LilyPAAAAD ~ Structural Design

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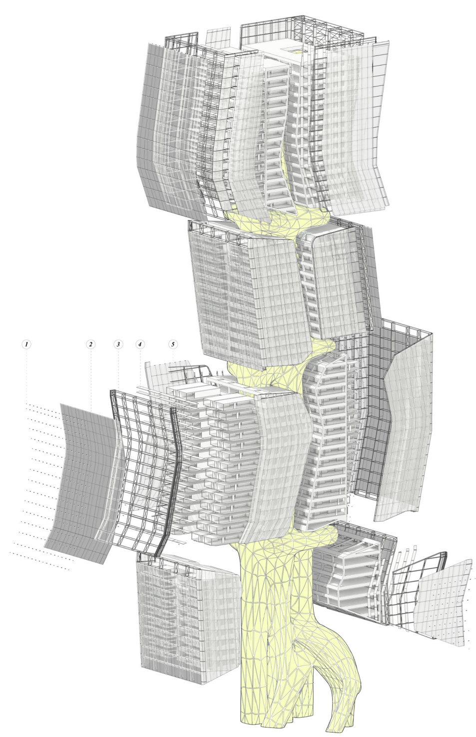
Executive Summary

This report tells the story of the structural design process of the LilyPAAAAD tower. The highlights of this process include precedent studies, 2-D structural analysis studies, hand calculations, and drawings. Precedent studies gave insight into unknown possibilities and helped discover how other engineers achieved their design goals. Projects like Sendai Mediatheque and the HSBC Tower are innovative solutions to unique design criteria. 2-D structural studies revealed how the braced frame and outrigger systems worked. By changing member stiffness and studying the load path, the members that contributed the most to resisting the load could be identified. Hand calculations were essential for checking the results of the computer model. Simplified calculations helped to pinpoint elements that needed to be adjusted and determined if the model was accurate. Lastly, drawings were used to communicate the design and illustrate the story. Through this process, the structural system of the LilyPAAAAD Tower was created, analyzed, and depicted.

Project Narrative

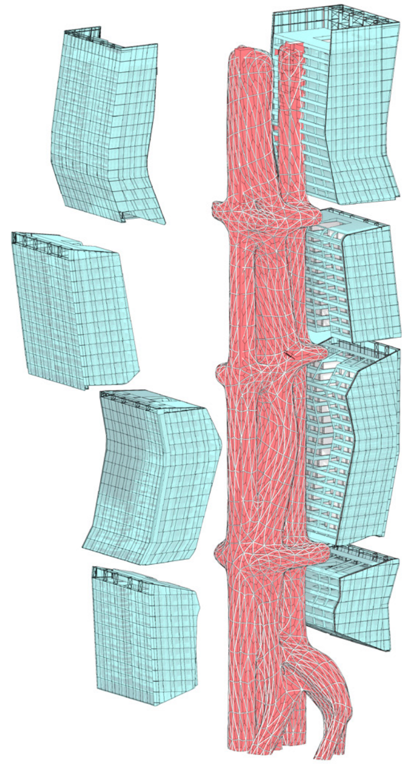
00. CONCEPT

The lilyPAAAAD is a residential high rise proposal for 1 Oak Street in San Francisco with a structural and spatial approach derived from the water lily. By hanging the mega-frame residential “pads” from a structural core the lilyPAAAAD seeks to inform variations in programmatic density and specificity throughout the tower mass. These “looser” zones seek the allowance of broader public use in an otherwise restrictive building typology. The structural core and atrium provides for vertical circulation to the pads as well as vibrant mixing in and around the them. The atrium includes dynamic functions such as rave pits, bath houses, waterparks and more! By forcing the circulation through the dynamic atrium presumably upper class tenants are forced to associate with the gyrating masses of otherwise undesirables. This association strives to derail the traditionally evident socio-economic hierarchy within a tower.



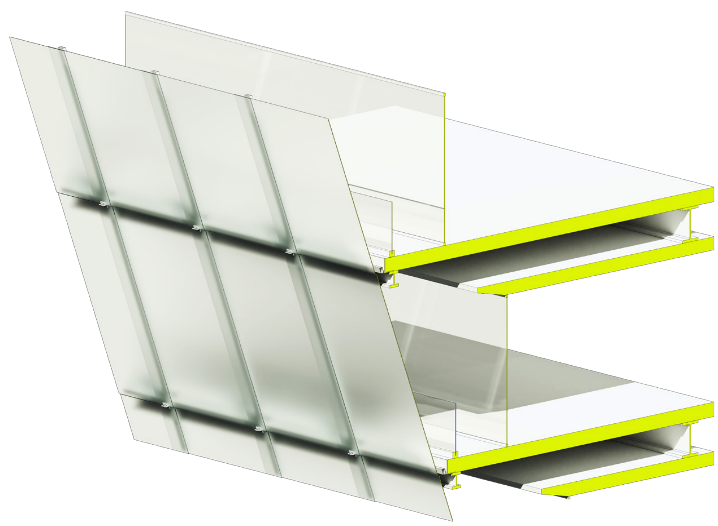
AA. TECTONICS

Drawing inspiration from the the water lily, the lilyPAAAAD's structural system consists of two steel diagrid core linked together with trusses. The cores house the elevators and stairs while the self supporting diagrid atrium informs the void space. The housing (leaf) units are suspended from these cores with hat trusses, giving the atrium the flexibility to break from normativity and provide for vibrant circulation and public function throughout the tower.



BB. PERFORMATIVE ENVELOPE

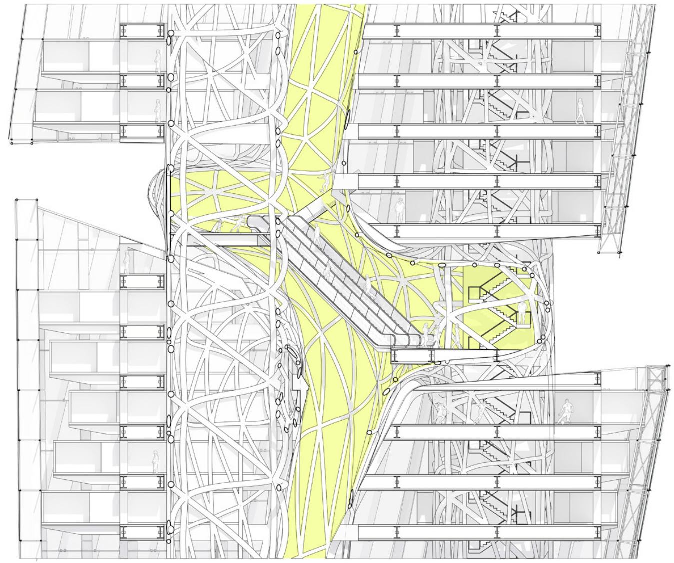
The lilyPAAAAAD features a double skin envelope. The outer skin allows for the filtration of harmful sun rays, while still allowing ventilation to reach the inner layer. The inner skin provides for weather-proofing and insulation. This combination allows for the possibility of outdoor spaces to occur between the two respective envelope layers. West facades feature vertical shading elements which are angled for the optimal blockage of sun, while the South facade features horizontal shading elements.



CC. FUNCTION

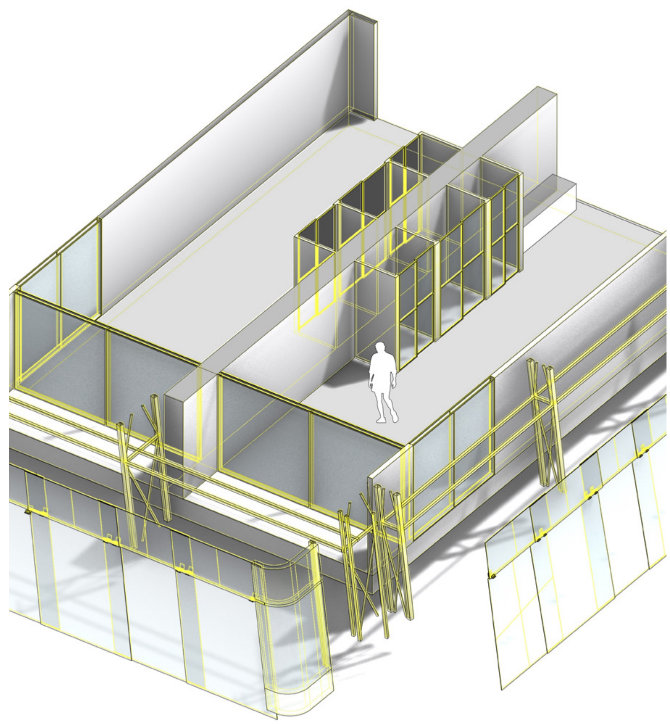
1. Vertical Community

The atrium hopes to provide vibrancy and energy to the tower by activating them with rave pits, bath houses, and dynamic circulation bringing all sorts of people up into the tower mass. Through the introduction of these programmatically dynamic functions, the tower hopes to create mashup and tension between the people associated with each specific function.



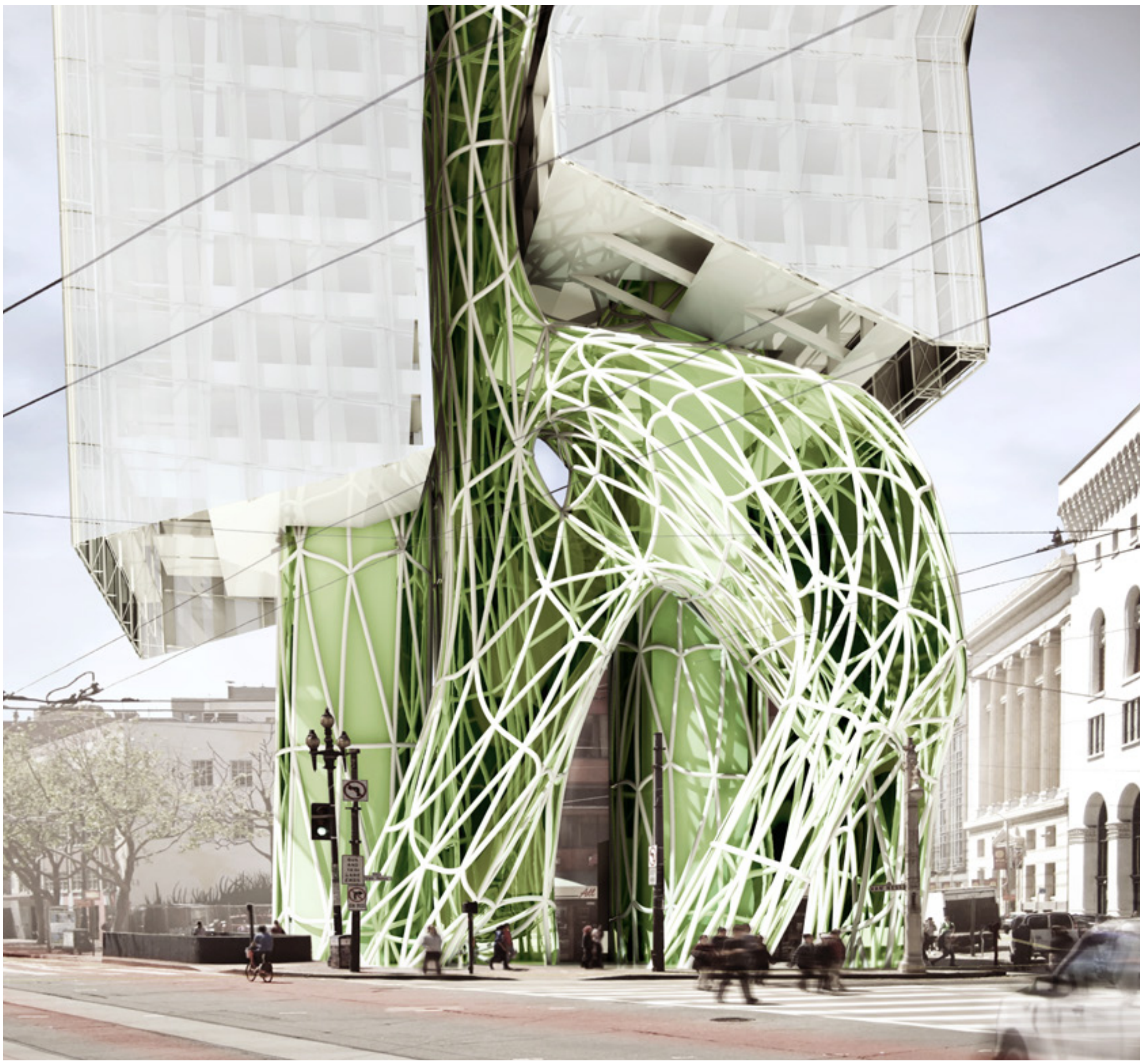
2. Housing Level & Housing Unit

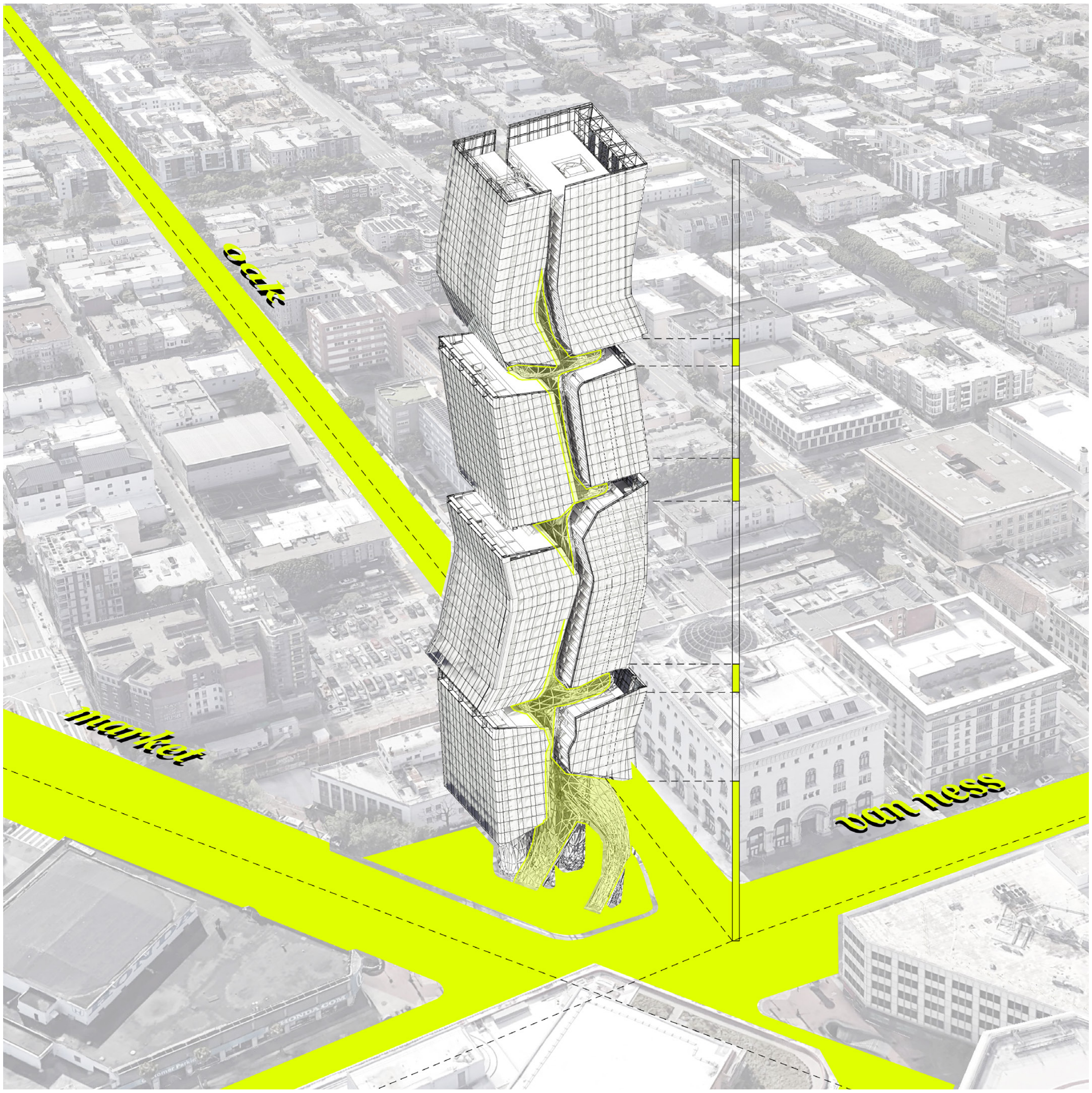
The housing unit strives to achieve the same level of variation in programmatic specificity as the rest of the tower does, by incorporating a single programmed wall which features all necessary residential functions. This allows the rest of the unit to become more loosely programmed so that the users might have agency in determining the specific use of the space.



3. Podium Level

At the podium level the lilyPAAAAAD roots itself into the ground dramatically. This root is informed by the manner that the water lily roots into the ground, as well as the extreme structural demand occurring at the root level. The podium displays a dramatic sense of structuralism which hopes to make the community aware of the structural systems at play within the tower. While simultaneously attempting to invite the general public into the rest of the tower via visual and physical connections between the podium and tower body.

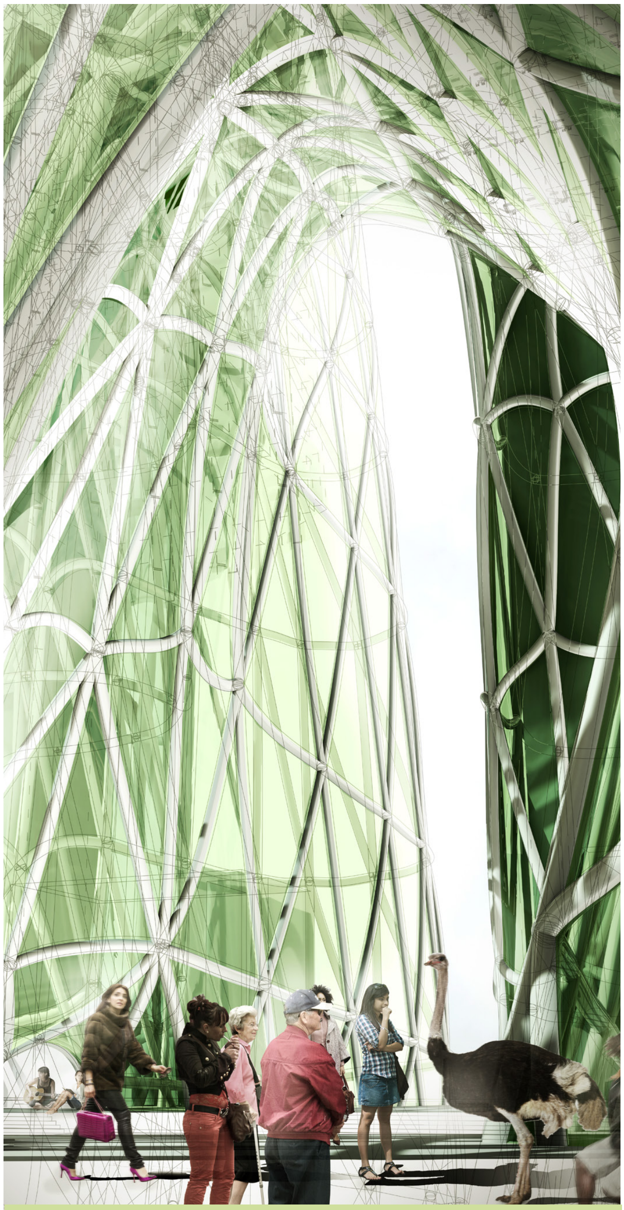




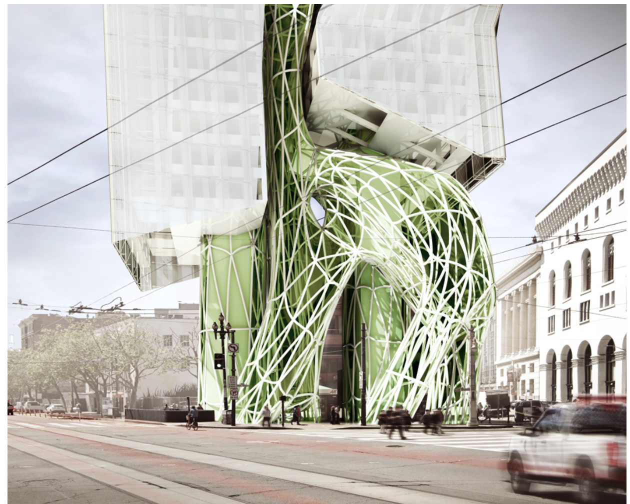
DD. URBAN PLACEMAKING

The tower exists in connection with the rest of the city by opening the entirety of its podium and atrium space to the community. It hopes to provide vibrancy and energy to these spaces by activating them with rave pits, bath houses, and water parks bringing all sorts of people up into the tower mass. Through the introduction of these programmatically dynamic functions, the tower hopes to create mashup and tension between the people associated with each specific function. This tension seeks to act as a derailing agent for people's expectations as well as for the traditional hierarchical problems of high rise design.

Tower Renderings



Atrium at Ground Level



Atrium Root Street View

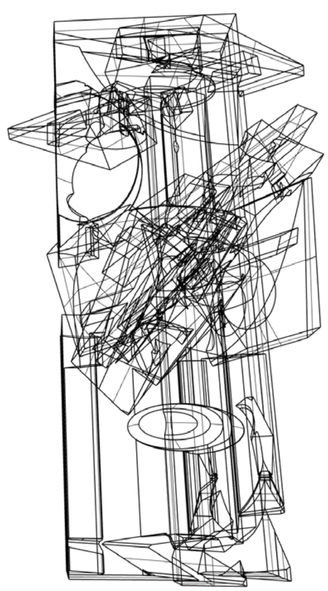
Community Level

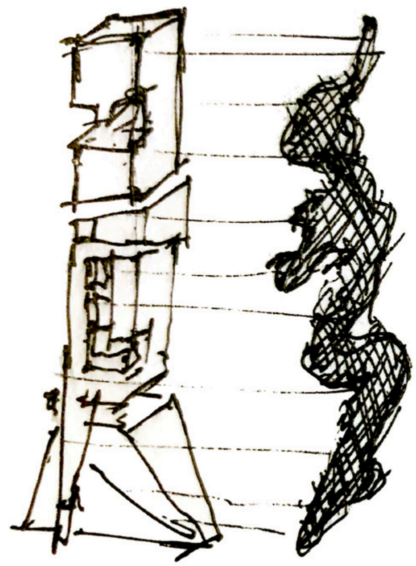
Inside the Housing Unit

Housing Modules

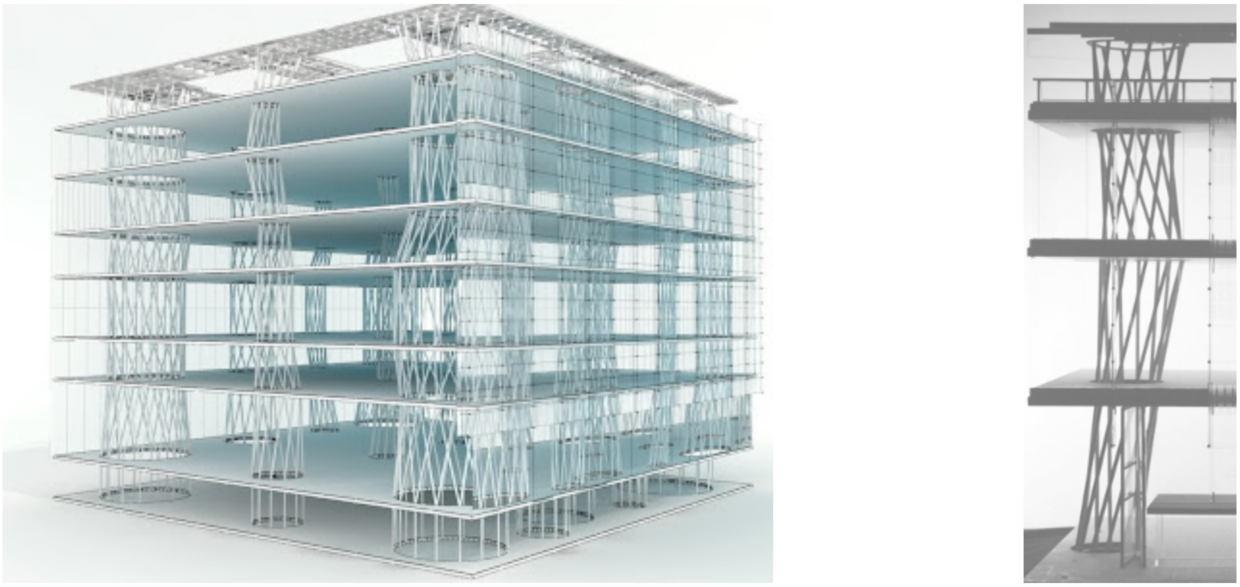
Interpretation of Concept

This project began with the simple idea of a lily pad. Inspired by its life-sustaining structure and spacial approach, the leaf, stem, and root became highlights in the tower. Where the leaves or lily pads are the housing units, the stem is the continuous atrium, and the root makes up the podium level.





Precedents



1. Sendai Mediatheque, Japan by Toyo ito

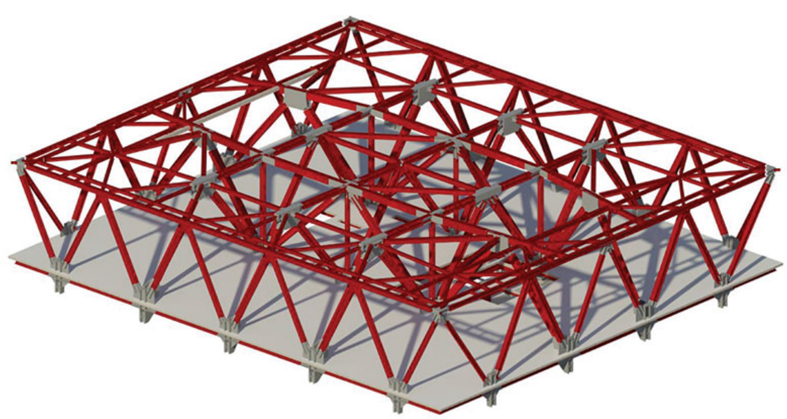
Sendai Mediatheque inspired the cores of the tower. Toyo Ito created columns that provided the building with its gravity and lateral resisting systems as well as vertical circulation.

2. HSBC Tower, Hong Kong

The HSBC Tower provided insight into how floors can be hung from trusses. Studying the load path for gravity and lateral forces had a positive impact on the LilyPAAAAD Tower design.

3. SOHO Tower, Beijing

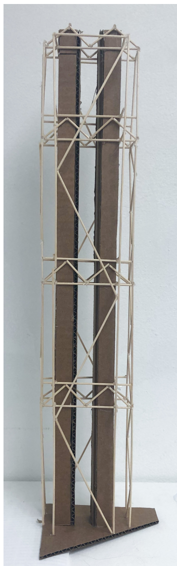
The SOHO tower has two cores that are tied together with belt trusses disguised as sky bridges. This building had similar elements that we wanted to achieve in the LilyPAAAD Tower design, such as a continuous atrium, two cores, and discontinuous diaphragms.



4. 111 Main, Salt Lake City by SOM

111 Main used a hat truss to hang the floors over another building. This precedent provided insight into the structure needed to hang a large number of stories similar to the goal of hanging the LilyPAAAAD housing units.

Beginning Models


[1]


[2]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The process began with the importance of expressing the leaf, stem, and root in the tower. It was decided that the tower should be supported by two cores to create space for the atrium's natural curvature. It was important for the leaf units to be defined by the void space surrounding them. Therefore, it was decided that they should be hung from the cores, rather than fully supported by gravity columns. Lastly, the root structure should be exposed because it is an open and inviting space.

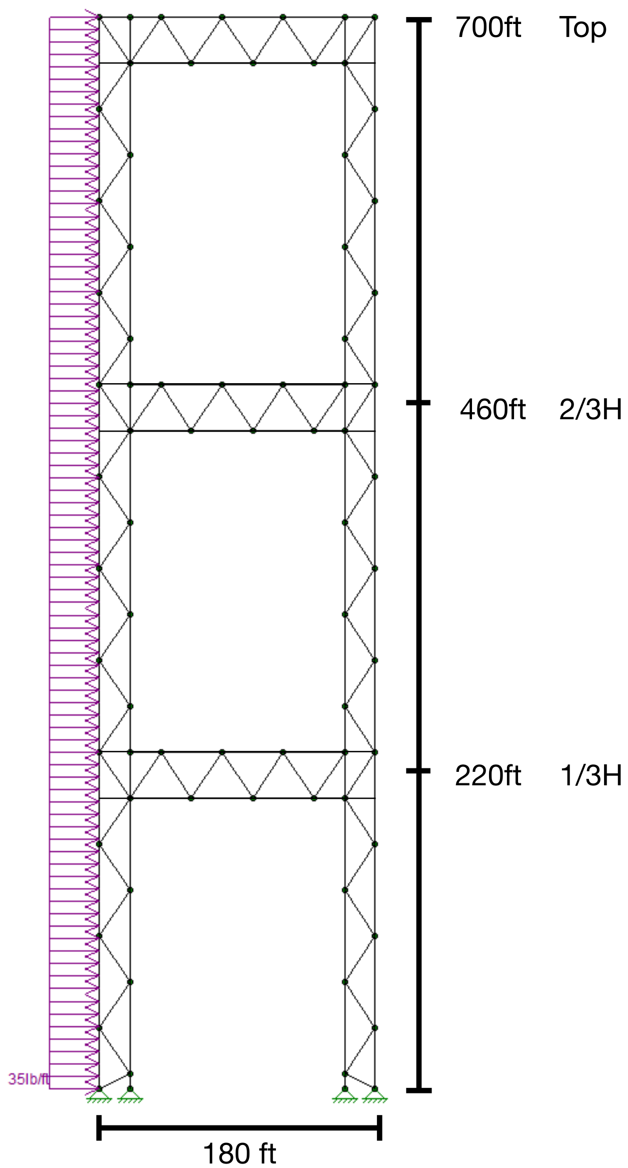
Figures 1-2, above, show the initial structural models. The first model looked at the connection of the cores to act as a cohesive member. The second model showed the units hanging from the braced steel cores. Figures 3-5 were architectural models, looking at the form and contrast of the lily pad units and the open atrium.

Structural Studies

Mega Frame Analysis

This model is a general building behavior study with a focus on the mega braced frame system.

- *Comparing stiffness of beams vs columns*
- *Comparing stiffness of beams and columns (flange members) vs bracing (web members)*



Find:

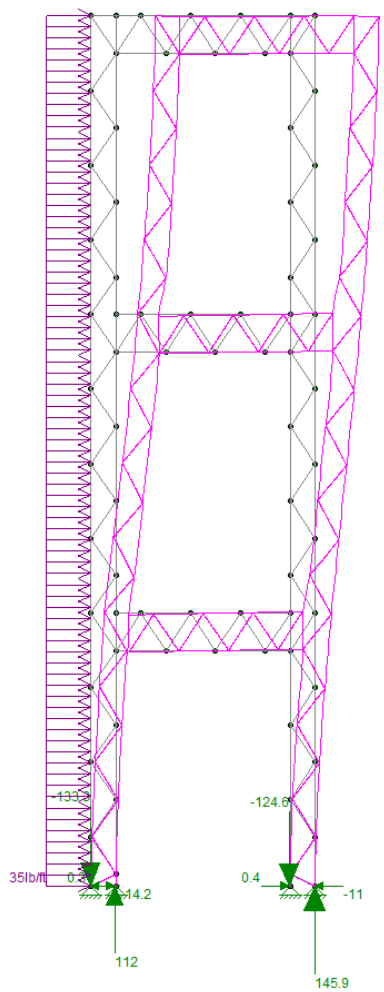
- Determine if its more efficient to stiffen the “columns” or the “beams”
- How would those members be stiffened?

Given:

- Allowable Deflection h/500= 16.8 in
- Dead Load = 70psf
- Live Load = 40 psf
- Wind Load = 35 psf

Mega Frame Analysis ~ Comparing stiffness of beams vs columns

STIFFER COLUMNS



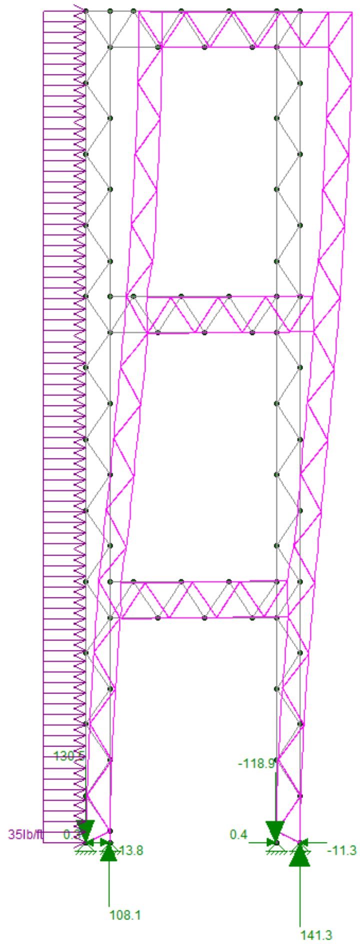
Member	Size
Column	W14x109
Column Bracing	W14x109
Beam	W14x30
Beam Bracing	W14x30

STIFF COLUMNS - RESULTS

Stories	Section Height (ft)	Deflection (in)	Drift	Drift Ratio
Top	240	15.4	4.4	0.15%
2/3H	240	11	7.1	0.25%
1/3H	220	3.9	3.9	0.15%

This model is looking at stiffening the columns to reduce the deflection while the beams and beam bracing member sizes remain constant.

STIFFER BEAMS



Member	Size
Column	W14x90
Column Bracing	W14x90
Beam	W14x109
Beam Bracing	W14x109

STIFF BEAMS - RESULTS

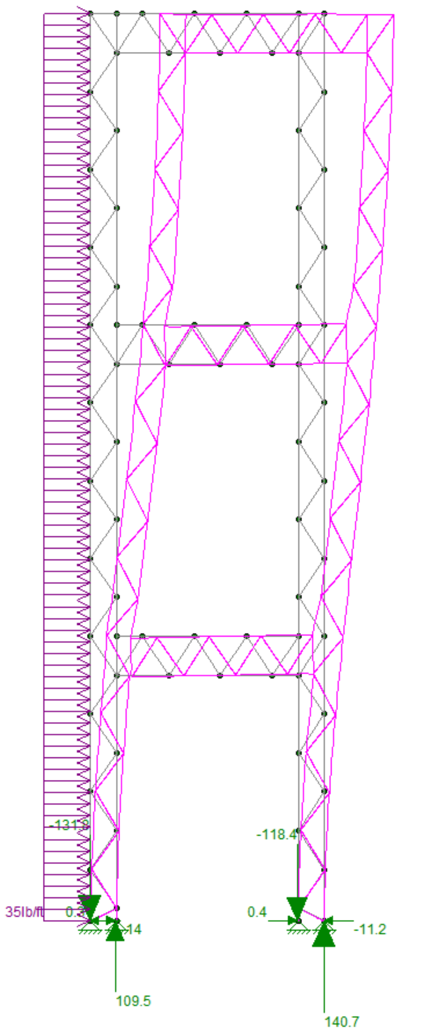
Stories	Section Height (ft)	Deflection (in)	Drift	Drift Ratio
Top	240	15.5	3.7	0.13%
2/3H	240	11.8	7.4	0.26%
1/3H	220	4.4	4.4	0.17%

This model is looking at stiffening the beams to reduce the deflection while the columns and column bracing member sizes remain constant.

Conclusion: Both results have very similar deflections and drift ratios with the chosen member sizes, but stiffening the columns has slightly lower drift ratios. Also, increasing the size of the columns has a more significant impact than increasing the beams. Therefore, it is more efficient to stiffen the columns.

Mega Frame Analysis ~ Comparing stiffness of beams and columns (flange members) vs bracing (web members)

STIFFER BRACES



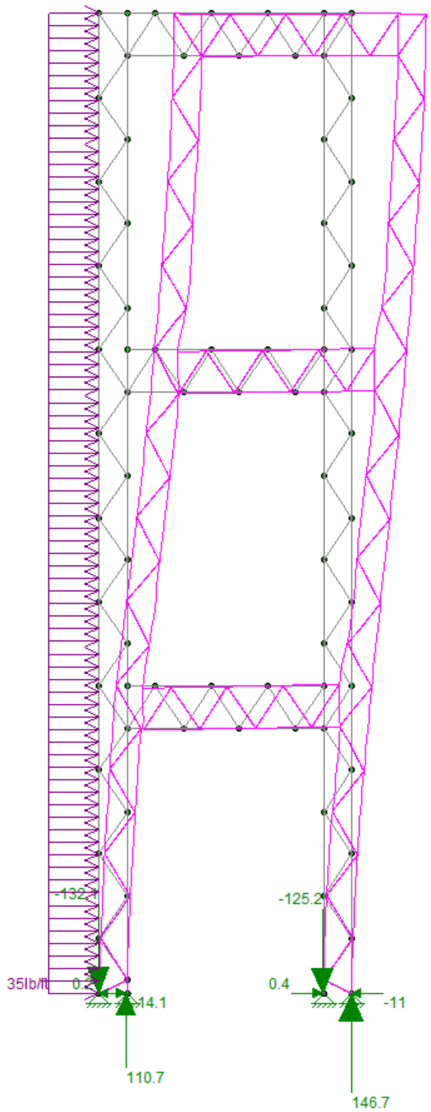
Member	Size
Column	W14x90
Column Bracing	W14x159
Beam	W14x30
Beam Bracing	W14x159

STIFF BRACES - RESULTS

Stories	Section Height (ft)	Deflection (in)	Drift	Drift Ratio
Top	240	16	4	0.14%
2/3H	240	12	7.6	0.26%
1/3H	220	4.4	4.4	0.17%

This model is looking at stiffening the braces within the outer columns and connecting beams to reduce the deflection.

STIFFER COLUMNS AND BEAMS



Member	Size
Column	W14x109
Column Bracing	W14x30
Beam	W14x109
Beam Bracing	W14x30

STIFF COLUMNS AND BEAMS - RESULTS

Stories	Section Height (ft)	Deflection (in)	Drift	Drift Ratio
Top	240	15.9	4.2	0.15%
2/3H	240	11.7	6.5	0.23%
1/3H	220	5.2	5.2	0.20%

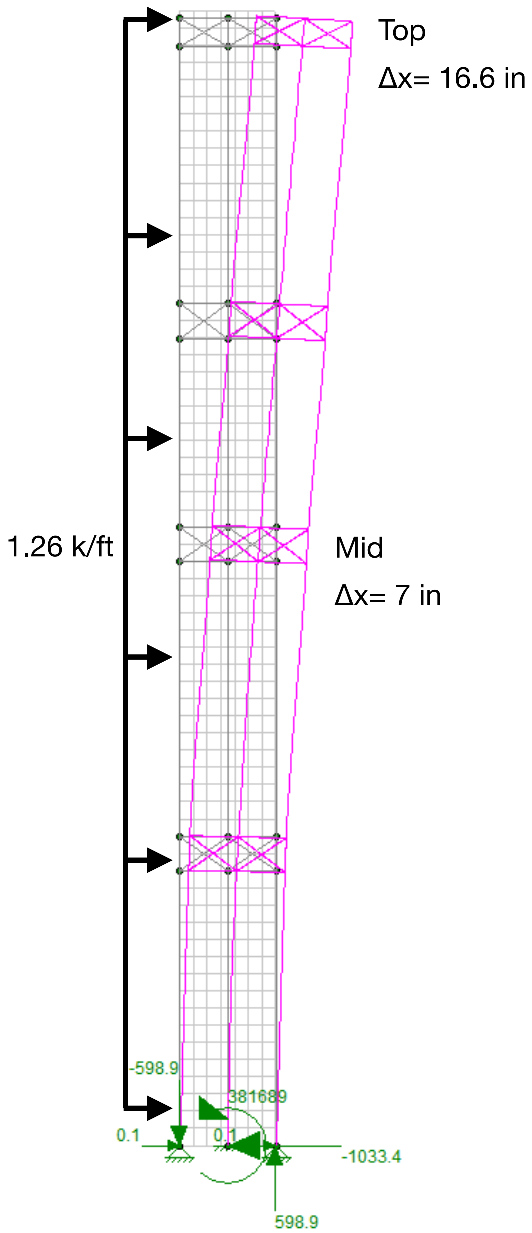
This model is looking at stiffening the beams and columns to with lighter bracing members reduce the deflection.

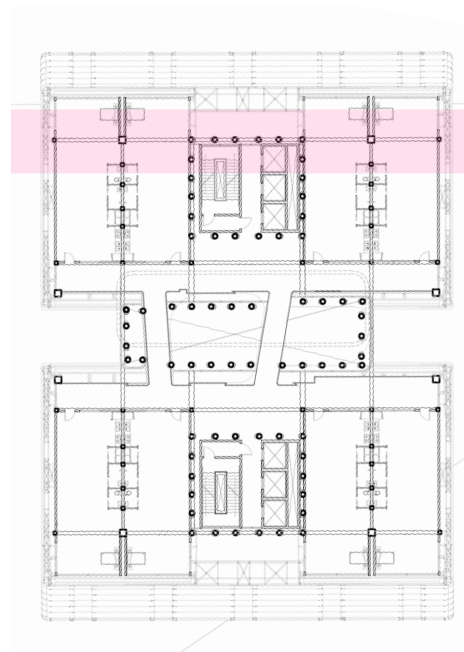
Conclusion: Again, both results have very similar deflections and drift ratios with the chosen member sizes. However, stiffening the columns and beams proved to be more efficient than stiffening the bracing. Smaller members are needed to achieve the 16.8in deflection limit in the second model. Therefore it is more efficient to stiffen the columns and beams (flange members) rather than the bracing members (web members).

Outrigger Truss Analysis

This is a model of the LilyPAAAAD building behavior study with a focus on the outrigger system.

Lateral Analysis





Location of Section Modeled

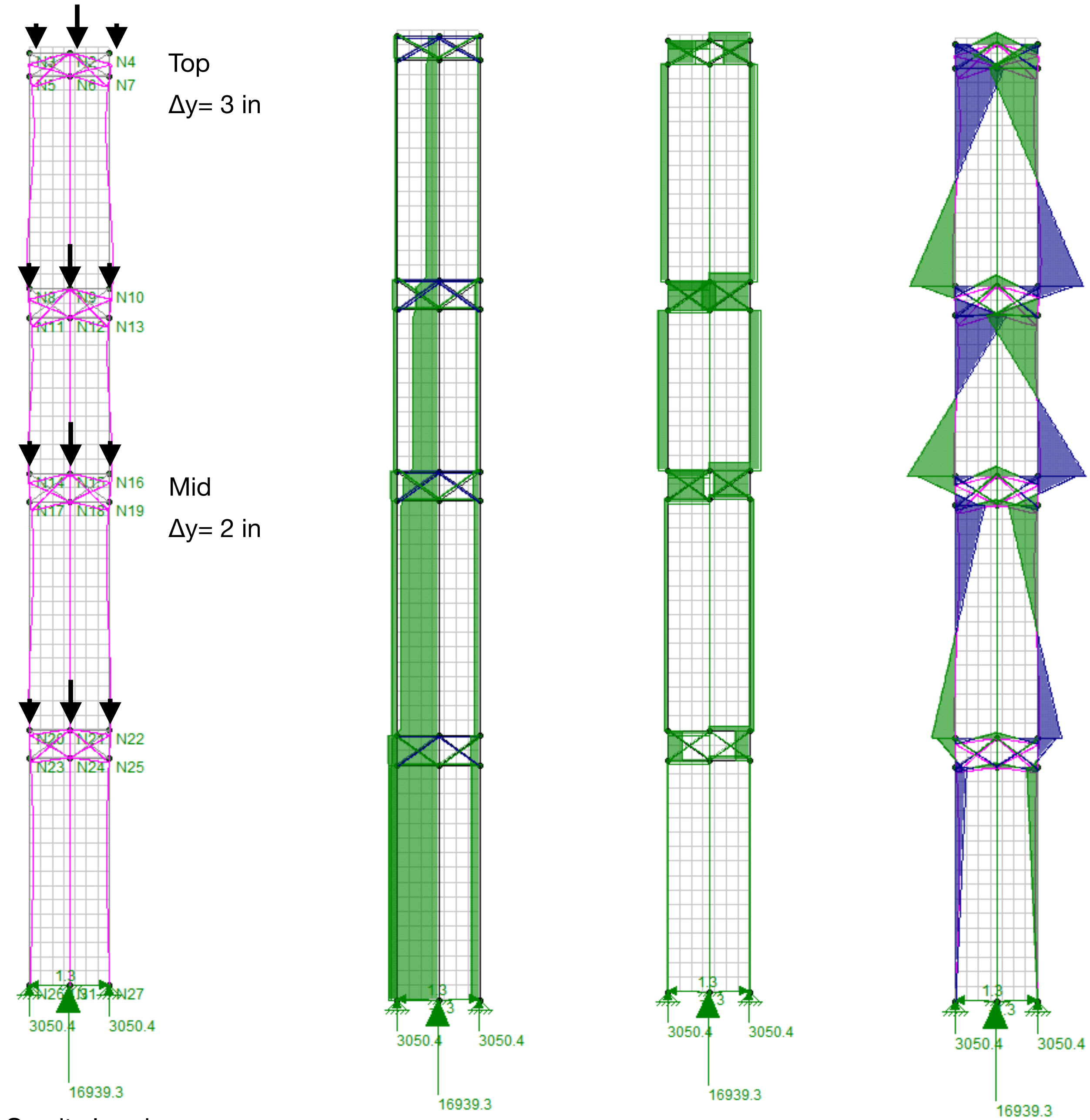
Member sizes

Core	30’ x 30’
	55in thick steel (for now)
Outrigger Columns	W36x925
Truss Chords	W21x93
Braces	W14x61

Deflection Limit: 19.7 in

This outrigger truss model has members sized based on hand calculations and estimations. However, the core is sized to take all of the load and is 55 inch thick steel, which is not realistic. The next steps were to calculate a more reasonable core thickness and size the outrigger columns to resist those lateral forces axially.

Outrigger System ~ Gravity Analysis



Gravity Loads

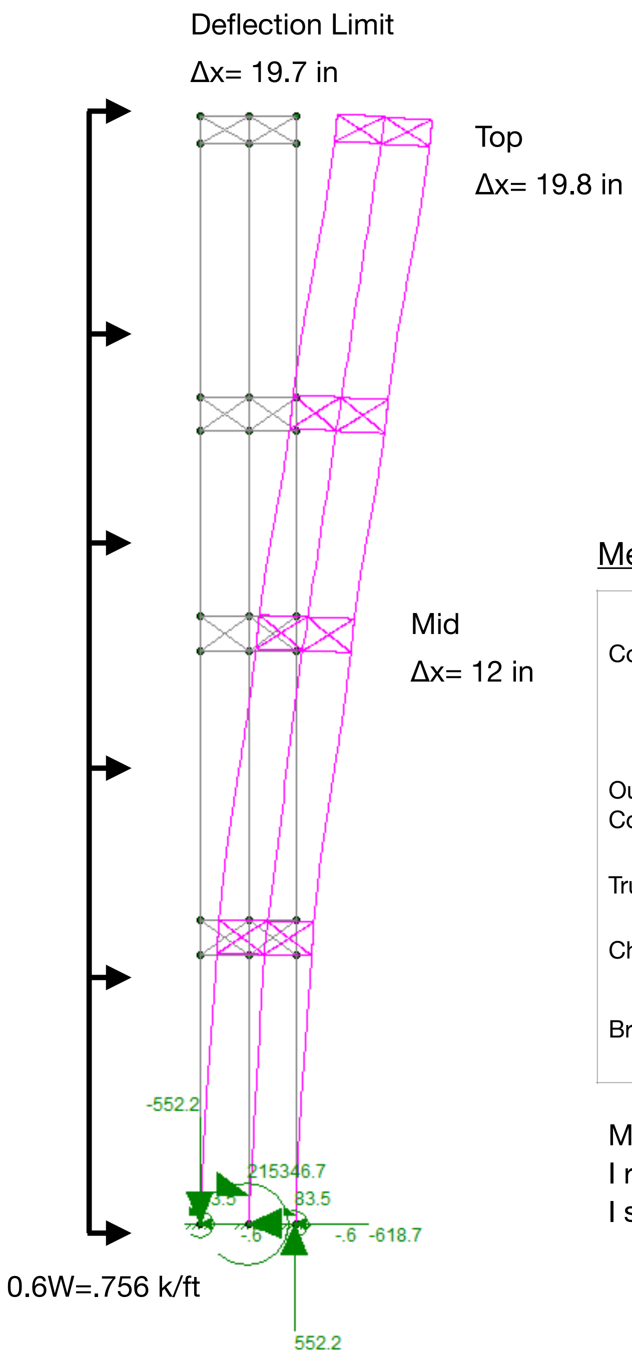
Axial

Shear

Moment

These images are showing the load path from the housing units hung at the trusses. The core is taking most of the load, with the outrigger columns in bending. This means that the trusses are bending and causing rotation. From this, it was discovered that the model needs adjustments because outrigger columns should not be in bending and only resists loads axially. The next steps were to change the connections from fixed to pinned so that the connections don't transfer moment.

Outrigger System ~ Lateral Analysis



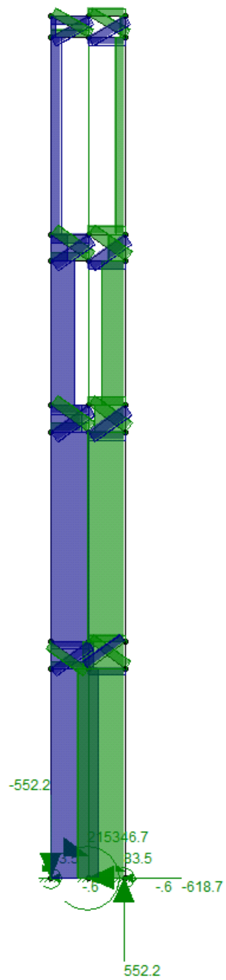
<u>Member sizes-3</u>

	Size	**Ix**	**A**
Core	30’ x 30’ 4.25in thick steel -> (6) W14x873 (max area of 257in^2)	Ix = 6.38E+07 in^4 *half the core	
Outrigger Columns	16 in x 16 in -> W14x873		A= 256 in^2 *one column
Truss	25ft depth	Ix = 4.19E+05 in^4	
Chords	W14x873	-	9.31in^2 *one chord
Braces	W14x873	-	-

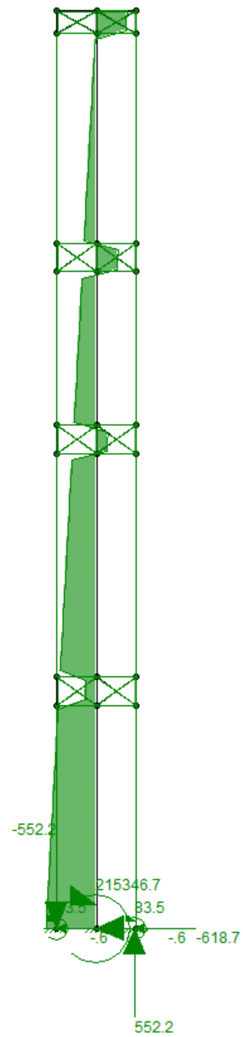
Moment of inertia of the system
I req = 1.29E+08 in^4
I system = 3.08E+08 in^4

The core was reduced to 4.25in thick solid steel to minimize the stiffness to distribute the load and utilize the outrigger columns. All other members were approximated to be W14x873. The next steps were to model the core as six columns with bracing and test the braced frame side of the tower.

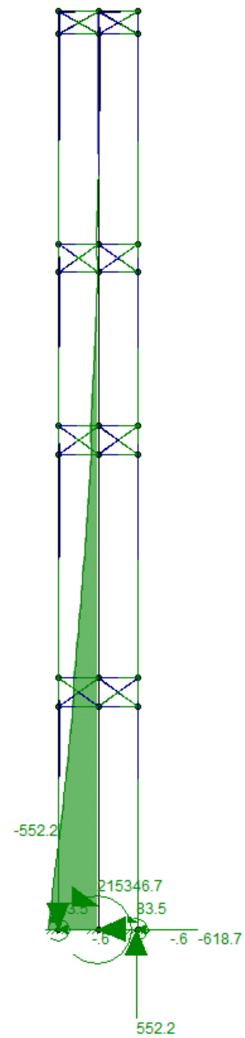
Outrigger System ~ Lateral Analysis Continued



Axial



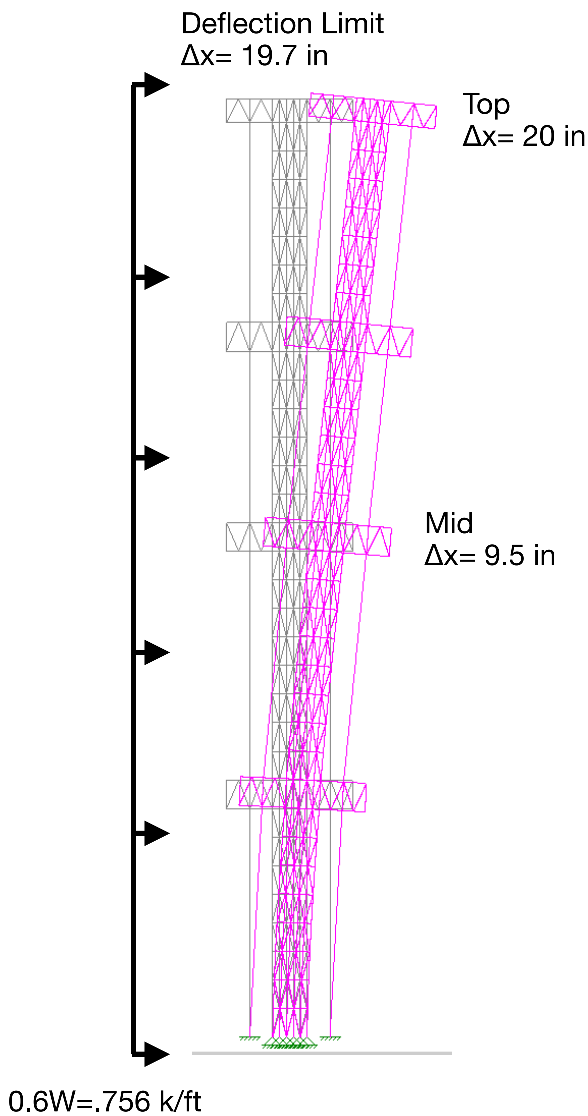
Shear



Moment

These diagrams show that the outrigger columns are only taking axial loads while the core is resisting shear and moment.

Outrigger System ~ Final Model of Lateral Analysis



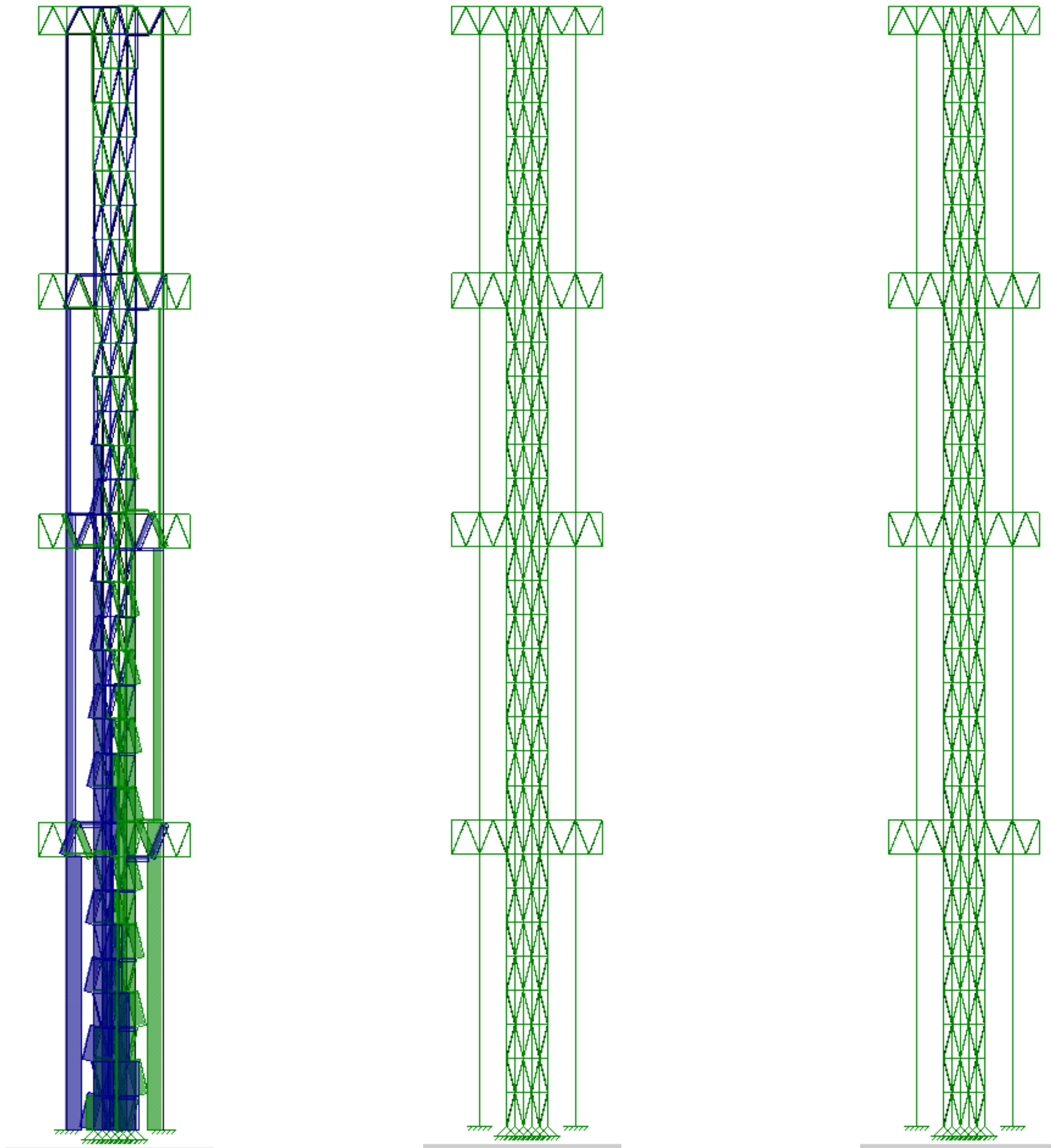
<u>Member sizes-1</u>

	Size	**Ix**	**A**
Core	30' x 30' (6) W14x873 per side	Ix = 6.38E+07 in^4 *half the core	257in^2 per
Outrigger Columns	W14x873		A= 257 in^2 *one column
Truss	25ft depth	Ix = 4.19E+05 in^4	
Chords	W14x873	-	9.31in^2 *one chord
Braces	W14x873	-	-

The Outrigger system's final model consists of six W14x873 columns per side of the core, with W14x873 diagonal braces connecting the columns. All members of the outrigger trusses are W14x873.

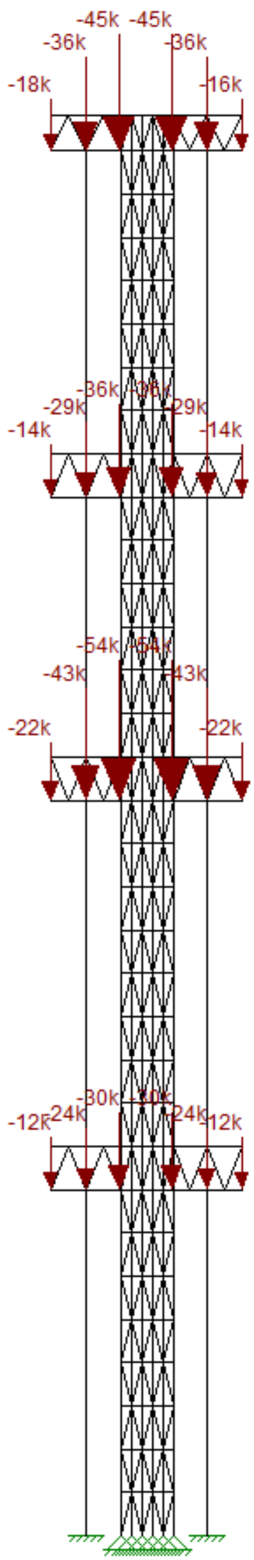
The outrigger system reduces rotational deflection at each truss level. The outrigger columns provide the system with additional stiffness by resisting the movement of the trusses.

Outrigger System ~ Final Model of Lateral Analysis Continued



Axial Shear Moment

These loading diagrams show that all members are loaded axially. The left column is in tension, and the right column is in compression.

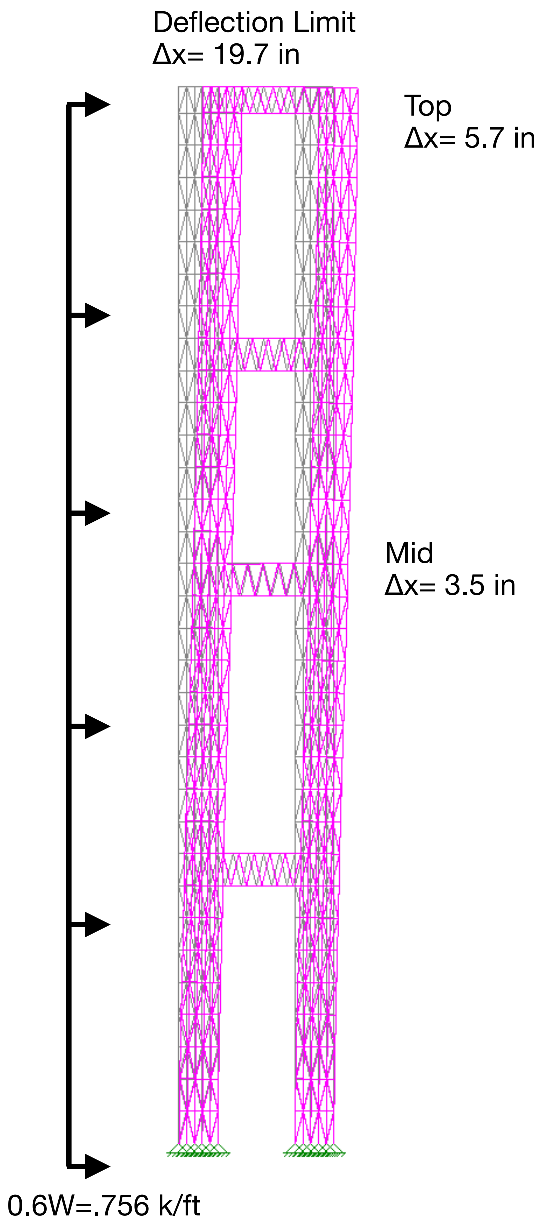


Member sizes-1-1

	Size
Core	30’ x 30’ (6) W14x873 per side
Outrigger Columns	W14x873
Truss	25ft depth
Chords	W14x873
Braces	W14x873

All truss members are W14x873. The max deflection at the top of the building is .05 inches. The load is from the housing units hanging off the trusses.

Mega Braced Frame System ~ Final Model of Lateral Analysis Continued

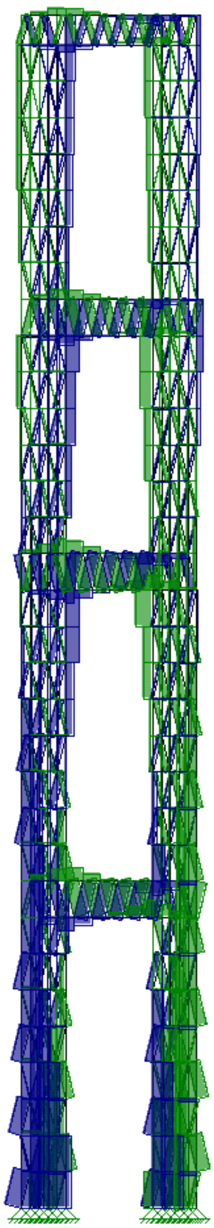


Member sizes-2

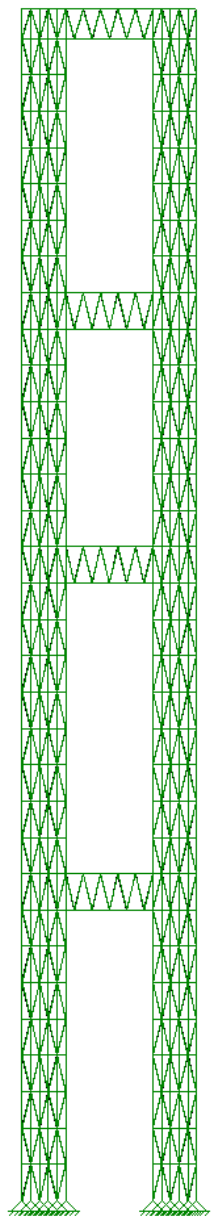
	Size	Ix	A
Core	30' x 30' (6) W14x873 per side	Ix = 6.38E+07 in^4 *half the core	257in^2 per
Outrigger Columns	W14x873		A= 257 in^2 *one column
Truss	25ft depth	Ix = 4.19E+05 in^4	
Chords	W14x873	-	9.31in^2 *one chord
Braces	W14x873	-	-

The Mega Braced Frame system's final model consists of two cores, 60 feet apart, with W14x873 members in the truss coupling beam. The cores have six W14x873 columns per side with W14x873 diagonal braces connecting the columns.

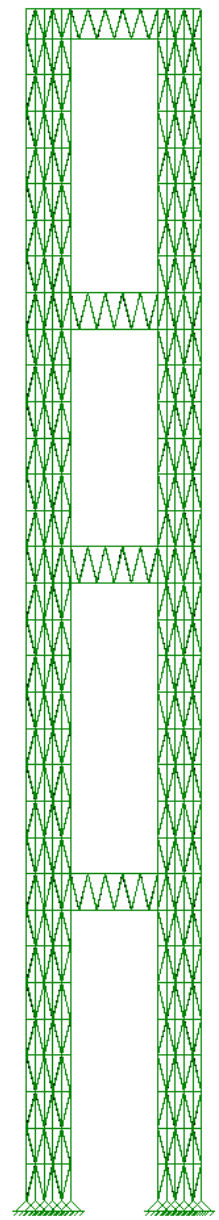
Mega Braced Frame System ~ Final Model of Lateral Analysis Continued



Axial



Shear

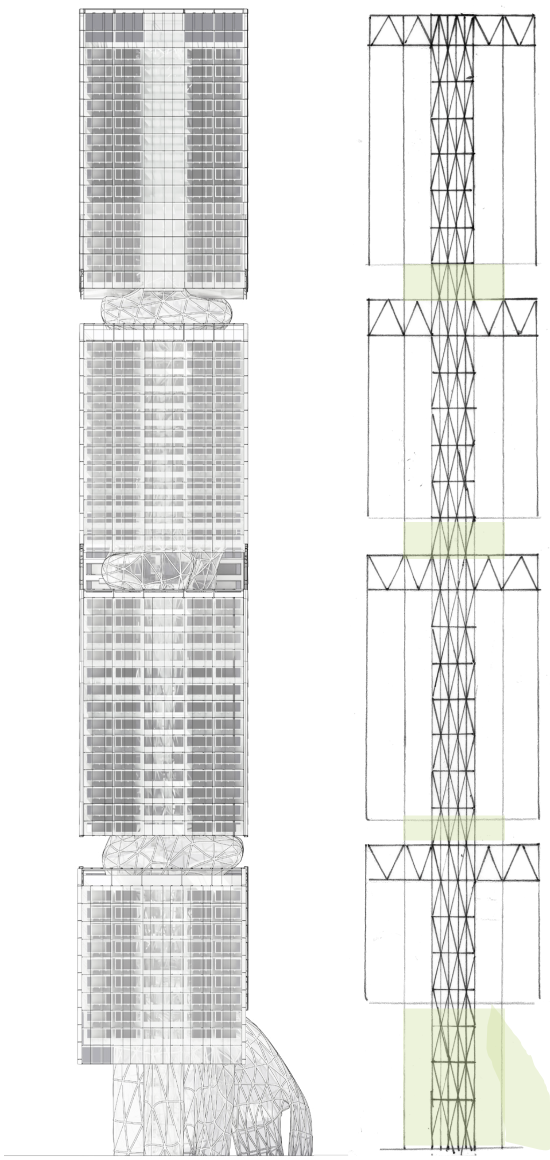


Moment

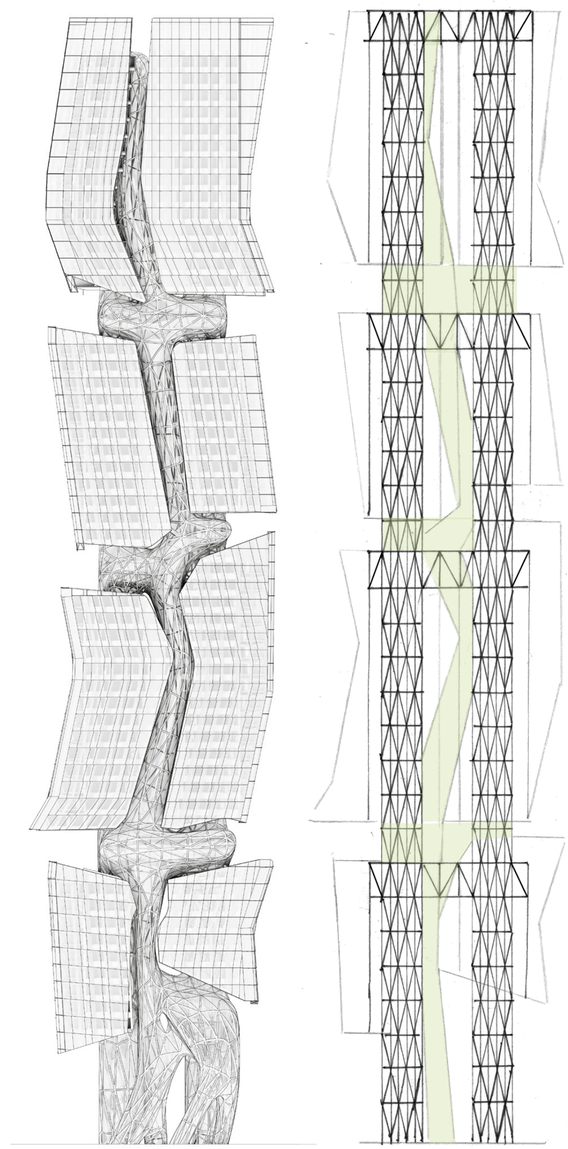
These loading diagrams show that all members are loaded axially.

Drawings

Lateral Systems ~ Stem



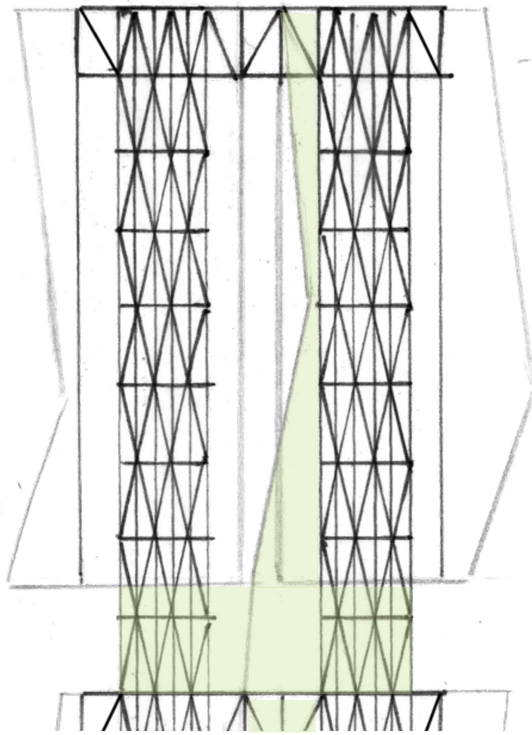
OUTRIGGER SYSTEM



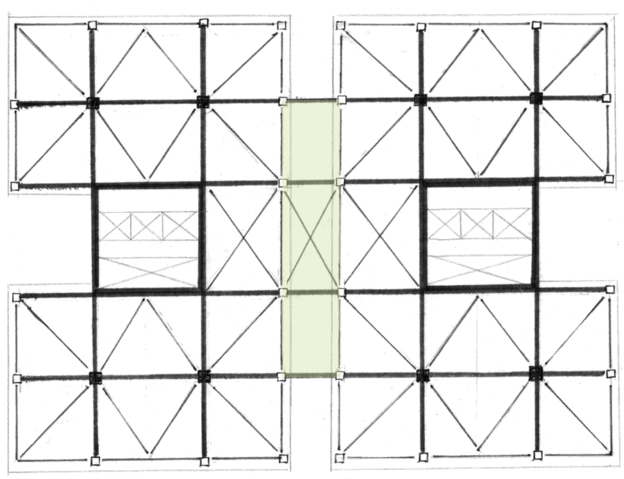
BRACED FRAME SYSTEM

The final tower design has two 30’x30’ cores spaced 60 feet apart. Since the cores are in the same plane, it was necessary to have two lateral resisting systems: outrigger system and braced frame system. The outrigger system utilizes the columns and trusses to reduce deflection while maintaining the transparency and openness between the housing units. The braced frame uses the stiffness of the cores by linking them together with trusses.

<u>Gravity System ~ Leaf</u>

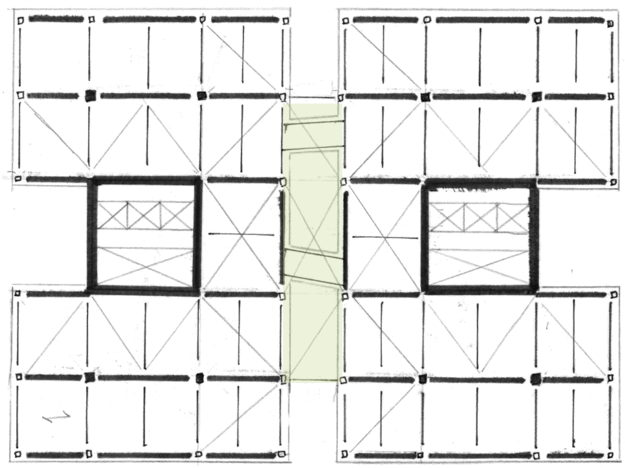


HAT TRUSS IN SECTION



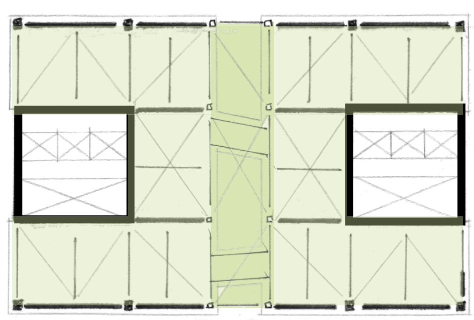
HAT TRUSS LEVEL

Hat trusses will hang the housing units at the top of each housing module. These trusses will also tie the cores together to form the mega braced frame system (right to left in plan) as well as extend to the outrigger columns (up and down in plan) to form the outrigger truss system. The two diaphragms will be connected together with diagonal braces on every floor.



TYPICAL HOUSING FLOOR PLAN

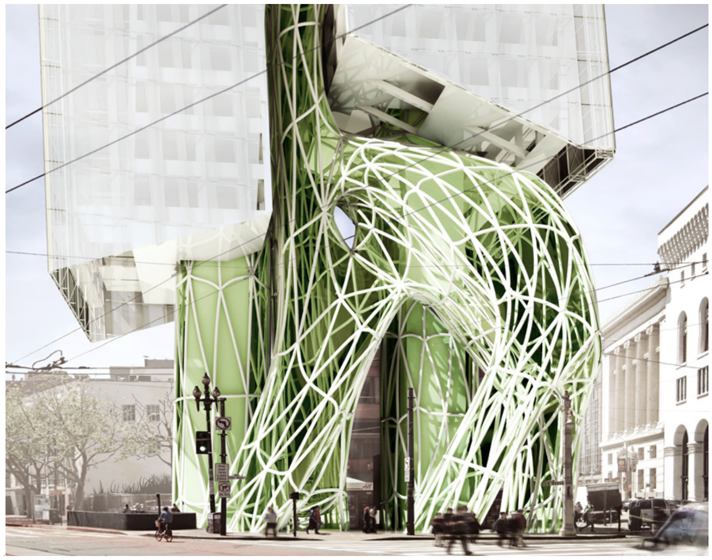
The Typical Housing Floor Plan shows the primary framing members, outrigger columns, tension columns, girders, beams, and diagonals.

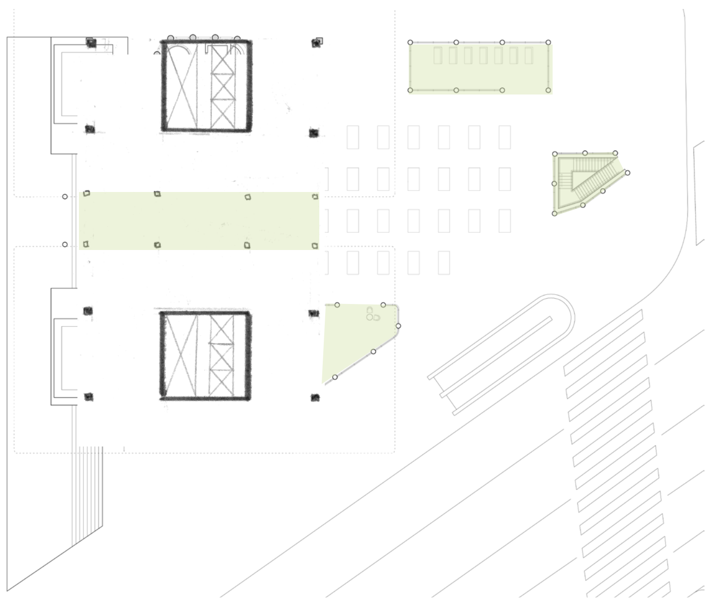


TYPICAL COMMUNITY LEVEL FRAMING PLAN

The Typical Community Level shows the main framing elements at the open space between the housing units. This space is a defining part of the expression of the stem. At this level, the atrium opens up to provide clarity to the lily pad units above and below.

Podium ~ Root

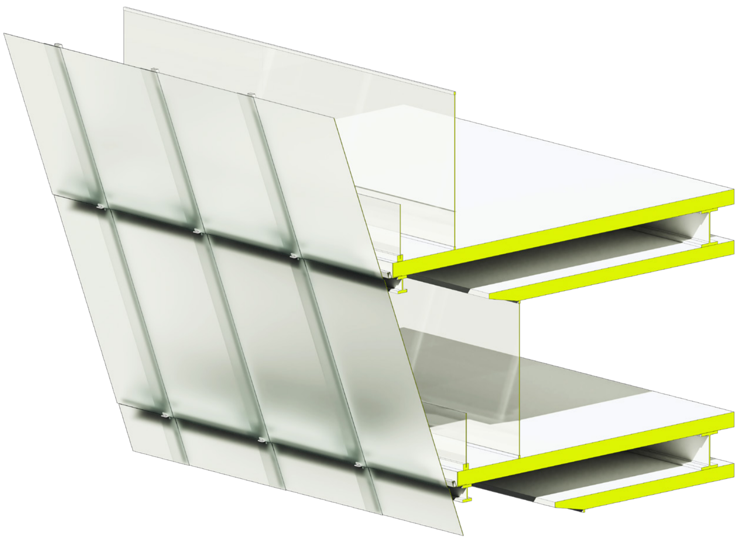


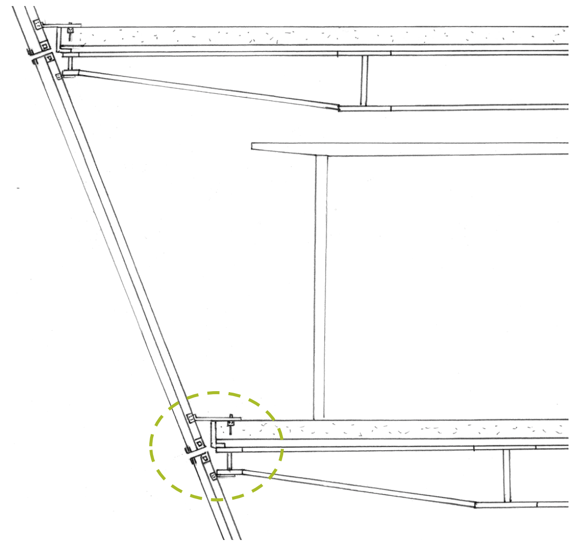


PODIUM AT GROUND LEVEL

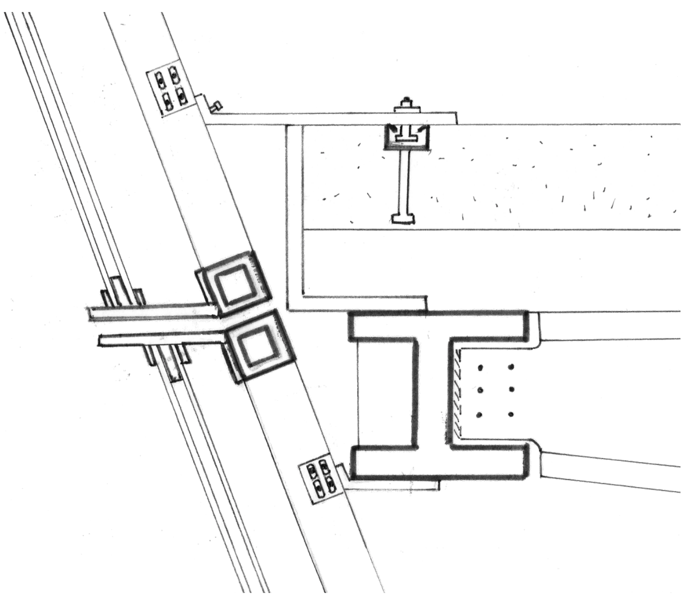
An essential aspect of the root structure design was for it to be open and transparent, inviting the city life into the tower at the ground level and encouraging them to explore the upper floors. The root structure touches the ground at the green areas shown on the plan above. These spaces provide shelter and circulation to the tower.

Facade

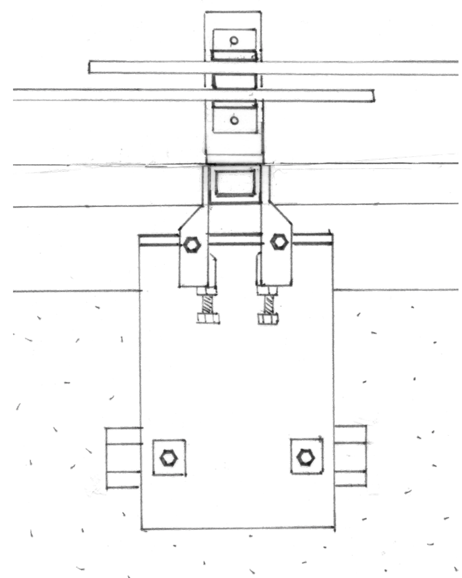




SOUTH SECTION



CONNECTION DETAIL



CONNECTION PLAN

Frosted glass was chosen as the facade material to soften the light as it enters in the units. A cast-in channel will hold up the framing elements. This channel allows for horizontal and vertical tolerances with its bolted connections. The brackets holding up the exterior glass allows for horizontal tolerances as well. They are separated by a small gap that prevents bearing and the glass from breaking with story drift.

Conclusion

The LilyPAAAAD Tower was created from the structural and spacial approach of the water lily. The idea was realized through model making and enriched with precedents studies. 2-D structural studies, in correlation with hand calculations, refined the clarity of the system. Lastly, drawings were used to communicate and illustrate the LilyPAAAAD Tower's structural system.