

TENSION CRANES



a collaboration of architecture and arce students by the names of:
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Structural Design

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General Information

The inspiration of "Tension Cranes" stems from the desire to capture the fast-paced, thriving construction industry throughout Oakland and San Francisco. The design concept comes directly from the cranes seen in the Port of Oakland and throughout San Francisco. Much like a construction crane is made up of a mast, jib (the projecting arm of the crane), and suspension rods; the "Tension Cranes" tower consists of a braced steel core (mast), cantilevered trusses (jib), and suspension rods used to "hang" building elements from the jibs. The building's core becomes a place for vertical circulation and community space. At the podium, only the core touches the ground while other elements hang above. The cantilevering of building spaces allows the site at the pedestrian level to open up, it provides space to access the Muni station underground, and serve as a public outdoor space. The housing modules face north and south with views of the bay and the Golden Gate Bridge. The tower also takes advantage of available airspace by cantilevering the housing modules over adjacent buildings. This creates room for more despite the limitations of the site.

Background

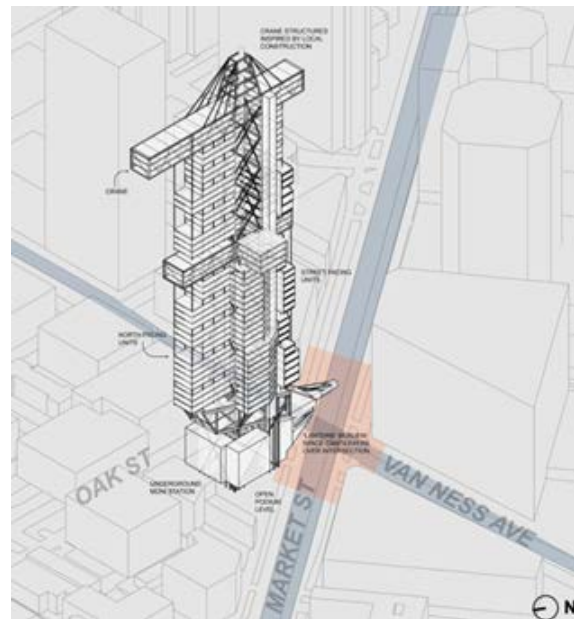
In collaboration with SOM, interdisciplinary teams of architecture and architectural engineering students worked to design a high rise building considering design aspects of tectonics, function, urban placemaking, and performative envelope. This report aims to address all of these items, but with an emphasis on tectonics. The teams were also given a choice of structural typologies with the goal to make structural art. The typology the Tension Cranes tower utilizes is TENSION//INVERSION. This idea prompted the team to rethink the way buildings are designed and turn what is typically all compression elements into tension elements.

Project Description

The project is located at 1 Oak Street, San Francisco CA, which is the intersection of Market Street and Van Ness Avenue. The building is 760 ft tall with 55 floors. The programming consists of 50 floors of residential housing units with a museum and retail space in the 5 floors (85 ft tall) of podium space.

Statistics

Height	760'
Girth	190'
Floor to Floor Height	12.5'
Total Tower Floors	55
Podium Height	85'
Podium Floors	5
Podium Floors Height	17'
Housing Floors Total	50
Housing Units Per Floor	8
Housing Units Sq Footage (Avg.)	1,000 sf
Core Size on each floor (Avg.)	100' x 80'
Vertical Community Space Sq Footage	2400 sf



1 oak site . urban fabric effect

Executive Summary

Tectonics

The tower's structural system is seen as three levels: the bottom third, middle third, and top third. There is a telescoping core consisting of three concentric rectangular diagonally braced steel cores. At each third of the building, the outside core ends, and the inner cores continue. This happens until only the center core remains. At each third level, there are also "crane jibs" or cantilevered trusses that reach out on each side of the core. These are used to hang the housing units on. For the gravity system, the load from the hanging housing units goes up through suspension rods that are connected to cranes then down through the core. The lateral system consists of the concentric diagonally braced steel cores, diagonal bracing in the housing modules, as well as the diagonally braced diaphragm on each floor.

"What's the function of this tower?"

Program

The tower is primarily residential with 400 units at about 1000 square feet each. The ground floor has an open plan encouraging activity connected to the Muni Station underneath the site and outdoor gathering space at the intersection of Market Street and Van Ness Avenue. The structure also includes a museum cantilevered the intersection at the upper podium levels as well as retail and cafe space at the lower podium levels.



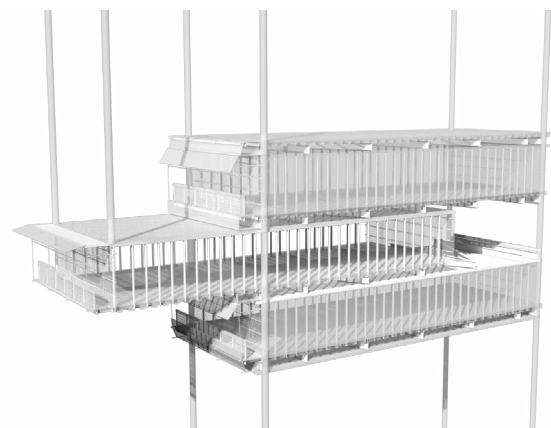
Crane Vertical Community Space

Vertical Community

On a macroscale, the vertical community space is the atrium in the mast of the crane. This space joins each set of housing modules to create a sense of community as well as a unique view at each level of the building. This atrium is continuous in each building section, only to be intersected by the cranes at each telescoping level of the tower. On a microscale, community space for the individual tenant is created in two ways: through outdoor gathering spaces in the gap between housing modules, and interior gathering spaces at each of the three cranes.

Housing Level and Housing Unit

The tower features a modular system that allows individual housing units to be lifted into place by the crane. These units create sets of modules that are hung by each crane. The modules consist of three to four floors of eight housing units on each floor. Much of the inspiration for this concept comes from shipping containers and modular housing.



Housing Unit-- prefabricated

Podium Level

At the podium level, the goal was to cultivate a strong sense of community for the public as well as the residents. By creating a courtyard on the ground floor, spaces for stores, shops, cafes, and the cantilevering museum throughout the rest of the podium floors, people are invited into the tower to explore, dine, shop, and connect with others. By utilizing the podium as public community space, the residents can have the connection to the overarching community of San Francisco, while also feeling the privacy of their residential space throughout the rest of the tower.

Urban Placemaking

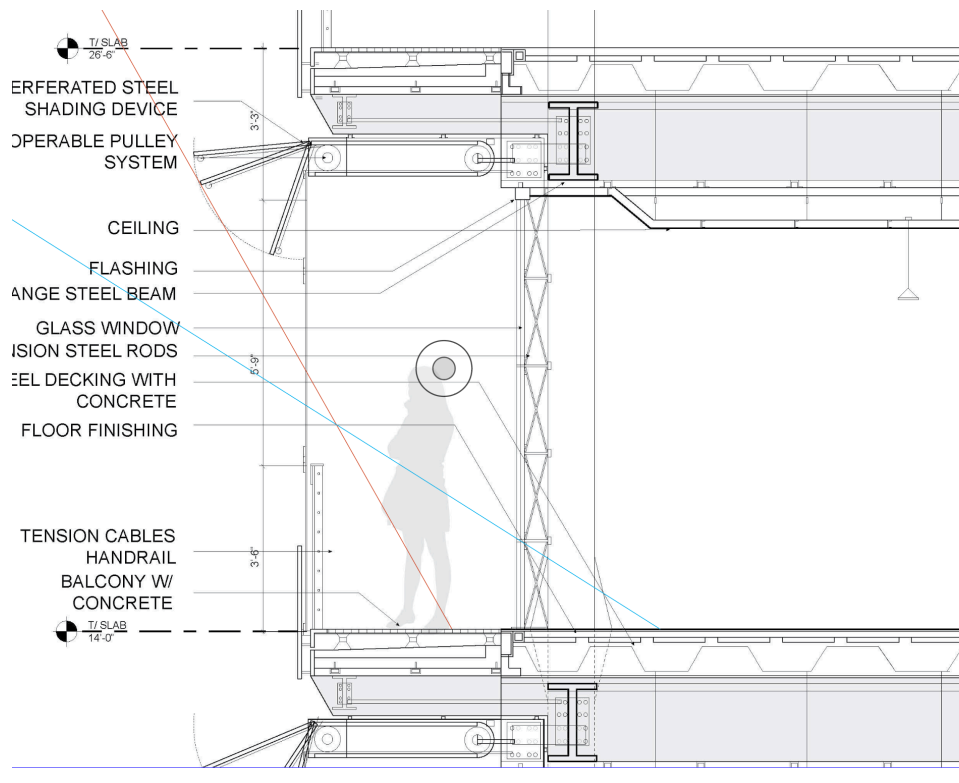
The design of the "Tension Crane Tower" creates a unique experience by connecting to the idea of construction and development of San Francisco, mirroring the changing city it is surrounded by. The tension system is used in many different ways, one of which is the cantilevering museum space over the intersection of Van Ness Ave and Market St. This emphasizes the importance of the location as the "hub" of downtown San Francisco.



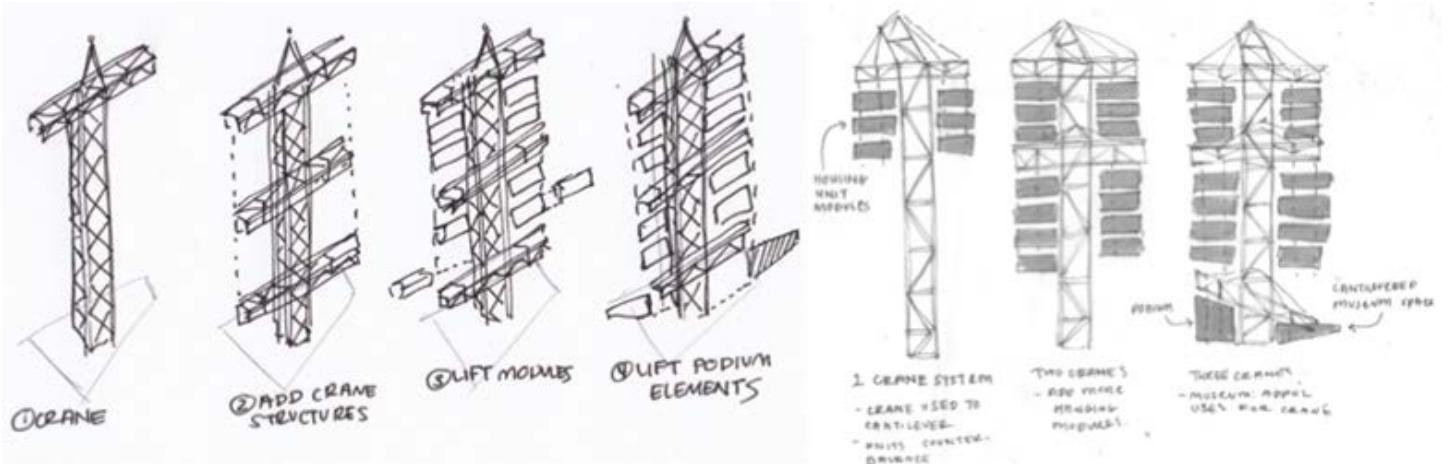
Podium Level Museum---
Connection to Urban Fabric

Performative Envelope

The performative envelope follows the theme of tension. Glass fixtures throughout the building are supported by a tensile net system. For each unit, that same glass tensile net system is used to separate the interior space from the outdoor deck area, and the overhang of the deck doubles as a shading device for the unit below. Above the deck, there is a perforated operable shading device that allows tenants to adjust based on their preferences of shade to sunlight.

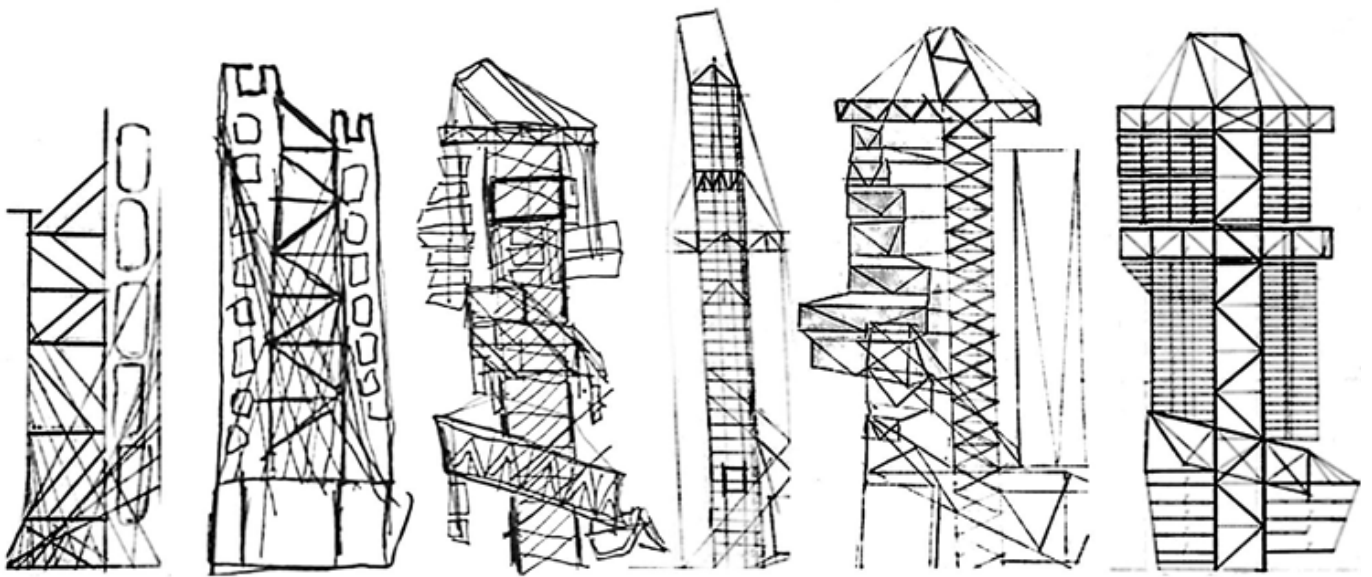


Tension Cranes Design Process



Project Exploration and Inspiration:

The design process began by drawing inspiration from San Francisco's rapidly growing construction industry as well as the Port of Oakland shipyard cranes. After looking at the structure of cranes and how they work, we became amazed at how such a skinny structure can lift such heavy loads and build the tallest buildings in the world. Using the inspiration of a crane lifting objects into place, this idea transformed into thinking about how to use the crane as a way to suspend housing modules with a tensioned pulley system. This exploration process began by using one large "crane" to suspend one line of hanging modules. From there, multiple cranes were then added into the design with more housing modules on multiple sides of the building. This created a balance where everything was hanging from the cranes. The "tension crane" system allows the building to cantilever over the air space of the adjacent buildings, creating an opportunity for more housing in the San Francisco area. This creates a meaningful experience at this important point in downtown San Francisco.

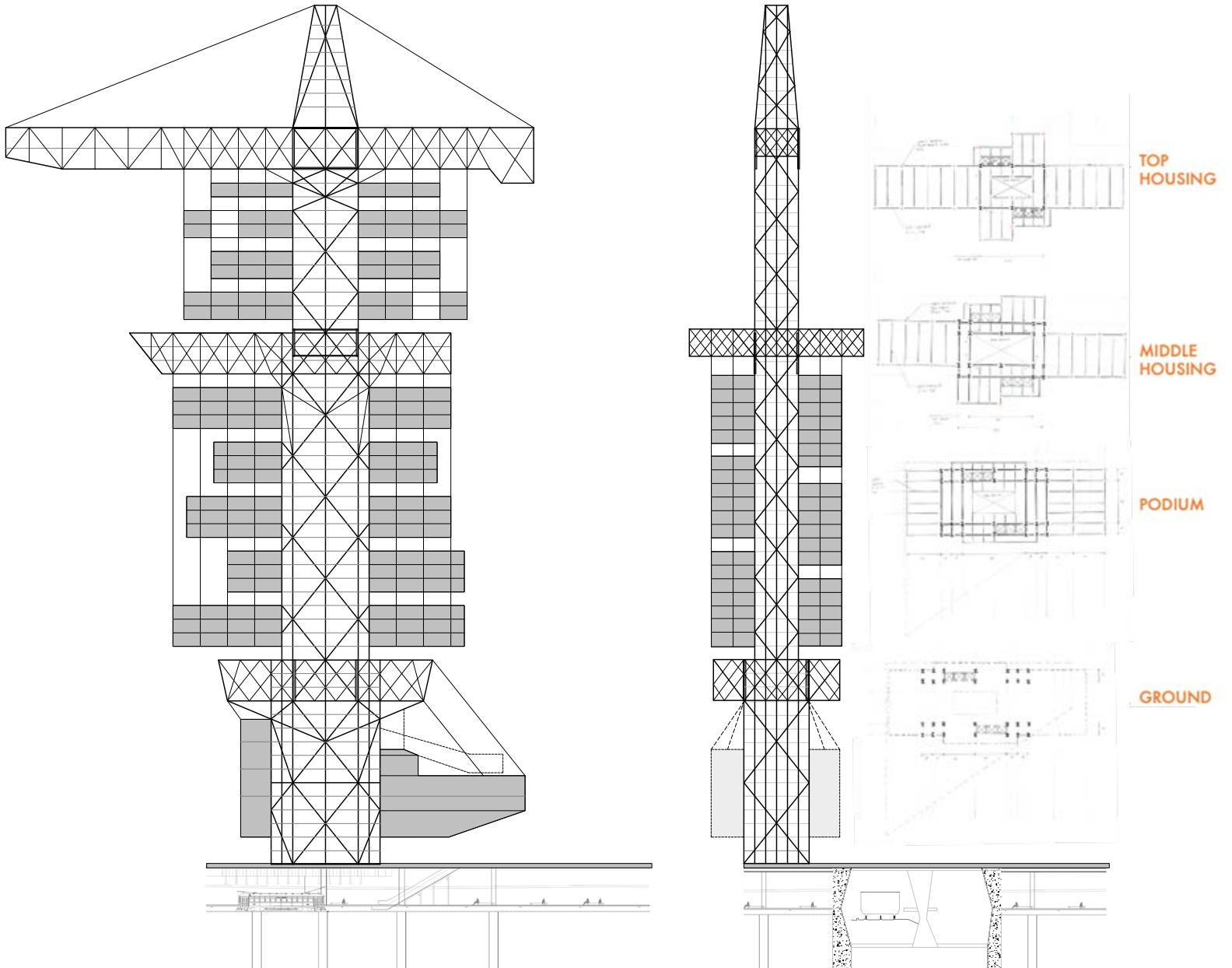


Structural Form Finding Exploration

Following the lead of the architectural form-finding process, ideas related to the industrial parts of San Francisco were explored. This was done entirely through physical models. The models were at approximately $1/32" = 1'$, standing approximately 24-26" tall. This scale was large enough to see the simplicity of design, but small enough that many iterations could be made. Starting out, we wanted to capture the iconic nature of the Golden Gate Bridge, one San Francisco's most recognizable features. This tower was braced with a zigzagging elevator core to show the views of the city to the south along with a cable net to not only shade the building but also to provide lateral support. Unfortunately in high seismic areas, such as San Francisco, horizontal bracing through the use of cables is not permitted in high rise buildings by ASCE. This has to do with them only being able to brace in one direction. The cables would buckle and the tower would likely collapse. Next, the team looked at various applications of the outrigger truss, and using tensile cables sculpturally and not as a lateral system. This proved to be far too complex. Torsional irregularities, imbalances and overall a system that did not work. The biggest problem was that the team wanted a tension structure. Outriggers act mostly as compression elements which made them not fit with the typology of the structure. As an alternative, the team kept the idea of tensile sculpture but soon eroded the outriggers into a diagonally braced core system. This mimicked the Hancock Center or Chicago and proved to limit the lateral drift due to wind.

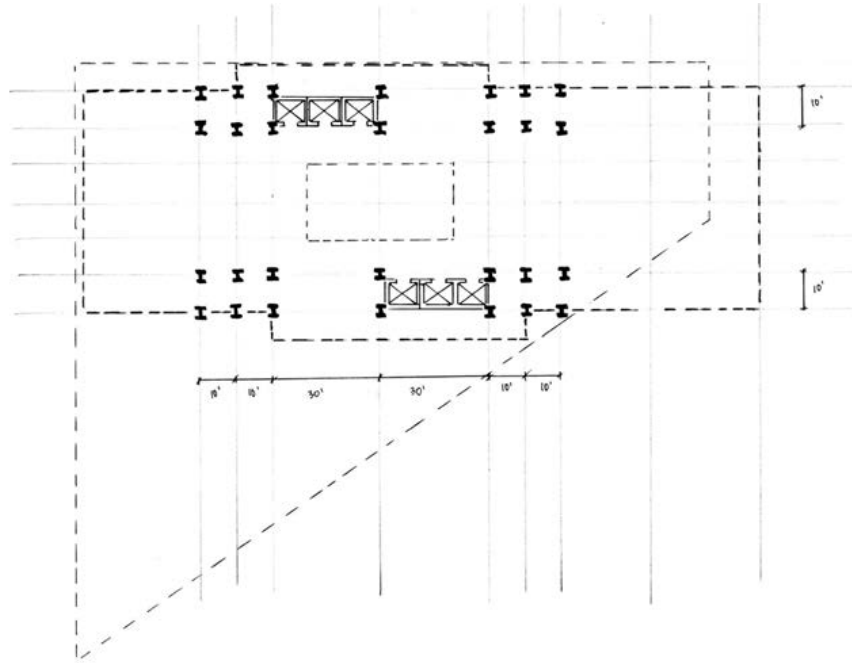
Tension Cranes ARCE Design

Structural Sections

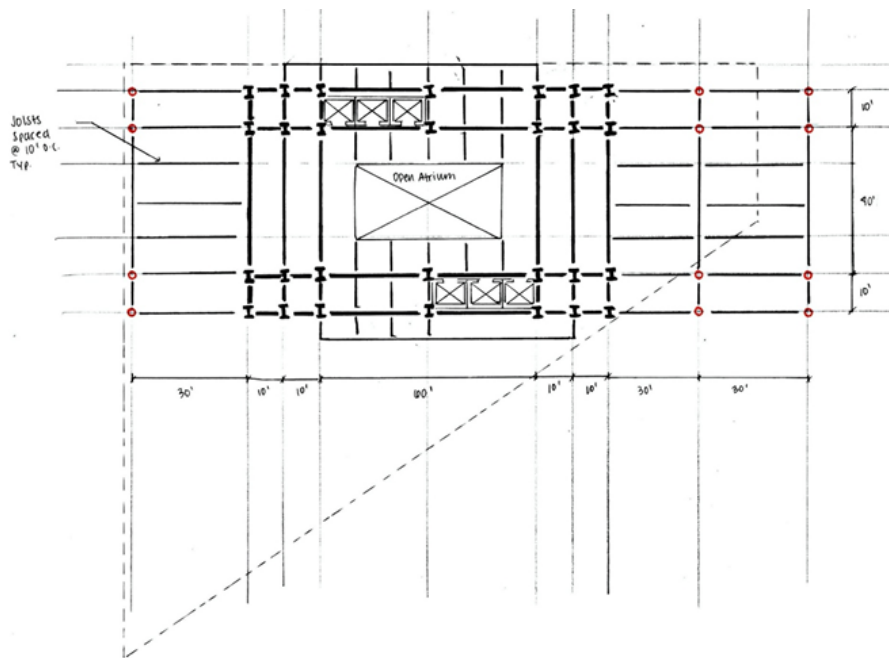


The tower's structural system mirrors the structure of a crane. The crane mast is its core, the crane jibs are the cantilevering trusses, and the suspension rods are the cables used to hang the housing modules. The mast is a telescoping core consists of three concentric rectangular diagonally braced tubes that change dimensions in three sections. The base is 100 feet by 80 feet, the middle is 80 feet by 80 feet, and the top is 60 feet by 60 feet. The North-South side, (or the long side of the building) steps in twice, while the East-West side (or the short side) only steps in once. The columns are W 14x873 W-Shapes and are spaced 10 feet apart. The core is diagonally braced with HSS20 x 20 members at approximately 45 degrees. Attached to the core are the cantilevering trusses (or cranes) that hold up the housing units. These cranes are three to four floors deep or approximately 40 to 50 feet. The steel members making up these cranes are W36 chords, W18 x 55 beams, HSS 20 x 20 webs. The suspension rods that attach the housing modules to the cranes are HSS round 8 in diameter steel pipes.

Structural Framing Plans

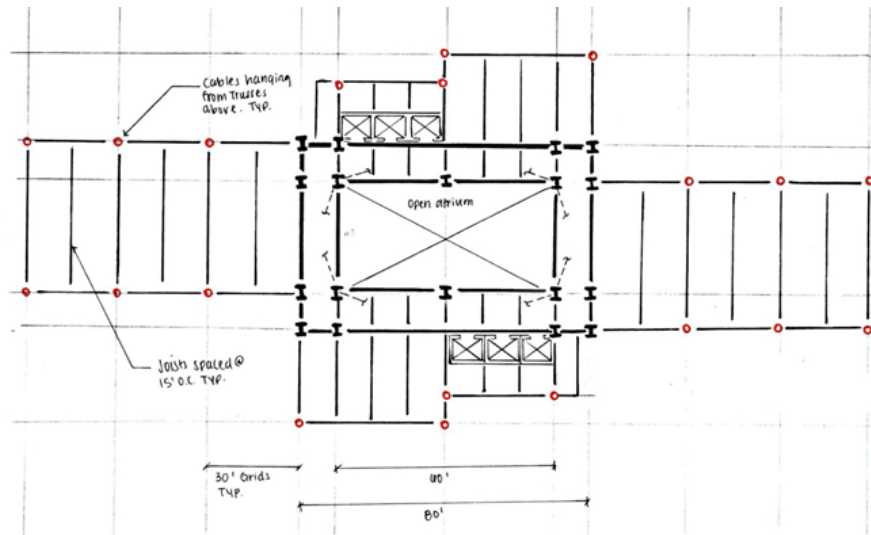


Ground Floor Framing Plans

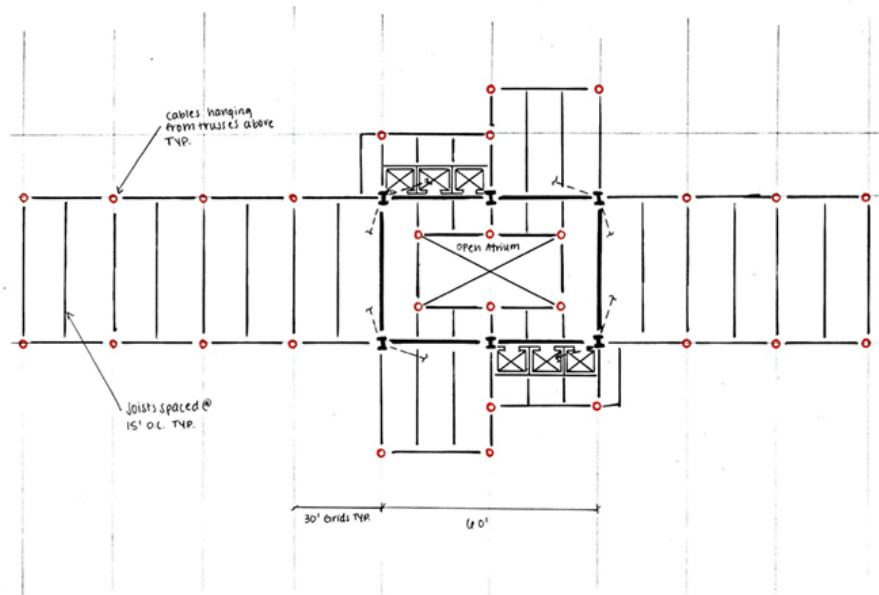


Podium Floor Framing Plans

Structural Framing Plans(cont.)



Typical Housing Floor Framing Plan



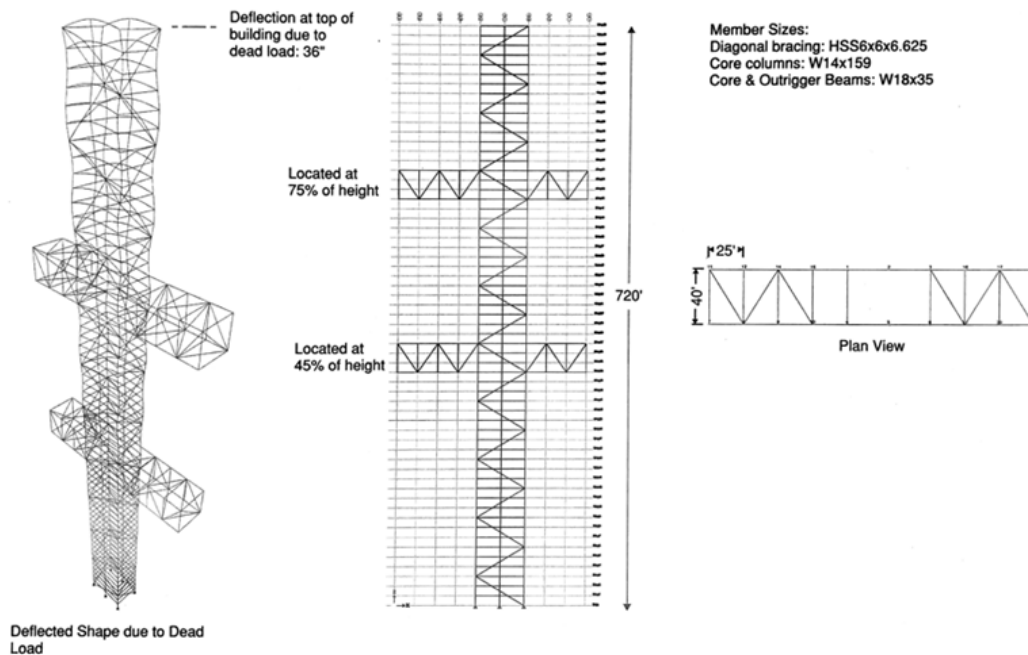
Top Housing Floor Framing Plan

These framing plans show the column layout of the telescoping core as well as the beam spacing and location of suspension rods (shown as orange circles). The ground plan shows that the only elements that touch the ground are the column and elevators. The podium, middle housing, and top housing show the continuous wide flange columns and the discontinuous steel cables. The steel beams are spaced 15 feet on center.

Structural Studies

Winter Quarter Studies

During the first 10 weeks of this project, the goal was to work alongside the architects to get a building form while also digging into some simple studies. The studies informed the building form while helping us understand the vastness of tall buildings and their behavior in wind and seismic events. Different structure types were researched and experimented with. The structural system selected for more in-depth studies was an outrigger truss system. The analysis started out with a simple box building with different variations of the system: steel core vs. concrete core, different outrigger truss locations, and various bracing configurations. These studies helped us understand load flow, gravity systems, and lateral systems of tall buildings.



This is the final model from the end of the winter quarter. It is an outrigger truss system and a first pass at representing the "Tension Cranes Tower". The goal of this study was to see how the building behaves under gravity loads from the hanging housing modules. This model showed a deflection of 36 inches, which exceeds the allowable value, indicating more studies needed to be done.

Explanation

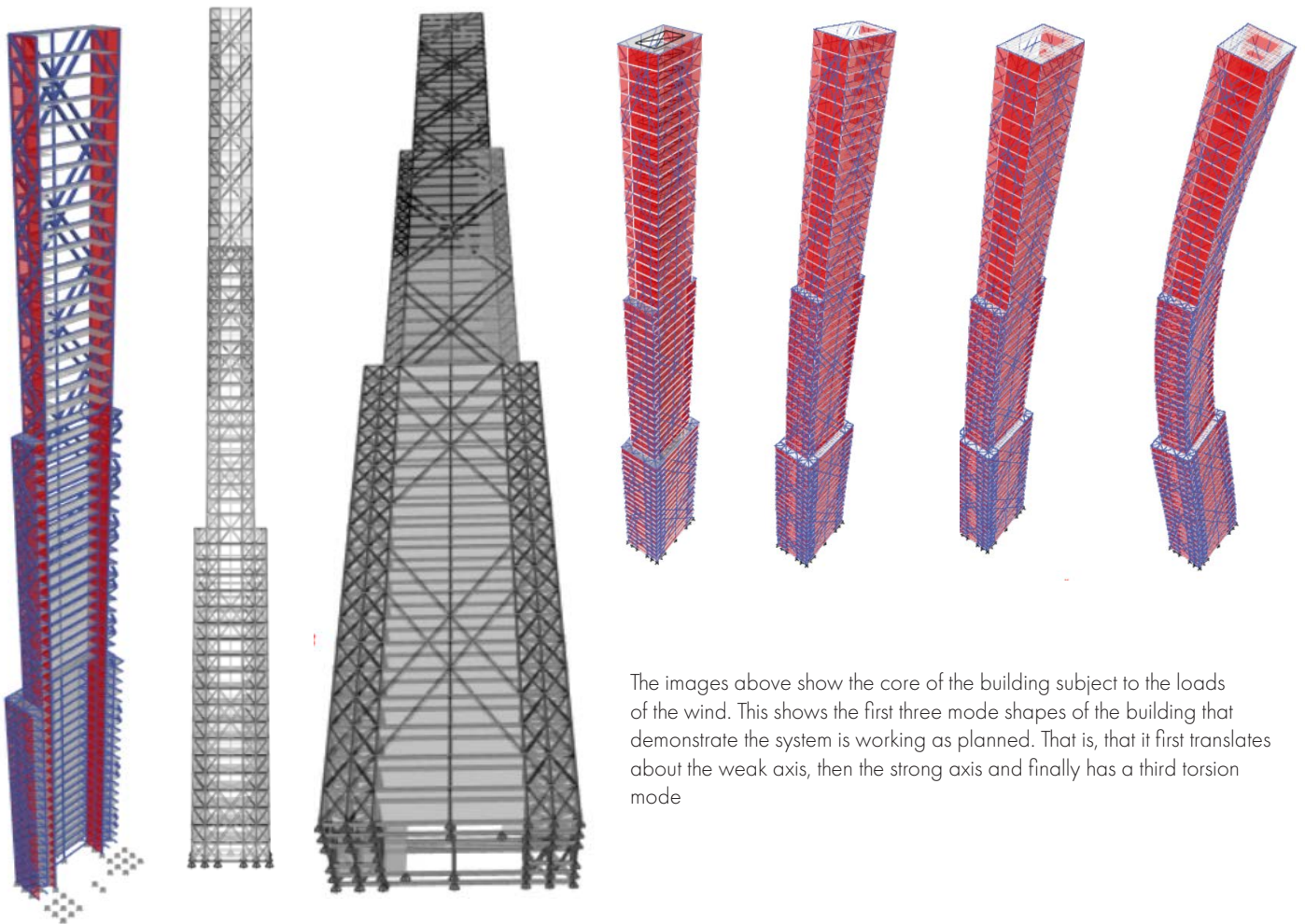
In this RISA study, on the short side of the tower, the telescoping core and was simplified to an 80 foot wide braced frame. Lateral loads were applied to the frame representing wind pushing on the long face of the building. There were three goals for this study: find the column area required to meet the deflection limit, find the percent contribution of deflection from flexural vs. shear, and check the model with hand calculations.

The first goal was to find the column area required for the frame to meet the deflection limit of 18 inches. To meet the deflection limit, it was found that each column needs an area of approximately 500 square inches. While this is about double the biggest section size available, 257 square inches, this model provided a starting point for column stiffness and size.

The second goal was to see the percentage of deflection of flexure (columns) vs. shear (braces). With the column size and bracing used to keep the structure within the deflection limit, it was found that the flexure was contributing 90% and shear only 10%. This showed that adjusting the number of columns, their sizes, and configuration was the best step forward to getting realistic column sizes.

Lastly, the goal was to run this model while also backing it up with hand calculations. An excel spreadsheet was used to estimate required column sizes, bracing sizes, and deflections. All of the numbers were within 5% of those calculated in RISA. The spreadsheet can be seen in the appendix.

Study No. 2: Diagonally Braced Tube Configuration:

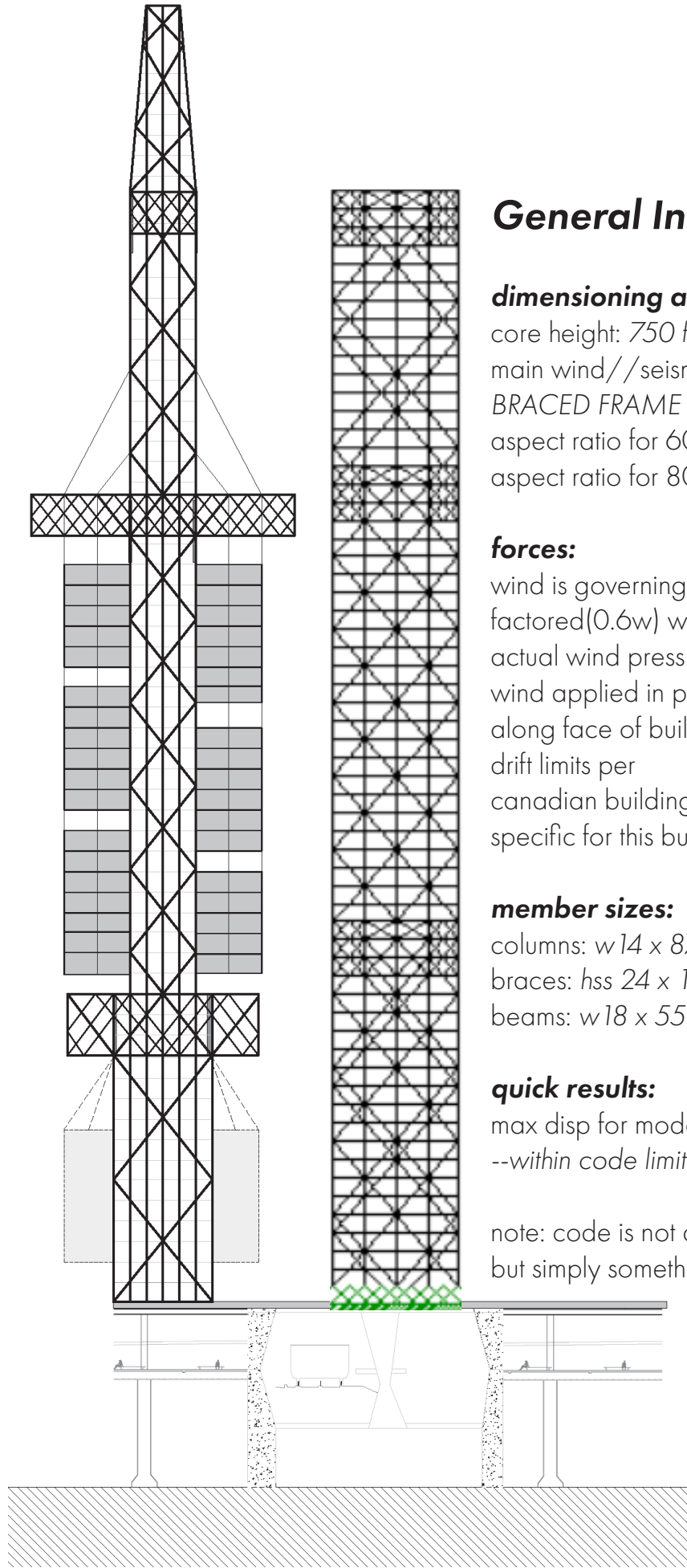


The images above show the core of the building subject to the loads of the wind. This shows the first three mode shapes of the building that demonstrate the system is working as planned. That is, that it first translates about the weak axis, then the strong axis and finally has a third torsion mode

15 Configurations on 22 Iterations

a study of variations on the diagonally braced tube

80 ft side core --- number of solutions : 1



General Information

dimensioning and aspect ratio:

core height: 750 ft

main wind//seismic force resisting system:
BRACED FRAME

aspect ratio for 60ft width: 12.5

aspect ratio for 80ft width: 9.375

forces:

wind is governing force

factored(0.6w) wind pressure: 35 psf

actual wind pressure: 60 psf

wind applied in point loads

along face of building

drift limits per

canadian building code: $h/400$

specific for this building: *limit = 22.5in*

member sizes:

columns: w14 x 873

braces: hss 24 x 12 x 0.5

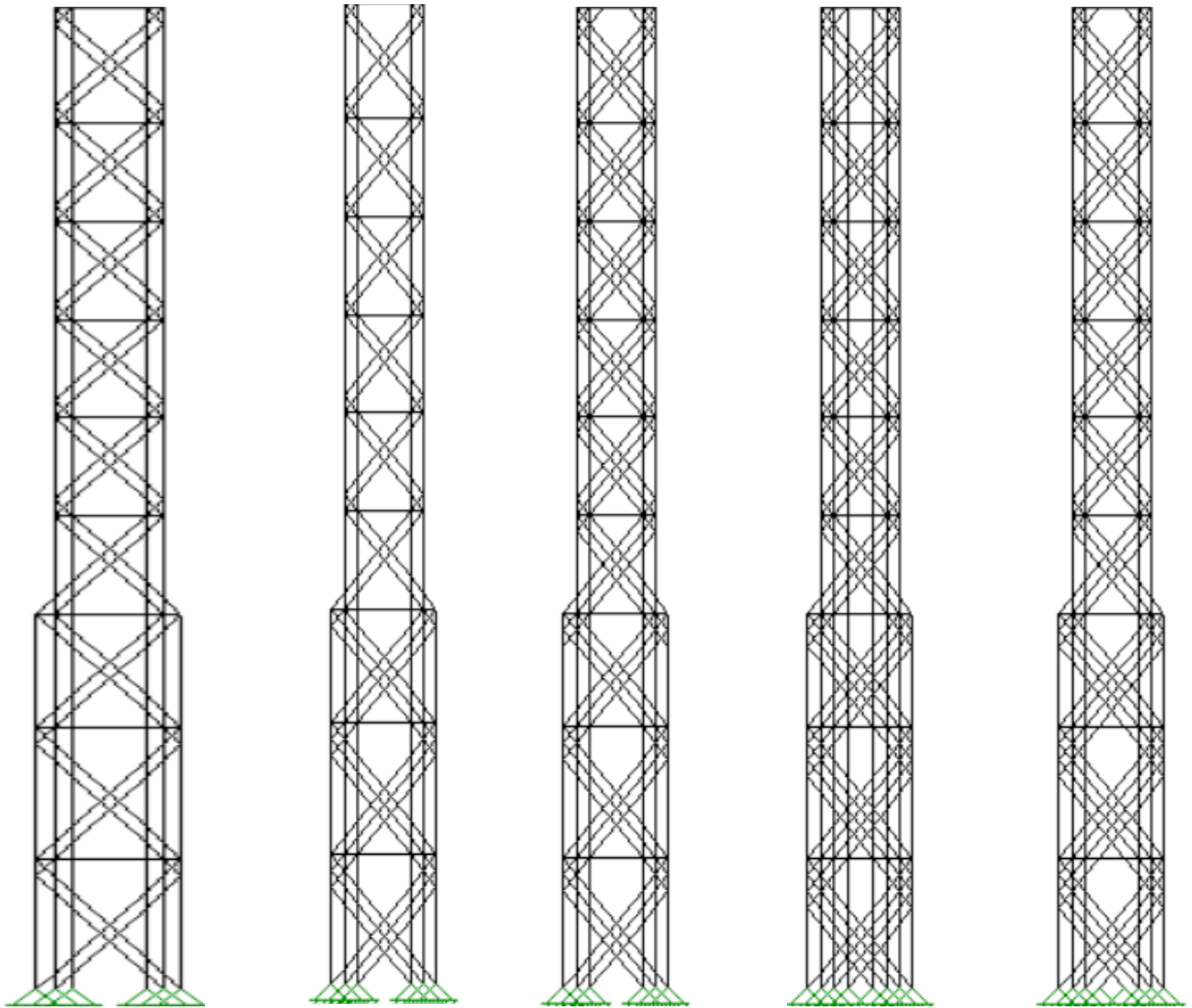
beams: w18 x 55

quick results:

max disp for model: 22.479in

--within code limits

note: code is not a ubc//ibc requirement
but simply something to reference.

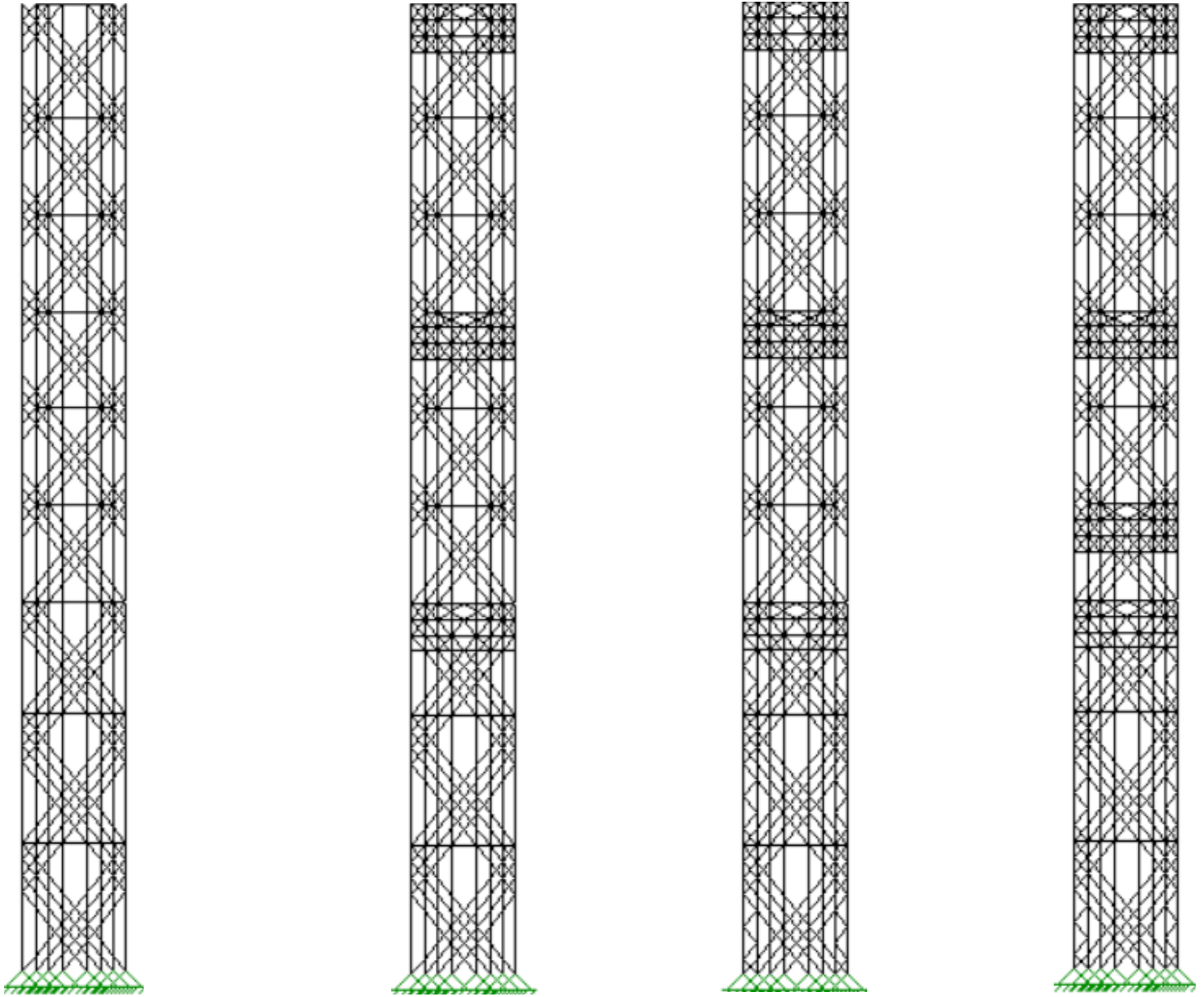


Beginning Tapering Iterations:

These iterations were 2d risa studies. From left to right represents the progression of modeling. Each model allowed Will to learn more about which elements have the greatest impact on drift in this situation. On the farthest left, there is a model that started it all. There were minimal node placements, but soon this needed to change. Excel was used to generate mass amounts of node coordinates. Notice the significant cleanliness of the models of this first set after nodes were installed to establish a clear pattern of bracing.

These first few were going off of the assumption that quantity of braces and size of braced frame member affected drift the most. No belt trusses were used. This conflicted with the architectural model, but Will wanted to know what was doing the most effort structurally and if the braces were enough to tie the structure together. In the end, the drift was at the least around 70-80 in for all of the final iterations of this set. One important observation was that the bottom 1/3 of the tower seemed to be relatively stiff compared to the rest of the building. This likely has to do with the superior aspect ratio of 9.375 compared with the aspect ratio of the top being 12.5. The top is simply too slender. This is fixed in later iterations.

note: all connections modeled as pins

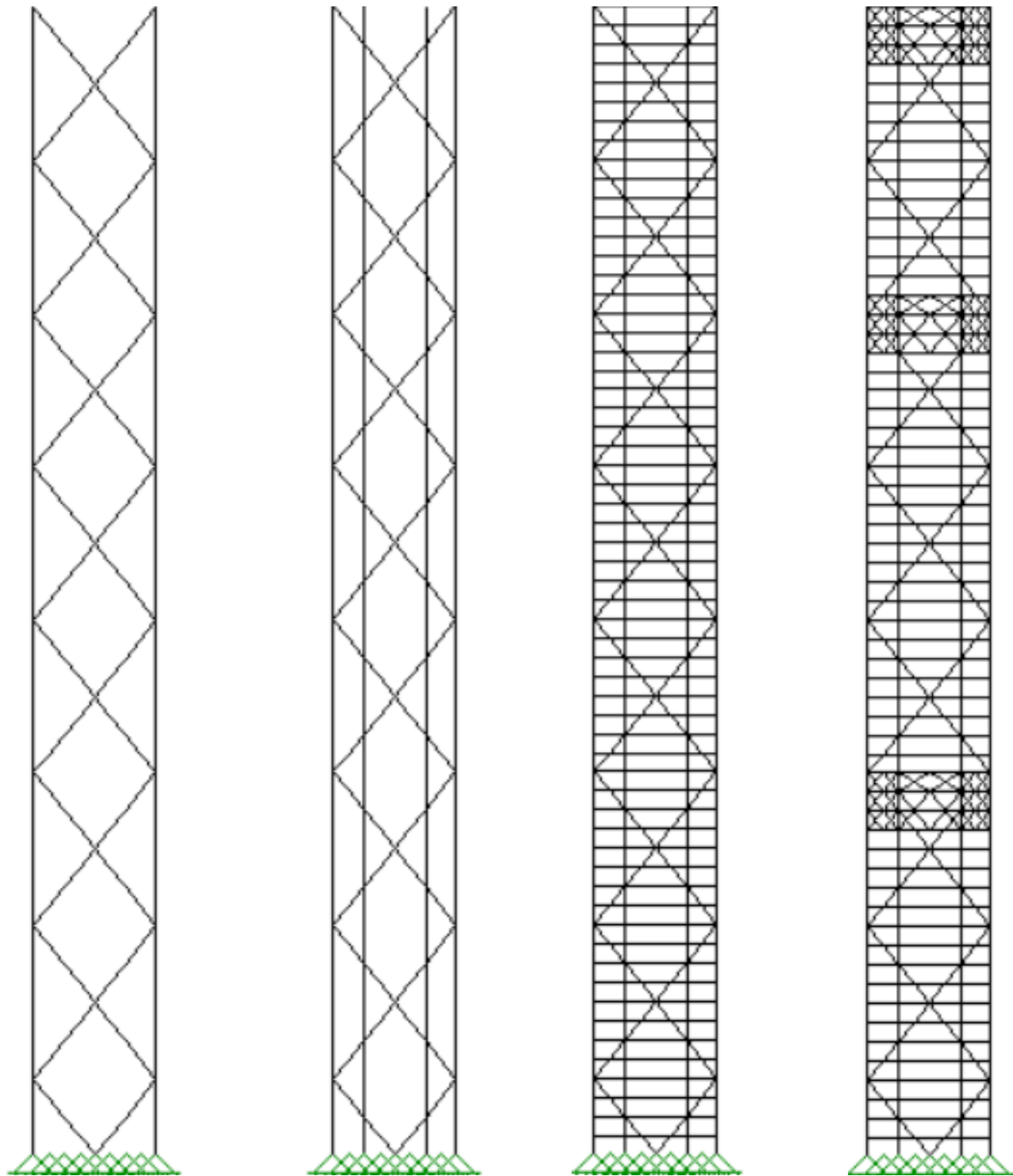


Braced Belt Truss// Aspect Ratio iterations:

These iterations were 2d risa studies. From left to right represents the progression of modeling. Each model allowed Will to learn more about which elements have the greatest impact on drift in this situation. On the farthest left, a control model without belt trusses was used to compare to the belt truss models. The density of braces only increased one time from left to right. The biggest change was the addition of the belt trusses and the added columns to obtain a superior aspect ratio. This lowered the drift to 59 - 65 in.

This is then going off of the assumption that the belt truss would stitch the columns together to form a tube. This then negates the previous argument that the braces would be enough to unite the columns together. Belt trusses were added at the 1/3 points of the tower according to prior studies. Although the unified aspect ratio and belt trusses did prove to have the whole tower to have approximately the same stiffness, it did not meet drift requirements.

conclusion: neither the belt trusses or the density of bracing is what is needed to help the system meet the drift limit.



Column Size iterations:

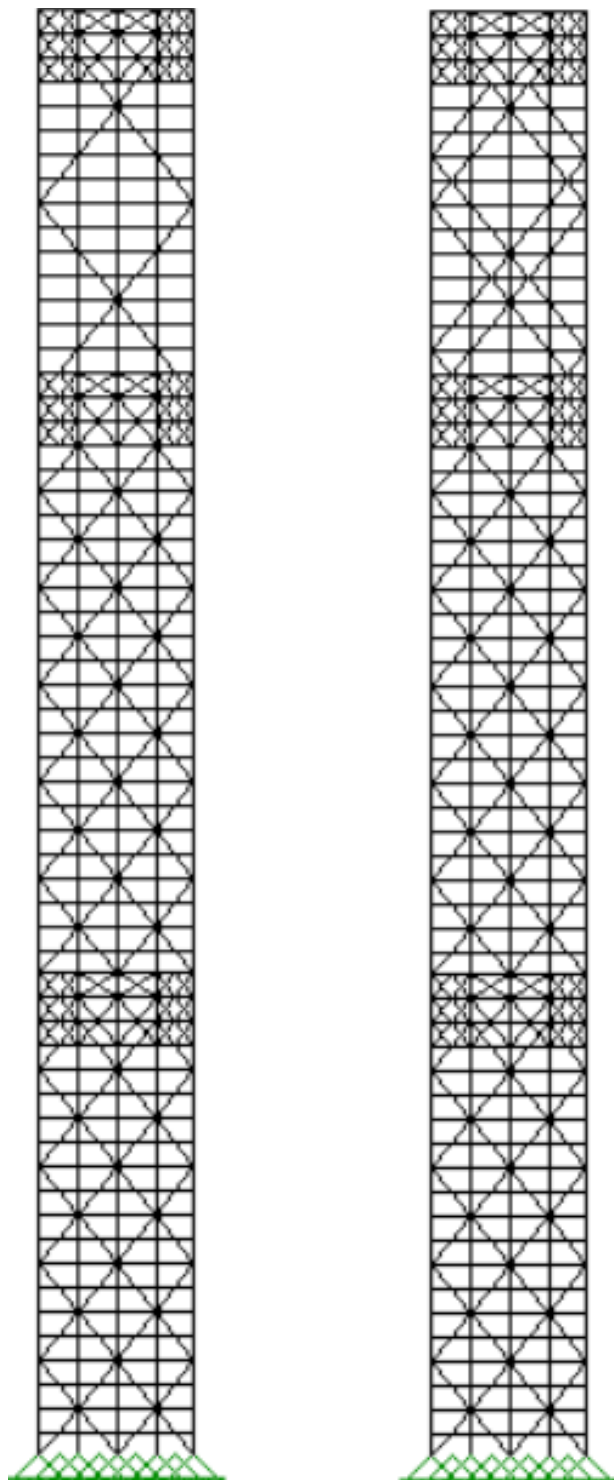
In these iterations, column sizes were increased on the model farthest left from w14x145 to w14x873 gradually in order to find a column size that made the tower work for drift. Continuity of Risa 2D required that beams be placed in order for the system to not have free pins and thus instabilities.

Max disp at top went from 36in ---- 26in with the added beams, braces and belt trusses with the increased column size.

conclusion: column size is required to be larger for tall buildings and the braces simply unite them.

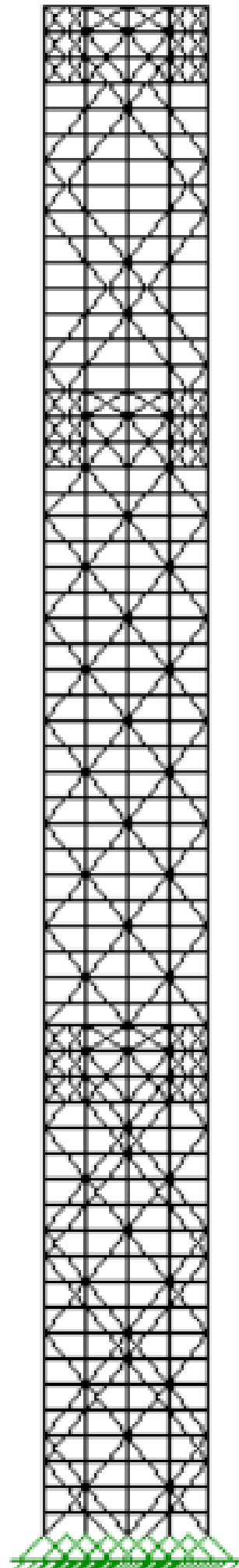
column size of w14x873 still fits within the area allotted in architectural plans which is the reason for not using the more efficient w36 section.

Final Model



final iterations to meet drift limits:

A diagrid was added for the first 2/3 or so of the building. The belt trusses were also modeled as the same elevations as the hanger trusses in the architectural drawings. Patterning is meant to taper off instead of the footprint of the building. The bracing is densest on the bottom and lightest on the top. Additional double bracing on the final model to the right was needed to obtain another inch of drift to meet the 22.5in limit.

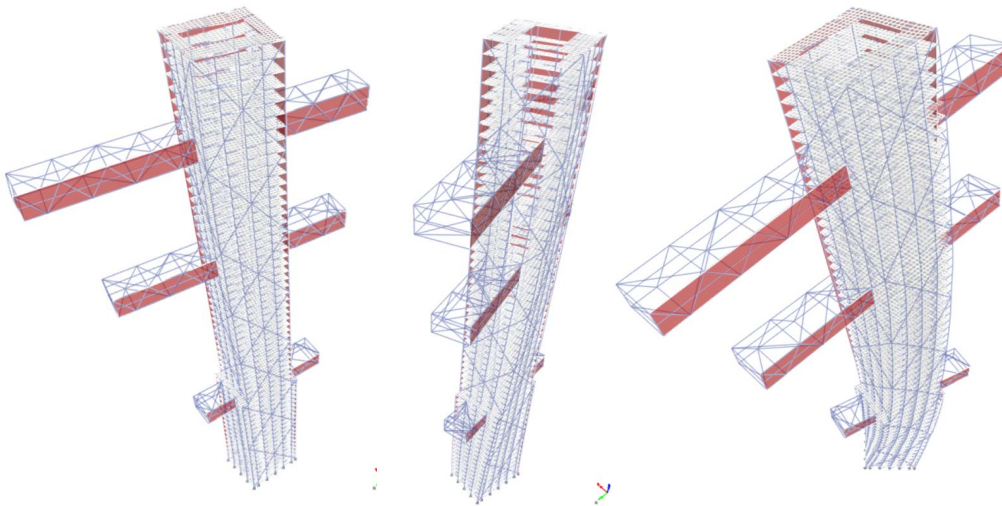
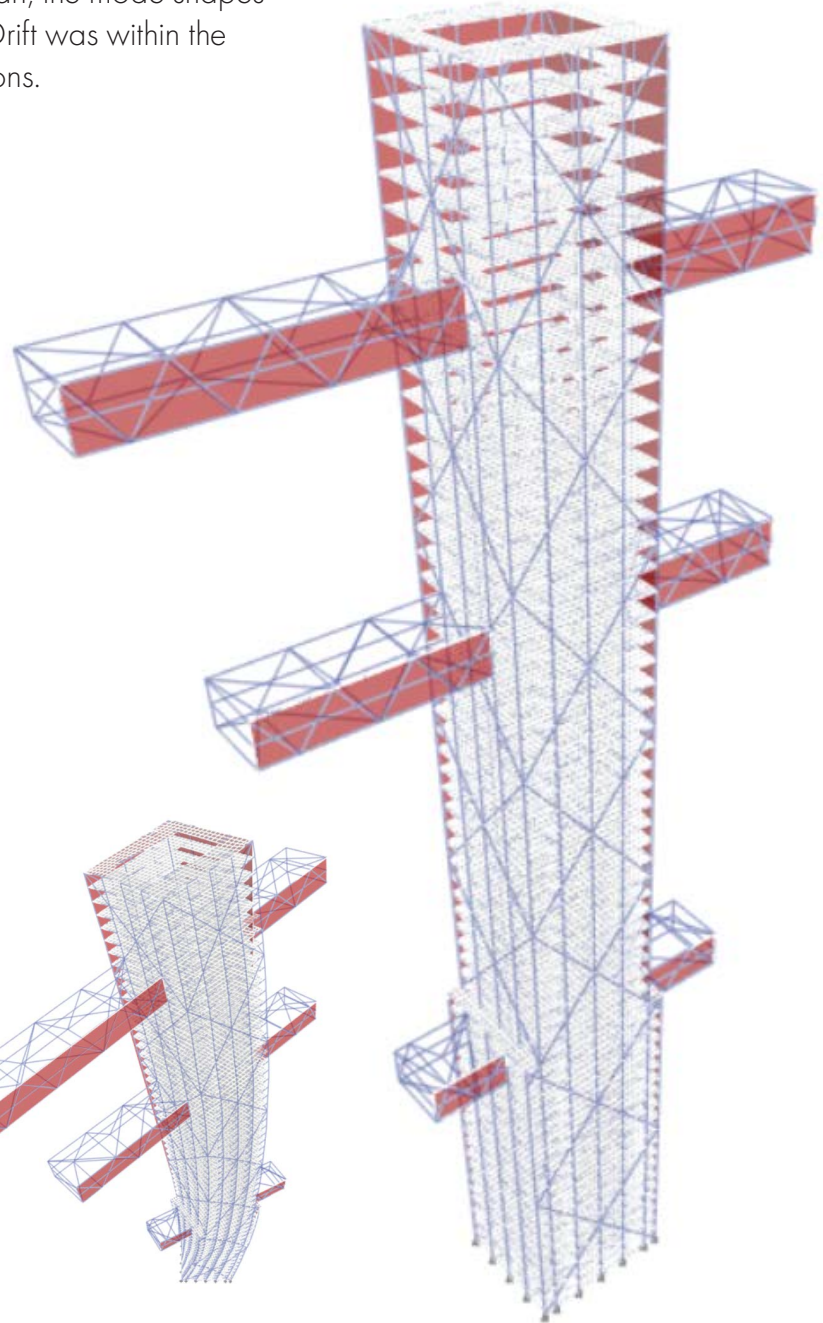


Final Model and Drift Checks:

The images at the bottom of the page show the mode shapes of our final tower and the way it behaves. Wind was consistently found to be the governing force. A uniform load of 35 psf was applied to the tower in the N//S direction and E//W directions to find max deflection values. Some torsion was expected in the mode shapes but for the most part, the mode shapes were as anticipated; translation, translation, rotation. Drift was within the $h/500$ canadian building code limit for both directions.

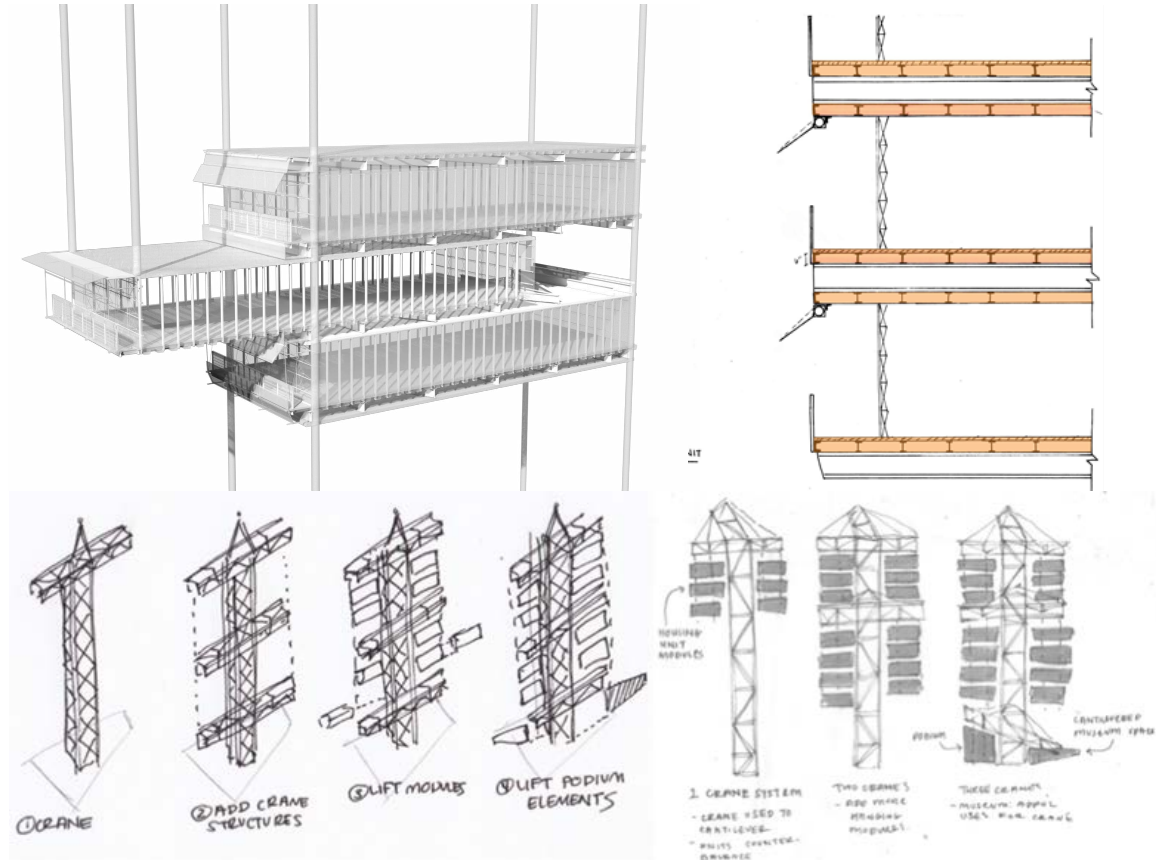
TOWER PROJECT IMPORTANT NUMBERS

Height	760'
Girth	190'
Floor to Floor Height	12.5'
Total Tower Floors	55
Podium Height	85'
Podium Floors	5
Podium Floors Height	17'
Housing Floors Total	50
Housing Units Per Floor	8
Housing Units Sq Footage (Avg.)	1,000 sf
Core Size on each floor (Avg.)	50' x 70'
Vertical Community Space Sq Footage	2400 sf



Design Elements

Modular Unit



The housing units are 25 feet by 40 feet, giving each tenant 1000 square feet of living space. The units are pre-fabricated and designed to be lifted by the building's cranes and slid into place.

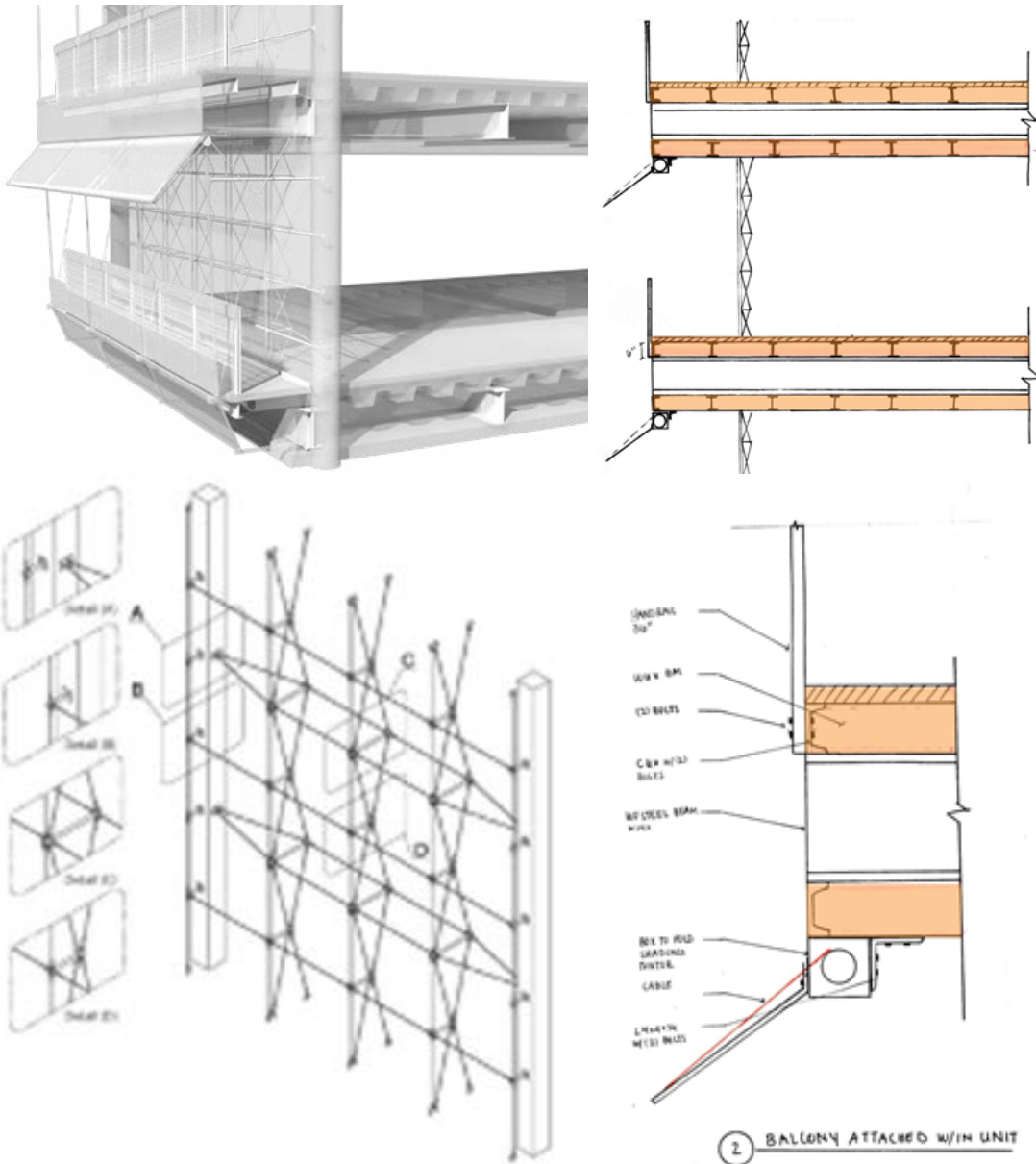
The images shown above:

Top left: unit sliding into place

Top right: building section highlighting the modular unit structure in orange that is resting on top of the building structure

Bottom: sketches illustrate the construction sequence.

Modular Unit



The performative envelope consists of a glass tensile net system (used to separate the interior space from the outdoor deck area), a deck overhang (doubles as a shading device for the unit below), and an operable perforated shading device (located above the deck allowing tenants to adjust the device based on their preferences of shade to sunlight). These elements are connected to the housing unit which is then slid into the tower as one piece. Because the facade is discontinuous at each floor, there is no need to allow for differential movement due to story drift at the connections. Everything is either bolted or welded to the housing unit frame shown in the section and detail above, and like the images shown for the housing units, the orange indicates the unit's structure.

Conclusion

Throughout the structural process of the Tension Cranes tower, many design philosophies were considered, and many structural systems were tested. This was the first time that anyone on the team had done high rise design at this scale. It was completely new. Some very exciting discoveries were made. The first being the beauty of structural art. The models that were in sketches and computer models were actually constructible by hand and made for amazing objects to look at and marvel at. This structural rationalism gave a comfort of the design and a freedom that the team had not experienced before. It seems as though the clarity of the structural system in a piece of architecture adds to its beauty. That somehow subconsciously the human population sees structure and associates it with comfort and beauty. The second discovery is more technical, and that is that aspect ratio and bending stiffness of a tower are primarily the predictors of the displacement at the top of the tower. For the most part if the aspect ratio of the tower was above 9, the team had a tough time making the models made in ETABS work for serviceability or drift. This was found to have the most change when changing column size. A larger column gave the tower a higher moment of inertia and thus more bending stiffness. Third, working alongside architects, instead of from a distance and separately proves to provide the most interesting projects and the best of both worlds. This is truly the best way to work and will certainly result in responsibly designed projects.

Reflection and Lessons Learned:

WA: In my time at Cal Poly San Luis Obispo, I have never worked with a more driven and creative team of individuals. All of us worked tirelessly on this project and wanted this amazing end result that you see before you. I am truly proud of this project which is not something to be said about all of the projects I have worked on. This way of working with architects and getting to experiment in their world is the best way to do things. The architects grow in their structural knowledge and the engineers grow in their architectural thinking. It's enjoyable to see what the amazing creative minds of architects come up with and even more rewarding to make their dreams come true with a sprinkle of the structural engineer to nudge them in the right direction. I started off this studio running into a dark tunnel of the unknown and slowly learned and developed into the light. I learned how to use ETABS which is a completely new skill and also how to represent my structural findings. I got to see my classes in building systems really come alive within a skyscraper. I thank SOM, Kevin Dong, and Tom Fowler for their dedication to my personal learning and the studio as a whole.

MS: This studio has pushed me to do things I never thought I would be able to. I have learned many new skills both technical and collaborative. With all the structural studies in Risa and ETABS, I learned how to take a complex building form and simplify it to predict its behavior while also verifying those results through simple hand calculations. From working with my teammates, I learned how talented they are and the work they do is truly amazing. I loved this collaborative process and really enjoyed getting to work alongside architects. From the many reviews from SOM I learned how important it is for every decision to have a reason behind the "why" which comes from the site, the people inhabiting the building, and the surrounding environment. Thank you to all those involved in this project at SOM, professors: Kevin Dong and Tom Fowler, and my teammates: Will Adam, Ellie Zukowski, and Max Heintz for your dedication and hard work these past 20 weeks.

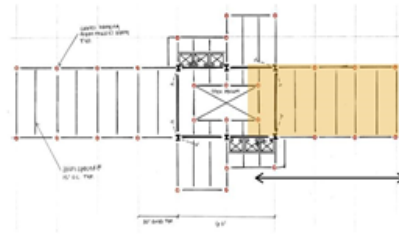
Appendix

Study No.1 Hand Calc Spreadsheet

Calculations

Input Variables

Wind load	w	2.1	k/ft
Mod. Of Elasticity, Steel	E	29000	Ksi
Distance btwn Cols	D	80	Ft
1/2 the distance between the cols	d	40	Ft
Total Height of Bldg	H	750	Ft
Angle of braces	θ	32.01	Deg
Average Shear	Vavg	787.5	K
# of Levels Bracing is spaced at		15	
Truss Depth (or Level height)		50	ft
Brace Diagonal Length		94.3	



Assumptions:
 Service Load (0.6W) = 20 psf wind load
 Core short side it taking ~100' trib area
 W = 2.1 k/ft or P = 105k at every joint

Column Area

Building Height (ft)	Deflection Limit, Δ (h/500)	$I_{req'd} = wH^4/\Delta 8E$	$A_{req'd} = I_{req'd}/2d^2$ (ft ²)	(in ²)	#' x #' col size	
750	16	14917	ft ⁴	5	671	2.2

**Max WF shape area ~ W14x873 = 257 in²
 W36x925 = 272 in²

Shear Deflection (w/ Vavg) base on Brace Size

Brace Area (in ²)	Shear Deflection (in)
215	1.988

**Max HSS shape area ~ HSS22x22x7/8 = 67.3 in²

Flexural and Shear Deflection per Floor

Total deflection	Flexural deflection	Shear Deflection
17.99	16.00	1.99
Percentage:	88.9%	11.1%