High Rise – An Exploration of Structural Systems in Tall Buildings

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Abstract

This report summarizes the exploration of tall buildings completed as an interdisciplinary senior project through the Architectural Engineering department at California Polytechnic State University. The project focused on the structural behavior of various lateral systems in tall buildings while considering architectural form and typology. The project was conducted under the advising of Kevin Dong and took place during winter and spring quarter of 2021.

Background

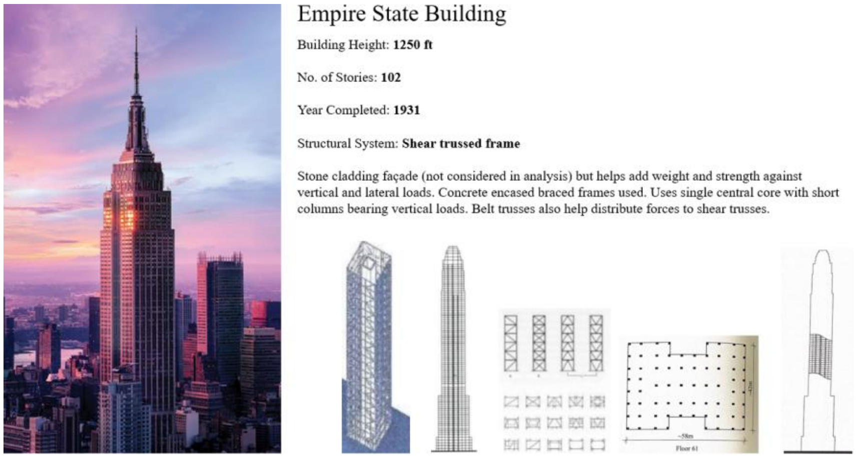
Having been intrigued by tall buildings since my youth, I wanted to further explore the systems involved in high rise buildings and the approach to design. The goal of this independent study was to gain an understanding of the various gravity and lateral systems and their behavior in tall buildings. This involved an in-depth examination of many case studies that influenced which lateral systems would be further explored through research and parametric studies. The building form and typology was adapted from the design by Cal Poly students Katelyn Smith, Weilu Pan and Chad Miller as part of the high-rise collaborative studio in 2020.

Three common lateral systems were chosen to be examined individually. These systems were 1) a concrete core, 2) outriggers, and 3) a diagrid. For each system, certain parameters were changed through several iterations to observe the differences and draw conclusions from them.

Case Studies

Before diving straight into the systems that would be studied, roughly three weeks were dedicated towards looking at case studies and precedents. The goal of this was to understand what types of systems were used in buildings of different heights. Super-tall buildings, or some of the tallest built structures, tended to use multiple lateral systems together or use a "mega" system where the cross-sections of the members in that system are incredibly large. For example, Taipei 101 *(Figure 5)* uses mega columns that are as large as 9ft x 9ft in cross section and are steel filled with concrete in addition to outriggers and a tuned mass damper. In Aspire Tower *(figure 2)* and HSB Turning Torso *(figure 3)*, a concrete mega core is used that can be up to 6ft in wall thickness.

A few of the case studies that were looked at are shown and summarized below:



Empire State Building

Building Height: **1250 ft**

No. of Stories: **102**

Year Completed: **1931**

Structural System: **Shear trussed frame**

Stone cladding façade (not considered in analysis) but helps add weight and strength against vertical and lateral loads. Concrete encased braced frames used. Uses single central core with short columns bearing vertical loads. Belt trusses also help distribute forces to shear trusses.

Figure 1 – Empire State Building Case Study

Aspire Tower

Building Height: **984 ft**

No. of Stories: **36**

Year Completed: **2006**

Structural System: **Mega core system**

Mega core acts as spine of building and resists all vertical and lateral loads. The core also supports the cantilevered modules (each module has several floors buttressed at the bottom floor of each module). The mega core has a varying diameter across the height of the building and is constructed of reinforced concrete. Part of the façade is permeable such that the across-wind effect due to vortex shredding is reduced.

Figure 2 – Aspire Tower Case Study

HSB Turning Torso

Building Height: **623 ft**

No. of Stories: **57**

Year Completed: **2005**

Structural System: **Mega core**

Central mega core with (9) 5-story modules, each with a pentagonal floor shape and rotated from the module below. Mega core supports all the vertical and lateral loads. It uses reinforced concrete as a shear wall with circular cross section and wall thicknesses varying across the height of the building. Discontinuous columns support floors with the bottom floor of each module being a strengthened reinforced concrete slab that supports the discontinuous columns. A concrete column follows the rotation of the building on the exterior and helps to reduce drift.

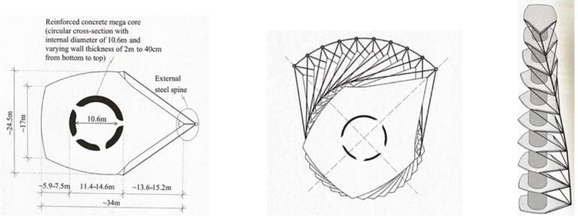


Figure 3 – HSB Turning Torso Case Study

Burj Khalifa

Building Height: **2717 ft**

No. of Stories: **163**

Year Completed: **2010**

Structural System: **Outriggers / buttressed core system**

Appears like bundled modules at different levels but is NOT a bundled tube system (no tubular structure to it). Reduction in floor area across height of building reduces the wind forces at upper levels (less surface area for wind). Location, number, and height of offsets were determined through wind tunnel tests. The offsets help break the up the organization of the wind flow.
Hexagonal central core buttressed with shear walls in each "wing." Outriggers connect the core to the perimeter shear walls. Maximum lateral drift at top was set to 47 inches. The upper part of the building uses steel braces connected to the core.

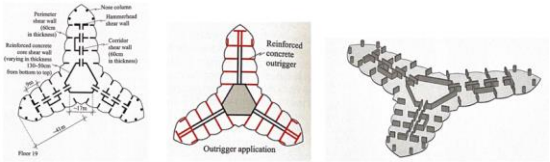


Figure 4 – Burj Khalifa Case Study

Taipei 101

Building Height: **1667 ft**

No. of Stories: **101**

Year Completed: **2004**

Structural System: **Outrigger frame system**

Form inspired by form of bamboo. Setbacks and saw-tooth corners help break up wind and reduce base moment by 25%. All columns are composite. Perimeter mega columns and columns around the core are box-section filled with concrete. Perimeter columns and core columns are connected through outriggers at each module (wherever the building has an offset). Outriggers are 1-2 stories deep. Due to high winds (as much as 97mph) and seismic region, a 730-ton tuned mass damper is used near top of building.

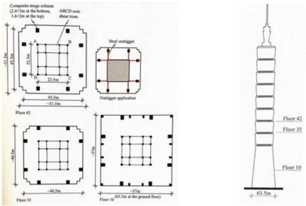


Figure 5 – Taipai 101 Case Study

The Site

The location for this building is in Seattle. This site is an open lot for sale near the heart of downtown and was chosen because Seattle is seismically active and wind is also a prevalent factor in the lateral loading.

Figure 6 – Building location in Seattle WA.

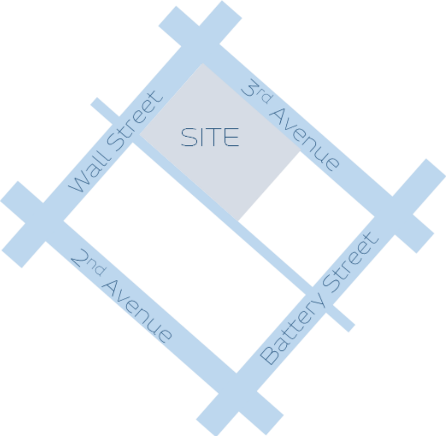


Figure 7 – Plan view map of site in Seattle, WA.

Design Philosophy

Choice of Material:

Steel was chosen as the primary material. This was because I was more comfortable with designing and estimating steel member sizes using steel than with concrete or composite. In reality, many tall buildings are designed compositely, often with concrete encased in steel. The gravity framing used typical wide flange sections for beams and columns and the core system (which took both gravity and lateral loads) used reinforced concrete.

Code References:

The challenge of designing tall buildings is that the typical building codes don't explicitly apply. For example, the procedure for wind loading per ASCE 7-16 (directional procedure) can be a poor estimate of the actual wind pressures on the building. It is highly recommended that wind tunnel testing is done to estimate these pressures. Wind tunnel testing also helps account for any additional pressures or unique wind patterns caused by nearby structures which can be a major issue.

The directional procedure (ASCE 7-16, Ch. 27) is used in this project. The National Building Code of Canada (NBCC) has a different procedure for determining the wind pressures on tall buildings and was looked at as a comparison. The NBCC defines a building as *dynamically sensitive* if the height is over 60 meters and thus requires a dynamic procedure for finding the wind pressures. This procedure is much more complicated and involves factors such as fluctuation rate, turbulence, damping, and natural frequency of vibration. It is also recommended that wind tunnel testing be conducted for buildings classified as dynamically sensitive.

Gravity System

Assumed Loading:

For this project, it was assumed that the occupancy would be residential, giving a live loading of 40 pounds per square foot. A dead load take-off was performed to determine the gravity loading as shown below.

Gravity Loading - Dead Load Take-off

Inputs	
Location	[242 3RD Ave, Seattle]()
No. of Stories	60
Occupancy	Residential

Typical Residential Floor (floors 2 through 60)

Item	Beams		Girders		Columns		Seismic	
3 1/4" LW Concrete infill over	46	psf	46	psf	46	psf	46	psf
W3x18Ga. Verco Metal Decking	3	psf	3	psf	3	psf	3	psf
WF Beams	3	psf	3	psf	3	psf	3	psf
WF Girders	-	psf	3	psf	3	psf	3	psf
WF Columns	-	psf	-	psf	3	psf	3	psf
Lateral System	-	psf	-	psf	4	psf	4	psf
Fireproofing	2	psf	2	psf	2	psf	2	psf
Mechanical	5	psf	3	psf	3	psf	3	psf
Ceiling/Lighting	3	psf	3	psf	3	psf	3	psf
7/8" Hardwood Flooring	4	psf	4	psf	4	psf	4	psf
Subtotal	66	psf	67	psf	74	psf	74	psf
Miscellaneous (5-7% subtotal)	4	psf	4	psf	4	psf	4	psf
TOTAL	70	psf	71	psf	78	psf	78	psf

Figure 8 – Dead Load Take-off

Framing:

The gravity framing was considered through several schematics. The framing layout could change based on each lateral system used. Initially, it was thought that two cores would be examined. Ultimately, only one single core was used, and the steel framing had to align with the concrete core. The diagrid system changed the layout due to there being no vertical columns around the perimeter and instead the diagonal members took both the lateral and gravity loads.

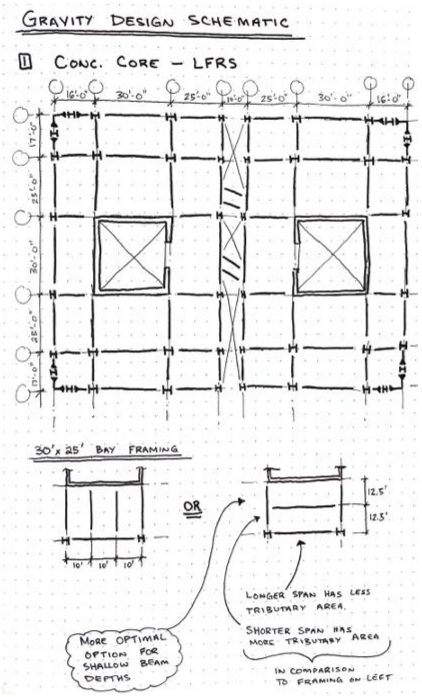


Figure 9 – Initial Schematic for Gravity Framing

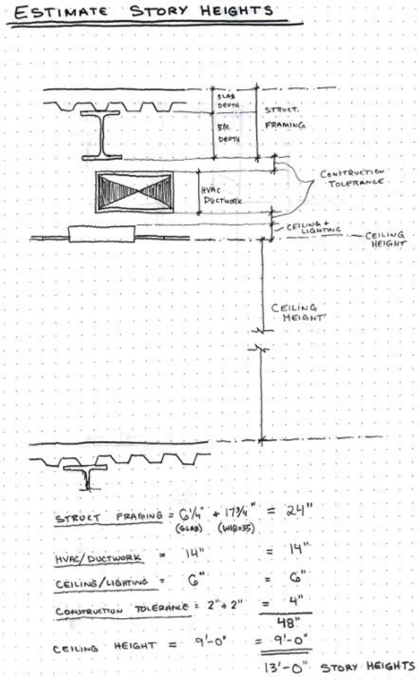


Figure 10 – Story Heights Determination

Story Heights:

The story heights and overall height of the structure were based on the design of a typical steel beam. Story heights were then calculated from the structural framing, mechanical requirements, lighting, and added construction tolerances. The resulting residential story height was 13ft assuming a 9ft ceiling height. It was decided that the bottom story would be 5ft taller to provide a large lobby and entrance to the structure, giving the building a total height of 785ft.

Axial Shortening:

The concept of axial shortening presents a major issue in high rise buildings. The gravity loads increase exponentially from the roof down to the ground. These huge axial loads can result in shortening of vertical members. Steel, concrete, and composite sections are all susceptible to this and special consideration must be made to ensure the effects of axial shortening are not too large. If not properly considered, the whole structure can have large deformations (as much as several inches) and affect both structural and nonstructural components.

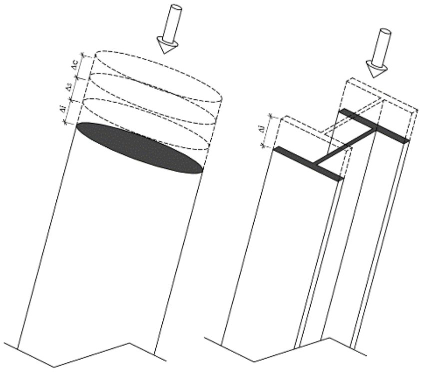


Figure 11 – Axial Shortening Illustration for Concrete and Steel
Image Source: BSB Group, Axial Shortening of Columns in Tall Buildings, 2019

Lateral Loading

Wind vs. Seismic

Due to the region, both wind and seismic loading needed to be considered. As noted earlier, the wind pressures were estimated through the Directional Procedure of ASCE 7-16. Additionally, the Equivalent Lateral Force Procedure of ASCE 7-16 was used for the seismic loading. A graph is shown below of the story shears comparing the wind and seismic story shears.

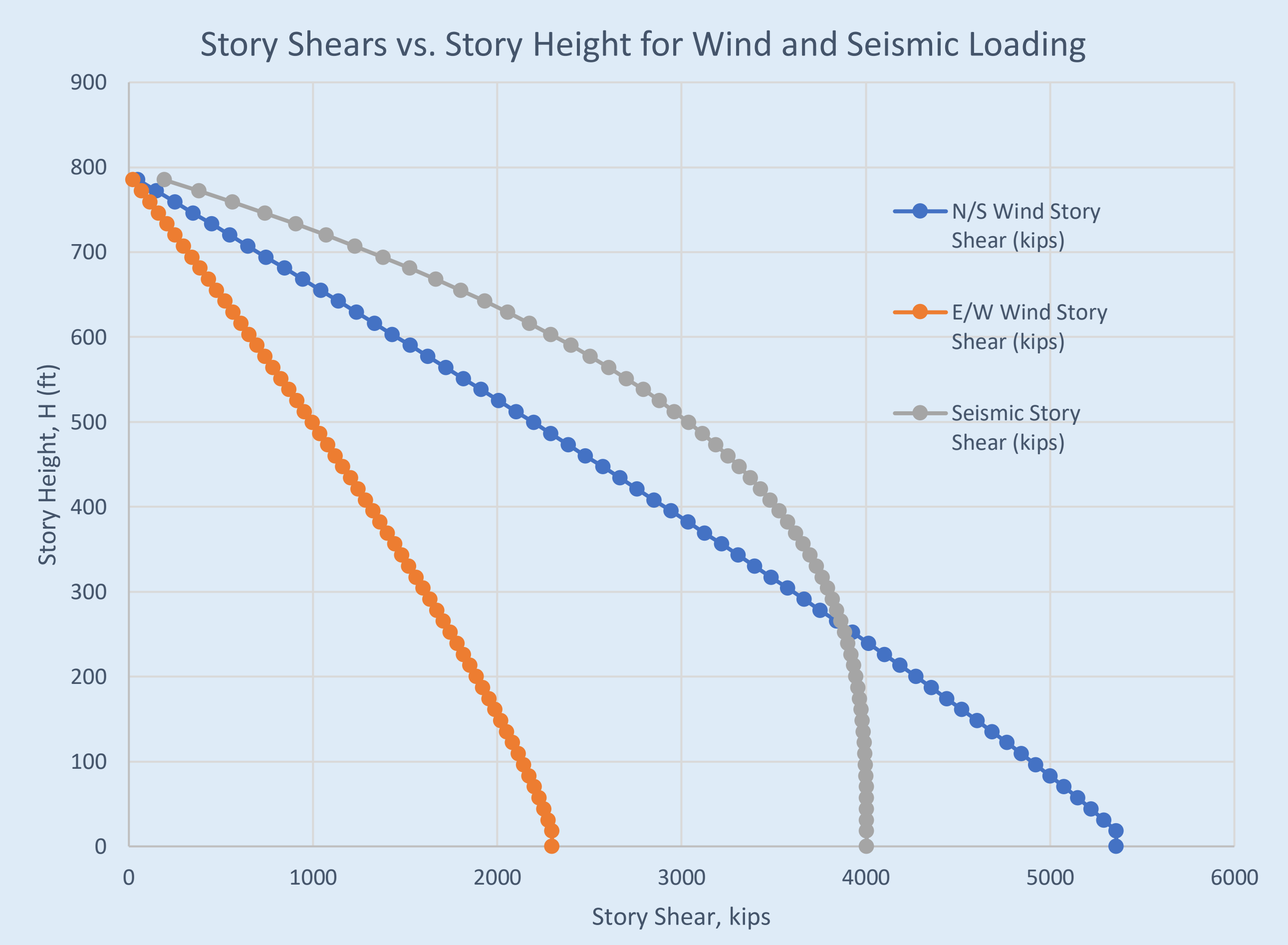


Figure 12 – Story Shears for Wind and Seismic Loads

As seen above, the base shear due to wind in the north/south direction governs over the seismic base shear. Interestingly, the story shears and story forces due to seismic are actually higher than those for wind near the top of the building. For this project, the wind was taken as the governing case, although in reality seismic story forces govern in some locations.

Wind Loading Parameters:

WIND LOADING PARAMETERS				
Parameter				**Reference**
Risk Category	RISK	III		ASCE 7-16, Table 1.5-1
Basic Wind Speed	V =	104	mph	ASCE Wind Hazard
Wind Directionality	K_d =	0.85		ASCE 7-16, § 26.6
Building Exposure	EXPOSURE	C		ASCE 7-16, § 26.7
Topographic Factor	K_{zt} =	1		ASCE 7-16, § 26.8
Ground Elev. Factor	K_e =	1		ASCE 7-16, § 26.9
Gust Effect Factor	G =	0.85		ASCE 7-16, § 26.11
Internal Pressure	GC_{pi} =	0.18		ASCE 7-16, § 26.13
External Pressure (Windward)	C_p =	0.8		ASCE 7-16, Fig. 27.3-1
External Pressure (Leeward)	C_p =	0.5		ASCE 7-16, Fig. 27.3-2
Building Height	h =	785	ft	
Story Height	h_{STORY} =	13	ft	
Dim // to Wind	L =	114	ft	
Dim ⊥ to Wind	B =	152	ft	
Height	z_g =	900	ft	ASCE 7-16, Table 26.11-1
Factor	α =	9.5		ASCE 7-16, Table 26.11-2

Figure 13 – Parameters for Wind Loading in N/S Direction

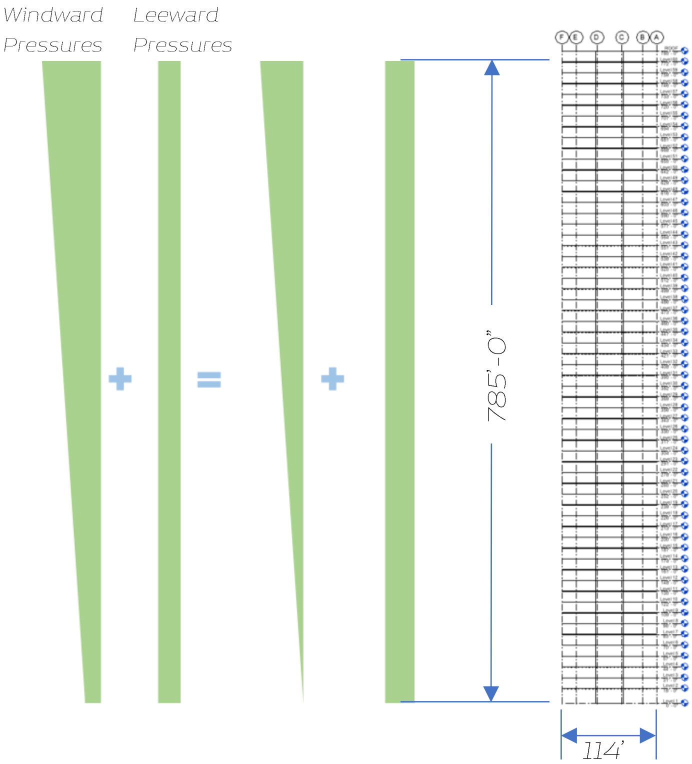


Figure 14 - Wind N/S direction pressures. Windward and leeward pressures combined to form a uniform pressure and triangular pressure.

Seismic Loading Parameters:

EARTHQUAKE LOADING PARAMETERS				
Parameter				**Reference**
Seismic Design Category	SDC =	D		ASCE 7-16, § 11.5
Response Modification, Special Reinf. Conc. Shear Wall	R =	5		ASCE 7-16, Table 12.2-2
Importance Factor	I_e =	1.25		ASCE 7-16, Table 1.5-2
0.2s Design spectral accel.	S_{DS} =	1.11	g	SEAOC Design Maps
1s Design spectral accel.	S_{D1} =	0.585	g	SEAOC Design Maps
1s MCE_R ground motion	S_1 =	0.484	g	SEAOC Design Maps
Long period transition period	T_L =	6	sec	SEAOC Design Maps
Approx. Period parameter	C_t =	0.02		ASCE 7-16, Table 12.8-2
Structural height	h_n =	785	ft	
Approx. Period parameter	x =	0.75		ASCE 7-16, Table 12.8-2
Approx. Period, $T_a = C_t h_n^x$	T_a =	2.97	sec	ASCE 7-16, § 12.8.2.1
Seismic Response Coefficient, $C_s = S_{DS}/(R/I_e)$	C_s =	0.278		ASCE 7-16, § 12.8.1.1
C_s need not exceed:				
For $T_a \le T_L$ $C_s = S_{D1}/T_a(R/I_e)$	C_s =	0.049		ASCE 7-16, 12.8-3
For $T_a > T_L$ $C_s = (S_{D1})(T_L)/(T_a)^2(R/I_e)$	C_s =	N/A		ASCE 7-16, 12.8-4
C_s shall not be less than:				
$C_s = 0.044 S_{DS} I_e \ge 0.01$	C_s =	0.061		ASCE 7-16, 12.8-5
If $S_1 \ge 0.6g$, Cs not less than:				
$C_s = 0.5 S_1/(R/I_e)$	C_s =	N/A		ASCE 7-16, 12.8-6
Final C_s value	C_s =	0.049		
Effective Seismic Weight	W =	81095	kips	
Seismic Base Shear $V = C_s W$	V =	**4005**	**kips**	ASCE 7-16, 12.8-1

Figure 15 – Parameters for Seismic Loading and Base Shear

Other Effects of Wind:

Vortex shedding is a major concern in tall buildings and depends on the shape and form of the building. As shown below, the shape of the building largely affects whether there is large or small amounts of vortex shredding and crosswind movement.

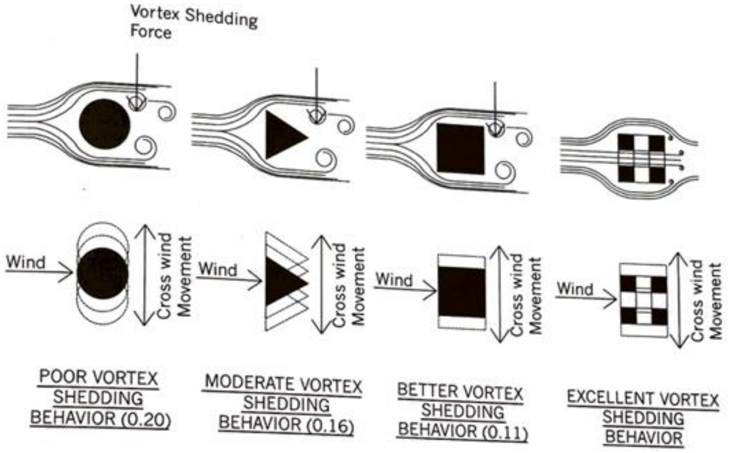


Figure 16 – Graphic Illustration of Vortex Shedding and Effects of Wind.

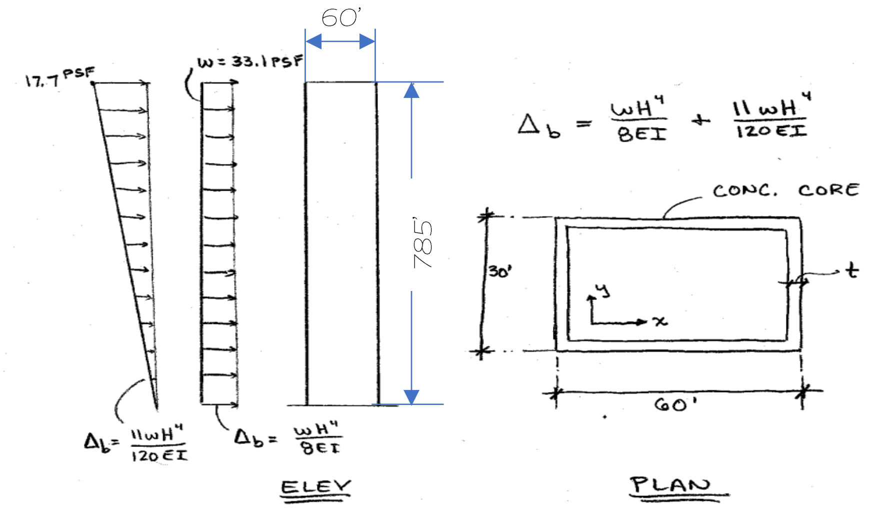
Lateral Systems – Overview

Three lateral systems were chosen to be studied through research and computer modeling by parametric studies. Observations were made in the behavior of each system and how changing parameters affect the deflections, moments in the core, and axial forces in various members.

The lateral load distribution was assumed as a distributed load broken up into a uniform load and a triangular load. For models in SAP2000, these loads were distributed into singular forces at 10-story modules. For models in ETABS, the actual story forces based on tributary area were calculated and applied at every story.

Concrete Core

The first system explored looked at a reinforced concrete core at the center of the building. It was idealized as a "tube" cross section neglecting openings for doors at each floor. It also assumed a constant wall thickness up the height of the building.



Aspect Ratios:

Weak Direction:

H/L = 785'/30' = ***26.17***

Strong Direction:

H/L = 785'/60' = ***13.1***

Figure 17 – Assumed loading and configuration for core study.

A 30ft by 60ft configuration in plan view was developed and looked at for bending deflection. For a tall building, bending deflection of the core is considerably larger than the shear deflection. For bending about the weak axis, the shear deflection is only 0.5% of the total bending deflection for a 36" wall thickness. For this reason, shear deflection was ignored and the deflection at the roof due to bending was analyzed.

A study was done looking at the thickness of the core walls to find at what thickness would the core best reduce the deflections to within the allowable limit *(Figure 18)*. The allowable limit for deflection was 18.84 inches based on H/500, where H is the total height of the building (785ft). The results are shown in *Figure*

18 below and it can be seen that the core system alone is not able to limit the deflections to within the allowable limit.

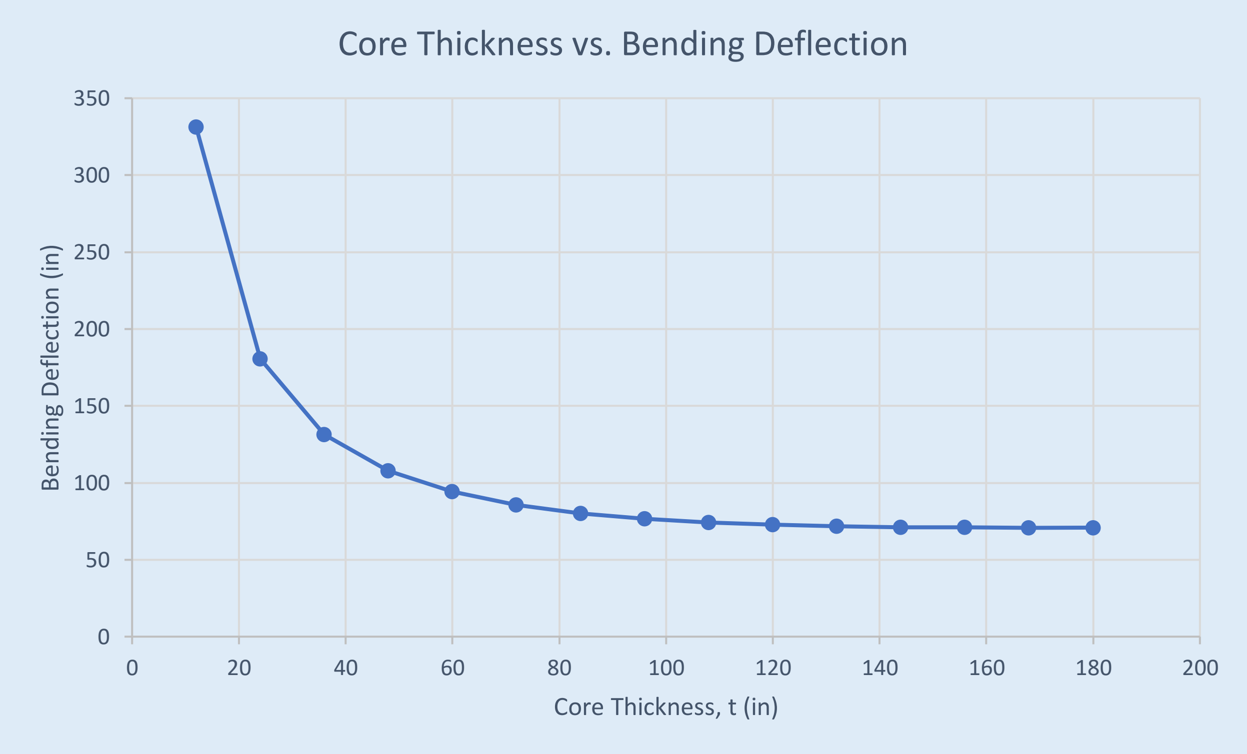


Figure 18 – Concrete Core Study Bending Deflection Parametric Study

Since the bending deflection was considerably higher than the allowable, a separate study examined various structural heights and their corresponding deflections. Assuming the same loading and deflection criteria of H/500, a 36" thick core wall that measured 30ft by 60ft was compared for a variety of heights. The results show that past about 400ft, or roughly 30 stories, the core system alone was no longer efficient or capable of resisting the bending deflection under the assumed wind loading. Assuming the same building widths, because only the height is changing, the aspect ratios will decrease. At 400ft, the aspect ratios are 6.67 and 13.33 (where H=400ft and L = 60ft or 30ft depending on direction). Compared to an aspect ratio of 13.1 and 26.17 for H=785ft, some conclusions can be drawn about the efficiency of limiting deflections when aspect ratios are so large. This observation was important to note because the outrigger and diagrid systems had decreased aspect ratios when the width (L) was increased to the full width of the building.

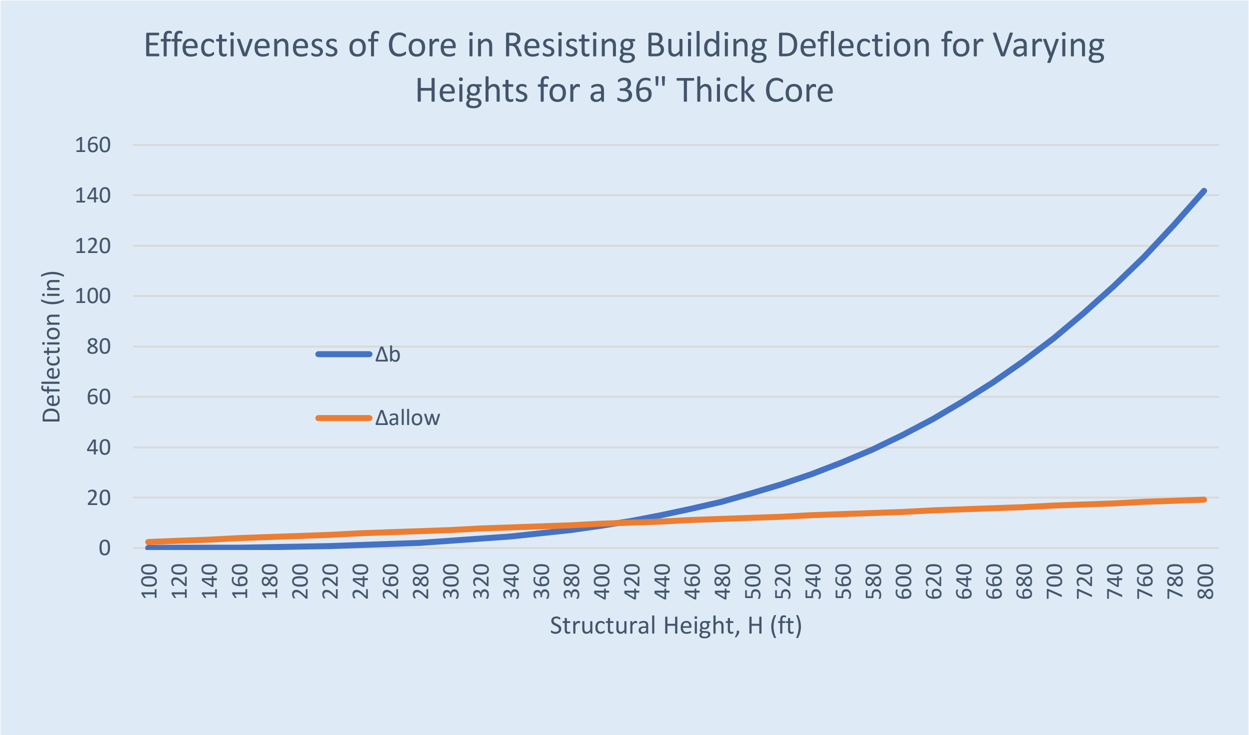
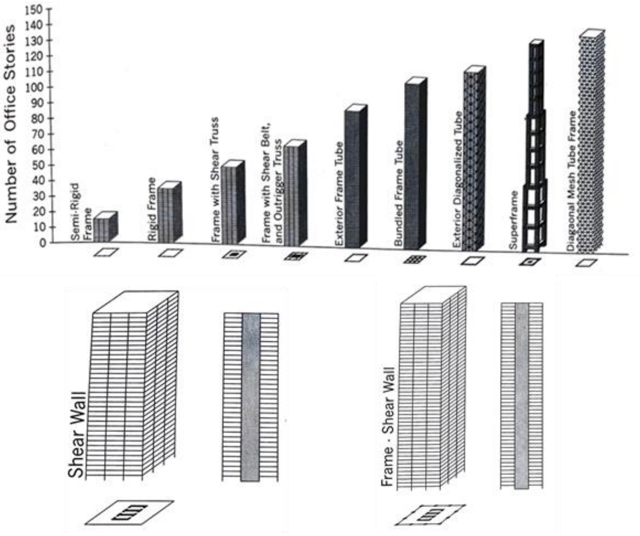


Figure 19 – Examination of the effectiveness of the core system for various heights.



Structural Limit:

~35 stories or 376ft

Structural Limit:

~50 stories or 534ft

Figure 20 – Suggested Structural Height Limits for Core Systems.

The results from the study done and summarized in *Figure 19* is consistent with recommendations for structural limits of core systems in buildings *(Figure 20)*. In the figures above, the structural limit is about 35 to 50 stories. In the figure on the right, a perimeter "tube" of continuous columns help transfer the lateral loading and reduce deflections, resulting in slightly higher height limitations.

Outrigger System

The outrigger system uses outriggers, or horizontal members “reaching” out to vertical columns, to stabilize the structure and increase the aspect ratios from the very slender core. The outriggers act like the arms of a skier and the vertical columns act like ski poles pinned at the ground. These outriggers help transfer the lateral loads in the core to the perimeter columns through a tension/compression force couple.

A belt truss is commonly used with outriggers to engage all the perimeter columns. The outriggers only engage the columns they are connected to. A belt truss provides a closed “loop” or “tube” attached to all perimeter columns and helps transfer the forces in the outriggers to all the columns around the perimeter.

A parametric study was run considering various locations of outriggers along the height of the building. Some of the configurations are shown in *Figure 22*.

Figure 21 – Illustration of Outrigger System.

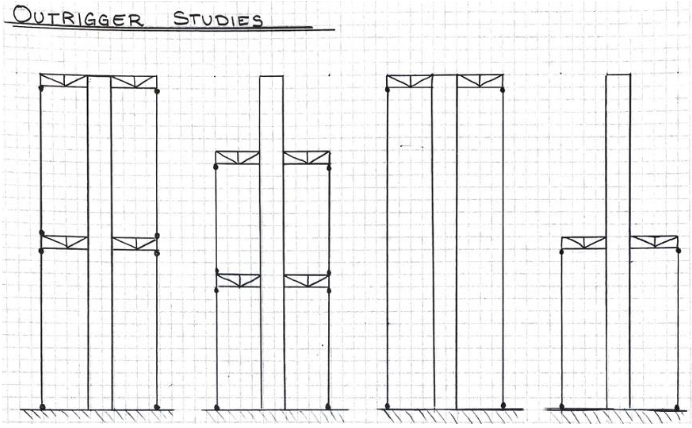
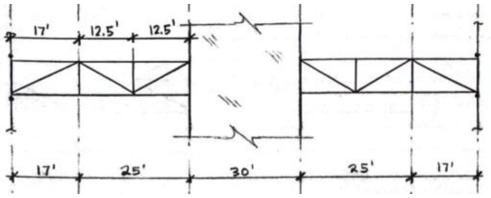
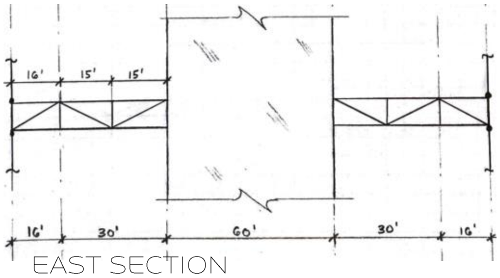


Figure 22 – Outrigger Configurations



NORTH SECTION



EAST SECTION

A single outrigger was compared to two outriggers in their ability to reduce deflection at the roof, moments in the core, and axial forces in the columns.

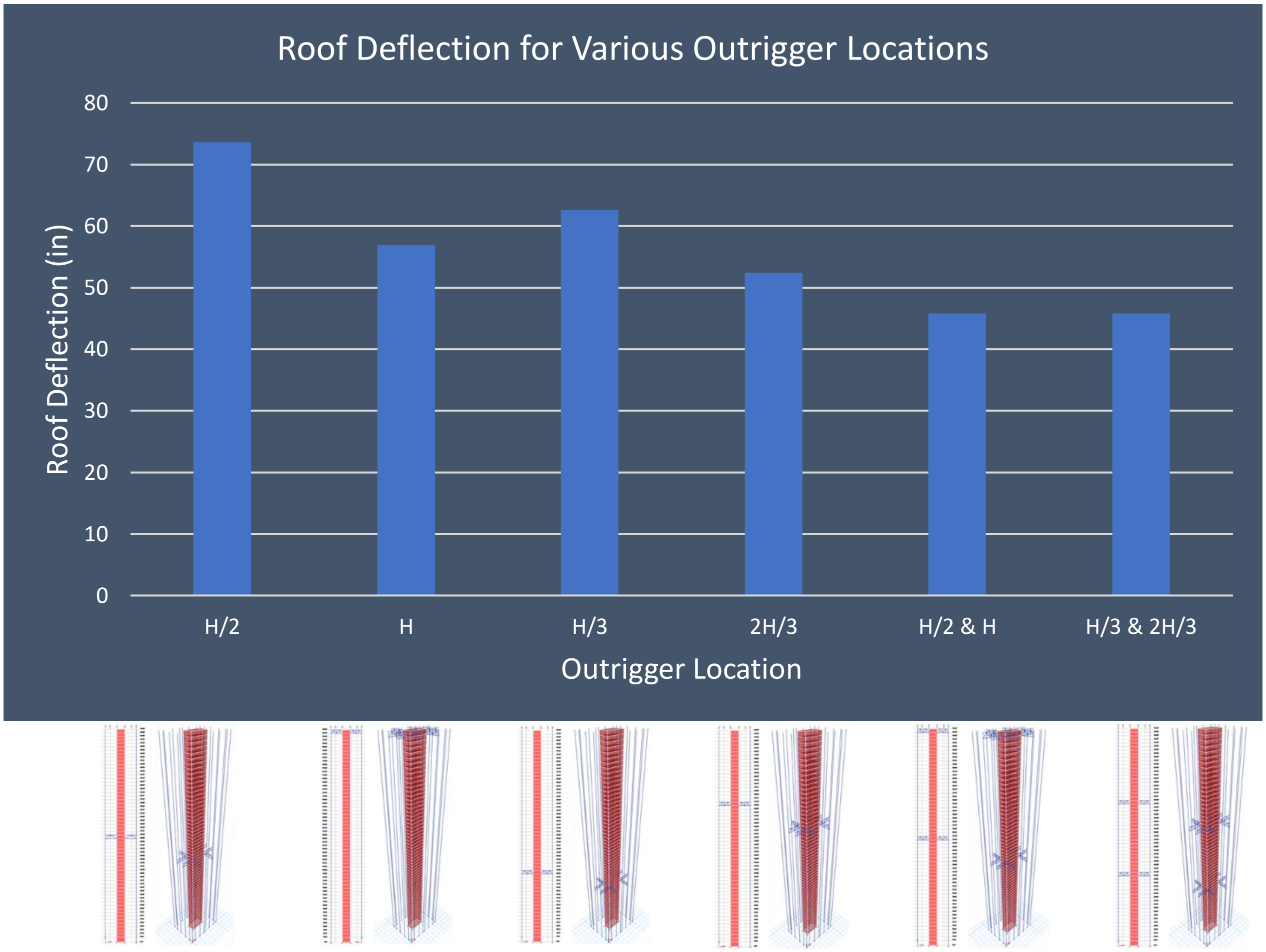


Figure 23 – Comparison of Deflections at Roof for Different Outrigger Locations.

The configuration with two outriggers, each at thirds along the height of the building was the best at reducing deflection. It should also be noted that the moments in the core are reduced from the single core alone and the amount reduced depends on the location and number of outriggers used. This reduction in moment is carried by the tension/compression coupling force in the columns and is important to consider because these large axial forces contribute further to the axial shortening of columns. A comparison of these moments in the core and axial forces in the columns are shown below.

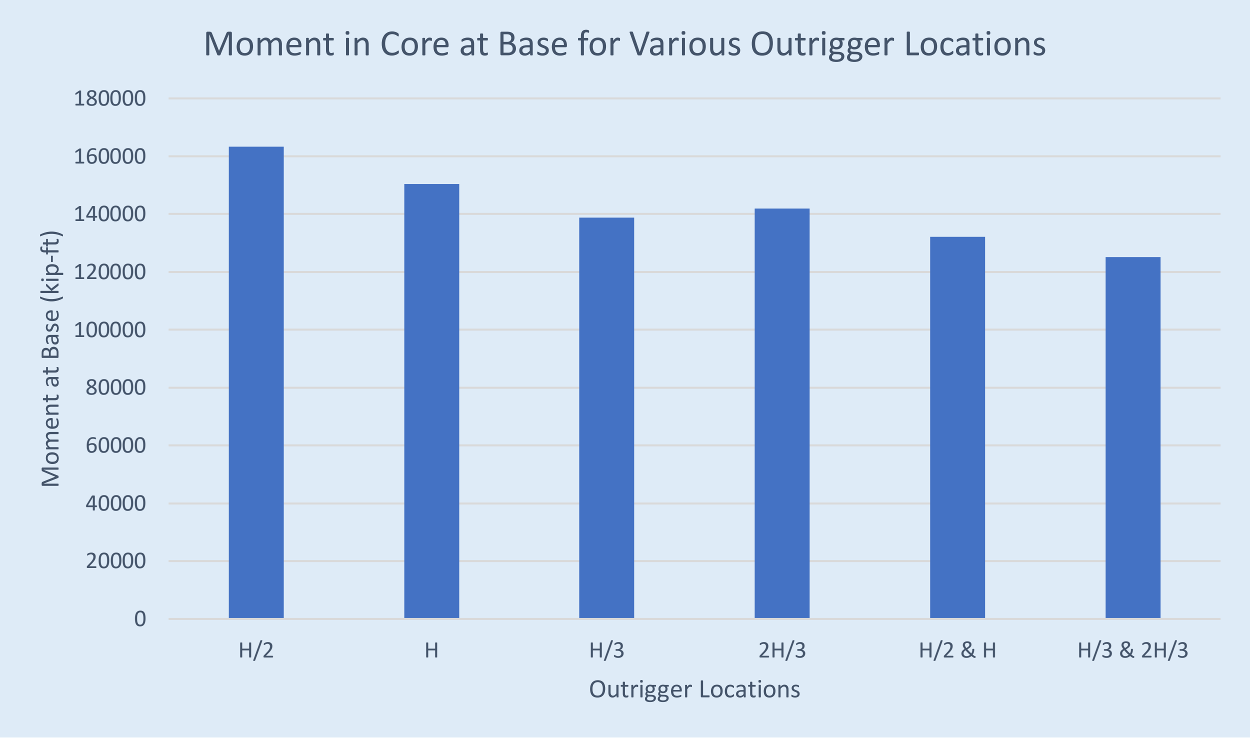


Figure 24 – Comparison of the Moments in the Concrete Core at the Base when Outriggers are Used.

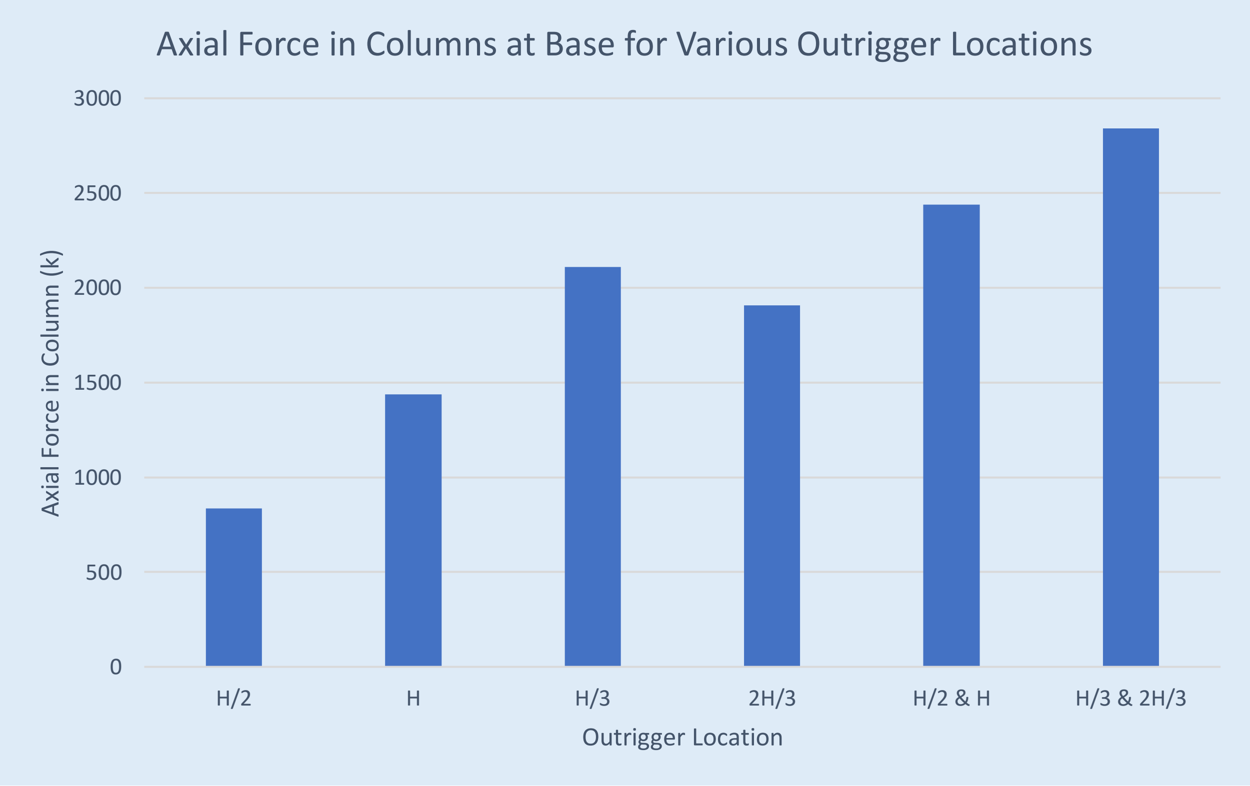


Figure 25 – Comparison of axial forces in columns at base engaged by outriggers.

Diagrid Studies

The diagrid was the last study to be conducted and looked at various configurations.

For tall buildings with aspect ratios of between 4:1 and 9:1, the optimum angle for braces is between 60 and 70 degrees. This optimum range has been determined through research by the Kyoung Sun Moon at Yale University looking at a 60-story building measuring 118ft by 118ft in plan. The study also found that the most effective angle in that range is 69 degrees. For the parametric study, this 69-degree angle was chosen and an angle of 52 degrees (slightly outside the optimum range) were chosen to compare. The number of diagonal members were also compared by changing the number of stories that each diagonal spanned between.

Configurations…

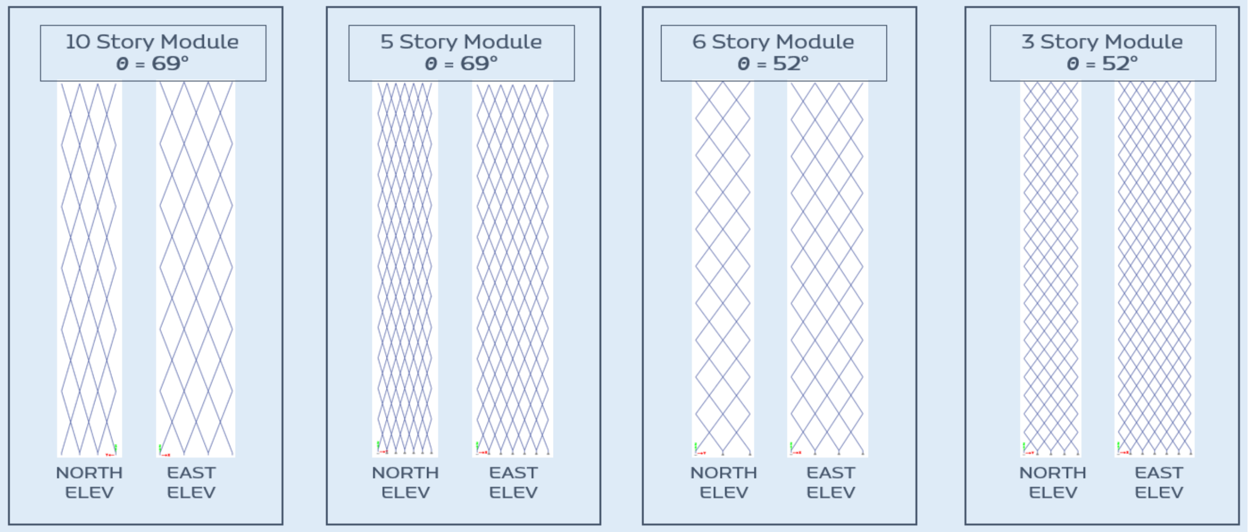


Figure 26 – Configurations for Diagrid Parametric Study.

Results:

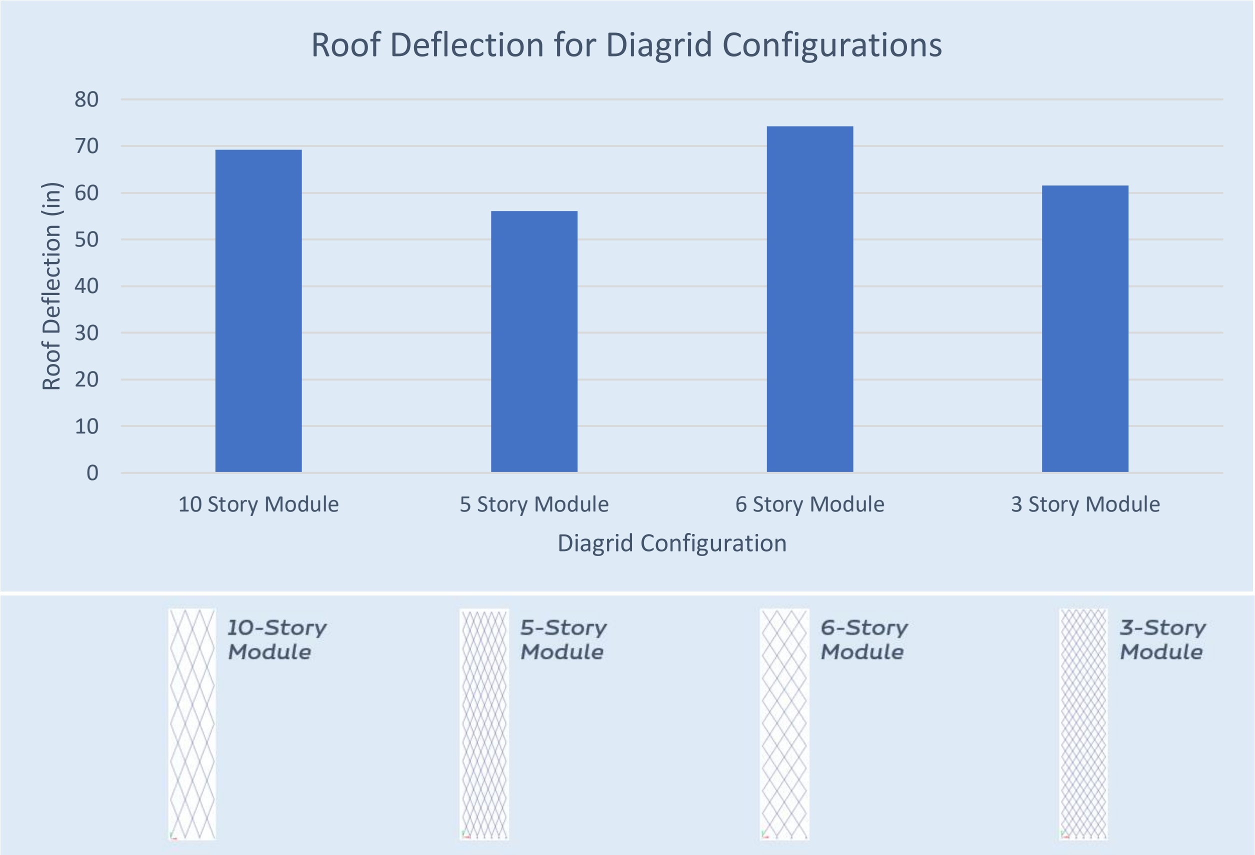


Figure 27 – Comparison of roof deflections for the 4 different diagrid configurations.

Lessons Learned

After studying the behavior of tall buildings, I learned many important takeaways.

1. High Rise is Complicated

   The systems in tall buildings can be very complicated and the scale of structural members can be drastically bigger than that which I was used to in low-rise buildings. The loading and behavior are rarely linear and require much more consideration. The lateral loading is dynamic, the gravity loading exponential, and all systems and structural members must work together to adequately transfer forces and limit deflections.

2. I know More than I realized.

   I was able to use rather simple analyses and concepts to determine the forces in members in these complicated systems. This was important to verify the results of computer output. It was also an important lesson to learn in taking the knowledge I have to apply to more complicated systems I haven't seen before.

3. Be Careful in Trusting Computer Programs

   An incredibly important lesson was in the trust and validity of computer programs. Especially for the scale of tall buildings and having never designed or analyzed them, it was difficult to decipher whether the forces in members were reasonable. Hand calculations were often performed to estimate the forces in members to prove that the computer model was accurate and output seemed reasonable.

4. Tall Buildings Require Several Connected Systems

   I studied several systems on their own to understand their behavior, however tall buildings often utilize many different systems together or even use "mega" systems, where the members are massive in scale.

Studying high rise was an interesting experience, incredibly informative, and always a surprise with the scale of forces, displacements, and members that were required.

Special thanks goes to Kevin for his expertise and knowledge that was shared throughout this project. I'm incredibly grateful for this experience and feel a more confident engineer as a result.

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