a new topic, method, technique, perspective, or solution that may ultimately help or interest you. At a point, I was regularly sharing resources I had come across in my study or research that may have been helpful or related to other classmates' work, and they would reciprocate. In such a small community, academic acquaintances became friends who supported me academically and personally.

Perhaps the largest challenge I had in the class was to detach and divest in a project. When a project is as demanding and engulfing of your time as this, it was difficult to distinguish the quality of the project process from the quality of my personal work process. Regardless of the all the "overtime" I dedicated, no amount of brute force would overcome the fact that the excessive investment and commitment had caused burn-out and resentment in my work. Healthy boundaries between you and your work were necessary, and a conversation about a group member's expected commitment and prioritization of this project was imperative. If one student were to have less commitment to the project, there is only so much you can give to compensate before it becomes burdening. This was the hardest thing for me to accept, as I was so used to

always using the brute force of time to resolve issues like this. What matters is that I recognize my own merits and work, even if others do not.

The academic, technical, and soft skill growth in this studio was more than I could imagine. It has reaffirmed my affinity for architecture and helped me realize the cleavage between the two disciplines is a little more arbitrary when it comes to form development and expression. The exposure to this studio has made me keener on pursuing a master's degree to explore the ideas I have only glimpsed. Design is an exciting process, and I hope I will have the opportunity to design as creatively and acrobatically as I have in this studio.

6.2.2 Tony Nguyen

At the start of the twenty weeks, I was not quite sure what to expect because this would be my first experience in a highly integrated and involved studio class. However, I did anticipate for this class to be a lot of work and fun. I also thought of it as a fantastic opportunity to apply Cal Poly's "Learn by Doing" motto. The 2020 Skyscraper Collaboratory was the perfect chance to demonstrate the principles we learn in the classroom and substantially build upon our knowledge. The challenge then was to design and bring our design to fruition. From the start, we hit the ground running with this project because we had to design a skyscraper from scratch. My learning was accelerated with considerable guidance from professors, SOM advisors, and my wonderfully capable team. However, this project meant more than learning outside the classroom. It is a real-world experience of being an architectural engineer and a glance into the future of the profession in an integrated class. I found it to be a privilege that few undergraduate students come by. We had to pick up things that we otherwise never learned in our studies, such as soft skills like staying organized and coordinating with each other to stay on schedule. We had to delegate tasks and play to our strengths.

In addition, I learned that working in a team is perhaps the greatest win of all because you are not only surrounded by intelligent minds, but also people who have different perspectives and can thus formulate diverse solutions. As with any team, I found that we all had our strengths and weaknesses, but we quickly became interdependent. Trying to do one thing on your own was impractical and impossible to accomplish without frustrations. Another lesson that came with teamwork is that it is acceptable and even encouraged to ask for help. Inquiry, whether it be due to confusion, for clarification, or for assistance is key for success. Communication and constant inquiry between each other and with advisors helped us accomplish our design with the utmost efficiency. Feedback from faculty and industry advisors also played a vital role in making our decisions well informed.

Overall, I highly enjoyed being a part of this interdisciplinary studio as I got to see how other teams within the class applies the same basic building criteria and come to different finished products. As stated before, participating in this studio was a privilege that few engineering students can do or perhaps are aware of. This project was especially meaningful for me, as I hope to work for an interdisciplinary firm in my professional career.

7.0.0 Acknowledgements

Our thanks go to SOM and advisors, Kevin and Tom. As eager and perseverant as students can be, we can only go so far without the guidance of mentors and professors. There is a direct correlation between the amount of feedback, lectures, and reviews SOM partners and associates invested into the studio and the quality of the student projects. Our experience in this integrated studio would not have been as beneficial without the knowledge of SOM and our advisors. They provided constant insight that would have otherwise been overlooked and brought with them a novelty that inspired our work ethic. The lectures were invaluable, and the genuine involvement with our project even more so.

An additional thanks go to architecture majors Moriah Haley and Faisl Alabdali, of whom this project would have never been developed without. Their work ethic, insights, and design skills made this project an exciting and worthwhile endeavor. The craft and creativity of these two students made every late-night rewarding.

We also extend our sincerest gratitude and appreciation to the donors of the Castagna Scholarship, of which both Lilliann and Tony are recipients. Our ability to succeed in time-intensive and rewarding classes like these have been supported by the generosity of these donors.

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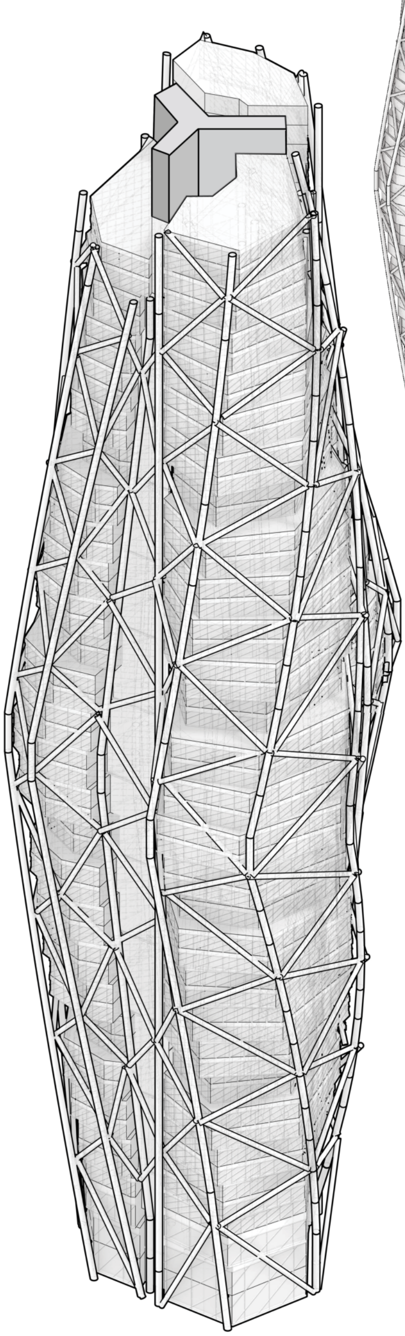
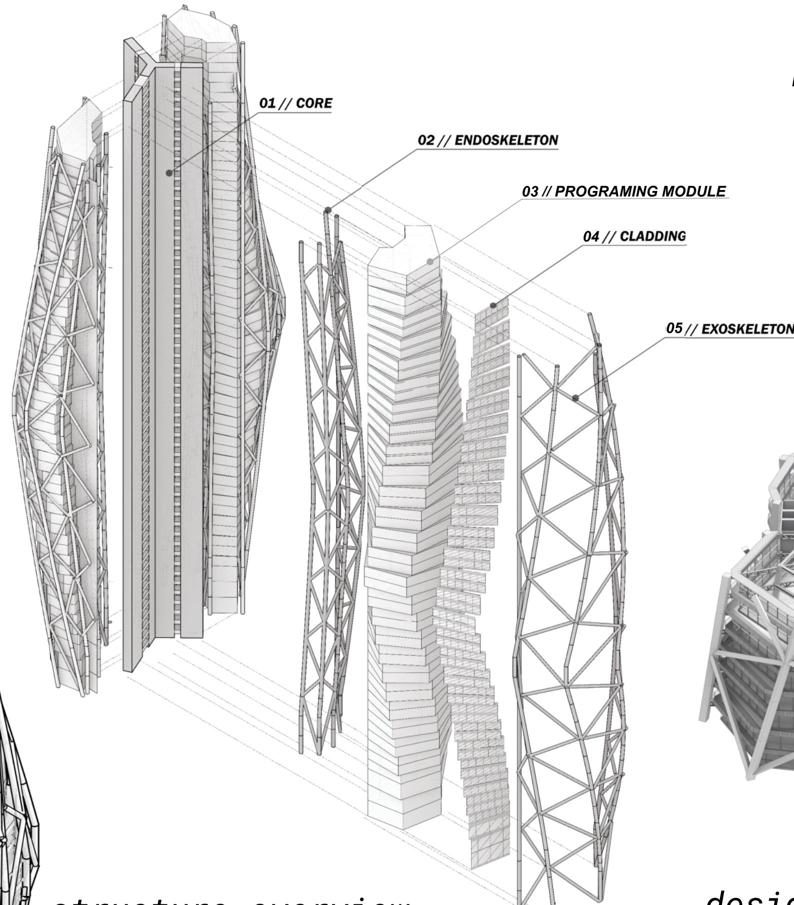
APPENDIX A

the ALOE

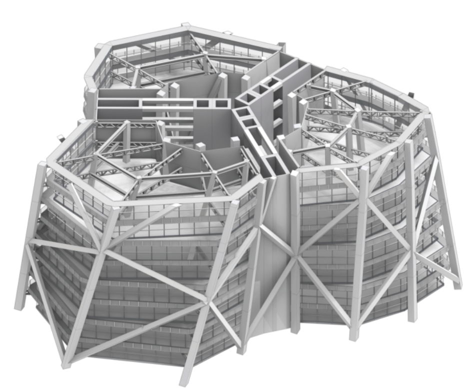
architects: faisl alabdali
moriah haley
engineers: lilliann lai
tony nguyen





project overview

1 oak st, sf, ca
725'
50 floors
300 residential units
12.5' floor to floor
5 community levels
18,000 sf per floor

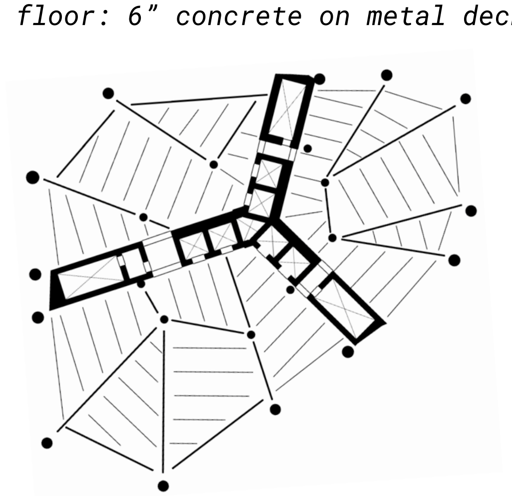


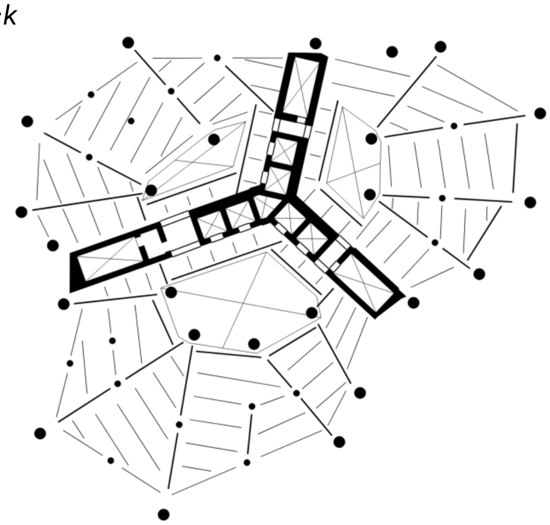
structure overview

columns: 36x2 pipe
griders: 22" composite open web joist
beams: composite W18x5
floor: 6" concrete on metal deck

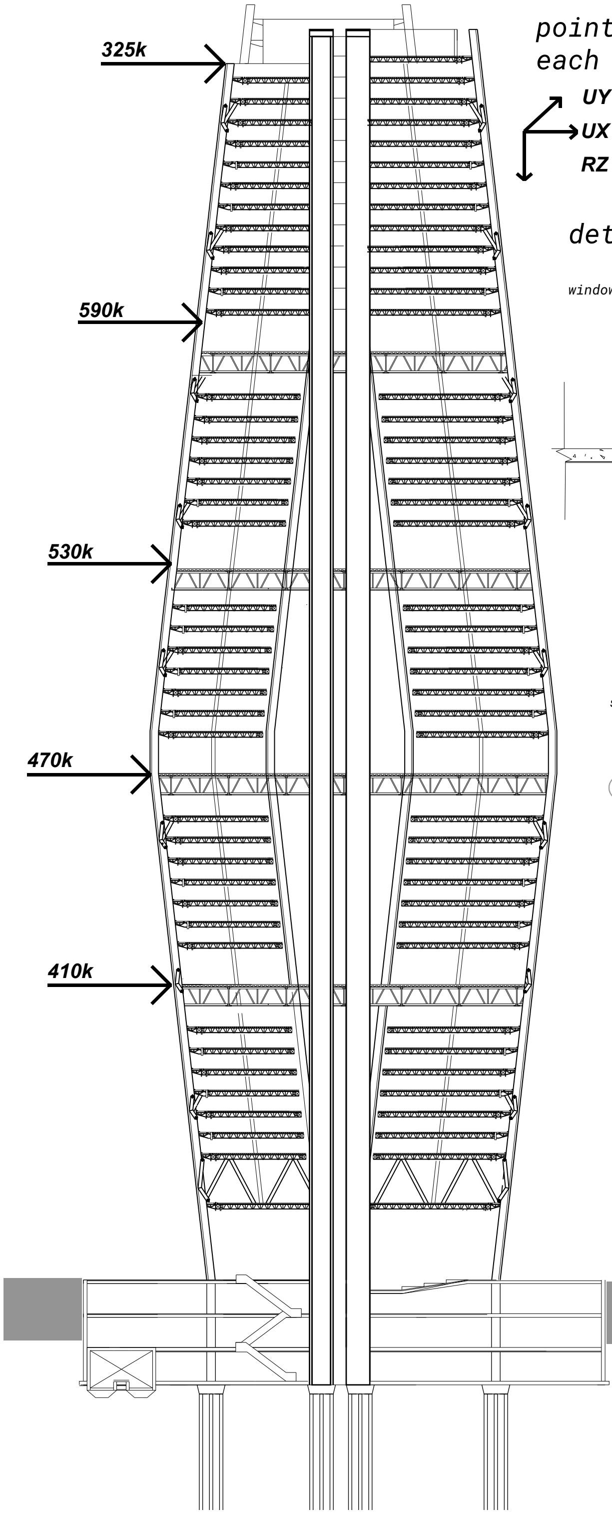
design challenges

torsion
diaphragm discontinuties
continuous load paths





analysis
wind & modal

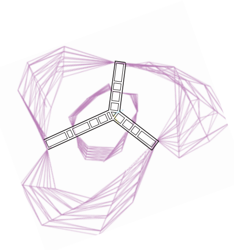


point mass at each floor

UY = 74.5 Ks²/ft
UX = 74.5 Ks²/ft
RZ = 480,357 Ks²ft

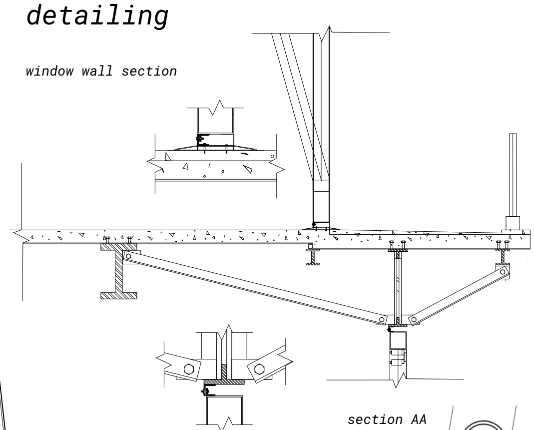
results

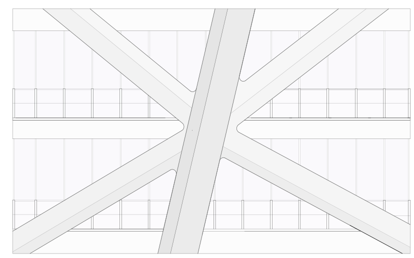
period	5.471 s	
mode 1	X	Δallow = 17.4"
mode 2	Y	Δallow = h/500
mode 3	↺	Δ = 16.10"
mode 4	X	Δ = h/463
mode 5	Y	
mode 6	↺	



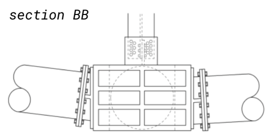
detailing

window wall section

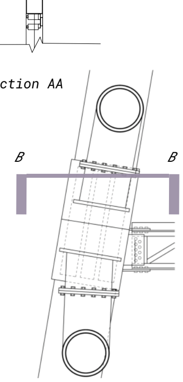


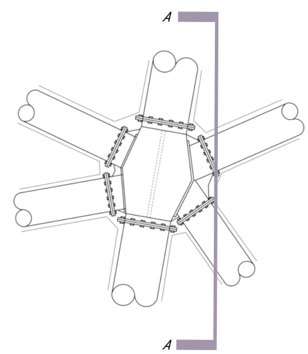


section BB

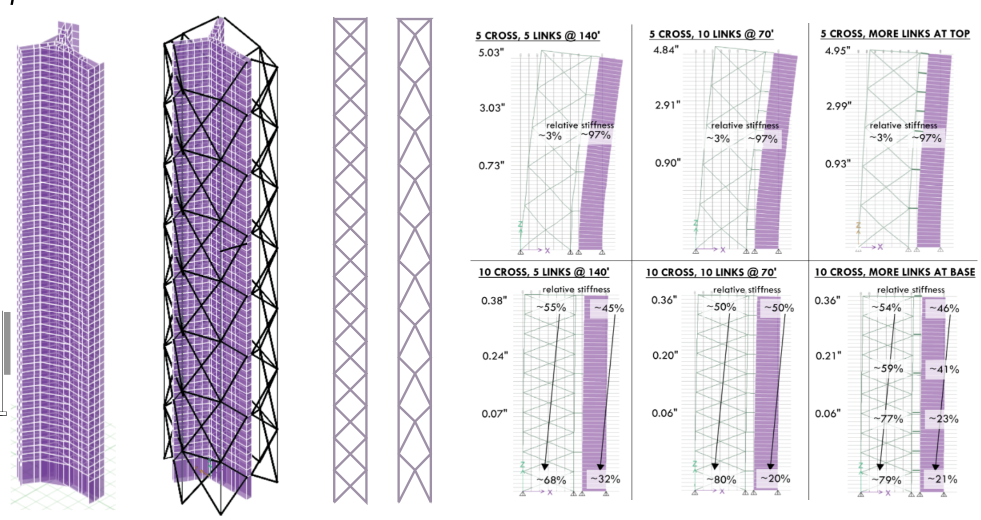


section AA



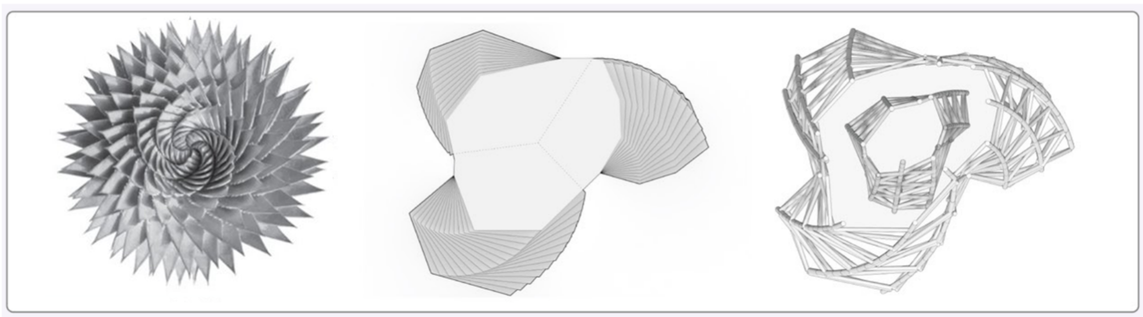


parametric studies



APPENDIX B

team 09: aloe



architects: faisl albidali | moriah haley

engineers: lilliann lai | tony nguyen

spring 2020 high rise design studio lai | nguyen

1

building statistics

725’

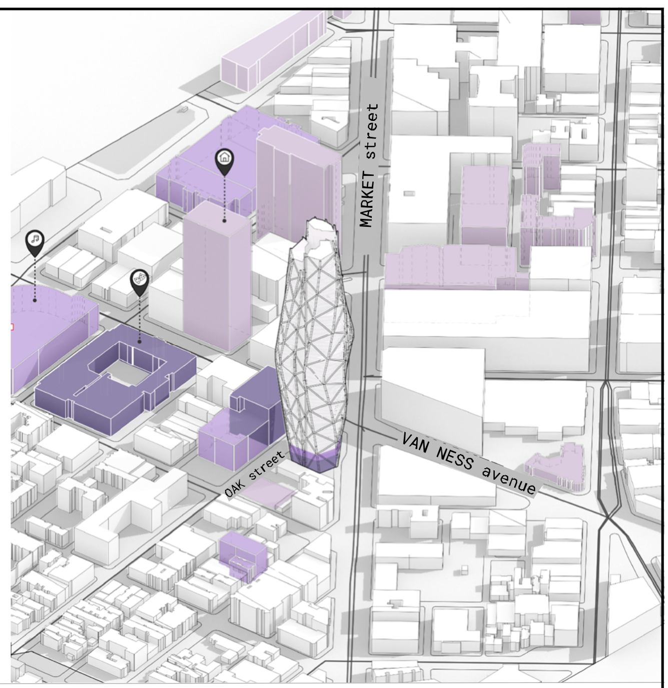
50 floors

300 residential units

12.5’ floor to floor

5 community levels

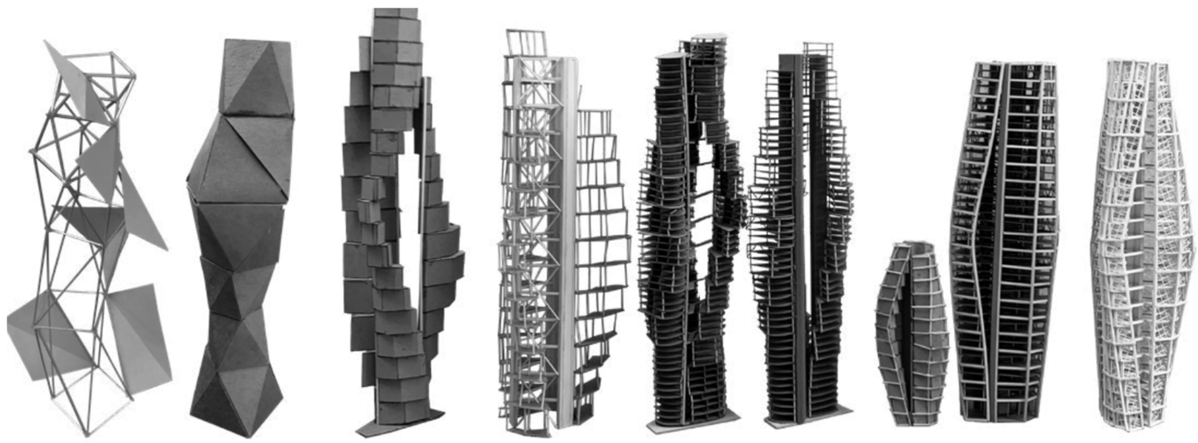
18,000 sf per floor



spring 2020 high rise design studio lai | nguyen

2

evolution | front end



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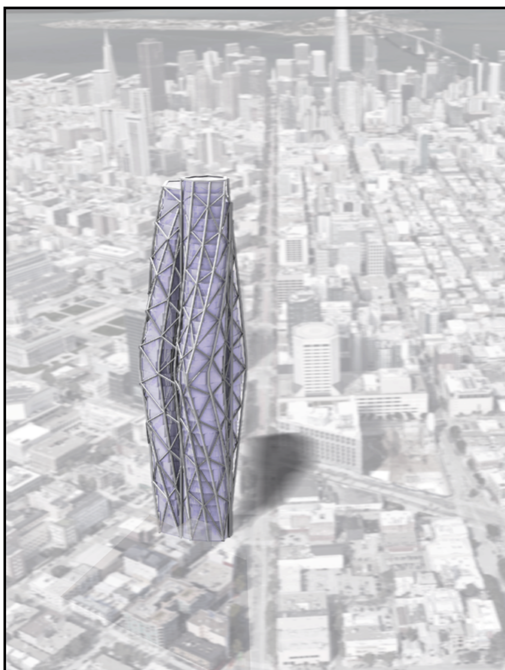
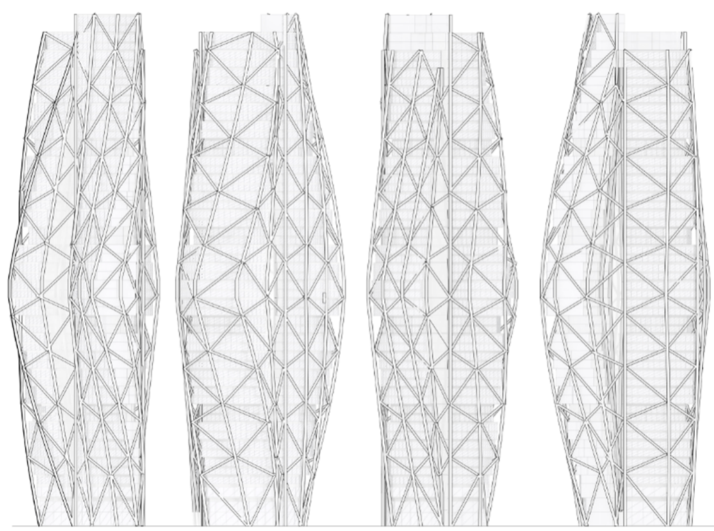
3





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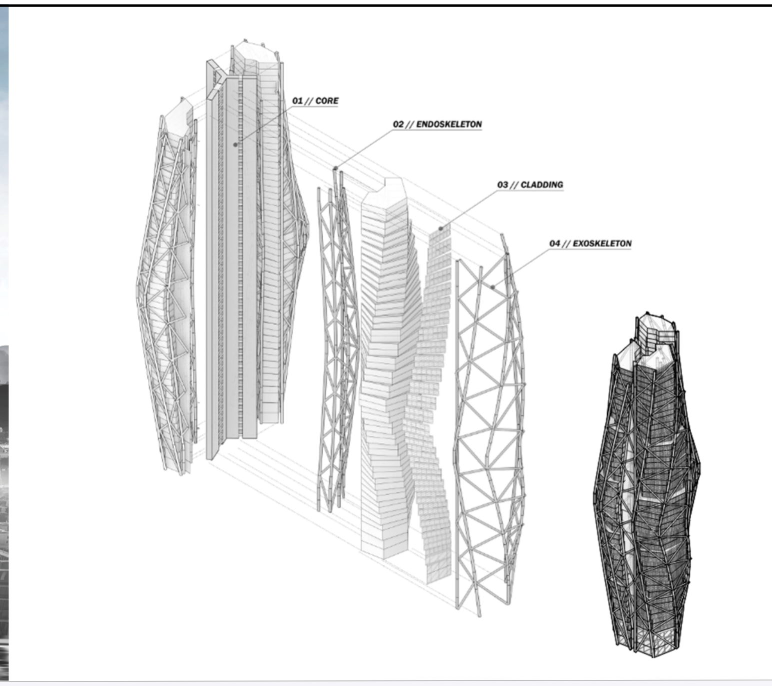
4



spring 2020 high rise design studio lai | nguyen

5

precedents

1.0_Agora Tower

1.1_Grove at Grand Bay

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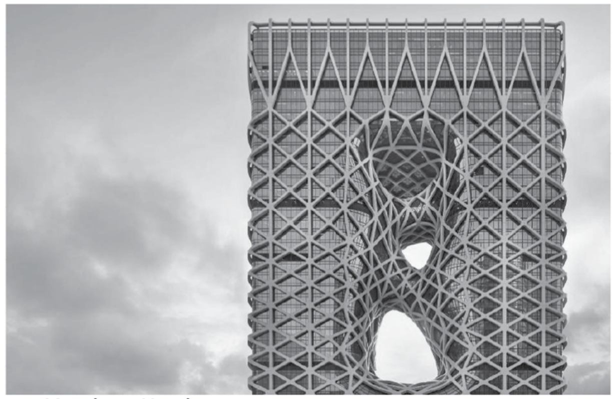
6

precedents

1.3_Poly International Plaza



1.4_Morpheus Hotel

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7

notable structural challenges

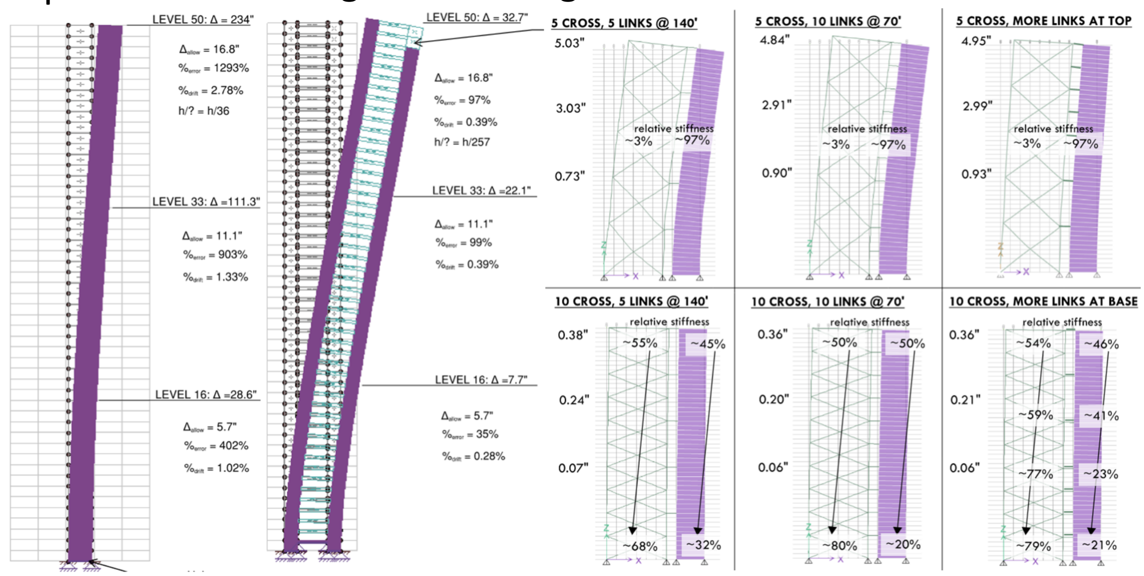
1. torsion

2. tying towers together

spring 2020 high rise design studio lai | nguyen

8

experimental big box building



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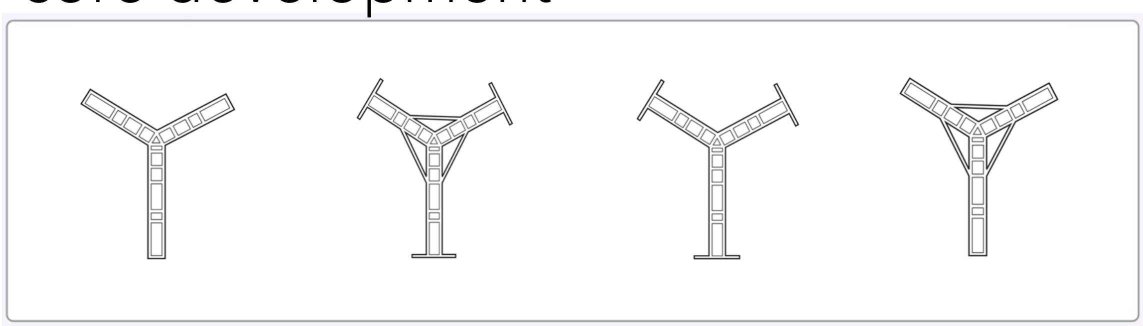
9

core development



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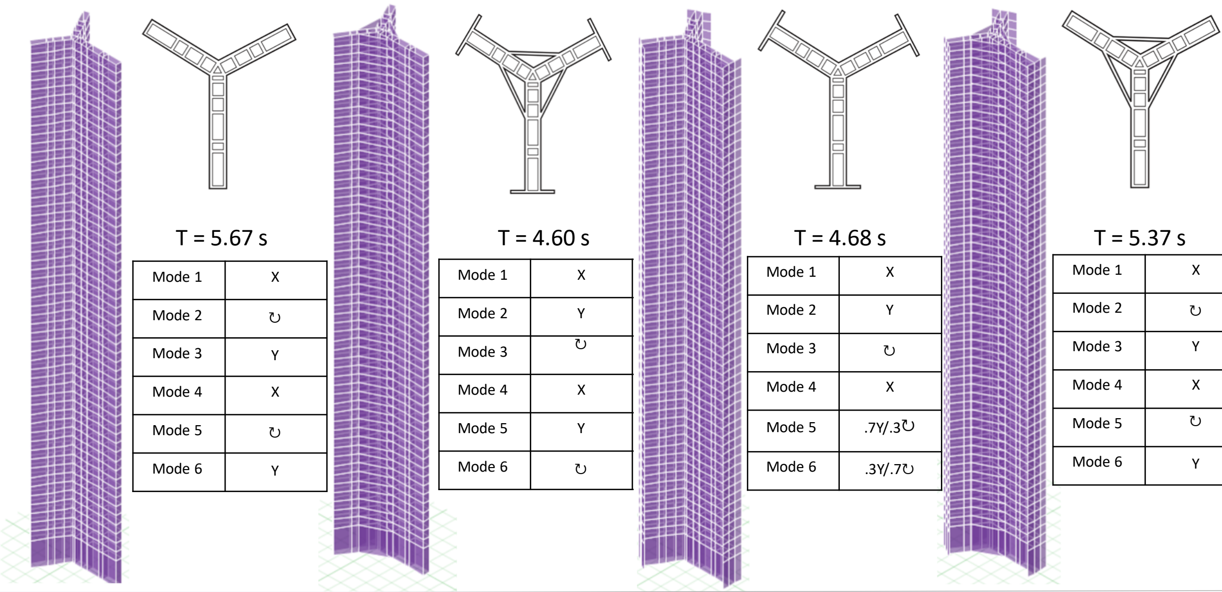
10

core studies



T = 5.67 s

Mode 1	X
Mode 2	↻
Mode 3	Y
Mode 4	X
Mode 5	↻
Mode 6	Y

T = 4.60 s

Mode 1	X
Mode 2	Y
Mode 3	↻
Mode 4	X
Mode 5	Y
Mode 6	↻

T = 4.68 s

Mode 1	X
Mode 2	Y
Mode 3	↻
Mode 4	X
Mode 5	.7Y/.3↻
Mode 6	.3Y/.7↻

T = 5.37 s

Mode 1	X
Mode 2	↻
Mode 3	Y
Mode 4	X
Mode 5	↻
Mode 6	Y

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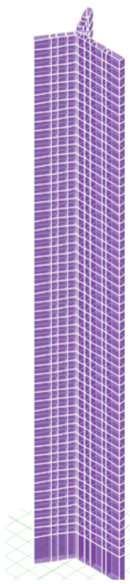
11

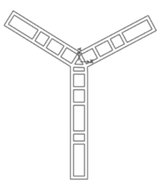
brace development

spring 2020 high rise design studio lai | nguyen

12

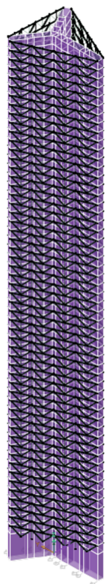
brace studies

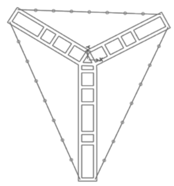




T = 5.35 s

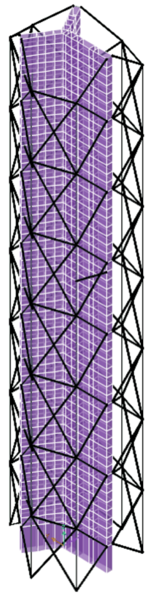
Mode 1	X
Mode 2	↻
Mode 3	Y
Mode 4	X
Mode 5	↻
Mode 6	Y

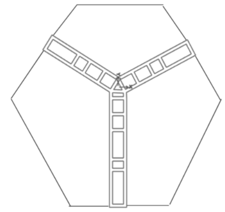




T = 4.12 s

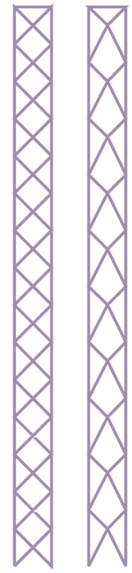
Mode 1	X
Mode 2	↻
Mode 3	Y
Mode 4	↻
Mode 5	.75X/.25↻
Mode 6	.75X/.25↻





T = 3.93 s

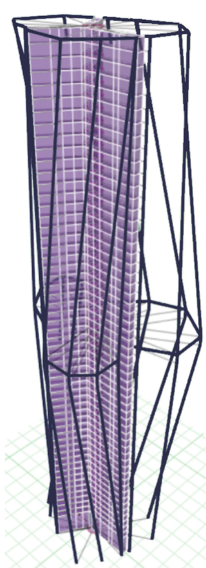
Mode 1	X
Mode 2	Y
Mode 3	↻
Mode 4	X
Mode 5	Y
Mode 6	↻

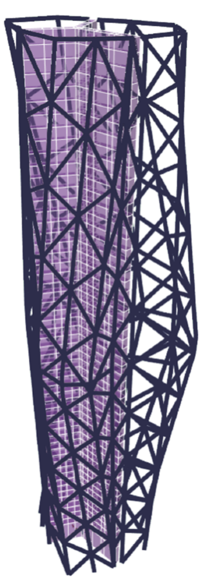


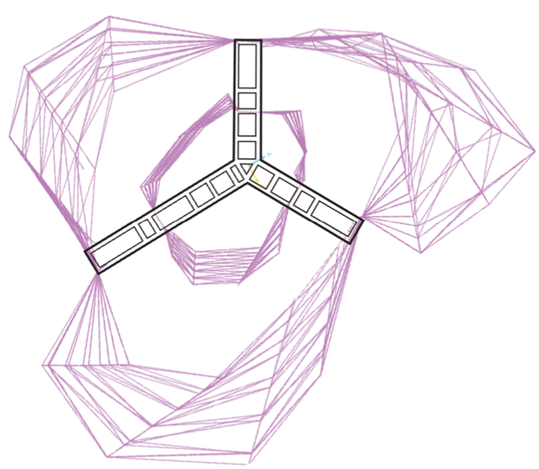
spring 2020 high rise design studio lai | nguyen

13

combined systems





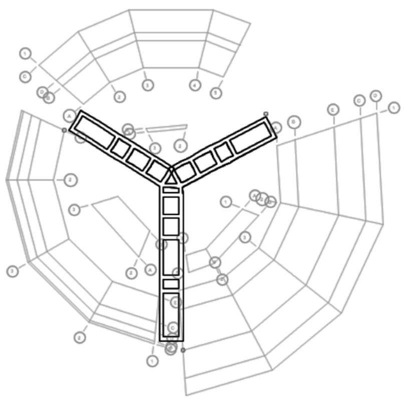


plan view

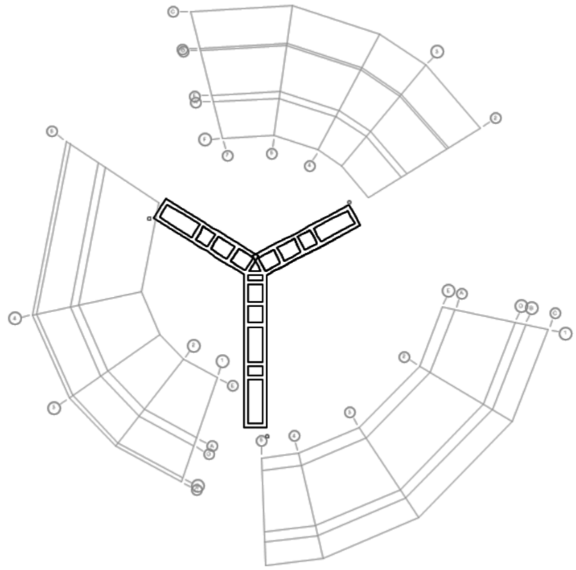
spring 2020 high rise design studio lai | nguyen

14

combined systems



1st and 56th plan



mid-height plan

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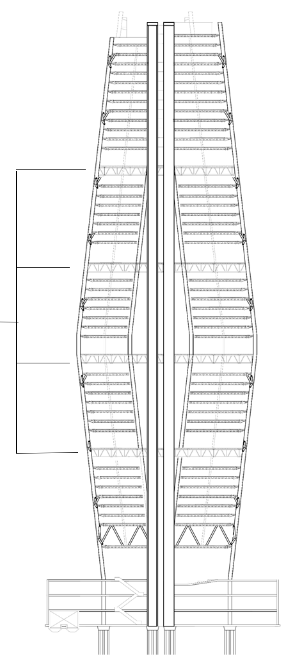
15

tying it all together

continuous diaphragms



spring 2020 high rise design studio lai | nguyen

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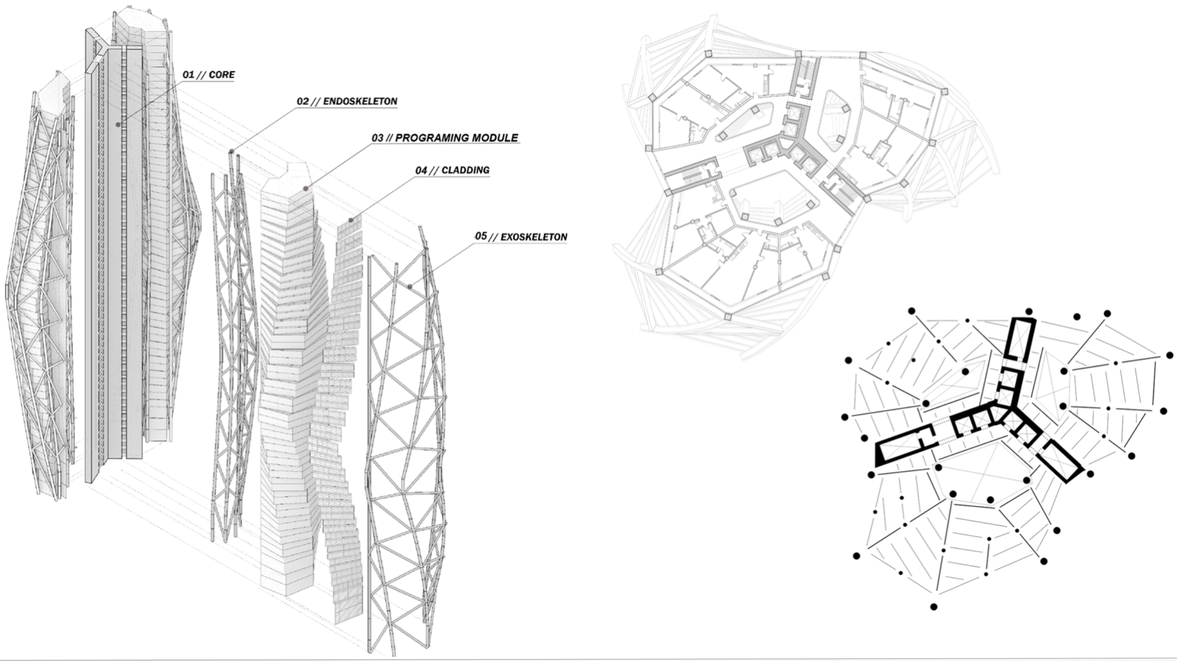

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final analysis

design inputs

- 12" core walls @ 10ksi
- 36"x2" A992 hollow tubes
- semi-rigid joint diaphragms

loading

- wind: 32.9psf-17.7psf
- gravity: 120 psf

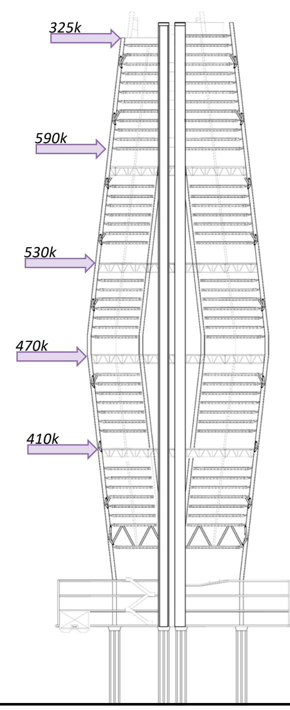
UY = 74.5 Ks²/ft
UX = 74.5 Ks²/ft
RZ = 480,357 Ks²ft

wind results

Δallow	17.40"
Δallow	h/500
Δ	16.10"
Δ	h/463

modal results

Period	5.47 s
Mode 1	X
Mode 2	Y
Mode 3	↻
Mode 4	X
Mode 5	Y
Mode 6	↻



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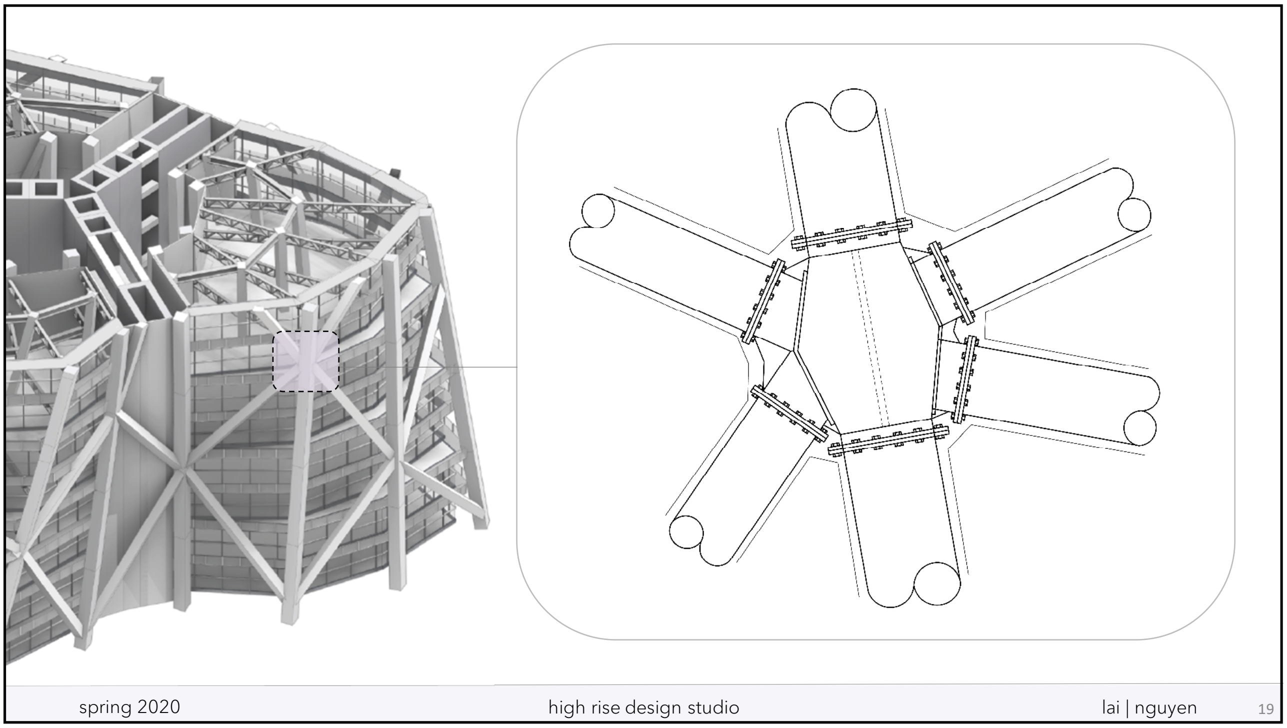
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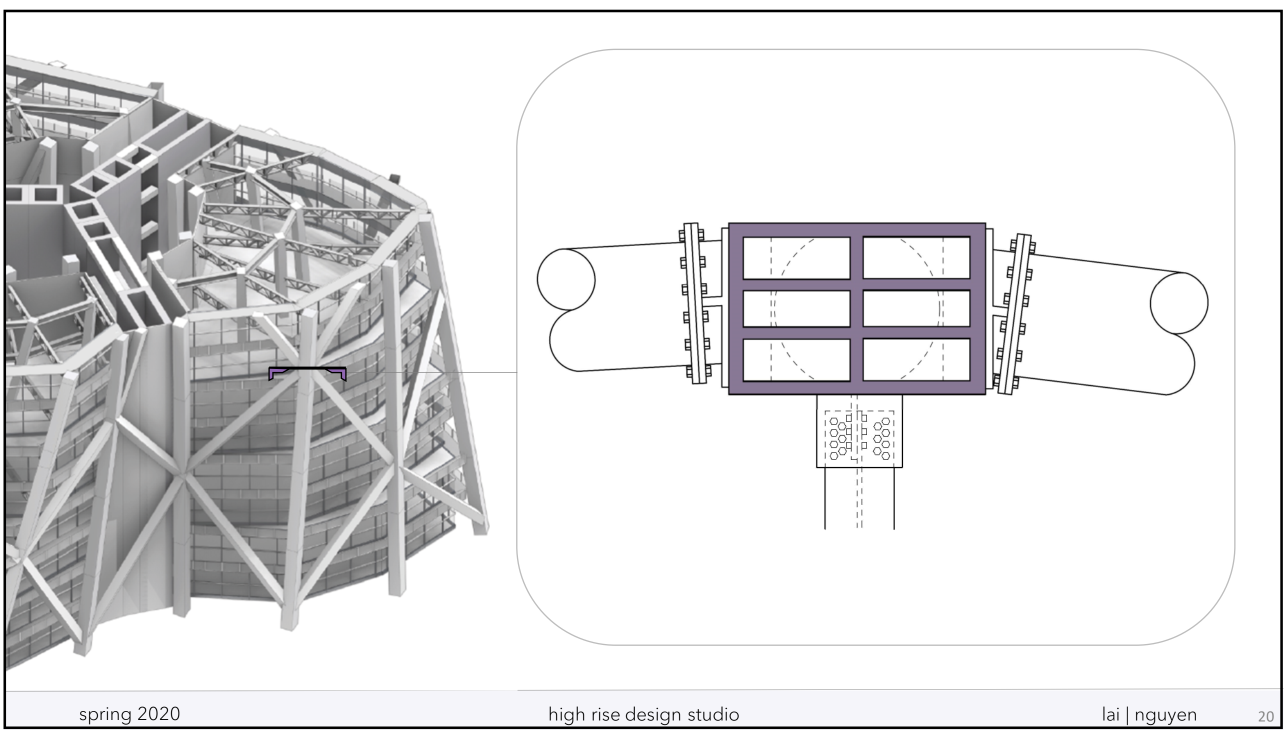
19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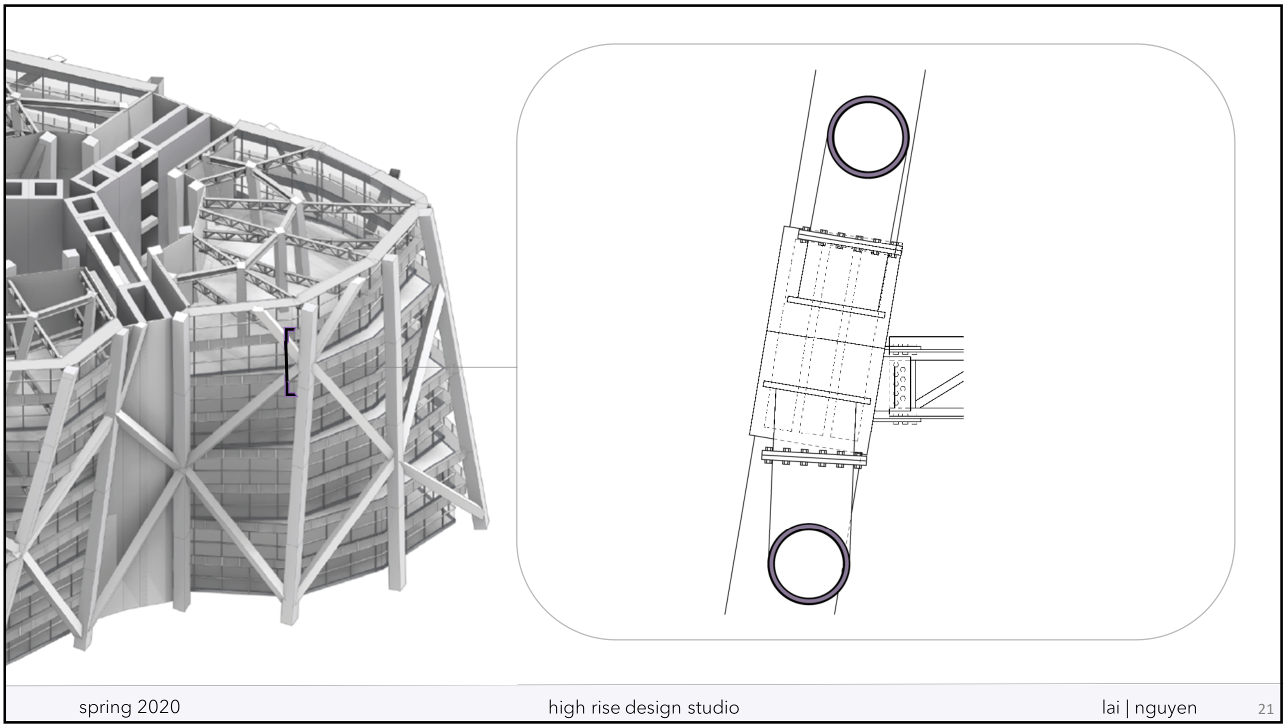
20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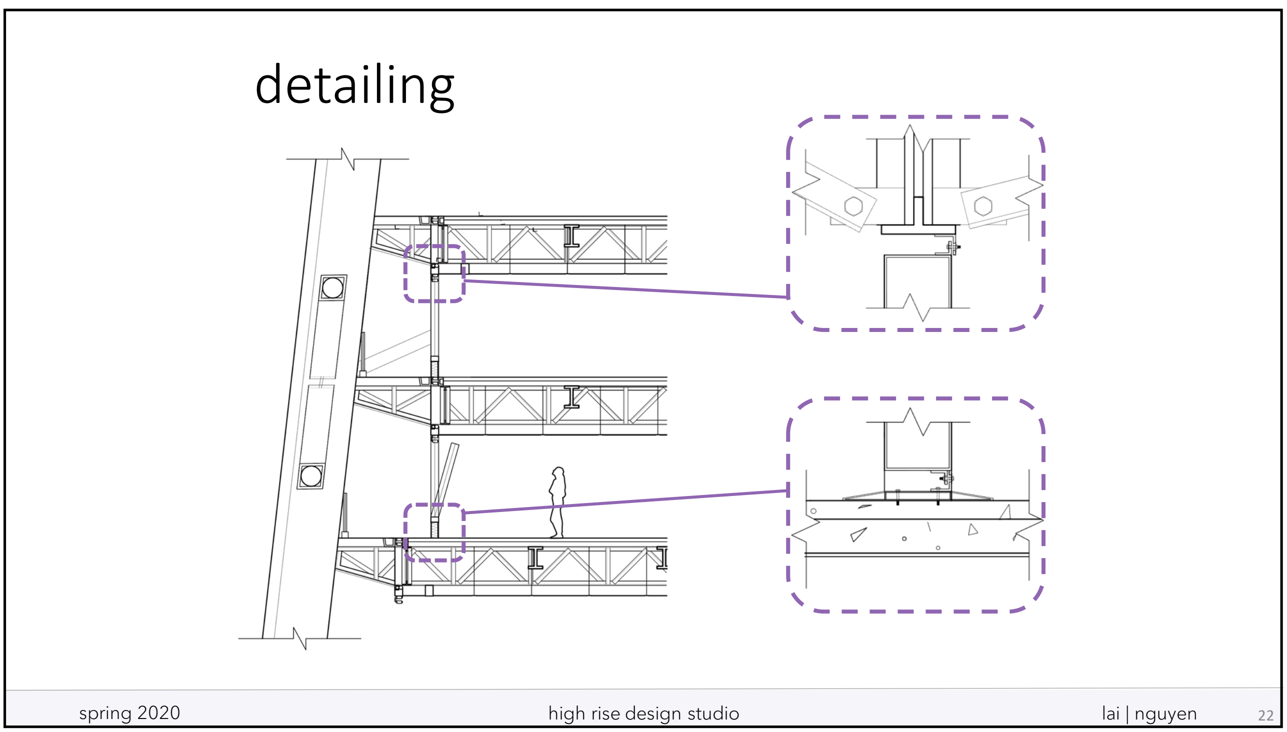
21


detailing
spring 2020
high rise design studio
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22

22

reflection

- Lilliann
  - Relative stiffness
  - Equivalent stiffness translations
  - Diaphragm Discontinuities
- Tony
  - Increase structural efficiency and optimization
  - Application of CFT
  - Pandemic

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Thank You

Questions?

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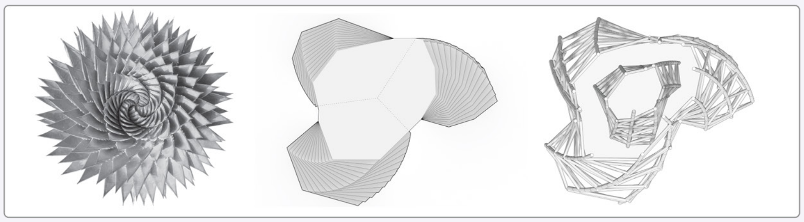
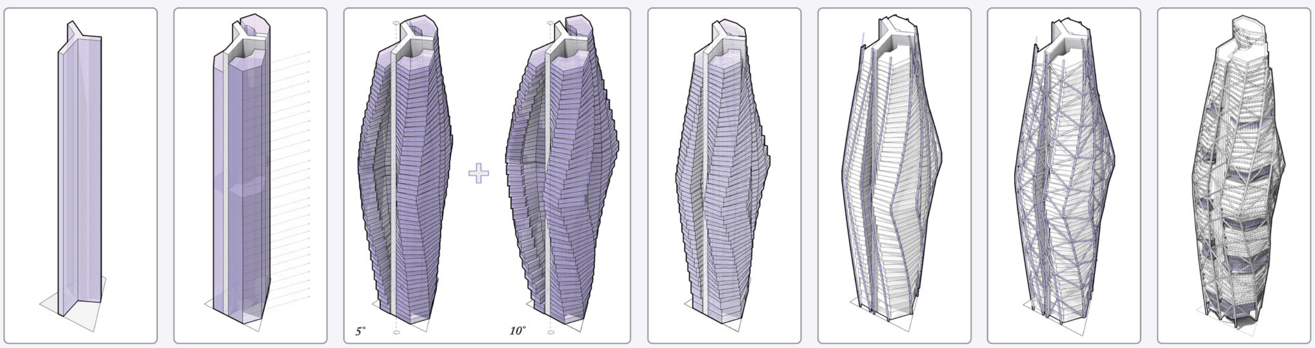
APPENDIX C

the ALOE



The aloe plant rotates outwards to maximize surface area for sufficient sunlight, necessary for survival. The rotational strategy inspires the three rotating towers which maximize views, daylighting, and vertical community.

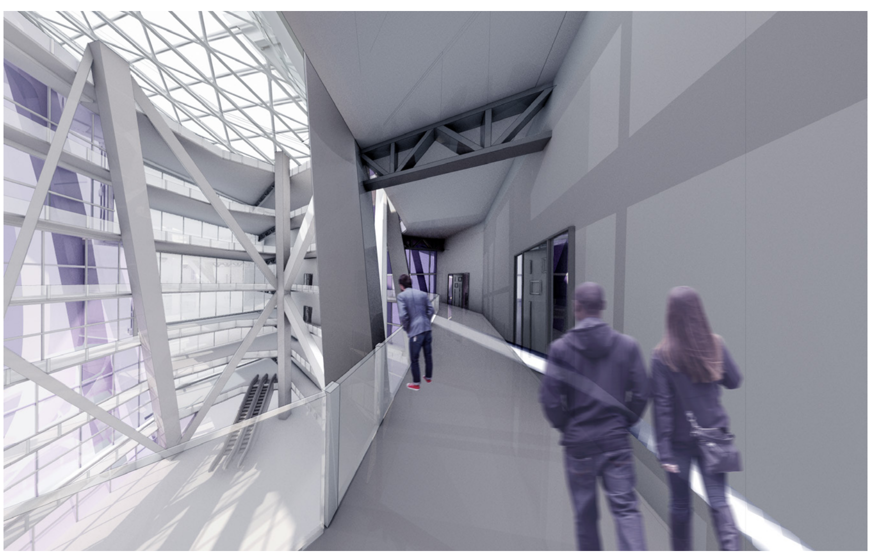


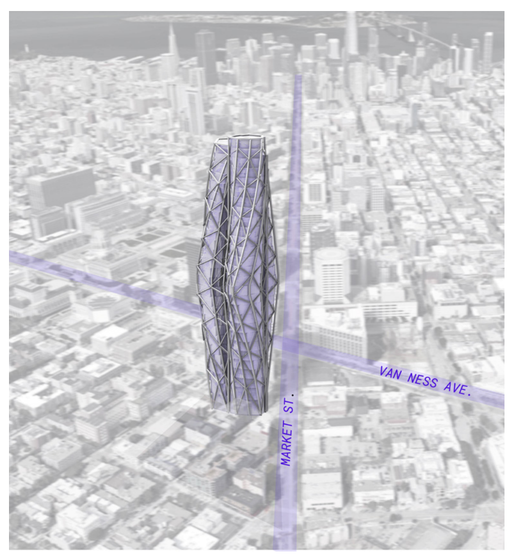
01_ SPLIT · 02_ MODULATE · 03_ ROTATE · 04_ SUPERPOSITION · 05_ CANTED COLUMNS · 06_ DIAGRID · 06_ COMMUNITY

faisl alabdali
moriah haley
lilliann lai
tony nguyen

team09

2





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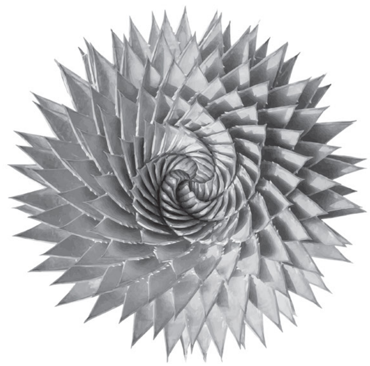
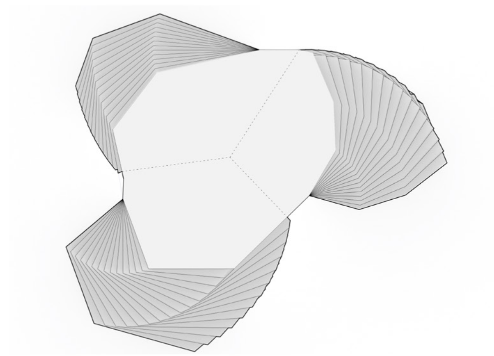
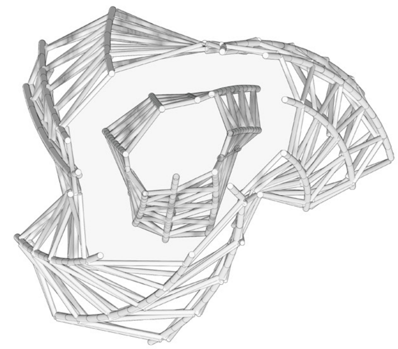
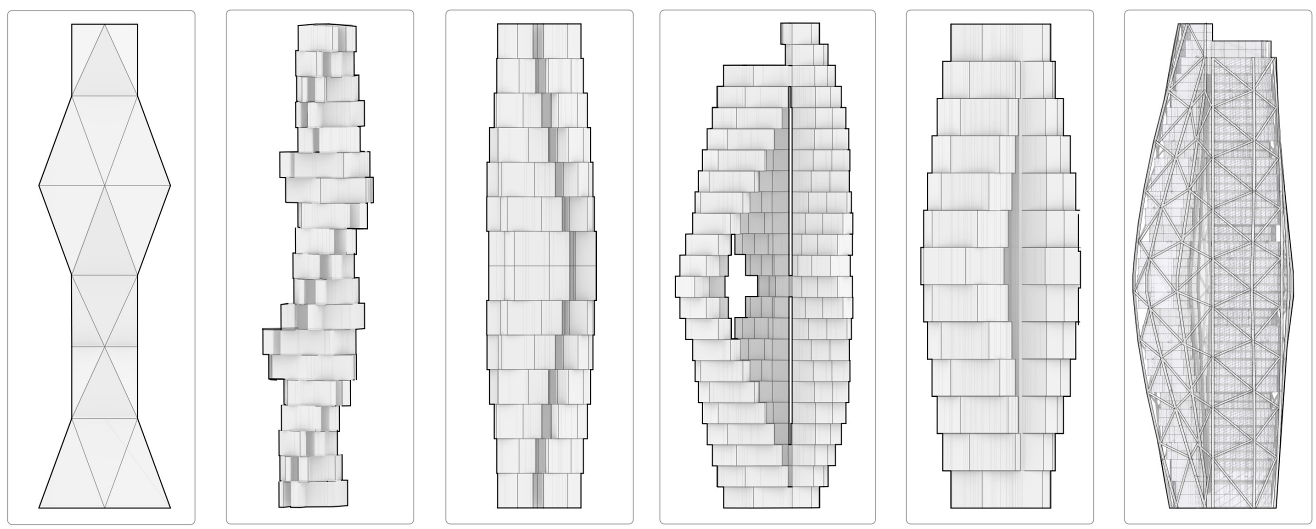




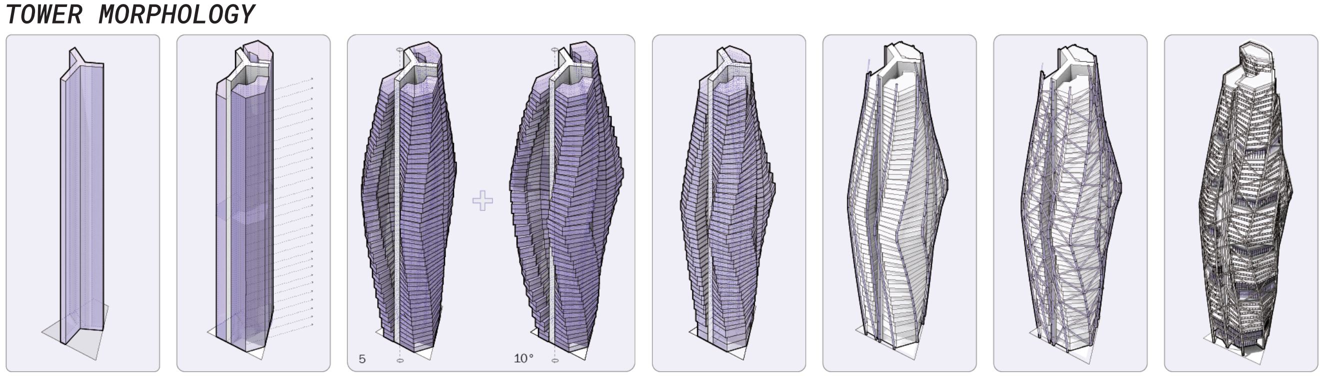


DESIGN ITERATIONS



1.1 *ROTATE* ***1.2*** *MODULATE* ***1.3*** *ORIENT* ***1.4*** *BULGE* ***1.5*** *CONSOLIDATE* ***1.6*** *DIAGRID*

TOWER MORPHOLOGY

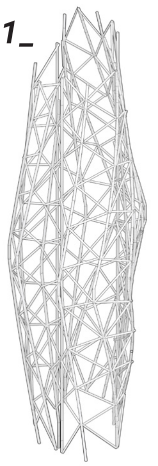


2.1 *SPLIT* ***2.2*** *MODULATE* ***2.3*** *ROTATE* ***2.4*** *COMBINE* ***2.5*** *COLUMNS* ***2.5*** *DIAGRID* ***2.5*** *COMMUNITY*

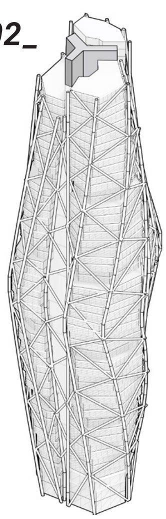
4

Concept

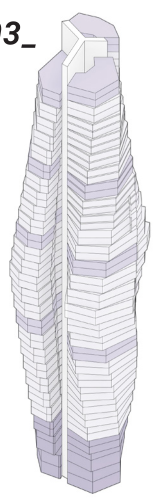
01_

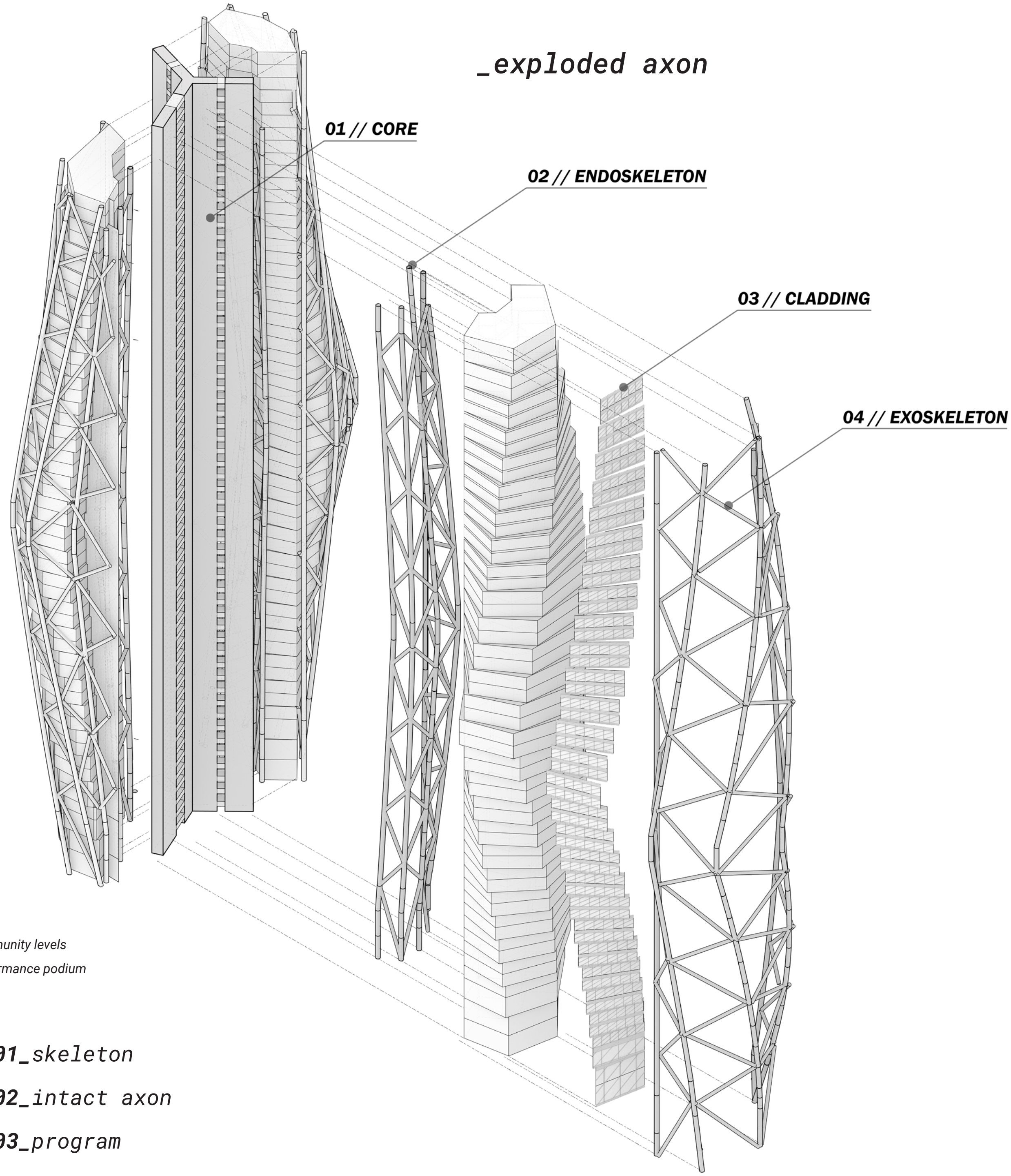


02_



03_



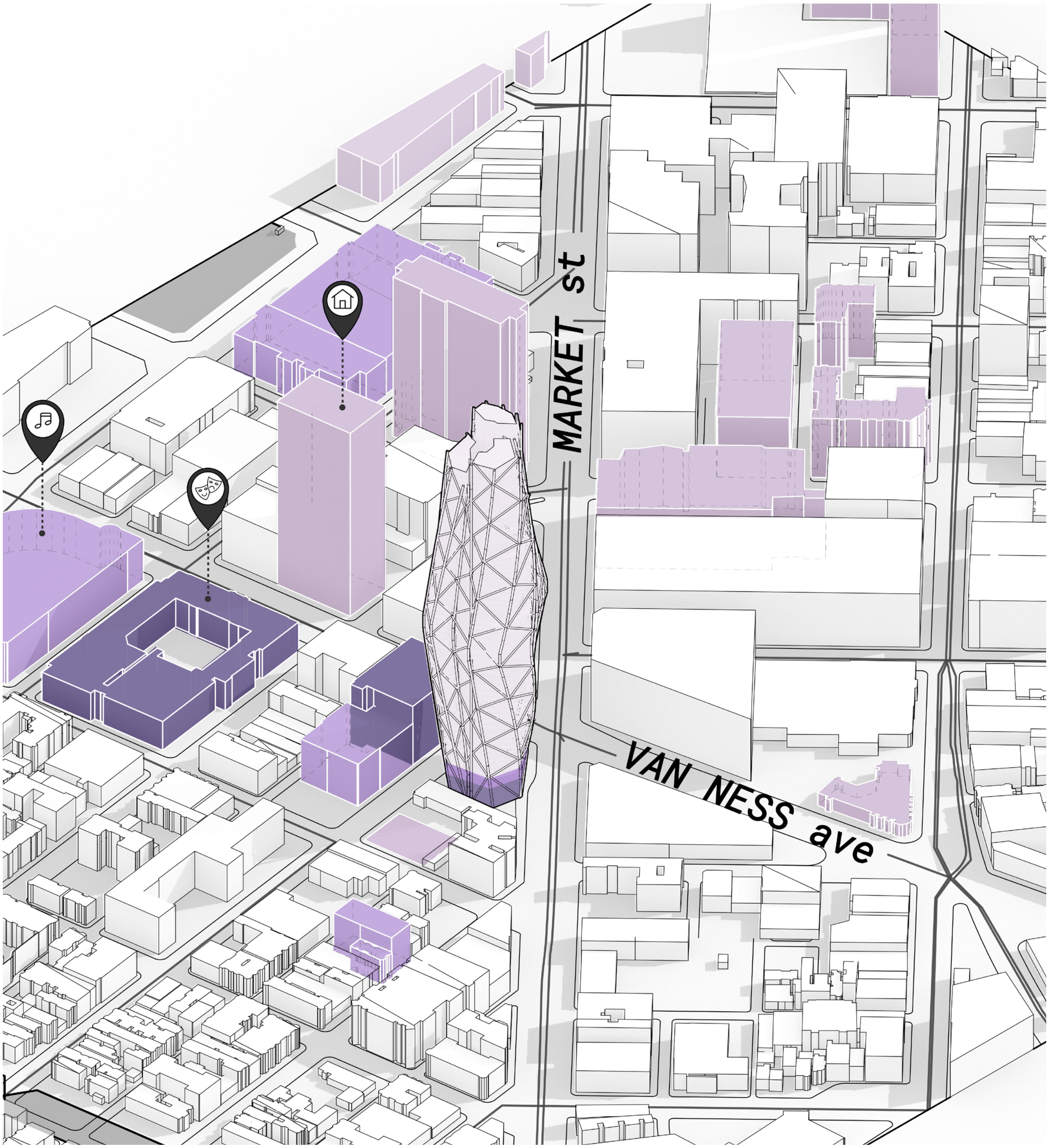


01_skeleton

02_intact axon

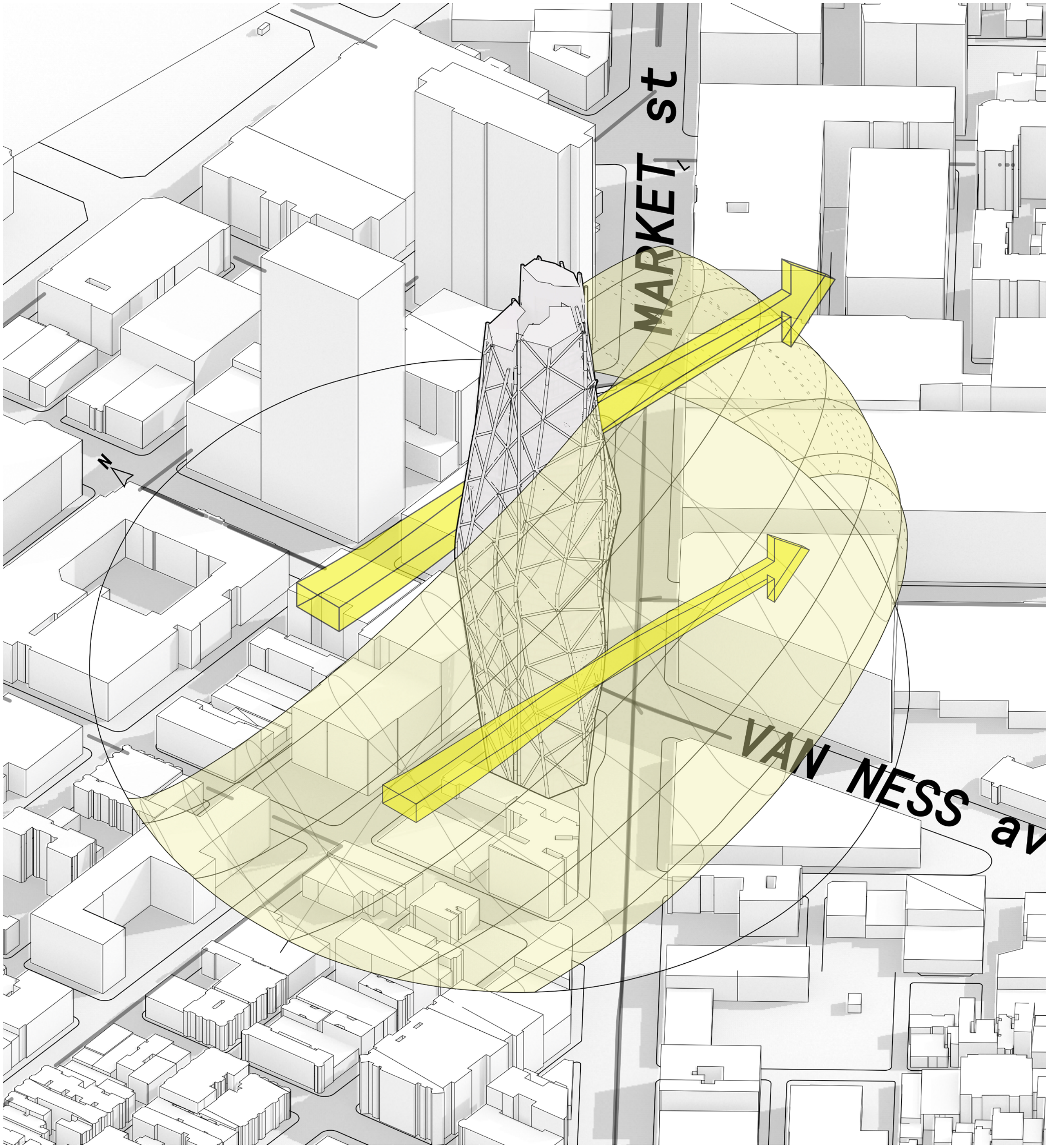
03_program

5



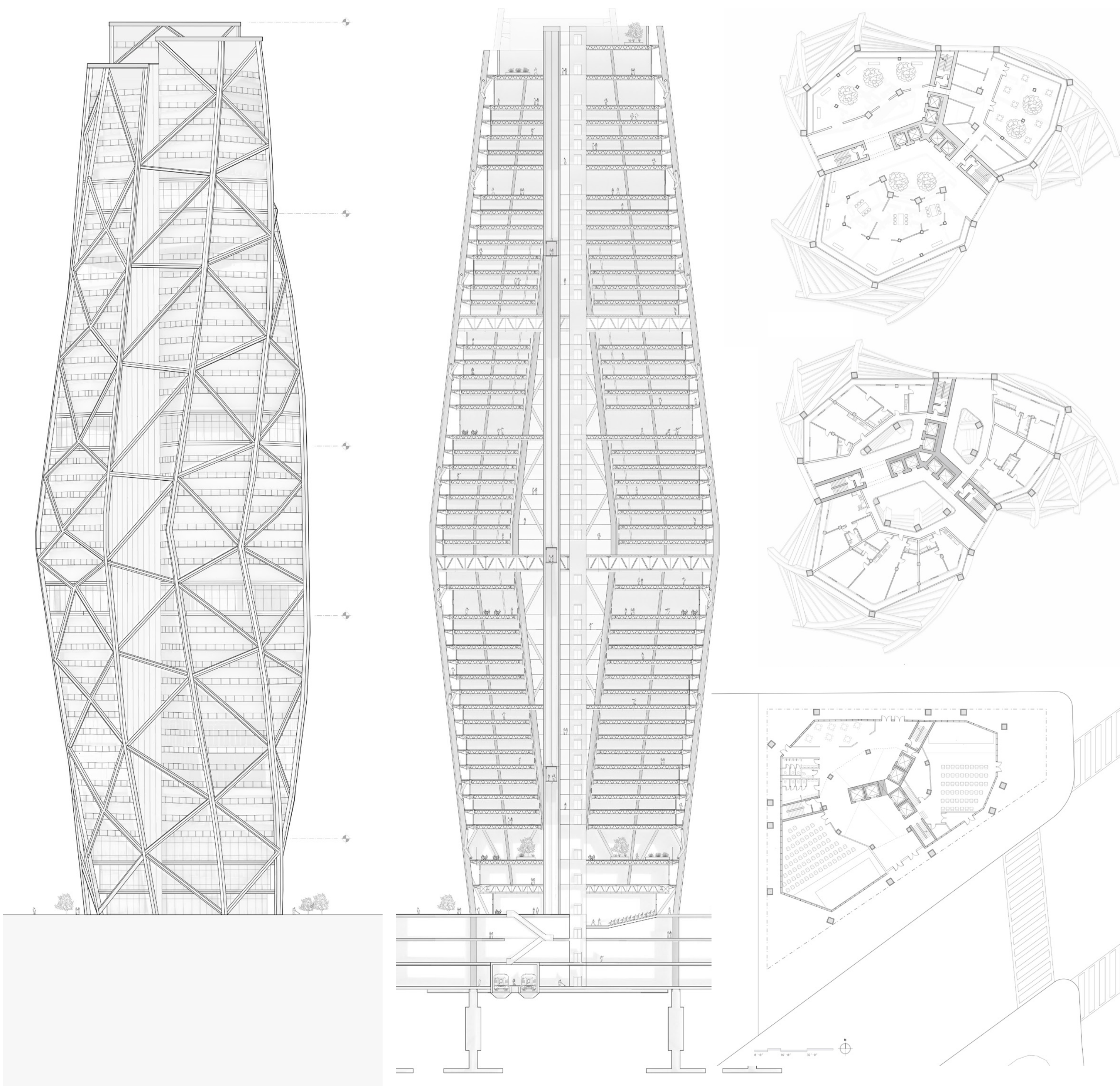
6

Urban Placemaking

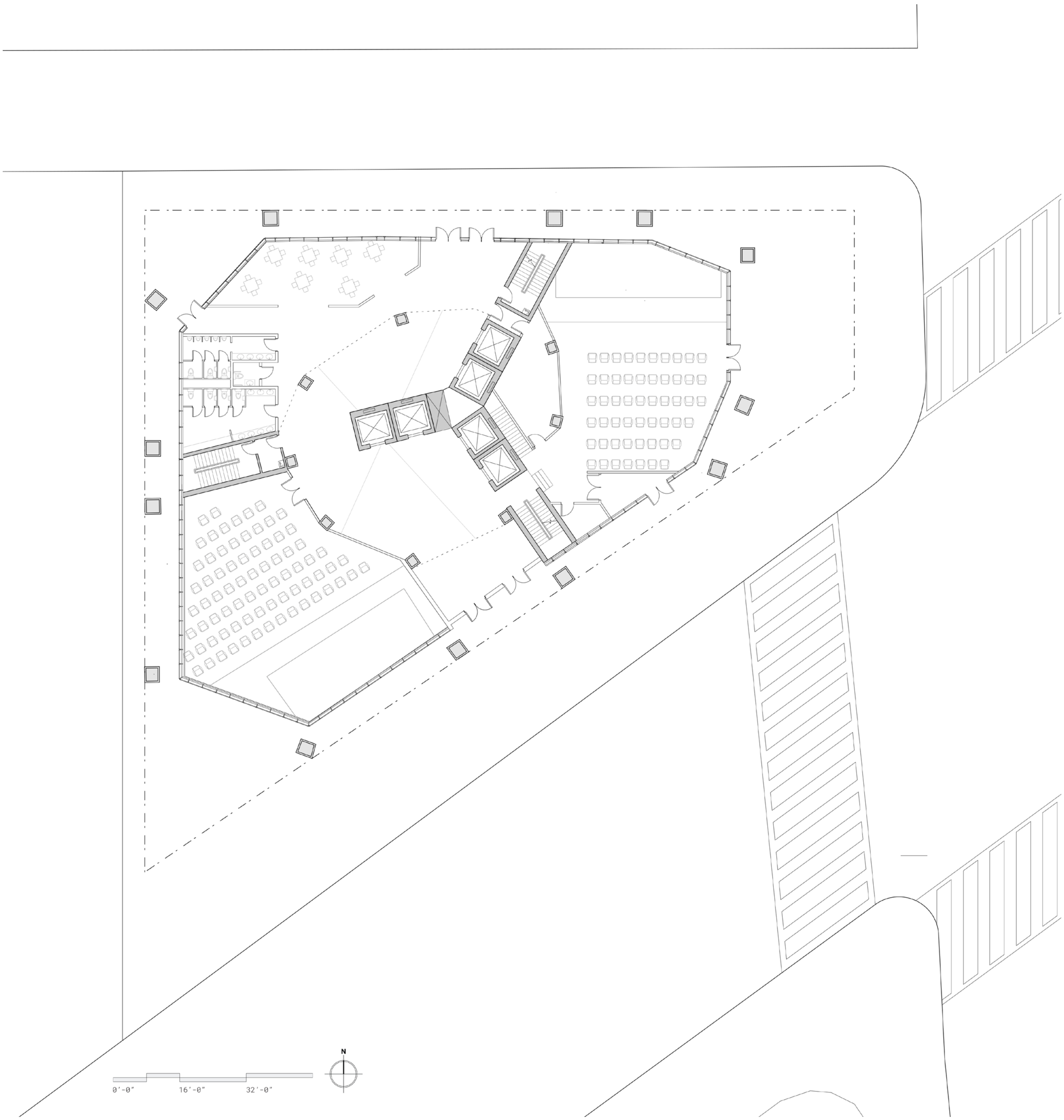


Environmental Factors

7

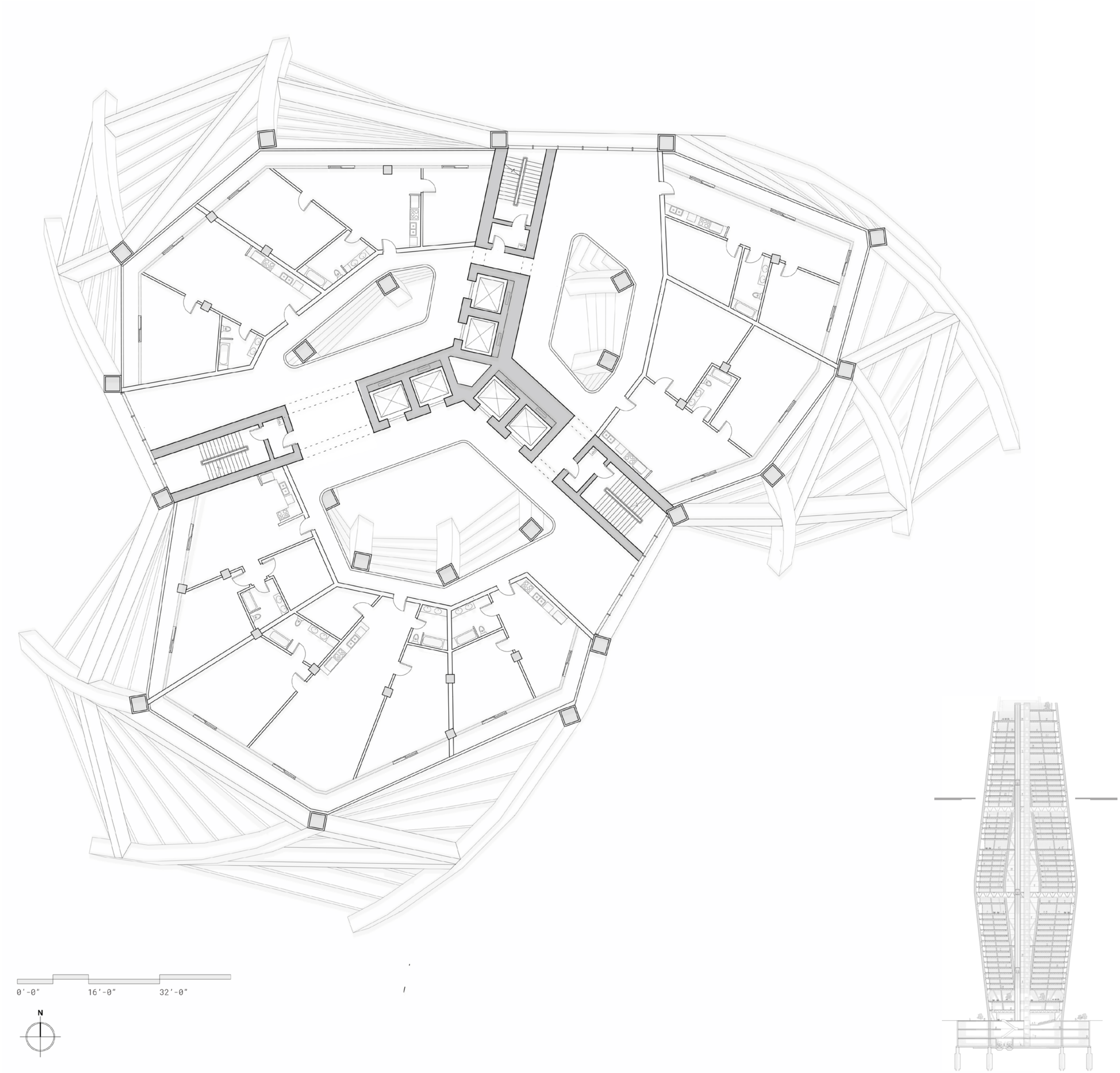


8

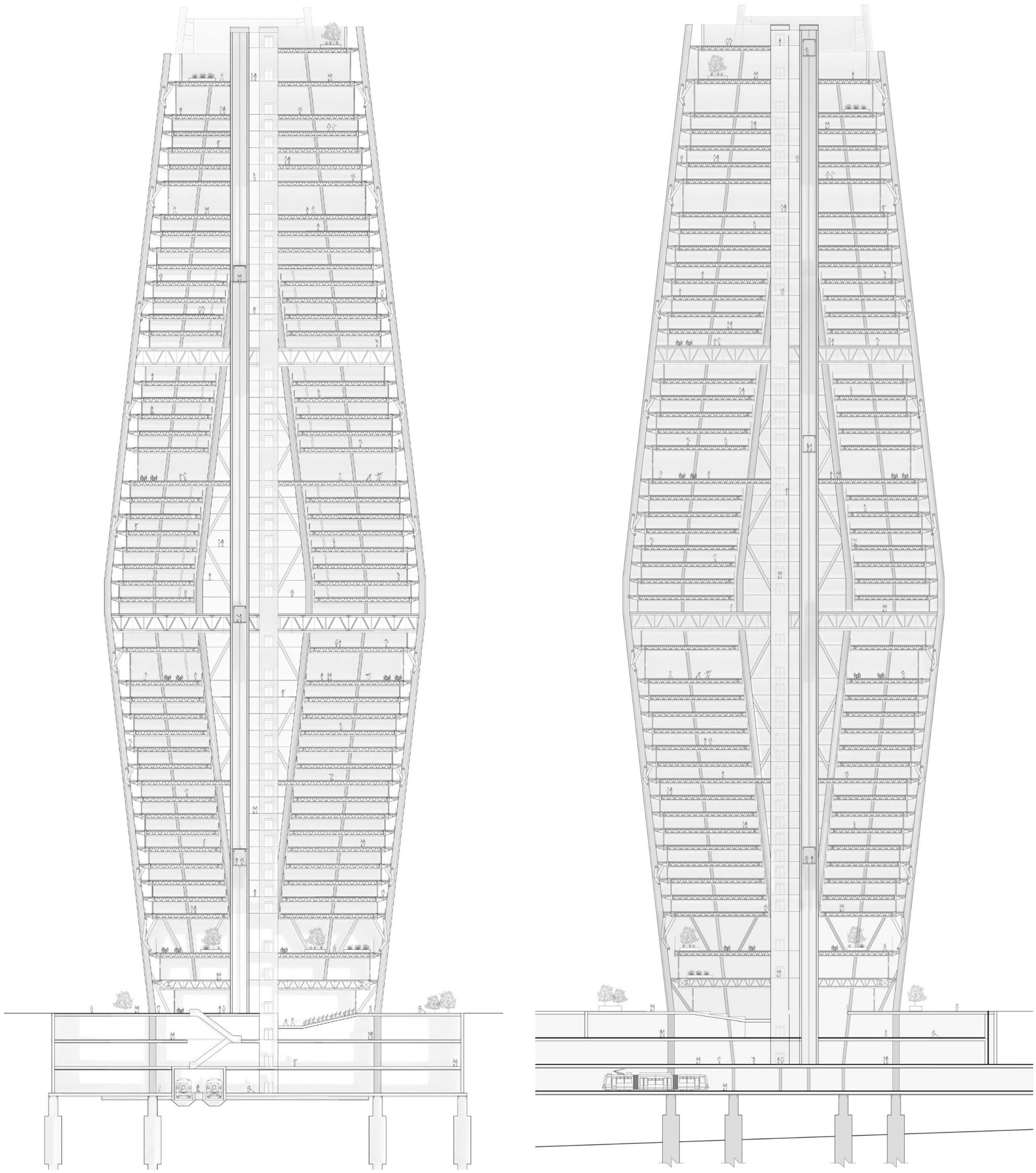


Ground Floor

9

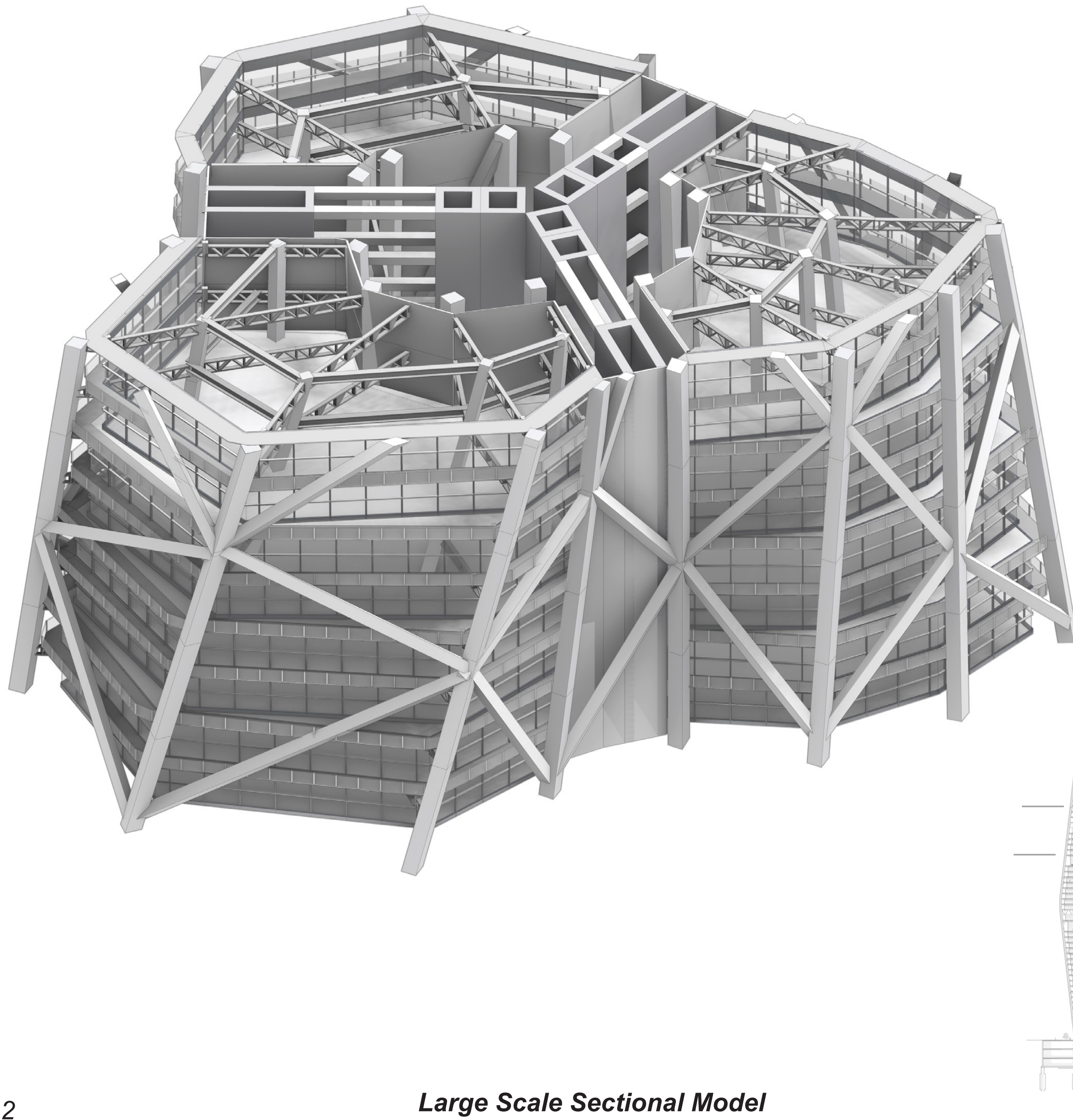


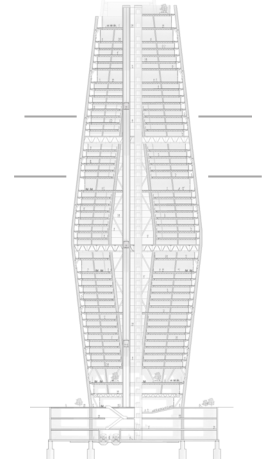
10 ***Housing Floor***



Vertical Cross Sections

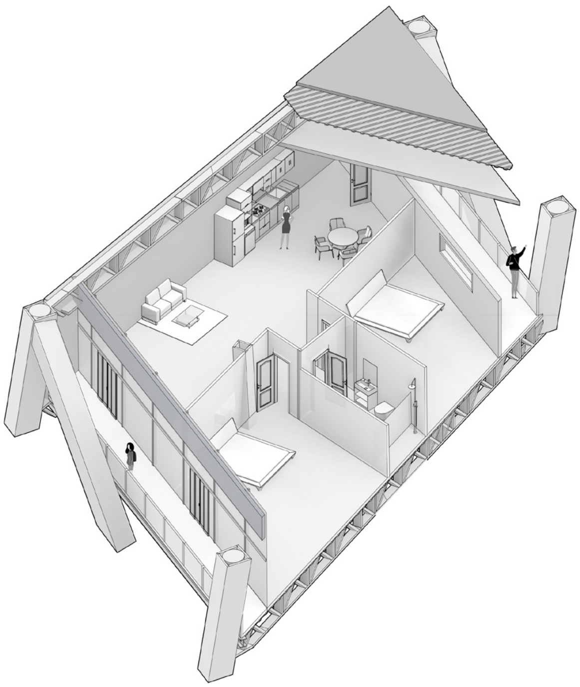
11

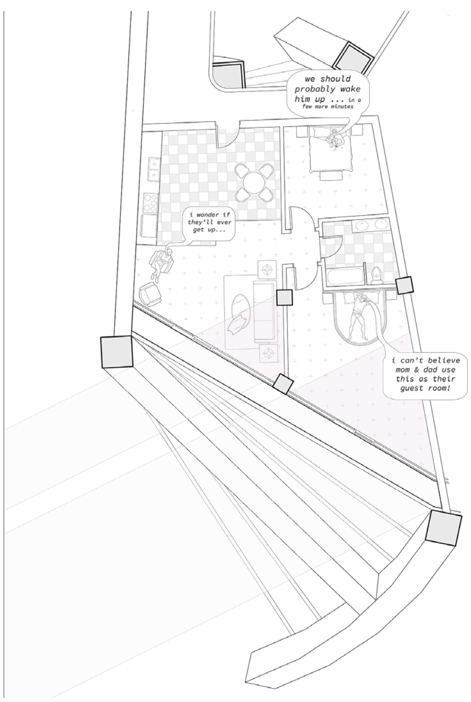


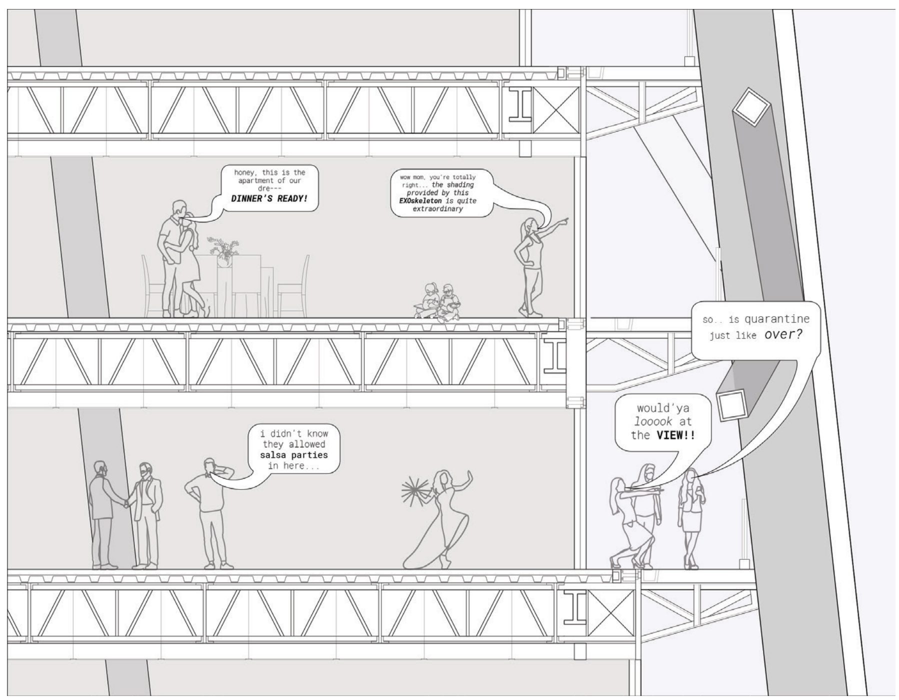


12

Large Scale Sectional Model

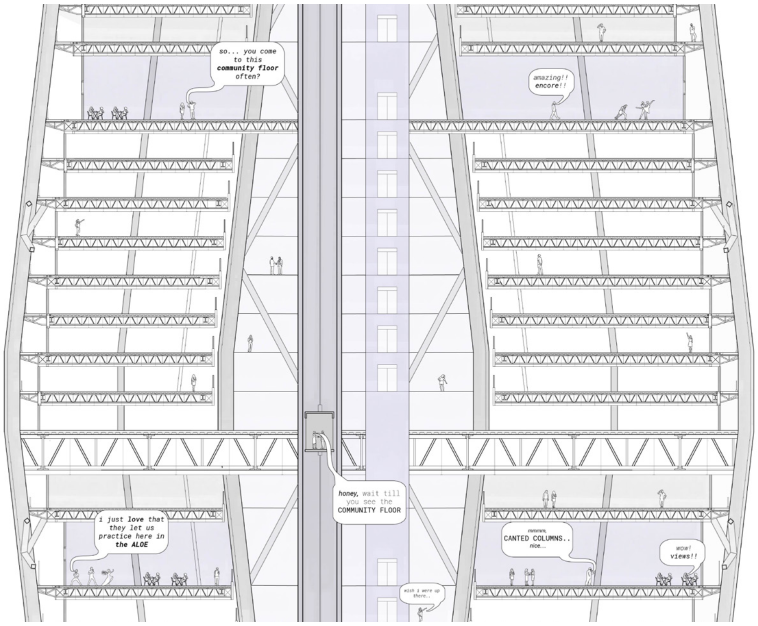


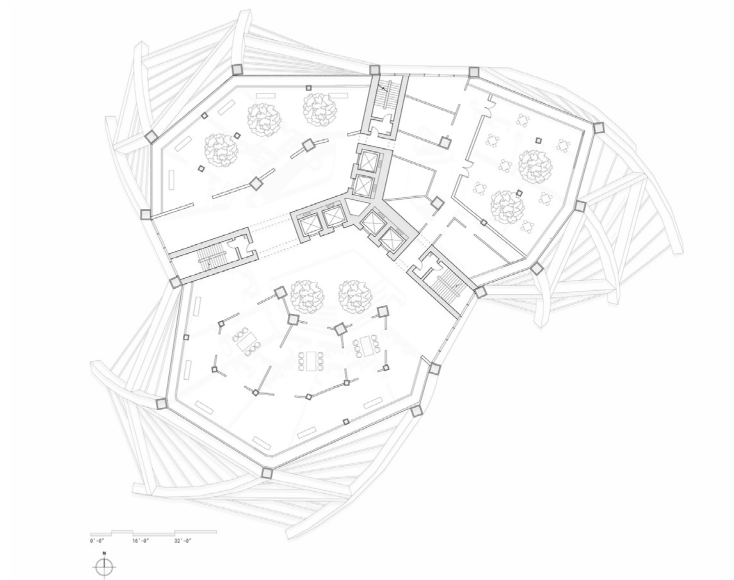


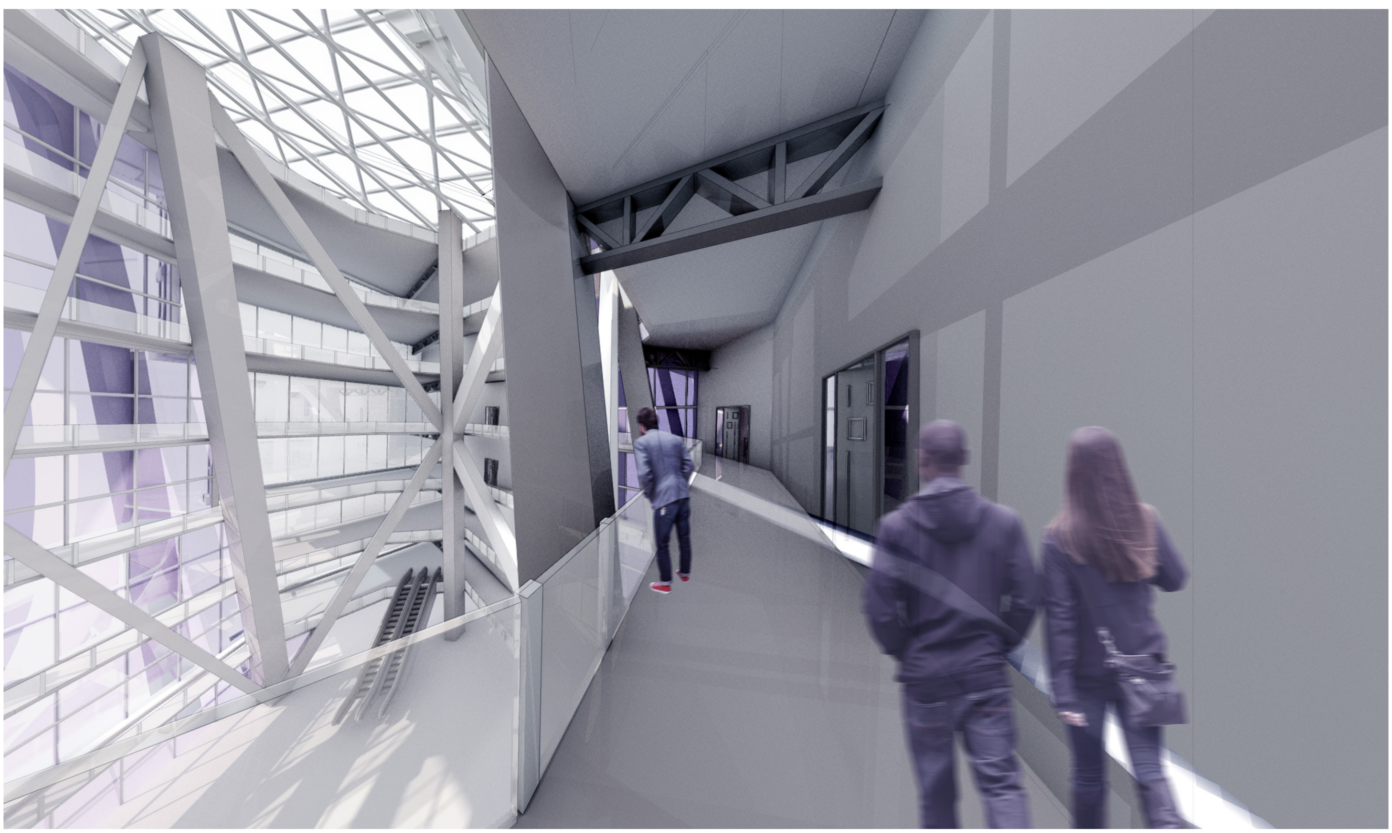


Large Scale Housing Layout

13

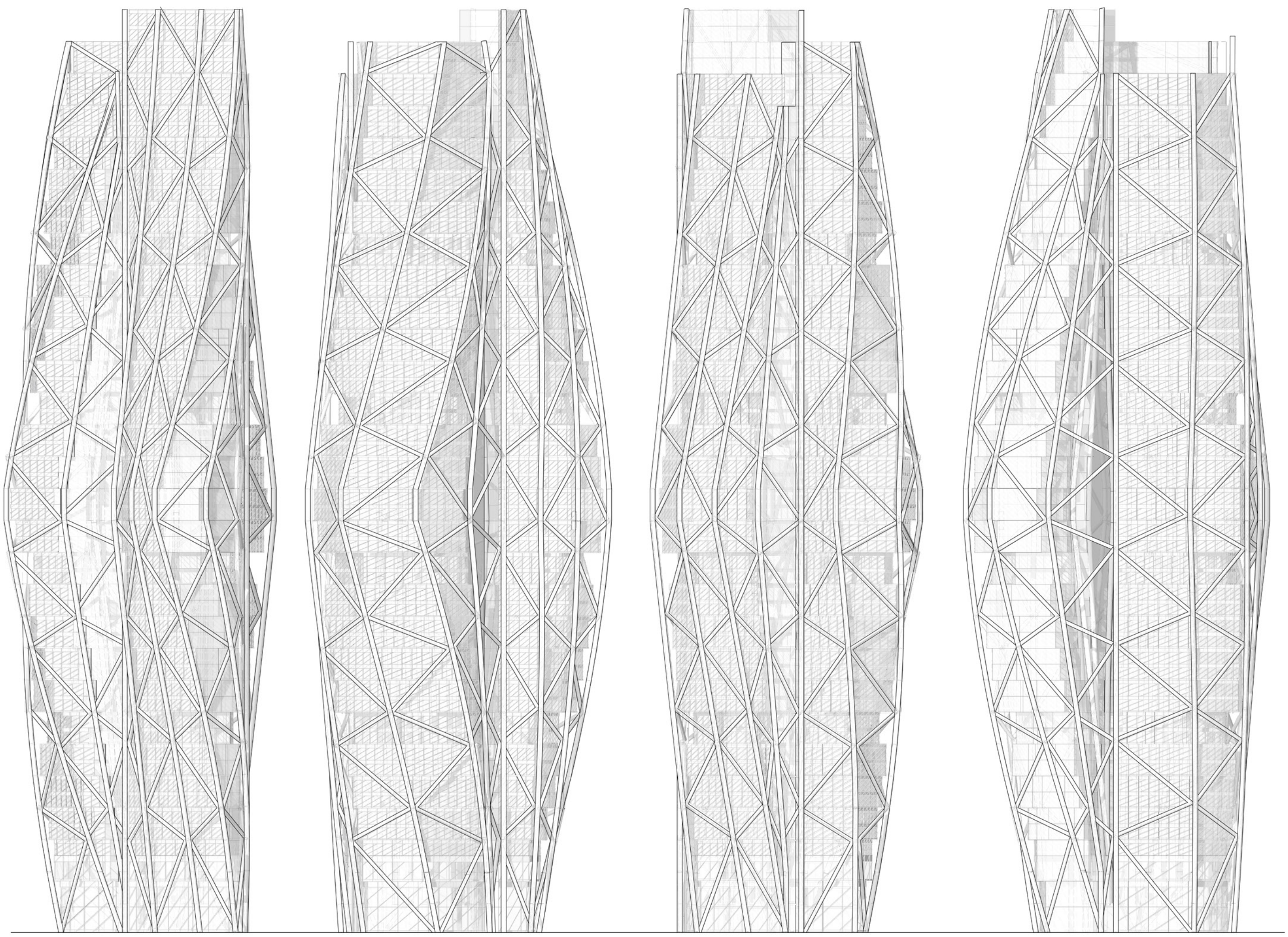




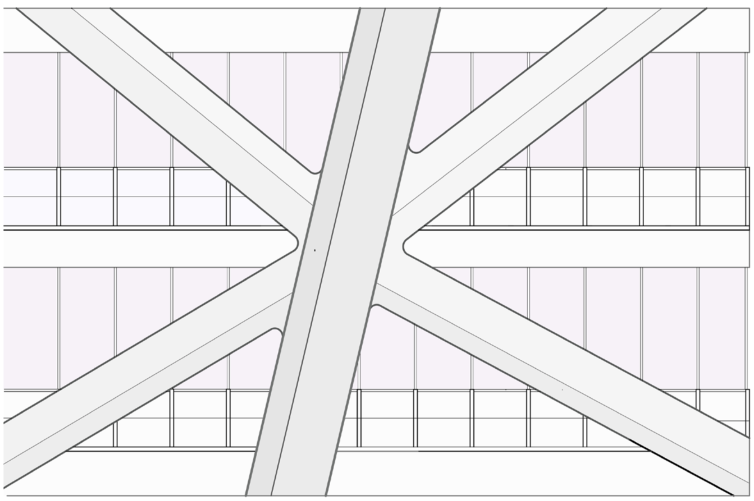


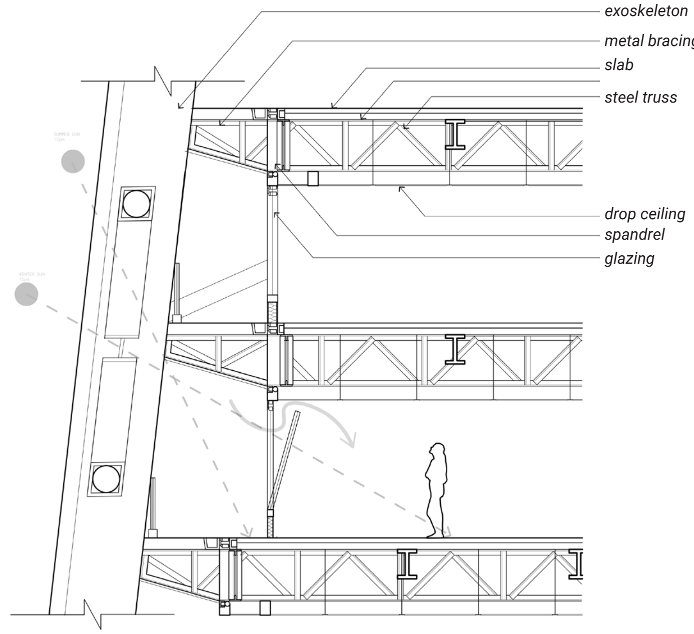
14

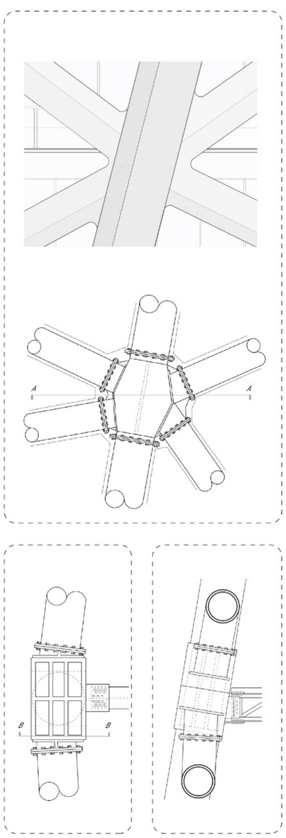
Large Scale Vertical Community

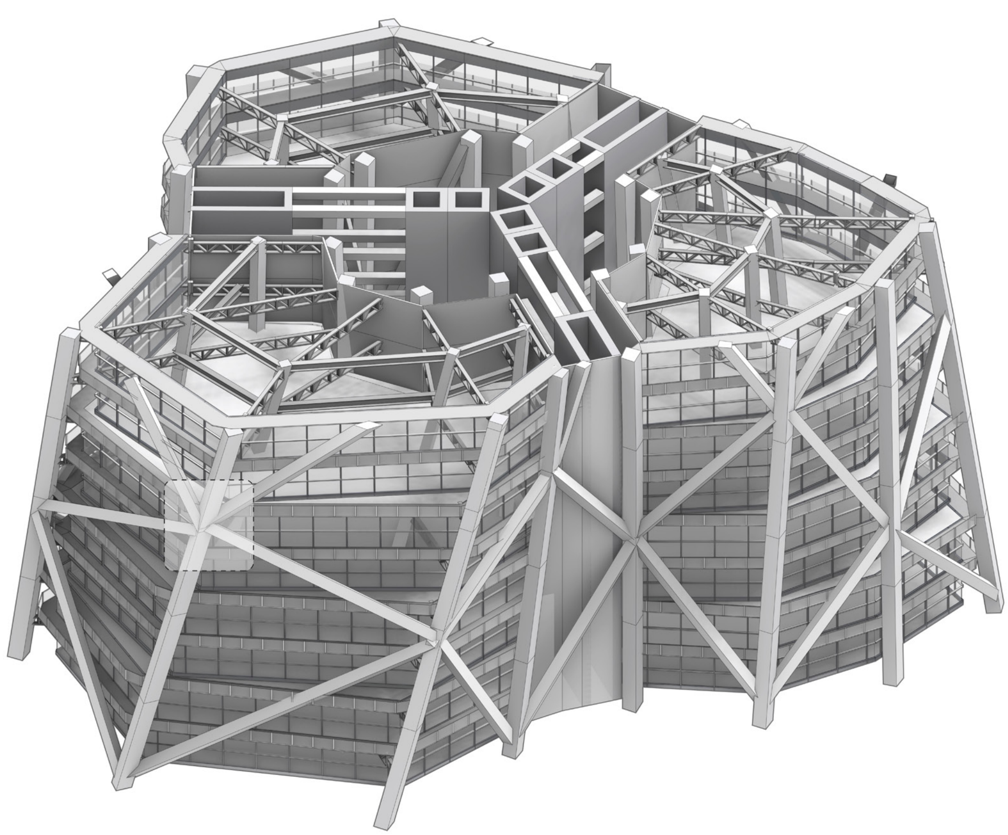


Elevations



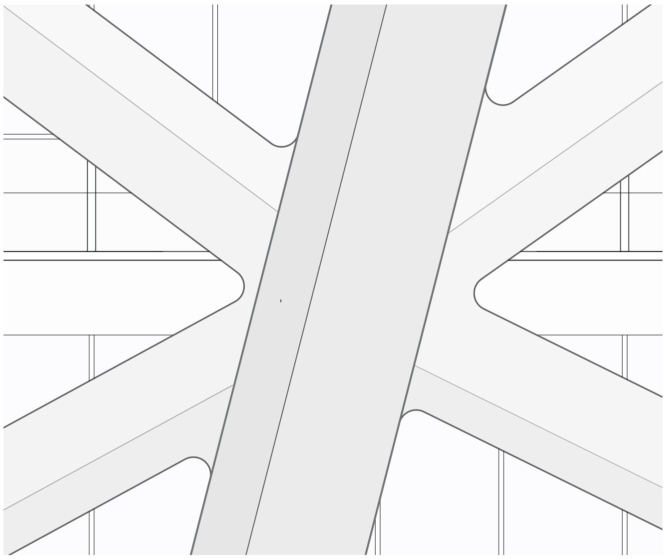




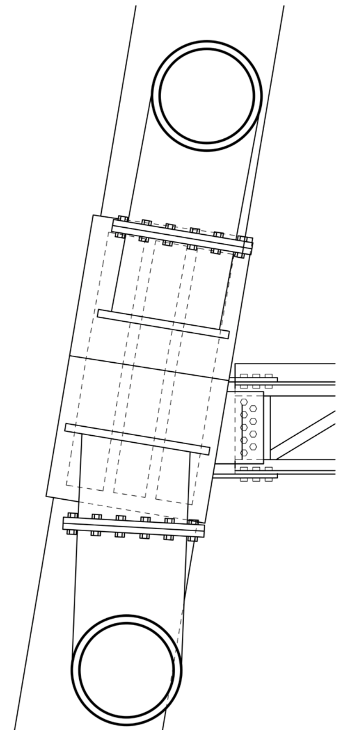


Performative Envelope

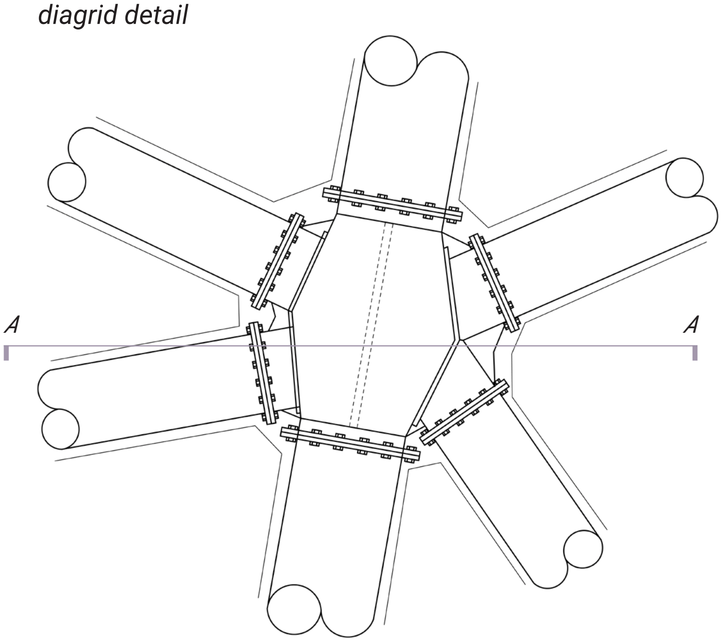
diagrid elevation



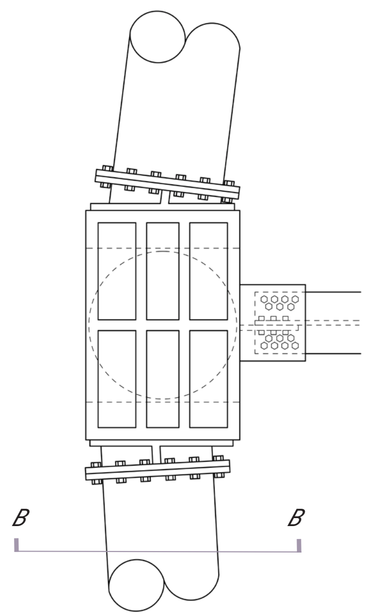
detail B-B



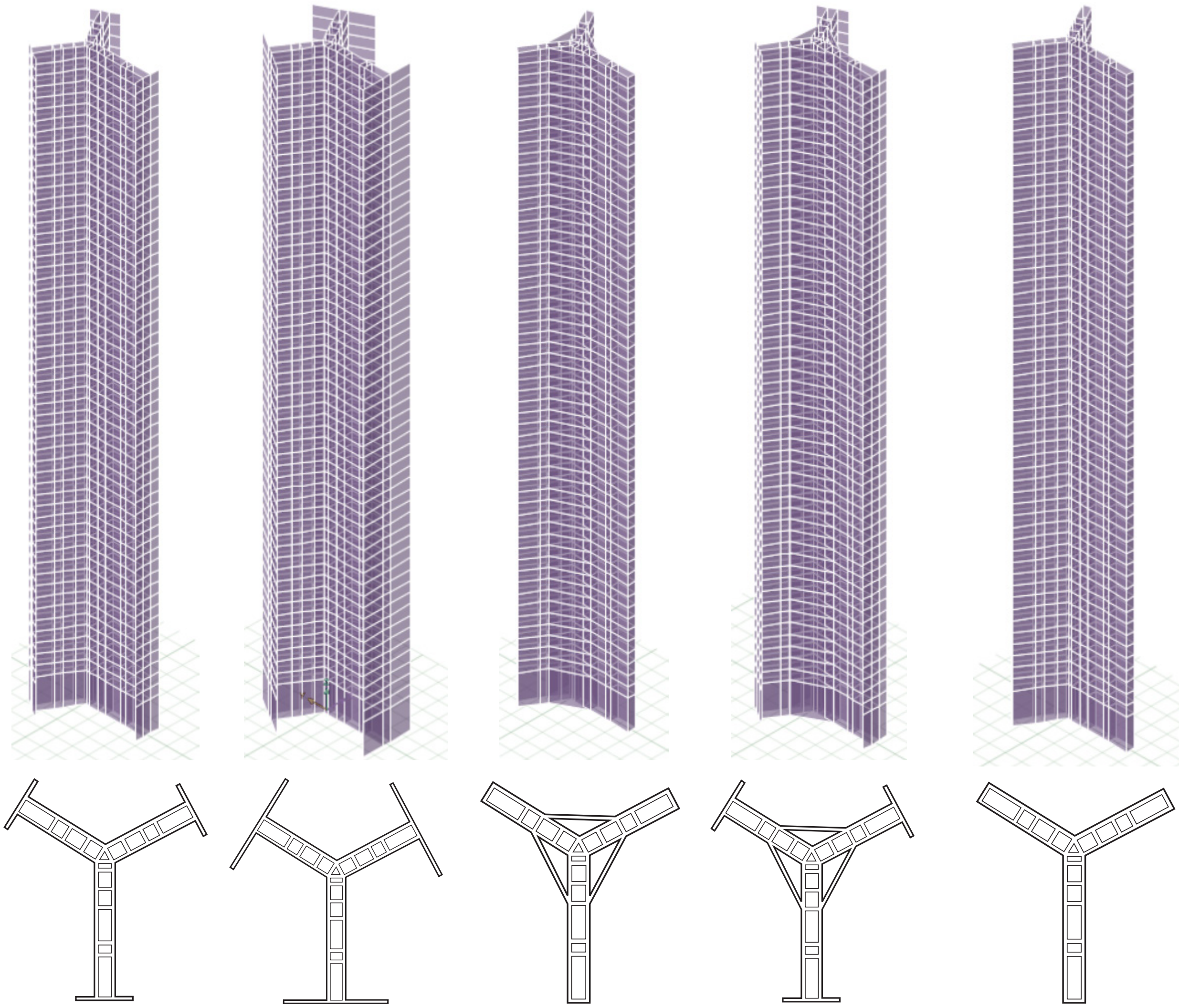
diagrid detail



detail A-A



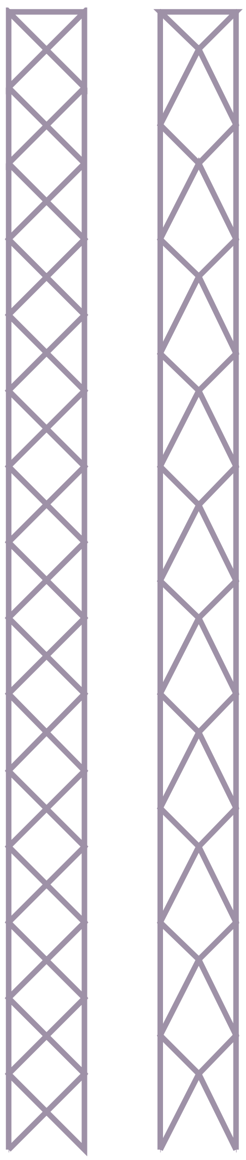
Large Scale Details



PERIOD	5.345	3.926	4.599	4.626	5.269
MODE 1	X	X	X	X	X
MODE 2	↺	Y	Y	Y	Y
MODE 3	Y	↺	↺	↺	↺
MODE 4	↺	X	X	X	X
MODE 5	X	.6Y/.4↺	.7Y/.3↺	Y	Y
MODE 6	↺	.4Y/.6↺	.3Y/.7↺	↺	↺

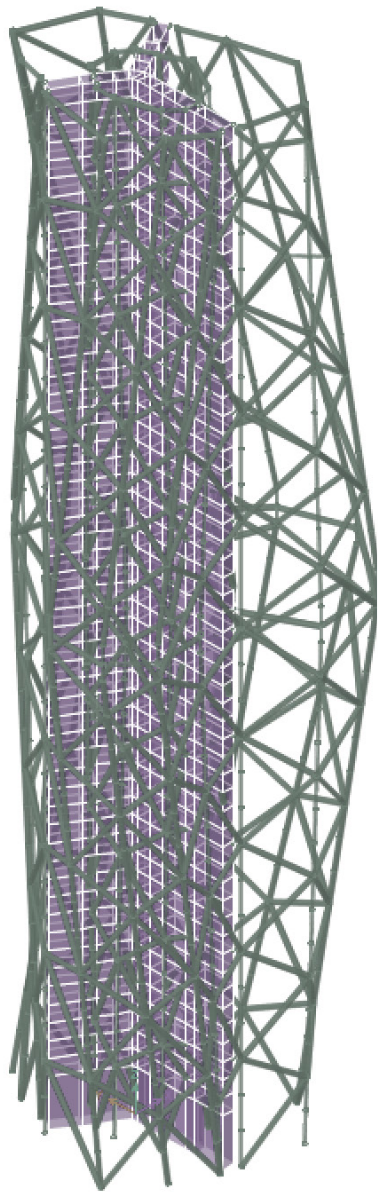
18 ***Structural Framing***

Brace Configuration Study



Right configuration is 5% stiffer

(Wind And Modal Analysis Only)

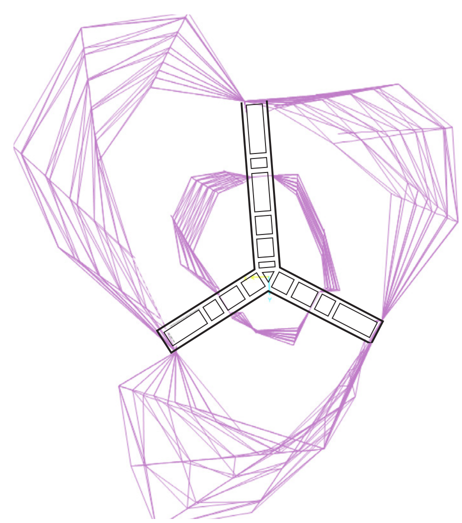


12" Core Walls
10 ksi Concrete
36" HSS Tube Braces

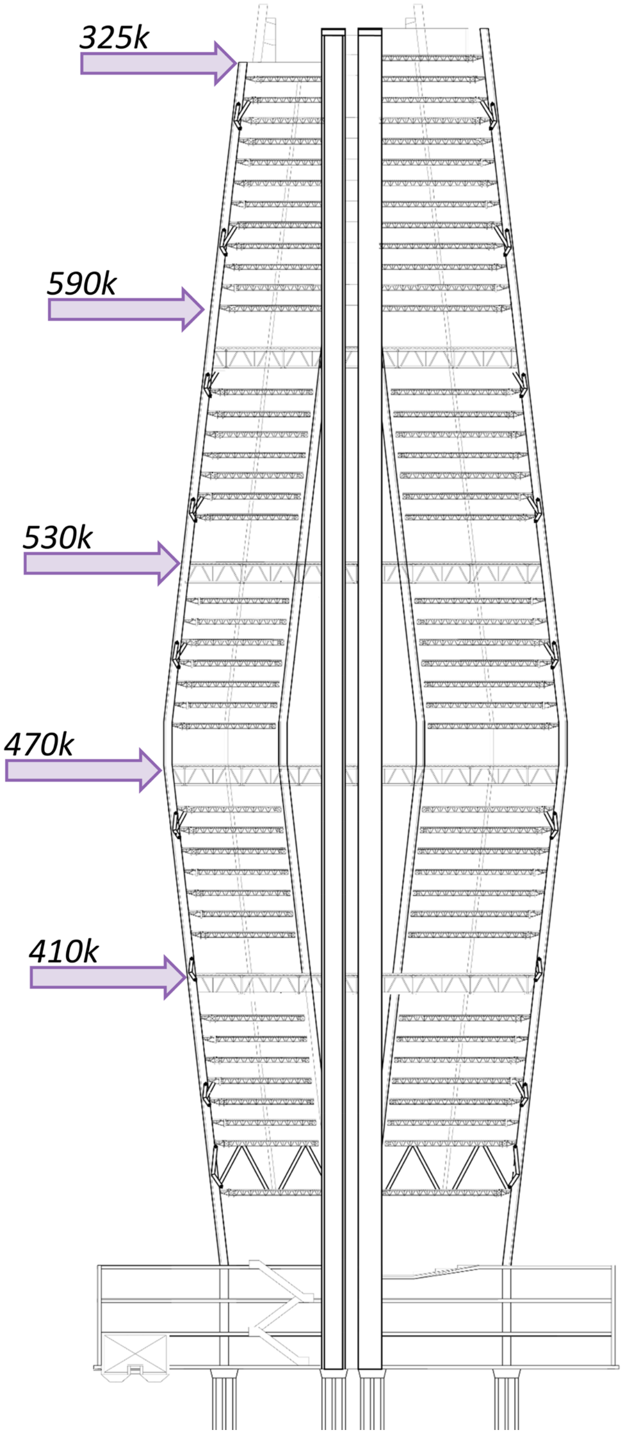
RESULTS

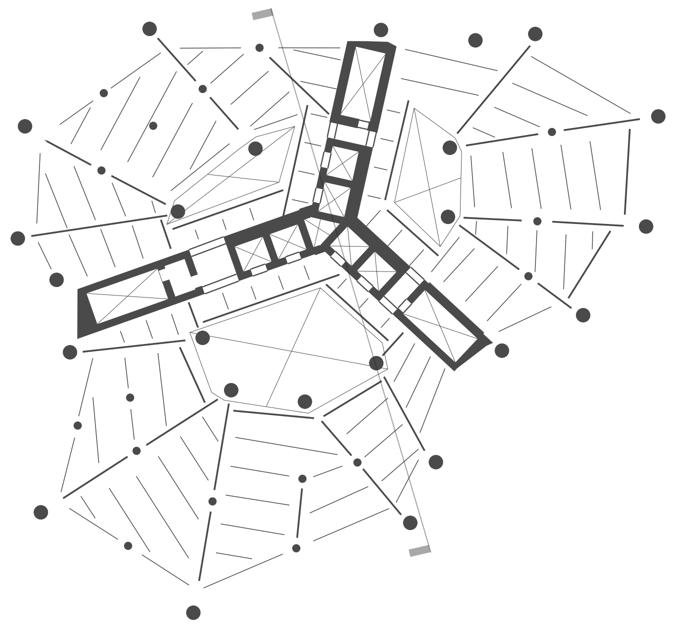
PERIOD	5.471
MODE 1	X
MODE 2	Y
MODE 3	↺
MODE 4	X
MODE 5	Y
MODE 6	↺

Δ = 7.10"
Δ = h/210

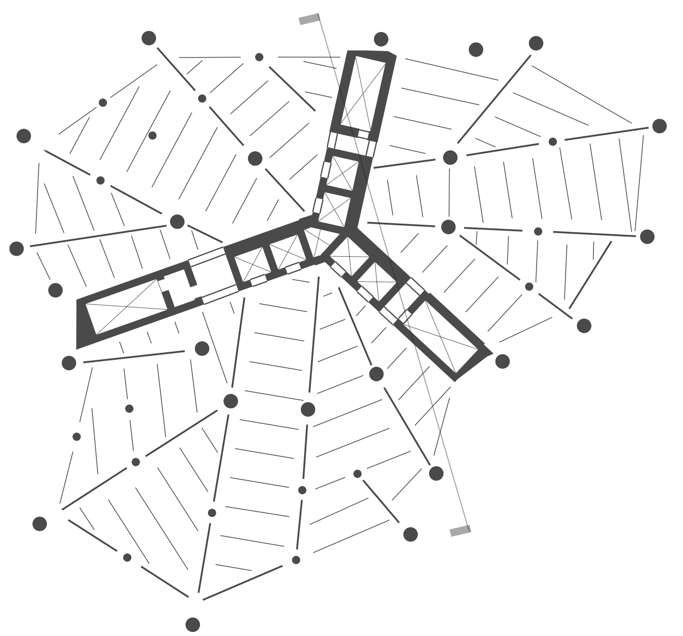


Structural Framing



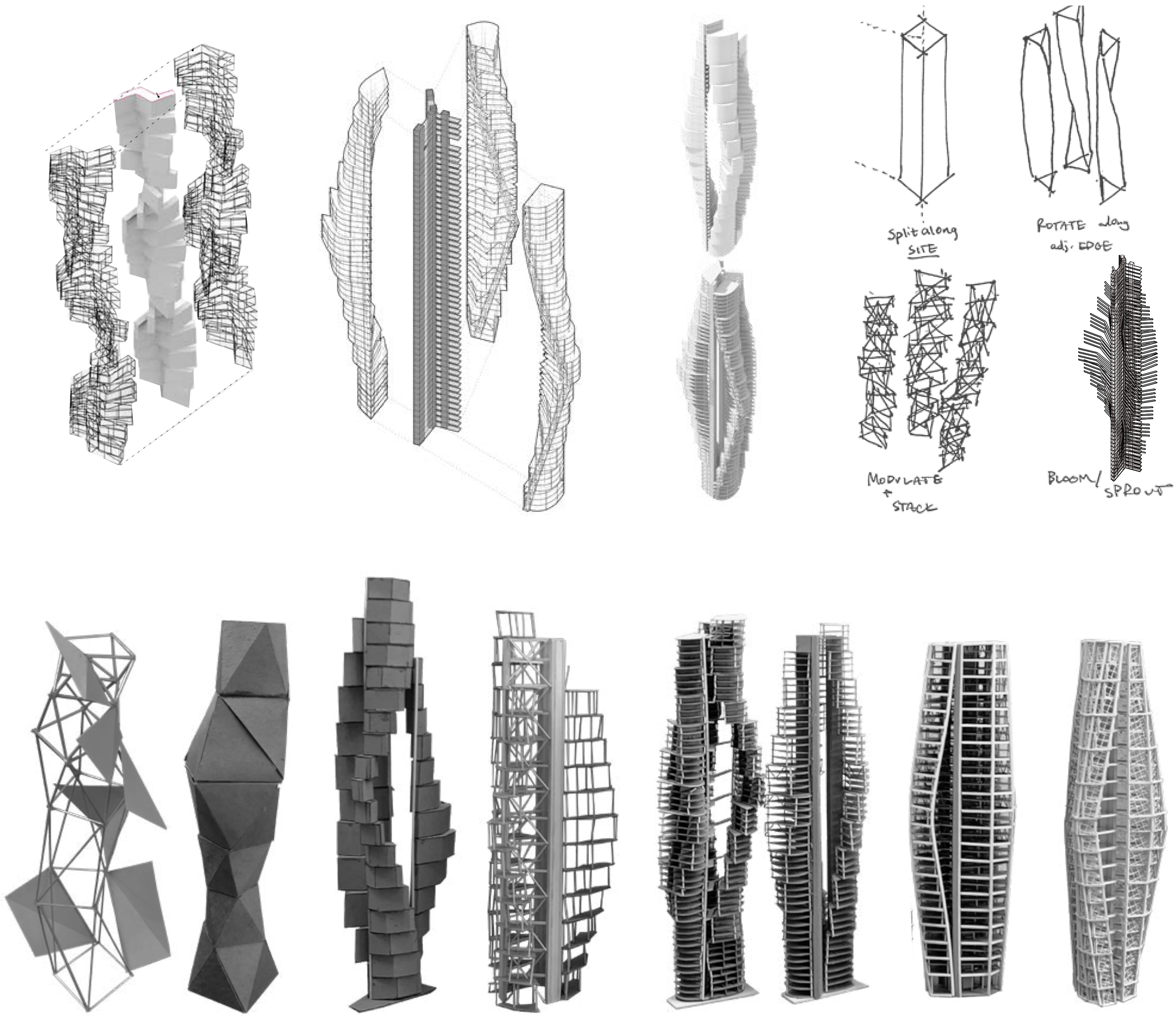


Typical Sizes:
Girder: 22" Composite Joists
Beams: W21x55
Columns 42" Pipes

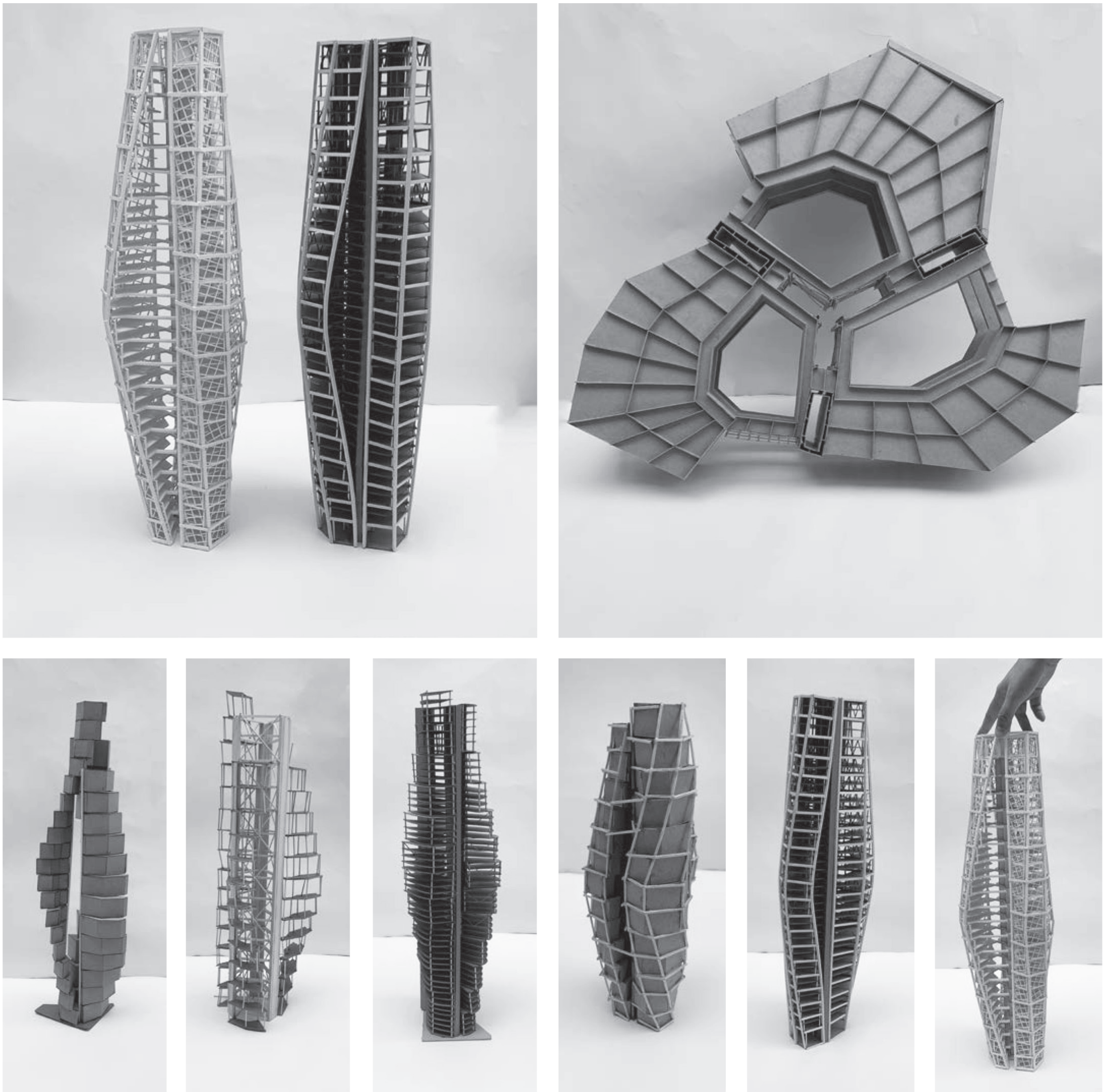


20

Structural Framing



Design Process



Design Process

*1.1*_Agora Tower

*1.2*_Leeza Soho

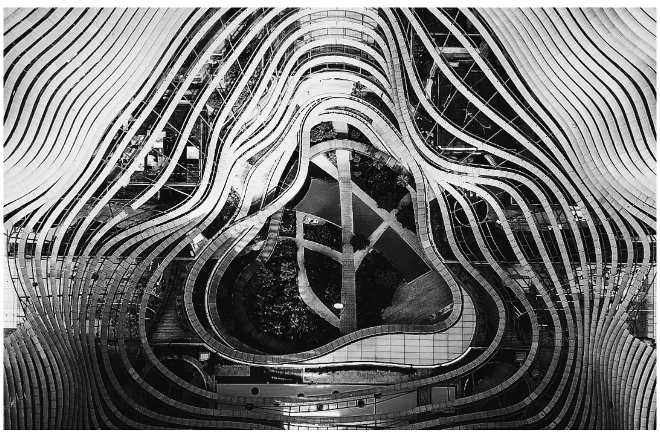
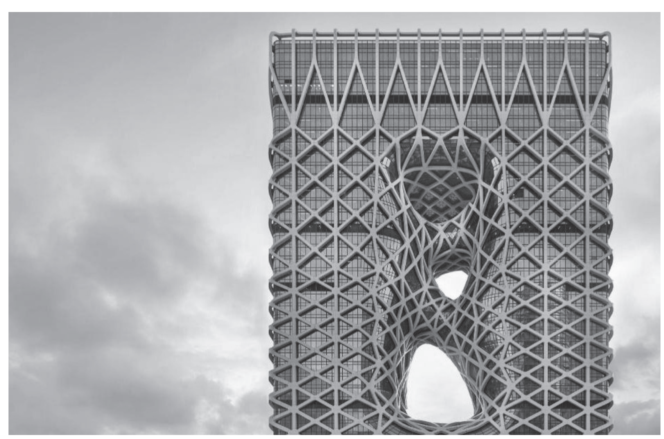


*Figure 1.3*_Marina One

*Figure 1.4*_Absolute Towers

*1.5*_Poly International Plaza



*1.6*_Morpheus Hotel

Precedents

23

TOWER PROJECT STATISTICS

Height	700'-0"
Girth	150'x 120'
Floor to Floor Height	12.5'
Total Tower Floors	51
Podium Height	70'-0"
Podium Floors	3
Podium Floors Height	17'-0", 25'-0"
Housing Floors Total	43
Housing Units Per Floor	7
Housing Units Sq Footage (Avg.)	1,000 sf
Core Size on each floor (Avg.)	2,400 sf
Vertical Community Space Sq Footage	50,000 sf

INDIVIDUAL REFLECTIONS from TEAM MEMBERS

Faisl Alabdali: I've learned how to work efficiently with other open minded designers and engineers who have taught me tons over the course of two quarters. The professionalism and office-like environment of this studio allowed me to gain significant insight into architectural design, and I'm excited to continue to sharpen my skills.

Moriah Haley: Prior to this studio, I thought the design process followed a semi-linear course but have quickly realized that building systems and various scales must be designed holistically, all at once, and all of the time. I have learned that structure and architecture cannot be separated and must be considered throughout all points of design.

Lilliann Lai: Somewhere between drawing architectural plans and analyzing structural behavior, I learned that the cleavage between architecture and structure is a dynamic and arbitrary relationship in terms of exploring the formal, social, and tectonic implications of building tall. The studio was a catalyst for students to realize the difference between a coordinated project and an integrated project, and that lead to a more successful project overall.

Tony Nguyen: ""Who's talking? The architect or engineer?" During our Zoom reviews and meetings, I learned that it is good for there to be ambiguity as to which student is speaking about their project. In these past months I have felt comfortable enough to discuss a building's architecture as much as a team architect can describe the structure because they are one in the same.

PROJECT NARRATIVE

00. CONCEPT
In nature, the aloe plant rotates outwards in order to increase the maximum surface area to obtain sufficient sunlight for the plant's survival. Similarly, our design uses this same rotational concept to increase inhabitants' access to sunlight, overlooked views of San Francisco,and adequately daylit vertical community spaces.

AA. TECTONICS
An exoskeletal column system is expressed to accentuate the rotation and curvature of the structure. This system captures gravity load that could not be done by our sparse continuous columns, as the building form has less than 50% overlapping floor area. A "Y" shaped core is the lateral force resisting system, and two-story trusses spanning the depth of each unit provide lateral stiffness. It is also anticipated that these trusses resolve the thrust of the canted columns.

BB. PERFORMATIVE ENVELOPE
Our current performative envelope is directly connected to our structural system. The canted exoskeleton is the outermost element, followed by balconies, mullions, and glazing on the units' walls and vertical community spaces. The shading provided by the balcony overhangs as well as the exoskeleton blocks the harsh sun. Each unit is equipped with operable windows for natural ventilation.

CC. FUNCTION

1. Vertical Community
Aspire to develop more inviting space for socialization and connection between tenants commuting to and from units. The circulation both horizontally and vertically allows some transparency into the community a tenant is a part of, and with the development of satellite auxiliary spaces to supplement amenities floors, tenants may have public spaces available to chat or decompress as they experience the atrium.

2. Housing Level & Housing Unit
Our rotated forms allow each unit to have its own unique view, that adds a sense of privacy while still connecting to the overall community within the building. Each module consists of three units on each floor, with atria between them. A strong connection to immediate neighbors is present, and the vertical openings allow for a sense of greater community.

3. Podium Level
Our podium aspires to create a connection to art and performance venues in proximity to our site. Our podium level plans include performance spaces which tie into the arts district nearby, as well as foster a sense of community that connects working individuals to adjacent modes of transportation.

DD. URBAN PLACEMAKING
Our building sits on the corner of Market and Van Ness, and contributes significant foot traffic due to the nearby MUNI station and offices adjacent. Our rotational form strives to emulate the dynamism of urban life and connect to the community of San Francisco through its organic form which is alike to the organic nature of the ocean waves, the fog, and the arts/ theater district of San Francisco.

TEAM BIOS

I am a fourth year architectural engineering undergraduate from Cal Poly.

I hope to gain experience in collaborative design for large scale structures and to improve my technical communication skills to deliver successful design solutions.

Tony Nguyen
Davenport, Iowa

I am a third year undergraduate architecture student at Cal Poly.

I am really interested in expanding my architectural horizons and am excited to work alongside Architectural Engineers to fully integrate structure and design.

Faisl Alabdali
Santa Monica, California

Four years of undergraduate architectural engineering toil will culminate and conclude with what I hope to be huge insights to the considerations and integration of structural and architectural design.

I hope to develop the collaboration skills needed to be successful in multi-disciplinary group work and be reminded of where and how my prowess lacks.

Lilliann Lan Lai
Sacramento, California

I am a third year undergraduate architecture student at Cal Poly.

I would like to gain experience with design in an urban context and see the technical aspects of a project come to fruition. It is exciting to work with a large design team to integrate architecture and architectural engineering.

Moriah Haley
Boise, Idaho

FINAL SOM REVIEW FEEDBACK

The feedback from SOM regarding the final developments of the aloe tower focused mainly on the building expression in its entirety. The structural system had become notably clearer, with the external bracing, sloped column, and core plan shape working well to communicate structural tectonics. There was good clarity in section, plans, and the relationship of structure to architectural boundaries, such as with exoskeleton columns aligning with the unit walls. Within a global scope, the exoskeleton very significantly impacted how the form was read and interpreted, and there was note that some of the dynamics of the original building was changed, lost, or translated into a different type of dynamic affect. With such a strongly expressed system, transitions between or within the system were important to consider, and the connection of the diagrid structure across the ends of the cruciform core disengaged a visual expression of the original twisting form. In addition, the diagrid wrapping about the entirety of the structure diluted the individuality of each rotating lobe, and the aloe plant connection may have been lost. The community plans of the building seemed to be at arbitrary heights, and not quite taking full advantage of an opportunity at the point of inflection of the tower.

THANK YOU TO SOM!!
As eager and perseverant as students can be, we can only go so far without the guidance of mentors and professors. There is a direct correlation between the amount of feedback, lectures, and reviews SOM invested into the studio and the quality of the student projects. Our experience in this studio would not have been as beneficial without the knowledge of SOM. They provided constant insight that would have otherwise been overlooked and brought with them a novelty that inspired our work ethic. The lectures were invaluable, and the genuine involvement with our project even more so.

ENDNOTE CITATION
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