Massachusetts General Hospital - Building for the Third Century

Lateral System Analysis and Confirmation Design

55 Fruit Street
Boston, MA 02114

The Pennsylvania State University
Department of Architectural Engineering
Senior Thesis 2007-2008

November 21st 2008

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EXECUTIVE SUMMARY:

Purpose

This Lateral System Structural study of the Main Lateral Force Resisting System of the Massachusetts General Hospital project "The Building for the Third Century" provides information about the building response to both wind and seismic loads.

Building Description

The B3C hospital facility contains 530,000 square feet total including: 162,300 square feet of patient bed space, 45,900 square feet of mechanical, and 114,900 square feet of procedural space. The façade of the building is mostly glass. The main structural system consists of a steel moment frame with composite metal deck flooring. The columns transfer load through concrete load bearing elements to bedrock. The systems are being constructed in a manner which allows for fast track construction to ensure that the hospital will become operational in a timely manner.

Lateral System Check Conclusion

The lateral forces within the building are transmitted through the floor system which serves as a rigid diaphragm. The loads are distributed among the respective frames based on the stiffness of those frames. The lateral system was determined to be controlled by the wind moving in the north and south directions of the building. Aided by computer modeling, the lateral system was determined to be within allowable limits of drift. Uplift and overturning were not considered in this report due to the nature of the foundations being utilized on this project.

Massachusetts General Hospital –Building for the Third Century Pro-Con Structural Study of Alternate Flooring Systems

55 Fruit Street
Boston, MA 02114

INTRODUCTION

This comparative structural study of alternate flooring systems contains information about the existing floor system as well as three alternate floor systems. Flooring systems will be developed in a schematic manner but include calculations to determine preliminary sizes through checking stress and deflections. Comparisons of the systems will include: fire protection and rating, constructability, weight, deflections, architectural considerations, costs, and system depth.

BACKGROUND

The Building for the Third Century (B3C) project (Cover and Figure 1) is located at 55 Fruit Street in Boston, Massachusetts (Figure 2). The site of the present construction once held three outdated hospital buildings. The Clinics, Tilton and Vincent Burnham Kennedy Buildings were demolished in order for this project to move forward. Logically located at the center of the city, the hospital campus is able to serve over a million patients each year.

Construction of the ten story super structure and four subterranean levels is currently underway through an up-down construction process. B3C was designed for Massachusetts General Hospital (MGH) by NBBJ Architects of New York with the charge of bringing the hospital into its third century of existence. In order to bring this design into a functioning reality NBBJ enlisted the services of several technical firms including: Michael Van Valkenburgh Associates, Inc., Thompson Consultants, Inc., Engineered Solutions Inc., Mcnamara/Salvia, Inc., and Vanasse Hangen Brustlin Inc. Fast tracked construction is being coordinated by the experienced Turner Construction Company to ensure that the facility is operational in a timely manner.

Holding true to its charge the B3C design team has created a unique hospital facility which will improve the patient experience. Functions of the hospital lead to the design of the spaces in an efficiency and comfort driven environment. Lower levels of the building serve as the vehicle access areas such as the loading docks to supply the hospital and the ambulance dock to receive emergency cases. Floors three through four are utilized for procedural space including: general operating rooms (ORs), orthopedic ORs, and neurological ORs. Utilizing the fifth floor of the building for mechanical equipment allows for the roof space to be developed as a green space. Patient beds occupy the top five floors of the building, a short distance from a large Bamboo filled five-story atrium. The subterranean levels of the building house the sterile processing and radiation oncology departments. Housed in the lowest level of the hospital are eight linear accelerators used for cancer treatment.

Structural System Overview

The structural system overview section of this report will focus on all of the main structural features of the building. Discussion of these systems will provide supporting material for the subsequent discussion of the alternate flooring systems. The features to be discussed include: general floor framing, structural slabs, the lateral force resisting system, foundation system, secondary structural systems, the exterior envelope, and expansion joints. An understanding of the interaction of these building components will allow for deeper study of specific components of the system.

General Floor Framing – The main framing type for this building is a composite steel frame with beams transferring load to girders and girders to columns. The system is constructed of mostly W shapes whose strengths may be found in Appendix C. Most of the connections in the system are simple or shear connections however the main lateral force resisting system consists of a moment frame, which will be discussed later. Beams commonly have 30ft spans in the building but there are spans of up to 42ft. Floor heights vary between 14ft and 30ft. Column splices commonly occur at 4ft above the floor level of the splice. This framing system necessarily holds up the structural slabs of the building which are discussed next.

Structural Slabs – Superstructure levels of the hospital are designed with a composite steel floor system which allow for lesser depths of the W-shapes used in the frame of the building. Another important function of the floor system is to provide a rigid diaphragm for transmittal of the lateral loads of the building to the main lateral force resisting system in the building, a perimeter moment frame. Four levels of this hospital facility are subterranean on the site and play an interesting part in the construction process of the building. The structural slabs of the basement levels are flat slabs supported by the steel columns of the building and drop panels. The slab thickness is 14 inches in most areas and an additional 8 inches is employed for the drop panel areas of the slab. Material strengths of the concrete and the reinforcement utilized in these structural slabs have been documented in Appendix D. The construction of this hospital has been fast tracked, due to its obvious importance, and these structural slabs play an important role in the up-down construction process being utilized on this site.

Main Lateral Force Resisting System – As previously described, the main lateral force resisting system is based on a moment frame. Columns set approximately 10ft inside the perimeter of the slabs, on floors 1-10, make up the moment frame. This system wraps around the building on all sides, as is portrayed in Figure 3. The member strengths of this moment frame may also be found on Appendix D. The lateral system will be discussed in greater detail later in this report.

Foundation System – There are several important parts to the foundation system including: a slurry wall, load bearing elements, and caissons. Describing these components in order of construction will be beneficial in describing the construction process being used on this fast track site. The first element of the foundation system is a 30 inch thick slurry wall. The perimeter of the building was excavated to bed-rock for bearing and then reinforcing steel cages were lowered into the slurry filled holes. Concrete is then pumped into the hole while the slurry is removed. These walls resist the soil pressures presented by solids and the water table. Excavation for the Load Bearing Elements (LBEs) was completed simultaneously with the slurry wall excavation. These LBEs support the majority of the gravity loading of the building. Thus the columns imbedded in the LBEs are vital to the structural integrity of the hospital. Those columns reach from the lowest basement level floor to the first floor when they are placed. This column and slurry wall layout allows for "Up – Down" Construction to take place. This construction method calls for a crew to be working under ground to excavate under the floor slabs and the steel crew to be setting steel going up. A diagram of the Up-Down process is presented in Figure 7 of Appendix A. Caissons also play an important role in the structural support of the building. The caissons carry the load of the massive shielding walls needed for the use of the Linear Accelerators used to create radiation for cancer treatment. All of the material used in the foundations elements can be found in Appendix D.

Other structural considerations that will need to be made later on are the lateral soil loads that the slurry walls will have to withstand after the lower levels have been excavated. Also the water table is high in this area, due to its proximity to the river, which will necessitate consideration of uplift on the structure.

Secondary Structural Systems – In order to create a more connected atmosphere within the hospital campus bridges are being constructed to a few of the nearby buildings. The Yawkey Center for Outpatient care and the Wang Ambulatory Care Center will be the buildings connected to. This requires creating a structure that will not transfer loads from the new building to the older buildings. These bridges are framed with large W shapes, have concrete on metal deck flooring, and glass facades.

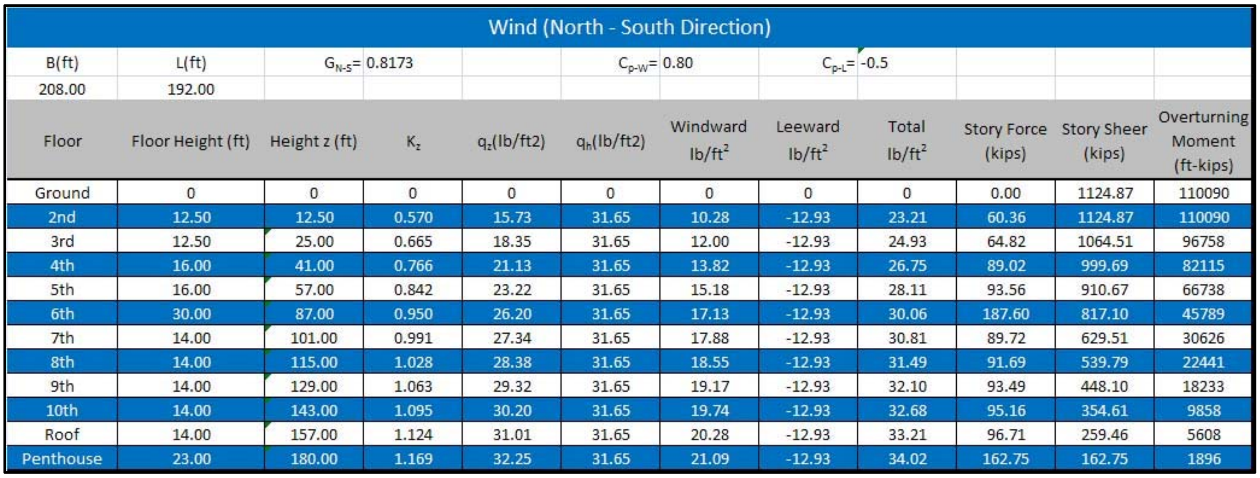
There is also a canopy located at the entrance of the building which was designed to resist wind and snow loading.

Exterior Envelope – The façade of the B3C project is designed to let in maximum amounts of natural light and thus is composed of mostly glass. The curtain wall system is hung from embedded mounts at each floor level. This allows the lateral loads to be transferred directly into the composite floor and eventually to the moment frame serving as the main lateral force resisting system. The curtain wall system also plays an important role in the environmental control in the building but its structural significance is lateral load transmission. Again this transmission is represented in Figure 4. This system is how the building meets the wind, how the building meets other buildings will be discussed next.

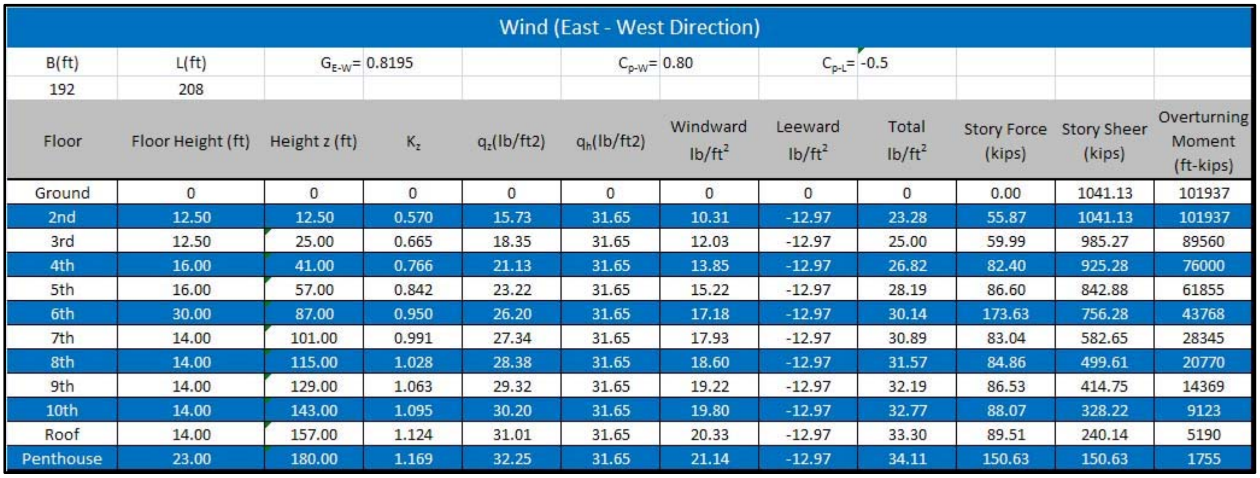
Expansion Joints – The building itself does not have any notable expansion joints causing the need for internal load separation but there are important expansion joints between the B3C and other adjacent buildings. Buildings close enough to require expansion joints are Ellison and White. The materials most commonly used in the expansion joints are large rubber gaskets and aluminum plates. These joints are commonly located where a floor, ceiling, or wall meets a similar feature of the joining buildings. The importance of these joints is to provide transition from one building to another while not transmitting loads from one building to the other. Space is built into these joints to allow for movement of the buildings as well. It is appropriate to end our discussion of the structural system with a discussion about expansion joints because the B3C project is all about expanding into the third century of the hospital's existence.

Loads Discussion

Structural systems resist gravity loads and lateral loads allowing spaces to be enclosed and serve as an artificial environment for people or buildings. Structural requirements have obvious implications on the architectural design of a building; the opposite is also true. Loads presented by the building materials chosen, shape of the building, and occupancy of the building will all change the structural system of a building. Several aspects of the B3C affecting the loading of the building are due to the location of the building including: the wind, seismic, and soils loading on the building. The wind characteristics within the Boston area dictate the design velocity of the wind. The wind velocity used in subsequent problems in this report is 105mph. This high wind load is due to the close proximity to the Atlantic Ocean. The wind loads are tabulated in following tables:

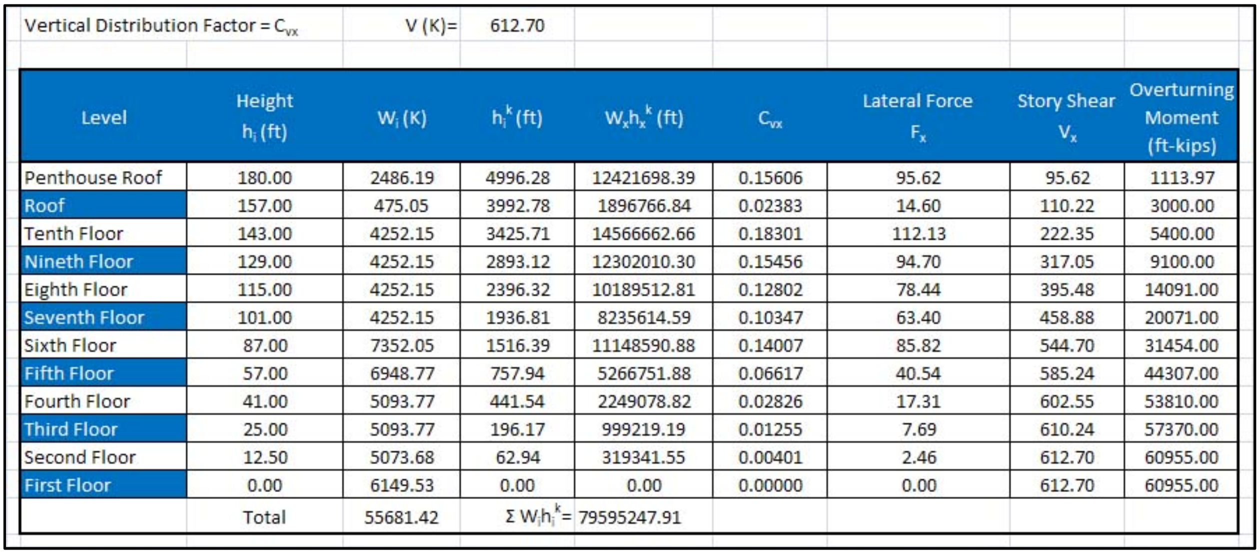


Wind (North - South Direction)											
B(ft)	L(ft)	G_{N-S}=	0.8173	C_{p-W}=	0.80	C_{p-L}=	-0.5				
208.00	192.00										
Floor	Floor Height (ft)	Height z (ft)	K_z	q_z(lb/ft2)	q_h(lb/ft2)	Windward lb/ft^2	Leeward lb/ft^2	Total lb/ft^2	Story Force (kips)	Story Sheer (kips)	Overturning Moment (ft-kips)
Ground	0	0	0	0	0	0	0	0	0.00	1124.87	110090
2nd	12.50	12.50	0.570	15.73	31.65	10.28	-12.93	23.21	60.36	1124.87	110090
3rd	12.50	25.00	0.665	18.35	31.65	12.00	-12.93	24.93	64.82	1064.51	96758
4th	16.00	41.00	0.766	21.13	31.65	13.82	-12.93	26.75	89.02	999.69	82115
5th	16.00	57.00	0.842	23.22	31.65	15.18	-12.93	28.11	93.56	910.67	66738
6th	30.00	87.00	0.950	26.20	31.65	17.13	-12.93	30.06	187.60	817.10	45789
7th	14.00	101.00	0.991	27.34	31.65	17.88	-12.93	30.81	89.72	629.51	30626
8th	14.00	115.00	1.028	28.38	31.65	18.55	-12.93	31.49	91.69	539.79	22441
9th	14.00	129.00	1.063	29.32	31.65	19.17	-12.93	32.10	93.49	448.10	18233
10th	14.00	143.00	1.095	30.20	31.65	19.74	-12.93	32.68	95.16	354.61	9858
Roof	14.00	157.00	1.124	31.01	31.65	20.28	-12.93	33.21	96.71	259.46	5608
Penthouse	23.00	180.00	1.169	32.25	31.65	21.09	-12.93	34.02	162.75	162.75	1896



Wind (East - West Direction)											
B(ft)	L(ft)	G_{E-W}=	0.8195	C_{p-W}=	0.80	C_{p-L}=	-0.5				
192	208										
Floor	Floor Height (ft)	Height z (ft)	K_z	q_z(lb/ft2)	q_h(lb/ft2)	Windward lb/ft^2	Leeward lb/ft^2	Total lb/ft^2	Story Force (kips)	Story Sheer (kips)	Overturning Moment (ft-kips)
Ground	0	0	0	0	0	0	0	0	0.00	1041.13	101937
2nd	12.50	12.50	0.570	15.73	31.65	10.31	-12.97	23.28	55.87	1041.13	101937
3rd	12.50	25.00	0.665	18.35	31.65	12.03	-12.97	25.00	59.99	985.27	89560
4th	16.00	41.00	0.766	21.13	31.65	13.85	-12.97	26.82	82.40	925.28	76000
5th	16.00	57.00	0.842	23.22	31.65	15.22	-12.97	28.19	86.60	842.88	61855
6th	30.00	87.00	0.950	26.20	31.65	17.18	-12.97	30.14	173.63	756.28	43768
7th	14.00	101.00	0.991	27.34	31.65	17.93	-12.97	30.89	83.04	582.65	28345
8th	14.00	115.00	1.028	28.38	31.65	18.60	-12.97	31.57	84.86	499.61	20770
9th	14.00	129.00	1.063	29.32	31.65	19.22	-12.97	32.19	86.53	414.75	14369
10th	14.00	143.00	1.095	30.20	31.65	19.80	-12.97	32.77	88.07	328.22	9123
Roof	14.00	157.00	1.124	31.01	31.65	20.33	-12.97	33.30	89.51	240.14	5190
Penthouse	23.00	180.00	1.169	32.25	31.65	21.14	-12.97	34.11	150.63	150.63	1755

The properties of the geographic area present the design factors used in the seismic loads of the building. The building shape and size also contribute to its behavior with seismic loading. The shears and moments existing because of the conditions are summarized in the following table:



Vertical Distribution Factor = C_{vx} V (K)= 612.70

Level	Height h_i (ft)	W_i (K)	h_i^k (ft)	$W_x h_x^k$ (ft)	C_{vx}	Lateral Force F_x	Story Shear V_x	Overturning Moment (ft-kips)
Penthouse Roof	180.00	2486.19	4996.28	12421698.39	0.15606	95.62	95.62	1113.97
Roof	157.00	475.05	3992.78	1896766.84	0.02383	14.60	110.22	3000.00
Tenth Floor	143.00	4252.15	3425.71	14566662.66	0.18301	112.13	222.35	5400.00
Nineth Floor	129.00	4252.15	2893.12	12302010.30	0.15456	94.70	317.05	9100.00
Eighth Floor	115.00	4252.15	2396.32	10189512.81	0.12802	78.44	395.48	14091.00
Seventh Floor	101.00	4252.15	1936.81	8235614.59	0.10347	63.40	458.88	20071.00
Sixth Floor	87.00	7352.05	1516.39	11148590.88	0.14007	85.82	544.70	31454.00
Fifth Floor	57.00	6948.77	757.94	5266751.88	0.06617	40.54	585.24	44307.00
Fourth Floor	41.00	5093.77	441.54	2249078.82	0.02826	17.31	602.55	53810.00
Third Floor	25.00	5093.77	196.17	999219.19	0.01255	7.69	610.24	57370.00
Second Floor	12.50	5073.68	62.94	319341.55	0.00401	2.46	612.70	60955.00
First Floor	0.00	6149.53	0.00	0.00	0.00000	0.00	612.70	60955.00
	Total	55681.42	$\Sigma W_i h_i^k$=	79595247.91				

Finally the location of the building affects the soil pressure presented on the foundation walls of the hospital. Water table height causes more the soils being held by the walls to be saturated and thus present more pressure to the wall. The slurry walls surrounding the basement levels of the building are not analyzed within this report due to limited understanding of the design of such structures. It is understood that the lateral soil loads are resisted by the slurry walls.

Load Distribution

Lateral force distribution throughout the structure can be determined using relative stiffness comparison of the lateral frames. The lateral forces are distributed through the building in the floor system which acts as a rigid diaphragm. Loads are distributed to frames relative to their stiffness. Stiffer frames support more of the lateral loading of the building than those that are less stiff.

Relative Stiffness - This relative stiffness can be determined by deflecting floors of the frames 1 inch. The force needed to deflect the structure 1 inch is divided by 1 inch to get the stiffness (k) of that frame at that level. Designers often assume only one relative stiffness per lateral frame but if the stiffness is checked at multiple floors the building can be more fully understood. The relative stiffness for each level are included in the table below which also shows the direct shear on the frames as a result of the wind forces as well as the seismic forces. The equation used to determine the direct shears on the build is:

$$F_{Direct} = \frac{K_i}{\sum K}(F_i)$$

East - West Direction

Floor	Frame Stiffness - k (k/in)			Story Force	Direct Shear (kips)		
	B	C	H	F (kips)	B	C	H
Second	100.00	332.00	220.00	55.87	8.57	28.45	18.85
Third	100.00	332.00	220.00	59.99	9.20	30.55	20.24
Fourth	100.00	332.00	220.00	82.40	12.64	41.96	27.80
Fifth	100.00	332.00	220.00	86.60	13.28	44.10	29.22
Fifth Mez	88.50	264.88	196.25	86.82	13.98	41.84	31.00
Sixth	77.00	197.75	172.50	86.82	14.95	38.38	33.48
Seventh	0.00	168.28	133.75	83.04	0.00	46.27	36.77
Eighth	0.00	168.28	133.75	84.86	0.00	47.28	37.58
Ninth	0.00	138.80	95.00	86.53	0.00	51.37	35.16
Tenth	0.00	113.50	66.67	88.07	0.00	55.48	32.59
Pent	0.00	113.50	66.67	89.51	0.00	56.39	33.12
Roof	0.00	88.20	0.00	150.63	0.00	150.63	0.00

North - South Direction

Floor	Frame Stiffness - k (k/in)		Story Force	Direct Shear (kips)	
	1	8	F (kips)	1	8
Second	225.00	350.50	60.36	23.60	36.76
Third	225.00	350.50	64.82	25.34	39.47
Fourth	225.00	350.50	89.02	34.81	54.22
Fifth	225.00	350.50	93.56	36.58	56.98
Fifth Mez	199.00	300.00	93.80	37.41	56.39
Sixth	173.00	249.50	93.80	38.41	55.39
Seventh	140.13	187.50	89.72	38.37	51.35
Eighth	140.13	187.50	91.69	39.21	52.47
Ninth	107.25	125.50	93.49	43.08	50.41
Tenth	83.33	125.50	95.16	37.97	57.18
Pent	83.33	125.50	96.71	38.59	58.12
Roof	0.00	0.00	162.75	0.00	0.00

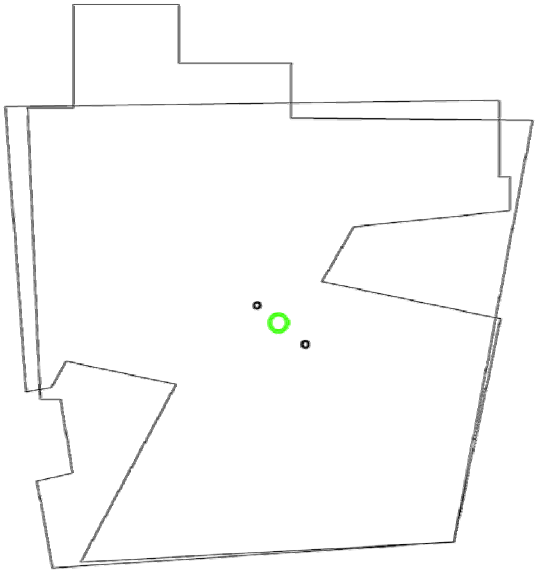
East - West Direction

Floor	Frame Stiffness - k (k/in)			Story Force	Direct Shear (kips)		
	B	C	H	F (kips)	B	C	H
Second	100.00	332.00	220.00	612.70	93.97	311.99	206.74
Third	100.00	332.00	220.00	612.70	93.97	311.99	206.74
Fourth	100.00	332.00	220.00	610.24	93.60	310.74	205.91
Fifth	100.00	332.00	220.00	602.55	92.42	306.82	203.31
Fifth Mez	88.50	264.88	196.25	585.24	94.23	282.04	208.96
Sixth	77.00	197.75	172.50	544.70	93.78	240.84	210.08
Seventh	0.00	168.28	133.75	458.88	0.00	255.67	203.21
Eighth	0.00	168.28	133.75	395.48	0.00	220.35	175.13
Ninth	0.00	138.80	95.00	317.05	0.00	188.22	128.83
Tenth	0.00	113.50	66.67	222.35	0.00	140.07	82.28
Pent	0.00	113.50	66.67	110.22	0.00	69.44	40.78
Roof	0.00	88.20	0.00	95.62	0.00	95.62	0.00

North - South Direction					
Floor	Frame Stiffness - k (k/in)		Story Force F (kips)	Direct Shear (kips)	
	1	8		1	8
Second	225.00	350.50	612.70	239.54	373.16
Third	225.00	350.50	612.70	239.54	373.16
Fourth	225.00	350.50	610.24	238.58	371.66
Fifth	225.00	350.50	602.55	235.58	366.97
Fifth Mez	199.00	300.00	585.24	233.39	351.85
Sixth	173.00	249.50	544.70	223.04	321.66
Seventh	140.13	187.50	458.88	196.26	262.62
Eighth	140.13	187.50	395.48	169.15	226.33
Ninth	107.25	125.50	317.05	146.09	170.95
Tenth	83.33	125.50	222.35	88.73	133.62
Pent	83.33	125.50	110.22	43.98	66.24
Roof	0.00	0.00	95.62	0.00	0.00

Center of Rigidity – To determine the center of Rigidity the stiffness values in the above chats must be used in the following equation:

Once the values are determined a graphical representation of the results can be developed. The adjacent diagram represents placement of the center of Rigidity inside the perimeter of two of the most common floors in the building.



Design Deflection Criterion

The following design criterion was also used and can be found in IBC 2006 and ASCE 7-05:

- Δ = H/400 for Allowable Story and Building Drift due to Wind Loading
- Δ = $0.015h_{sx}$ for Allowable Story and Building Drift due to Seismic Loading

Design Load Combinations

The following Load and Resistance Factor Design load combinations were considered for analysis, as noted in ASCE 7-05 Chapter 2:

- 1.4(Dead)
- -1.2(Dead) + 1.6(Live) + 0.5(Roof Live)
- 1.2(Dead) + 1.6(Roof Live) + 0.8(Wind)
- 1.2(Dead) + 1.6(Snow) + 0.8(Wind)
- 1.2(Dead) + 1.6(Snow) + 1.0(Live)
- 1.2(Dead) + 1.6(Wind) + 1.0(Live) + 0.5(Snow)
- 1.2(Dead) + 1.6(Wind) + 1.0(Live) + 0.5(Roof Live)
- 1.2(Dead) + 1.0(Earthquake) + 1.0(Live) + 0.2(Snow)

Through inspection it can be determined that the governing lateral force on this building will be the wind forces. This steel structure will be affected less by seismic loads than a similarly sized concrete building because the weight of the concrete causes the mailer to get

Existing Lateral System

As previously discussed, lateral forces resisted by buildings include wind, seismic, and soil loads. There are several framing options available for engineers to design to resist these forces. Moment frames were chosen as the main lateral force resisting system for the hospital to allow for the most open floor plan possible. Braced frames were not used within the building due to the desired open spaces within the hospital. Braced frames would limit the architect's space planning; requiring planning around the brace location. Moment connections, seen in Appendix A Figure:6 are pivotal to the function of the existing lateral system. A Direct-welded flange connection is represented in the figure and commonly used throughout the building. Requiring very few connecting elements this fully restrained moment connection serves its physical purpose and is economical. Load distribution to these frames will be presented in the following section.

Conclusions

In conclusion it was determined that the lateral system of the building was designed in an efficient manner to address both wind and seismic conditions. Calculations for tensional effects are at this time not completed due to some of the intricacies of the building shape and making the correct assumptions to correctly model the building frame for torsion.

Document and Code Review

Here is provided a list of the Documents and Codes utilized in analysis and discussion of the structural system.

- ASCE/SEI 7-05 *Minimum Design Loads for Buildings and Other Structures* published in 2006 by the American Society of Civil Engineers (ASCE 7)
- *AISC Steel Construction Manual 13th Edition* published December 2005 by the American Institute of Steel Construction, Inc. (AISC 13th ed.)
- ACI 318-08 *Building Code Requirements for Structural Concrete* published August 2008 by the American Concrete Institute (ACI 318)
- Construction Documents S100 – S602 Dated February 29 2008
- *Unified Design of Steel Structures* Published 2008 Author Louis F. Geschwindner

Professional Contacts

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Appendix A - Figures

Figure 1 – Birds Eye Views of B3C Project

Figure 2 : Site Map

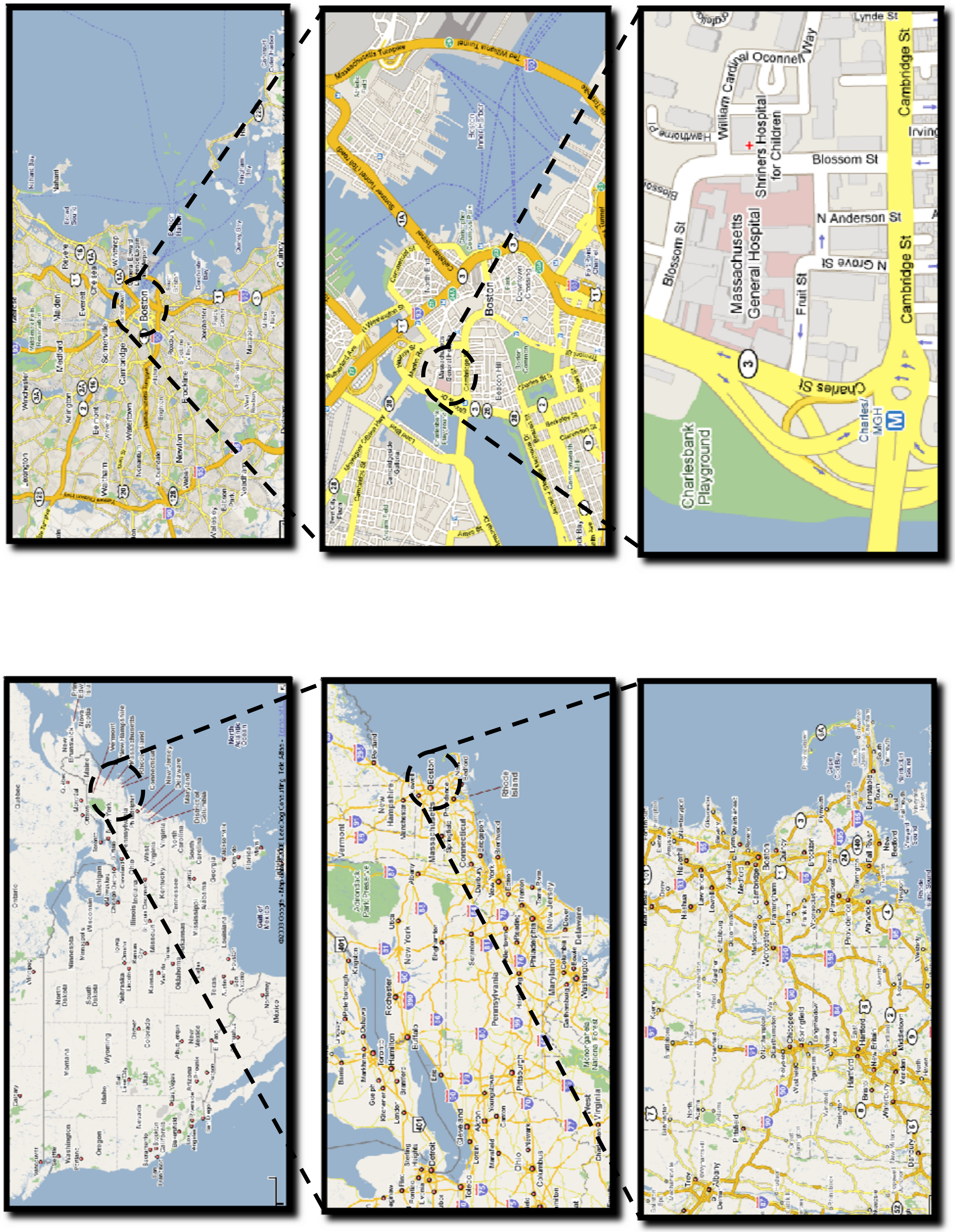
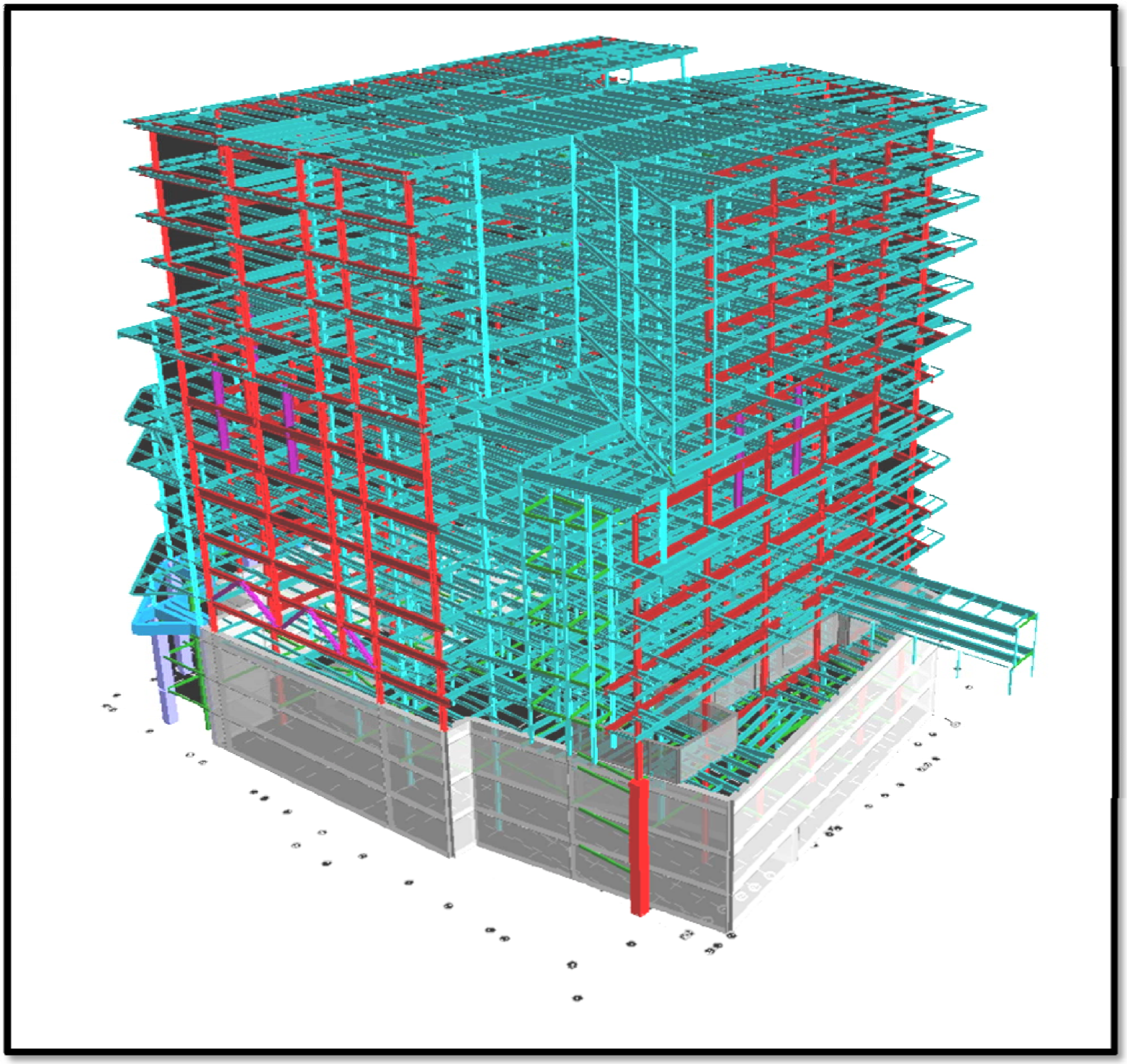


Figure 3: Structural Perspective



Note: The members shown in red are those included in the main lateral force resisting system. This image is courtesy of McNamara/Salvia Inc.

Figure 4: Elevations of Lateral Frame Spanning East to West

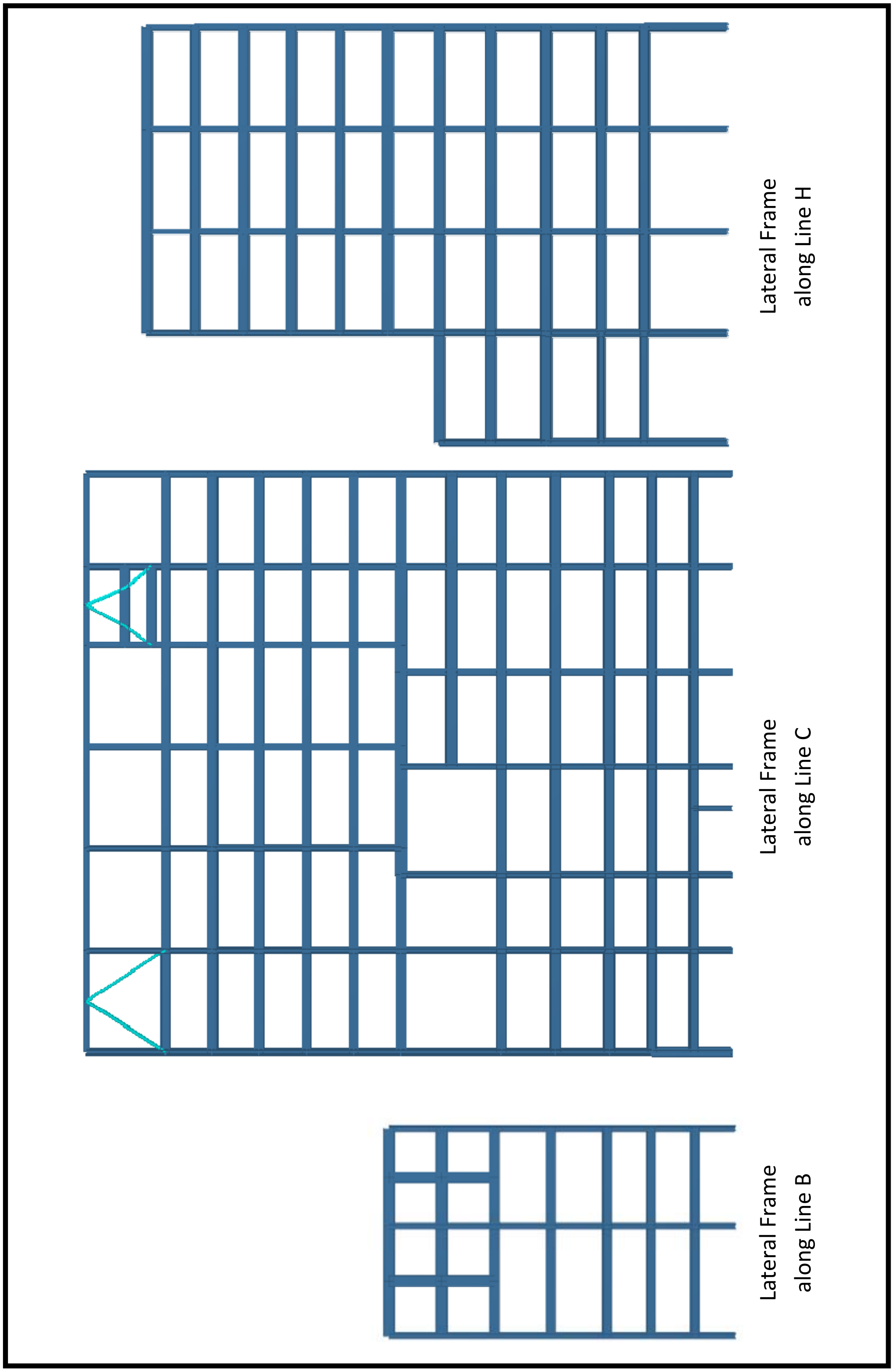


Figure 5: Elevations of Lateral Frame Spanning North to South

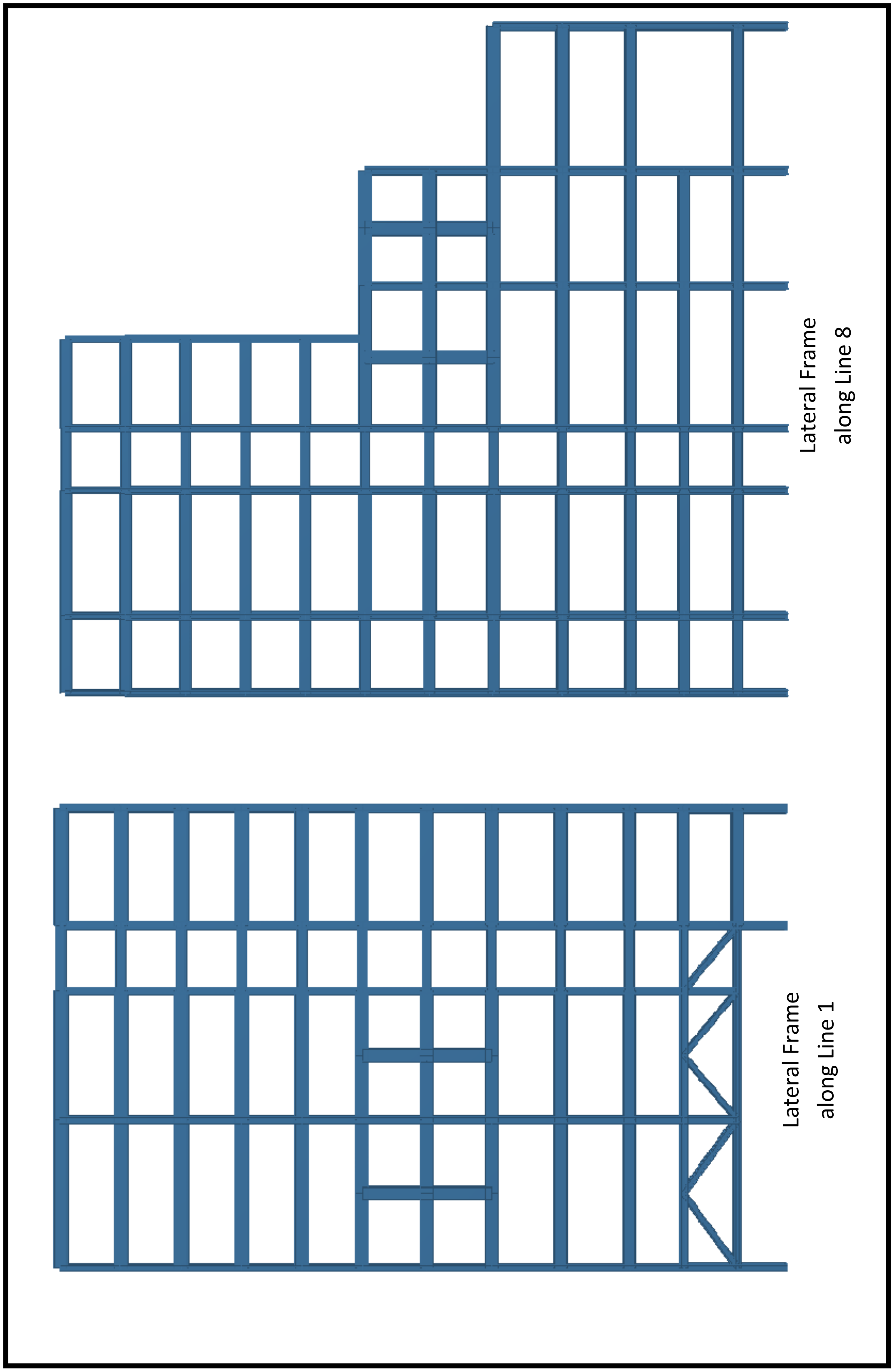
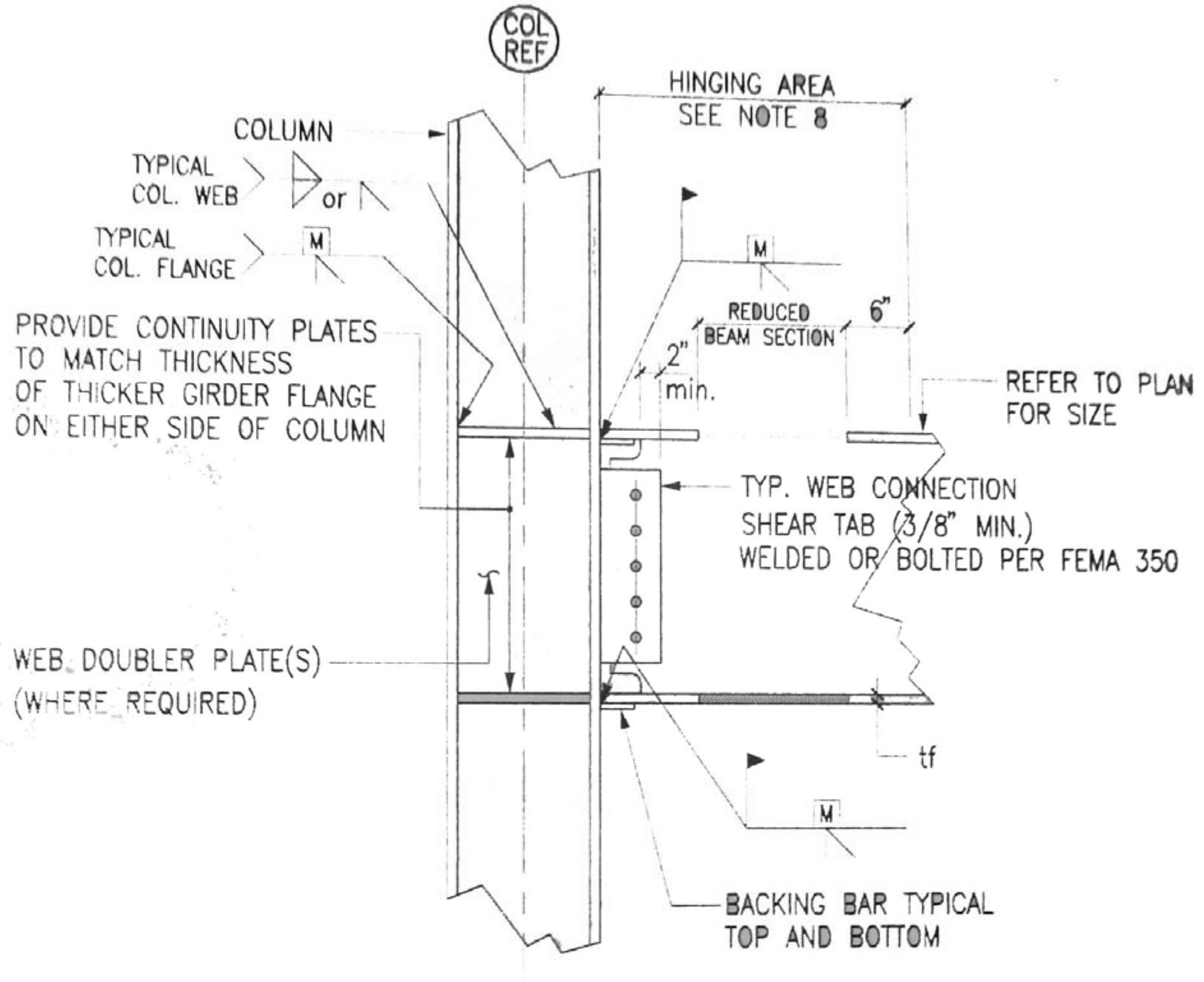
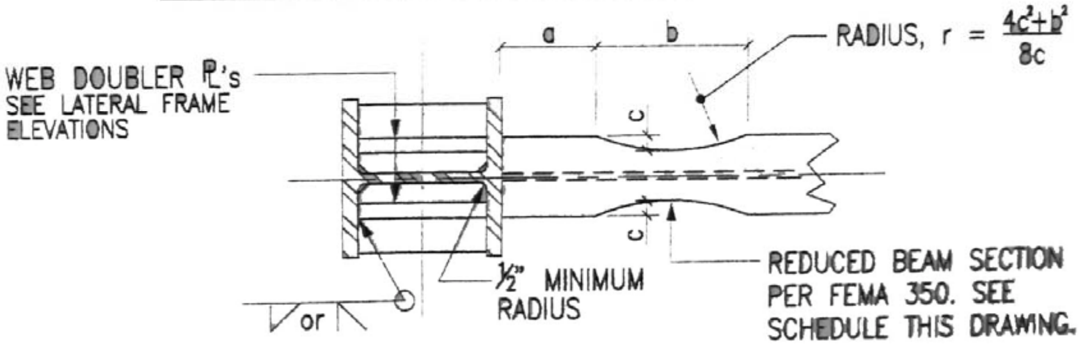


Figure 6: Typical Moment Connection



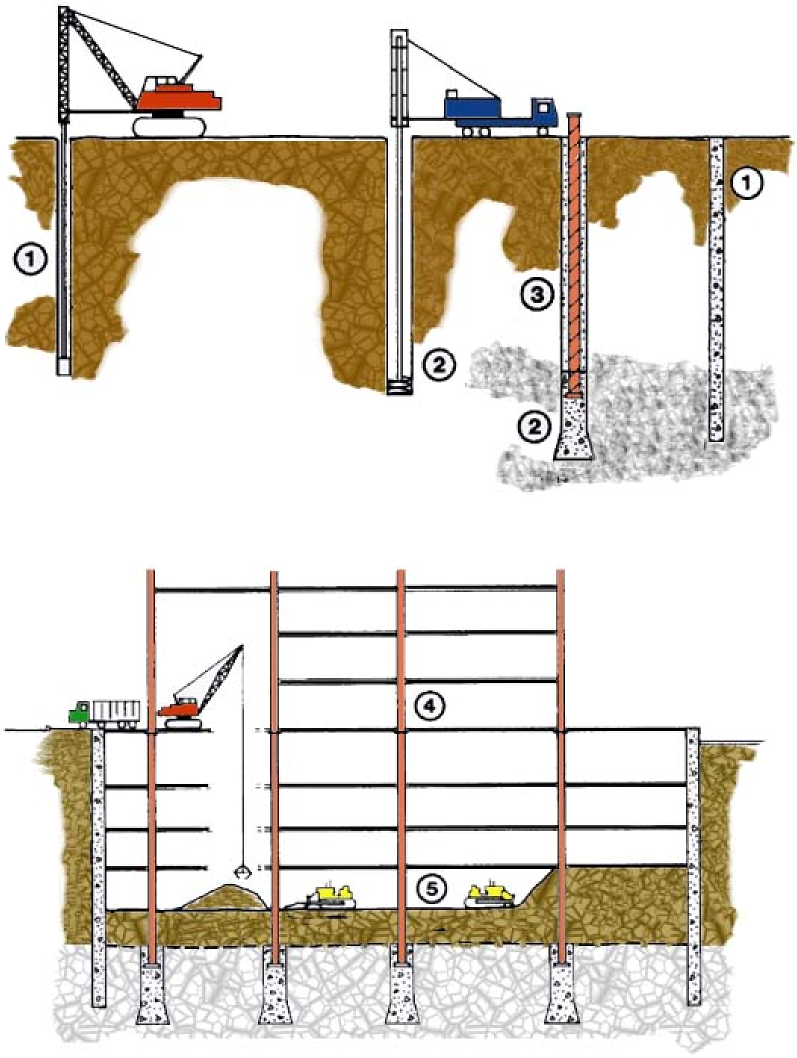
GIRDER–TO–COLUMN FLANGE ELEVATION



GIRDER–TO–COLUMN FLANGE PLAN

REFER TO NOTES BELOW FOR ADDITIONAL REQUIREMENTS

Figure 7: Up-Down Construction Process



① - Excavation of the slurry wall perimeter on the site takes place first. Subsequently the the reinforcement cages are placed followed by concrete.

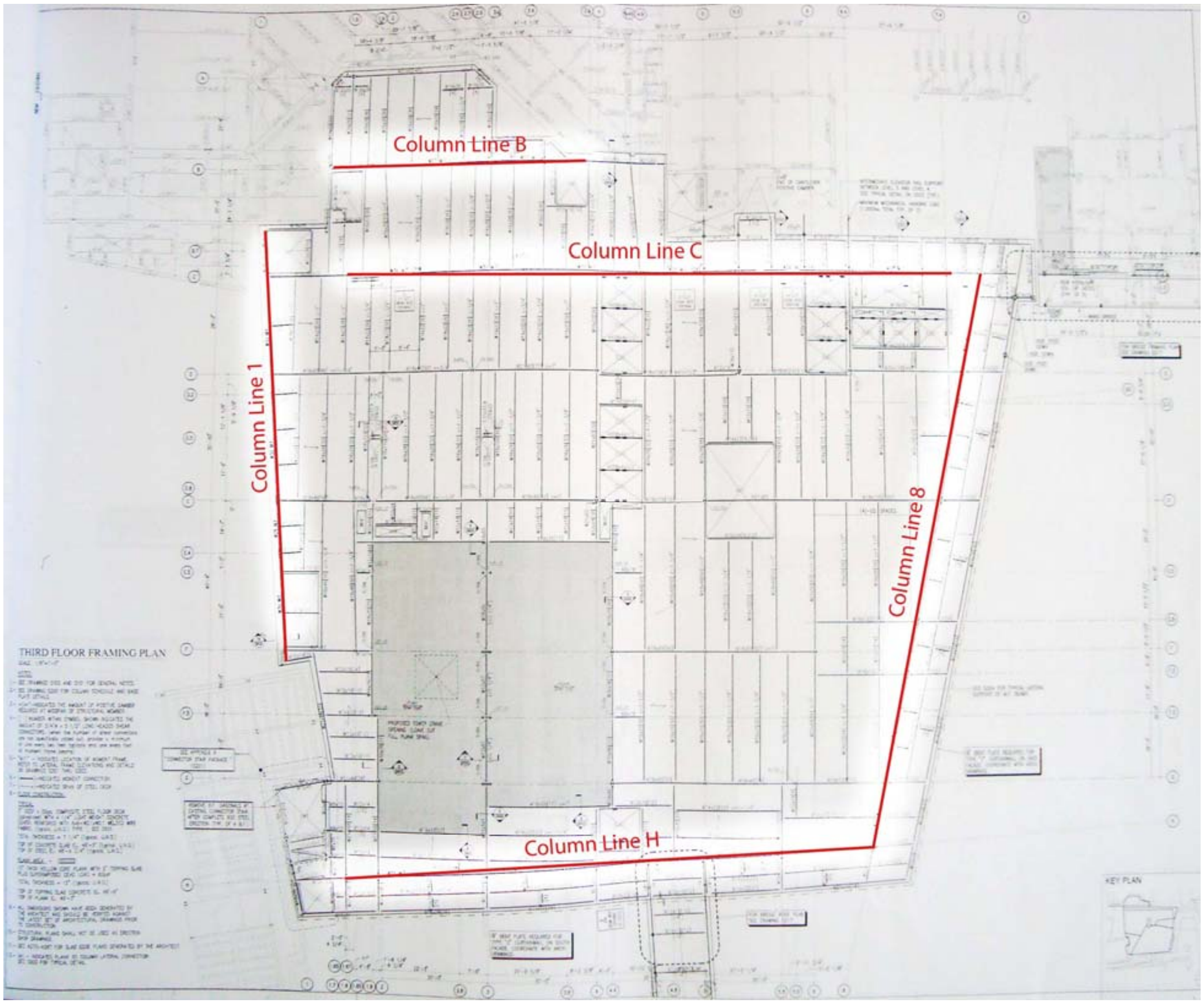
② - Excavation for the Load Bearing Elements takes place throughout the site in preparation for setting the columns as imbedded members in the LBEs.

③ - A protective layer of concrete is placed around the columns to be removed later in construction

④ - Construction of the superstructure can begin imeadiately because the columns have already been set.

⑤ - A team of workers are given the task of excavating below sucessive slabs placed on grade to construct the lower levels of the building.

Figure 8: Column Layout



AE 481 THESIS | TORSION CONSTANTS | Matthew J Decker

$$I_x = \Sigma k_{iy} x_i^2$$

$$I_y = \Sigma k_{ix} y_i^2$$

AT LEVEL 9

$I_x = 138.8\ k/in\,(32ft)^2 + 95\ k/in\,(203ft)^2$
$I_x = 4056946.2$

$I_y = 125.5\ k/in\,(194ft)^2$
$I_y = 4723318$

AT LEVEL 6

$I_x = 197.75\ k/in\,(32ft)^2 + (172.5\ k/in)(203ft)^2$
$I_x = 7\ 311\ 048.5$

$I_y = 247.5\ k/in\,(194ft)^2$
$I_y = 9371364$

AT LEVEL 5

$I_x = 332\ k/in\,(32ft) + 220\ k/in\,(203ft)^2$
$I_x = 9\ 405\ 948$

$I_y = 350.5(194ft)^2$
$I_y = 13\ 191\ 418$

AE 481 THESIS | CENTER OF RIGIDITY | Matthew J Decker

$$X_{cm} = \frac{\Sigma A_i (X_i)}{\Sigma A} \qquad Y_{cm} = \frac{\Sigma A_i (Y_i)}{\Sigma A}$$

Formulas USED FOR CENTER OF MASS

NOTE These formulas will be used in three stages to account for the lower, upper, and combined floors.

$$X_{CR} = \frac{\Sigma k_i d_{ix}}{\Sigma K_x} \qquad Y_{CR} = \frac{\Sigma k_i d_{iy}}{\Sigma K_y}$$

Formulas USED FOR CENTER OF RIGIDITY

NOTE THESE EQUATIONS WILL BE USED ON FRAMES AT LEVELS 9, 6, and 5

LEVEL 9

$$Y_{CR} = \frac{0(0) + (138.8\ k/in)(32ft) + (95\ k/in)(203ft)}{138.8\ k/in + 95\ k/in}$$

$$Y_{CR} = 101.5\ ft$$

$$X_{CR} = \frac{(107.25\ k/in)(0ft) + (125.5\ k/in)(194ft)}{(107.25\ k/in + 125.5\ k/in)}$$

$$X_{CR} = 88.42\ ft$$

LEVEL 6

$$Y_{CR} = \frac{77\ k/in(0ft) + (197.75\ k/in)(32ft) + (172.5\ k/in)(203ft)}{77\ k/in + 197.75\ k/in + 172.5\ k/in}$$

$$Y_{CR} = 92.4$$

$$X_{CR} = \frac{173.00\ k/in\ (0ft) + (249.5\ k/in)(194ft)}{173.00\ k/in + 249.5\ k/in}$$

$$X_{CR} = 114.56\ ft$$

AE 481 THESIS | CENTER OF RIDGIDITY | Matthew J. Decker

LEVEL 5: $$Y_{cR} = \frac{100\,k/in\,(0\,ft) + 332\,k/in\,(32\,ft)(32\,ft) + 220\,k/in\,(203\,ft)}{100 + 332 + 220}$$

$$Y_{cR} = 84.771'$$

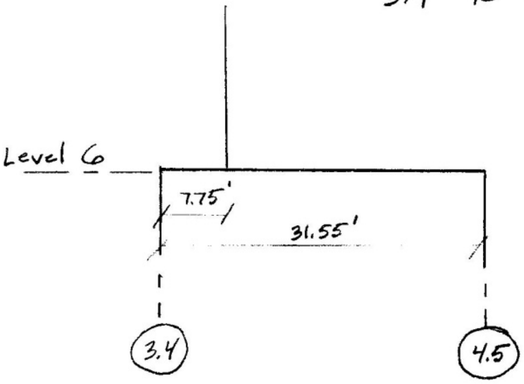
$$X_{cr} = \frac{225\,k/in\,(0\,ft) + 350.5\,(194\,ft)}{225 + 350\,k/in}$$

$$X_{cr} = 118.15'$$

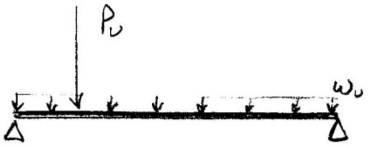
AE 481 THESIS | STRENGTH → SPOTCHECK | Matthew J Decker

LATERAL FRAME ALONG LINE C

Check the Beam spanning from Column line 3.4 to line 4.5 at level 6



THIS BEAM IS NOT A PART OF THE MOMENT FRAME BUT ACTS AS A TRANSFERE GIRDER. TO ALLOW FOR THE CHANGE IN COLUMN LAYOUT.



DEAD LOAD ↓

$P = (8' + 14')(5 \text{ floors})(139.727 \text{ psf})(29.67')$

$P = 456 \text{ k}$

$w = (8' + 14')(117.34 \text{ psf}) = 2581 \text{ plf}$

LIVE 80 PSF

$P_u = 1.2D + 1.6(L)$

$P_u = 1.2(456 \text{ k}) + 1.6(22' \times 29.67' \times 80 \text{ psf})$

$P_u = 630.7 \text{ k}$

$w_u = 1.2(D) + 1.6(L)$

$= 1.2(2.6 \text{ klf}) + 1.6(1.8 \text{ klf})$

$= 6 \text{ klf}$

$$M_u = \frac{P_u ab}{l} + \frac{w_u l^2}{8}$$

$$M_u = \underbrace{\frac{630.7\text{k}(7.75')(23.8')}{31.55'}}_{3687 \text{ kft}} + \underbrace{\frac{6\text{klf}(31.55')^2}{8}}_{747 \text{ kft}}$$

$M_u = 4434 \text{ kft}$ DESIGN FOR THIS MOMENT

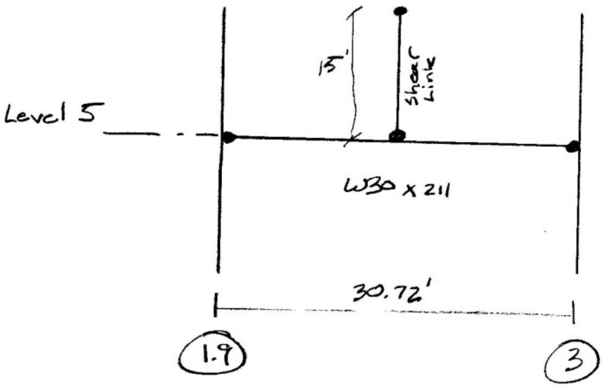
CHECK EXISTING SIZE W 40 x 593
NOT IN TABLE 3-19 OF AISC
BUT W40 x 297 → SMALLER ∴ CONSERVATIVE
WILL SUPPORT M_u of 4434 kft ∴ OK ✓

AE 481 THESIS | STRENGTH → SPOT CHECK | Matthew J Decker

LATERAL FRAME ALONG LINE B

Check the beam spanning from column line 1.9 to line 3 because a shear link frames into it

Diagram of condition

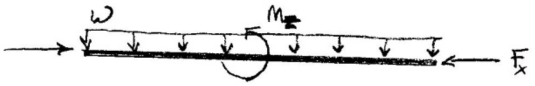


—●— → Moment Connection

Neglecting Second Order Effects

Shear link necessary because there is no composite action due to lack of floor on 5 Mezzanine level.

$$M_z = \frac{F_x @ 5m}{2}(15')$$



ω = self weight + Floor weight

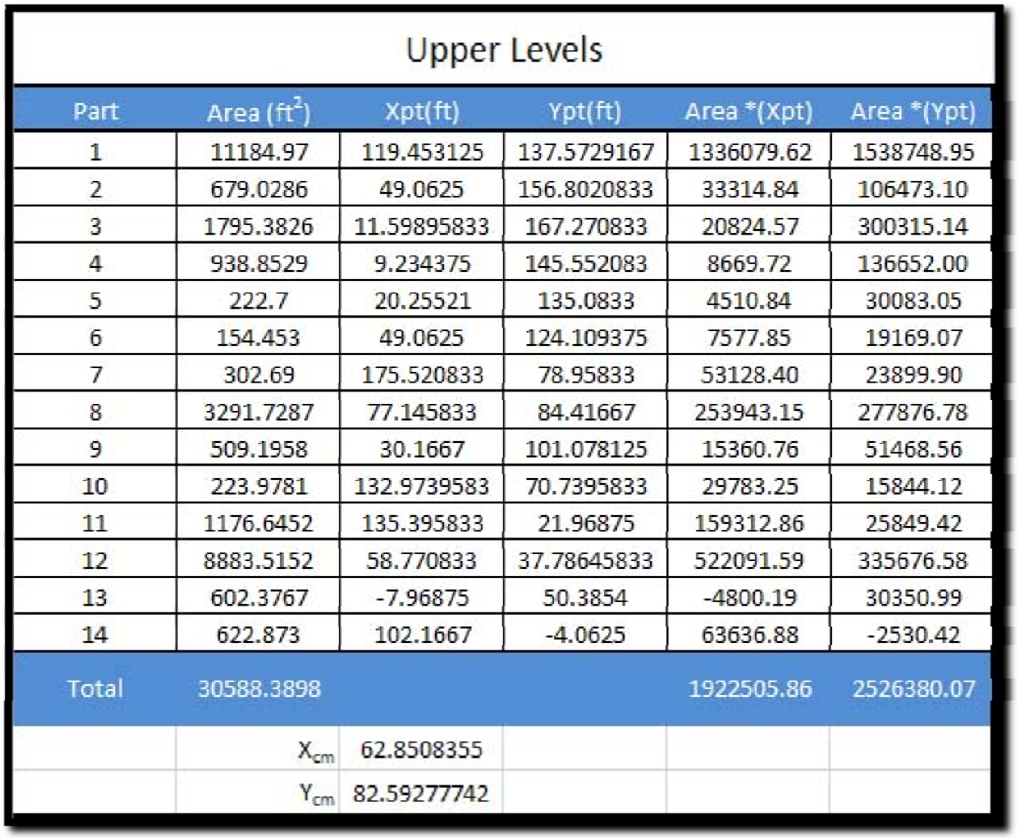
$$\omega = 211\text{ plf} + \left(\frac{4494120\text{ lb}}{38300\text{ ft}^2} \times 25'\right)$$

$$\omega = 211\text{ plf} + 2933.5\text{ plf}$$

$$\omega = 3.14\text{ klf}$$

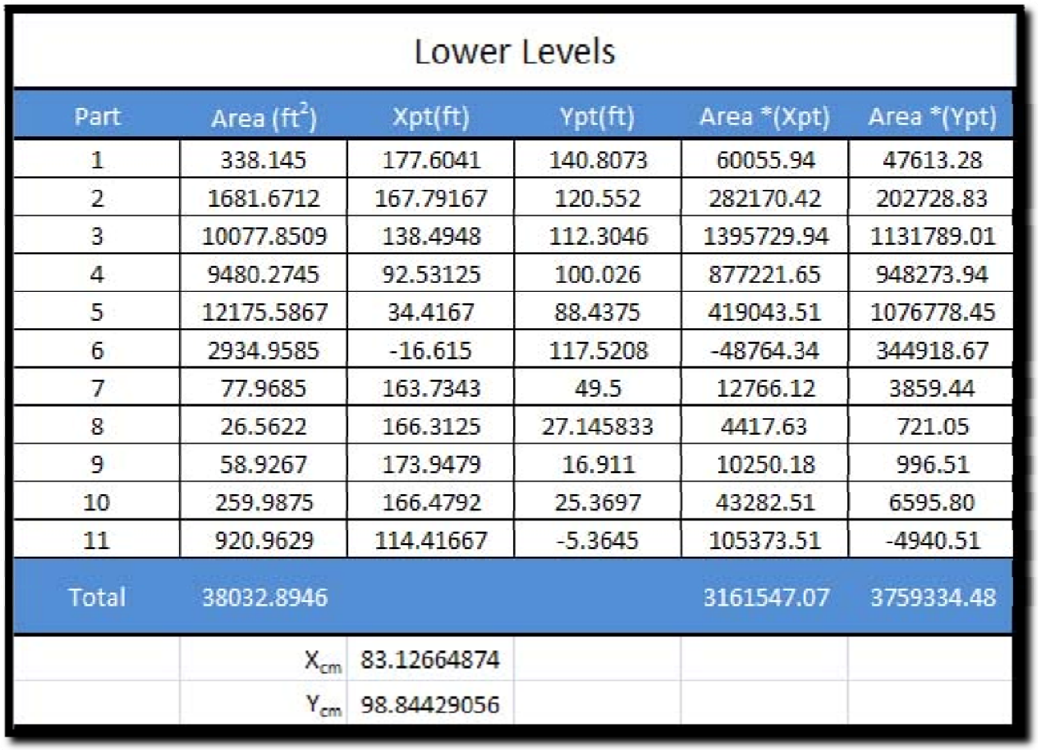
Appendix C: Supplemental Charts

Center of Mass



Upper Levels

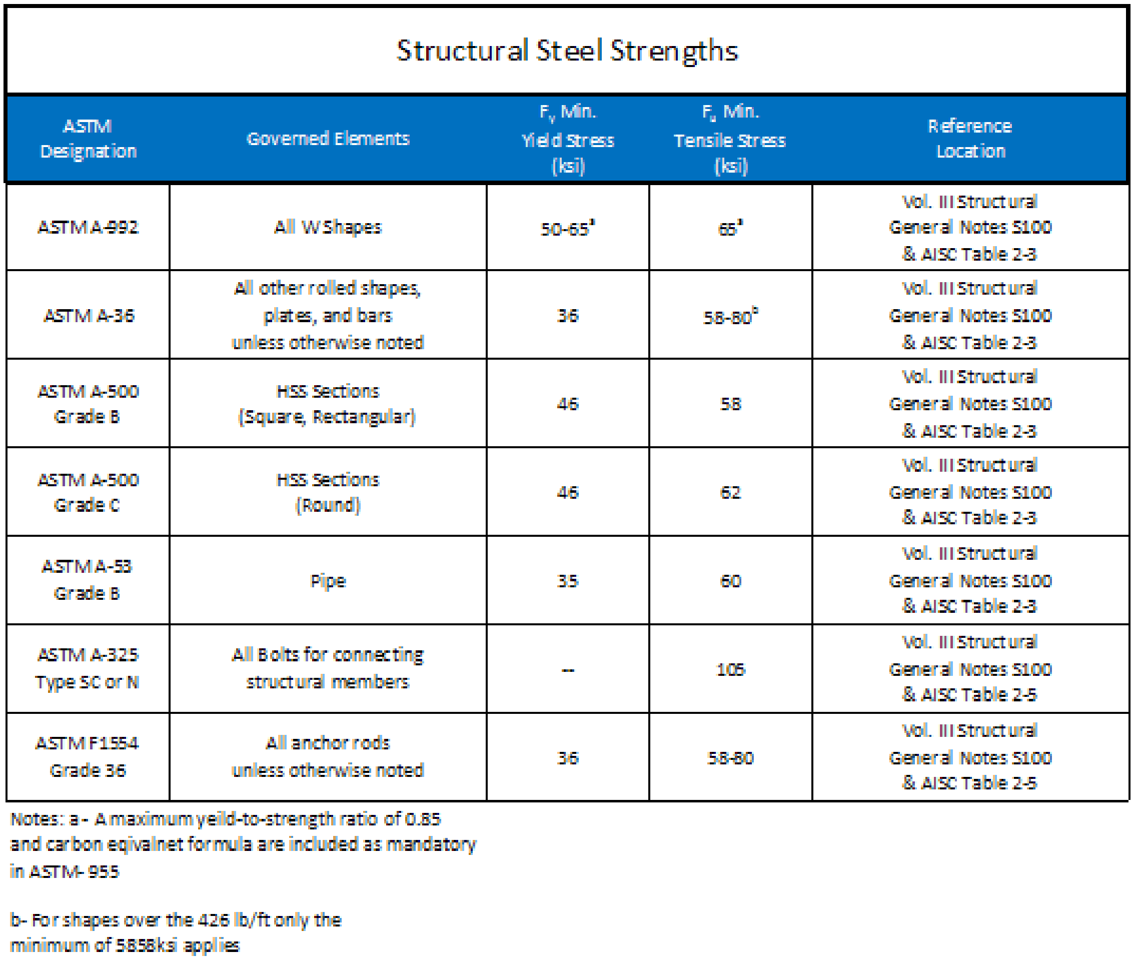
Part	Area (ft^2)	Xpt(ft)	Ypt(ft)	Area *(Xpt)	Area *(Ypt)
1	11184.97	119.453125	137.5729167	1336079.62	1538748.95
2	679.0286	49.0625	156.8020833	33314.84	106473.10
3	1795.3826	11.59895833	167.270833	20824.57	300315.14
4	938.8529	9.234375	145.552083	8669.72	136652.00
5	222.7	20.25521	135.0833	4510.84	30083.05
6	154.453	49.0625	124.109375	7577.85	19169.07
7	302.69	175.520833	78.95833	53128.40	23899.90
8	3291.7287	77.145833	84.41667	253943.15	277876.78
9	509.1958	30.1667	101.078125	15360.76	51468.56
10	223.9781	132.9739583	70.7395833	29783.25	15844.12
11	1176.6452	135.395833	21.96875	159312.86	25849.42
12	8883.5152	58.770833	37.78645833	522091.59	335676.58
13	602.3767	-7.96875	50.3854	-4800.19	30350.99
14	622.873	102.1667	-4.0625	63636.88	-2530.42
Total	30588.3898			1922505.86	2526380.07
	X_{cm}	62.8508355			
	Y_{cm}	82.59277742			



Lower Levels

Part	Area (ft^2)	Xpt(ft)	Ypt(ft)	Area *(Xpt)	Area *(Ypt)
1	338.145	177.6041	140.8073	60055.94	47613.28
2	1681.6712	167.79167	120.552	282170.42	202728.83
3	10077.8509	138.4948	112.3046	1395729.94	1131789.01
4	9480.2745	92.53125	100.026	877221.65	948273.94
5	12175.5867	34.4167	88.4375	419043.51	1076778.45
6	2934.9585	-16.615	117.5208	-48764.34	344918.67
7	77.9685	163.7343	49.5	12766.12	3859.44
8	26.5622	166.3125	27.145833	4417.63	721.05
9	58.9267	173.9479	16.911	10250.18	996.51
10	259.9875	166.4792	25.3697	43282.51	6595.80
11	920.9629	114.41667	-5.3645	105373.51	-4940.51
Total	38032.8946			3161547.07	3759334.48
	X_{cm}	83.12664874			
	Y_{cm}	98.84429056			

Appendix E: Material Strengths



Structural Steel Strengths

ASTM Designation	Governed Elements	F_y Min. Yield Stress (ksi)	F_u Min. Tensile Stress (ksi)	Reference Location
ASTM A-992	All W Shapes	50-65[a]	65[a]	Vol. III Structural General Notes S100 & AISC Table 2-3
ASTM A-36	All other rolled shapes, plates, and bars unless otherwise noted	36	58-80[b]	Vol. III Structural General Notes S100 & AISC Table 2-3
ASTM A-500 Grade B	HSS Sections (Square, Rectangular)	46	58	Vol. III Structural General Notes S100 & AISC Table 2-3
ASTM A-500 Grade C	HSS Sections (Round)	46	62	Vol. III Structural General Notes S100 & AISC Table 2-3
ASTM A-53 Grade B	Pipe	35	60	Vol. III Structural General Notes S100 & AISC Table 2-3
ASTM A-325 Type SC or N	All Bolts for connecting structural members	--	105	Vol. III Structural General Notes S100 & AISC Table 2-5
ASTM F1554 Grade 36	All anchor rods unless otherwise noted	36	58-80	Vol. III Structural General Notes S100 & AISC Table 2-5

Notes: a - A maximum yeild-to-strength ratio of 0.85 and carbon eqivalnet formula are included as mandatory in ASTM- 955

b- For shapes over the 426 lb/ft only the minimum of 5858ksi applies

Concrete Strengths

Governed Elemets	Minimum Compressive Strenght (f'c) psi	Reference Location
Caissons, LEBs	5,000	Vol. III Structural General Notes S100
Slurry Wall Concrete Diaphram	5,000	Vol. III Structural General Notes S100
Cap Walls	5,000	Vol. III Structural General Notes S100
Two-Way Concrete Slabs	5,000	Vol. III Structural General Notes S100
Formed Walls	4,000	Vol. III Structural General Notes S100
Topping Slabs	4,000	Vol. III Structural General Notes S100
Slabs on Grade	4,000	Vol. III Structural General Notes S100
Fill Concrete Mud Slabs	2,000	Vol. III Structural General Notes S100
LinAcc Sielding	5,000	Vol. III Structural General Notes S100

Reinforcing

ASTM Designation	Bars	Minimum Yield Strength (psi)	Minimum Tensile Strength (psi)
A 615 Grade 60	Less than #11	60,000	90,000
A 615 Grade 75	#11 and greater	75,000	100,000
A 706	To be welded	60,000	80,000