

2009-2010 AE Senior Thesis

Thesis Proposal

Structural Redesign of University Medical Center at Princeton

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Executive Summary

The New Hospital of the University Medical Center at Princeton is a six-story facility which rises 106'-0" above grade and is the centerpiece of an entire medical complex currently under construction in Plainsboro, NJ. The current structural system of the hospital is steel framing with a composite beam floor diaphragm. Lateral forces are resisted by eighteen braced frames spread throughout the building and two long moment frames on both the north and south exterior faces. Spread footings are located underneath each steel column to carry the loads to the ground.

Due to strong lateral loads on the structure, the base of each braced frame experiences a net tensile force depending upon the direction of the loading. In order to resist this upward pull on the foundation, tension only mini-piles are anchored into the bedrock below and then attached to the spread footings underneath each braced frame.

The proposed thesis includes a redesign of the structural system using concrete rather than steel framing. The overall goal is to increase the weight of the building enough so that the downward compressive force at the footing is greater than the upward tension force, thereby eliminating the need for mini-piles underneath the footings. A second goal is to improve vibration performance of the original composite beam floor system by redesigning it as a two-way flat slab. The structure will be modeled and redesigned in RAM Structural System. Hand calculations will be performed to check these designs.

By changing the structural material to concrete, the lateral force resisting system of the building will be redesigned with concrete shear walls in both the N-S and E-W directions. Since the self-weight of the building is increased, the spread footings will need to be upsized in order to properly handle the increased compressive forces. An effort will be made to maintain the original layout in order to reduce the architectural impact of the redesign.

A concrete redesign will also present new issues that must be addressed. One of these issues is the increase in seismic forces due to a heavier structure. Seismic forces will be recalculated based upon the Equivalent Lateral Force Procedure set forth in ASCE7-05 and compared with the wind forces to determine the controlling load combination on the redesigned structure. Floor vibrations due to walking and mechanical equipment must fall within guidelines for a hospital set forth in AISC Design Guide II.

A scheduling and cost analysis will be performed to evaluate the advantages and disadvantages of the redesign. Finally, an architectural study of the south façade will be performed to determine the impact of replacing exposed circular HSS columns with circular concrete columns along the south façade of the hospital.

Introduction

The University Medical Center at Princeton is a new state-of-the-art medical facility currently under construction in Plainsboro, NJ. The project consists of a Central Utility Plant, a Diagnostic and Treatment Center (D&T) and a New Hospital. The site already has an existing building (Building #2) and it will be connected to the north side of the New Hospital as part of the project. The Medical Office Building (MOB) is only proposed at this time. The 800,000 square foot complex is set to be complete by the summer of 2010.

The scope of this thesis project will be limited to structural analysis and re-design of the New Hospital (Figure 1). This is the tallest portion of the complex at 92'-0" from grade to roof with a 14'-0" metal panel system above for a total height of 106'-0" above grade.

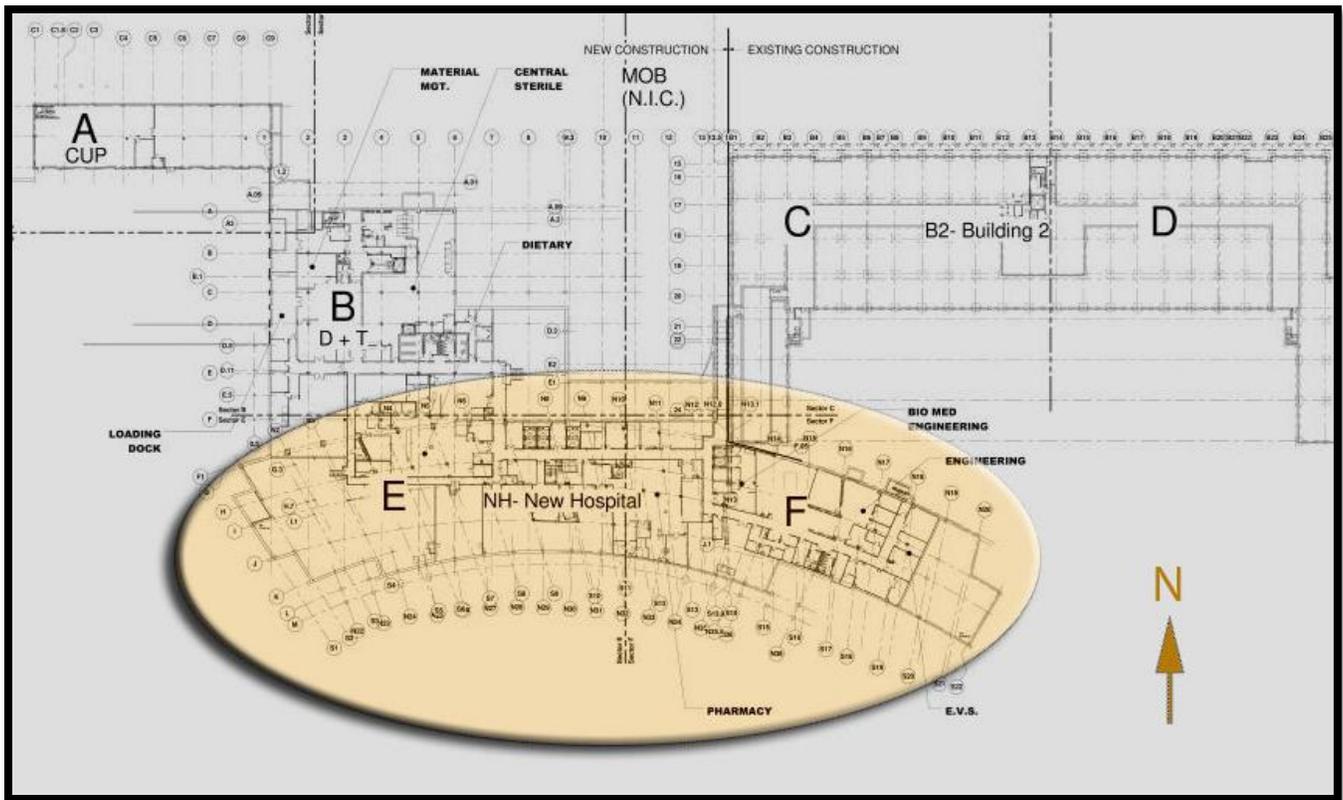


Figure 1: Overall Plan University Medical Center at Princeton

Structural System Overview

The structural system of the New Hospital at the University Medical Center was designed by structural engineers at O'Donnell & Naccarato using a Load Resistance Factor Design approach. It is a structural steel building with a composite floor diaphragm. Braced frames run in both directions and there are two long moment frames spanning the entire length of the building on both the south and north facades as seen below in Figure 2. Both the braced and moment frames are the building's main resistance to lateral load. Due to the great length of the building in the west-east direction, an expansion joint was placed at a distance from the western façade roughly equal to $\frac{2}{3}$ of the total building length. This effectively splits the building into two different structures which behave on their own.

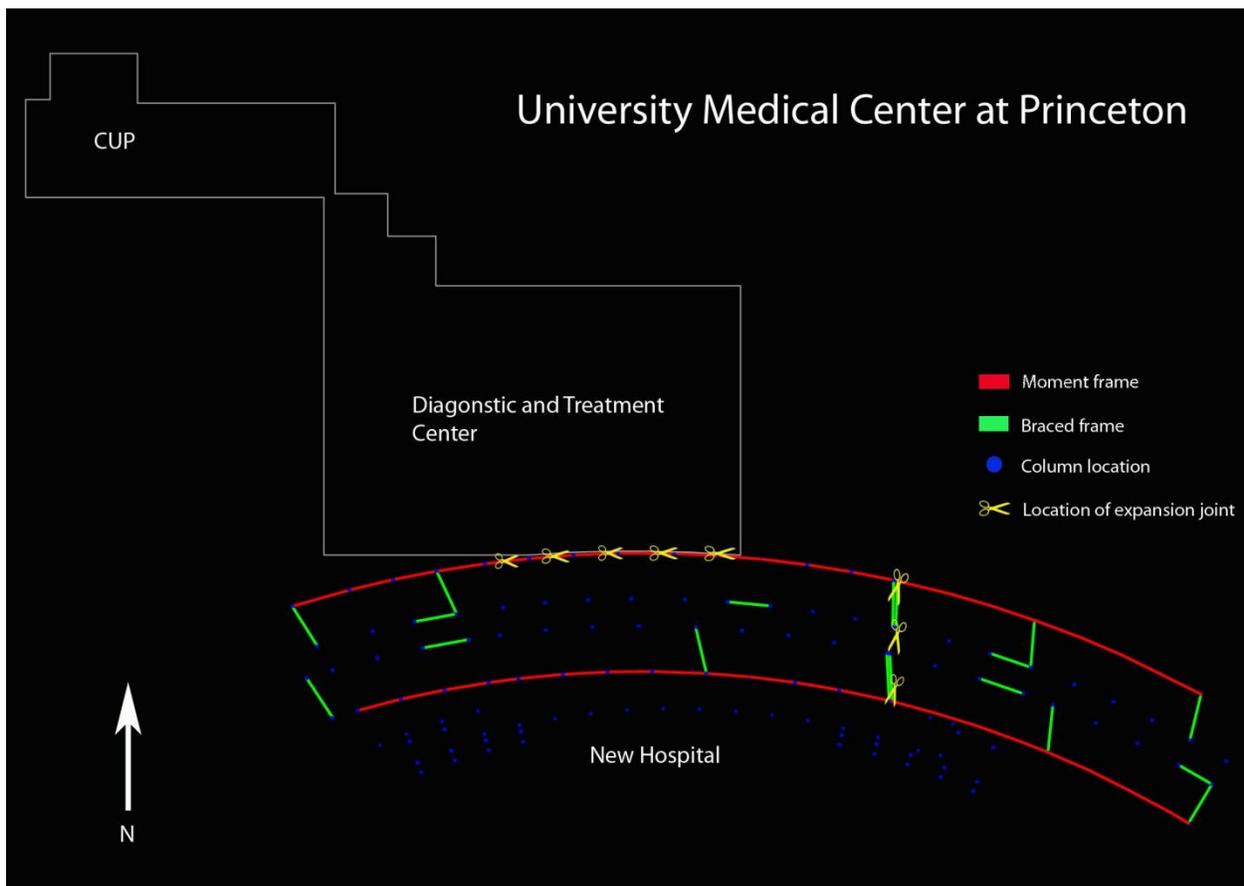


Figure 2: Overall schematic of lateral force resisting elements

Foundation

Concrete piers with sizes anywhere from 18" x 18" to 48" x 78" are attached to the base of the steel columns and transmit vertical load from the superstructure to the concrete spread footings. The size of these footings varies from as small as 3'-0" x 3'-0" x 14" to as large as 21' x 21' x 50".

All footings supporting braced frame columns have mini-piles attached at their base in order to handle high tension forces resulting from lateral loading. These piles extend to decomposed bedrock (8'-30' deep). The top of all exterior footings are at a minimum depth of 42" below grade.

The floor at the base level is concrete slab-on-grade with thicknesses from 4"-12".

Huge concrete retaining walls with footings up to 17'-0" wide trace the perimeter of the foundation system.

Superstructure

The structural steel provides both gravity and lateral load resistance for the building. Columns are typically W14 while beams and girders range from W12-W27 shapes. Rectangular HSS shapes are used for the diagonal members in the braced frames and round HSS columns support the massive glass façade on the south face of the hospital. The HSS columns are intentionally exposed for architectural purposes. The floor layout (Figure 3) is uniform and has a typical bay size of 30' x 30'.

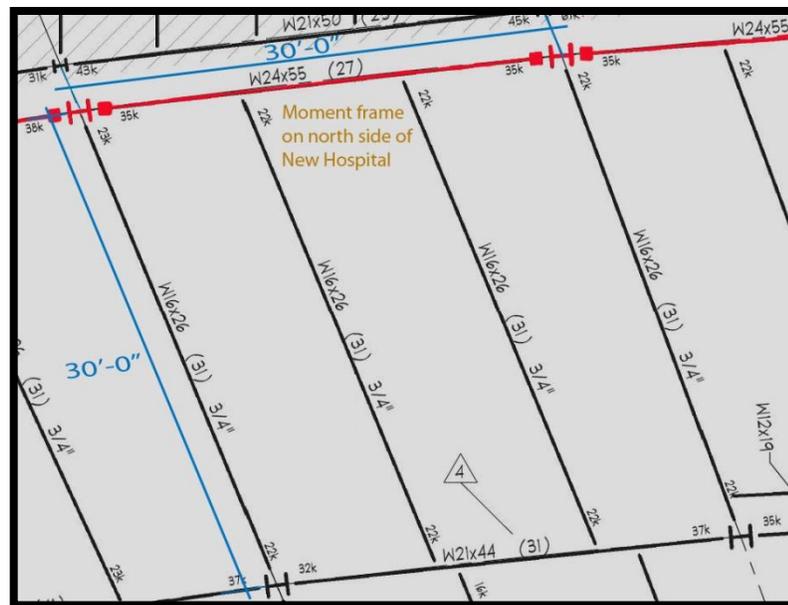


Figure 3: Typical 30'0" x 30'-0" bay size.

The floor system spanning over the main area of the building is composite construction. Typically, the concrete slab is 3-1/4" lightweight concrete poured over a 3" composite metal deck. In certain mechanical and roof areas, the floor system switches to a 6-1/2" normal weight concrete due to higher loads in those areas.

The composite floor is considered to act as a rigid diaphragm and therefore able to transmit lateral forces from the façade to the braced and moment frames.

Lateral System

The primary components of the lateral force resisting system in the New Hospital are braced and moment frames. On the western wing of the facility, there are six braced frames running in the N-S direction. In the W-E direction, there are three braced frames and two long moment frames. The eastern wing has a similar layout with six braced frames in the N-S and three in the W-E as well as two moment frames in the W-E. (See Figure 2 above)

Since the stiffness of each braced frame is significantly larger than the stiffness of the moment frames, most of the lateral load is handled by the braced frames. However, each of the eighteen braced frames is unique due to slight modifications in member sizes or bracing pattern. Three of the eighteen braced frames are shown in elevation below (Figure 4).

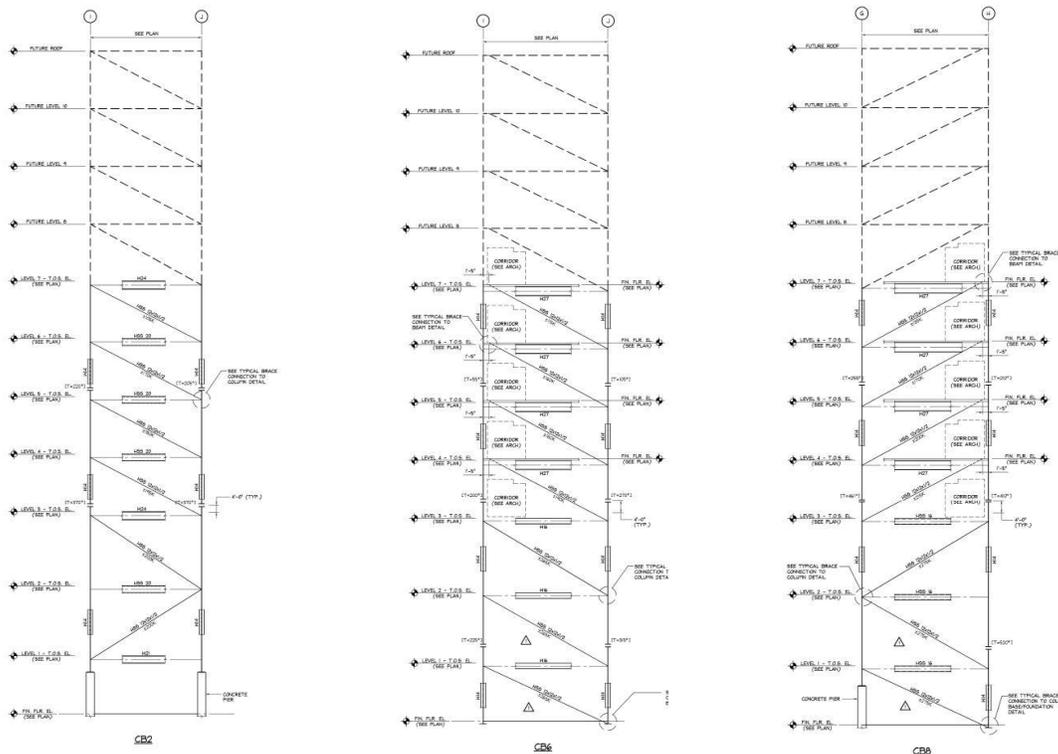


Figure 4: Elevations of braced frame #2, #6, and #8. All eighteen frames have a unique design.

Background

When lateral load (such as a force from wind pressure) is levied upon the building, the façade receives it and transfers this force into the rigid floor diaphragm. The diaphragm then distributes that force to the braced and moment frames throughout the building based upon the relative stiffness of each frame.

When the proportional amount of force is transmitted to any of the braced frames, the diagonal braces accept the force axially and deliver it to the columns on either side of the frame where it is then taken down to the foundation.

As a result the columns on either end of the frame are in tension or compression, depending upon the direction of the wind (Figure 5).

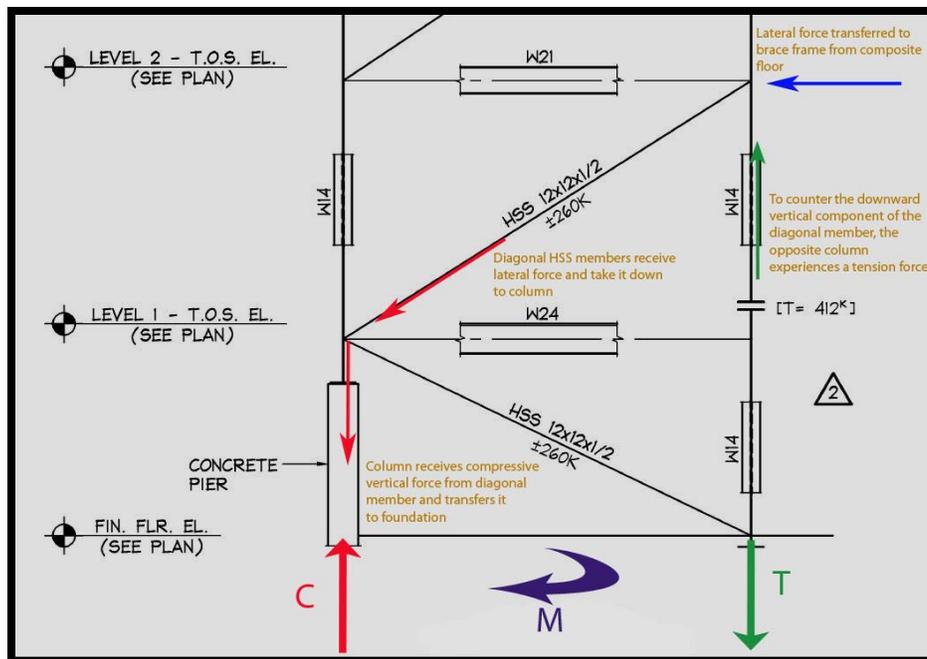


Figure 5: Load path through typical braced frame.

Problem Statement

The spread footing beneath the *column in compression* has to be able to resist the compressive force from the column as well as the force resulting from the weight of the entire building above. The spread footing supporting the *column in tension* is a different story. The tension force creates a reaction at the base of the column which acts against the dead load force of the building. If the tension force is higher, the result will be a net tensile force on the footing which essentially tries to lift the frame out of the ground.

The lateral loading on the New Hospital at the University Medical Center is great enough to cause net tensile forces at the base of the braced frames. One objective of this thesis project is to redesign the structural system so that the net tensile force at the base of the braced frame is either eliminated or can be handled by the foundation without the use of mini-piles.

Since this building is a hospital, there are additional design concerns regarding floor vibrations that are important for quality building performance. While the original composite beam floor system met these vibration requirements an overall concrete redesign will necessitate a new floor system. Therefore, a second objective of this thesis project will be to design a floor system which is not only compatible with a concrete frame but also enhances vibration performance.

Proposed Solution

The design engineers working on the University Medical Center opted to design the foundation to handle the net tensile force. This was accomplished by driving tension only mini-piles into the bedrock below and attaching the top of those piles to the spread footings underneath the braced frames (Figure 6 below). The frictional force between the surface of the pile and the rock is strong enough to resist the upward force thereby keeping the brace frame from overturning.

While mini-piles are a perfectly legitimate design solution, this thesis project aims to solve the problem in a different way: by eliminating the net tensile force altogether. This can be accomplished if the dead load from the building is greater than the tension force caused by lateral loading. Since the structure is initially designed as a steel framed building, it is conceivable that switching to a concrete frame could increase the building weight enough to eliminate the need for mini-piles underneath the spread footings.

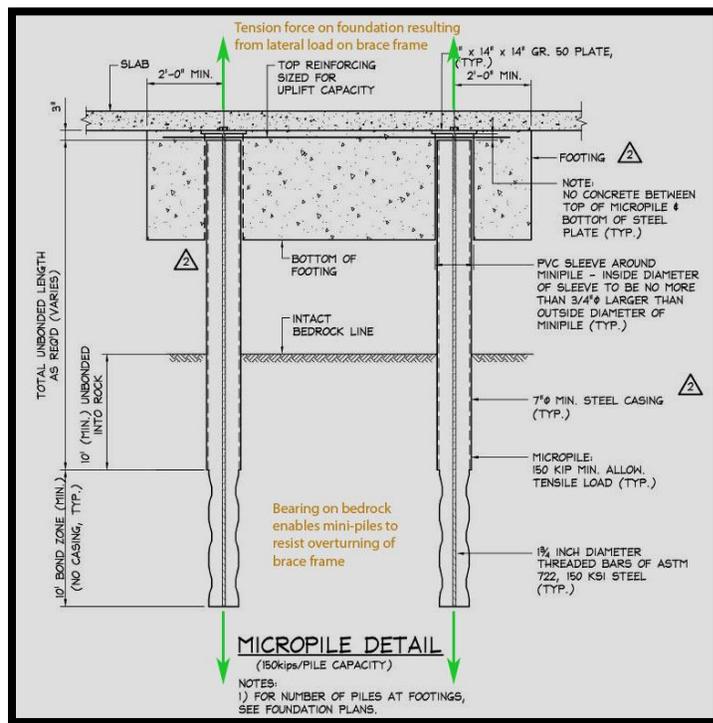


Figure 6: Tension only mini-piles attached to footing of braced frame.

While switching from steel to concrete might solve the problem of overturning, it does introduce a host of issues which will need to be considered. First, increasing the weight of the structure will necessitate a redesign of the foundation system due to increased compressive forces. Initially this doesn't appear to be solving the problem since the foundation was the reason for switching to concrete in the first place. But because spread footings are made of concrete, they are much better in compression than in tension. Upsizing a footing to handle compressive forces is more manageable than upsizing to handle tension forces.

Redesigning in concrete will require the removal of all braced frames which effectively changes the entire lateral force resisting system. Since the structure will be redesigned in concrete, shear walls will replace the steel braced frames as the main component of the hospital's lateral system. The placement of these shear walls will be of utmost importance because of torsion effects. Different shear wall layouts will be investigated in order to determine a design which is effective in the resistance of overall building torsion while also limiting architectural impact.

One advantage of concrete is the monolithic connection between columns and beams, forming a natural moment connection. The proposed redesign will include concrete beams along the exterior of the building, effectively creating long moment frames which will provide additional lateral resistance in the E-W direction. These concrete frames will replace the steel moment frames that are currently on the north and south faces of the hospital.

Of course, with an increase in building weight comes an increase in seismic forces. These forces must be recalculated and then compared with the wind forces to determine the controlling load case for lateral design.

The redesign of the floor slab must also not be forgotten. In Technical Report II, it was determined that the original composite beam floor system met vibration requirements for a hospital. The proposed redesign will set out to improve upon the vibration performance of the floor system by further investigating a two-way flat slab system. It was previously concluded in Tech II that two-way flat slab is a viable alternative to the original composite beam floor system. However, vibration conclusions from that report were determined using simplified assumptions which need further investigation in order to conclusively prove an enhanced vibration performance. Therefore, a thorough study of floor vibrations in concrete floor systems will be included as part of this thesis.

It is clear that redesigning the structure in concrete will have a dramatic impact on the original design. The ultimate goal of this thesis project is to a) eliminate the need for tension-only mini piles underneath the foundation and b) improve vibration performance of the floor system without dramatically affecting the schedule, cost, and architecture of the hospital.

Breadth Issues

A redesign in concrete creates the need for several other studies to be performed outside of immediate structural impacts. The first is an overall cost and schedule analysis between the steel and concrete systems. Both have advantages and disadvantages which will have to be evaluated and compared.

Another important study involves the architectural effect of concrete framing versus steel. The southern façade is the defining architectural feature of the New Hospital and was designed to be supported by circular HSS columns. These steel HSS columns were intended to be exposed as an architectural feature but would be replaced with circular concrete columns.

Also, the replacement of steel braced frames with concrete shear walls will most likely impact the layout of the floor plan. Both of these issues have significant architectural ramifications and must be investigated so that the intentions of the owner are satisfied.

MAE Course Related Study

The MAE requirement for this class will be met by utilizing computer models to aid with the design of the structure. This is a direct application of the material taught in AE 597A. Also, seismic calculations and analysis will have to be performed which will apply course material from AE 538.

Solution Methods

The re-design of the New Hospital at University Medical Center will follow code set forth in ASCE7-05 and ACI 318-08. Loading used for the design will be determined by ASCE7-05 and by industry standard practice. This exercise was already completed in Technical Report I.

Floor slabs will be designed using the equivalent frame method as specified in Chapter 13 of ACI 318-08. The computer program ADOSS will be used to model the slabs and this program will produce a design based upon the equivalent frame method. Slab thickness, amount of reinforcement, and reinforcement detailing will be confirmed with hand calculations which follow procedures from ch. 13. Floor vibrations due to walking and mechanical equipment will be thoroughly researched in order to justify improved performance of the redesigned floor system.

The gravity, lateral, and foundation systems will be modeled in RAM Structural System with all applicable load combinations applied as well as live load patterns. Once modeled, design output utilizing a LRFD approach will be developed. These designs will be confirmed by procedures specified in ACI318-08. Wall thicknesses (ch. 14), amount and detailing of reinforcement (ch. 7, 12), footing sizes (ch. 15), and all member sizes (ch. 8, 9, 10, 11) will be checked with hand calculations. Design output from RAM will also be used to check drift, torsion response, and overturning.

Primavera software will be used to develop a project schedule and RSMeans 2009 will be used to determine overall system cost.

A 3-D building model will be created in Revit Architecture in order to aid in the schedule and cost analysis as well as the architectural study of the south facade.

Tasks

- I. Redesign lateral system with concrete shear walls
 1. Determine design loads
 - i. Determine live loads per ASCE7-05
 - ii. Determine dead loads based upon standard industry practice and calculation of structure self-weight
 - iii. Determine wind loads per Method II of ASCE7-05
 - iv. Determine seismic loads per Equivalent Lateral Force Procedure of ASCE7-05
 2. Determine shear wall placement
 - i. Develop multiple models using RAM structural system each with different shear wall layouts
 - ii. Evaluate each layout due to torsion effects
 - iii. Determine the most effective layout in terms of torsion and architectural impacts
 3. Model structure in RAM Structural System
 - i. Run design process under all applicable load combinations
 - ii. Obtain sizes for beams and columns
 - iii. Modify sizes to achieve a more uniform design
 - iv. Verify that design meets all drift criteria set forth in ASCE7-05
 4. Verify computer design
 - i. Check column and beam designs via hand calculations
- II. Redesign gravity system with reinforced concrete and two-way flat slab with drop panels
 1. Model gravity system in RAM Structural System
 - i. Run analysis of gravity system using member designs obtained from lateral design
 - ii. Verify that column and beam designs are sufficient to handle both gravity and lateral loading
 - iii. Determine minimum slab thickness based on vibration criteria for hospitals
 - iv. Run design of slab in ADOSS.
 - v. Evaluate performance of flat slab with drop panels system to original composite beam design
 2. Verify computer design
 - i. Check column, beam, and slab design via hand calculations

- III. Redesign spread footings
 1. Model foundation system in RAM Structural System
 - i. Evaluate tension/compression forces at base of each column
 - ii. Run design process for spread footings under all applicable load combinations
 2. Verify computer design
 - i. Check footing design via hand calculations
 - ii. Check overturning of footing

- IV. Evaluate schedule and cost impact of redesign
 1. Develop complete construction schedule using Primavera
 - i. Determine critical path for project completion
 - ii. Determine sequencing for construction
 2. Perform cost analysis for redesign
 - i. Determine labor, material, and equipment costs using RSMeans 2009
 3. Evaluate schedule and cost of redesign
 - i. Compare with original design

- V. Analyze architectural impact of south façade and shear wall placement
 1. Develop Revit models
 - i. Original design
 - ii. Redesign
 2. Investigate impacts
 - i. Discuss impact of concrete columns versus steel HSS columns in relation to architecture of façade
 - ii. Reorder floor plan in order to allow for appropriate placement of shear walls
 - iii. Discuss impact of reordered floor plan on the functionality of the space

