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{Structural Option}

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Virginia Commonwealth University School of Medicine

Richmond, Virginia

Structural Thesis Final Report

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{Mid-Atlantic Regional Office}

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PSU AE Faculty

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Executive Summary

The following report is a comprehensive thesis that not only investigated the structural implications of redesigned gravity and lateral systems for the James W. & Frances G. McGlothlin Medical Education Center, but also explored the impacts on cost of the entire project, time required for construction, and architecture. A summary of the original structural system is provided in the report for comparison. To answer all building functions and program requirements, rational design alternatives of a non-composite system with bar joists and steel girders and a lateral system composed of moment frames with minimal bracing were explored. Hand calculations were completed to size members, check vibration control, and calculate loadings. Computer modeling was also utilized to verify hand calculations, apply loadings, and evaluate drift control.

Research was also completed on two breadth topics: cost/schedule analysis and architectural impacts caused by the redesign. An estimate was completed for the redesigned gravity system along with an assessment of the implications of the redesigned system on the total cost of the project. A predicted schedule was also drafted for the redesigned system; all of this research was then compared with the original system to evaluate the cost and time savings. The redesign of the lateral system was determined to have an effect on the layout of the building – removal of bracing allowed for alteration of walls to create more open spaces. The redesigned gravity system also created an opportunity to move towards a more passive fire suppression system.

The final results of the research demonstrated that the redesigned gravity and lateral systems are an economical alternative. Some of the benefits of the redesigned structural system are lighter members, satisfactory drift control, small cost and time savings, decreased bracing, and potential for altered fire suppression system. However, it was determined that some of the improvements are only marginal when compared to the original system. Even though the advances might only be minor, it is reasonable to say that either option, the original or the redesigned system, would result in an efficient, economical structure.

Abstract

James W. & Frances G. McGlothlin Medical Education Center

Virginia Commonwealth University – Richmond, VA

Project Information

Type of Building :	Multipurpose Education Facility
Functions :	Administrative/Classrooms/Research
Size :	220,000 GSF
Height :	13 stories
Time Frame :	Oct. 2009 – March 2013
Cost :	$159 million
Delivery :	Design–Assist–Build

Project Team

Owner :	Virginia Commonwealth University
CM :	Gilbane Building Company
Architect :	Ballinger
Structural + MEP :	Ballinger
Exterior Façade :	Pei Cobb Freed & Partners
Civil :	Draper Aden Associates
Geotechnical :	Geotech, Inc.

Architectural

– Erected following demolition of 8-story A.D. Williams Building, which previously housed VCU School of Medicine

– Exterior façade was designed by internationally acclaimed design firm Pei Cobb Freed & Partners

Sustainability

– Climate Wall System: double-layered glass walls on South & West facades trap & exhaust heated air

– Recovery Wheels: recover exhausted air & use contained energy to heat & cool building

– Storm Water Retention: collect water from roof to be used in toilets/urinals

Structural

– Drilled pier/slab-on-grade system works in conjunction with pre-existing caissons

– Structural steel braced moment frame system

– Bridge connects 2nd Floor of building to adjacent Main Hospital 1st Floor across E. Marshall Street

MEP

– 6 Air Handling Units serve the Lobby, Student Forum, Auditorium, and Chilled Beam system

– Cooling Tower on roof removes heat from 3 Chillers

– Use of Recovery Wheels saves 450 tons of cooling

– Daylighting sensors throughout building ensure energy is conserved

Marissa Delozier

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http://www.engr.psu.edu/ae/thesis/portfolios/2013/mnd5036/

Building Introduction

The James W. & Frances G. McGlothlin Medical Education Center, also known as the new Virginia Commonwealth University School of Medicine Education Center, is located in Richmond, Virginia. The 13 story, 220,000 square foot building was completed in early 2013. The project was constructed following the demolition of the A.D. Williams Building, which previously housed the VCU School of Medicine faculty offices, outpatient clinics, and laboratories. The new construction, as shown in Figure 1, encompasses all of these program requirements, along with various collaborative spaces, classrooms, and a 300-seat auditorium accessible via the second and third floors.

The building rests atop approximately 60 drilled piers of varying capacities and a 10" thick slab-on-grade. As the building progresses skyward, the structural lateral load resisting system is composed of steel concentrically braced frames, structural steel members, and composite concrete slabs on metal decking. The exterior of the building, designed by internationally acclaimed architecture firm Pei Cobb Freed & Partners, does not contribute to the structural strength of the building, but is intended for aesthetic and environmental purposes. The project is currently under review by the U.S. Green Building Council in hopes of achieving a LEED (Leadership in Energy & Environmental Design) Silver status.

Figure 1 – James W. & Frances G. McGlothlin Medical Education Center when approaching on E. Marshall Street

Structural System Overview

The James W. & Frances G. McGlothlin Medical Education Center, known as the Virginia Commonwealth University School of Medicine (VCU SOM) project during development and construction, is a 13-story building that has both a basement and small sub-basement located below ground level, which is at an elevation of 153 feet. Since the VCU SOM project was constructed following the demolition of the A.D. Williams Building, the foundation system is designed to accommodate existing conditions. The superstructure of the building is composed of a composite concrete/steel deck with steel members and steel concentrically braced frames. Both the 13th Floor and the rooftop house mechanical equipment, requiring added strength. All of these systems are further explained below.

Foundation System

All site investigation and test drillings, six borings total, were completed by Geotech Inc.; their professional recommendations were then reported in April of 2009. Of the four schemes suggested, an arrangement using three differently sized piers extending 54'-0" below the sub-basement level was applied. The different drilled piers used were intended to account for three variations of loadings: those loads considered "small" (≤ 450 kips), "medium" (730 to 1640 kips), and "heavy" (1640 up to roughly 3300 kips). To support all "small" loads, straight shaft drilled piers ranging in diameter from 3'-0" to 8'-0" were used. When loads were considered "medium", single-belled drilled piers with shaft diameters from 3'-0" to 6'-0" were used, under the condition that the bell diameters were not to exceed 3 times the shaft diameters. For all the "heavy" loads, double-belled drilled piers were utilized, with shaft diameters between 3'-0" and 6'-0" and bell diameters between 9'-0" and 13'-6". Test boring sites, drilled pier schemes, and column layouts for the Sub-Basement and Basement Levels can be found in Appendix A: Structural System Overview for reference.

During Geotech Inc.'s thorough site investigation, it was concluded that some existing piers would in fact conflict with piers necessary for support of columns in the new construction. To avoid removal of existing piers, a caisson grade beam system was used where conflicts existed. The grade beams used in this configuration are all 48" deep and range in width, from 24" to 60". The sub-basement and portions of the basement floors are slab-on-grade – there are two different slab-on-grades, but the differences are only minor. The slab-on-grade located at the sub-basement level is 6" concrete slab on 4" crushed stone and the slab-on-grade located at the basement level is 5" concrete slab on 5" crushed stone.

Floor System

The typical slab-on-deck found on floors 2 through 12 is a composite concrete/steel system. Most floors utilize 3", 20 gauge composite galvanized steel decking with a 3 ½" lightweight concrete topping. ½" diameter steel rebars placed at 12" on center provide reinforcement for the concrete. Shear studs, placed along the beams and girders, provide for composite behavior between the members and floor system. Variations of the composite concrete/steel floor system for each floor can be seen in Table 1.

Building Floor	Concrete	Steel Decking	Reinforcement
1st	5" LW	3", 16 Gauge	#4@12" o.c. each way
2nd	3 ½" LW	3", 16 Gauge	#4@12" o.c. each way
3rd	3 ½" LW	3", 20 Gauge	#4@12" o.c. each way
4th	3 ½" LW	3", 20 Gauge	#4@12" o.c. each way
5th – 12th	3 ½" LW	3", 20 Gauge	#4@12" o.c. each way
13th	8" NW	3", 16 Gauge	#4@12" o.c.

Table 1 – Slab-on-Deck Components by Building Floor

Framing System

The VCU SOM framing system is composed of steel members: columns, beams, and girders. Since a variety of loads are applied, the columns range anywhere in size from W10x88 to W14x455, with the majority of the columns closer in size to W14x145. Beams and girders throughout the structure are also composite steel construction; the beams are typically W18x35 and the girders are typically W24x76, excluding areas where extra strength is required.

Due to the irregularity of the structure's shape, a single typical bay is not common throughout the entire building. However, the 4th thru 13th Floors are closer in design and function, and therefore are more ordered. There are two bay sizes that make up the majority of these floors: a 30' x 20' bay and a 30' x 40' bay. A typical floor plan showing the 30' x 20' size bay can be seen in Figure 2 at the top of the following page. To allow for open classroom space on several floors, the 30' x 40' bay is necessary, explaining the variant bay size. In the typical bays (both 30' x 20' and 30' x 40'), the beams span the 30'-0" length.

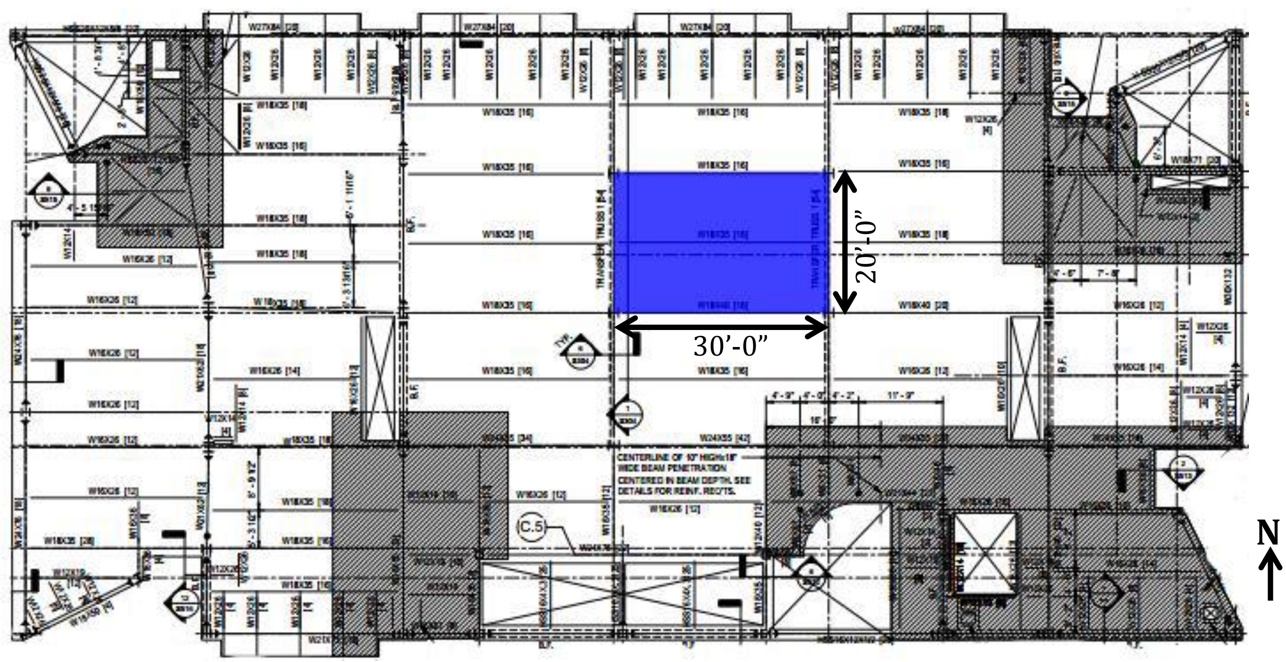


Figure 2 – Typical Floor Plan with Typical 30' x 20' Bay Size Emphasized

Lateral Force Resisting System

The VCU SOM's main lateral force resisting system is a combination of braced frames and moment connections throughout the structure. There are seven steel concentrically braced frames, six traveling in one direction, with one frame contributing to the strength in the other path. The braced frames can be found highlighted in Figure 3. The layout of the braced frames accounts for lateral loads that could be applied from any of the possible directions. All of the frames are concentric, but each frame differs in size, material used [wide flange or HSS (Hollow Structural Sections)], and levels included. Detailed drawings of the seven braced frames can be found in the supplemental drawings in Appendix A: Structural System Overview. A basic description of the applied lateral loads can be found on the following page.

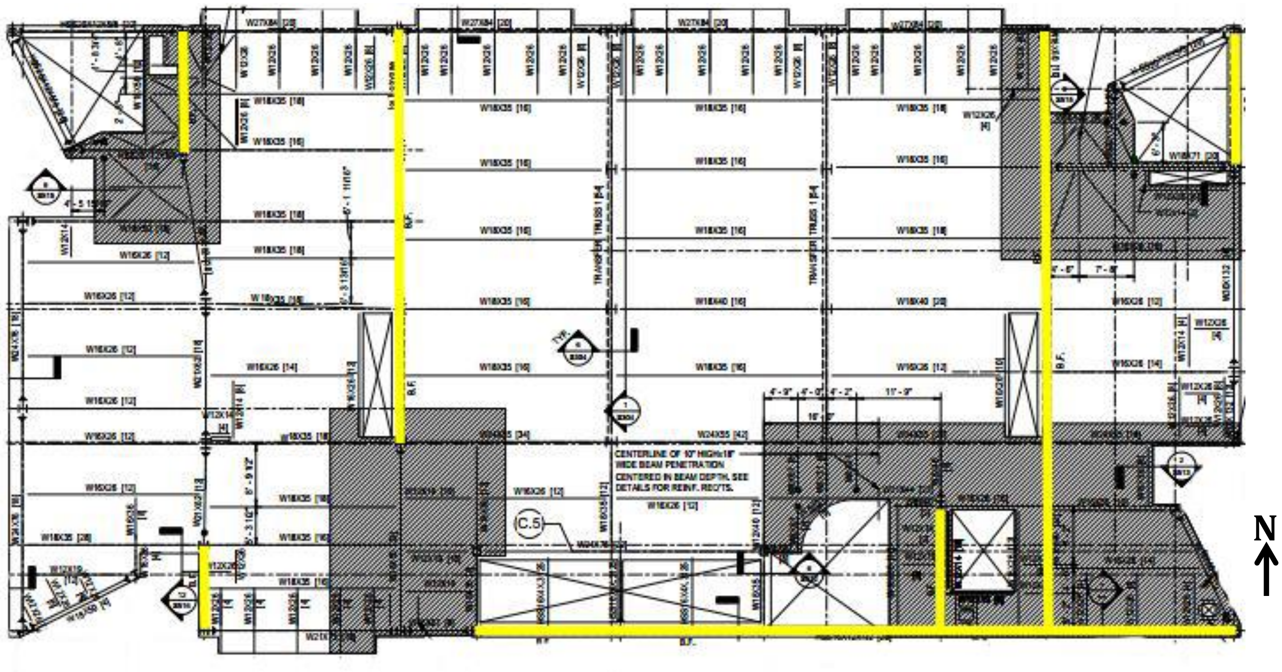


Figure 3 – Framing Typical to Floors 4th thru 12th with Braced Frames Highlighted

As seen in Figure 3, the braced frames throughout the structure span both directions, with the majority of the strength running North to South. The VCU SOM project is surrounded by equally tall buildings, but the wind tunnel effect cannot be discounted. The basic idea behind the lateral force resisting system used in this project is that all “roads” will lead to the braced frames. Lateral loads hitting the building from any direction will traverse perpendicularly from their original direction across the floor through the beam and girder system. These loads will then be applied to the braced frames, which have been designed to withstand these pressures.

Roof System

The roofing system found in the VCU SOM project consists of 1 ½”, 18 gauge wide-rib steel roof deck covered with a rubber roofing membrane (EPDM). This Ethylene-Propylene-Diene-Monomer (EPDM) rubber roofing is fully adhered on top of tapered insulation. Often referred to as white roofing for its coloring, EPDM installed in this building was required to have a specific solar reflectance to contribute to LEED certification. The roof deck is supported from below by W16x26 beams spaced at 5’-0” and W27x84 girders every 30’-0”.

Bridge to Main Hospital

One of the more complicated structural elements found in the VCU SOM project is the bridge that connects the 2nd Floor to the existing Main Hospital, crossing E. Marshall Street. Approximately 65’ in length, the bridge exits the VCU SOM building at an angle and travels on a diagonal towards the Main Hospital, as shown in Figure 4. The bridge also slopes 2" towards the Main Hospital, starting at an elevation of 169'-2" and ending at an elevation of 169'-0". The bridge has a height of roughly 14'-6" from the surface of the bridge floor to the bottom of the roof deck (at the intersection with the VCU SOM project). Plan and elevation views of the bridge are available in Appendix A: Structural System Overview for further inspection.

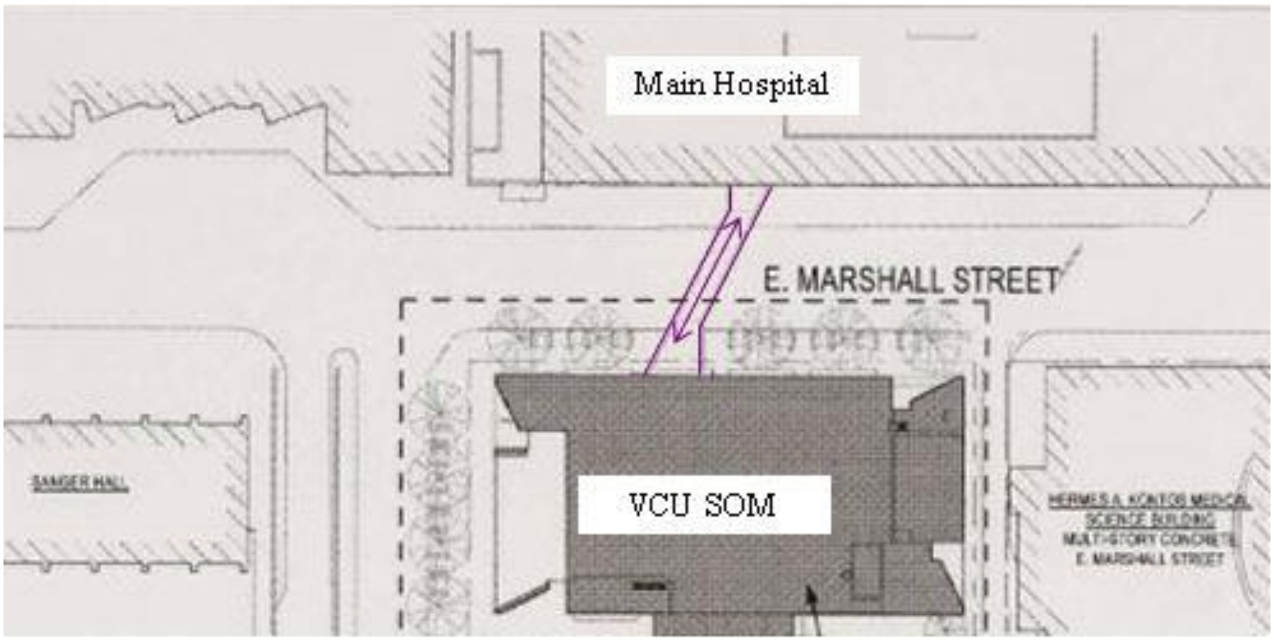


Figure 4 – Bridge Connecting VCU SOM to Main Hospital across E. Marshall Street

Structural Design Alternative

Objective

As mentioned in the Structural System Overview, the VCU SOM building is composed of steel structural members, a composite concrete/steel floor system, and steel concentrically braced frames. While investigating alternate systems in Structural Technical Report III, it was determined that steel was the most economical option for the gravity system. Steel is moderately easy to construct, reasonably priced, and lightweight. While a composite deck and beam/girder system is used in the project, the possibility exists that using alternative steel systems could help reduce costs, decrease the schedule, and allow for larger spans and bay sizes.

The Lateral Load Resisting System for the VCU SOM building could also be altered to ultimately improve the building as a whole. The current system, seven concentrically braced frames, limits the layout for classrooms, offices, and open learning spaces on each level. With the addition of moment frames traveling in the East-West direction of the structure, the opportunity exists to edit and/or eliminate the bracing in the North-South direction.

Proposed Solution

In order to ensure the most efficient gravity system is being used, an alternative steel system will be designed and compared to the original. From Structural Technical Report III, it was determined that a gravity system consisting of non-composite decking with K-series bar joists and steel girders could be feasible. The use of bar joists has the potential for a decreased schedule, but the question does exist if the bar joists really are less expensive in the “big picture” of the building. The validity of the alternative steel system will be analyzed not only for its structural strength, but also its feasibility and serviceability.

The lateral load resisting system will also be altered to ensure the most effective system is in place; both moment and braced frames will be used in conjunction in hopes of creating a more efficient, open building. Braced frames will remain in the North-South direction, but moment frames will be designed to travel in all directions of the structure. With the addition of the moment frames, some of the current braced frames will either be edited or removed entirely. The editing of the braced frames, to occur after preliminary design of the moment frames, will be based on the strength required to carry the lateral loads and resist applicable torsional effects.

Solution Method

The redesign of the steel gravity system will be completed with the assistance of the Steel Design Guide 11, AISC Steel Construction Manual, and Vulcraft Steel Roof & Floor Deck Catalog. Non-composite flooring, steel floor framing members, and columns will be designed by hand. Once member sizes are found, they will be compared to RAM design output utilizing the same loadings to ensure both hand calculations and RAM output is accurate for given conditions.

The redesign of the lateral load resisting system will require more iteration, especially since the braced frames will involve editing or elimination. The AISC Steel Construction Manual will again be referenced, along with specific design examples found on the AISC website. Once a preliminary design is found using hand calculations and application of basic wind & seismic loadings, a RAM model will be created and verified. Utilizing RAM, all other wind & seismic loadings will be completed to ensure no extreme torsional effects exist.

Breadth Studies

Cost & Schedule Analysis (Breadth 1)

While the new structure (both gravity and lateral load resisting systems) will remain steel construction, both the cost and schedule need to be further analyzed to fully understand the effects of the redesign. It is misleading to state that the cost will decrease due to the gravity system change – K-series joists are typically less expensive in comparison to rolled beams when only considering the amount of steel required and installation. However, K-series joists result in higher floor vibrations, larger floor-to-floor heights, and additional fireproofing measures. All of these consequences have an associated price that affects the total cost of the project. An in-depth cost analysis will need to be completed for the entire project and then compared to the original to have an accurate comparison. A schedule analysis will also be completed, focusing solely on the structural system, since the redesign will change lead times, installation, and fireproofing required. The new schedule will then be compared to the structural system schedule for the original project.

Architectural Considerations (Breadth 2)

The VCU SOM project was intended to create an environment conducive to a redesigned curriculum for the school – open floor plans that provide spaces for team meetings, faculty consultations, and large group classes. While the original design achieved this on several floors, the opportunity exists to create more open spaces with the redesign of the lateral system. With addition of moment frames traveling in the East-West direction, some of the braced frames traveling North-South could be eliminated or removed entirely. The editing or removal of braced frames could produce a more open environment, void of cumbersome steel bracing members. Fireproofing requirements for the building could also be altered due to the installation of a redesigned structural system. Spray applied fireproofing on K-series joists is more time intensive and costly due to the increased depth and varying shape – this increase in time and cost could be offset with alterations to the existing passive and active fire measures. Another architectural impact caused by the redesign stems from the gravity system: K-series joists typically are deeper when supporting the same floor. The added height would result in larger floor-to-floor heights, affecting the final elevation of the building. All of the architectural impacts will need to be considered to validate if the structural design alternative is truly feasible.

Depth – Structural Redesign

Gravity System

In order to achieve a more efficient gravity system, the investigation revolved around considering all possible configurations of joists and girders for the typical bay sizes found in the VCU SOM project. The four possible configurations examined are listed below:

I. 30' x 20' bay with joists traveling in the 30' direction (E-W)
II. 30' x 40' bay with joists traveling in the 30' direction (E-W)
III. 30' x 20' bay with joists traveling in the 20' direction (N-S)
IV. 30' x 40' bay with joists traveling in the 40' direction (N-S)

All configurations were designed to have a 2 ½" NW concrete topping to satisfy the necessary 2 hour fire rating for the slab. Normal weight concrete was chosen in order to compare and contrast to the original design, which featured lightweight concrete on all slab-on-decks (excluding the roof).

Joist & Girder Sizing

Hand calculations, which can be found in Appendix B: Gravity System Redesign, were completed for all four layouts. Assumptions were made for the applicable live and dead loads based on previous analysis of the original gravity system. Steel decking was designed to both span the necessary lengths and also support the calculated superimposed uniform loads. Due to the similar span lengths, configurations with joists traveling in the same direction were designed to have the same steel decking. New total loads were calculated, taking in to consideration the weights of both the concrete and steel deck.

From the total loads, both the factored and unfactored uniformly distributed loads were found. Using these numbers and referencing the Catalog of Standard Specifications and Load and Weight Tables for Steel Joists and Joist Girders (42nd Edition), appropriately sized joists were selected. Weights of joists, load capacities, and depths were all considered to ensure economical selections were made. K-series joists were satisfactory for all four configurations, eliminating the need to install stronger long-span joists.

Factored uniformly distributed loads were once again calculated – this iteration considered the loads applied to the wide flange girders. Using the uniformly distributed loads, the required strength, or bending moment, was found. Possible girders were then selected based on available strength and required moment of inertia to meet live load deflection requirements.

Vibration Control

A major concern when using joists in steel framed floor systems is vibration serviceability due to human traffic. Since the VCU SOM project does contain areas used for offices, classrooms, and laboratories, it was necessary to check all four configurations for vibration in order to achieve comfort for the building occupants. While live load deflections were considered when redesigning the girders, this is not enough to ensure noticeable vibrations won't occur in the framing system.

Utilizing the AISC (American Institute of Steel Construction) Design Guide 11, all four configurations were evaluated for both walking excitation and floor stiffness. In an office setting, it was determined that an acceleration of 0.5%g (acceleration of gravity) was the maximum accepted. The floor stiffness must also be less than 9 Hz. The deflection, panel width, and panel weight were found separately for the joists and girders. The properties were then combined to find the total deflection, frequency, and equivalent weight for the framed floor system. These values were then compared to the requirements previously mentioned. When reviewing the results for the four configurations, it was determined that I, II, and III met the requirements. Configuration IV [30' x 40' bay with joists traveling in the 40' direction (N-S)] did not meet the standards for offices for the walking evaluation, having a maximum acceleration of 0.58%g. The detailed calculations for vibration control for all four configurations can be found in Appendix B: Gravity System Redesign.

RAM Analysis

To fully compare the efficiencies of the four configurations, separate RAM models were created and analyzed for each possible bay layout. A basic rectangular layout, similar to the actual shape of the VCU SOM project, was created and used in each model. Views of the elements and layout from the RAM models can be viewed in Appendix B: Gravity System Redesign.

All assumptions made were kept throughout each trial to ensure a fair comparison. The loadings and concrete thickness assumed during hand calculations were also applied to the RAM models, along with the steel decking that was designed to support the uniformly distributed loads. The RAM Beam Design function was then used to find the joists and girders necessary to carry the assumed loadings.

Once the members were calculated for each configuration, the results were compared to the hand calculations performed. Not only did this comparison serve as a check for the hand calculations, but also demonstrated the ability to use computer modeling as a design assistance tool. The comparisons between the results can be seen in Table 2 and all calculations can be found in Appendix B: Gravity System Redesign. Checks were completed for all joists and girders calculated in the RAM model. For the joists, both the factored and unfactored uniformly distributed loads were checked to meet requirements found in the hand calculations. Required strength and required moment of inertia, determined during hand calculations, were verified for the girders designed using the computer modeling program. Only minor differences were found between the two means of design, verifying the results.

	Bay Size	Decking	Hand Calculations		RAM Model		Final Evaluation	Issues
			Joists	Girders	Joists	Girders		
I	30’ x 20’	1.0C24	22K10	W18x35	28K7	W18x40	Yes	-
II	30’ x 40’	1.0C24	22K10	W24x146	28K7	W30x108	No	$\phi M_n < M_u$
III	30’ x 20’	0.6C24	14K4	W24x68	16K3	W24x55	No	$\phi M_n < M_u$
IV	30’ x 40’	0.6C24	26K12	W24x76	30K9	W27x84	Yes	-

Table 2 – Gravity System Redesign – Comparison of RAM Output to Hand Calculations

Design Summary

To finalize the design of the gravity system for the VCU SOM, all factors previously mentioned had to be considered. Economical decking, joists, and girders were selected for the four possible configurations, taking in to account the applied loadings and deflection limits. Although all of the steel members met the necessary requirements during initial hand calculations, one configuration in particular, IV [30’ x 40’ bay with joists traveling in the 40’ direction (N-S)], did not meet vibration serviceability requirements due to human traffic. In order to avoid the need for additional bracing in the floor framing system, configuration IV was eliminated as a possibility.

Reviewing the RAM models, it was decided that using a combination of configurations I and II would be satisfactory for the gravity system. The finalized design can be seen in Table 3. The finalized design is a combination of members found using both methods of design (hand calculations and RAM modeling). A more advanced RAM model, one almost identical to the VCU SOM project in size and shape, was created using the finalized design and it met all requirements when analyzed in the program.

	Bay Size	Decking	Joists		Girders	
			Size	Length	Size	Length
I	30’ x 20’	1”, 24 gauge	22K10	30’-0”	W18x40	20’-0”
II	30’ x 40’	1”, 24 gauge			W30x124	40’-0”

Table 3 – Final Design for Non-Composite Steel Gravity System

Since the floor framing system (decking, joists, and girders) had been finalized, it was necessary to find columns capable of supporting both bay sizes. With the member sizes found in Table 3 above, the dead load for framing was calculated and added to the assumed loads mentioned earlier. The controlling load combination (1.2D + 1.6L + 0.5Lr) was determined and was used to find the total axial loads. For configurations I and II, W14x120 and W14x233 members were determined to be adequate (respectively). These members were compared with the more advanced RAM model, and their legitimacy was verified.

Lateral System

Similar to the gravity system redesign, it was determined that steel was still the most efficient option for the lateral load resisting system. The original system, highlighted in yellow in Figure 3 found on page 10 and also shown below, was composed of seven concentrically braced frames. As proposed, a predominantly moment frame system with only limited bracing was investigated. The installation of moment frames and removal of braced frames not only allows for the possibility of a more open floor layout, but also decreased the drift and torsional effects on the building.

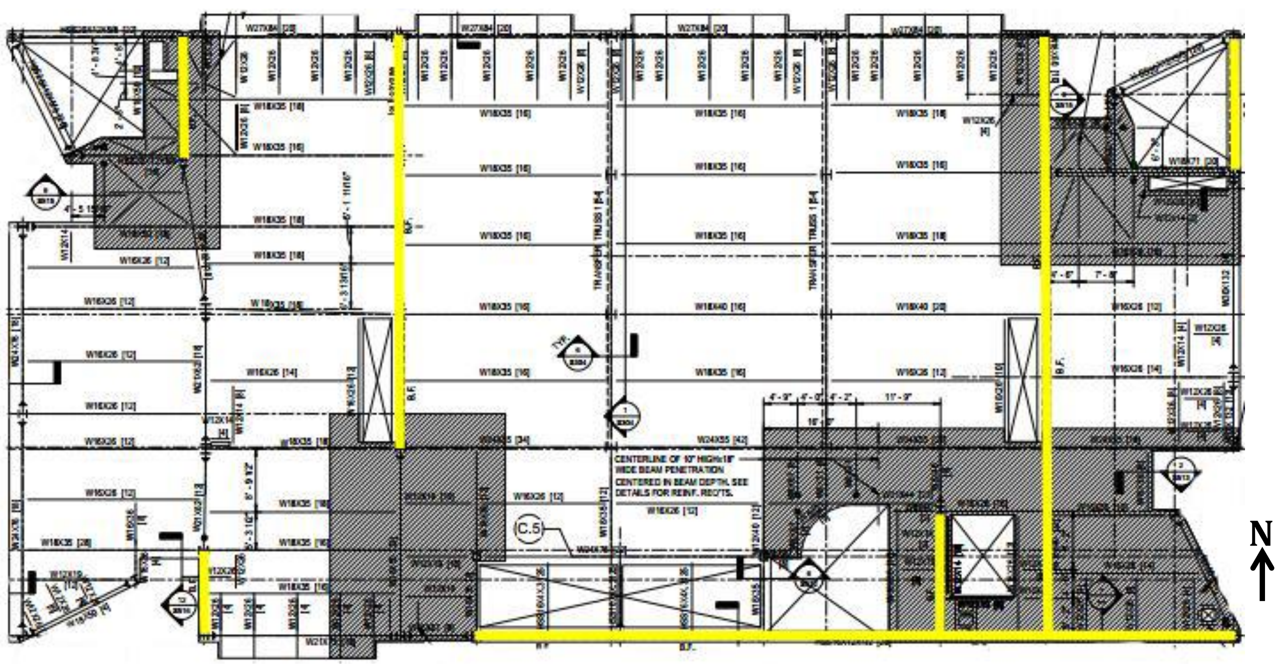


Figure 3 – Framing Typical to Floors 4th thru 12th with Braced Frames Highlighted

Loadings for Redesign

To accurately assess the lateral load resisting system, calculations were first completed for the applicable wind loadings and seismic loadings. The loadings found can be seen below, while the hand calculations can be referenced in Appendix C: Lateral System Redesign. Table 4 and Table 5 highlight the wind loadings applied in the X-direction (E-W) and Y-direction (N-S), respectively. The seismic loadings (same values for both directions) are shown in Table 6.

Floor	Contributing Ht (ft)	Floor-to-Ground Ht (ft)	Length (ft)	Resultant Wind F (k/ft)	Story Load (k)	Story Shear (k)	Overturning M (ft-k)
Roof	10	196	86	0.11	9.8	9.8	1917
13	17.333	176	86	0.38	32.9	42.6	5783
12	14.667	161.33	86	0.32	27.3	69.9	4396
11	14.667	146.67	86	0.31	26.8	96.7	3932
10	14.667	132	86	0.30	26.2	122.9	3456
9	14.667	117.33	86	0.30	25.5	148.4	2990
8	14.667	102.67	86	0.29	24.5	172.9	2514
7	14.667	88	86	0.28	24	196.8	2109
6	14.667	73.33	86	0.27	23	219.8	1688
5	14.667	58.67	86	0.26	22	241.8	1288
4	14.667	44	86	0.24	20.7	262.5	912
3	14.667	29.33	86	0.22	18.9	281.4	554
2	7.333	14.67	86	0.21	17.8	299.2	260

Table 4 – Calculated Wind Loadings Applied in the X-Direction (East-West)

Floor	Contributing Ht (ft)	Floor-to-Ground Ht (ft)	Length (ft)	Resultant Wind F (k/ft)	Story Load (k)	Story Shear (k)	Overturning M (ft-k)
Roof	10	196	177	0.25	44.3	44.3	8683
13	17.333	176	177	0.40	70.8	115.1	12461
12	14.667	161.33	177	0.38	67.3	182.4	10858
11	14.667	146.67	177	0.37	65.5	247.9	9607
10	14.667	132	177	0.37	65.5	313.4	8646
9	14.667	117.33	177	0.36	63.7	377.1	7474
8	14.667	102.67	177	0.35	62	439.1	6365
7	14.667	88	177	0.34	60.2	499.3	5298
6	14.667	73.33	177	0.33	58.4	557.7	4283
5	14.667	58.67	177	0.32	56.6	614.3	3321
4	14.667	44	177	0.30	53.2	667.4	2336
3	14.667	29.33	177	0.28	49.6	717	1455
2	7.333	14.67	177	0.27	47.8	764.8	701

Table 5 – Calculated Wind Loadings Applied in the Y-Direction (North-South)

Floor	Story Force (k)	Story Shear (k)	Overturning M (ft-k)
Roof	70.9	70.9	13896
13	66.5	137	24112
12	57.4	195	31460
11	48.8	244	35787
10	40.8	284	37488
9	33.4	318	37312
8	26.6	344	35317
7	20.7	365	32120
6	15.2	380	27867
5	10.4	391	22939
4	7	398	17512
3	3.5	401	11763
2	0.9	402	5896

Table 6 – Calculated Seismic Loadings Applied in Both X and Y-Directions (E-W & N-S)

When comparing the loadings shown above, wind loadings, more noticeably in the Y-direction (N-S), controlled for the redesign of the lateral load resisting system. Four different cases were possible for the wind loadings, based on the eccentricity of the redesigned structure. The eccentricity, or difference between the Center of Mass and Center of Rigidity of the structure, also contributed to the torsional effects applied to the building.

The original structural system had a large eccentricity due to the placement of the seven braced frames. In order to achieve a much smaller eccentricity (and therefore decrease torsion on the structure), it was an important goal to create a more symmetric layout for the new lateral load resisting system. Another aim, mentioned previously, of the redesigned lateral system was to eliminate as much bracing as possible. Using the loading calculations, original system frame participation, and the finalized redesigned gravity system, addition of moment frames, in a symmetric and logical pattern, was completed. The design of the new system was mainly completed using RAM modeling tools, and this analysis will be described in the following section.

RAM Analysis

A preliminary moment frame layout was created using information gained through study of the structure and the applied loadings; the initial layout of the moment frames can be seen highlighted in Figure 5. Members were initially sized by level, using wide flange steel members on the same magnitude as the original design. Wind Loads (only Case 1), previously determined to control the design, were applied to the frames and the deflected shapes were reviewed. Using the Drift function of RAM Frame Modeler, the participation of each frame was also reviewed.

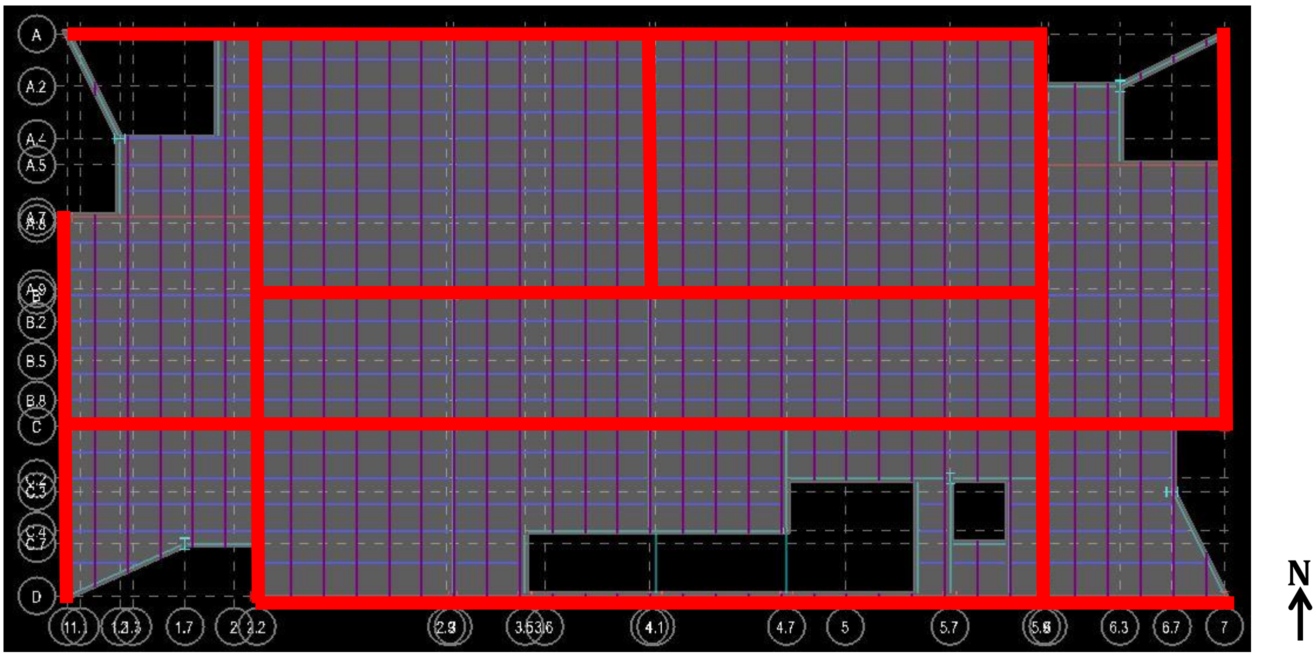


Figure 5– Layout of Moment Frames for Redesigned Lateral Load Resisting System – Iteration #1

Using both the deflected shapes and the frame participation, it was determined that this layout was not the most efficient option. Deflections were unacceptable in the X-direction (E-W), specifically on the North side of the structure. Drift was also large on the East and West ends for wind loadings traveling in the Y-direction (N-S), with the frame located half way across the X-axis having little contribution to the resistance of the lateral loads. The layout of the moment frames was reviewed and altered several times before finalizing the moment frame layout found in Figure 6.

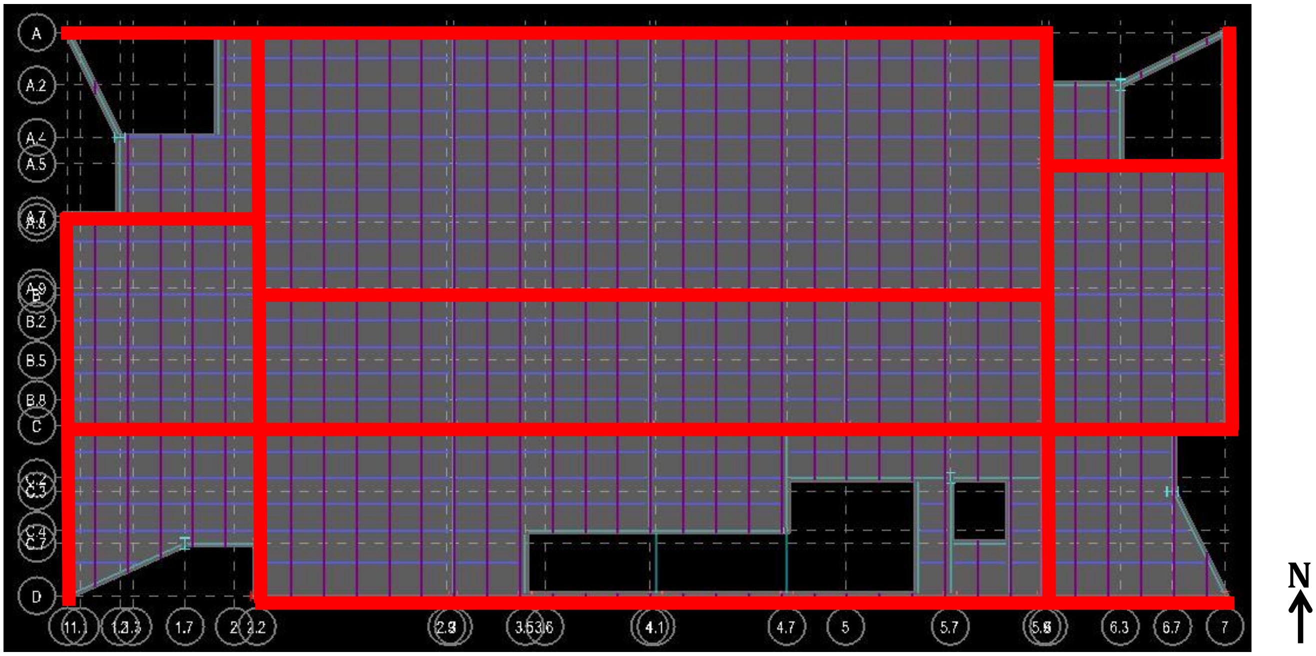


Figure 6 – Finalized Layout of Moment Frames for Redesigned Lateral Load Resisting System

The finalized moment frame layout found in Figure 6 eliminated the drift concerns in the X-direction (East-West); however, deflections in the Y-direction were still large and did not meet the requirements. Due to the large wind loadings in the Y-Direction, it was determined that a few of the frames would require the original bracing. Frames on the exterior of the building or located at elevator/stair shafts were the only viable options due to the goal to decrease bracing in interior spaces. As shown highlighted in yellow in Figure 7 on the following page, three sections of the original braced frame layout were selected, modeled in RAM, and then analyzed. The addition of the original bracing in those three sections remedied the deflection issues – drift requirements were met for both wind loads (all four cases) and seismic loads. With the finalized system, eccentricity was also greatly decreased when compared to the original system. All of the eccentricity and drift calculations can be found in Appendix C: Lateral System Redesign.

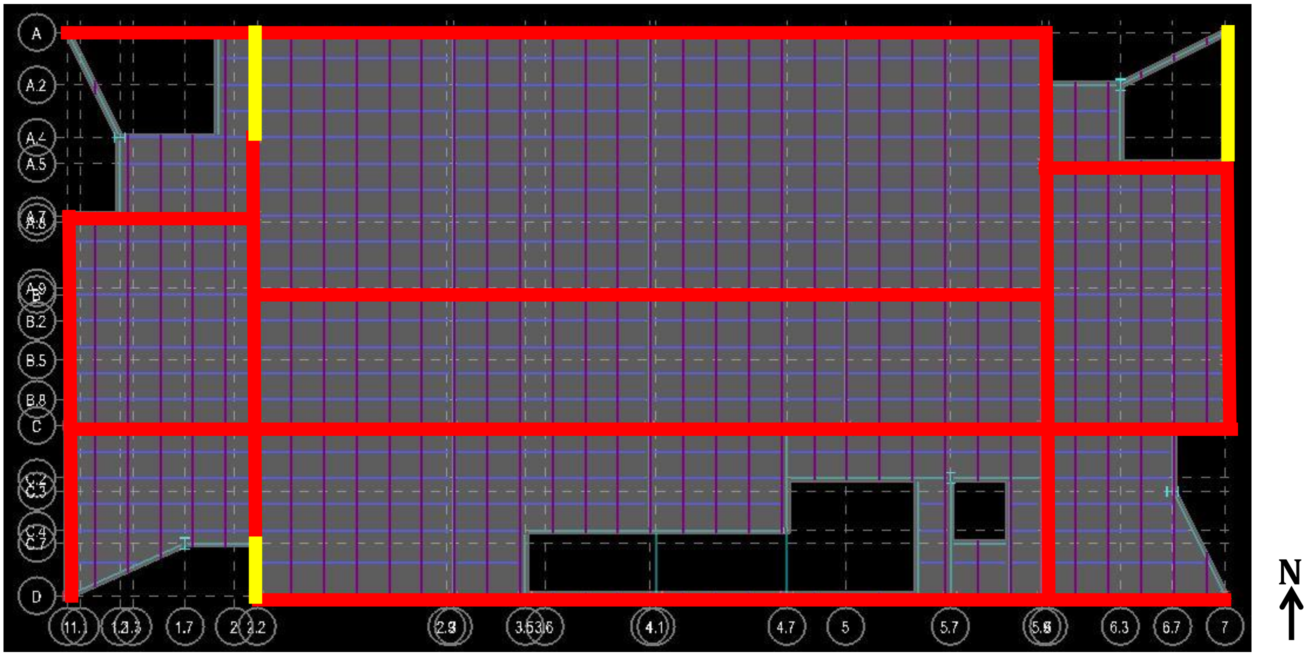


Figure 7 – Finalized Lateral Load Resisting System – Combination of Moment & Braced Frames

Design Summary

When comparing the redesigned lateral load resisting system versus the original, there are several positive points that emerge. First, the introduction of a mainly moment frame system eliminated the need for extensive bracing throughout the structure. Some bracing was required, but it was strategically placed in order to avoid interference with the floor plans. The moment frame system also used members roughly on the same magnitude as the original system. Some columns and girders were enlarged to carry more of the anticipated loadings, but the changes were not extreme. Most importantly, the moment frame system was capable of controlling drift just as well, if not better, than the original braced frame system. When comparing the drift results to those found in Structural Technical Report IV: Lateral System Analysis Study, the moment frame system has lower values at almost every single level for all wind and seismic cases.

Structural Redesign Conclusions

As mentioned previously, it had been determined prior to the commencement of the redesign that steel would be the most economical option for both the gravity and lateral systems. The original system consisted of composite concrete/steel floor system with wide flange beams and girders and concentrically braced frames with moment connections. The objective of the redesign was to find alternative steel systems that could perform to the same standard while potentially reducing the cost, decreasing the schedule, and eliminating cumbersome members where appropriate. The floor framing and lateral framing systems were designed with these objectives in mind, and these goals were in fact achieved. A gravity system of non-composite flooring with K-series joists and wide flange girders was designed – not only was it deemed capable of spanning the bays without unsatisfactory vibrations, but it also reduced the total system weight, allowing for slightly smaller columns. The lateral system also reached these goals; an almost entirely moment frame system with minimal bracing was able to meet all drift requirements while eliminating some bracing throughout the structure.

Cost & Schedule Analysis (Breadth 1)

When investigating alternative structural systems in Technical Assignment III: Typical Member Spot Checks & Alternate Systems Design, it was determined that steel would result in not only the most efficient system but also the least expensive. This was a key factor in choosing to remain with steel when redesigning the gravity and lateral systems. While some may argue that the change to a joist system will be cheaper than using wide flange members, it is not entirely a true statement. The material required is in fact less expensive, but additional measures must be taken when using a joist system that affects the cost of the entire project. The amount of time required to install joists is also less when compared to the original system (with heavier members and welded shear connections), but the application of fireproofing is more intensive and time-consuming for the redesign. This breadth focuses on the cost (both structurally and for the total project) and schedule (just gravity system) comparisons; information on both can be found in more detail below.

Cost Impacts

Structural System Cost Effects

While the original and redesigned gravity systems are both composed mainly of steel members, there is a significant difference in price for material and installation. To accurately compare the two systems, RSMeans Building Construction Cost Data from 2013 was used to identify the total price for all items found in each gravity system. Both the typical short (30' x 20') and long (30' x 40') bays were analyzed for the original and redesigned gravity systems. The finalized price per square foot for each bay analyzed can be found in Table 7; the detailed estimates are located in Appendix D: Cost & Schedule Analysis (Breadth 1).

		Material ($/SF)	Installation ($/SF)	Total ($/SF)
Original System	Short Bay	14.79	2.72	17.50
	Long Bay	22.50	2.45	24.95
Redesigned System	Short Bay	10.01	3.69	13.70
	Long Bay	17.88	3.69	21.52

Table 7 – Comparison of Structural System Costs between the Original & Redesigned Systems

Evident from the comparison seen in Table 7, the redesigned system featuring non-composite decking, K-series joists and wide flange girders was less expensive in terms of material and installation. The averages for each system are as follows: Original System was $21.23/SF on average and Redesigned System was $17.61/SF. The total gross square footage for the building was roughly 220,000 – the redesigned system could potentially decrease the project cost by $725,000. However, this decrease in cost only reflects the changes to the gravity system. To accurately assess the savings gained by the redesign, the total project cost effects had to be evaluated.

Total Project Cost Effects

There are two main areas that were researched when assessing the additional costs of a joist framing system: curtain wall changes and added fireproofing. As discussed in "A Whole Building Cost Perspective to Floor Vibration Serviceability" by Professor Linda M. Hanagan, PhD, PE, and Melissa C. Chattoraj there is not as large of a variance in cost between rolled beam systems and joists systems, especially when the cost of the whole building is reviewed. It is a common misconception in the construction industry that lighter members intrinsically are cheaper – this, however, does not account for ripples felt throughout the entire structure.

The redesigned system was roughly 15 psf less than the original system – the depth of the redesign system though was increased by about 6". This increased system depth could affect the building in two ways:

1. If the floor-to-floor height must remain 14'-8", the ceiling height would need to be reduced from 11'-0" to 10'-6".
2. If the ceiling height must remain 11'-0", the floor-to-floor height would need to be increased from 14'-8" to 15'-2". This would increase the total building height from 196'-0" to roughly 203'-0".

Both of the options above would result in changes to the curtain wall system. In the worst case scenario, this change in gravity system would cause a 4% increase in the square footage of the curtain wall system.

Another area that would be altered due to a joist floor framing system would be the required fireproofing to meet code standards. Once again, there are two possible options:

1. Spray-Applied Fire Resistive Material (SFRM) on all steel members, non-rated ceilings, and sprinklers throughout all areas
2. Factory applied fire resistive material on joists, field SFRM on girders, rated ceilings, and non-sprinkler areas where acceptable

The first option (more similar to the original system) would cause about $0.90/SF increase to the original cost – the second option, deviating from the original system, would increase the original cost by $1.15/SF. These changes when compared to the original cost are 4% and 5.5% increases, respectively. Breakdowns of the exact costs for the fireproofing changes can be found in Appendix D: Cost & Schedule Analysis (Breadth 1) for reference.

Schedule Impacts

An estimated schedule for the installation of the original steel floor framing system was obtained from Gilbane Building Company – a copy of this schedule can be seen in Appendix D: Cost & Schedule Analysis (Breadth 1). The duration for steel erection, detailing, and setting of deck was 122 days for the original system. Pouring of the elevated floor slabs and fireproofing all members required 89 days in the original schedule. The final action in the steel sequence, removal of the tower crane, infilling the building hole where it resided and pouring concrete for said building hole, was 31 days.

In order to gain an accurate picture of the time required to install the redesigned system, a new schedule (focusing solely on the floor framing system) was created using Microsoft Project. A detailed copy of this schedule can be found in Appendix D: Cost & Schedule Analysis (Breadth 1). Using the daily output values from RSMeans and restrictions found in the original schedule, durations for tasks were assigned. On average, the erection and detailing of the redesigned system would take 2 to 3 days less per sequence. Not only are joists easier to pick and set (lighter construction), the non-composite system does not require labor intensive welded shear connectors. Conversely, the time required to fireproof was increased due to the intricacy of the joists. The work associated with tower crane removal and infill of the hole it left remained the same duration, 31 days.

Comparison to Original System

The redesigned gravity system, though similar in materials to the original building, caused many changes in the anticipated cost and duration of the VCU SOM project. As expected, the redesigned system featuring non-composite decking and K-series joists was cheaper when comparing floor framing materials and installation. However, other costs associated with the installation of the new system were investigated and proved to have merit. Even though several extra feet of a curtain wall system might seem insignificant for a towering building, this change would cause roughly a 4% increase on a substantial part of the budget. The additional fireproofing required directly affects the cost of the project as well – it would add on average $1.03/SF, or $200,000 if applied over the entire structure. In the end, the redesigned system would still be less expensive than the original; however, the savings achieved wouldn't necessarily be enough to justify the change.

The schedule for the project would also be greatly influenced by the change to the gravity system. Keeping with the time restrictions applied to the original project, a new schedule was created for the redesigned gravity system. The lightweight joists would be easier to lift, place, and detail when compared to the original wide flange beams, which would result in time savings during the steel sequencing. The fireproofing, however, would require more days of work to ensure the spray applied material was up to code standards. In the end, the redesigned system would reduce the schedule, saving roughly a week of work – a substantial amount of time by construction standards, especially when time equals money.

Architectural Considerations (Breadth 2)

Prior to the inception of the James W. & Frances G. McGlothlin Medical Education Center, VCU School of Medicine began efforts to completely reevaluate their curriculum, hoping to change the way medicine was taught in the 21st century. After identifying the key themes that both faculty and students valued, VCU SOM worked with architects and engineers to create a building that would reflect these changes. The VCU SOM project was born, and with it the hope to foster open, cooperative learning among students, faculty, and staff. While the original building did achieve the goals set out by the VCU SOM, changes made to both the gravity and lateral systems in the redesign were determined to affect, both positively and negatively, architectural aspects of the project.

VCU Program Requirements

Some of the key goals of the VCU SOM project directly reflected changes that had been made to the curriculum prior to and during construction. Of the eight themes detailed in the VCU SOM curriculum, two of the objectives directly correlated with the layout of the project. First, the "Ability to function in systems and to teach each other (teams)" had a major impact on the design. Most floors of the building were outfitted with areas for student interaction, readily available work stations, and other student centric spaces. This objective also specifically stated that "learning teams" (groups of students) should have easy access to teachers on an almost daily basis. The second theme that had an impact on the original design was the goal to "Be active learners". This goal highlighted the move from PowerPoint dependence to a more active lecture environment. Student participation was emphasized, specifically in lectures and classrooms – the building, therefore, was designed to have multiple lecture rooms with smaller meeting rooms adjacent for student led discussions.

Effects of Eliminated Bracing

As detailed above, the VCU SOM redesigned curriculum focused on the need for cooperation and communication – not only among students, but also between faculty and staff. With the elimination of several braced frames, specifically those on column lines 3 and 6, in the lateral system, the opportunity existed to create an even more open environment to promote team learning. Shown in the RAM modeled floor plan in Figure 8, the redesigned moment frame system (with limited bracing) is highlighted in red. The original braced frames that created the most limitations in terms of floor layout are shown in light blue.

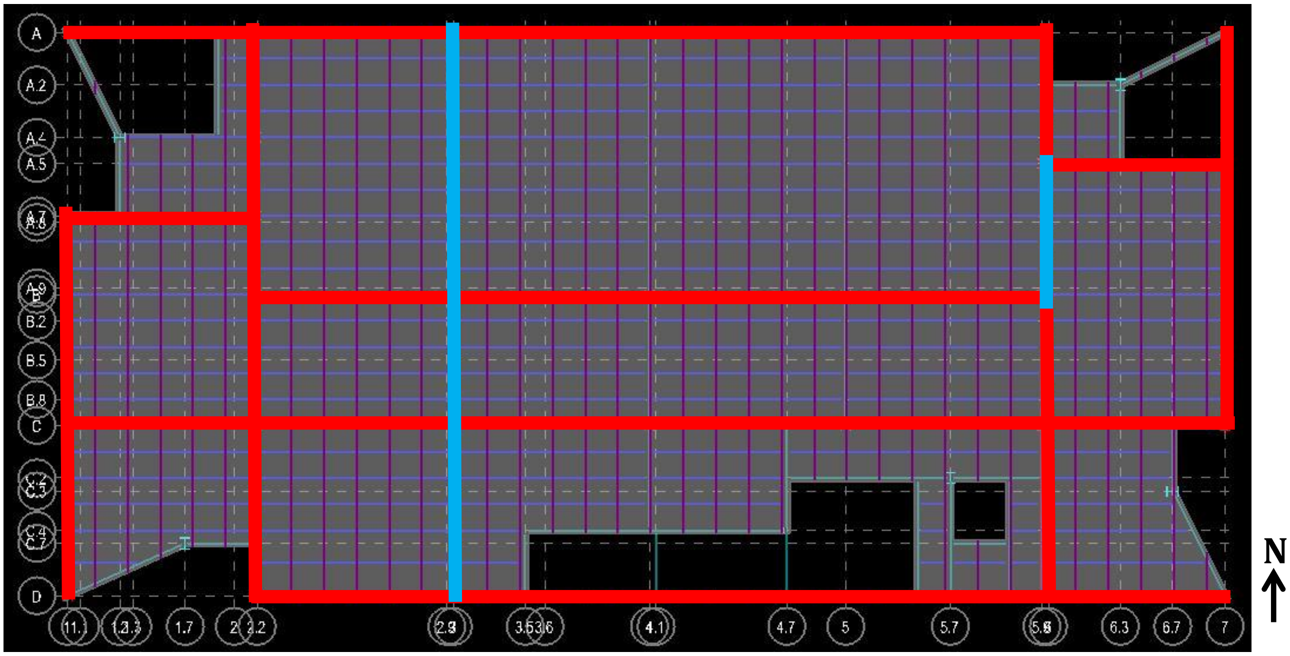
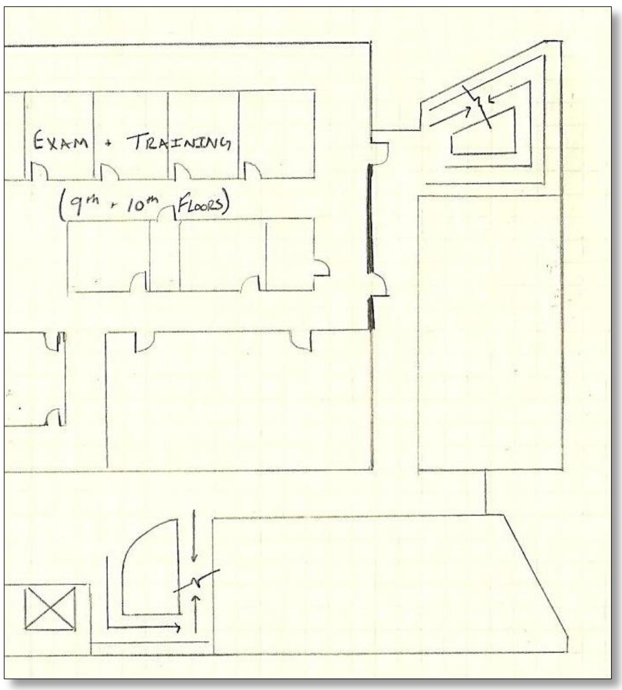


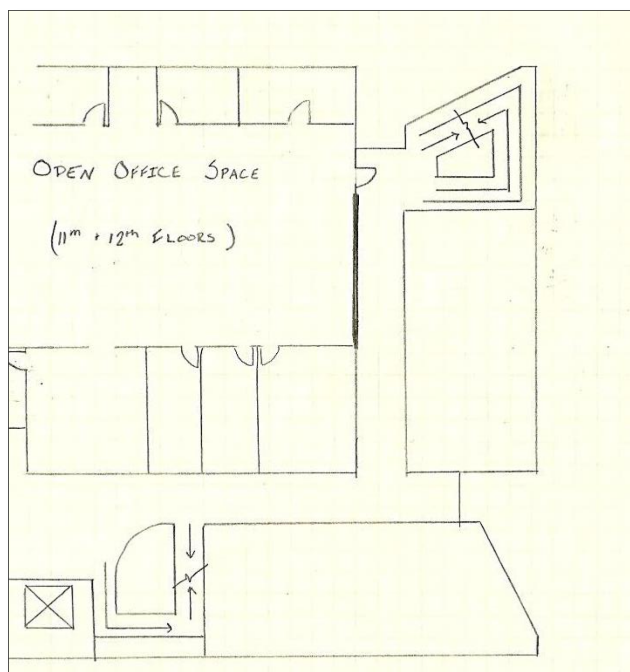
Figure 8 – Redesigned Lateral Force Resisting System (Highlighted in Red) with Notable Original Braced Frames (Highlighted in Blue)

The braced frames from the original system shown in blue in Figure 8 are located on column lines 3 and 6 (detailed drawings of these braced frames are available in Appendix A: Structural System Overview). The bracing found on column line 3, the braced frame closer to the west side of the building, has major impacts on the 1st through 3rd Floors. The bracing that continues throughout the entirety of the structure on that specific column line is adjacent to a shaft opening, decreasing its impact on the layout. For the 1st through 3rd Floors, the bracing is hidden within a large wall that interrupts the entrance lobby, reception area, and the interaction area outside the 2nd Floor auditorium entrance. While the cumbersome wall is camouflaged at the main entrance by serving as the "Donor Wall", the elimination of the bracing, and therefore the wall, is a positive change for the layout. The redesigned system allows for a more open entrance in to the building, and also permits a better sight line from the interaction area outside the 2nd Floor auditorium entrance to the lobby open below.

The bracing eliminated on column line 6, the braced frame closer to the east side of the building, may seem small in comparison to the size of the structure, but its impact is large on the flow of the floor plans. Bracing in this specific frame extends the height of the building – its impact, however, is felt most on the 9th through 12th Floors. On both the 9th and 10th Floors immediately west of the braced frame are examination and training rooms. Instead of having immediate access in to these areas, the entrances are offset to the far sides of the frame (where doors will fit without interfering with the structure). On both the 11th and 12th Floors, the area immediately west of the braced frame is open office space. Once again, the entrances are offset due to the bracing. Sketches of these areas can be seen below in Sketches 1 and 2; the darkened wall is where the bracing is located. With the elimination of bracing, the entrances for the 9th and 10th Floor training areas can be centered on the hallways, creating a better flow in to the spaces. The same can be done to the 11th and 12th Floors, or the wall could be eliminated entirely. As mentioned previously, the VCU SOM redesigned curriculum heavily emphasized an open collaboration between students and teachers – breaking down these walls would help in both the literal and figurative senses.



Sketch 1 – 9th & 10th Floors, East Side



Sketch 2 – 11th & 12th Floors, East Side

Fireproofing Redesign

Fireproofing has been a major concern throughout the entire redesign process – not only did it increase the cost of the project (due to use of joists instead of beams), but it also increased certain sequences in the schedule. Once again, fireproofing is a topic of interest, this time when reviewing the occupancies for the building and the applicable codes, both nationally [International Building Code (IBC) 2006 Edition] and locally [Virginia Uniform Statewide Building Code (VUSBC) 2006 Edition]. The original system was composed of Spray-Applied Fire Resistive Material (SFRM) and sprinklers throughout the entire building. As set out in the plans, a required 3 HR minimum fire resistance was applied to all primary structure members, i.e. columns and girders. Secondary structure, beams and joists, needed to meet a 2 HR minimum, while roof construction only needed a 1 ½ HR minimum fire resistance. All floor levels were also outfitted with active fire protection measures, such as sprinklers, based on square footage and anticipated occupants.

When investigating the cost implications of fireproofing associated with the redesign of the structural system, there were two options presented:

1. Spray-Applied Fire Resistive Material (SFRM) on all steel members, non-rated ceilings, and sprinklers throughout all areas
2. Factory applied fire resistive material on joists, field SFRM on girders, rated ceilings, and non-sprinkler areas where acceptable

Option 1 would not result in major changes in the fireproofing, both passive and active, when compared to the original system. Option 2, on the other hand, would have major effects on the fire prevention measures for the project. While costs for the factory applied fire resistive material and rated ceilings caused an increase in the budget (as studied in Breadth 1), the impact of removing sprinklers was not investigated previously. In order to meet all necessary requirements, both the IBC and VUSBC were referenced. The VUSBC 2006 Edition (effective May 2008) was used since this was the code applied in the original design; the IBC effective at that time was also the 2006 Edition. All applicable code requirements can be found in Appendix E: Architectural Considerations (Breadth 2); ones deemed essential are discussed below.

The building has three occupancies found throughout: B, Business; A-3, Assembly; and H-3, Hazardous at Fuel Oil Storage. The H-3 occupancies are only found in the sub-basement, so those areas were not used in this evaluation. B occupancies are not required to have automatic sprinkler systems; however, A-3 occupancies must have automatic sprinklers if any of the following occur:

1. The fire area exceeds 12,000 square feet
2. The fire area has an occupant load of 300 or more
3. The fire area is located on a floor other than the level of exit discharge

The A-3 occupancies were featured prominently on the first three levels, but they were also found in smaller areas throughout the rest of the floors. Even though the areas deemed A-3 occupancies on the 4th through 12th Floors had less than 12,000 SF and occupant loads less than 300, they were all located on floors other than the level of exit discharge. Since these areas would still require active fire protection, the code required that a 2 HR Fire Barrier must be present to separate the differing occupancies (IBC 2006 ed. Table 508.3.3). Since a 2 HR Fire Barrier is not possible at certain assembly areas (specifically the Interaction Area) that were designed to be open to corridors, those areas was considered accessory. On the 4th through 12th Floors, A-3 was subsidiary to the main occupancy of the building, B (Business), and the Interaction Area did not occupy more than 10% of the SF of the floor and was less than 750 SF. With these code requirements in mind, each floor was evaluated to determine the number of sprinklers that could be removed and the linear feet of 2 HR fire barrier needed to be installed. This evaluation can be seen in more detail in Table 8 on the following page.

Floor	Main Occupancies	Areas (sf) (respectively)	Occupant Load (respectively)	Accessory Area Added (sf)	New Areas (sf) (respectively)	Sprinklers Removed	Additional Fireproofing
1	A & B	5340 – 4610	357 – 47	–	–	–	–
2	A & B	1650 – 4955	240 – 50	–	–	–	–
3	A & B	3515 – 2770	365 – 28	–	–	–	–
4	B	885 – 10980	60 – 110	470	415 – 10980	120	2 HR Fire Barrier (65 LF)
5	A & B	2055 – 9271	137 – 279	470	1585 – 9271	90	2 HR Fire Barrier (300 LF)
6	A & B	2055 – 9340	137 – 280	470	1585 - 9340	90	2 HR Fire Barrier (300 LF)
7	A & B	2055 – 9271	137 – 279	470	1585 – 9271	90	2 HR Fire Barrier (300 LF)
8	A & B	2055 – 9271	137 – 279	470	1585 – 9271	90	2 HR Fire Barrier (300 LF)
9	B	695 – 10990	46 – 129	470	225 – 10990	150	2 HR Fire Barrier (26 LF)
10	B	945 – 11020	63 – 130	470	475 – 11020	120	2 HR Fire Barrier (65 LF)
11	A & B	1840 – 10015	123 – 101	470	1370 – 10015	100	2 HR Fire Barrier (150 LF)
12	A & B	1640 – 9935	109 – 100	470	1170 – 9935	100	2 HR Fire Barrier (56 LF)
13	–	–	–	–	–	–	–
			Total Possible # of Sprinkler Heads Eliminated =			**950**	
			Total Possible LF of 2 HR Fire Barriers =				**1562**

Table 8 – Evaluation of Possible Fire System Changes for Redesigned System

Conclusions for Architectural Considerations

While the original project embraced the redesigned VCU SOM curriculum, opportunities existed to further enhance the layout of the floors to create an environment conducive to teamwork. The original lateral force resisting system of braced frames required bulky members to be hidden in walls in various parts of the building. When the system was redesigned to feature more moment frames with minimal bracing, some of these walls became obsolete and could be eliminated or altered. These alterations would allow for more open, welcoming environments in the entrance lobby, interaction area outside the 2nd Floor auditorium entrance, examination/training rooms, and open office area on the upper floors. A change in fire suppression system was also investigated. It was determined earlier in the research that installing rated ceilings might cause an increase in cost; however, with rated ceilings, additional fire barriers, and strategic placing of assembly areas, the number of sprinklers required would be greatly decreased. The change in system would cost money, but the savings by eliminating most of the active fire protection would be significant. As mentioned previously, the redesigned system might have negative effects on the project (increased cost for fireproofing), but the positives (more open layouts on half of the floors in the building and immense potential savings in active fire protection) greatly outweighed the negatives.

Final Conclusions

As mentioned prior to this report and demonstrated throughout the text, rational alternatives existed for both the gravity and lateral systems found in the James W. & Frances G. McGlothlin Medical Education Center. A redesigned gravity system consisting of non-composite flooring, K-series joists, and wide flange girders was investigated. Joists and girders were sized with hand calculations using distributed loadings and required strength. Vibration calculations were also completed to ensure that all members met the walking excitation and floor stiffness requirements. RAM models were created and used to verify the hand calculations. Once the floor framing was finalized, column checks were completed to ensure members were adequate.

The lateral system was also redesigned with the goal of achieving a more efficient, economical structure. After multiple iterations, a layout of moment frames was selected. RAM was once again utilized; hand calculated wind and seismic loadings were applied using the program to check drift between floors of the building. Additional bracing was implemented to meet drift requirements and frame participation percentages were checked to ensure each member was contributing.

The first breadth focused on the changes to the cost and schedule for the VCU SOM project due to the redesigned structural system. Estimates for material and installation were completed for the original and redesigned gravity systems – the redesigned system resulted in a savings of $3.62/SF on average. However, the redesigned system caused additional costs, specifically related to the curtain wall system and required fireproofing, when reviewing the total project. A schedule analysis was also completed, comparing the floor framing systems, and the redesigned resulted in at least one week of time savings.

The second breadth researched some of the architectural impacts caused by the redesigned structural system. The removal of the majority of the bracing used in the original design provided the opportunity to eliminate walls, creating more open environments. Redesigned fireproofing measures were also evaluated – the move towards more passive fire suppression than active would ultimately result in savings.

Some of the benefits of the redesigned system are lighter construction, satisfactory drift control, slightly lower cost and schedule, decreased bracing, and the potential for increased cost savings in altered fire prevention. However, some of the improvements are only marginal when compared to the original system. In the end, it is reasonable to state that either option, the original or the redesign, would result in an efficient, economical structure.

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Appendices

Appendix A: Structural System Overview

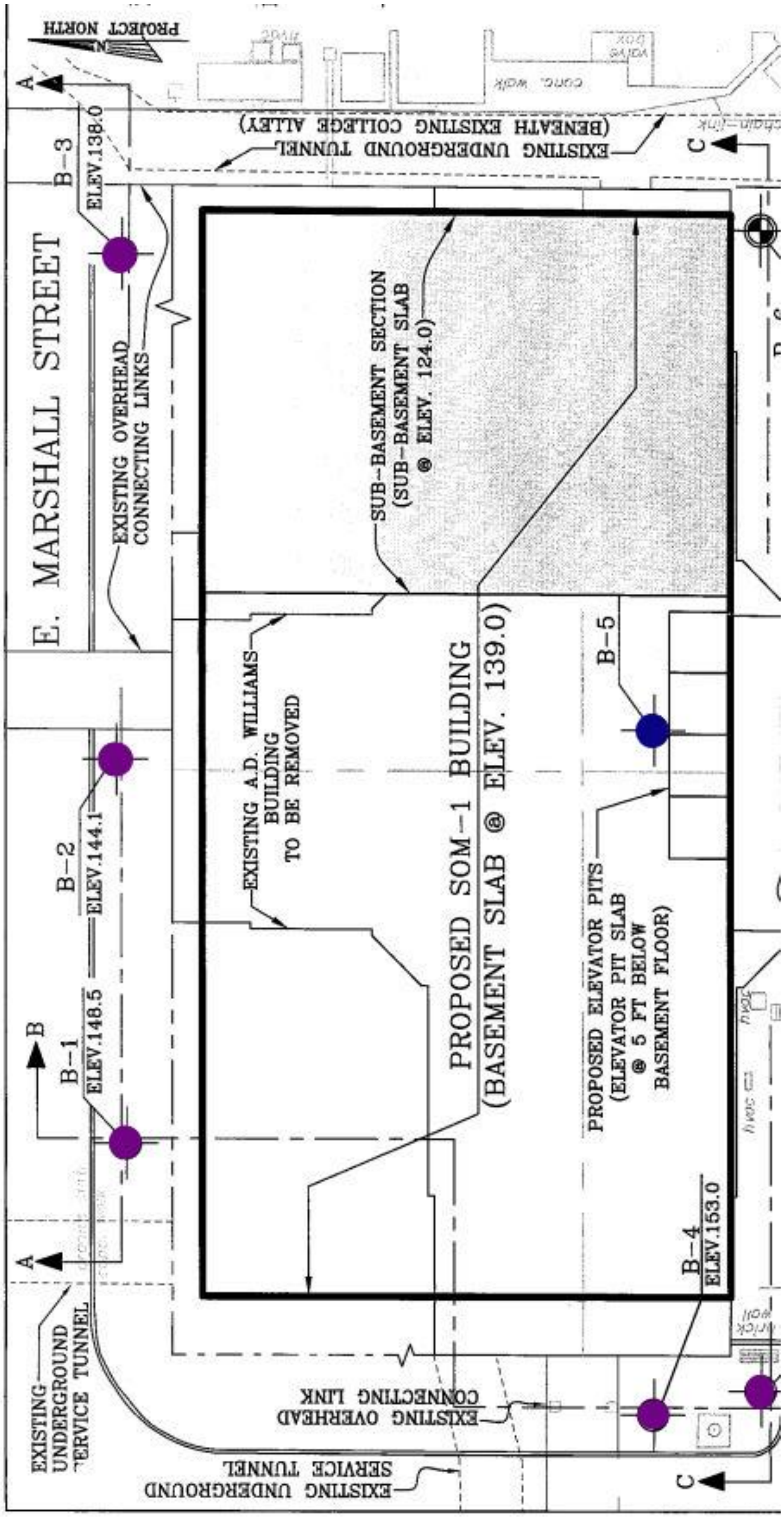
Appendix B: Gravity System Redesign

Appendix C: Lateral System Redesign

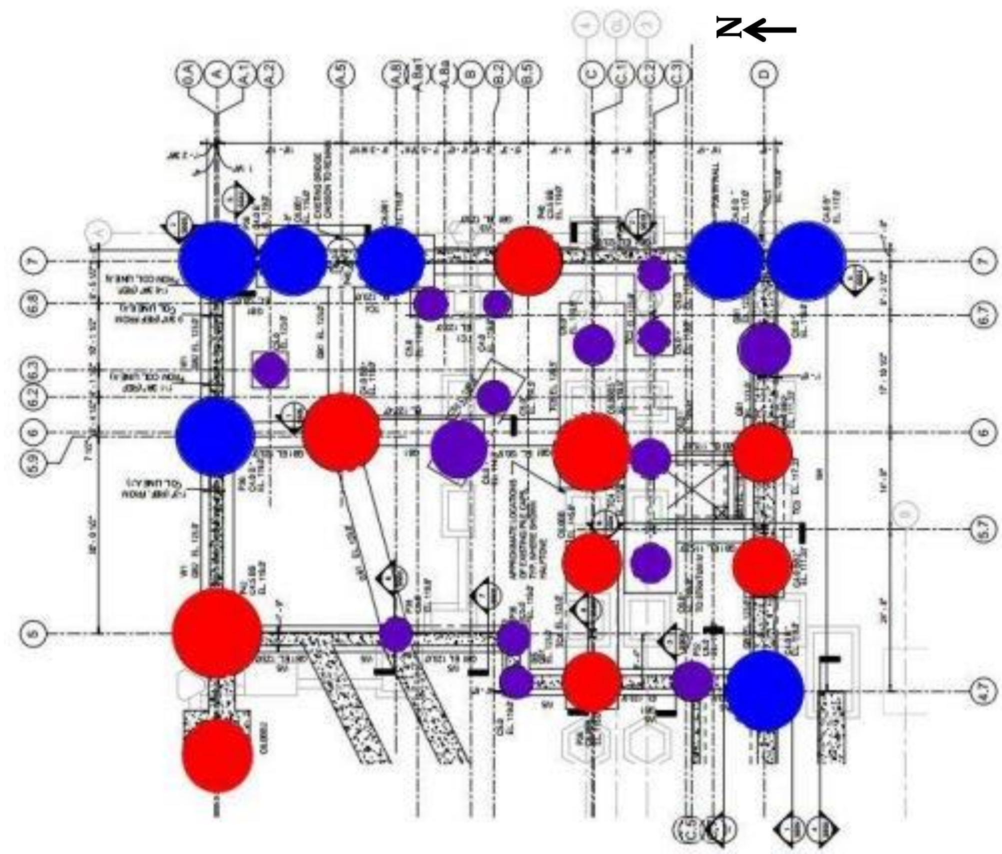
Appendix D: Cost & Schedule Analysis (Breadth 1)

Appendix E: Architectural Considerations (Breadth 2)

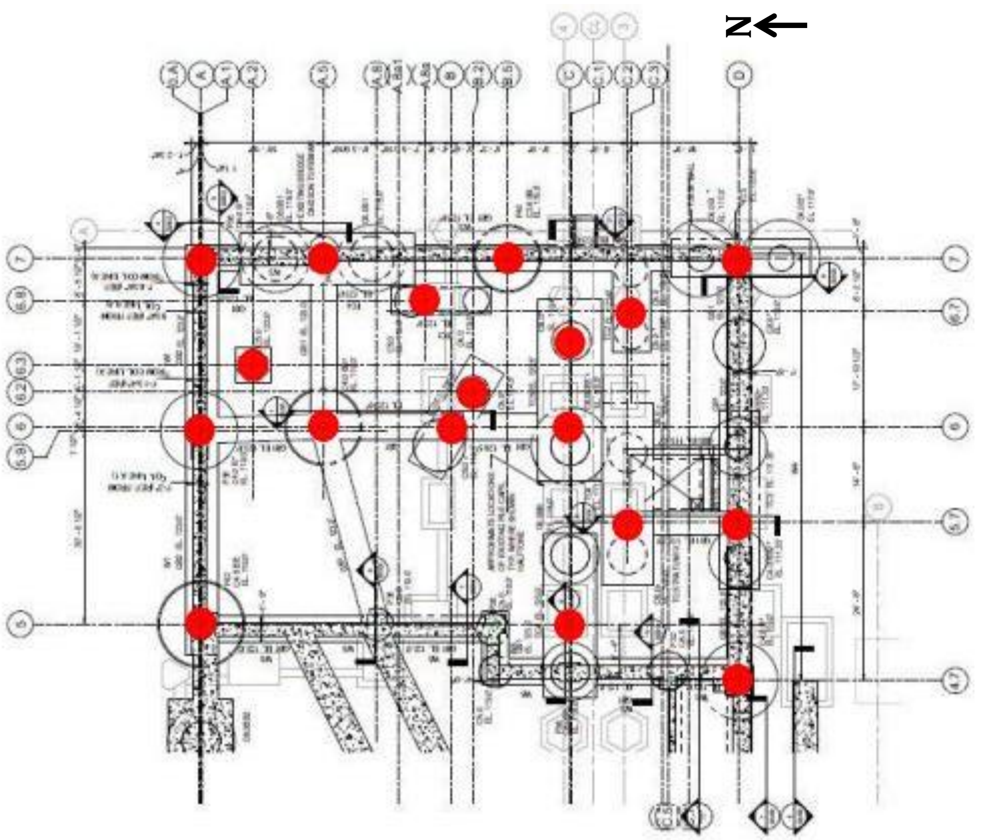
Appendix A: Structural System Overview



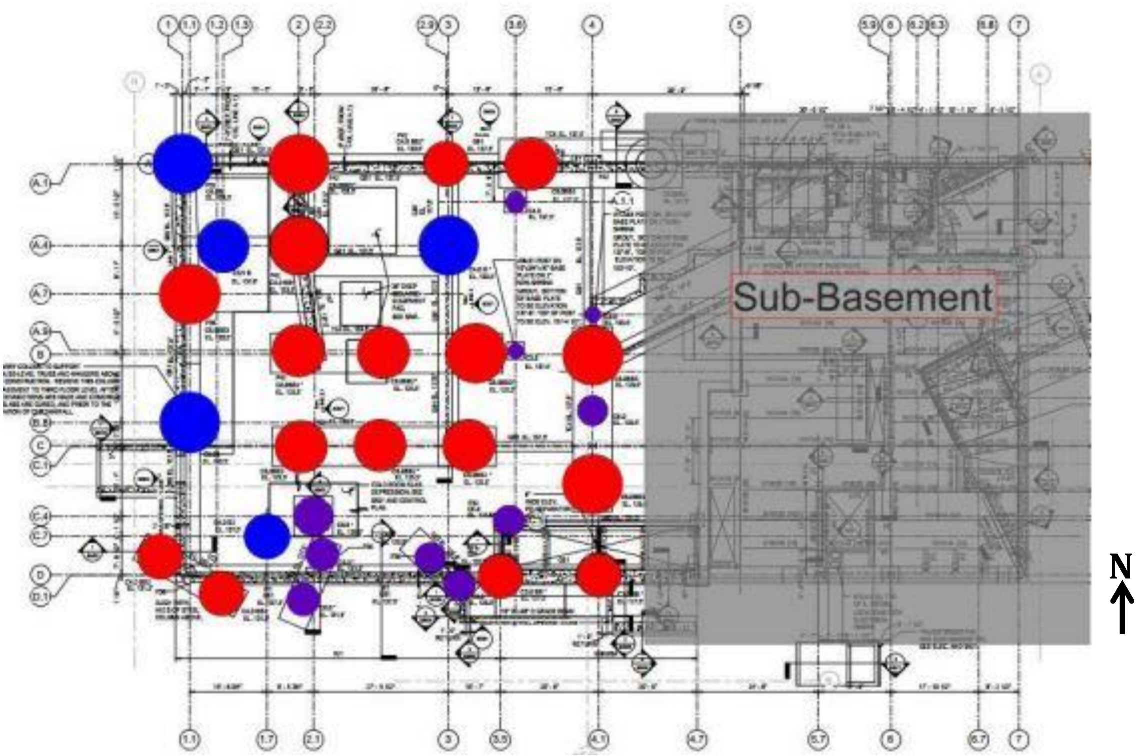
Test Boring Sites established in the field by civil engineer Geotech, Inc.
(Boring sites completed prior to demolition of the A.D. Williams Building shown in purple; Boring site completed after demolition of the A.D. Williams Building shown in blue)



Drilled Pier Scheme for the Sub-Basement Level
(Straight Shaft = Purple; Single-Belled = Blue; Double-Belled = Red)

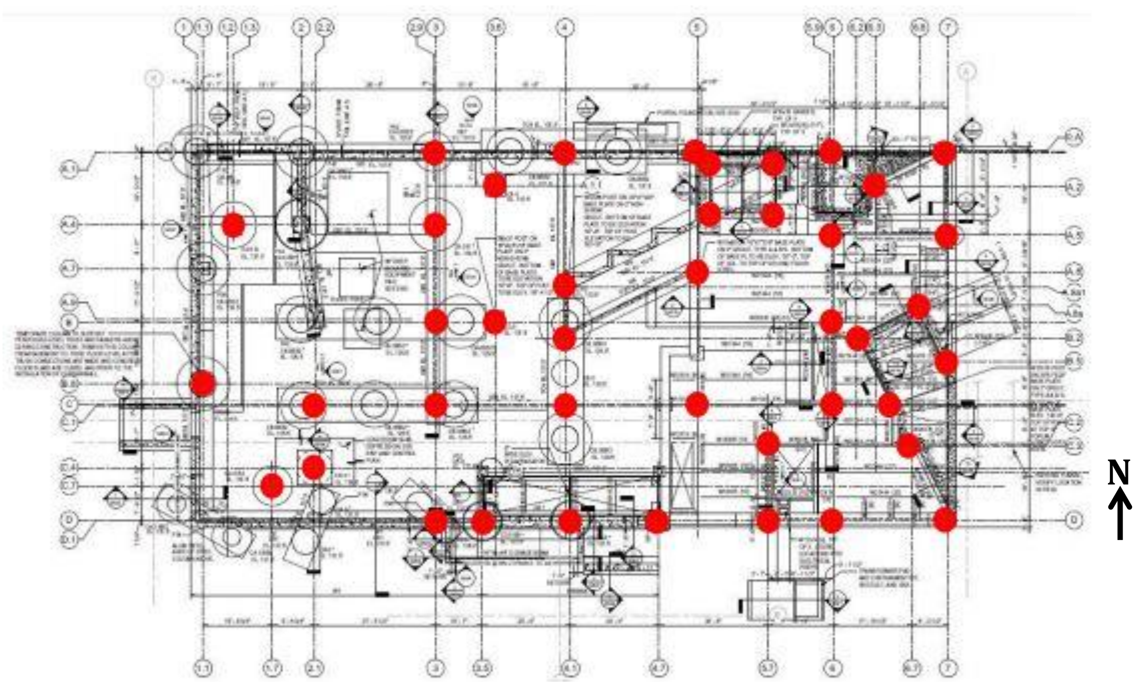


Column Layout (Highlighted in Red) for the Sub-Basement Level

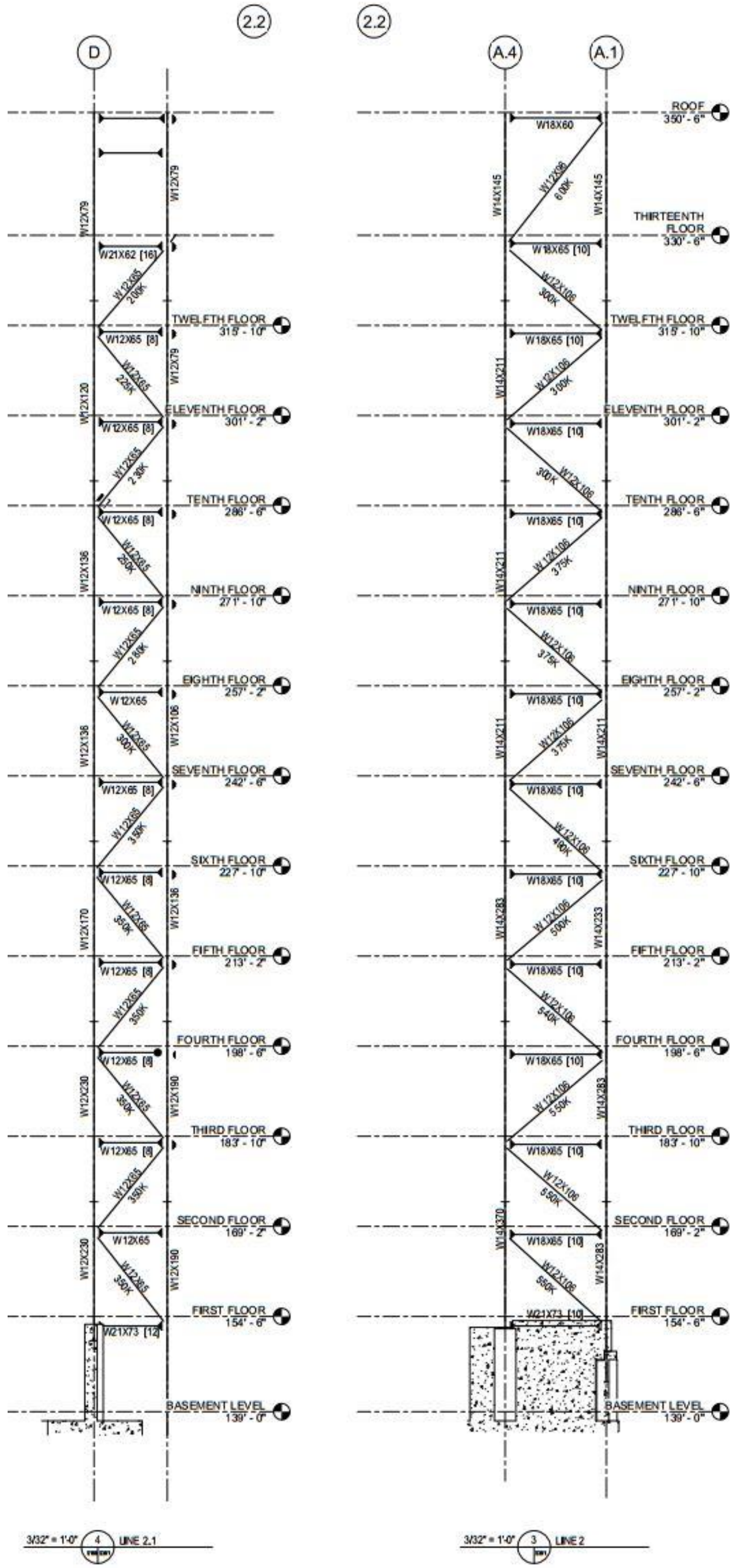


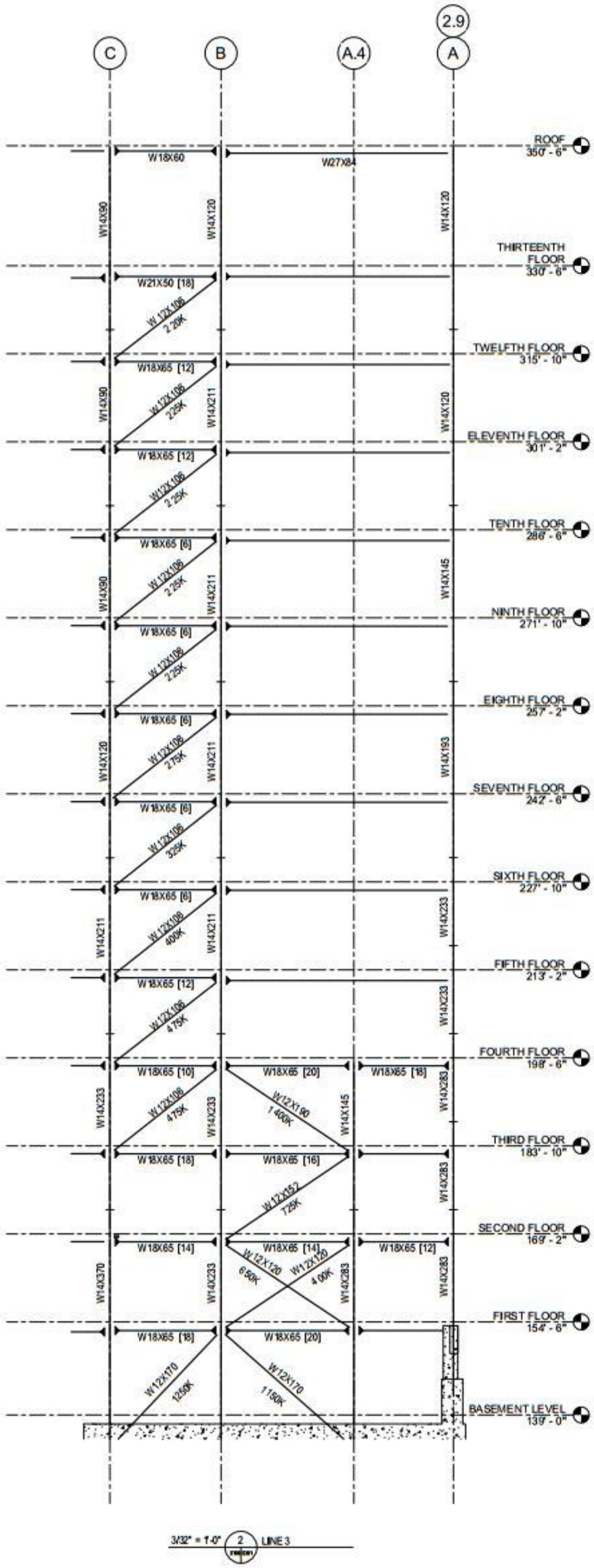
Drilled Pier Scheme for the Basement Level

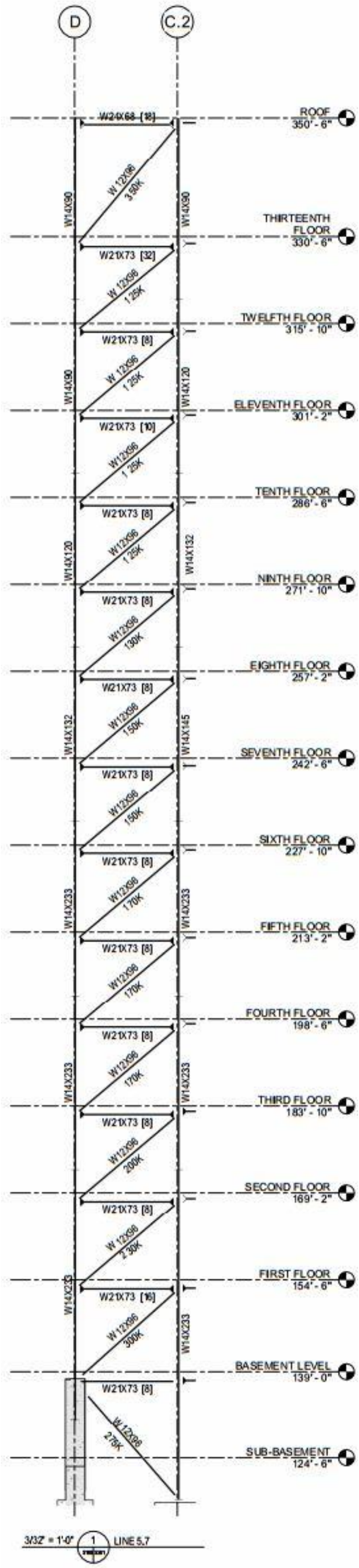
(Straight Shaft = Purple; Single-Belled = Blue; Double-Belled = Red)

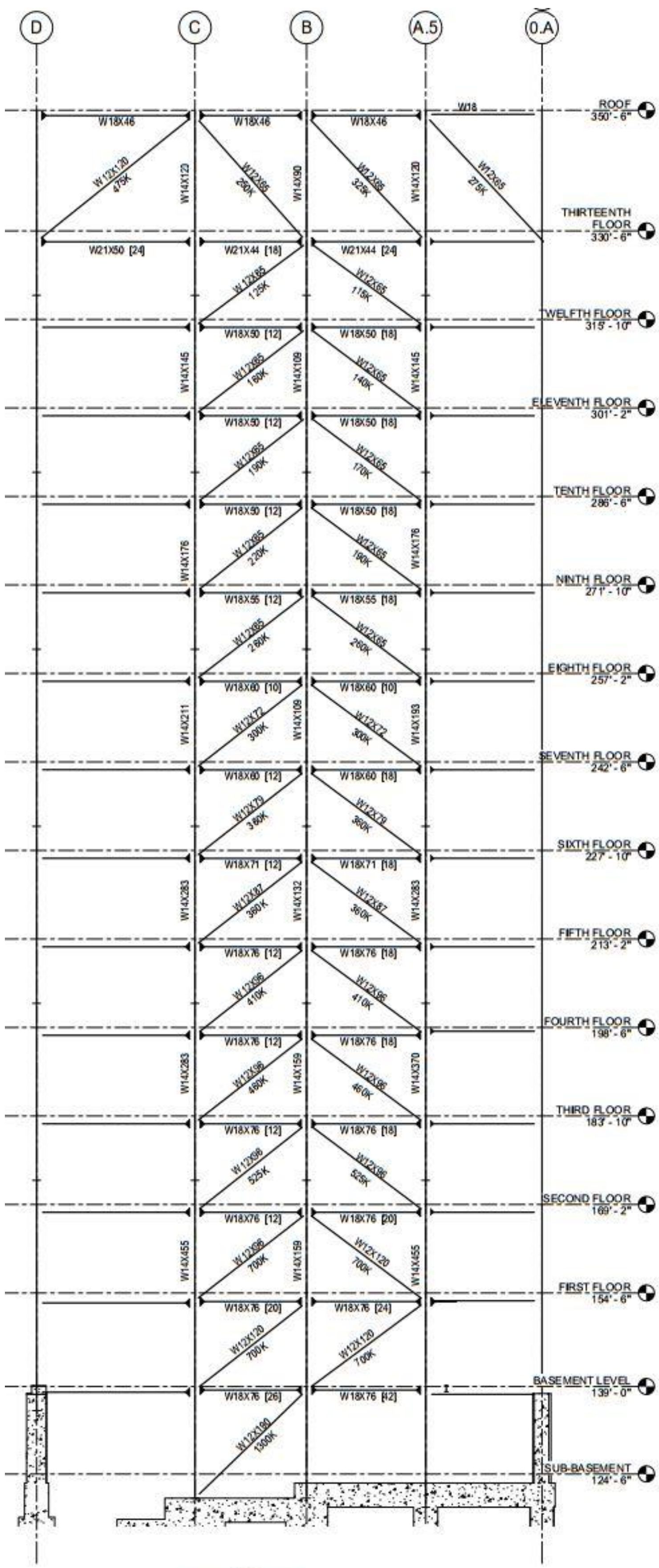


Column Layout (Highlighted in Red) for the Basement Level

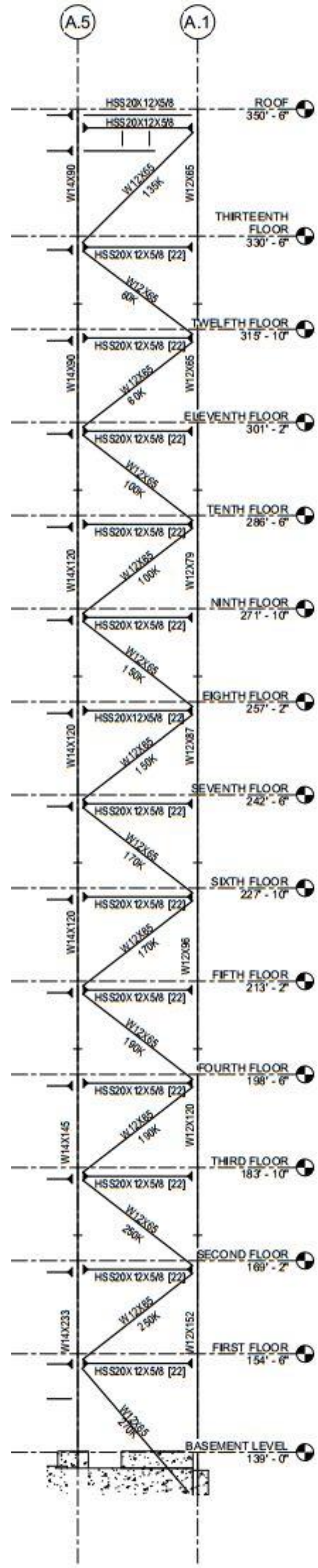

ROOF
350' - 6"
THIRTEENTH FLOOR
330' - 6"
TWELFTH FLOOR
315' - 10"
ELEVENTH FLOOR
301' - 2"
TENTH FLOOR
286' - 6"
NINTH FLOOR
271' - 10"
EIGHTH FLOOR
257' - 2"
SEVENTH FLOOR
242' - 6"
SIXTH FLOOR
227' - 10"
FIFTH FLOOR
213' - 2"
FOURTH FLOOR
198' - 6"
THIRD FLOOR
183' - 10"
SECOND FLOOR
169' - 2"
FIRST FLOOR
154' - 6"
BASEMENT LEVEL
139' - 0"
3/32" = 1'-0" 4 LINE 2.1
3/32" = 1'-0" 3 LINE 2


C
B
A.4
2.9
A
ROOF 350' - 6"
THIRTEENTH FLOOR 330' - 6"
TWELFTH FLOOR 315' - 10"
ELEVENTH FLOOR 301' - 2"
TENTH FLOOR 286' - 6"
NINTH FLOOR 271' - 10"
EIGHTH FLOOR 257' - 2"
SEVENTH FLOOR 242' - 6"
SIXTH FLOOR 227' - 10"
FIFTH FLOOR 213' - 2"
FOURTH FLOOR 198' - 6"
THIRD FLOOR 183' - 10"
SECOND FLOOR 169' - 2"
FIRST FLOOR 154' - 6"
BASEMENT LEVEL 139' - 0"
3/32" = 1'-0" 2 LINE 3

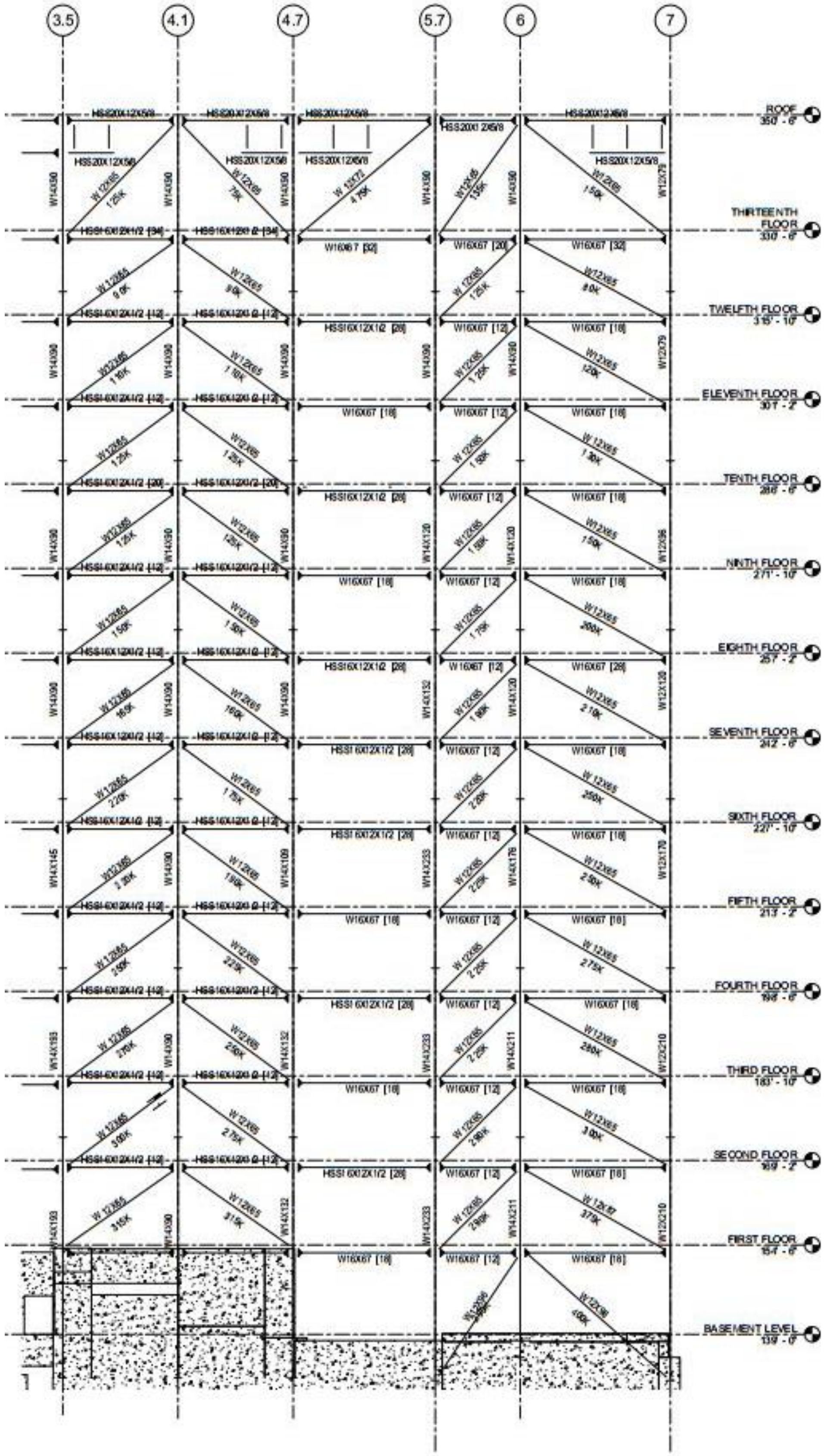

D
C.2
ROOF 350' - 6"
THIRTEENTH FLOOR 330' - 6"
TWELFTH FLOOR 315' - 10"
ELEVENTH FLOOR 301' - 2"
TENTH FLOOR 286' - 6"
NINTH FLOOR 271' - 10"
EIGHTH FLOOR 257' - 2"
SEVENTH FLOOR 242' - 6"
SIXTH FLOOR 227' - 10"
FIFTH FLOOR 213' - 2"
FOURTH FLOOR 198' - 6"
THIRD FLOOR 183' - 10"
SECOND FLOOR 169' - 2"
FIRST FLOOR 154' - 6"
BASEMENT LEVEL 139' - 0"
SUB-BASEMENT 124' - 6"
3/32" = 1'-0" 1 LINE 5.7



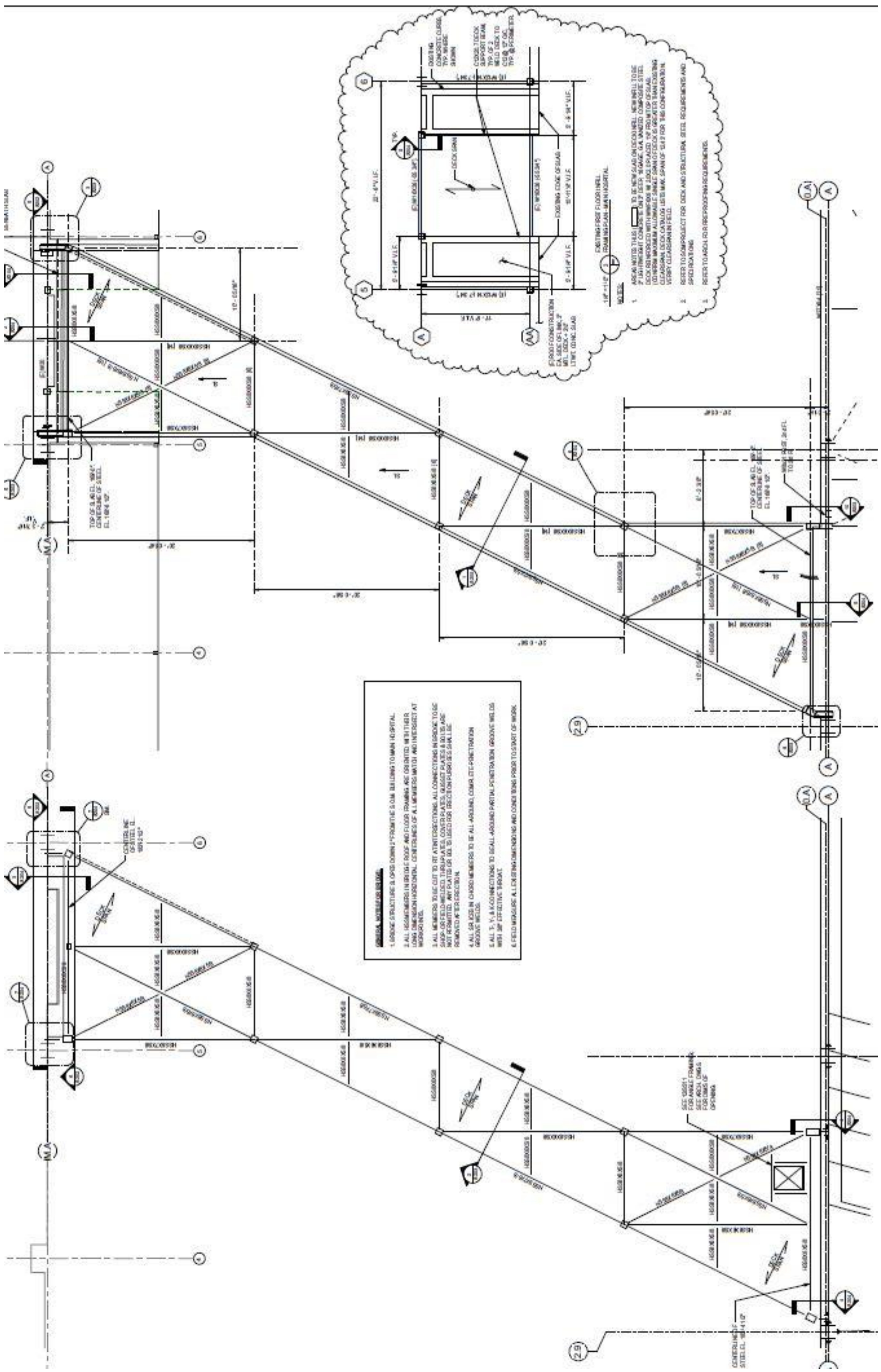
3/32" = 1'-0" 3 LINE 6



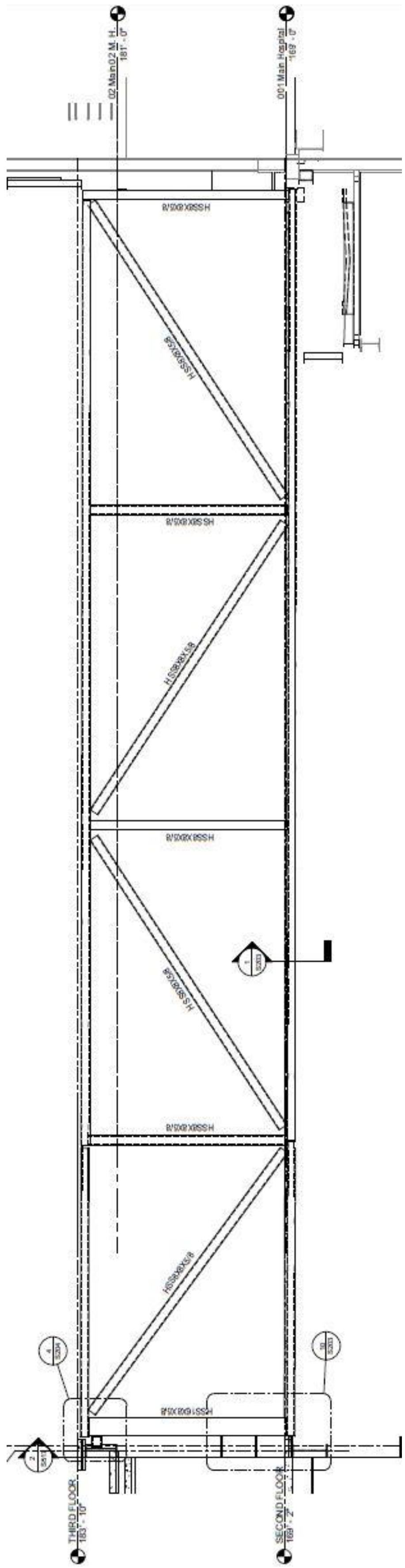
3/32" = 1'-0" 2 BRACING ELEVATION LINE 7



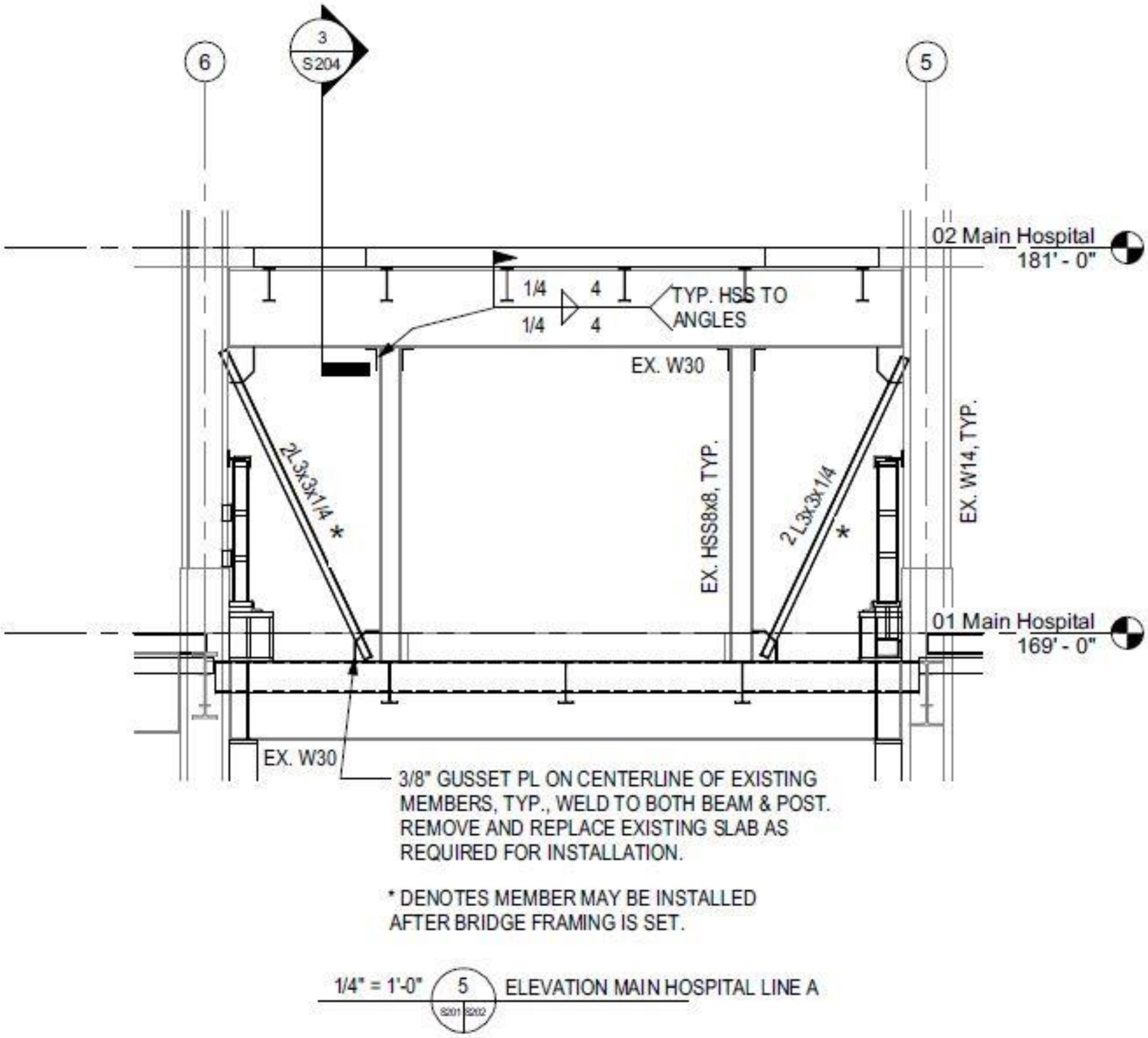
3/32" = 1'-0" 1 BRACING ELEVATION LINE D



Bridge Plan (S201)



Bridge Elevation (S202)



Bridge Detailed Elevation at Connection to Main Hospital (S202)

Appendix B: Gravity System Redesign

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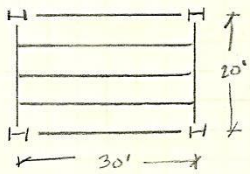
Objective: Redesign current gravity system utilizing non-composite floor system with bar joists and steel girders

Assumptions: LL = 80 psf
DL = 10 psf (does not include slab/deck or self wt)
2 hr fire rating reqd. → 2 ½" NW concrete topping (still require fireproofing on bar joists & girders)
4 possible configurations to consider:
I. 30' x 20' w/ joists traveling in 30' dir.
II. 30' x 40' " " " " " "
III. 30' x 20' " " " " 20' "
IV. 30' x 40' " " " " 40' "

I. 30' x 20' Bay (w/ joists traveling in 30' direction)



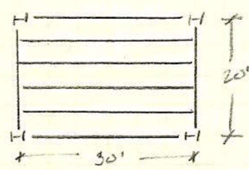
Total Load = 1.2(10) + 1.6(80) = 140 psf

Try 5', 2 spans
Possible Decking:
- 1.0C20, 160 psf, 7'3" ✗
- 1.3C22, 154 psf, 7'10" ✗

158 psf > 140 psf ∴ ok ✓
7'3" > 5' ∴ ok ✓
weight = 38 psf
New Total Load = 1.2(38) + 140 = 186 psf

W_{TL} = (186)(5) = 930 lb/ft + joist wt W_{LL} = (38 + 10 + 80)(5) = 640 lb/ft + joist wt

Possible Joists: K-series cannot be used, W_{TL} is too high!



Try 4', 1 span
Possible Decking:
- 1.0C24, 147 psf, 4'4" ✓
- 1.3C26, 145 psf, 4'3"

147 psf > 140 psf ∴ ok ✓
4'4" > 4' ∴ ok ✓
Weight = 37 psf
New Total Load = 1.2(37) + 140 = 184.4 psf

W_{TL} = (184.4)(4) = 738 lb/ft + joist wt W_{LL} = (37 + 10 + 80)(4) = 508 lb/ft + joist wt

Possible Joists: 20K10, 799, 12.2, 336 ✗
22K10, 825, 12.6, 385 ✓
24K9, 816, 12.0, 419
26K8, 816, 12.1, 457

Try 20K10 → 738 + (12.2)(1.2) = 753 < 799 ∴ ok ✓
w for L/240 = 336(1.5) = 504 < 508 ∴ NOT ok

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I. (cont.)

Try 22K10 → 738 + (12.6)(1.2) = 753 < 825 ∴ ok ✓
w for L/240 = 385(1.5) = 578 > 508 ∴ ok ✓

∴ use 22K10 bar joists at 4'

LL = 80 psf
DL = 10 + 37 = 47 psf

$W_u = [1.2(47) + 1.6(80)](20) = 3.69$ klf
$M_u = W_u L^2/8 = (3.69)(20)^2/8 = 185$ ft·k

Possible Girders:	ϕM_n	I
W16x40	274	518
W18x35	249	510 ✓
W14x34	205	340

$\Delta = L/240 = (20)(12)/240 = 1''$ $\Delta_{LL} = L/360 = (20)(12)/360 = 0.67''$

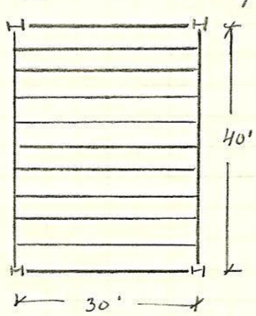
$\Delta_{LL} = \frac{5wL^4}{384EI} \le 0.67'' \rightarrow \frac{5(80/1000)(30)(20)^4(1728)}{384(29000)I} \le 0.67''$

∴ $I \ge 445$ in⁴

Try W18x35 → 249 > 185 ∴ ok ✓
510 > 445 ∴ ok ✓

∴ use W18x35 girders

II. 30' x 40' Bay (w/ joists traveling in 30' direction)



Total Load = 140 psf

Using 1.0C24 decking found in ex. I,
4', 1 span

22K10 bar joists at 4' will still apply

LL = 80 psf $W_u = [1.2(47) + 1.6(80)](40) = 7.38$ klf
DL = 47 psf $M_u = (7.38)(40)^2/8 = 1476$ ft·k

Possible Girders:	ϕM_n	I
W33x118	1560	5900
W30x124	1530	5360
W24x146	1570	4580

$\Delta = L/240 = (40)(12)/240 = 2''$ $\Delta_{LL} = L/360 = (40)(12)/360 = 1.33''$

$\Delta_{LL} = \frac{5wL^4}{384EI} \le 1.33'' \rightarrow \frac{5(80/1000)(30)(40)^4(1728)}{384(29000)I} \le 1.33''$ ∴ $I \ge 3584$ in⁴

∴ use W24x146 girders

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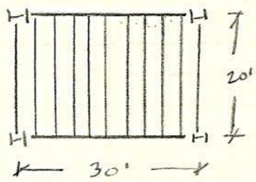
III. 30' x 20' Bay (w/ joists traveling in 20' direction)



Total Load = 140 psf

Try 3', 2 spans

Possible Decking:

- 0.6C24 , 151 psf , 3'11" ✓
- 1.0C26 , 187 psf , 4'4"

151 psf > 140 ∴ ok ✓

3'11" > 3' ∴ ok ✓

Weight = 35 psf

New Total Load = 1.2(35) + 140 = 182 psf

$W_{tl} = (182)(3) = 546$ lb/ft + joist wt $W_{LL} = (35 + 10 + 80)(3) = 375$ lb/ft + joist wt

Possible Joists:

12K5	613	7.1	230	X
14K4	642	6.7	287	✓
16K3	615	6.3	330	

Try 12K5 → 546 + 7.1(1.2) = 555 < 613 ∴ ok ✓
w for L/240 = 230(1.5) = 345 < 375 ∴ NOT OK

Try 14K4 → 546 + 6.7(1.2) = 554 < 642 ∴ ok ✓
w for L/240 = 287(1.5) = 431 > 375 ∴ ok ✓

∴ use 14K4 bar joists at 3'

LL = 80 psf

DL = 10 + 35 = 45 psf $w_u = [1.2(45) + 1.6(80)](30) = 5.46$ klf

$M_u = (5.46)(30)^2/8 = 614$ ft·k

$\Delta = L/240 = (30)(12)/240 = 1.5"$ $\Delta_{LL} = L/360 = (30)(12)/360 = 1"$

$\Delta_{LL} = \frac{5wL^4}{384EI} \le 1" \rightarrow \frac{5(80/1000)(20)(30)^4(1728)}{384(29000)\,I} \le 1"$ ∴ $I \ge 1006$ in^4

Possible Girders:	ϕM_n	I	
W24x68	664	1830	✓
W21x73	645	1600	

Try W24x68 → 664 > 614 ∴ ok ✓
1830 > 1006 ∴ ok ✓

∴ use W24x68 girders

IV. 30' x 40' Bay (w/ joists traveling in 40' direction)

Total Load = 140 psf

Using 0.6C24 decking found in ex. III, 3', 2 spans

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IV. (cont.)

W_{TL} = 546 lb/ft + joist wt W_{LL} = 375 lb/ft + joist wt

Possible Joists:

24K12	657	16.0	247	X
26K10	589	13.8	243	X
26K12	657	16.6	269	✓
28K10	636	14.3	284	

Try 24K12 → 546 + 16(1.2) = 565 < 657 ∴ ok ✓
w for L/240 = 247 (1.5) = 371 < 375 ∴ Not ok

26K10 → Not ok

Try 26K12 → 546 + 16.6(1.2) = 566 < 657 ∴ ok ✓
w for L/240 = 269 (1.5) = 404 > 375 ∴ ok ✓

∴ use 26K12 bar joists at 3'

w_u = 5.46 klf M_u = 614 ft·k   Δ = 1.5" Δ_{LL} = 1"

$$\Delta_{LL} = \frac{5(80/1000)(40)(30)^4(1728)}{384(29000)\,I} \le 1'' \quad \therefore I \ge 2011 \text{ in}^4$$

		ϕM_n	I	
Possible Girders:	W24x76	750	2100	✓
	W21x93	829	2070	
	W18x119	983	2190	

Try W24x76 → 750 > 614
2100 > 2011

∴ use W24x76 girders

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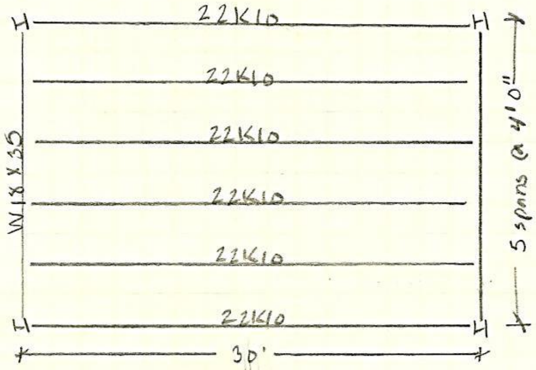
Vibration Control

Reference: AISC Design Guide 11 - Floor Vibrations Due to Human Activity

I)



Deck

$W_c = 145$ pcf $f'_c = 3000$ psi

thickness $= 2\frac{1}{2}" + 1" = 3\frac{1}{2}"$

slab + deck wt = 37 psf

Offices | Classrooms = LL = 11 psf

Joists

22K10

Wt = 12.6 plf

D = 22"

$I_{chords} = 26.767(W)(L^3)(10^{-6}) = 26.767(385)(30-0.33)^3(10^{-6})$ ← found from load table

$I_{chords} = 269 \text{ in}^4$

$A_{chords} = I_{chords}/(D/2)^2 = 269/(22/2)^2 = 2.22 \text{ in}^2$

assume $y_c = 11"$

$E_c = w_c^{1.5}\sqrt{f'_c} = 145^{1.5}\sqrt{3.0} = 3025$ ksi

n = modular ratio $= E_s/1.35E_c = 29000/(1.35)(3025) = 7.1$

$\bar{y} = \dfrac{2.22(1+11) - (48/7.1)(2.5)(2.5/2)}{2.22 + (48/7.1)(2.5)} = 0.30"$ below top of deck

$I_{comp} = 269 + 2.22(1+11-0.3)^2 + \dfrac{(48/7.1)(2.5)^3}{12} + (48/7.1)(2.5)(0.3+\frac{2.5}{2})^2$

$= 622 \text{ in}^4$

since $6 \le L/d = (30\times12)/22 = 16.4 \le 24 \rightarrow C = 0.9(1-e^{-0.282(16.4)})^{2.8}$

$C = 0.88$

$\gamma = \frac{1}{C} - 1 = \frac{1}{0.88} - 1 = 0.14$

$I_{joist} = \dfrac{1}{\frac{\gamma}{I_{chords}} + \frac{1}{I_{comp}}} = \dfrac{1}{\frac{0.14}{269} + \frac{1}{622}} = 470 \text{ in}^4$

$W_{joist} = (48/12)(11 + 37 + 5) + 12.6 = 225$ plf

$\Delta_{joist} = \dfrac{5w_jL_j^4}{384E_sI_j} = \dfrac{5(225)(30)^4(1728)}{384(29\times10^6)(470)} = 0.30"$

$f_{joist} = 0.18\sqrt{g/\Delta_j} = 0.18\sqrt{386/0.30} = 6.46$ Hz

$D_{slab} = 12d_e^3/12n = 12(3)^3/(12)(7.1) = 3.8 \text{ in}^4/\text{ft}$

$D_{joist} = I_{joist}/S = 470/(4) = 118 \text{ in}^4/\text{ft}$

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I) (cont) $B_j = C_j (D_s/D_j)^{1/4} L_j$ ($C_j = 2.0$ for most joists)
$= 2(3.8/118)^{1/4}(30) = 25.4' < \frac{2}{3}(3 \times 20') = 40'$ ∴ ok ✓
$W_j = (w_j/s) B_j L_j = (225/4)(25.4)(30) = 42.8^K$

Girders
W18x35
$A = 10.3 \text{ in}^2$
$I_x = 510 \text{ in}^4$
$d = 17.7 \text{ in}$

$w_{eff} = 0.4 L_g = 0.4(20)(12) = 96" < L_j = 30 \times 12 = 360"$
$d_c = 2.5 + 1.0/2 = 3.0"$

$\bar{Y} = \frac{10.3(0.5 + 3.5 + 17.7/2) - (96/7.1)(3)(3/2)}{10.3 + (96/7.1)(3)} = 1.41"$ below

$I_{girder} = 510 + 10.3(0.5 + 3.5 + (17.7/2) - 1.41)^2 + (96/7.1)(3)^3/12 + (96/7.1)(3)(1.41 + 1.5)^2$
$= 2232 \text{ in}^4$

$I_{g\,red.} = I_{nc} + (I_c - I_{nc})/4 = 510 + (2232 - 510)/4 = 941 \text{ in}^4$

$w_{girder} = L_g(w_j/s) + \text{girder wt} = 20(225/4) + 35 = 1160 \text{ plf}$

$\Delta_{girder} = \frac{5(1160)(20)^4(1728)}{384(29 \times 10^6)(941)} = 0.15 \text{ in}$

$f_{girder} = 0.18\sqrt{386/0.15} = 9.13 \text{ Hz}$

$D_{joist} = 118 \text{ in}^4/\text{ft}$ $D_{girder} = I_g/L_j = 941/30 = 31.4 \text{ in}^4/\text{ft}$

$B_g = C_g (D_j/D_g)^{1/4} L_g$ ($C_g = 1.6$ for girders supporting joists)
$= 1.6(118/31.4)^{1/4}(20) = 44.6 \text{ ft} < \frac{2}{3}(3 \times 30) = 60'$ ∴ ok ✓

$W_g = (w_g/L_j) B_g L_g = (1160/30)(44.6)(20) = 34.5^k$

Combined

$L_g < B_j \longrightarrow \Delta_g' = \frac{L_g}{B_j}\Delta_g = \frac{20}{25.4}(0.15) = 0.118 \text{ in}$

$f_n = 0.18\sqrt{g/(\Delta_j + \Delta_g')} = 0.18\sqrt{386/(0.30 + 0.118)} = 5.47 \text{ Hz}$

$W = \frac{\Delta_j}{\Delta_j + \Delta_g'} W_j + \frac{\Delta_g'}{\Delta_j + \Delta_g'} W_g = \frac{0.30}{0.30 + 0.118}(42.8) + \frac{0.118}{0.30 + 0.118}(34.5)$
$W = 40.5^K$

$\beta W = 0.05(40.5) = 2023 \text{ lbs}$ ($\beta = 0.05$ for full height partitions)

Walking Evaluation
$P_o = 65 \text{ lbs}$ $\frac{a_p}{g} = \frac{P_o \exp(-0.35 f_n)}{\beta W} = \frac{65 \exp[-0.35(5.47)]}{2023} = 0.47\%$ of g

0.47% < a_o/g limit of 0.5%

Floor Stiffness Evaluation $\longrightarrow$ 5.47 Hz < 9 Hz ∴ acceptable

Final Evaluation → Floor system is acceptable
0.47% < 0.5% and 5.47 Hz < 9 Hz ∴ ok ✓

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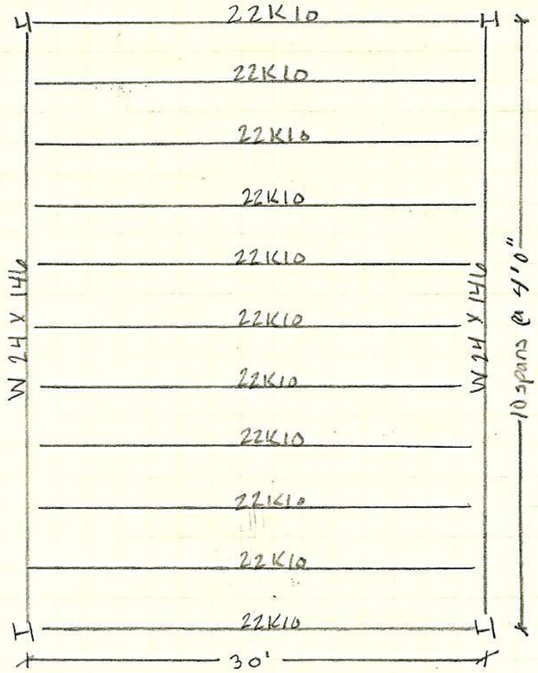
II)



Deck

$W_c = 145$ pcf $f'_c = 3000$ psi

thickness = 3 1/2"

slab + deck wt = 37 psf

Joists

22K10

Wt = 12.6 plf

D = 22"

$I_{chords} = 269\ in^4$

$A = 2.22\ in^2$

$Y_c = 11"$

*joist sizing, spacing, length, etc. did not change from configuration I, ∴ all values found for joists will remain the same

$I_j = 470\ in^4$ $w_j = 225$ plf

$\Delta_j = 0.30"$ $f_j = 6.46$ Hz

$D_s = 3.8\ in^4/ft$ $D_j = 118\ in^4/ft$

$B_j = 25.4'$ $W_j = 42.8^k$

Girders

W24X146

$A = 43\ in^2$

$I_x = 4580\ in^4$

$d = 24.7$ in

$W_{eff} = 0.4L_g = 0.4(40)(12) = 192" < L_j = 360"$

$d_c = 3"$

$\bar{Y} = \dfrac{43(0.5+3.5+24.7/2) - (192/7.1)(3)(3/2)}{43 + (192/7.1)(3)} = 4.68"$ below

$I_g = 4580 + 43(0.5+3.5+(24.7/2) - 4.68)^2 + (192/7.1)(3)^3/12 + (192/7.1)(3)(4.68+1.5)^2$
$= 13{,}595\ in^4$

$I_{grad} = 4580 + (13595 - 4580)/4 = 6834\ in^4$

$w_g = 40(225/4) + 146 = 2396$ plf

$\Delta_g = \dfrac{5(2396)(40)^4(1728)}{384(29\times10^6)(6834)} = 0.70"$

$f_g = 0.18\sqrt{386/0.7} = 4.23$ Hz $D_g = 6834/30 = 228\ in^4/ft$

$B_g = 1.6\,(118/228)^{1/4}(40) = 54' < 60'$ ∴ ok ✓

$W_g = (2396/30)(54)(40) = 173$ k

Combined

$L_g > B_j \longrightarrow f_n = 0.18\sqrt{g/(\Delta_j+\Delta_g)} = 0.18\sqrt{386/(0.30+0.70)} = 3.54$ Hz

$W = \dfrac{0.3}{0.3+0.7}(42.8) + \dfrac{0.7}{0.3+0.7}(173) = 134^k$

$\beta W = 0.05(134) = 6700$ lbs

Walking Evaluation

$\dfrac{a_p}{g} = \dfrac{65\exp[-0.35(3.54)]}{6700} = 0.28\%$ of g $< 0.5\%$ ∴ ok ✓

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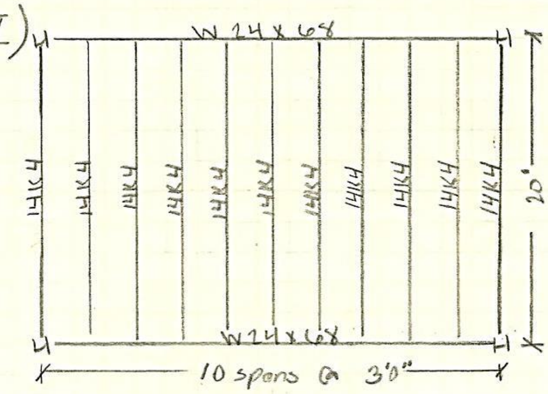
II) (cont) Final Evaluation → Floor System is acceptable

$0.28\% < 0.5\%$ and $3.54\ Hz < 9\ Hz$ ∴ OK ✓

III)



Deck
$W_c = 145$ pcf $f'_c = 3000$ psi
thickness = 2 1/2" + 9/16" ~ 3"
slab + deck wt = 35 psf

Joists
14K4
wt = 6.7 plf
D = 14"

$I_{chords} = 26.767(287)(20-0.33)^3(10^{-6}) = 58.5\ in^4$

$A = 58.5/(14/2)^2 = 1.19\ in^2$

$y_c = 7"$

$E_c = 3025$ ksi $n = 7.1$

$\bar{Y} = \frac{1.19(0.5+7) - (36/7.1)(2.5)(2.5/2)}{1.19 + (36/7.1)(2.5)} = 0.5"$

$I_{comp} = 58.5 + 1.19(0.5+7+0.5)^2 + \frac{(36/7.1)(2.5)^3}{12} + (36/7.1)(2.5)(2.5/2 - 0.5)^2$
$= 148\ in^4$

since $6 \le L/d = (20 \times 12)/14 = 17.1 \le 24 \rightarrow C = 0.9(1 - e^{-0.282(17.1)})^{2.8} = 0.88$

$\gamma = 0.14$ $I_j = \frac{1}{\frac{0.14}{58.5} + \frac{1}{148}} = 109\ in^4$

$W_j = (36/12)(11 + 35 + 5) + 6.7 = 160$ plf

$\Delta_j = \frac{5(160)(20)^4(1728)}{384(29 \times 10^6)(109)} = 0.18"$ $f_j = 0.18\sqrt{386/0.18} = 8.34\ Hz$

$D_{slab} = 12(2.75)^3/(12)(7.1) = 2.93\ in^4/ft$ $D_j = 109/3 = 36.3\ in^4/ft$

$B_j = 2(2.93/36.3)^{1/4}(20) = 21.3' < 60'$ ∴ OK ✓

$W_j = (160/3)(21.3)(20) = 22.7^K$

Girders
W24x68
$A = 20.1\ in^2$
$I_x = 1830\ in^4$
$d = 23.7$ in

$W_{eff} = 0.4(30)(12) = 144" < L_j = 20 \times 12 = 240"$

$d_e = 2.75"$

$\bar{Y} = \frac{20.1(0.25 + 3 + 23.7/2) - (144/7.1)(2.75)(2.75/2)}{20.1 + (144/7.1)(2.75)} = 2.99" \sim 3"$

$I_g = 1830 + 20.1(0.25 + 3 + 23.7/2 - 3)^2 + (144/7.1)(2.75)^3/12 + (144/7.1)(2.75)(3 + \frac{2.75}{2})^2$
$= 5876\ in^4$

$I_{g\,red} = 1830 + (5876 - 1830)/4 = 2842\ in^4$

$W_g = 30(160/3) + 68 = 1668$ plf

$\Delta_g = \frac{5(1668)(30)^4(1728)}{384(29 \times 10^6)(2842)} = 0.369"$

$f_g = 0.18\sqrt{386/0.369} = 5.82\ Hz$

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III) (cont) $D_j = 36.3\ in^4/ft$ $D_g = 2842/20 = 142\ in^4/ft$

$B_g = 1.6\,(36.3/142)^{1/4}(30) = 34.1' < \frac{2}{3}(3 \times 20) = 40'$ ∴ ok✓

$W_g = (1668/20)(34.1)(30) = 85.3^K$

Combined

$L_g > B_j \longrightarrow f_n = 0.18\sqrt{386/(0.18+0.369)} = 4.77\,Hz$

$W = \frac{0.18}{0.18+0.369}(22.7) + \frac{0.369}{0.18+0.369}(85.3) = 64.8^K$

$\beta W = 0.05(64.8) = 3240\ lbs$

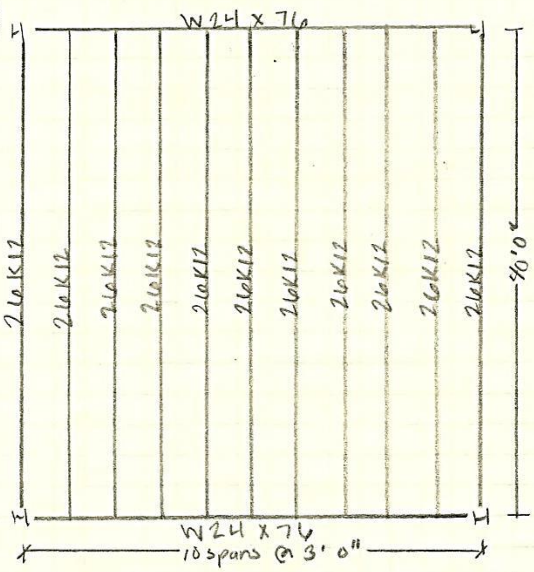
Walking Evaluation

$\frac{a_p}{g} = \frac{65\exp[-0.35(4.77)]}{3240} = 0.38\% < 0.5\%$ ∴ ok✓

Final Evaluation ⟶ Floor System is acceptable

$0.38\% < 0.5\%$ and $4.77\,Hz < 9\,Hz$ ∴ ok✓

IV)



Deck

$W_c = 145\,pcf$ $f'_c = 3000\,psi$

thickness $= 2\frac{1}{2}" + \frac{1}{2}" = 3"$

slab + deck wt = 35 psf

Joists

26K12

wt = 16.6 plf

D = 26"

$I_{chords} = 26.767(269)(40-0.33)^3(10^{-6})$
$= 450\ in^4$

$A = 450/(26/2)^2 = 2.66\ in^2$

$y_c = 13"$

$E_c = 3025\,ksi$

$n = 7.1$

$\bar{y} = 2.66(0.25+13) - (36/7.1)(2.5)(2.5/2) / [2.66 + (36/7.1)(2.5)] = 1.26"$

$I_{comp} = 450 + 2.66(13.25-1.26)^2 + (36/7.1)(2.5)^3/12 + (36/7.1)(2.5)(1.26+2.5/2)^2$
$= 919\ in^4$

$6 \le L/d = (40 \times 12)/26 = 18.5 \le 24 \longrightarrow C = 0.9\left(1 - e^{-0.282(18.5)}\right)^{2.8} = 0.89$

$\gamma = \frac{1}{0.89} - 1 = 0.12$ $I_j = \frac{1}{\frac{0.12}{450} + \frac{1}{919}} = 738\ in^4$

$w_j = 3(11+35+5) + 16.6 = 170\ plf$

$\Delta_j = \frac{5(170)(40)^4(1728)}{384(29 \times 10^6)(738)} = 0.458"$ $f_j = 0.18\sqrt{386/0.458} = 5.23\ Hz$

$D_s = 2.93\ in^4/ft$ $D_j = 738/3 = 246\ in^4/ft$

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IV) (cont.) $B_j = 2(2.93/246)^{1/4}(40) = 26.4' < 60'$ ∴ ok ✓

$W_j = (170/3)(26.4)(40) = 59.8^k$

Girders

W24x76

$A = 22.4$

$I_x = 2100$

$d = 23.9$

$W_{eff} = 144''$

$d_c = 2.75''$

$\bar{Y} = \frac{22.4(3.25 + 23.9/2) - (144/7.1)(2.75)(2.75/2)}{22.4 + (144/7.1)(2.75)} = 3.37''$

$I_g = 2100 + 22.4(0.25 + 3 + 23.9/2 - 3.37)^2 + (144/7.1)(2.75)^3/12 + (144/7.1)(2.75)(3.37 + \frac{2.75}{2})^2$

$= 6526\ in^4$

$I_{g\,red} = 2100 + (6526 - 2100)/4 = 3207\ in^4$

$W_g = 30(170/3) + 76 = 1776\ plf$

$\Delta_g = \frac{5(1776)(30)^4(1728)}{384(29 \times 10^6)(3207)} = 0.35''$ $\quad f_g = 5.98\ Hz$

$D_j = 246\ in^4/ft$ $\quad D_g = 3207/40 = 80.2\ in^4/ft$

$B_g = 1.6(246/80.2)^{1/4}(30) = 63.5' < 80'$ ∴ ok ✓

$W_g = (1776/40)(63.5)(30) = 84.6^k$

Combined

$L_g > B_j \rightarrow f_n = 0.18\sqrt{386/(0.458 + 0.35)} = 3.93\ Hz$

$W = \frac{0.458}{0.458 + 0.35}(59.8) + \frac{0.35}{0.458 + 0.35}(84.6) = 56.5^K$

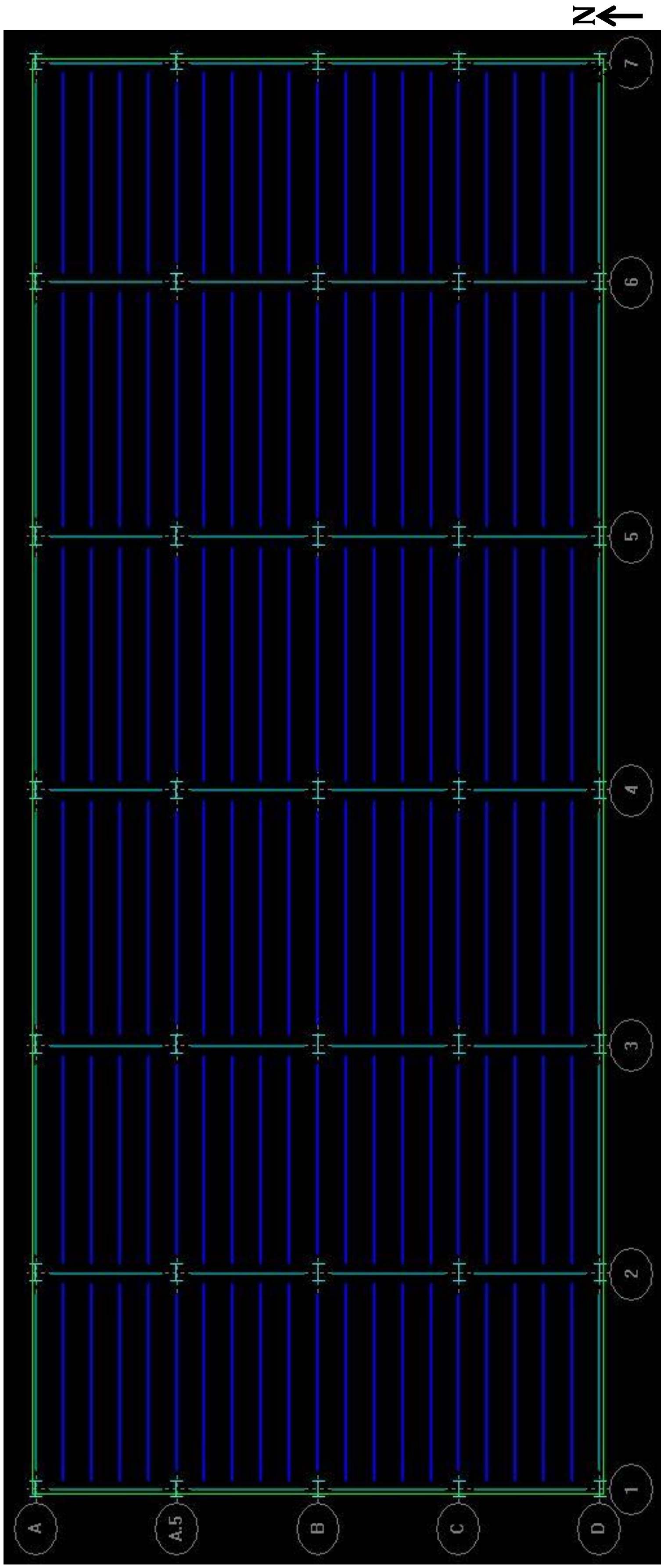
$\beta W = 0.05(56.5) = 2825\ lbs$

Walking Evaluation

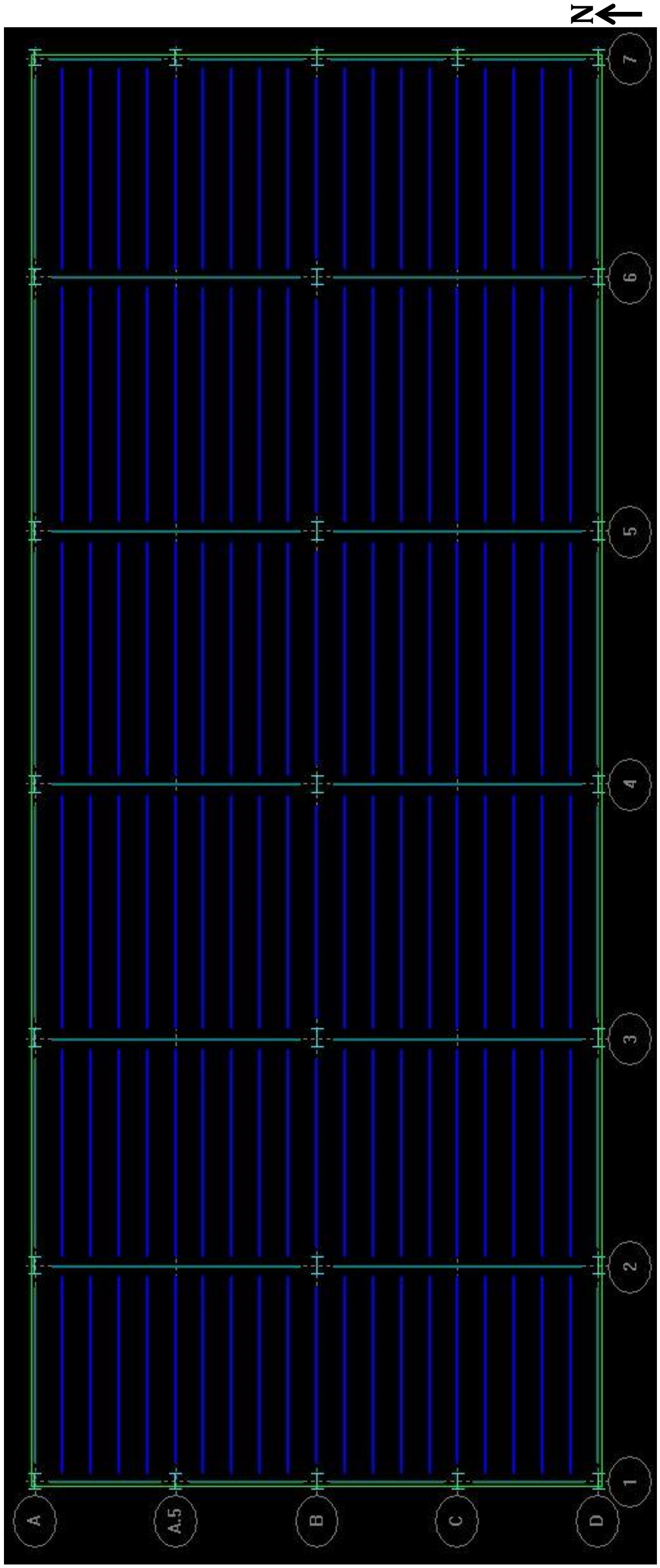
$\frac{a_p}{g} = \frac{65\exp[-0.35(3.93)]}{2825} = 0.58\% > 0.5\%$ ∴ NOT OK

Final Evaluation → this Floor System is adequate but not acceptable by comfort standards

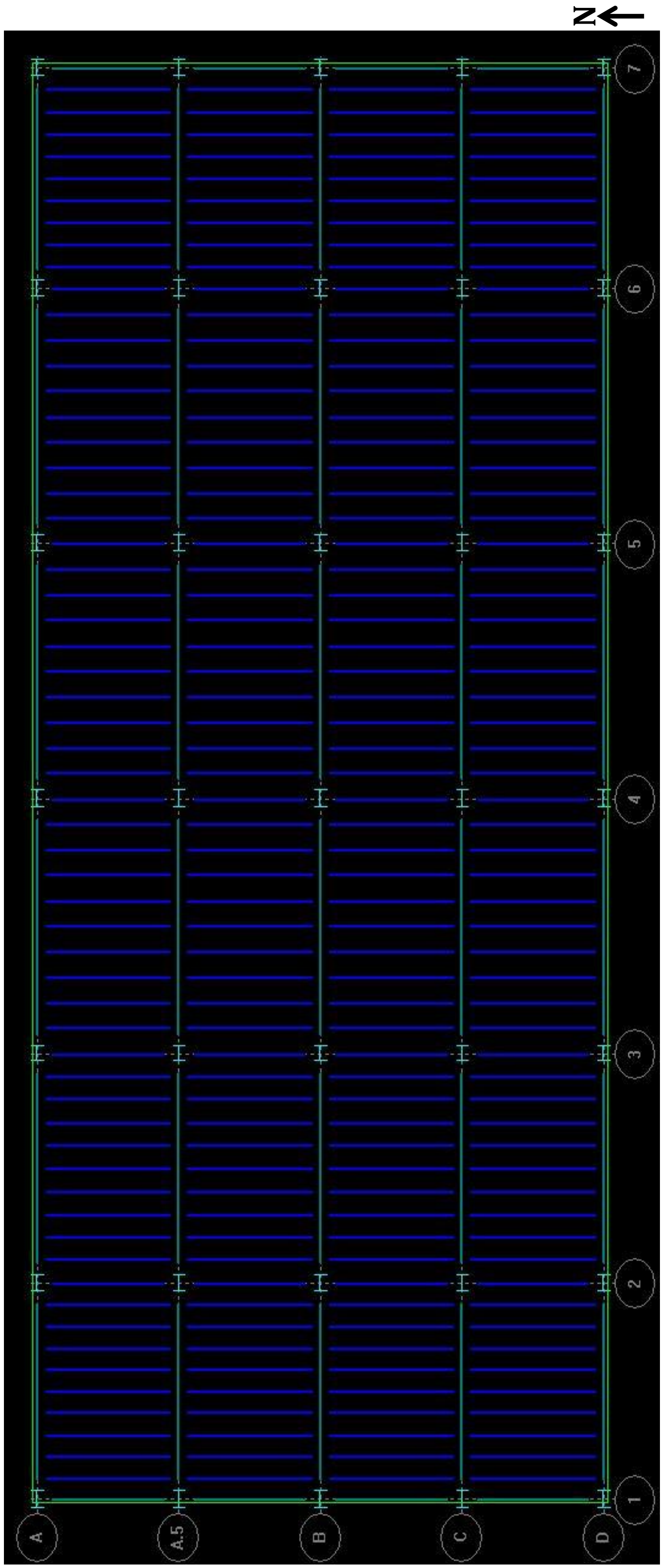
- utilizing Figure 2.1 in AISC Design Guide 11, the floor system is at the brink of unacceptable with a peak acceleration of 0.58% g and a frequency of 3.93 Hz



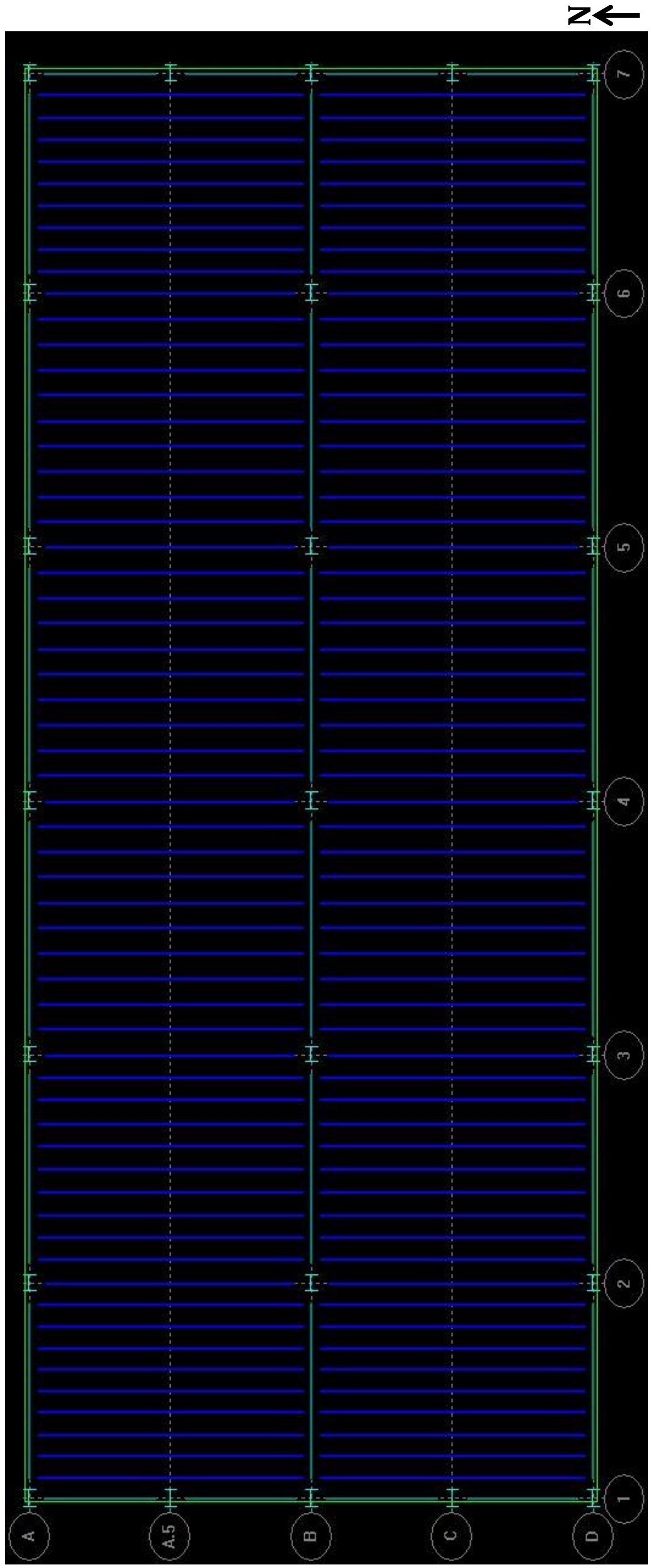
Gravity System Redesign – Configuration I
(30' x 20' Bay with Joists Traveling in the 30' Direction, East-West)



Gravity System Redesign – Configuration II
(30' x 40' Bay with Joists Traveling in the 30' Direction, East-West)



Gravity System Redesign – Configuration III
(30' x 20' Bay with Joists Traveling in the 20' Direction, North-South)



Gravity System Redesign – Configuration IV
(30' x 40' Bay with Joists Traveling in the 40' Direction, North-South)

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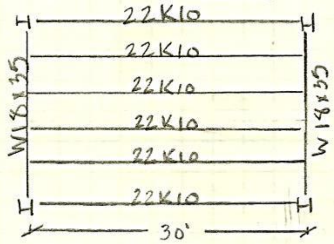
Comparison to RAM Design

Objective: Compare detailed hand calculations to RAM Design output for frame size, layout, and loads. Confirm both are similar to check not only hand calculations but also application of RAM program

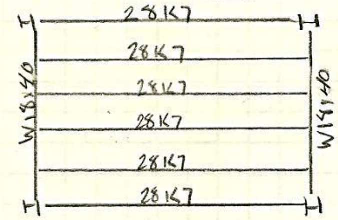
I. 30' x 20' Bay (w/ joists traveling in 30' direction)

Calculations



LL = 80 psf
DL = 10 psf
1.0C24 Deck
37 psf
3 1/2" thick

RAM



Properties

W18x35 : $\phi M_n = 249$ ft·k
$I = 510$ in^4

W18x40 : $\phi M_n = 294$ ft·k
$I = 612$ in^4

22K10 : Load Capacity = 825 lb/ft
w for $\ell/360$ = 385 lb/ft
wt = 12.6 lb/ft

28K7 : Load Capacity = 796 lb/ft
w for $\ell/360$ = 486 lb/ft
wt = 11.8 lb/ft

Check

28K7 → 738 lb/ft + (11.8 lb/ft)(1.2) = 752 < 796 ∴ ok ✓
w for $\ell/240$ = 486(1.5) = 729 > 508 ∴ ok ✓
W18x40 → ok ✓ (so similar to selection → ∴ will pass requirements)

Comparison

	22K10	vs	28K7
Joists →			
Weight	—		✓
Depth	✓		—
Load Capacity	✓		

Final Evaluation? → 22K10 is economical choice

Girders → W18x40 is accurate, economical selection

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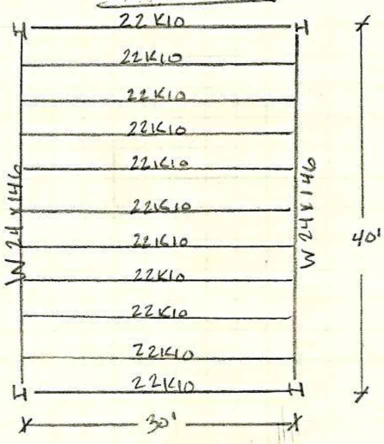
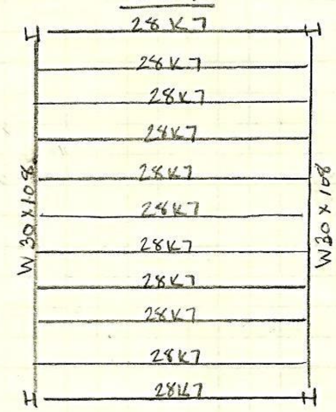
II. 30' x 40' Bay (w/ joists traveling in 30' direction)

Calculations



LL = 80 psf
DL = 10 psf
1.0C24 Deck
37 psf
3 1/2" thick

RAM



Properties

W24x146: ϕM_n = 1570 ft-k
I = 4580 in^4

W30x108: ϕM_n = 1300 ft-k
I = 4470 in^4
camber = 1/2"

W22K10: Load Capacity = 825 lb/ft
w for $l/360$ = 385 lb/ft
Wt = 12.6 lb/ft

W28K7: Load Capacity = 796 lb/ft
w for $l/360$ = 486 lb/ft
Wt = 11.8 lb/ft

Check

28K7 → still acceptable (same properties/values as I.)

W 30x108 → M_u = 1476 ft-k ϕM_n = 1300 < 1476 ∴ NOT OK
Δ_{LL} = 1.33" $I \geq$ 3584 I = 4470 > 3584 ∴ OK ✓

Comparison

Joists →	22K10 vs	28K7
Weight	—	✓
Depth	✓	—
Load Capacity	✓	—

Final Evaluation → 22K10 is still most economical option

Girders →	W24x146 vs	W30x108
Weight	—	✓
Depth	✓	—
ϕM_n	✓	—
I	✓	—
Max Load	✓	—

Final Evaluation? → First, explore options between W24x146 & W30x108

	W24x146 vs	W30x116	W24x146 vs	W30x124
Weight	—	✓	—	✓
Depth	✓	—	✓	—
ϕM_n	✓	—	—	✓
I	—	✓	—	✓
Max Load	✓	—	✓	—

Final Evaluation? → use W30x124, ϕM_n = 1530 > 1476 I = 5360 > 3584

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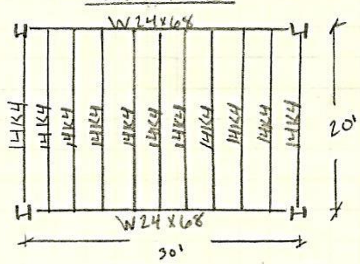
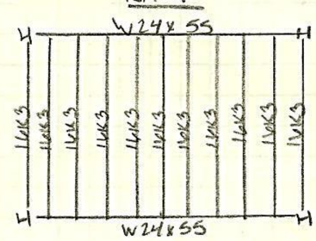
III. 30' x 20' Bay (w/ joists traveling in the 20' direction)

Calculations



LL = 80psf
DL = 10psf
0.6C24 Deck
35 psf
3" thick

RAM



Properties

W24x68: ϕM_n = 664 ft·k
I = 1830 in^4

14K4 : Load Capacity = 642 lb/ft
w for L/360 = 287 lb/ft
wt = 6.7 lb/ft

W24x55: ϕM_n = 503 ft·k
I = 1350 in^4

16K3: Load Capacity = 615 lb/ft
w for L/360 = 330 lb/ft
wt = 6.3 lb/ft

Check

16K3 → 546 + (6.3)(1.2) = 554 < 615 ∴ ok ✓
w for L/240 = 330(1.5) = 495 > 375 ∴ ok ✓

W24x55 → M_u = 614 ft·k ϕM_n = 503 ft·k < 614 ∴ NOT OK
Δ_{LL} = 1" I ≥ 1006 in^4 1350 > 1006 ∴ ok ✓

Comparison

Joists →

	14K4	vs 16K3
Weight	—	✓
Depth	✓	—
Load Capacity	✓	—

Final Evaluation → 14K4 is most economical choice

Girders →

	W24x68	vs W24x55
Weight	—	✓
Depth	—	—
ϕM_n	✓	—
I	✓	—
Max Load	✓	—

	W24x68	vs W21x68
Weight	—	—
Depth	—	✓
ϕM_n	✓	—
I	✓	—
Max Load	✓	—

Final Evaluation → W24x68 is most economical choice

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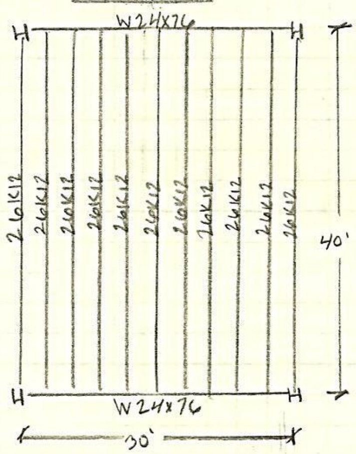
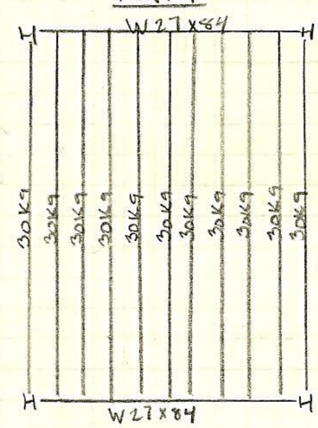
IV. 30'x 40' Bay (w/ joists traveling in the 40' direction)

Calculations



LL = 80 psf
DL = 10 psf
0.6C24 Deck
35 psf
3" thick

RAM



Properties

W24x76: ϕM_n = 750 ft·k
I = 2100 in^4

26K12 : Load Capacity = 657 lb/ft
w for $l/360$ = 269 lb/ft
Wt = 16.6 lb/ft

W27x84: ϕM_n = 915 ft·k
I = 2850 in^4

30K9 : Load Capacity = 576 lb/ft
w for $l/360$ = 278 lb/ft
Wt = 13.4 lb/ft

Check

30K9 ⟶ 546 + 13.4(1.2) = 562 lb/ft < 576 lb/ft ∴ ok ✓
w for $l/240$ = 278(1.5) = 417 lb/ft > 375 lb/ft ∴ ok ✓

W27x84 ⟶ M_u = 614 ft·k ϕM_n = 915 ft·k > 614   ∴ ok ✓
Δ_{LL} = 1"   I ≥ 2011 in^4 2850 > 2011   ∴ ok ✓

Comparison

Joists ⟶

	26K12	vs	30K9
Weight	—		✓
Depth	✓		—
Load Capacity	✓		—

Final Evaluation ⟶ 26K12 is most economical choice

Girders ⟶

	W24x76	vs	W27x84
Weight	✓		—
Depth	✓		—
ϕM_n	—		✓
I	—		✓
Max Load	—		✓

	W24x76	vs	W24x84
Weight	✓		—
Depth	—		—
ϕM_n	—		✓
I	—		✓
Max Load	—		✓

Final Evaluation ⟶ use W24x84 girders

Appendix C: Lateral System Redesign

Velocity Pressures at Heights Above Ground Level		
Height Above Ground Level (ft)	K_{zt}	q_z (psf)
0 – 15	0.57	11.5
20	0.62	12.5
25	0.66	13.4
30	0.70	14.2
40	0.76	15.4
50	0.81	16.4
60	0.85	17.2
70	0.89	18.0
80	0.93	18.8
90	0.96	19.4
100	0.99	20.0
120	1.04	21.0
140	1.09	22.1
160	1.13	22.9
180	1.17	23.7
200	1.21	24.5

Windward Wind Pressures – X-Direction (East-West)			
Floor	Height Above Ground Level (ft)	q_z (psf)	p (psf)
2	14.667	11.5	16.6
3	29.333	14.2	20.5
4	44	15.8	22.8
5	58.667	17.1	24.6
6	73.333	18.3	26.4
7	88	19.3	27.8
8	102.67	20.1	28.9
9	117.33	20.9	30.1
10	132	21.7	31.2
11	146.67	22.4	32.2
12	161.33	22.9	33
13	176	23.5	33.8
Roof	196	24.3	35
Parapet	200.67	24.5	35.3

Windward Wind Pressures – Y-Direction (North-South)			
Floor	Height Above Ground Level (ft)	q_z (psf)	p (psf)
2	14.667	11.5	7.82
3	29.333	14.2	9.66
4	44	15.8	10.7
5	58.667	17.1	11.6
6	73.333	18.3	12.4
7	88	19.3	13.1
8	102.67	20.1	13.7
9	117.33	20.9	14.2
10	132	21.7	14.8
11	146.67	22.4	15.2
12	161.33	22.9	15.5
13	176	23.5	16
Roof	196	24.3	16.5
Parapet	200.67	24.5	16.7

Calculated Dead Loads By Floor							
Floor	DL (psf)				Ext. DL (psf)		Total DL (psf)
	Misc.	Slab/Deck	Framing	Insul.	Panel	Glass	
1	10	0	3.5	0	-	-	15
2	10	37	3.2	2	22	11	90
3	10	37	8	2	45	5	107
4	10	37	7.7	2	45	5	107
5	10	37	7.5	2	33	8	98
6	10	37	7.2	2	33	8	98
7	10	37	7.2	2	33	8	98
8	10	37	7	2	33	8	97
9	10	37	6.7	2	33	8	97
10	10	37	6.5	2	33	8	97
11	10	37	6.3	2	33	8	97
12	10	37	6.1	2	33	8	97
13	10	37	6.2	2	33	8	97
Roof	10	2.5	4	3	66	0	86

Seismic Forces By Floor – Both X & Y-Directions (E-W & N-S)					
Floor	Dead Load (psf)	Weight (k)	Height (ft)	wh^k	Force (k)
2	90	1370	14.667	131720	0.9
3	107	1630	29.333	508982	3.5
4	107	1630	44	1014044	7
5	98	1492	58.667	1513695	10.4
6	98	1492	73.333	2211963	15.2
7	98	1492	88	3015709	20.7
8	97	1477	102.67	3879833	26.6
9	97	1477	117.33	4868496	33.4
10	97	1477	132	5947798	40.8
11	97	1477	146.67	7114767	48.8
12	97	1477	161.33	8365848	57.4
13	97	1477	176	9699560	66.5
Roof	86	1310	196	10330150	70.9
	W (k) =	19,278	$\sum wh^k$ =	58,602,565	

Comparison of Wind & Seismic Loads – Story Shears (k)				
Floor	Wind (X, E-W)	Wind (Y, N-S)	Seismic	Wind or Seismic Controls
Roof	9.8	44.3	70.9	Seismic
13	42.6	115.1	137	Seismic
12	69.9	182.4	195	Seismic
11	96.7	247.9	244	Wind
10	122.9	313.4	284	Wind
9	148.4	377.1	318	Wind
8	172.9	439.1	344	Wind
7	196.8	499.3	365	Wind
6	219.8	557.7	380	Wind
5	241.8	614.3	391	Wind
4	262.5	667.4	398	Wind
3	281.4	717	401	Wind
2	299.2	764.8	402	Wind

Comparison of Wind & Seismic Loads – Base Shear (k) & Overturning Moment (ft-k)				
	Wind (X, E-W)	Wind (Y, N-S)	Seismic	Wind or Seismic Controls
Base Shear (k)	300	765	402	Wind (Y, N-S)
Overturning Moment (ft-k)	31,800	81,500	333,500	Seismic

Center of Mass & Center of Rigidity		
	X	Y
C.o.M.	88	43.5
C.o.R.	91	39
X +e	88	48
X –e	88	39
Y +e	91	43.5
Y –e	85	43.5

Drift Calculations – Wind Loads – Case 1					
Floor	X-Direction (E-W)		Y-Direction (N-S)		Allowable Drift
	X Disp.	X Drift	Y Disp.	Y Drift	
Roof	3.69	0.12	4.35	0.41	0.6
13	3.57	0.12	3.94	0.31	0.44
12	3.45	0.17	3.63	0.34	0.44
11	3.28	0.21	3.29	0.35	0.44
10	3.06	0.26	2.93	0.37	0.44
9	2.81	0.30	2.56	0.38	0.44
8	2.51	0.33	2.18	0.39	0.44
7	2.18	0.36	1.79	0.38	0.44
6	1.82	0.40	1.41	0.37	0.44
5	1.42	0.42	1.03	0.34	0.44
4	1.00	0.42	0.69	0.30	0.44
3	0.57	0.38	0.39	0.24	0.44
2	0.20	0.20	0.15	0.15	0.44

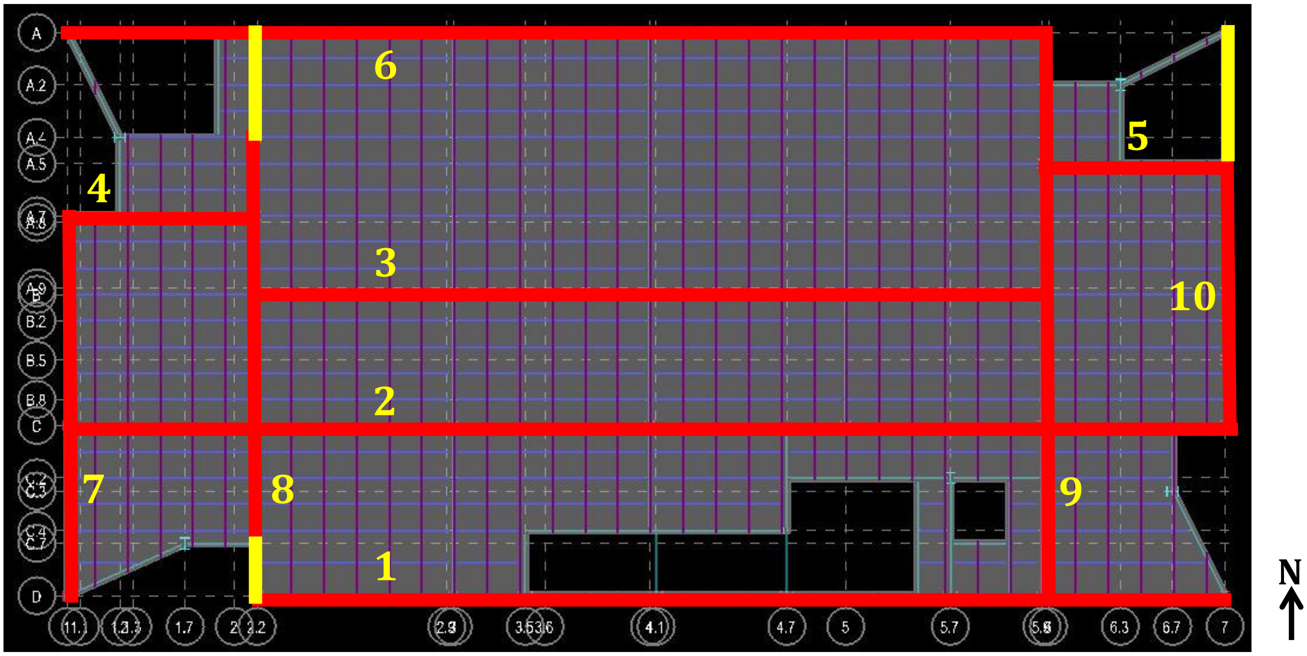
Drift Calculations – Wind Loads – Case 2									
Floor	X-Direction (E-W) (+/-e)				Y-Direction (N-S) (+/-e)				Allowable Drift
	X Disp.	X Drift	X Disp.	X Drift	Y Disp.	Y Drift	Y Disp.	Y Drift	
Roof	2.80	0.09	2.74	0.09	3.24	0.31	3.28	0.30	0.6
13	2.71	0.09	2.65	0.09	2.93	0.23	2.98	0.23	0.44
12	2.61	0.13	2.56	0.13	2.70	0.25	2.74	0.26	0.44
11	2.48	0.16	2.44	0.16	2.45	0.27	2.49	0.27	0.44
10	2.32	0.20	2.28	0.19	2.18	0.28	2.22	0.28	0.44
9	2.12	0.22	2.09	0.22	1.90	0.28	1.94	0.29	0.44
8	1.90	0.25	1.87	0.24	1.62	0.29	1.65	0.30	0.44
7	1.65	0.27	1.63	0.27	1.33	0.29	1.35	0.29	0.44
6	1.37	0.30	1.36	0.30	1.04	0.28	1.07	0.28	0.44
5	1.07	0.32	1.06	0.32	0.76	0.26	0.79	0.26	0.44
4	0.75	0.32	0.75	0.32	0.51	0.22	0.53	0.23	0.44
3	0.43	0.28	0.33	0.28	0.29	0.18	0.30	0.18	0.44
2	0.15	0.15	0.15	0.15	0.11	0.11	0.12	0.12	0.44

Drift Calculations – Wind Loads – Case 3									
Floor	X + Y				X – Y				Allowable Drift
	X Disp.	Y Disp.	X Drift	Y Drift	X Disp.	Y Disp.	X Drift	Y Drift	
Roof	2.73	3.24	0.08	0.30	2.81	-3.28	0.09	-0.31	0.6
13	2.64	2.93	0.09	0.23	2.71	-2.97	0.10	-0.24	0.44
12	2.56	2.70	0.12	0.25	2.62	-2.74	0.13	-0.26	0.44
11	2.43	2.45	0.16	0.26	2.49	-2.48	0.16	-0.27	0.44
10	2.27	2.19	0.19	0.28	2.32	-2.21	0.20	-0.28	0.44
9	2.09	1.91	0.22	0.28	2.13	-1.93	0.23	-0.29	0.44
8	1.87	1.63	0.24	0.29	1.90	-1.64	0.25	-0.30	0.44
7	1.62	1.33	0.27	0.28	1.65	-1.35	0.27	-0.29	0.44
6	1.36	1.05	0.29	0.28	1.37	-1.06	0.30	-0.28	0.44
5	1.06	0.77	0.32	0.25	1.07	-0.78	0.32	-0.26	0.44
4	0.75	0.52	0.32	0.22	0.75	-0.52	0.32	-0.23	0.44
3	0.43	0.22	0.28	0.18	0.43	-0.29	0.28	-0.18	0.44
2	0.15	0.11	0.15	0.11	0.15	-0.11	0.15	-0.11	0.44

Drift Calculations – Wind Loads – Case 4 – CW									
Floor	X + Y CW				X – Y CW				Allowable Drift
	X Disp.	Y Disp.	X Drift	Y Drift	X Disp.	Y Disp.	X Drift	Y Drift	
Roof	2.17	2.44	0.08	0.22	2.23	-2.45	0.09	-0.23	0.6
13	2.09	2.22	0.08	0.17	2.15	-2.21	0.08	-0.18	0.44
12	2.02	2.05	0.10	0.19	2.07	-2.04	0.11	-0.19	0.44
11	1.91	1.86	0.13	0.20	1.96	-1.85	0.14	-0.20	0.44
10	1.78	1.66	0.15	0.21	1.82	-1.65	0.16	-0.21	0.44
9	1.63	1.45	0.18	0.21	1.66	-1.43	0.18	-0.22	0.44
8	1.45	1.23	0.20	0.22	1.48	-1.22	0.20	-0.22	0.44
7	1.26	1.01	0.21	0.21	1.28	-1.00	0.22	-0.22	0.44
6	1.05	0.80	0.23	0.21	1.06	-0.78	0.23	-0.21	0.44
5	0.82	0.59	0.24	0.19	0.83	-0.57	0.25	-0.19	0.44
4	0.57	0.40	0.24	0.17	0.58	-0.38	0.25	-0.17	0.44
3	0.33	0.23	0.22	0.14	0.33	-0.21	0.22	-0.13	0.44
2	0.11	0.09	0.11	0.09	0.11	-0.08	0.11	-0.08	0.44

Drift Calculations – Wind Loads – Case 4 – CCW									
Floor	X + Y CCW				X – Y CCW				Allowable Drift
	X Disp.	Y Disp.	X Drift	Y Drift	X Disp.	Y Disp.	X Drift	Y Drift	
Roof	1.92	2.41	0.05	0.23	1.98	-2.48	0.06	-0.23	0.6
13	1.87	2.18	0.05	0.17	1.92	-2.25	0.06	-0.18	0.44
12	1.81	2.01	0.08	0.19	1.86	-2.07	0.09	-0.19	0.44
11	1.73	1.82	0.10	0.20	1.78	-1.88	0.11	-0.20	0.44
10	1.63	1.63	0.13	0.21	1.66	-1.68	0.13	-0.21	0.44
9	1.50	1.42	0.15	0.21	1.53	-1.46	0.16	-0.22	0.44
8	1.35	1.21	0.17	0.22	1.37	-1.25	0.18	-0.22	0.44
7	1.18	0.99	0.19	0.21	1.20	-1.02	0.20	-0.22	0.44
6	0.99	0.78	0.21	0.21	1.00	-0.81	0.22	-0.21	0.44
5	0.78	0.57	0.23	0.19	0.79	-0.59	0.23	-0.19	0.44
4	0.55	0.38	0.23	0.16	0.55	-0.40	0.24	-0.17	0.44
3	0.31	0.21	0.21	0.13	0.32	-0.23	0.21	-0.14	0.44
2	0.11	0.08	0.11	0.08	0.11	-0.09	0.11	-0.09	0.44

Drift Calculations – Seismic Loads									
Floor	X-Dir. +e		X-Dir. -e		Y-Dir. +e		Y-Dir. -e		Allowable Drift
	X Disp.	X Drift	X Disp.	X Drift	Y Disp.	Y Drift	Y Disp.	Y Drift	
Roof	6.31	0.36	6.26	0.35	3.67	0.40	3.67	0.41	2.9
13	5.96	0.30	5.91	0.30	3.26	0.30	3.27	0.30	2.9
12	5.65	0.39	5.61	0.38	2.96	0.32	2.96	0.33	2.9
11	5.27	0.46	5.21	0.45	2.64	0.33	2.64	0.33	2.9
10	4.81	0.51	4.78	0.51	2.30	0.34	2.31	0.34	2.9
9	4.30	0.56	4.27	0.55	1.97	0.33	1.97	0.33	2.9
8	3.74	0.58	3.72	0.58	1.63	0.33	1.63	0.33	2.9
7	3.16	0.60	3.15	0.59	1.30	0.31	1.30	0.31	2.9
6	2.56	0.61	2.55	0.61	1.00	0.29	1.00	0.29	2.9
5	1.95	0.62	1.94	0.62	0.71	0.25	0.71	0.25	2.9
4	1.33	0.59	1.32	0.59	0.46	0.21	0.46	0.21	2.9
3	0.74	0.49	0.74	0.49	0.25	0.16	0.25	0.16	2.9
2	0.25	0.25	0.25	0.25	0.09	0.09	0.09	0.09	2.9



Frame Participation - % by Floor Level – X-Direction (East-West)						
Frame #	1	2	3	4	5	6
Roof	11.1	41.4	30.1	4.8	3.0	9.6
13	19.5	33.3	21.6	3.8	3.9	17.9
12	19.4	32.7	21.8	4.1	4.3	17.8
11	19.8	33.5	21.3	4.2	4.3	16.9
10	19.9	33.8	21.1	4.2	4.4	16.4
9	19.9	34.1	21.0	4.2	4.5	16.2
8	19.9	33.4	20.9	4.4	4.4	16.9
7	19.5	33.3	20.1	4.8	4.4	18.0
6	19.8	30.9	19.4	5.4	4.8	19.7
5	21.6	26.9	18.4	6.0	5.3	21.8
4	21.8	26.3	17.8	6.3	5.5	22.3
3	21.9	25.4	17.8	6.7	5.9	22.4
2	20.8	26.5	18.9	5.6	4.4	23.7
AVERAGE	19.6	31.7	20.8	5.0	4.6	18.4

Frame Participation - % by Floor Level – Y-Direction (North-South)				
Frame #	7	8	9	10
Roof	2.5	58.0	16.0	23.5
13	5.5	51.2	20.6	22.7
12	7.2	50.0	21.3	21.6
11	7.3	51.3	20.8	20.6
10	6.9	54.6	19.3	19.2
9	6.7	54.1	19.3	19.9
8	5.9	55.5	17.7	20.9
7	5.5	53.8	17.0	23.6
6	4.9	54.3	14.6	26.2
5	4.2	52.2	12.7	31.0
4	3.1	54.7	8.6	33.7
3	2.2	53.7	5.4	38.7
2	1.3	60.1	2.9	35.7
AVERAGE	4.9	54.1	15.1	26.0

Appendix D: Cost & Schedule Analysis (Breadth 1)

Composite Steel Beams & Girders – Original System – Short Bay					
Description	**Quantity**	**Unit**	**Material**	**Installation**	**Total**
Welded wire fabric, 6x6 – W2.1x2.1 (8x8) 30 lb/CSF	6	CSF	17.35	25.5	42.85
Structural Conc., LW, Ready Mix, 110 #/CF, 3000 psi	175	CF	2.51	0	2.51
Structural Conc., placing, elevated slab, less than 6" thick, pumped	175	CF	0	0.85	0.85
Conc. surface treatment, curing, sprayed membrane compound	6	CSF	8.05	5.95	14
Welded Shear Connectors, 3/4" diam., 3- 3/8" long	44	Each	0.53	1.36	1.89
Structural steel members, Beam or girder, W18x35	60	LF	50	5.87	55.87
Structural steel members, Beam or girder, W18x65	40	LF	93	6.25	99.25
Metal decking, steel, non-cellular composite decking, galvanized, 3" deep, 20 ga.	600	SF	2.21	0.59	2.8
Sprayed cementitious fireproofing, 1" thick on beams & girders	400	SF	0.53	0.69	1.22
	Total ($/SF)		**14.79**	**2.72**	**17.50**

Composite Steel Beams & Girders – Original System – Long Bay					
Description	**Quantity**	**Unit**	**Material**	**Installation**	**Total**
Welded wire fabric, 6x6 – W2.1x2.1 (8x8) 30 lb/CSF	12	CSF	17.35	25.5	42.85
Structural Conc., LW, Ready Mix, 110 #/CF, 3000 psi	350	CF	2.51	0	2.51
Structural Conc., placing, elevated slab, less than 6" thick, pumped	350	CF	0	0.85	0.85
Conc. surface treatment, curing, sprayed membrane compound	12	CSF	8.05	5.95	14
Welded Shear Connectors, 3/4" diam., 3- 3/8" long	104	Each	0.53	1.36	1.89
Structural steel members, Beam or girder, W18x35	60	LF	50	5.87	55.87
Structural steel members, Beam or girder, W18x211	80	LF	246	6.45	252.45
Metal decking, steel, non-cellular composite decking, galvanized, 3" deep, 20 ga.	1200	SF	2.21	0.59	2.8
Sprayed cementitious fireproofing, 1" thick on beams & girders	800	SF	0.53	0.69	1.22
	Total ($/SF)		**22.50**	**2.45**	**24.95**

Non-Composite Steel Joists on Girders – Redesign – Short Bay					
Description	**Quantity**	**Unit**	**Material**	**Installation**	**Total**
Welded wire fabric, 6x6 – W2.9x2.9 (6x6) 42 lb/CSF	6	CSF	22.5	27.5	50
Structural Conc., Normal Wt, Ready Mix, 3000 psi	125	CF	3.59	0	3.59
Structural Conc., placing, elevated slab, less than 6” thick, pumped	125	CF	0	0.85	0.85
Conc. Finishing, floors, bull float, manual float, & broom finish	600	SF	0	0.53	0.53
Conc. surface treatment, curing, sprayed membrane compound	6	CSF	8.05	5.95	14
Open web bar joist, K series, 30’ to 50’ span, 22K10, 12.6 lb/LF	180	LF	9	2.89	11.89
Structural steel members, Beam or girder, W18x40	40	LF	57	5.87	62.87
Metal decking, steel, slab form, 24 ga., 1” deep, galvanized	600	SF	1.75	0.47	2.22
Sprayed cementitious fireproofing, 1” thick on joists & girders	800	SF	0.53	0.69	1.22
	Total ($/SF)		**10.01**	**3.69**	**13.70**

Non-Composite Steel Joists on Girders – Redesign – Long Bay					
Description	**Quantity**	**Unit**	**Material**	**Installation**	**Total**
Welded wire fabric, 6x6 – W2.9x2.9 (6x6) 42 lb/CSF	12	CSF	22.5	27.5	50
Structural Conc., Normal Wt, Ready Mix, 3000 psi	250	CF	3.59	0	3.59
Structural Conc., placing, elevated slab, less than 6” thick, pumped	250	CF	0	0.85	0.85
Conc. Finishing, floors, bull float, manual float, & broom finish	1200	SF	0	0.53	0.53
Conc. surface treatment, curing, sprayed membrane compound	12	CSF	8.05	5.95	14
Open web bar joist, K series, 30’ to 50’ span, 22K10, 12.6 lb/LF	330	LF	9	2.89	11.89
Structural steel members, Beam or girder, W30x124	80	LF	177.5	4.86	182.36
Metal decking, steel, slab form, 24 ga., 1” deep, galvanized	1200	SF	1.75	0.47	2.22
Sprayed cementitious fireproofing, 1” thick on joists & girders	1750	SF	0.53	0.69	1.22
	Total ($/SF)		**17.88**	**3.64**	**21.52**

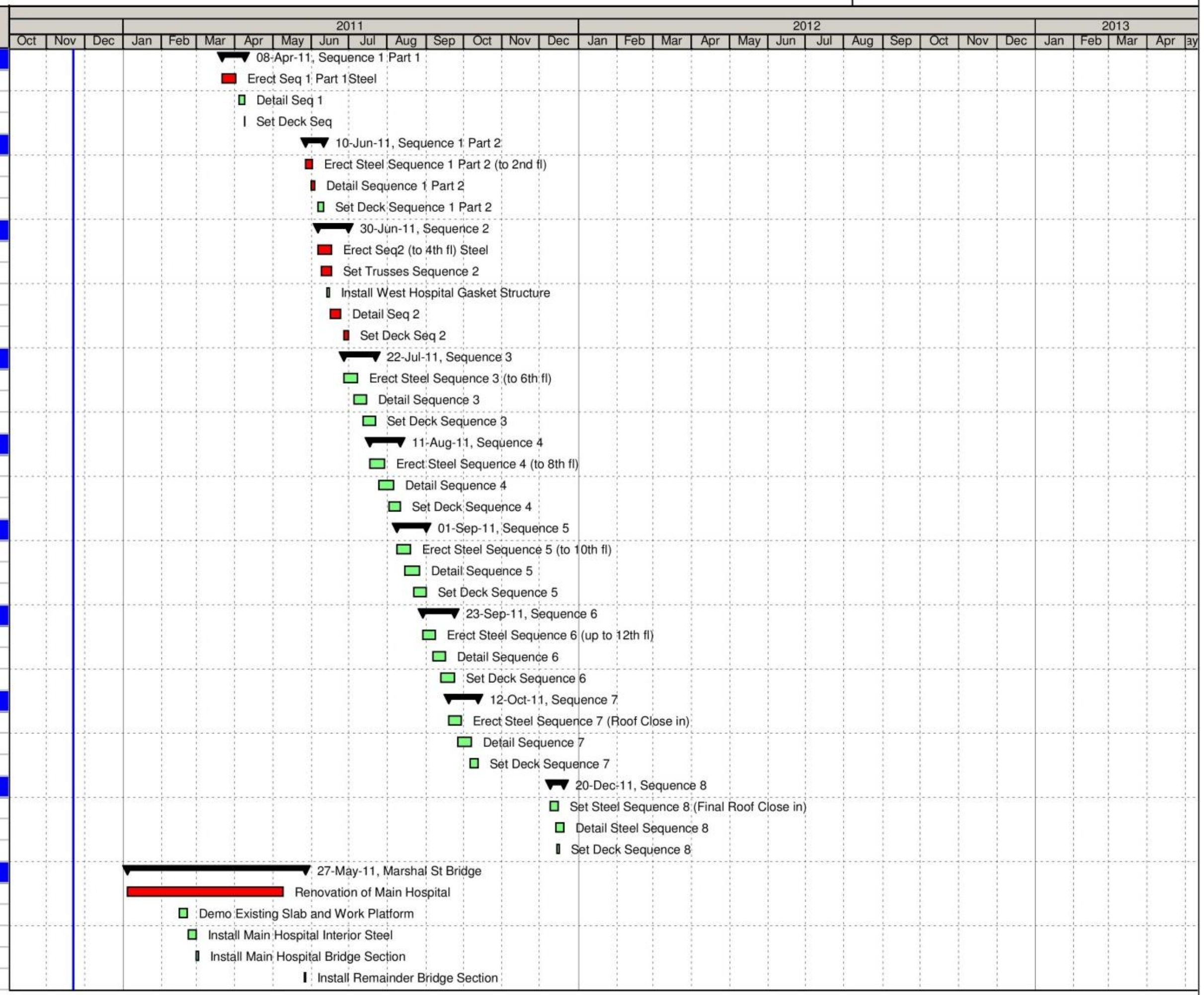
Costs Associated with Spray Applied Fireproofing				
	Material ($/SF)	Installation ($/SF)	Total ($/SF)	Price Increase vs Original
Original System	0.35	0.46	0.81	–
Redesigned System	0.74	0.96	1.70	+ $0.90/SF (~ 4%)

Costs Associated with Shop/Spray Applied Fireproofing & Rated Ceilings – Redesigned System				
	Material ($/SF)	Installation ($/SF)	Total ($/SF)	Price Increase vs Original
Shop Applied	1.04	0	1.04	-
Spray Applied	0.20	0.26	0.46	-
Rated Ceilings	-	-	0.45	-
Total	**-**	**-**	**1.95**	**+ $1.15/SF (~ 5.5%)**

Print Date - 02-Dec-10

Data Date - 22-Nov-10

Activity ID	Activity Name	Orig Dur	Start	Finish
Sequence 1 Part 1		15	21-Mar-11	08-Apr-11
5000	Erect Seq 1 Part 1Steel	10	21-Mar-11	01-Apr-11
5020	Detail Seq 1	5	04-Apr-11	08-Apr-11
5010	Set Deck Seq	1	08-Apr-11	08-Apr-11
Sequence 1 Part 2		10	27-May-11	10-Jun-11
5005	Erect Steel Sequence 1 Part 2 (to 2nd fl)	3	27-May-11	01-Jun-11
5015	Detail Sequence 1 Part 2	3	01-Jun-11	03-Jun-11
5025	Set Deck Sequence 1 Part 2	5	06-Jun-11	10-Jun-11
Sequence 2		19	06-Jun-11	30-Jun-11
5030	Erect Seq2 (to 4th fl) Steel	10	06-Jun-11	17-Jun-11
5060	Set Trusses Sequence 2	7	09-Jun-11	17-Jun-11
A1580	Install West Hospital Gasket Structure	3	13-Jun-11	15-Jun-11
5040	Detail Seq 2	7	16-Jun-11	24-Jun-11
5050	Set Deck Seq 2	4	27-Jun-11	30-Jun-11
Sequence 3		19	27-Jun-11	22-Jul-11
A1070	Erect Steel Sequence 3 (to 6th fl)	8	27-Jun-11	07-Jul-11
A1090	Detail Sequence 3	9	05-Jul-11	15-Jul-11
A1080	Set Deck Sequence 3	9	12-Jul-11	22-Jul-11
Sequence 4		19	18-Jul-11	11-Aug-11
A1100	Erect Steel Sequence 4 (to 8th fl)	10	18-Jul-11	29-Jul-11
A1120	Detail Sequence 4	10	25-Jul-11	05-Aug-11
A1110	Set Deck Sequence 4	8	02-Aug-11	11-Aug-11
Sequence 5		19	08-Aug-11	01-Sep-11
A1130	Erect Steel Sequence 5 (to 10th fl)	10	08-Aug-11	19-Aug-11
A1140	Detail Sequence 5	10	15-Aug-11	26-Aug-11
A1150	Set Deck Sequence 5	9	22-Aug-11	01-Sep-11
Sequence 6		19	29-Aug-11	23-Sep-11
A1160	Erect Steel Sequence 6 (up to 12th fl)	8	29-Aug-11	08-Sep-11
A1170	Detail Sequence 6	9	06-Sep-11	16-Sep-11
A1180	Set Deck Sequence 6	9	13-Sep-11	23-Sep-11
Sequence 7		18	19-Sep-11	12-Oct-11
A1190	Erect Steel Sequence 7 (Roof Close in)	9	19-Sep-11	29-Sep-11
A1200	Detail Sequence 7	10	26-Sep-11	07-Oct-11
A1210	Set Deck Sequence 7	5	06-Oct-11	12-Oct-11
Sequence 8		8	09-Dec-11	20-Dec-11
A1220	Set Steel Sequence 8 (Final Roof Clos...	5	09-Dec-11	15-Dec-11
A1230	Detail Steel Sequence 8	5	14-Dec-11	20-Dec-11
A1240	Set Deck Sequence 8	2	15-Dec-11	16-Dec-11
Marshal St Bridge		105	04-Jan-11	27-May-11
A1650	Renovation of Main Hospital	90	04-Jan-11*	09-May-11
A1610	Demo Existing Slab and Work Platform	5	15-Feb-11	21-Feb-11
A1620	Install Main Hospital Interior Steel	5	22-Feb-11	28-Feb-11
A1630	Install Main Hospital Bridge Section	2	01-Mar-11	02-Mar-11
A1640	Install Remainder Bridge Section	2	26-May-11	27-May-11



Remaining Level of Effort | Actual Level of Effort | Actual Work | Remaining Work | Critical Remaining W... | Summary Milestones

VCU New SOM Master Schedule

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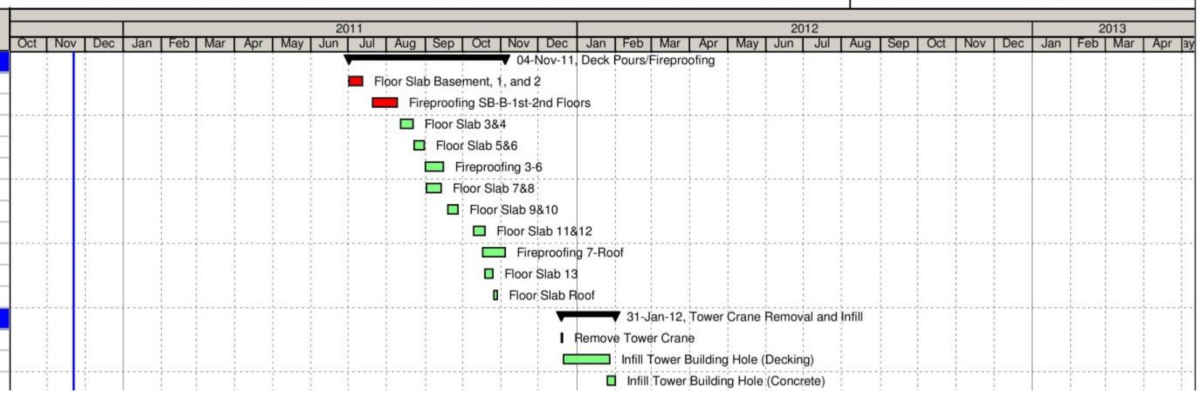
Gilbane

Original Floor Framing System Schedule (Provided by Gilbane Building Company)

Print Date - 02-Dec-10

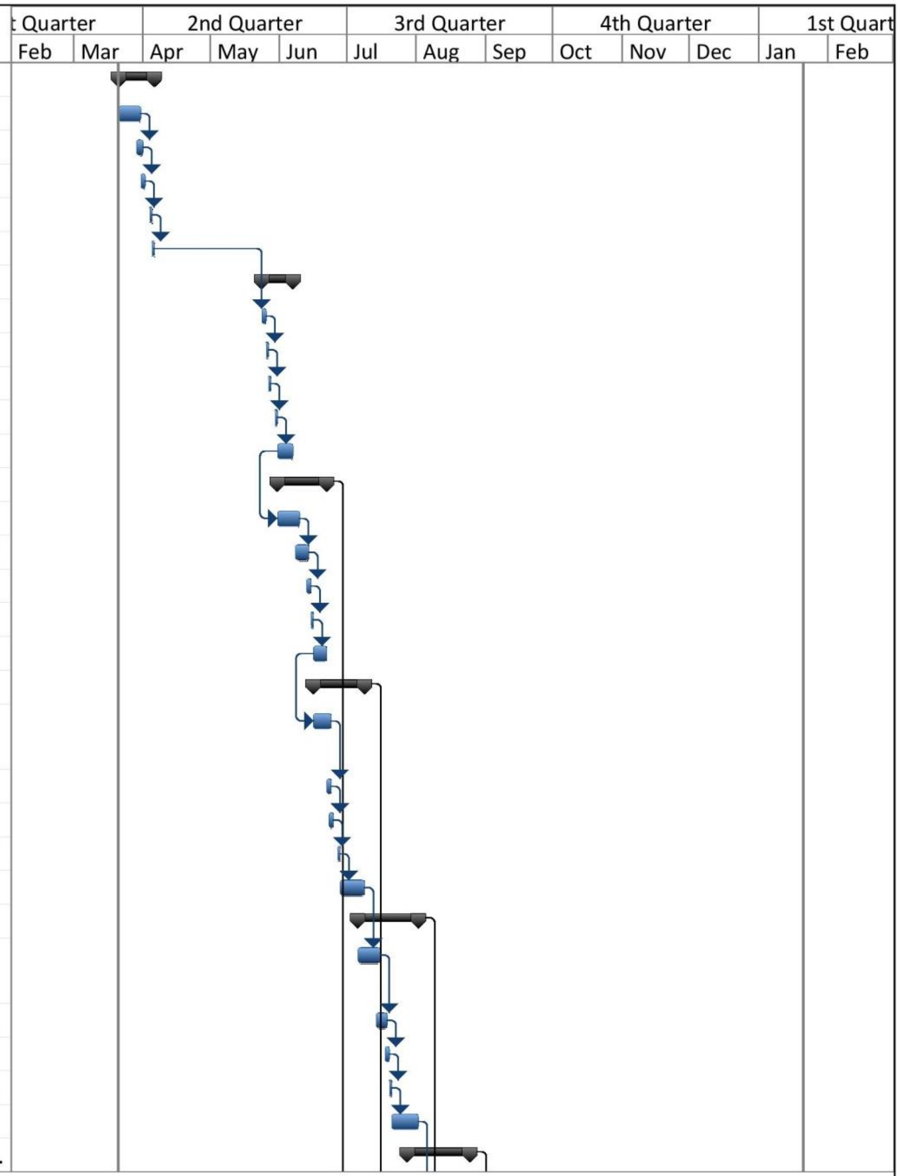
Data Date - 22-Nov-10

Activity ID	Activity Name	Orig Dur	Start	Finish
	Deck Pours/Fireproofing	89	01-Jul-11	04-Nov-11
F3000	Floor Slab Basement, 1, and 2	7	01-Jul-11	12-Jul-11
F3100	Fireproofing SB-B-1st-2nd Floors	15	20-Jul-11	09-Aug-11
F3010	Floor Slab 3&4	7	12-Aug-11	22-Aug-11
F3020	Floor Slab 5&6	7	23-Aug-11	31-Aug-11
F3090	Fireproofing 3-6	10	01-Sep-11	15-Sep-11
F3030	Floor Slab 7&8	7	02-Sep-11	13-Sep-11
F3040	Floor Slab 9&10	7	19-Sep-11	27-Sep-11
F3050	Floor Slab 11&12	7	10-Oct-11	18-Oct-11
F3110	Fireproofing 7-Roof	15	17-Oct-11	04-Nov-11
F3070	Floor Slab 13	5	19-Oct-11	25-Oct-11
F3060	Floor Slab Roof	3	26-Oct-11	28-Oct-11
	Tower Crane Removal and Infill	31	19-Dec-11	31-Jan-12
A1660	Remove Tower Crane	2	19-Dec-11	20-Dec-11
A1670	Infill Tower Building Hole (Decking)	26	21-Dec-11	27-Jan-12
A1680	Infill Tower Building Hole (Concrete)	5	25-Jan-12	31-Jan-12



Original Floor Framing System Schedule Continued (Provided by Gilbane Building Company)

ID	Task Name	Duration	Start	Finish
1	**Sequence 1 Part 1**	**12 days**	**Mon 3/21/11**	**Tue 4/5/11**
2	Erect Steel	8 days	Mon 3/21/11	Wed 3/30/11
3	Detail Steel	3 days	Tue 3/29/11	Thu 3/31/11
4	Set Joists	2 days	Thu 3/31/11	Fri 4/1/11
5	Detail Joists	1 day	Mon 4/4/11	Mon 4/4/11
6	Set Deck	1 day	Tue 4/5/11	Tue 4/5/11
7	**Sequence 1 Part 2**	**10 days**	**Tue 5/24/11**	**Mon 6/6/11**
8	Erect Steel (to 2nd fl)	2 days	Tue 5/24/11	Wed 5/25/11
9	Detail Steel	1 day	Thu 5/26/11	Thu 5/26/11
10	Set Joists (to 2nd fl)	1 day	Fri 5/27/11	Fri 5/27/11
11	Detail Joists	1 day	Mon 5/30/11	Mon 5/30/11
12	Set Deck	5 days	Tue 5/31/11	Mon 6/6/11
13	**Sequence 2**	**16 days**	**Tue 5/31/11**	**Tue 6/21/11**
14	Erect Steel (to 4th fl)	8 days	Tue 5/31/11	Thu 6/9/11
15	Detail Steel	4 days	Wed 6/8/11	Mon 6/13/11
16	Set Joists (to 4th fl)	2 days	Mon 6/13/11	Tue 6/14/11
17	Detail Joists	1 day	Wed 6/15/11	Wed 6/15/11
18	Set Deck	4 days	Thu 6/16/11	Tue 6/21/11
19	**Sequence 3**	**17 days**	**Thu 6/16/11**	**Fri 7/8/11**
20	Erect Steel (to 6th fl)	6 days	Thu 6/16/11	Thu 6/23/11
21	Detail Steel	2 days	Wed 6/22/11	Thu 6/23/11
22	Set Joists (to 6th fl)	2 days	Thu 6/23/11	Fri 6/24/11
23	Detail Joists	1 day	Mon 6/27/11	Mon 6/27/11
24	Set Deck	9 days	Tue 6/28/11	Fri 7/8/11
25	**Sequence 4**	**19 days**	**Wed 7/6/11**	**Mon 8/1/11**
26	Erect Steel (to 8th fl)	8 days	Wed 7/6/11	Fri 7/15/11
27	Detail Steel	3 days	Thu 7/14/11	Mon 7/18/11
28	Set Joists (to 8th fl)	2 days	Mon 7/18/11	Tue 7/19/11
29	Detail Joists	1 day	Wed 7/20/11	Wed 7/20/11
30	Set Deck	8 days	Thu 7/21/11	Mon 8/1/11
31	**Sequence 5**	**20 days**	**Thu 7/28/11**	**Wed 8/24/11**



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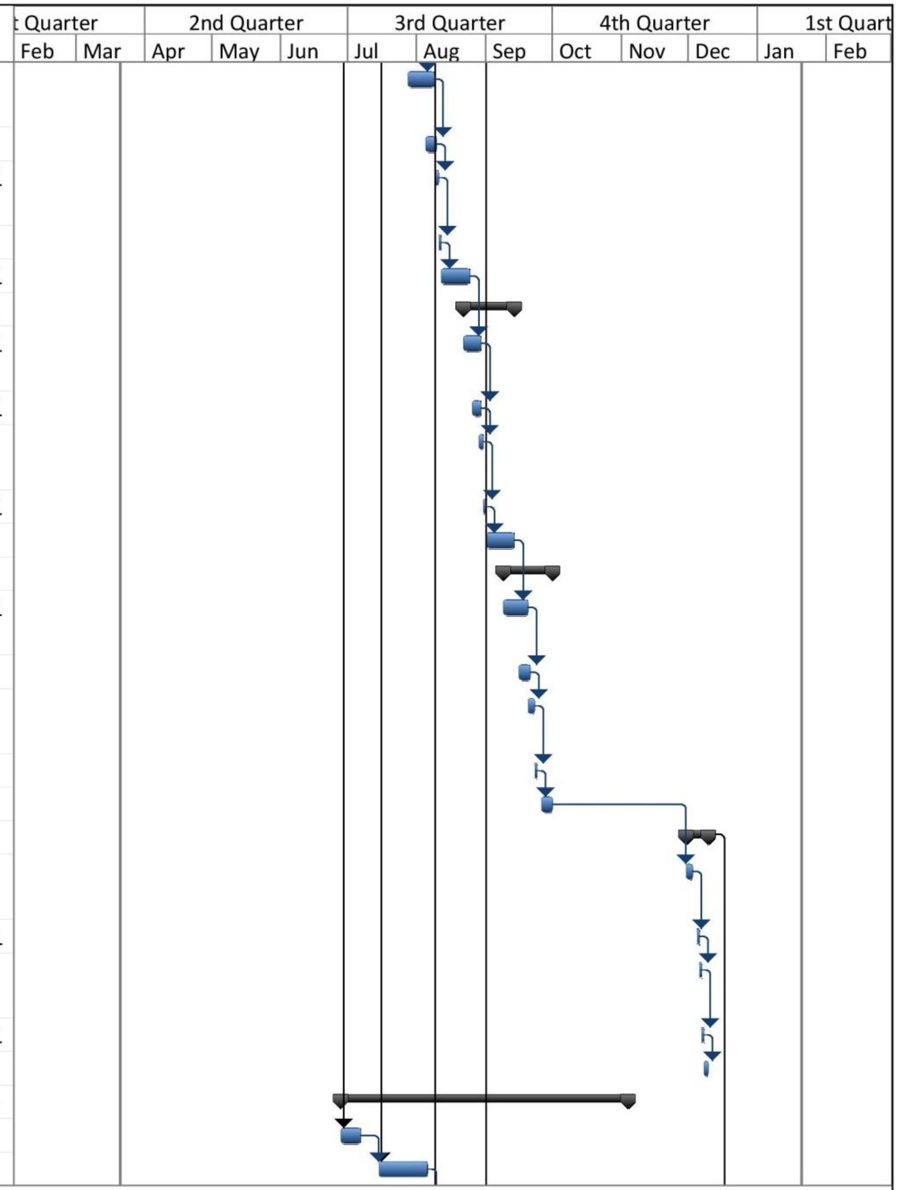
Redesigned Floor Framing System Schedule

ID	Task Name	Duration	Start	Finish
32	Erect Steel(to 10th fl)	8 days	Thu 7/28/11	Mon 8/8/11
33	Detail Steel	3 days	Fri 8/5/11	Tue 8/9/11
34	Set Joists (to 10th fl)	2 days	Tue 8/9/11	Wed 8/10/11
35	Detail Joists	1 day	Thu 8/11/11	Thu 8/11/11
36	Set Deck	9 days	Fri 8/12/11	Wed 8/24/11
37	**Sequence 6**	**17 days**	**Mon 8/22/11**	**Tue 9/13/11**
38	Erect Steel (to 12th fl)	6 days	Mon 8/22/11	Mon 8/29/11
39	Detail Steel	2 days	Fri 8/26/11	Mon 8/29/11
40	Set Joists (to 12th fl)	2 days	Mon 8/29/11	Tue 8/30/11
41	Detail Joists	1 day	Wed 8/31/11	Wed 8/31/11
42	Set Deck	9 days	Thu 9/1/11	Tue 9/13/11
43	**Sequence 7**	**16 days**	**Fri 9/9/11**	**Fri 9/30/11**
44	Erect Steel (Roof Close-in)	7 days	Fri 9/9/11	Mon 9/19/11
45	Detail Steel	3 days	Fri 9/16/11	Tue 9/20/11
46	Set Joists (Roof Close-in)	3 days	Tue 9/20/11	Thu 9/22/11
47	Detail Joists	1 day	Fri 9/23/11	Fri 9/23/11
48	Set Deck	5 days	Mon 9/26/11	Fri 9/30/11
49	**Sequence 8**	**8 days**	**Wed 11/30/1**	**Fri 12/9/11**
50	Erect Steel (Final Roof Close-in)	3 days	Wed 11/30/11	Fri 12/2/11
51	Detail Steel	1 day	Mon 12/5/11	Mon 12/5/11
52	Set Joists (Final Roof Close-in)	1 day	Tue 12/6/11	Tue 12/6/11
53	Detail Joists	1 day	Wed 12/7/11	Wed 12/7/11
54	Set Deck	2 days	Thu 12/8/11	Fri 12/9/11
55	**Deck Pours/Fireproofing**	**93 days**	**Tue 6/28/11**	**Thu 11/3/11**
56	Floor Slab 1 & 2	7 days	Tue 6/28/11	Wed 7/6/11
57	Fireproofing 1-2	16 days	Fri 7/15/11	Fri 8/5/11



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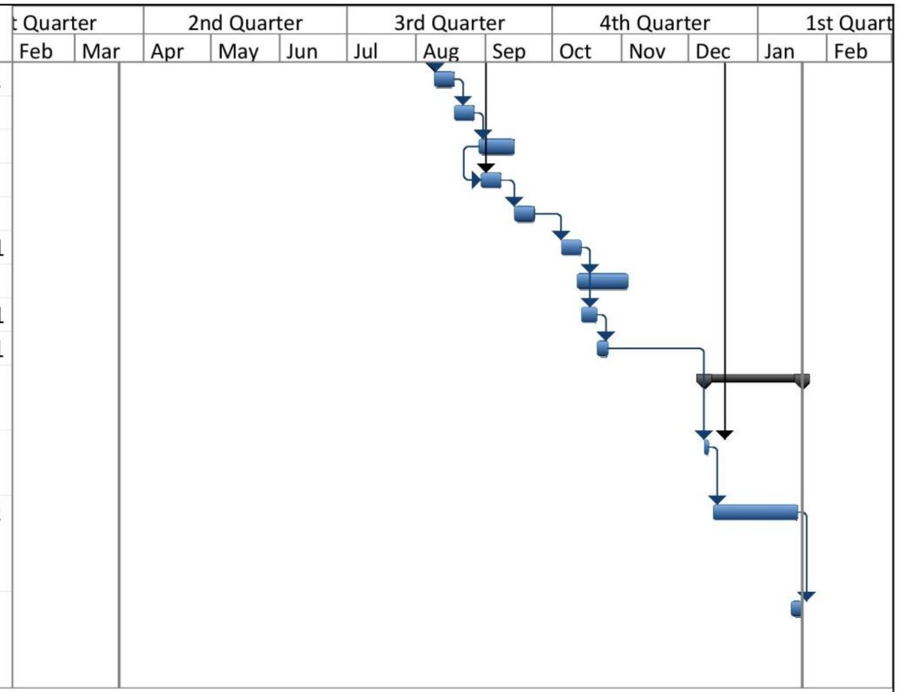
Redesigned Floor Framing System Schedule

ID	Task Name	Duration	Start	Finish
58	Floor Slab 3 & 4	7 days	Tue 8/9/11	Wed 8/17/11
59	Floor Slab 5 & 6	7 days	Thu 8/18/11	Fri 8/26/11
60	Fireproofing 3-6	12 days	Mon 8/29/11	Tue 9/13/11
61	Floor Slab 7 & 8	7 days	Tue 8/30/11	Wed 9/7/11
62	Floor Slab 9 & 10	7 days	Wed 9/14/11	Thu 9/22/11
63	Floor Slab 11 & 12	7 days	Wed 10/5/11	Thu 10/13/11
64	Fireproofing 7-Roof	17 days	Wed 10/12/11	Thu 11/3/11
65	Floor Slab 13	5 days	Fri 10/14/11	Thu 10/20/11
66	Floor Slab Roof	3 days	Fri 10/21/11	Tue 10/25/11
67	**Tower Crane Removal & Infill**	**32 days**	**Thu 12/8/11**	**Fri 1/20/12**
68	Remove Tower Crane	2 days	Thu 12/8/11	Fri 12/9/11
69	Infill Tower Building Hole (Decking)	28 days	Mon 12/12/11	Wed 1/18/12
70	Infill Tower Building Hole (Concrete)	5 days	Mon 1/16/12	Fri 1/20/12



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Redesigned Floor Framing System Schedule

Comparison of Original Gravity System & Redesigned Gravity System Project Durations									
		Original			Redesign			Comparison	
		Dates	Dur	Total Dur	Dates	Dur	Total Dur	By Tasks	Total
Steel Erection	Seq 1 Part 1	3/21 -4/8	15	122 days	3/21 -4/5	12	114 days	Redesign	Redesign
	Seq 1 Part 2	5/27 -6/10	10		5/24 -6/6	10			
	Seq 2	6/6 -6/30	19		5/31 -6/21	16			
	Seq 3	6/27 -7/22	19		6/16 -7/8	17			
	Seq 4	7/18 -8/11	19		7/6 -8/1	19			
	Seq 5	8/8 -9/1	19		7/28 -8/24	20			
	Seq 6	8/28 -9/23	19		8/22 -9/13	17			
	Seq 7	9/19 -10/12	18		9/9 -9/30	16			
	Seq 8	12/9 -12/20	8		11/30 -12/9	8			
Deck Pours/ Fireproofing	Floor Slab 1-2	7/1 -7/12	7	89 days	6/28 -7/6	7	93 days	Original	
	Fireproofing 1-2	7/20 -8/9	15		7/15 -8/5	16			
	Floor Slab 3-6	8/12 -8/31	14		8/9 -8/26	14			
	Fireproofing 3-6	9/1 -9/15	10		8/29 -9/13	12			
	Floor Slab 7-12	9/2 -10/18	21		8/30 -10/13	21			
	Fireproofing 7-Roof	10/17 -11/4	15		10/12 -11/3	17			
	Floor Slab 13	10/19 -10/25	5		10/14 -10/20	5			
	Floor Slab Roof	10/26 -10/28	3		10/21 -10/25	3			
Tower Crane Removal & Infill	Remove Crane	12/19 -12/20	2	31 days	12/8 -12/9	2	31 days	Redesign	
	Infill Hole (Decking)	12/21 -1/27	29		12/12 -1/18	28			
	Infill Hole (Conc)	1/25 -1/31	5		1/16 -1/20	5			

Appendix E: Architectural Considerations (Breadth 2)

International Building Code 2006 [Ninth Printing]

A-3 Assembly uses intended for worship, recreation or amusement and other assembly uses not classified elsewhere in Group A including, but not limited to:

Amusement arcades
Art galleries
Bowling alleys
Places of religious worship
Community halls
Courtrooms
Dance halls (not including food or drink consumption)
Exhibition halls
Funeral parlors
Gymnasiums (without spectator seating)
Indoor swimming pools (without spectator seating)
Indoor tennis courts (without spectator seating)
Lecture halls
Libraries
Museums
Waiting areas in transportation terminals
Pool and billiard parlors

304.1 Business Group B. Business Group B occupancy includes, among others, the use of a building or structure, or a portion thereof, for office, professional or service-type transactions, including storage of records and accounts. Business occupancies shall include, but not be limited to, the following:

Airport traffic control towers
Animal hospitals, kennels and pounds
Banks
Barber and beauty shops
Car wash
Civic administration
Clinic—outpatient
Dry cleaning and laundries: pick-up and delivery stations and self-service
Educational occupancies for students above the 12th grade
Electronic data processing
Laboratories: testing and research
Motor vehicle showrooms
Post offices
Print shops
Professional services (architects, attorneys, dentists, physicians, engineers, etc.)
Radio and television stations
Telephone exchanges
Training and skill development not within a school or academic program

508.3.1 Accessory occupancies. Accessory occupancies are those occupancies subsidiary to the main occupancy of the building or portion thereof. Aggregate accessory occupancies shall not occupy more than 10 percent of the area of the story in which they are located and shall not exceed the tabular values in Table 503, without height and area increases in accordance with Sections 504 and 506 for such accessory occupancies.

Exceptions:

1. Accessory assembly areas having a floor area less than 750 square feet (69.7 m^2) are not considered separate occupancies.

TABLE 508.3.3
REQUIRED SEPARATION OF OCCUPANCIES (HOURS)

	A[e], E		I		R[d]		F-2, S-2[c,d], U[d]		B[b], F-1, M[b], S-1		H-1		H-2		H-3, H-4, H-5	
OCCUPANCY	S	NS	S	NS	S	NS	S	NS	S	NS	S	NS	S	NS	S	NS
A[e], E[e]	N	N	1	2	1	2	N	1	1	2	NP	NP	3	4	2	3[a]
I	—	—	N	N	1	NP	1	2	1	2	NP	NP	3	NP	2	NP
R[d]	—	—	—	—	N	N	1	2	1	2	NP	NP	3	NP	2	NP
F-2, S-2[c,d], U[d]	—	—	—	—	—	—	N	N	1	2	NP	NP	3	4	2	3[a]
B[b], F-1, M[b], S-1	—	—	—	—	—	—	—	—	N	N	NP	NP	2	3	1	2[a]
H-1	—	—	—	—	—	—	—	—	—	—	N	NP	NP	NP	NP	NP
H-2	—	—	—	—	—	—	—	—	—	—	—	—	N	NP	1	NP
H-3, H-4, H-5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	N	NP

803.1 General. Interior wall and ceiling finishes shall be classified in accordance with ASTM E 84. Such interior finish materials shall be grouped in the following classes in accordance with their flame spread and smoke-developed indexes.

Class A: Flame spread 0-25; smoke-developed 0-450.

Class B: Flame spread 26-75; smoke-developed 0-450.

Class C: Flame spread 76-200; smoke-developed 0-450.

TABLE 803.5
INTERIOR WALL AND CEILING FINISH REQUIREMENTS BY OCCUPANCY[k]

GROUP	SPRINKLERED[l]			NONSPRINKLERED		
	Exit enclosures and exit passageways[a,b]	Corridors	Rooms and enclosed spaces[c]	Exit enclosures and exit passageways[a,b]	Corridors	Rooms and enclosed spaces[c]
A-1 & A-2	B	B	C	A	A[d]	B[e]
A-3[f], A-4, A-5	B	B	C	A	A[d]	C
B, E, M, R-1, R-4	B	C	C	A	B	C
F	C	C	C	B	C	C
H	B	B	C[g]	A	A	B
I-1	B	C	C	A	B	B
I-2	B	B	B[h, i]	A	A	B
I-3	A	A[j]	C	A	A	B
I-4	B	B	B[h, i]	A	A	B
R-2	C	C	C	B	B	C
R-3	C	C	C	C	C	C
S	C	C	C	B	B	C
U	No restrictions			No restrictions		

[F] 903.2.1.3 Group A-3. An automatic sprinkler system shall be provided for Group A-3 occupancies where one of the following conditions exists:

1. The fire area exceeds 12,000 square feet (1115 m^2).
2. The fire area has an occupant load of 300 or more.
3. The fire area is located on a floor other than the level of exit discharge.

Exception: Areas used exclusively as participant sports areas where the main floor area is located at the same level as the level of exit discharge of the main entrance and exit.