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BUILDING DESIGN STUDIES FOR GATEWAY PARK

A Major Qualifying Project

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

in Civil Engineering

by

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Abstract

The purpose of this project is to recommend a structural design layout for a proposed mixed-use commercial building as part of the Gateway Park expansion. Using *AISC*, *ACI*, and *MSBC* provisions, two structural steel designs and two reinforced concrete designs were investigated with respect to the size of each bay. Typical concrete footing designs with reinforcing steel were also developed. In addition, floor layouts were established to meet functional requirements, and alternative cladding and green roofing systems were explored. The final design was chosen based on cost, space limitations, LEED specifications, and constructability criteria.

Authorship

This project was a collaborative effort between the three team members. Each section was written separately, though all sections were reviewed and edited by all team members. A general delineation of responsibilities is listed below.

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Capstone Design Statement

As part of the Major Qualifying Project (MQP) a capstone design experience was completed. The capstone design experience was based on skills previously learned in the classroom, the application of appropriate engineering standards, and independent learning. It was also incorporated the following seven realistic constraints: economic, constructability, health and safety, ethical, political, social, and sustainability. The treatment of each constraint is outlined below.

The first constraint is economics. In evaluating different designs, cost had a major effect on the selection process. We selected the most cost efficient design by examining different alternatives to construction, floor layouts, and materials. A cost analysis was also done using material quantities from our design with unit cost data, and square footage order of magnitude estimate from *RS Means*.

The second constraint is constructability. In this project several floor layouts were examined with different arrangements of beams and columns. Thought went into defining the different members sizes and footings sections in the alternative steel and reinforced concrete designs so that the complexity of construction was minimized. Typical sizes were used throughout construction as well as standard materials. In order o assess constructability, the welds and bolts of each design are graded to make a final recommendation.

Health and Safety is also a major concern throughout this project. Adjustments were made to the floor layout to assure the safety of the tenants. Special consideration was given when designing the FPE Department's floor plan and lab space to assure safety throughout the building. The FPE labs will be dealing with, at times hazardous experiments, so by making sure the hallways were wide and exits close, students and faculty can leave the building safely in the event of an emergency. The bio labs on the upper floor could also have potentially hazardous experiments, making the need for easy egress a factor. The building structure followed the provisions of the *Massachusetts State Building Code*, City of Worcester Zoning Ordinance, and the Americans with Disabilities Act (ADA) Standards for Accessible Design.

Much knowledge was gained talking with Fred DiMauro and other faculty members about the construction of Gateway Park and other commercial buildings. When building any structure there are always many ethical, social and political concerns, especially in a city like Worcester. As proposed, Gateway Park is expected to bring in many jobs for people in the surrounding areas and possibly provide jobs for graduating students at WPI. Gateway 2 will continue to enhance WPI's image in the local economy by expanding the school's involvement in research and promoting commercial and high tech development in the City of Worcester. It will also provide a place to mold young minds by relocating Mass Academy High School. Being exposed to standard architectural graphics and gaining insight into architectural strategies, allowed for the design of the floor layouts to assure that WPI's image would be enhanced. Many people might agree that Gateway 2 would be a positive contribution but concerns could arise when looking environmental inpact and the types of research being done within the Biotech companies. There also could be concerns if the site is not Americans with Disabilities Act (ADA) compliant considering in 2000, there were 38,068 people in Worcester, MA listed as disabled (Worcester, Massachusetts Census Data).

Finally, sustainability constraints are dealt with in this project. This project follows LEED specifications for Sustainable Sites Credit 7.2- Heat Island Effect- Roof. The New York Times' education blog “The Choice” mentions Worcester Polytechnic Institute (WPI) as one of several schools that have improved in sustainability effort. In continuing this effort this project

looks at different alternatives to roof designs by incorporating a green roof. Sustainability was assessed as part of the grading system used to make the final recommendation.

Acknowledgments

We would like to take a moment to thank all of those who have helped us complete this project. First and foremost, we would like to thank Professor Leonard Albano for advising our project. Without his help we could not have accomplished the amount of work that we did. Second, we would like to thank Alfred DiMauro and Professor Kathy Notarianni of the FPE Department for providing us with information used to create the floor plans which determined the bay sizes for design. Last we would like to thank Mr. David Puza of Merritt Construction Services, Inc. for allowing the use of their subscription to *CostWorks*, which was used to compile the cost estimate.

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Chapter 1: Introduction

WPI is a growing community that strives to create and convey the latest science and engineering knowledge in ways that would be most useful to society (WPI Faculty, 1987). In continuing to do this, WPI and the Worcester Business Development Corporation (WBDC) worked together to develop Gateway Park in 2005. Gateway Park is designed as a 12-acre mixed-use destination that will provide a home for life sciences and biotech companies. The Gateway Park is part of a larger 55-acre redevelopment project that will provide an environment that fosters the exchange of ideas among scientists, scholars, students, and entrepreneurs (Gateway Park, 2008).

Gateway Park, formally an industrial site, is now home to the WPI Life Sciences and Bioengineering Center. This site is also designed to hold four other life science buildings, condominiums, and several retail establishments (see Figure 1).

Figure 1: Proposed Gateway Park Complex

This project will focus specifically on Lot 3, which will accommodate a four-story, 80,000 sq. ft. facility that will be referred to as Gateway 2 for this report. Alfredo DiMauro, Assistant VP for Facilities, stated that WPI will lease the land to a private developer who plans on beginning construction in the spring of 2011(DiMauro, 2010). The school then plans on renting space within the building in order to accommodate the growing hands-on approach to bio-manufacturing education and training and the Fire Protection Engineering (FPE) Department. The FPE Department currently is located in Salisbury and Higgins Labs, and the move to Gateway Park would centralize and enable expansion of the program. WPI's Bio-manufacturing Education and Training Center plans on renting 10,000 square feet that will provide hands-on bio-manufacturing training to support industry workforce development (Gateway Park, 2008). The Massachusetts Academy of Math and Science at WPI will relocate to the building, as their lease is up at their current location. The building will also house many bio-tech companies. For example, Massachusetts Biomedical Initiatives (MBI) will expand its incubator resources by developing a new wet-lab core facility to help more companies launch, grow and provide jobs (Dorsey, 2010). To assure that the building accommodates all the tenants, the building layout will need to include several classrooms, offices, and laboratories.

This project developed and evaluated several structural designs using steel and reinforced concrete systems. The evaluation criteria were to maximize the usable space within the building, be environmentally friendly, and be cost efficient. The project goal was completed in several ways. Interviews with the principal of Mass Academy High School, Head of the Bio-manufacturing Department and FPE Department, and examination of other floor layouts, including the existing Life Sciences and Bio-engineering Center, contributed to the creation of a floor layout. For typical rooms, such as offices, bathrooms, and classrooms, standard architectural designs were investigated from the literature. By using the standards and provisions of the *American Institute of Steel Construction (AISC) Manual 13th Edition* and the *American Concrete Institute (ACI) Concrete Code*, and designing for the floor layout and design loads using the *Massachusetts State Building Code (MSBC)*, several structural frames were defined. Foundation designs were also completed; each with respect to the structure above and the loads that the structure conveys. The addition of a green roof and exterior enclosures were also investigated to provide an environmentally friendly approach. To determine if the structural systems were cost efficient, a cost analysis was performed using unit cost data from sources such as *RS Means: Heavy Construction Cost Data 23rd Annual Edition*, *RS Means CostWorks*, and standard production rates.

All of the aforementioned concepts are combined into a final recommendation. This recommendation is based on criteria deemed important so that a competent choice can be made. Criteria such as: cost, layout, sustainability, and materials used were investigated and analyzed.

Chapter 2: Background

To understand the objectives of the aforementioned goal, a body of information ranging from design criteria to performance of environmentally friendly materials was assembled and reviewed. The *MSBC* was investigated to assure the building was designed according to standards. Geotechnical data and zoning constraints were also examined to obtain a better understanding of the site and consideration for its development. In order to make Gateway 2 a more environmentally friendly building, LEED design, criteria, and specifications were researched. Consideration to a green roof and exterior cladding were also given. Finally, cost estimation was researched to provide a base for evaluating alternative and making recommendations.

2.1 *Massachusetts State Building Code*

Each state has a set of documents enacted as laws to regulate construction within its borders. In the Commonwealth of Massachusetts, the *MSBC* governs all types of construction, imposing standards and limits that reflect the Commonwealth of Massachusetts (780 CMR). The *MSBC* states its mission is to "insure public safety, health and welfare insofar as they are affected by building construction, through:

- Structural strength
- Adequate means of egress facilities
- Sanitary conditions
- Light and ventilation
- Energy conservation
- Fire safety
- Secure safety to life and property from all hazards related to a building." (780 CMR)

The code is separated into 35 main sections, of which this project focuses on the following seven sections: 6 (Types of Construction), 14 (Exterior Walls), 16 (Structural Design), 18 (Foundation and Retaining Walls), 19 (Concrete), and 22 (Steel). While the other sections are important, they are not within the scope of this work. The sections mentioned all provide the minimum requirements for the design and construction of steel and concrete structures in Massachusetts, as well as the type of cladding used on them. More importantly, these sections define the minimum design loadings based on usage and local coefficients for snow, wind, and earthquake loads.

2.2 City of Worcester Zoning Ordinance

The City of Worcester Zoning Ordinance (*COWZ*) expands upon the basic requirements set forth in the *MSBC*. This document is explicit to the City of Worcester, detailing the specific requirements of all types of construction within the city limits. For the purpose of this project, *COWZ* was examined and followed for the building of structures. Depending on where in the city a building is to be placed, certain requirements and restrictions exist, often reserving certain areas for a certain classification of structure. Like the *MSBC*, the *COWZ* defines its purpose in the forward of its text; it is stated as follows:

- Create and maintain conditions under which people and their environment can fulfill the social, economic, and other needs of present and future generations.
- Facilitate the adequate and economic provision of transportation, water supply, drainage, sewerage, schools, parks, open space, light, and other public requirements.
- Encourage the creation and preservation of housing of such type, size, and cost suitable for meeting the current and future needs of the city.
- Protect against: overcrowding of land; air and water pollution; use of land incompatible with nearby uses; undue intensity of noise; danger and congestion in travel and

transportation; and loss of life, health, or property from fire, flood, panic, or other dangers.

- Protect natural resources as well as the scenic and aesthetic qualities of the community.
- Promote the preservation of historically/architecturally significant land uses. (City of Worcester, 2007)

These six tenants expand upon the *MSBC* tenants, but still leave room for interpretation and ingenuity. They allow for the city to have more control over construction within its limits.

Gateway 2 specifically falls into the zoning district labeled, BG-6.0. This zone is defined by its maximum floor area ratio (FAR), which is 6:1. This ratio states that there cannot be more than six square foot of building floor area per one square foot of land. While no specific height limit is described, the FAR couples the building height and building footprint, implying that taller buildings require smaller footprints. The size of the building is also limited by other limitations within the *COWZ*, such as a rear yard setback of ten linear feet to name one. There are also ways to gain more space past the 6:1 FAR. For example, should an off-street parking facility be provided within 1000 feet of the building, then 600 square feet per parking space can be added to the building (City of Worcester, 2007).

2.3 Geotechnical Data

Geotechnical data for Lot 3 was obtained from a geotechnical study completed in October of 2005 for the parking structure near the first Gateway building. This report, completed by Maguire Group Inc., contains data from 25 borings done throughout the site. These borings, while not on Lot 3 specifically, do give important insights to the soil conditions around Lot 3. The results of the borings show that the soil profile of the parking structure, which is close to Lot 3, is consistently a medium to very dense sand; a stable base for foundations. It was assumed that this soil profile also exists on Lot 3. Soil with this description has a bearing capacity of about 3 tons per square foot.

2.4 LEED

The decision to design Gateway 2 to be a "green" building was pertinent, regardless of WPI's dedication to building LEED certified buildings. Buildings consume more than 39% of the energy and 74% of the electricity annually in the United States (Green Building Design, 2009). Based on that information, green buildings can reduce or eliminate the environmental impacts through design, construction, high-performance machinery and operations.

The WPI Board of Trustees endorsed a policy in 2007 that stated all future buildings on campus are to be environmentally friendly and designed to meet LEED certification ("WPI's East Hall," 2009). Leadership in Energy and Environmental Design (LEED) is a green building certification system that was developed by the U.S. Green Building Council (USCGC). LEED certifies that a building is designed to improve energy savings, water efficiency, CO_2 emissions reduction and indoor environmental quality. LEED is a rating system used by the USCGC that grants points based on certain met criteria within a number of prescribed categories. There are four levels in the rating that a building can be given: certified (40-49); silver (50-59); gold (60-79); and platinum (80- 110). The categories for evaluating new construction are: sustainable sites, water efficiency, energy and atmosphere, materials and resource, indoor environmental quality, innovation and design process, and regional priority credits. Figure 2 shows the breakdown of categories with the corresponding maximum points that can be earned.

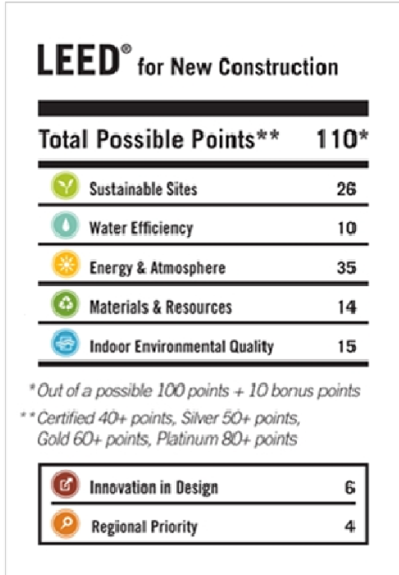

Figure 2: LEED Breakdown

LEED strives for better environmental and sustainability performance which in turn provides many benefits. There are potential cost benefits in constructing a LEED-certified building. An upfront investment of about two percent of construction costs typically yields life cycle savings of over ten times the initial investment (Kats, 2003). A more detailed look at cost savings shows that LEED buildings have lower energy usage; water disposal; water costs; lower environmental and emissions costs; and savings from increased productivity and health ("Green Building Design and Construction", 2009). Figure 3 summarizes a study done by Capital E Analysis in California which concludes that the financial benefits of green buildings are over ten times the average investment required to design and construct a green building ("Summary of government LEED incentives," 2009).

Financial Benefits of Green Buildings
Summary of Findings (per ft^2)

Category	20-year NPV
Energy Value	$5.79
Emissions Value	$1.18
Water Value	$0.51
Waste Value (construction only) - 1 year	$0.03
Commissioning O&M Value	$8.47
Productivity and Health Value (Certified and Silver)	$36.89
Productivity and Health Value (Gold and Platinum)	$55.33
Less Green Cost Premium	($4.00)
Total 20-year NPV (Certified and Silver)	**$48.87**
Total 20-year NPV (Gold and Platinum)	**$67.31**

Source: Capital E Analysis

Figure 3: Financial Benefits of Green Buildings.

There are a few key LEED highlights with the Gateway 2 design which will continue WPI's recent tradition that all new buildings must be LEED certified. First, the project site is considered a brownfield site. A brownfield site is an abandoned or underused, industrial, or commercial facility available for reuse. By building Gateway Park on this brownfield, it saved previously undeveloped or greenfield space, which in turn did not compromise any ecosystems or create an environmental impact on these lands. When constructing buildings on brownfields, there is more of an effort to remove all hazardous materials from the soil and thus eliminate the previous exposure to humans and wildlife.

The government offers many incentives to encourage the design and construction of LEED certified facilities. These include: density bonus; expedited permitting; fee reduction/waiver; tax break; grant; free consultation/promotional services and low interest loans ("Summary of Government", 2009). Tax incentives are the most popular and widely used mechanisms because of the different level of tax breaks that can be given based on the level of

LEED accreditation granted to the project. The proper design and construction of a green roof is one of the many ways that a project can earn a LEED point.

2.5 Green Roof

There is a larger upfront cost to the owner to build a green roof; however, after considering the tax incentives and the amount of money saved in energy costs, a green roof is essential to have on buildings, which will be installed on the roof of the Gateway 2 building, due to its financial and environmental benefits. Most buildings have dark roofs that absorb a significant amount of heat emitted by the sun when compared with roofs of lighter colors. This absorbed heat radiates around the building as well as inside, causing increased temperatures within the building and its surrounding neighborhood. The direct result from this is increased energy consumption to then cool this building as well as surrounding ones. Having a green roof will significantly reduce the amount of energy used for cooling and therefore reduce the amount of pollution produced by energy power plants. According to the EPA, green roofs save residents and building owners 20% to 70% in annual cooling energy costs (Green Building and Design, 2009). To determine if a vegetated roof meets LEED requirement, a formula is used which takes into consideration the vegetated area, roofing materials, and mechanical equipment area (REF):

$$\left(\frac{Area\ of\ Low\text{−}Slope\ SRI\ Material}{78 * \frac{0.75}{SRI\ Value}} + \frac{Vegetated\ Roof\ Area}{0.5}\right) \geq (Total\ Roof\ Area - Deducted\ Area).$$

A significant aspect of the design of a green roof is to determine the percentages of the roof that is to be covered by the vegetation and low-slope SRI material. There is no right or wrong percentages as long as they comply with the credit requirements. The amount of each percentage will vary regionally. Also, operations and maintenance must also be considered. Materials with high reflectivity must be cleaned at least every two years to maintain good reflectance. Building operators will have to obtain information on how to maintain a vegetated roofing system. Green roof systems with low-growing plants are generally easier to maintain when compared to deeper soil and larger plants.

The type of high-reflectance material needs to also be selected which differ based upon their solar reflectance index (SRI) which is calculated from emissivity and solar reflectance values. SRI performance varies by roofing material and brand but there are multiple testing methods available for measuring emissivity and solar reflectance. The green roof will be designed and material will be selected based upon the values obtained by the Lawrence Berkeley National Laboratory Cool Roofing Materials Database. Table 1 shows examples of SRI values for typical roof surfaces.

Table 1- Solar Reflectance Index (SRI) for Typical Roofing Materials

SRI Values for Solar Infrared Temperatures	Solar Reflectance	Infrared Emittance	Temperature Rise	SRI
Gray EPDM	0.23	0.87	68ºF	21
Gray Asphalt Shingle	0.22	0.91	67ºF	22
Unpainted Cement Tile	0.25	0.90	65ºF	25
Light Gravel on Built Up Roof	0.34	0.90	57ºF	37
Aluminum Coating	0.61	0.25	48ºF	50
White EPDM	0.69	0.87	25ºF	84
White Cement Tile	0.73	0.90	21ºF	90
PVC White	0.83	0.92	11ºF	104
White Coating, 2 Coats, 20 mils	0.85	0.91	9ºF	107
Source: Lawrence Berkeley National Laboratory Cool Roofing Materials Database				

2.6 Cladding

A cladding system acts as the shell of a building. It protects the interior of the building and provides the building with weather and wind resistance on the exterior walls. Cladding systems can be load bearing, where they provide structural strength, or non-load bearing where they act as a veneer. Because cladding systems do not have to provide strength to the building more systems are being designed thinner and utilize many new technologies for color, texture, cost, moisture resistance thermal barrier and maintenance (Reid, page 30). For the structural steel design, the cladding system must be able to clip to the frame. However, in the reinforced concrete design, the walls can remain concrete or another cladding material can be clipped to the beams and columns. The different types of cladding systems that are discussed in this chapter are Masonry, Glass, Plywood, and Sheathing. These systems were investigated for each design alternative, looking for how they connect to the frame of the building as well as the implications of each the cladding system. Factors considered when investigating and selecting cladding systems include but are not limited to: additional weight on the frame, effect on the wind loads, and the stability of the frame.

2.6.1 Masonry Cladding Systems

Several different types of material are used in masonry cladding. Historically, masonry cladding walls carried the loads of the structure. However, since technology has advanced and the installation of cladding systems has progressed, cladding systems are attached to the frame and the loads are supported by the structure. Masonry cladding has good thermal and moisture resistance but much consideration must go into the connection of the masonry cladding because it is possible for the veneer to pull away from the frame exposing the interior of the wall.

One of the earliest materials used is brick. Originally bricks were used to hold the loads of the beams that held up the roof but as new design practice was established bricks started being used as filler material between the columns. Brick facing comes in many different colors and can be arranged in different ways depending on the bond pattern. Bricks are stacked on a base or sill to carry the weight of the bricks above. Depending on the height of the building several sills might need to be used.

Concrete blocks are also used as a cladding system. They are made from aggregate and cement and then poured into a mold to harden. Blocks are similar to bricks but have large air spaces which make for excellent thermal insulation and fire resistance. However, the concrete itself is very porous and can let moisture and water leak into the wall. For this reason a veneer is usually placed over the block wall. To increase the strength of the blocks, steel rods are used for reinforcement.

Similar to bricks and concrete blocks, stone is also used as an exterior enclosure. Overtime, stone became less of a structural element and more of an architectural appeal. The thickness of the stone has been reduced minimizing the strength of the material. Compared to bricks and blocks, stone is not as weather resistant without the presence of sheathing and insulation placed under the stone. Because of its natural appeal stone is also used as an interior finish.

2.6.2 Glass Cladding Systems

Glass cladding has a very modern and attractive appeal. Glass can either be opaque or transparent allowing in light and revealing the interior of the building. Glass cladding is usually attached to a metal frame with clips and is sealed using adhesives. Glass material can come in many forms. Sheet, plate, and float glass are all used in cladding. They can come in many different shapes, colors, and sizes depending on the panels that hold the glass in place. The panels should be able to hold the glass in place and resist wind pressure and strong enough that structural movements are not transferred to the glass. Adhesives and sealants have different tensile strengths, thicknesses, and temperature ratings depending on the size of the glass and the area of construction.

2.6.3 Plywood and Sheathed Cladding System

Plywood and Sheathed cladding systems are typical in residential buildings. There are many forms of sheathing but the most common is a light fibrous board that is nailed to the exterior of the wall. On top of the sheathing can be several forms of finish that range in color, texture, and cost. Vinyl and metal are two common materials used as siding. Wood can also be used but can be expensive and hard to maintain. Metal panels are typically manufactured as sandwich construction with a polystyrene insulation material enclosed within two thin metal skins. Metal panels are fire and thermal resistant. Metal panels are used on warehouses and industrial buildings.

Chapter 3: Methodology

To complete a competent recommendation for the construction of Gateway 2, the key features of this project needed to unfold in a certain manner. Certain features, such as design of structural steel and reinforced concrete elements, came from prior experiences, while material on topics such as LEED components and cladding were new and required research. All of these elements factor into a self-made criteria which lead to the recommendation at the conclusion of this project.

The initial step was to complete a preliminary layout of the structure. This defined the limitations for the main and alternate bay sizes of the design phase. A primary and secondary design was completed based on the two bay sizes devised for each of the structural steel and reinforced concrete mediums chosen. In-depth detail about each design is available in each medium's respective chapter. Each design was analyzed with the aid of RISA to assess the effect of lateral loading on the frames, and a typical column footing was designed to support the vertical loading.

In the interests of keeping with WPI's commitment to sustainable construction, consideration was given to types of cladding that could be applied to the structure and an alternate green roof. Three types of cladding systems were investigated: masonry, glass, and plywood and sheathing. Research for the green roof centered around different types of vegetative systems and alternative materials for roofing. Each piece was incorporated into the designs, investigating the effect of each on the already completed frames. Research was done to assess the sustainability of if the choice of cladding and roofing would contribute to the structure.

A cost estimate of each design was completed in two different formats. In-depth estimates of each structural design, based on quantity take-offs, were compared to a general square foot estimate of a building of similar size and make. The costs come from *RS Means* data for both the in-depth and square foot estimates. These costs gave perspective later on in the final recommendation.

With the designs complete or mostly complete, consideration was given to forming a design recommendation. The recommendation is intended to express the most logical option based on the design and discovered knowledge. This is done so that so that others can use the information within this project easily. Research into types of grading criteria and importance scales led to the creation of specific criteria that were applicable to the desired outcome. These criteria are: Layout and Space, Connections, Material Maintenance, Environmental Impact/LEED, and Cost. Each of the four designs, two structural steel and two reinforced concrete, were evaluated based on the criteria chosen and a final recommendation was made in the Conclusion chapter.

Chapter 4: Layouts

The architectural layouts of the building needed either to be obtained or designed before any structural steel or reinforced concrete design could begin. The floor layout for the Massachusetts Academy of Math and Sciences and WPI Biomanufacturing were the only layouts provided to the group by WPI. The layouts for the WPI Department of Fire Protection and for several BioTech Companies were then designed based on information obtained from field studies, interviews, and reference standards. For all floor layouts the reference book, *Architectural Graphic Standards* by the American Institute of Architects was utilized in order to determine standard sizes of various rooms throughout the building.

The current WPI Department of Fire Protection was then toured in order to gain knowledge of the sizes and quantity of their current facilities (i.e. laboratories, classrooms and offices). An interview was conducted at the WPI Department of Fire Protection which gave an idea of the quantity of laboratories, classrooms and office space that was wanted by the department at the new Gateway 2 location. The floor layout for the BioTech companies was designed by touring current and similar facilities at Gateway 1. A typical layout was created for the BioTech companies with each company only utilizing one half of the floor space.

All floor layouts for both the small bay design and large bay design were created with AutoCAD 2010. Workable drawings were then obtained, forming a basis for the bay sizes for each of the large and small designs. The designs for the small and large bay have primarily the same layout; however, a few minor changes in room size and/or location were made in order to ensure a column wasn't located in the middle of a corridor or room. Elevator and stair locations were provided on the first floor of the Massachusetts Academy of Math and Sciences layout, and therefore these elements had to be properly accommodated and designed for on the second and third floors.

4.1 Massachusetts Academy of Math and Science

The proposed floor layout for the Massachusetts Academy of Math and Science which will be located on the first floor of the Gateway 2 building can be seen in Figure 4. This floor contains all the necessary rooms, labs and office space for the Massachusetts Academy of Math and Science at WPI. There are two sets of stairs which will connect with the above floors as well as an elevator.

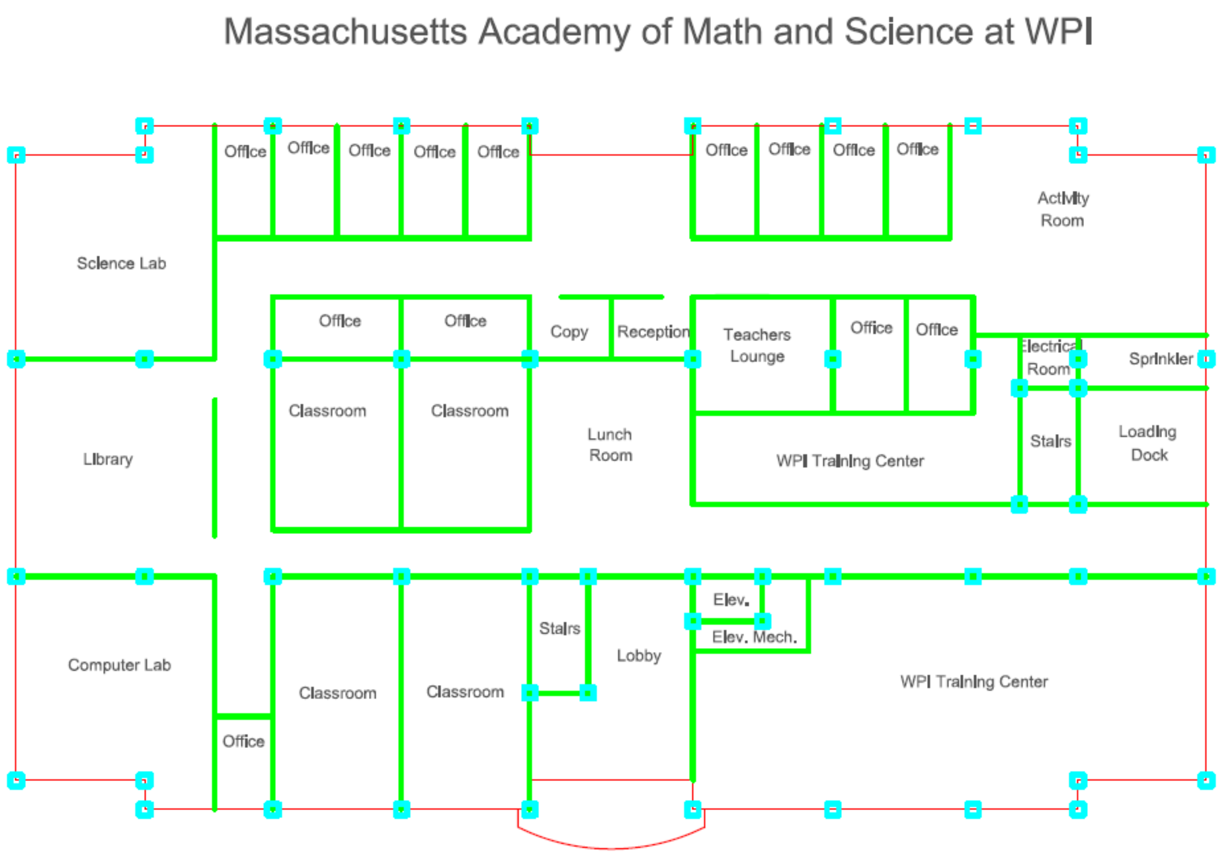

Figure 4- Floor layout for Massachusetts Academy of Math and Science

4.2 Biomanufacturing Education and BioTech Companies

The floor layout for the WPI Biomanufacturing Education and Training Center and BioTech company which will be on the second floor of Gateway 2 can be seen in Figure 6. The WPI Biomanufacturing and Education center will be located on the left side of the layout with a typical floor layout for the BioTech companies will be on the right side of the layout. The fourth floor will have two BioTech companies and can be seen in Figure 5. On the second floor, each half of the building is a separate, independent area of each other. The WPI Biomanufacturing and Education center contains all the necessary rooms, labs and offices for a college department to operate and run very efficiently. The layout for a typical BioTech Company located on the second and fourth floors of Gateway 2 will each be separate from other companies and will contain multiple offices, two labs and other multi-use rooms essential for a business to operate.

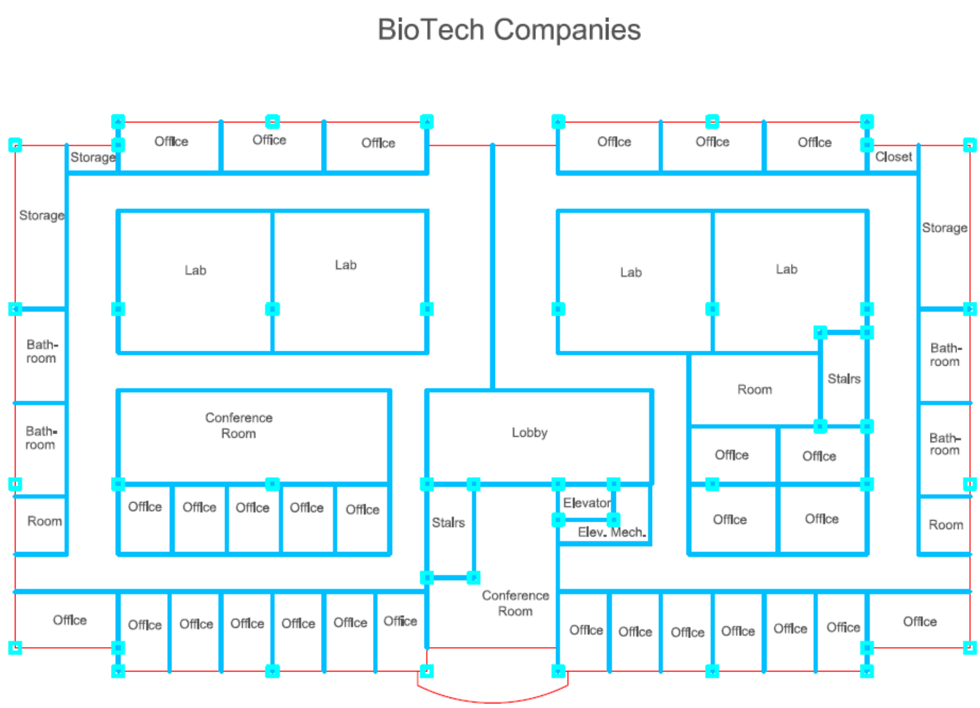

Figure 5- Floor layout of the BioTech Companies

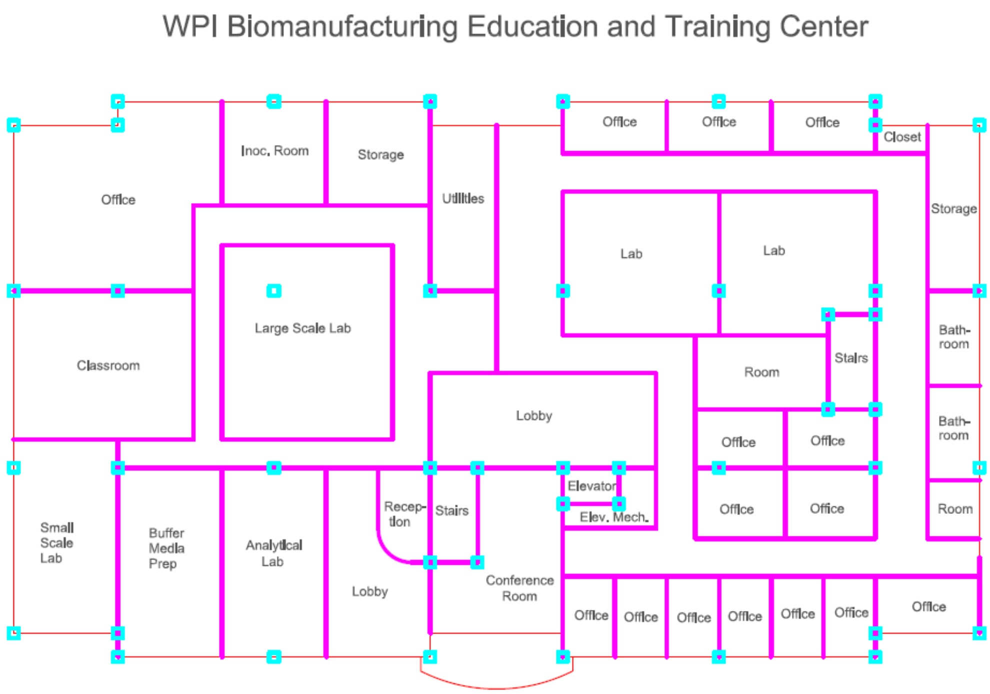

Figure 6- Floor Layout of the WPI Biomanufacturing and Education Center

4.3 Department of Fire Protection Engineering

The floor layout for the WPI Department of Fire Protection which will be on the third floor of Gateway 2 can be seen in Figure 7. The fire protection floor was designed for increased room size for the fire modeling, fire science and combustion laboratories. This is due to expected growth in students for this department as well as extra space deemed necessary for increased learning space. Also, multiple offices, classrooms, and a computer lab were designed for in this floor layout.

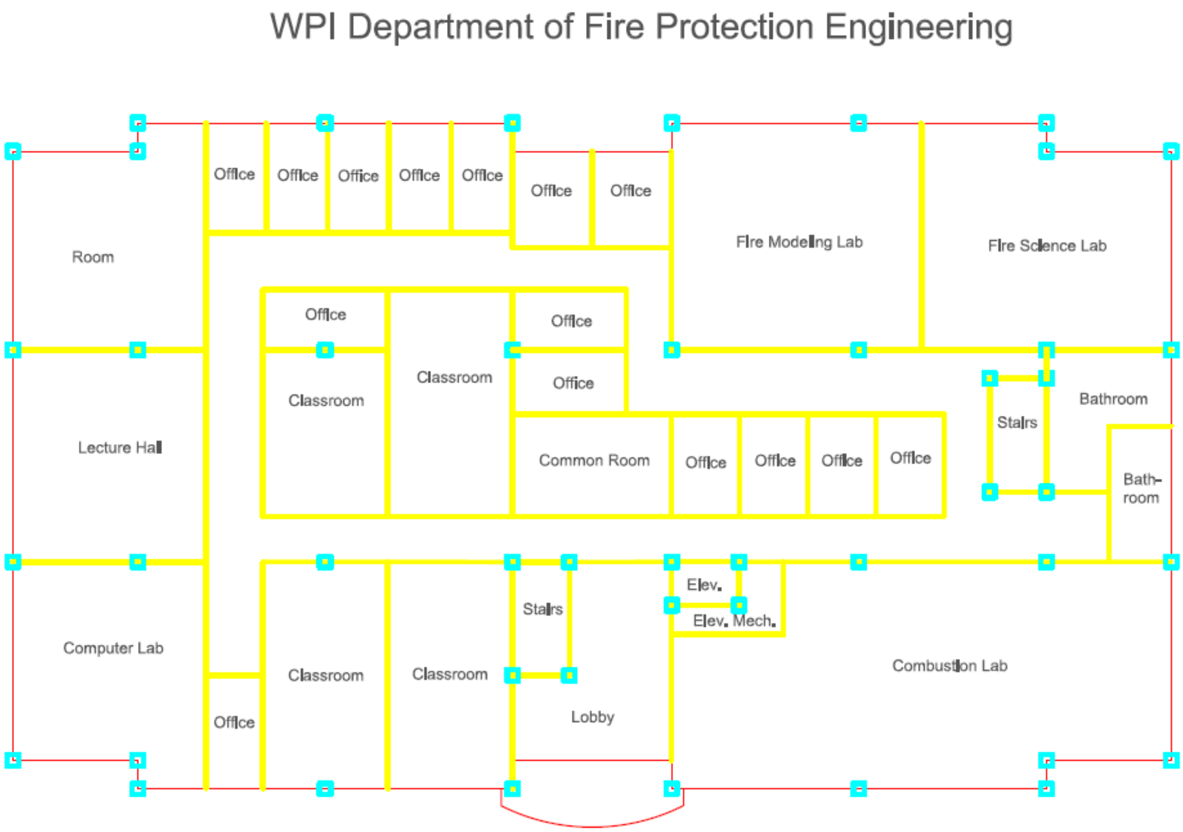

Figure 7- Floor layout for the WPI Department of Fire Protection

4.4 Alternative Bay Sizes

The layouts for the large and small bay designs are similar but not exact. Room dimensions and locations in certain areas may have been slightly moved, increased or decreased depending on the layout. This was done in order to insure the columns were properly located in the walls and not in the middle of any rooms. These slight changes to the floor layout can be seen in Appendix B.

Chapter 5: Steel Design

The design of the structural steel frame encompassed many steps in order to complete. The steel beams and concrete slab are compositely designed which means the slabs and supporting beams deflect the load together. Concrete slab and decking will be used in Gateway 2 and is the most common type of floor system. The bay sizes and filler beam spacing had to first be determined. The loading conditions due to lateral and gravitational load were then considered. Once a beam satisfied the conditions the number of studs was then designed. The columns could then be designed for using RISA-2D software. Lateral and gravitational loads were inputted into the software, and the column load effects were then analyzed. The base plates and connections were the final step in the steel design. All steel calculations can be found in Appendix C.

5.1 Concrete Slab and Steel Decking Design

Steel decking with a concrete slab is the most common type of floor system used today for office buildings and apartment buildings (McCormac, 2008). The advantage for using steel decking is that once it is placed it acts as a workable surface for construction. There are three major types of metal decking: form decking, composite decking, and cellular decking. In this case a composite decking was chosen because it serves as tensile reinforcement for the concrete slab. Shear studs are welded through the decking to the supporting girder and beams below. The number of studs used depends on the size of the beam and can be found in Appendix C. The metal decking is corrugated which increases its stiffness and spanning capabilities and therefore the height of the metal decking depends on the length of the span. The spans for the structural layouts of Gateway 2 are between 4 and 8 feet and therefore a 1.5” LOK floor metal deck was used (Shown in Figure 8). On top of the metal deck lays a three inch concrete slab. This allows enough space for the ¾" shear studs to be covered.

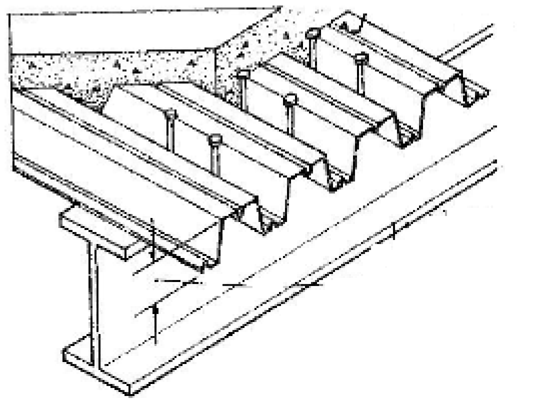

Figure 8: 1.5" LOK-floor decking with 3" concrete slab (Ching, 2008)

5.2 Beam and Girder Design

Two structural beam and girder designs were considered for Gateway 2: a small bay design and a large bay design, with the corresponding calculations found in Appendix C.1. The loading conditions were the same for the large bay and small bay design. The dead loads can be seen in Table 2. The concrete slab weight was determined from the three-inch slab which was used as well as the 145 pounds per cubic feet weight of concrete. The MEP/Ceiling and decking design loads were obtained from Table C3-1 Minimum Design Dead Loads from *ASCE 7*.

Table 2- Dead Loads for Steel Beam and Girder Design

Dead Loads	
Concrete Slab	40 psf
Decking	3 psf
MEP and Ceiling	8 psf
Total	*51 psf*

Table 3 shows the design live loads which were obtained from Table 4-1 Minimum Uniformly Distributed Live Loads from *ASCE 7*. A value of 100 psf was used throughout the entire structure because it is the maximum load given in Table 4-1 for which Gateway 2's occupancy or use falls under. It also enables flexible use of the space within the occupancy classification.

Table 3- Live Load for Steel beam and Girder Design

Live Loads	
Occupancy	100 psf

Figure 6-1 Basic Wind Speed from *ASCE 7* displays the nominal 3-second gust wind speeds at 33 feet above the ground. From this chart Worcester, MA is determined to be 100 miles per hour.

Table 4- Wind Loads for Steel Beam and Girder Design

Wind Loads	
Wind Speed	100 mph

The snow load can be found in Figure 7-1 of *ASCE 7* which displays the ground snow loads for the United States and Worcester, MA is determined to be in the 50 psf region.

Table 5- Snow Loads for Steel Beam and Girder Design

Snow Loads	
Snow Loads	50 psf

Composite action is provided in the design which allows for the loads to be supported by only the steel beams before the concrete is sufficiently hardened. This also means that unshored construction was used. There were many advantages to composite construction. Composite floors make use of concrete's high compressive strength by putting a large part of the slab in compression. Less steel tonnage was then required because a larger percentage of the steel was kept in tension. The only disadvantage for composite construction was the cost of furnishing and installing the shear connectors (McCormac, 2008). The filler beam spacing was determined based upon bay size with the concrete slab and metal decking weight. The spacing in early design was changed frequently in order to select light and appropriate beam sizes for the bay.

Typical bays for both the large and small structural steel design can be seen in Figures 9, 10, and 11. Figure 9 shows a typical small bay design, 35 feet by 22 feet, which consists of W21 x 50 girders and W14 x 34 beams. The beams have lengths of 35 feet with a tributary width of 5.5 feet.

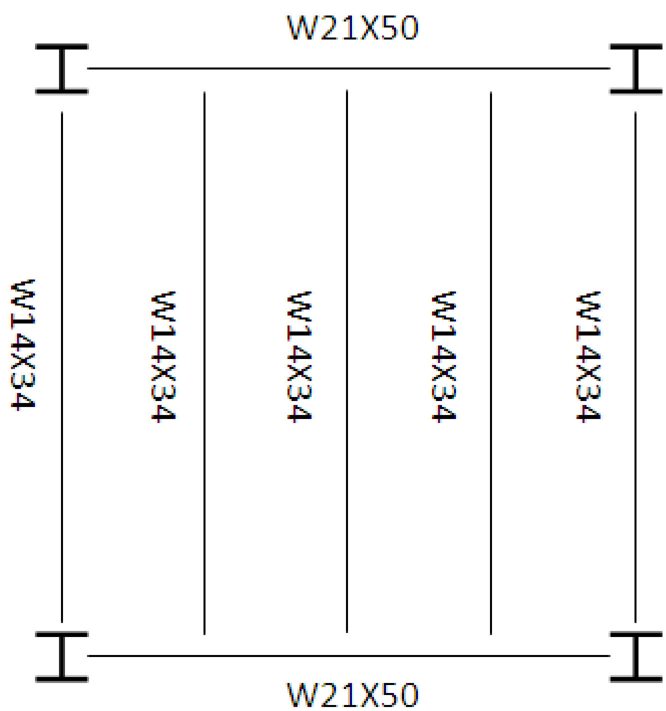

Figure 9- 35x22 Bay Design (typical)

Figure 10 shows a typical large bay design, 40 feet by 33 feet, which consists of W24 x 76 girders and W18 x 60 beams. The beams have a tributary width of 6.6 feet which span a length of 40 feet.

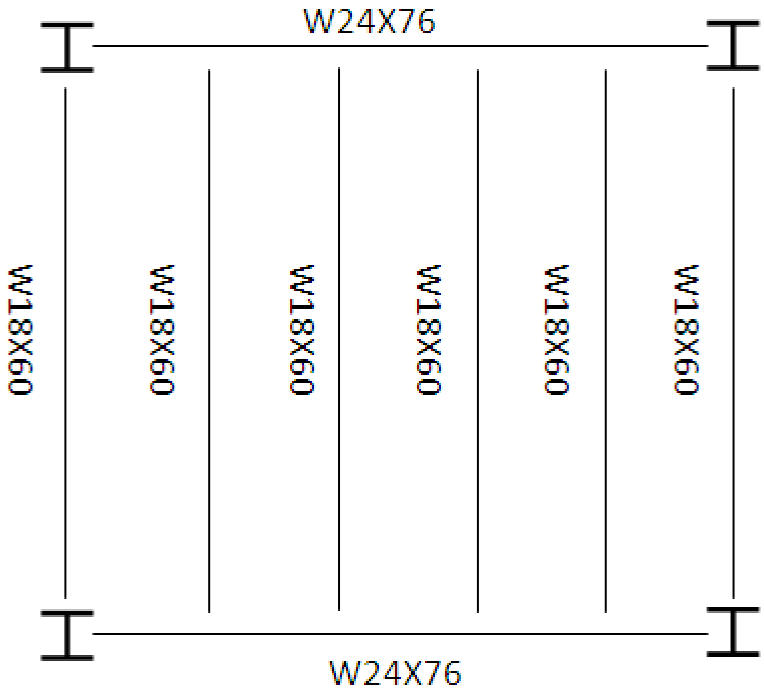

Figure 10- 40x33 Bay Design (typical)

Figure 11 shows a typical bay, 40 feet by 22 feet, which will be used on the sides of Gateway 2 for both the large and small bay designs. The bay uses a W21 x 44 girder and W18 x 46 beams which have a tributary width of 7.3 feet.

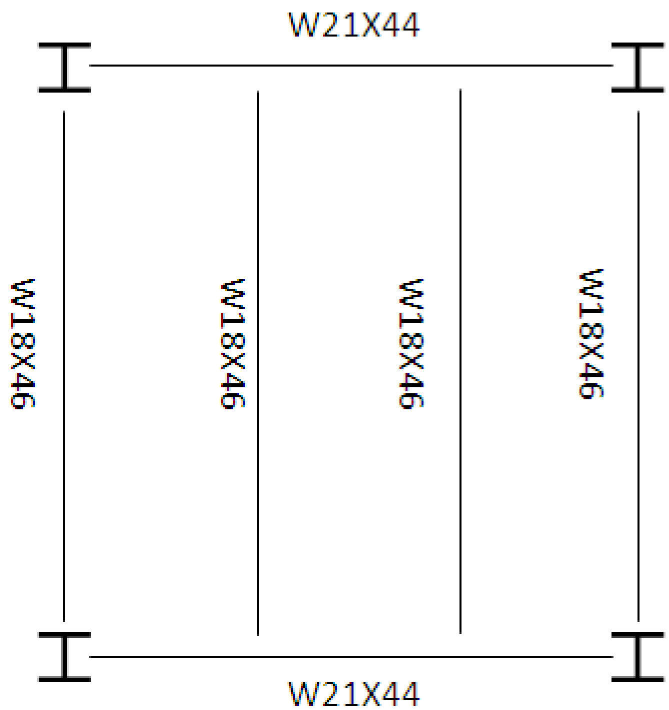

Figure 11- 40x22 Bay Design (typical)

5.3 Column Design

Columns that are within a rigid steel building frame almost always resist sizable bending moments. The columns supports at the base of the structure are fixed which allows them to resist lateral force, vertical force and moment. The structure was designed as a rigid frame as part of a lateral load resisting system to resist dead, live, wind and snow load. Seismic loads were considered; however, the loads were determined to have a smaller effect on the building which is why the wind loads were considered in the load combinations. Using RISA-2D, the axial, moment and shear forces in the columns were able to be determined. Two load combinations were considered using *ASCE 7*: U = 1.2D + 1.6(Lr or S or R) + (0.5LL or 0.8W) and U = 1.2D + 1.6W + 0.5L + 0.5S. For each combination the story stiffness method was used to determine the second-order strength values. B1 and B2 amplifiers were both considered to account for second-order effects caused by displacement between brace points. Interactions equations were then used to determine if the columns are acceptable for certain load combinations. Both the exterior and interior columns were analyzed to verify the adequacy of the combined bending and axial compression forces in accordance with AISC equations.

Figure 12 shows a typical large bay column design. The figure includes the side bay for Gateway 2 and then a typical bay that will be repeated throughout the middle of the building.

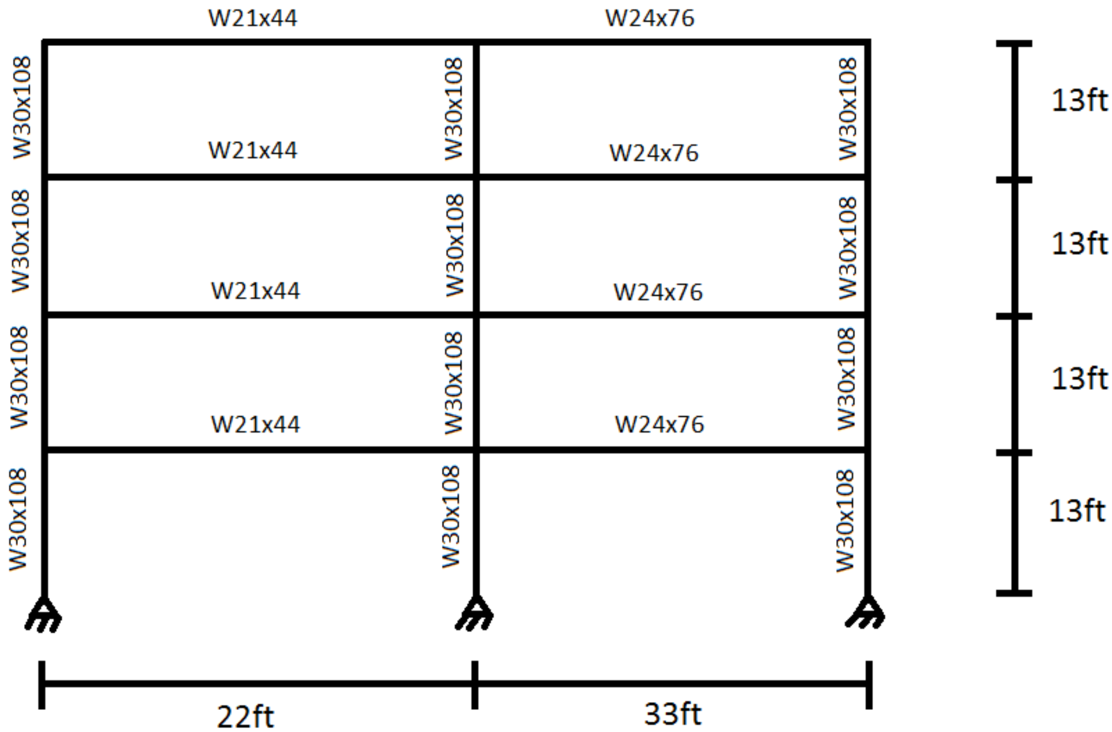

Figure 12- Large Bay Column Design

Figure 13 shows a typical small bay column design. The figure includes the side bay for Gateway 2 and then a typical bay that will be repeated throughout the middle of the building.

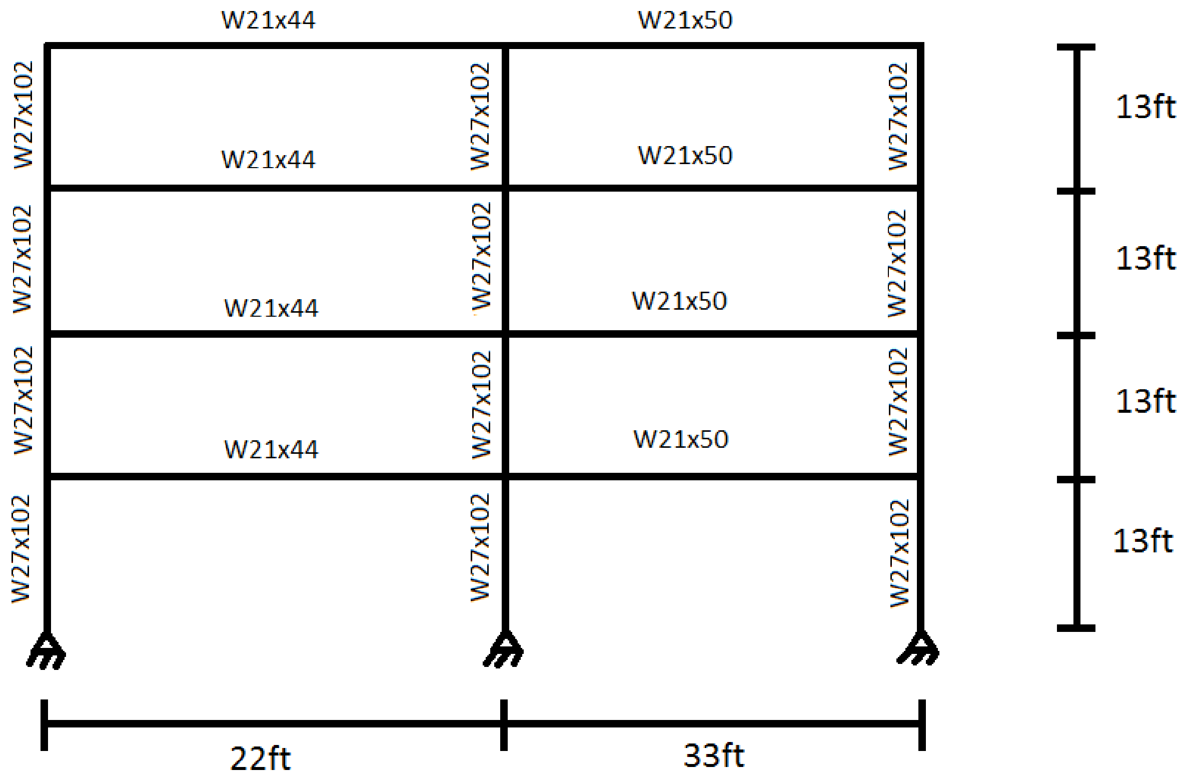

Figure 13- Typical Small Bay Column Design

Both small bay and large bay column designs have column lengths of 13 feet on every story. This story height will allow for a clear height of 10 feet between the ceiling height and the floor.

5.4 Green Roof Design

A green roof properly designed and constructed to meet the LEED requirements stated in Sustainable Sites Credit 7.2- Heat Island Effect- Roof will earn 1 point. Gateway 2 has a 23,936 square foot, low-slope roof and is designed to have both highly reflective roofing materials and a vegetated roof system. The vegetated roof area will be 35%, the white EPDM roofing with be 60%, and the mechanical equipment will be 5% of the total roof area. LEED provides no guidelines for the percentages that each roofing type must cover in order to earn a LEED point. The percentages are to be designed by the engineer and approved by the contractor and owner.

The Gateway 2 green roof was designed to balance roof types with maintenance and economy. Table 6 summarizes the roofing types and areas they represent.

Table 6: Total Green Roof Areas by Type

Roofing Type	Area (SF)
Vegetated roof area	8377.6
White EPDM roof area (SRI-85), low slope	14361.6
Mechanical Equipment	1196.8
Total Roof Area	**23,936**

In order to determine if the areas of qualifying and vegetated roofing are adequate to meet the LEED credit requirements the following equation must be met.

$$\left(\frac{Area\ of\ Low-Slope\ SRI\ Material}{78*\frac{0.75}{SRI\ Value}}+\frac{Vegetated\ Roof\ Area}{0.5}\right)\geq(Total\ Roof\ Area-Deducted\ Area)$$

$$\left(\frac{14361.6}{78*\frac{0.75}{84}}+\frac{8377.6}{0.5}\right)\geq(23936-1196)$$

The aforementioned percentages of vegetated roofing combined with the white EPDM roofing meets the requirement of LEED Sustainable Sites Credit 7.2 and will earn 1 point.

The white EPDM roofing material due to its high reflectivity must be cleaned at least every two years to maintain its heat island reduction properties (Green Building Design and Construction, 2009). The building operator will obtain necessary information to maintain the vegetated roofing system.

5.5 Base Plate Design

Base plates are essential when designing for reinforced concrete or masonry footings because they spread the column load over a larger area to minimize the bearing stress in the footing. Base plates can either be welded or bolted to the column. Anchor bolts will be used to attach the base plates to the footing. The anchor bolts pass through the lug angles which are welded to the columns. This arrangement can be seen in (Figure 14). Following OSHA regulations, four anchor bolts are used at each column (OSHA, 1926.754 b2).

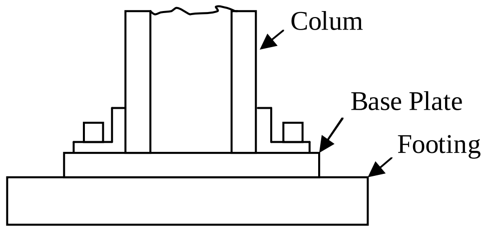

Figure 14: Column Base Plate Connection Method

A36 steel was used for each base plate and the design details were calculated following procedures from *Structural Steel Design* (McCormac, 2008). These calculations can be found in Appendix C.1. The typical base plate design was established using the maximum column load for the W27x102 and W30x108 columns. The dimension of each base plate can be found in Table 7.

Table 7: Column Base Plate Dimensions

Column	Length (in)	Width (in)	Thickness (in)
27 X 102	27	10	1.03
30 x 108	30	11	1.16

5.6 Connections

Two types of connection designs were prepared for the structural steel systems: beam-to-girder and girder-to-column. A simple single-angle connection was designed for all beam-to-girder connections. A double-angle connection was designed for all girder-to-column connections. Bolts and fillet welds were designed to fasten the connections. A fillet weld was selected because it is the most economical and the easiest to make well by welders of lesser skill. It is expected that the welds will be placed in the shop, and the bolts will be installed in the field.

5.6.1 Simple Connections

The design process can be found in Appendix C.

A 3 ½ x 3 ½ x ¼ inch single angle connection (typical) fastened from the filler beam to the web of the girder is designed. The single angle dimensions as shown in Figure 15.

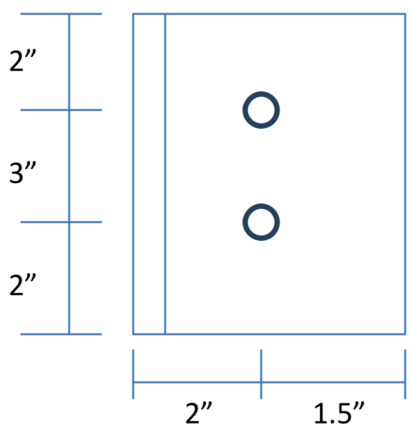

Figure 15- Typical Single Connection

The single angle connection from the beam to the girder is shown in Figure 16. The bolt pattern for the beam and girder are shown in Figure 17 and 18 respectively.

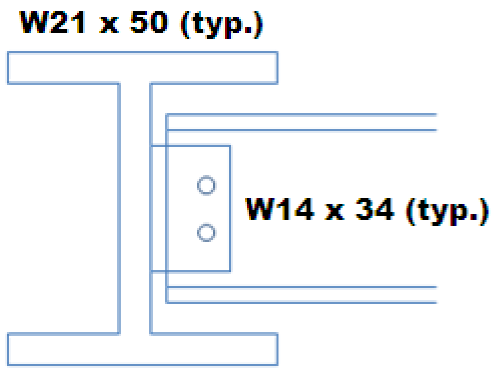

Figure 16- Single Angle Connection from Beam to Girder

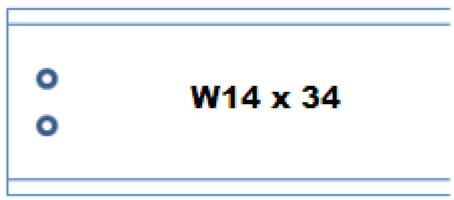

Figure 17- Single Angle Connection Bolt Pattern for the Beam

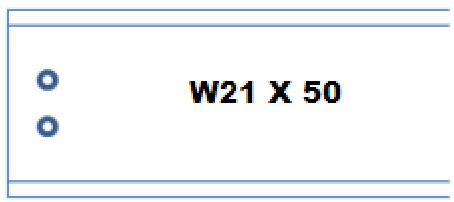

Figure 18- Single Angle Connection Bolt Pattern for the Girder

The single angle was shop-welded to the web of the girder and field-bolted to the beam. The weld length, size and position are shown in Figure 19.

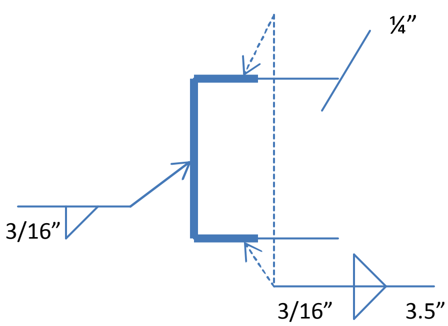

Figure 19- Single Angle Weld Length, Size and Position

5.6.2 Double Angle Connections

The design process can be found in Appendix C. A 3 ½ x 3 ½ x ¼ inch double angle connection was designed to fasten the girder to the flange of the column. Dimensions of the double-angle connection are shown in Figure 20.

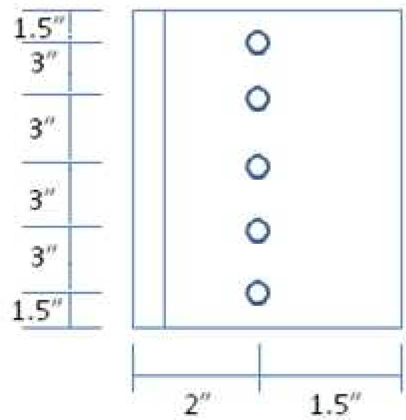

Figure 20- Double Angle Connection

The double angle was connected to the flange of the column as shown in Figure 21. The bolt pattern for the girder is shown Figure 22. The number of bolts per angle leg and their location connecting the girder to the column is shown in Figure 23.

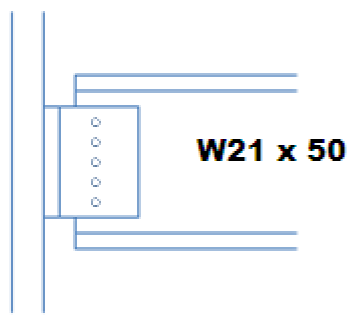

Figure 21- Double Angle Connection Girder to Column

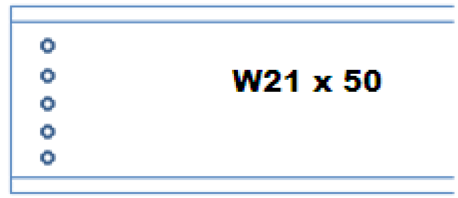

Figure 22- Double Angle Connection Bolt Pattern

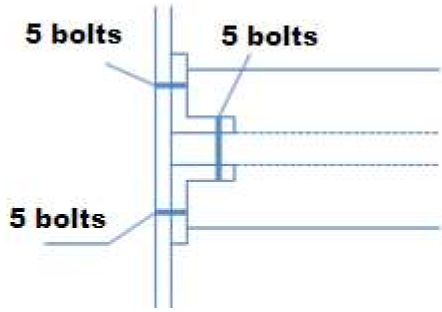

Figure 23- Double Angle Connection Bolts per Angle Leg and Location

The double angle is field-bolted to the girder web and shop welded with a fillet weld to the flange of the column. The weld length, size and position are shown in Figure 24.

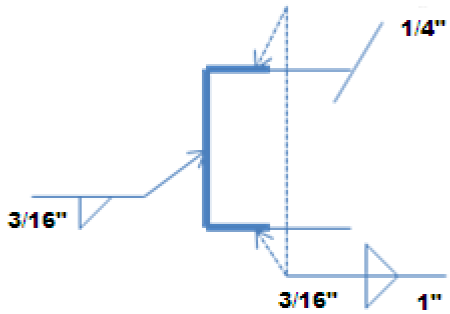

Figure 24-Double Angle Connection Weld Length, Size and Position

Chapter 6: Reinforced Concrete Design

Reinforced concrete, as the secondary design, was modeled as close to the structural steel design as possible. The original plan was to keep the design layout similar so that the comparison of the designs would be based on providing the same functional spaces and footing locations. By assuming all of the same design loadings except for the dead load, consistency could be maintained. However, during the investigation of a reinforced concrete system, several problems arose for each of the methods attempted.

6.1: Beam Girder Method

The design of the concrete system initially followed a similar path as the steel system. To keep the design similar to the steel system for comparison later, a beam-and-slab system was first used, assuming the same number of beams and layout of bays as the structural steel approach. Dead and live loads were acquired from: an assumed slab design, MEP & Ceiling loads, self-weight of the beams, and from the *MSBC*. Using equations and information from *Building Code Requirements for Structural Concrete* (ACI Code) and *Reinforced Concrete Design* 7th Edition by Wang et al.(2007), a system was created to design a concrete beam and its required reinforcement. This method, using LRFD design factors, examined the required moment based on the dead and live loads in comparison with the coefficient of resistance, which is based on an assumed reinforcement ratio of steel to concrete. Once a beam size was established, calculations defining the tension and compression within the member were used to determine the required area of tension and compression steel. Assumptions for this part of the design are that the reinforcement ratio is .0011 and the strength of the concrete is 4000 psi. The reinforcement ratio came from recommendation from the *ACI Code* presented in Wang et al.'s text, while the concrete strength was chosen as a mid-strength concrete.

This method, while yielding results, produced large beams and unwieldy girders. The calculations show that the girders needed to support a dead load almost ten times that of the beams, which made the girders massive in size.

Table 8: Member Sizes for Beam Girder Method

Bay Size(FT)	Beam Size(IN)	Girder Size(IN)
35x22	12x22	16x33
40x22	14x26	18x35
40x33	12x26	25x50

Table 8 depicts the size of the beams and girders for each bay size. From a strength and stiffness point of view these sections work; however, from a constructability and spatial layout point of view, these solutions do not work. All of the girders are three feet or more in depth. With a story height of 13 feet, these girder depths significantly cut into the clear ceiling height after MEP, fire protection, and tiles are installed. A full detail of the beam and girder method can be seen in Appendix D. Figures 25, 26, and 27 detail the layout of each bay of the beam and girder method, because this system did not produce effective results, a new system was designed.

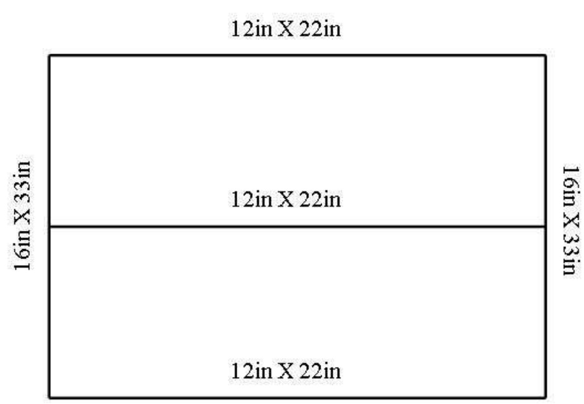

Figure 25: Concrete Beam Girder 35'x22' Bay

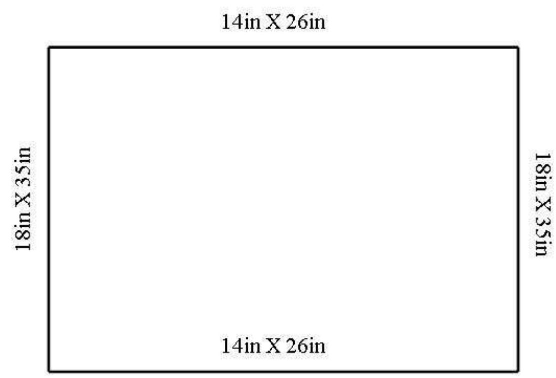

Figure 26: Concrete Beam Girder 40'x22' Bay

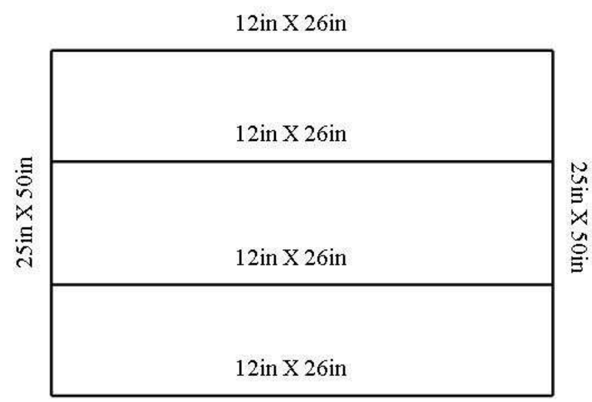

Figure 27: Concrete Beam Girder 40'x33' Bay

6.2: One-Way Slab System

After concluding that the beam and girder method was not an effective strategy, a one-way slab system was implemented. One-way slab systems utilize load transference from slab to T-beam to girder. For each bay size, slabs and T-beams were designed first, followed by a girder. Chapter 8 in Wang et al.'s text details this procedure and provides charts for moment calculations of the slab and T-beam section. This is detailed in the full work of the one-way slab in Appendix E. As with the beam girder method, certain assumptions were made during the design process based on recommendations from Wang et al.'s text. Some of the assumptions were values for the reinforcement ratio, concrete strength, and performance of the T-beams. T-beams were designed with a depth of compression block within their flange, so that they would behave similar to a simple rectangular beam. Since the original plan of not changing the layout of beams was disrupted by the more frequent placement of T-beams, beams were designed in a manner perpendicular to their orientation in the previous beam and girder design. This provided better data for the one-way slab system.

After completing the design of the floor system, a similar problem as the beam and girder method arose. The girders were once again large and unwieldy. Table 9 presents a summary of the design, while Figures 28, 29, and 30 show the bay spacing.

Table 9: Member Sizes for One-Way Slab system

Bay Size(FT)	T Beam Size(IN)	Girder Size(IN)	T-Beam Spacing(FT)
35x22	12x8	15x31	8.75
40x22	12x10.5	15x32	8
40x33	12x105	19x42	8

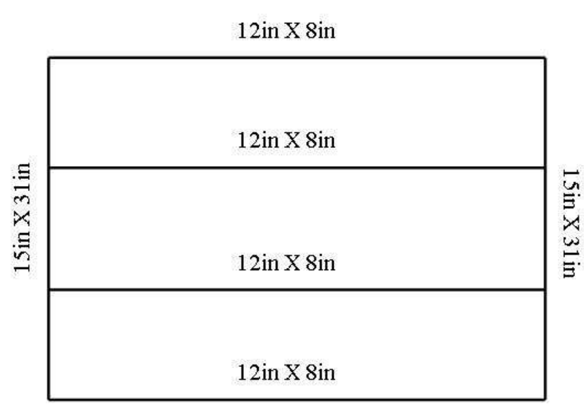

Figure 28: One-Way Bay 35'x22'

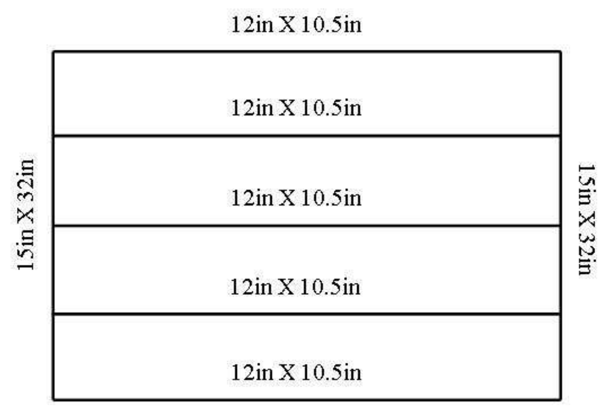

Figure 29: One-Way Bay 40'x22'

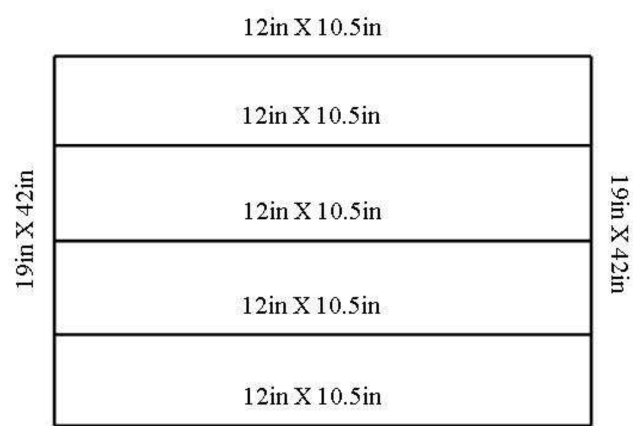

Figure 30: One-Way Bay 40'x33'

Even with considerably smaller beams, the one-way slab system produced girders of a similar size to those of the beam and girder method. The only way for the girders to decrease in size was for the bay size to decrease, which would have required the layout of the whole building to change. Since the objective was to find a system to support certain desired bay sizes, a reinforced concrete one-way slab design was not on acceptable approach.

With more time, a joist system could have been investigated and tested. Joist systems are defined by the beam spacing, which cannot exceed 30 inches. Equally, a waffle slab, or two way slab system could be used, further reducing the effects of the vertical loads on the beams and girders. Most importantly, if a reinforced concrete system is to be used then it must be compatible with the building's spatial layout. Reinforced concrete beams and girders do not have the strength-to-weight ratio of structural steel members, and therefore cannot cover longer spans without requiring large member sizes.

Chapter 7: Foundation Design

The loads from the building structure are supported by the foundation which is in direct contact with the soil. The function of the foundation is to transmit safely the high concentrated column and/or wall reactions to the ground without causing unsafe differential settlement of the supported structural system or soil failure (Nawy, 2008). Spread footings were designed for Gateway 2 which will act to transfer the loads directly from columns to the soil. The assumed strength of the concrete was 3000 pounds per square inch.

7.1 Soil Bearing Capacity

The soil boring results showed medium to very dense sand which provides a stable base for a foundation. The soil bearing capacity for that type of soil is 3 tons/ft^2 (Nawy, 2009).

7.2 Spread Footing Design

Spread footings are located under individual columns and are designed to prevent excessive settlement or rotation, to minimize differential settlement, and to provide adequate safety against sliding and overturning (Wang, 2007). The design of a square footing requires determining the size and depth of the footing and the amount of primary reinforcement in order to meet the necessary requirements. The footing weight and required area, 8.75 feet x 8.75 feet, were determined and compared to the permissible soil pressure to ensure it was not exceeded under the combined effects of column service load, footing weight and weight of overburden. The depth of the footing was determined next, and critical sections for shear, one-way and two-way, were investigated. The critical sections for moment and development of reinforcement occur at the face of column. The critical section for one-way action as a beam can be seen in Figure 31, and the critical section for the two-way action as a slab can be seen in Figure 32 (Wang, 2007).

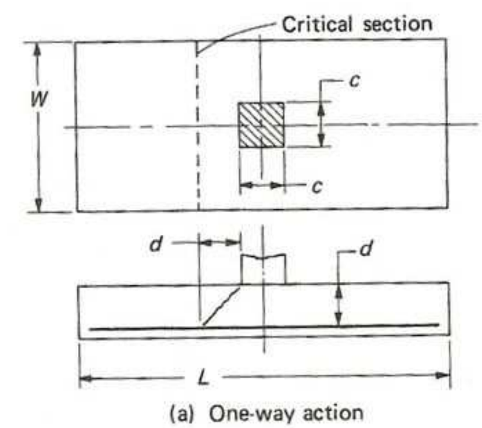

Figure 31: Square Footing One-Way Action (Wang, 2007)

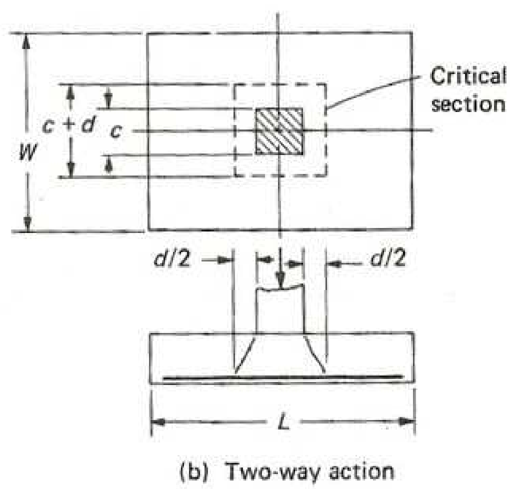

Figure 32: Square Footing Two-Way Action (Wang, 2007)

The transfer of load at the base column (ACI-15.8) was then checked by determining the compressive design strength based on the nominal ultimate bearing stress in the column. The development of reinforcement was then determined using ACI formula 12-1. The design sketch for the spread footing for the small bay can be seen in Figure 33, and the design sketch for the spread footing for the large bay can be seen in Figure 34.

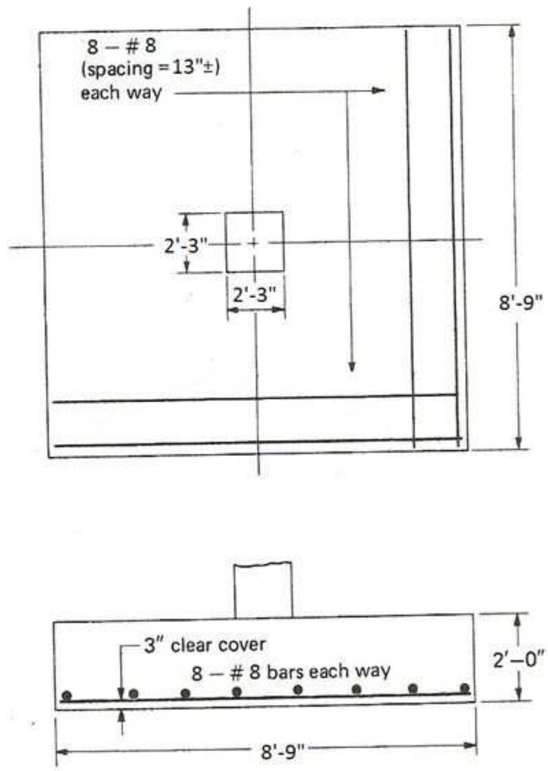

Figure 33: Design sketch for small bay spread footing (Wang, 2007)

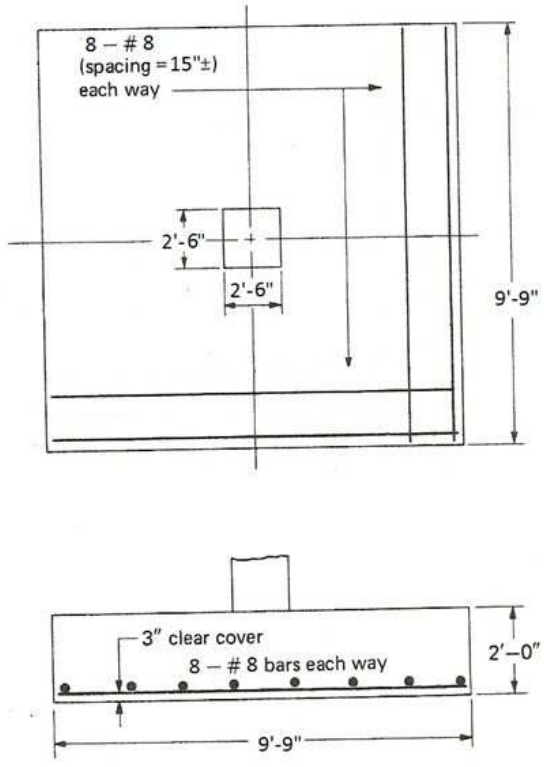

Figure 34: Design sketch for large bay spread footing (Wang, 2007)

Chapter 8: Proposed Cladding System

After exploring all topics and investigating the different parameter characteristics of each cladding system, an exterior enclosure was chosen for the Gateway 2 Building. Table 10 was adapted from *Architectural Graphic Standards, Eleventh Edition.* The table presents the different parameters that were investigated. For both the steel design and concrete design a brick veneer was chosen with a partial glass cladding system in certain areas. These two types of exteriors are similar in architectural aesthetics to the surrounding buildings, preserving the integrity and character of WPI.

Table 10: Design considerations for exterior enclosure

Exterior Wall Assembly	Weight (PSF)	Vertical Span Range (FT)	Recommended Climate and Precipitation Zones	Heat, Air, and Moisture	Maintenance
Brick Veneer on Metal Stud	54	Up to 15	All climates, extreme precipitation	Excellent	Washing, repointing joints
Insulated Metal Panels	6	Depends on Manufacturer	All except extremely cold, low precipitation	Low to Average	Washing, steam cleaning, painting, and joint sealers
Concrete and Brick Veneer	112	Up to 13 (reinforced 17)	All climates, moderate precipitation	Average	Washing, repointing joints, sandblasting
CMU and brick veneer	100	Up to 20	All climates, extreme precipitation	Excellent	Washing, repointing joints, sandblasting

The steel design and concrete design will use two similar methods for attaching the cladding systems to the structure. A brick veneer will not hold any structural loads but it will support the weight of each brick as they are stacked on top of each other. Steel angles and metal wall ties will be used to support the bricks as well to attach them to the frame. Figure 35 shows an example of a brick veneer attached by metal ties and angles. Steel framing will be used to help support the metal angles which will reduce the height of the ceiling.

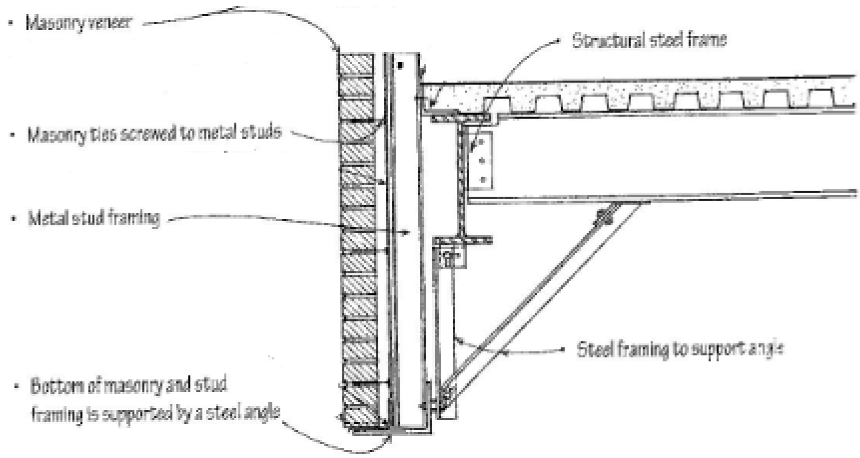

Figure 35: Brick veneer attached to metal frame (Ching, 2008)

The concrete design will also use metal angles and metal ties but because they cannot be simply screwed or bolted to the reinforced concrete elements, wedge insert boxes and dovetail slots will be used for fastening. Figure 36 shows an example detail for a brick veneer attached to a concrete structure.

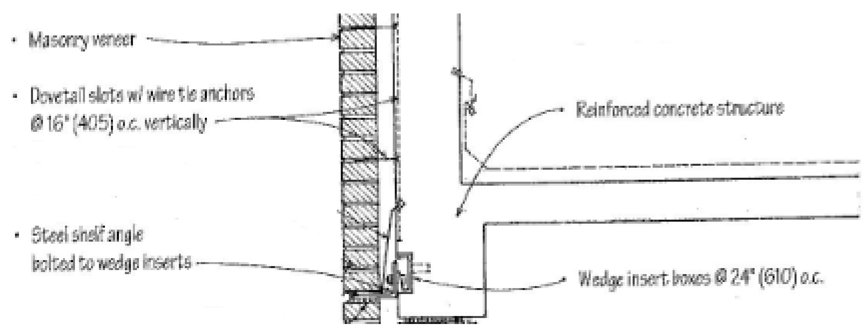

Figure 36: Brick veneer attached to reinforced concrete structure (Ching, 2008)

The glass cladding system will be attached to the frame using panels and wet glazing. Wet glazing allows the glass unit to float in its opening without any direct contact between the glass and the frame. An adhesive liquid of synthetic rubber will be inserted into the joint between the glass and the frame to form a water and air tight seal. Figure 37 shows an example of a glass veneer with wet glazing.

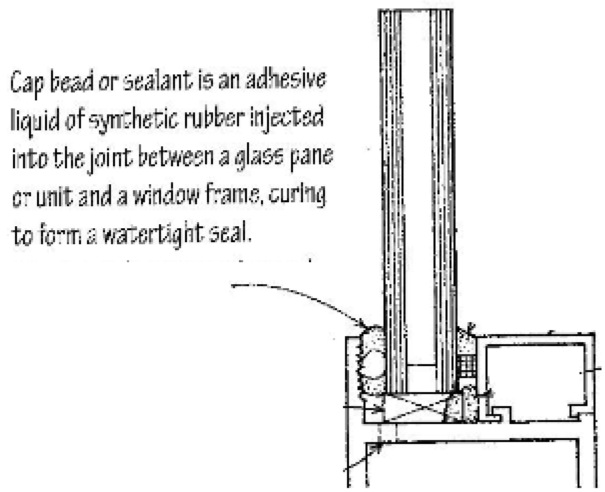

Figure 37: Glass veneer with wet glazing (Ching, 2008)

Chapter 9: Cost Estimate

Perhaps the most important and relevant part of the decision matrix used to make a final recommendation is the cost of the structure itself. As such a cost estimate was performed, investigating not only the cost of the parts created, but also a benchmark cost for a building of similar size and function. Two different methods of estimating were explored: Uniformat II, and Construction Specifications Institute (CSI) MasterFormat. Each piece of the cost played a key role in making the final decision. Because the reinforced concrete design did not produce a viable option, it was not priced.

The estimates were done with the aid of *RS Means CostWorks*, which catalogs all of their price data and puts it into a pick and choose spreadsheet for the estimator to make quick clean estimates (RS Means). *RS Means CostWorks* is a subscription based program that companies can pay a yearly fee to use. Merritt Construction Services, Inc. was gracious enough to allow the use of this program to aid this project. Figure 38 shows a basic view of the program while completing the long bay estimate. The tabs along the top allow the user to either track the project currently in operation, browse the *RS Means* cost catalog, perform a square foot estimate, or perform account maintenance.

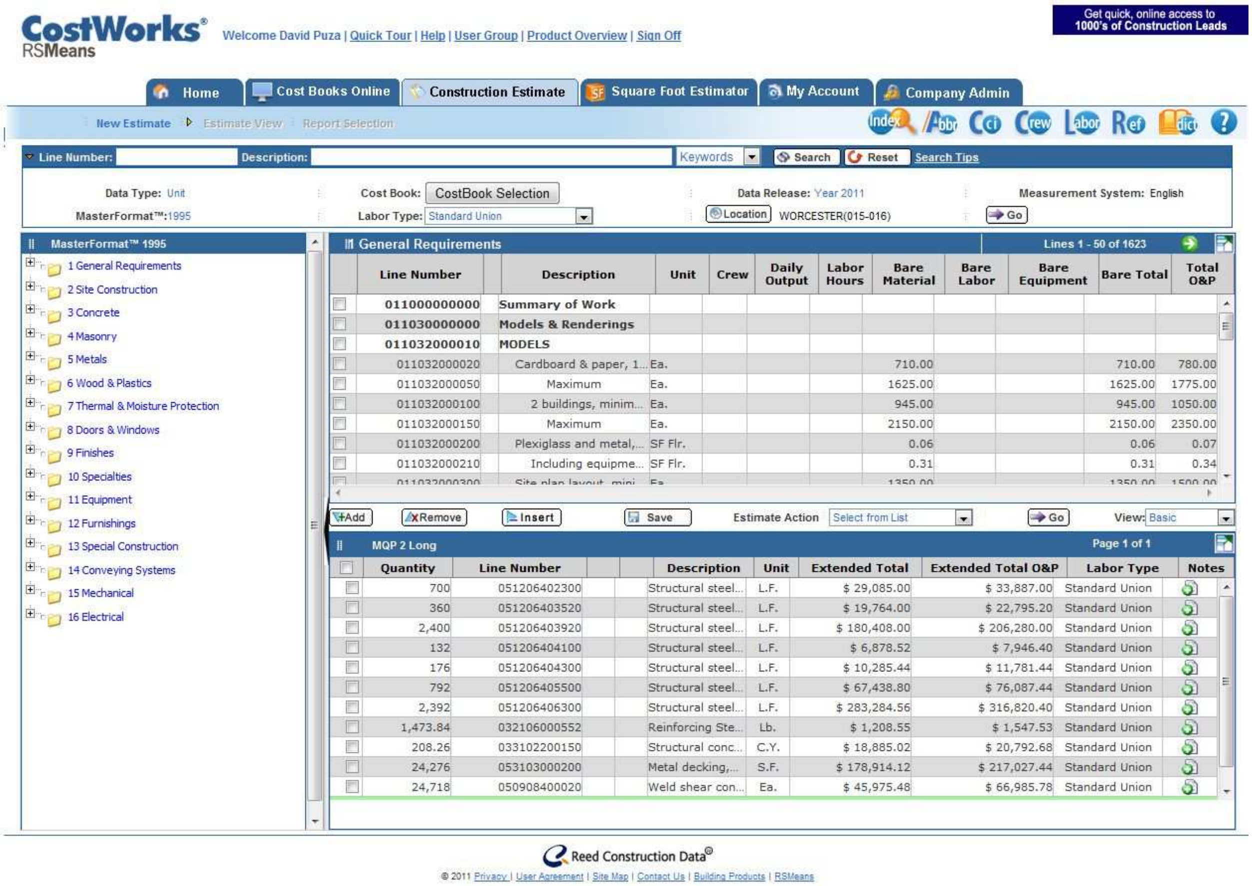

Figure 38: Screenshot of *CostWorks*

Initially the Uniformat II system was used to assess the price of the structures. Uniformat II is an assembly cost, focusing on sections of a structure, such as a floor, and pricing them as a whole. However, as the pricing progressed, the Uniformat II turned out to be less than adequate. Because it makes a lot of assumptions as to what goes into each section, floor, walls, etc…, the Uniformat II was not able to handle the designed members. The Uniformat II would be better suited for a more standardized building that does not require specific bay sizes.

Instead the CSI MasterFormat 1995 (MF) was used to price the structure. The MF involves a unit cost approach, divided into 16 different categories. It prices each individual material on a quantitative scale, thus allowing more freedom in the estimate. This gave the most accurate cost possible, because the individual steel members, which comprised the majority of the structural cost, could be defined and priced directly, versus the Uniformat II, where a relative bay size would have had to been chosen.

For this project, the cost of the designed structure was the only feasible cost to consider. While there is much more to a building, interior finishes and fixtures were assumed to be consistent between both bay sizes. Thus, the structural alternatives could be studied as marginal costs. Table 11 shows the cost of the structure for the two designs considered.

Table 11: Cost of Structure

Design	Cost	Cost per Square Foot
Short Bay (40x22)	$1,077,081	$44.37
Long Bay (40x33)	$981,951	$37.37
Difference	$95,103	$7

The difference in cost between the two is about ten percent of the cost of the Long Bay. The almost $100,000 difference translated to a $7 per square foot difference in cost, a significant amount of money for the structure. That amount is made more significant when compared next to the square foot estimate of a building of similar size and function.

CostWorks has a function that allows a square foot estimate to be calculated, based on design criteria, specifically area, stories, story height, and perimeter. For this estimate, an office building represented the closest function to that of Gateway 2. The cost for this building was $6,415,000, with a square foot cost of $264.04. However, the minimum story requirement was five, while Gateway 2 will only be four stories. By dividing the cost of the building by the number of floors a price per floor of $1,282,000 was found. Therefore, the projected cost for Gateway 2 is $5,128,000, or around $211 a square foot.

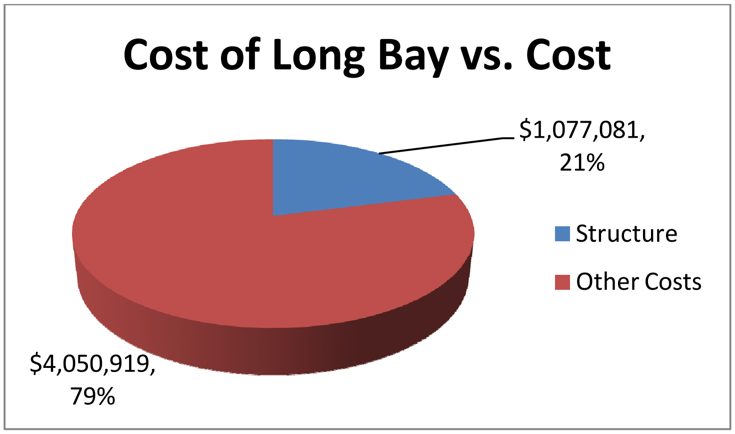

Figure 39: Cost of Long Bay vs. Cost

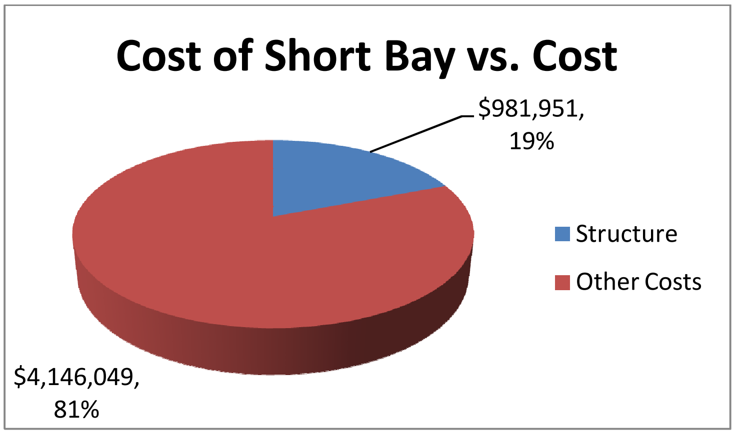

Figure 40: Cost of Short Bay vs. Cost

When one compares the price of the structure to that of the total building, as in Figures 39 and 40 above, the structure only consists of about one fifth of the cost. This shows that while the structure plays a big part in the cost of a project, it is not the dominant factor. Other construction, such as the interior, will consume most of the costs for this project.

This estimate was done within the available accuracy; however, there are still several inconsistencies in the cost. In terms of the costs that are accountable, there was not data for certain sizes of steel members. Because of this, the price of a larger member was taken, because a smaller member would be unacceptable by the design. This inconsistency is not a major cost, as the difference in price between the two members was off by a couple of dollars at most, and the fluctuation caused by this was not considerable. The major inconsistency is the total cost, based off of the square foot estimate. Because *CostWorks* is assuming a typical building, and not the one designed, the costs vary considerably from the intended design and quality of construction. This is further exacerbated by WPI's commitment to LEED certified buildings. LEED items tend to cost more than the average prices, and the estimated six million dollars may turn out to be something more on the order of seven or eight million, depending on what options WPI chooses. Nevertheless, the square foot estimate provides a widely used reference for presenting and evaluating cost estimates.

Chapter 10: Alternative Evaluation and Selection

In determining which design is most suitable for the Gateway 2 building, the project team applied techniques derived from a system developed by the California Department of Transportation (Caltrans) Value Analysis Program. The performance measurement system requires that performance criteria and measurements be integrated throughout the entire study to become jointed with cost factors (Hunter, 2002). The performance measurement system is designed to compare an original design with alternative solutions. The two steel designs that are established in this report for the construction of the Gateway 2 building are compared to one another in contrast to an original design presented in the paper by Hunter (2002). For this reason the performance measurement system was modified for the evaluation of each design. Instead of determining a value index (an arithmetic division of total performance by cost), cost was included as one of the decision criteria.

A list of five criteria was first established to measure the overall success and performance of each design: Space and Layout, Welds/Bolts, Material Maintenance, Sustainability/LEED, and Cost. Space and layout is essential to the design because it determines the number of rooms each floor can have. It also determines the overall comfort of the tenants. The amount of welds and bolts is a measure of constructability. It can determine the complexity of the design. This essentially can increase the cost and construction time of the building. Material maintenance was determined to evaluate the long term life of the building. How often the different materials need to be maintained can increase the cost as well as the life of the building. The Sustainability and LEED certification of the building is a major concern in the construction of the Gateway 2 building. Implementing a green roof or using recycled material can change the appeal of the building. The same green roof was used on both designs, as well as the same grade and percentage of recycled structural steel. The cost criterion is related to the short term, construction cost of each design. It reflects the weight, size, and geometry of the frame.

After the list of criteria was established, each criterion was weighted on a scale from zero to one, one having the most concern in the construction of the Gateway 2 building. Once each criterion was weighted, the different designs were evaluated on a scale from one to ten based on the description given to each criterion. Table 12 shows the list of criteria with their weights and the rating for each alternative.

Table 12: Performance Matrix

CRITERIA	PERFORMANCE	STEEL DESIGN	
		Short Bay	Large Bay
Layout and Space	Rating (1-10)	4	7
	Weight	0.9	0.9
	Contribution	3.6	6.3
Welds/Bolts	Rating (1-10)	8	5
	Weight	0.4	0.4
	Contribution	3.2	2
Material Maintenance	Rating (1-10)	6	6
	Weight	0.6	0.6
	Contribution	3.6	3.6
Sustainability/LEED	Rating (1-10)	10	10
	Weight	1	1
	Contribution	10	10
Cost	Rating (1-10)	5	8
	Weight	1	1
	Contribution	5	8
Total Performance		25.4	29.9

Each member of the project team evaluated the weights and ratings for the list of criteria. Once each member gave a value for the weights (0-1) and the ratings (1-10), the average was determined rounding to the nearest decimal place. The total performance is a summation of each criterion's rating multiplied by the weight. From the table above, the large steel bay design has the largest value of 29.9 making it the most suitable design.

Chapter 11: Conclusion

In conclusion, this project team recommends the use and design of a long bay structural steel system verses a small bay system. Overall it offers the best package, including layout and cost. While the short span scored higher in the weld/bolts section because it utilizes more of the same size bay, the long span allows for the desired layout to be untouched and uses less structural steel, thus lowering the cost of the frame. Assumptions were made about other parts of the structure that fit with WPI's current ideology and appearance. LEED standards, which WPI has committed to, were considered with the addition of a green roof. Also a brick veneer and curtain wall finish was chosen to adorn Gateway 2, which will help it fit in with WPI's existing structures.

This project has left plenty of questions unanswered due to time constraints and need to focus the result of the project. Within the time allotted a suitable reinforced concrete design could not be found to support the desired layout. Further investigation into two-way slab systems, joist systems, and reconfiguration of the layout could yield a design that is functional. In addition, further investigation into LEED requirements could assess if there is any significant structural aspect within today's consideration of green design. Exploring this question could possibly lead to more efficient designs that are environmentally sustainable.

Plans are already moving forward to create the Gateway 2 building. As of February 8th of 2011, WPI has entered into an agreement with the O'Connell Development Group to produce a new structure on the Gateway property (Cohen, 2011). In this agreement WPI and O'Connell agree to design and build a "four-story, 92,000 square-foot facility designed to achieve LEED certification, with laboratory, educational and office spaces for a range of academic and corporate uses" (Cohen, 2011). The two estimate that this project will cost around $30 million dollars, with WPI already holding half of the lease for its “new Biomanufacturing Education and Training Center (BETC); an expanded Fire Protection Engineering Department and research laboratory; and the graduate division of WPI's School of Business” (Cohen, 2010). The article mentions that Massachusetts Biomedical Initiatives and Blue Sky Biotech will be some of the companies taking space in the new building, but there is no mention of Mass Academy (Cohen, 2010). This building is far larger than the one designed in this project and while the square foot cost will change, it should not fluctuate more than the original $264 projected by *RS Means CostWorks*. The project team hopes that some of the information from this project will make its way into the decision making process, helping to make a long lasting effect on WPI as a whole.

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Appendix A: Proposal

14 October 2010

Project Numbers: LDA 1105

BUILIDNG DESIGN STUDIES FOR GATEWAY PARK

A Major Qualifying Project Proposal

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

in Civil Engineering

by

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Stephen J. Esposito

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Benjamin J. Etten

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Harold F. Reader III

Date:

Approved:

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Prof. L. D. Albano

Abstract

The purpose of this project is to plan several structural design layouts for a proposed mixed-use commercial building as part of the Gateway Park expansion. Two structural steel designs and two reinforced concrete designs are going to be investigated with respect to the size of each bay. A basic foundation design is also going to be investigated to support the structure. The final design will be chosen by a criteria based on scheduling, cost, space, and LEED specifications. In addition, an alternative roofing system is going to be investigated using a sustainable and environmental friendly approach.

Introduction

Worcester Polytechnic Institute (WPI) is a growing community that strives to create and convey the latest science and engineering knowledge in ways that would be most useful to society (WPI Faculty, 1987). In continuing to do this, WPI and the Worcester Business Development Corporation (WBDC) worked together to develop Gateway Park in 2005. Gateway Park is designed as a 12-acre mixed-use destination that will provide a home for life sciences and biotech companies. The Gateway Park is part of a larger 55-acre redevelopment project that will provide an environment that fosters the exchange of ideas among scientists, scholars, students, and entrepreneurs (Gateway Park, 2008).

Gateway Park, formally an industrial site, is now home to the WPI Life Sciences and Bioengineering Center. This site is also designed to hold four other life science buildings, condominiums, and several retail establishments (see Figure 1).

Figure 41: Proposed Gateway Park Complex

This project will focus specifically on Lot 3, which will accommodate a four-story, 80,000 sq. ft. facility that will be referred to as Gateway 2 throughout this report. Alfredo DiMauro, Assistant VP for Facilities, informed us that WPI will lease the land to a private developer who plans on beginning construction in the spring of 2011. The school then plans on renting space within the building in order to accommodate the growing biomanufacturing and Fire Protection Engineering (FPE) Department. The FPE Department currently is located in Salisbury and Higgins Labs, and the move to Gateway Park would centralize and expand the program. WPI's Biomanufacturing Education and Training Center plans on renting 10,000 square feet that will provide hands-on biomanufacturing training to support industry workforce development (Gateway Park, 2008). The Massachusetts Academy of Math and Science at WPI will relocate to the building, as their lease is up at their current previous location. The building will also house many bio-tech companies. For example, Massachusetts Biomedical Initiatives (MBI) will expand its incubator resources by developing a new wet-lab core facility to help more companies launch, grow and provide jobs ("Gateway Park").To assure that the building accommodates all the tenants, the building will need several classrooms, offices, and laboratories.

The purpose of this Major Qualifying Project is to evaluate several structural designs against criteria that will maximize the usable space within the building, be environmentally friendly, and be cost efficient. There are several ways that the project team plans on achieving this goal. First, the team will provide a floor layout that meets the needs of all tenants. This will be accomplished by interviewing the principal of Mass Academy High School, interviewing the Head of Biomanufacturing and Fire Protection Engineering Department and examining other floor layouts, including the existing Life Sciences and Bioengineering Center. Standard architectural designs for offices, bathrooms, and classrooms will also be investigated.

Another task that will aid in achieving our goal will be to design several structural frames using steel and reinforced concrete systems. We will investigate the relationships between structural systems, useable space and construction cost. This will be done by defining beams, columns, and girders using the provisions of the *American Institute of Steel Construction (AISC) Manual 13th Edition* and the *American Concrete Institute (ACI) Concrete Code* while taking into account the floor layout and design loads. A foundation design will also be investigated to withstand all loads of the structure. Finally, a green roof will be investigated to provide an environmentally friendly approach. Choosing the most cost efficient design will be done by using cost data obtained from sources such as *RS Means: Heavy Construction Cost Data 23rd Annual Edition*, *RS Means CostWorks* and standard production rates.

Background

At the start of this project there was much research done to develop understanding of our objectives and their deliverables. The *Massachusetts State Building Code* will be investigated to assure the building is built according to standards. Geotechnical data and zoning restraints were also examined to get a better understanding of the site. LEED specifications were researched to get a better understanding on how to make Gateway 2 a more environmentally friendly building. Finally, cost estimation was researched to provide a base for evaluating alternative and making recommendations. Our research data is explained in the following sections.

Massachusetts State Building Code

Each state has a set of documents enacted as laws to regulate construction within its borders. In the Commonwealth of Massachusetts, the *Massachusetts State Building Code (MSBC)* governs all types of construction, imposing standards and limits that reflect the area of Massachusetts (780 CMR). The *MSBC* states its mission to "insure public safety, health and welfare insofar as they are affected by building construction, through:

- Structural strength
- Adequate means of egress facilities
- Sanitary conditions
- Light and ventilation
- Energy conservation
- Fire safety
- Secure safety to life and property from all hazards related to a building." (780 CMR)

The code is separated into 35 main sections, of which this group will be focusing on sections: 6 (Types of Construction), 14 (Exterior Walls), 16 (Structural Design), 18 (Foundation and

Retaining Walls), 19 (Concrete), 22 (Steel), and 32 (Right of Way). While the other sections are important, they are not within the scope of this project. The sections mentioned all provide the minimum requirements for the design and construction of steel and concrete structures in Massachusetts, as well as the type of cladding used on them. More importantly, these sections define the minimum design loadings based on usage and local coefficients for snow, wind, and earthquake loads.

City of Worcester Zoning Ordinance

The City of Worcester Zoning Ordinance (*COWZ*) expands upon the basic requirements set forth in the *MSBC*. This document is explicit to the City of Worcester, detailing the specific requirements of all types of construction within the city limits. For the purpose of this project *COWZ* will be examined and followed for the building of structures. Depending on where in the city a building is to be placed, certain requirements and restrictions exist, often reserving certain areas for a certain classification of structure. Like the *MSBC,* the *COWZ* defines its purpose in the forward of its text; it is stated as follows:

- Create and maintain conditions under which people and their environment can fulfill the social, economic, and other needs of present and future generations.
- Facilitate the adequate and economic provision of transportation, water supply, drainage, sewerage, schools, parks, open space, light, and other public requirements.
- Encourage the creation and preservation of housing of such type, size, and cost suitable for meeting the current and future needs of the city.
- Protect against: overcrowding of land; air and water pollution; use of land incompatible with nearby uses; undue intensity of noise; danger and congestion in travel and

transportation; and loss of life, health, or property from fire, flood, panic, or other dangers.

- Protect natural resources as well as the scenic and aesthetic qualities of the community.
- Promote the preservation of historically/architecturally significant land uses. (City of Worcester, 2007)

These six tenants expand upon the *MSBC* tenants, but still leave room for interpretation and ingenuity. They allow for the city to have more control over construction within its limits.

Gateway 2 specifically falls into the zoning district labeled, BG-6.0. This zone is defined by its maximum floor area ratio (FAR), which is 6:1. This ratio states that there cannot be more than six square foot of building floor area per one square foot of land. While no specific height limit is described, the FAR couples the building height and building footprint, implying that taller buildings require smaller footprints. The size of the building is also limited by other limitations within the *COWZ*, such as a rear yard setback of ten linear feet to name one. There are also ways to gain more space past the 6:1 FAR. For example, should an off-street parking facility be provided within 1000 feet of the building, then 600 square feet per parking space can be added to the building (City of Worcester, 2007).

Geotechnical Data

The most recent geotechnical data about Lot 3 comes from a geotechnical Study completed in October of 2005 for the parking structure near the first Gateway building. This report, completed by Maguire Group Inc., contains data from 25 borings done throughout the site. These borings, while not on Lot 3 specifically, do give important insights to the soil within and around Lot 3. The results of the borings show that the soil profile of the parking structure close to Lot 3 is consistently a medium to very dense sand; a stable base for foundations. It is to be assumed that this soil also exist on Lot 3.

Cost Estimation

This project will complete a cost estimation of the materials and labor needed to construct the structural frame and foundation. Equally a grading criteria will be created to examine and compare up-front and life-cycle costs to recommend a final decision, as to which design will be the most cost effective. The RS Means cost data, in conjunction with the online RS Means estimation package, will be used to determine the cost of the project. A total rough order of magnitude estimate based off of the square footage of the structure will be completed to make a final comparison of the structures and decision. For items not covered in this project, square foot values will be accepted from RS Means. These include, but are not limited to, heating, ventilation, and air conditioning (HVAC); mechanical, electrical, and plumbing (MEP); and interior walls, and finishes. All costs will be categorized and distributed using the 2004 CSI Masterformat. Any anomalies will be dealt with as they arise during the project through further research.

LEED

The decision to design Gateway 2 to be a “green” building was immediate once the project was underway. Buildings consume more than 39% of the energy and 74% of the electricity annually in the United States (Green Building Design, 2009). With that said, green buildings can reduce or eliminate the environmental impacts through design, construction, high-performance machinery and operations.

The WPI Board of Trustees endorsed a policy in 2007 that stated all future buildings on campus are to be environmentally friendly and designed to meet LEED certification ("WPI's East Hall," 2009). Leadership in Energy and Environmental Design (LEED) is a green building certification system that was developed by the U.S. Green Building Council (USCGC). LEED certifies that a building is designed to improve energy savings, water efficiency, CO_2 emissions reduction and improved indoor environmental quality. LEED is a rating system used by the USCGC that grants points based on certain met criteria. There are four levels in the rating that a building can be given: certified (40-49); silver (50-59); gold (60-79); and platinum (80- 110). The categories for evaluating new construction are: sustainable sites, water efficiency, energy and atmosphere, materials and resource, indoor environmental quality, innovation and design process, and regional priority credits. Figure 2 shows the breakdown of categories with the corresponding maximum points earned.

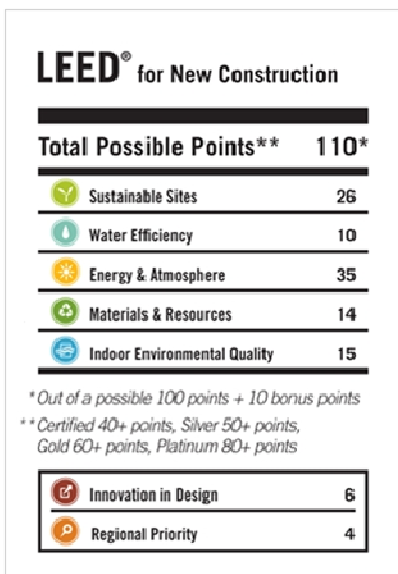

Figure 42: LEED Breakdown. www.usbgc.org/LEED

LEED strives for better environmental and sustainability performance which in turn provides many benefits. There are potential cost benefits in constructing a LEED-certified building. An upfront investment of about two percent of construction costs typically yields life cycle savings of over ten times the initial investment (Kats, 2003). A more detailed look at cost savings shows that LEED buildings have lower energy usage; water disposal; water costs; lower environmental and emissions costs; and savings from increased productivity and health ("Green Building Design and Construction", 2009). Figure 3 shows a study done by Capital E Analysis in California which concludes that the financial benefits of green buildings are over ten times the average investment required to design and construct a green building.

Financial Benefits of Green Buildings
Summary of Findings (per ft^2)

Category	20-year NPV
Energy Value	$5.79
Emissions Value	$1.18
Water Value	$0.51
Waste Value (construction only) - 1 year	$0.03
Commissioning O&M Value	$8.47
Productivity and Health Value (Certified and Silver)	$36.89
Productivity and Health Value (Gold and Platinum)	$55.33
Less Green Cost Premium	($4.00)
Total 20-year NPV (Certified and Silver)	**$48.87**
Total 20-year NPV (Gold and Platinum)	**$67.31**

Source: Capital E Analysis

Figure 43: Financial Benefits of Green Buildings.

There are a few key LEED highlights with the Gateway 2 design which will continue WPI's recent tradition that all new buildings must be LEED certified. The site on which this building was built is considered a brownfield site. A brownfield site is an abandoned or underused industrial and commercial facility available for reuse. By building Gateway Park on this brownfield, it saved previously undeveloped or greenfield space, which in turn didn't compromise any ecosystems or create an environmental impact on these lands. When constructing buildings on brownfields, there is more of an effort to remove all hazardous materials from the soil and thus eliminate the previous exposure to humans and wildlife.

Another green option is a vegetated roof which will be installed on the roof of this building. Most buildings have dark roofs that absorb a significant amount of heat emitted by the sun when compared with roofs of lighter colors. This absorbed heat radiates around the building as well as inside, causing increased temperature. The direct result from this is increased energy consumption to then cool this building as well as surrounding ones. Having a green roof will significantly reduce the amount energy used and therefore reduce the amount pollution produced by energy power plants. According to the EPA, green roofs save residents and building owners 20% to 70% in annual cooling energy costs (Green Building and Design, 2009). To determine if a vegetated roof meets LEED requirement, a formula is used which takes into consideration the vegetated area, roofing materials, and mechanical equipment area:

$$\left(\frac{Area\ of\ Low{-}Slope\ SRI\ Material}{78 * \frac{0.75}{SRI\ Value}} + \frac{Area\ of\ Steep{-}Slope\ SRI\ Material}{29 * \frac{0.75}{SRI\ Value}}\right) \geq (Total\ Roof\ Area - Deducted\ Area).$$

The government offers many incentives to encourage the design and construction of LEED credited facilities. These include: density bonus; expedited permitting; fee reduction/waiver; tax break; grant; free consultation/promotional services and low interest loans (“Summary of Government”, 2009). Tax incentives are the most popular and widely used mechanisms because of the different level of tax breaks that can be given based on the level of LEED accreditation granted to the project. There is a larger upfront cost to the owner to build a green roof; however, after considering the tax incentives and the amount of money saved in energy costs, a green roof is essential to have on buildings due to its financial and environmental benefits.

Cladding

The cladding will provide the building with weather and wind resistance on the exterior walls. Without having to provide strength, cladding systems are designed thinner and utilize many new technologies for color, texture, cost, moisture resistance thermal barrier and maintenance (Reid, page 30). For the structural steel design, the cladding system must be able to clip to the frame. However, in the reinforced concrete design, the walls can remain concrete or another cladding material can be clipped to the beams and columns. There are six main types of cladding systems: precast concrete; glass-reinforced polyester; glass-fiber-reinforced cement; formed metal including profiled metal; sheet metal, composite metal panels, and rain screens; and curtain walling-glazing systems. These systems will be investigated as to how they connect to the frame of the building, in conjunction with the implications of attaching the cladding system. Factors to be considered will include but not be limited to: additional weight on the frame, effect on the wind loads, and stabilization of the frame.

Methodology

This project will take many steps and activities to complete its scope, and this section details how it will be developed while also providing a basis for the schedule.

Once it was decided that Gateway 2 was the building that our group will be redesigning, the building location and floor plans are the first items to be investigated. Understanding the location is necessary because it's part of determining the type of soil that the building will be built on. The borings taken from the soil will also be examined to determine appropriate levels for the foundations of each design. The floor plans are crucial in order to determine the usage and the loads associated with each floor, types of rooms (labs, offices, classrooms etc.), and permissible column locations for building functionality. Only the preliminary plans for the Massachusetts Academy of Math and Science and the WPI Biomanufacturing Education and Training on the first two floors have been provided. Consequently, we will have to design the layouts for the top two floors of the building. This will have to be done after speaking with many people involved in the project. Fred DiMauro, Vice President for Facilities at WPI, will provide our group with background information as well as the contractors and proposed tenants for the building.

In order to finalize a layout design for the top two floors, a mix of research methods will be used to determine the intended use for the space needed by the tenants. Touring current facilities will contribute to understanding the sizes and numbers of labs, equipment, classrooms, and offices. Interviews will also be used to further determine the specific needs and wants of the proposed tenants. Also, reference books such as *Architectural Graphic Standards* by the American Institute of Architects will provide a base for standard sizes of various rooms. The *COWZ* and *MSBC* will need to be addressed to ensure the building is in compliance with the code. This research will be important for the design to determine room sizes and locations throughout the floors. Finally, the floor layouts will be drawn on AutoCAD so our group will have a working set of plans. From these electronic drawings, potential layouts can then be readily explored for columns may be moved to create larger or smaller bay size design.

The structural design for Gateway 2 will consider both steel and reinforced concrete frame systems. For both the steel and concrete designs, there will be two designs: smaller bay and a larger bay design. This will be done to compare the costs of each as well as the different layouts that might arise due different locations of columns, girders and beams. The loadings: snow, live, earthquake, and wind, for the building will be determined based upon the *MSBC*.

The steel design will be done according to the Load and Resistance Factor Design (LRFD) method. Three sources of information will be used to assist in the structural steel design: *Structural Steel Design* 4th Edition by Jack C. McCormac; *AISC Steel Construction Manual* 13th Edition and class notes from Professor Albano's CE3006 Design of Steel Structures. The RISA software package will be used to analyze the buildings structure.

The concrete design will be completed using three sources of information: *Building Code Requirements for Structural Concrete* (ACI Code); *Reinforced Concrete Design* 7th Edition by Wang, Salmon, and Pincheira; and class notes from Professor Jayachandran's CE3008 Reinforced Concrete Design.

For both reinforced concrete and structural steel alternatives, the frames will be designed to resist the gravity and lateral loads. The beam-slab system will be designed including filler beams and concrete slab. The girders can then be designed. Following this, the columns will be designed using the story-stiffness method. Connections and then footings can be designed for.

Options for cladding system of the building will also be researched and investigated. For this activity, books from the WPI Gordon Library, as well as research from online and experienced sources will be sought. There are many advantages and disadvantages to certain cladding types. For Gateway 2, the cladding system chosen will be evaluated based upon consideration of the following factors: cost; weight per square foot; wants and needs of the tenants; and advantages and disadvantages of each.

The green roof for Gateway 2 will be designed and chosen based upon the best financial and environmental option. The roofing material will have to meet the minimum area requirement and solar reflectance index value. The solar reflectance index is a measure of the constructed surfaces ability to reflect heat, as shown by a small temperature rise (Green Building Design and Construction, 2009). Also, the amount of vegetated roof area and mechanical equipment area will have to meet the requirements specified by LEED. The green roof will meet the Sustainable Sites Credit 7.2 and will receive one point towards the total of 110 possible points that a building can receive.

The cost estimation will include a quantity takeoff as well as parametric cost data. The quantity takeoff will include but not limited to the quantities of: structural steel, concrete, connections, reinforcing steel, cladding, earthwork, electrical, and plumbing. Parametric cost data will address those aspects of the building that were not within the design scope. The resulting estimate will be compared to similar buildings already constructed.

There is a collective responsibility on all sections of the MQP by all group members and to ensure everything is done correctly and in agreement there will be weekly group meetings amongst the members. However, different group members will be responsible for completing various sections or parts of the MQP project. Harold Reader will be responsible for the design of the large and small bay structural steel design. Ben Etten will be responsible for the design of the large and small bay reinforced concrete design. Stephen Esposito will be responsible for the cost estimation and foundation designs.

Schedule

This Major Qualifying Project will be accomplished in A, B, and C term of the 2010 and 2011 WPI academic year. Work will begin late August and finish early March. The following table provides a breakdown of each term with our deliverables and objectives.

Week	Date	Objectives
A Term		
1	8/30/2010 - 9/5/2010	Define Scope, Objective and Goals Begin Research
2	9/6/2010 - 9/12/2010	Meet with Advisor Finalize Scope
3	9/13/2010 – 9/19/2010	Begin Project Schedule Meet with Fire Protection Dept. and other Tenants
4	9/20/2010 – 9/26/2010	Begin Floor Layout Start Introduction, Methodology, Background and Capstone Design
5	9/27/2010 – 10/3/2010	Finalize Floor Layout and Column Locations Submittal: First Draft Proposal
6	10/4/2010 – 10/10/2010	Revisions to Proposal Begin Calculations
7	10/11/2010 – 10/14/2010	Submittal: Current state of the MQP Report including final proposal
B Term		

8	10/26/2010 – 10/31/2010	Begin Calcs for Steel Design Begin Calcs for Concrete Design Continue Research
9	11/1/2010 – 11/7/2010	Start Design Calcs w/ Cladding Green Roof Desgin w/ LEED components
10	11/8/2010 – 11/14/2010	Update Paper Complete Any Research Remaining
11	11/15/2010 – 11/21/2010	Create Criteria for Recommendation Update Paper
12	11/29/2010 – 12/5/2010	Finish Calcs for Round 1 Designs Begin Alternate Designs
13	12/6/2010 – 12/12/2010	Update Paper
14	12/13/2010 – 12/16/2010	Turn in Deliverables for B Term
	C Term	
15	1 /17/2011 – 1/23/2011	Finish Secondary Designs
16	1/24/2011 – 1/30/2011	Perform Cost Analysis
17	1/31/2011 – 2/6/2011	Continue Cost Analysis Update Paper
18	2/7/2011 – 2/13/2011	Finish Cost Analysis Form Recommendation Compile Paper
19	2/14/2011 – 2/20/2011	Turn in Draft Paper
20	2/21/2011 – 2/27/2011	Edit Paper

21	2/28/2011 – 3/4/2011	Complete Project

Conclusions

At the end of this project, this group aims to have identified the most cost effective design alternatives. Cost efficiency is influenced by several variables, of which this project will investigate material, labor cost, and order of magnitude. The four designs to be completed during the design phase will allow for a healthy comparison, with the time provided.

Of the minimum four designs to be completed, two will be long beam spans and two will be shorter beam spans. Equally, both types of spans will be designed using structural steel construction and reinforced concrete construction. These designs will be evaluated for the cost of the material and labor needed to create the structure, including the foundation on which the structure will stand. Lastly, the external cladding and green roof will be examined based on how it connects to the frame, and what that will cost.

Having no prior knowledge in cladding, and little knowledge in LEED, the costs of those sections are hard to predict. However, having prior experience with both steel and concrete design, this group has formed a hypothesis as to the final verdict of this project. This group believes that a steel frame, with longer but feasible spans, will be the best basic choice in lifetime cost because structural steel is a longer lasting material, requiring less up keep and maintenance than concrete structures. However, the concrete structure, with longer spans, will be a better cost up front because concrete costs less than steel.

Capstone Design

As part of the Major Qualifying Project (MQP) a capstone design experience will be accomplished. The capstone design experience will be based on skills previously learned in the classroom and the application of appropriate engineering standards. The capstone design experience will also incorporate the following realistic constraints: economic, constructability, health and safety, ethical, political, social, environmental and sustainability. The treatment of each constraint is outlined below.

The first constraint is economics. In evaluating different designs, cost will have a major effect on the selection process. We will be selecting the most cost efficient design by examining different alternatives to construction, floor layouts, and materials. A cost analysis will be done using material quantities from our design with unit cost data, and square footage order of magnitude estimate from RS Means.

The second constraint is constructability. In this project several floor layouts will be examined with different arrangements of beams and columns. Thought will go into defining the different size members in the alternative steel and reinforced concrete designs so that there is a typical size used throughout construction. There will also be much consideration when choosing the different floor layouts to maximize the space as well as meeting all tenants' needs.

Health and Safety is also a major concern throughout this project. Adjustments will be made to the floor layout to assure the safety of the tenants. Special consideration will be given when designing the FPE Department's floor plan and lab space to assure safety throughout the building. The building will also be built following Massachusetts Building Code, COWZ, and the Americans with Disabilities Act (ADA) Standards for Accessible Design.

When building any structure there are always many ethical, social and political concerns, especially in a city like Worcester. A project like Gateway Park would bring in many jobs for people in the surrounding areas and possibly provide jobs for graduating students at WPI. Gateway 2 would continue to provide a better image for WPI by expanding the school's involvement in research and promoting commercial and high tech development in the City of Worcester. It would also provide a place to mold young minds by relocating Mass Academy High School. Many people might agree that Gateway 2 would be a positive contribution but concerns could arise when looking at the effects it could have on the environment and the types of research being done within the Biotech companies. There also could be concerns if the site is Americans with Disabilities Act (ADA) compliant considering in 2000, there were 38,068 people in Worcester, MA listed as disabled (Disabled)

Finally, environmental and sustainability are constraints that will be dealt with in this project. This project will follow LEED specifications. The New York Times' education blog "The Choice" mentions Worcester Polytechnic Institute as one of several schools that have improved in sustainability effort. In continuing this effort this project plans on looking at different alternatives to roof designs by incorporating a green roof.

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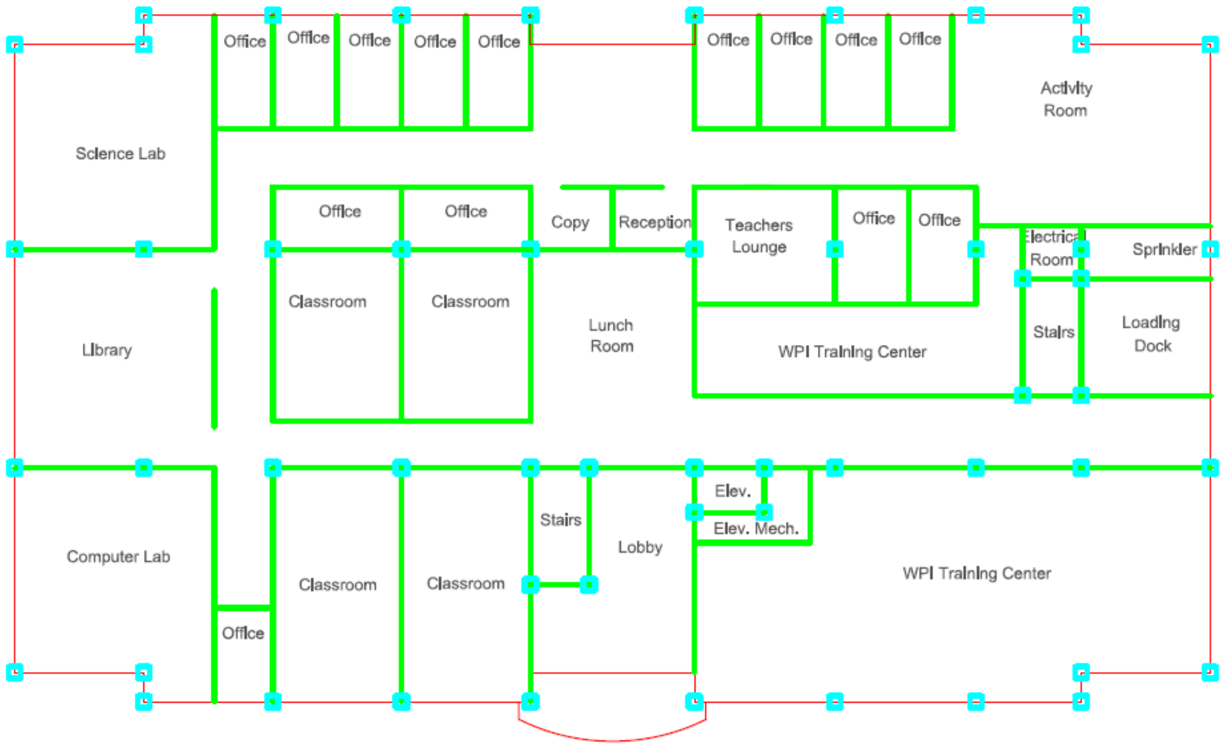
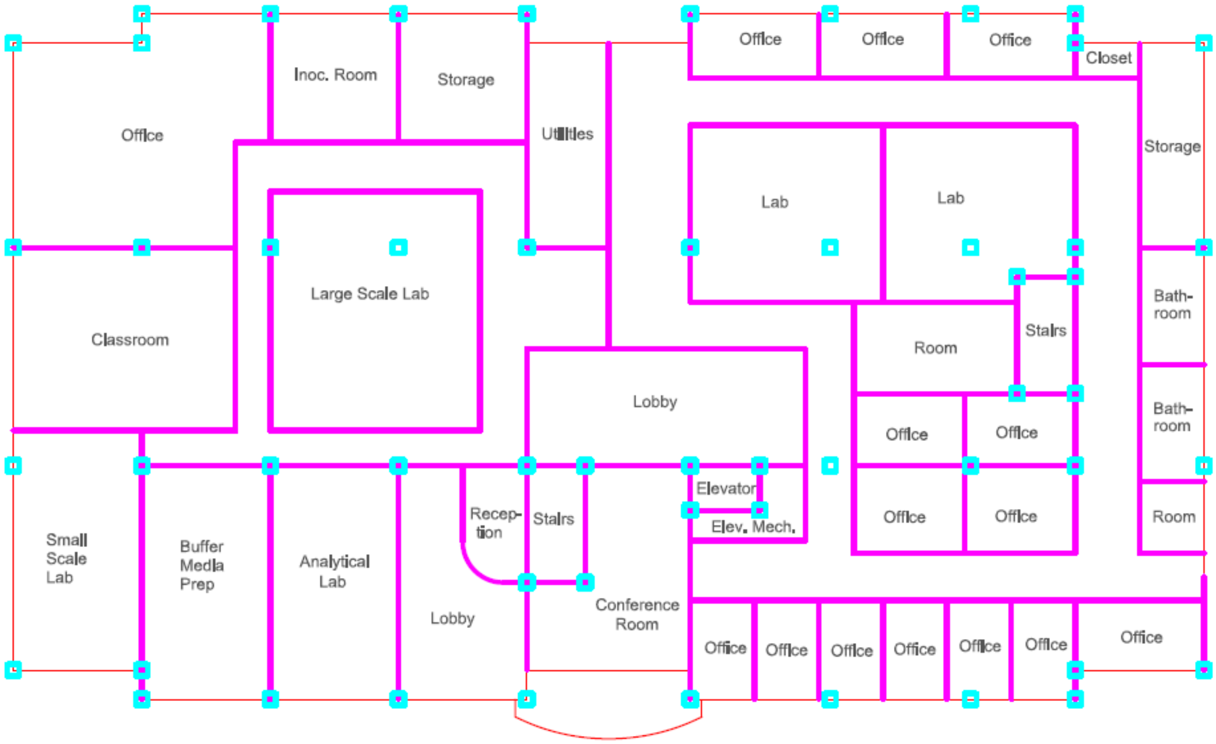
Appendix B: Layouts

B.1 Small Bay Design

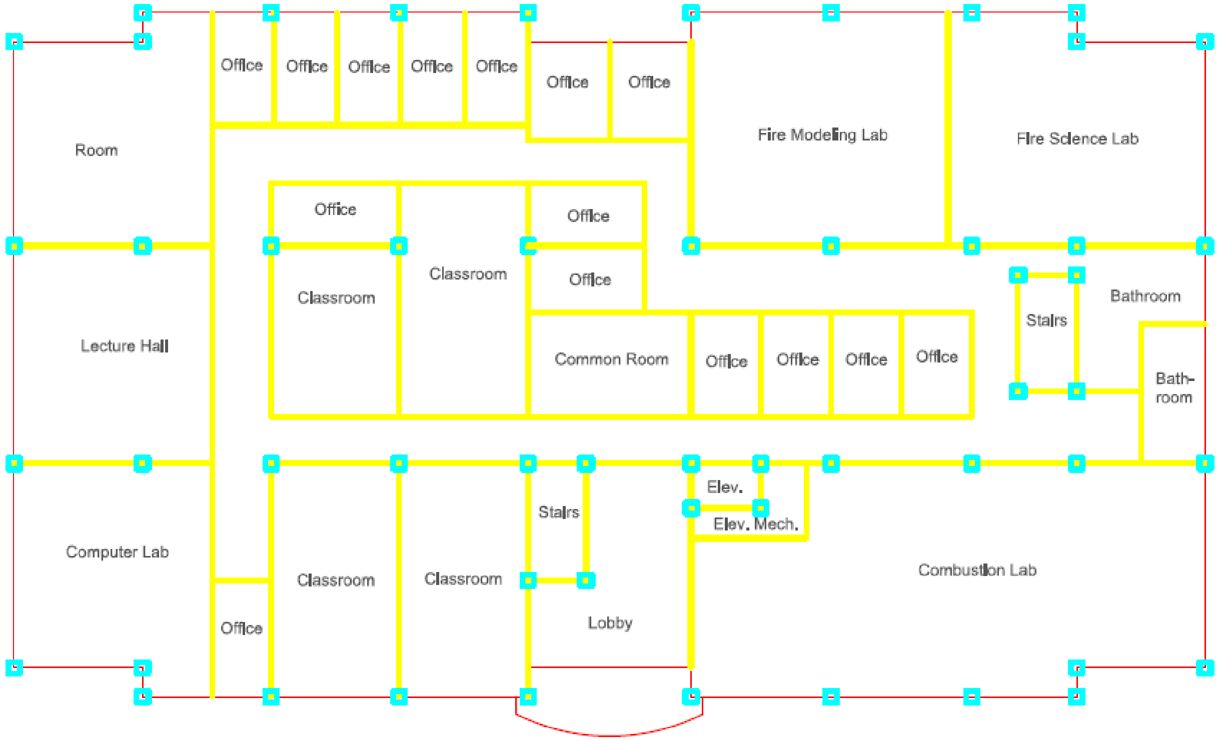
Massachusetts Academy of Math and Science at WPI



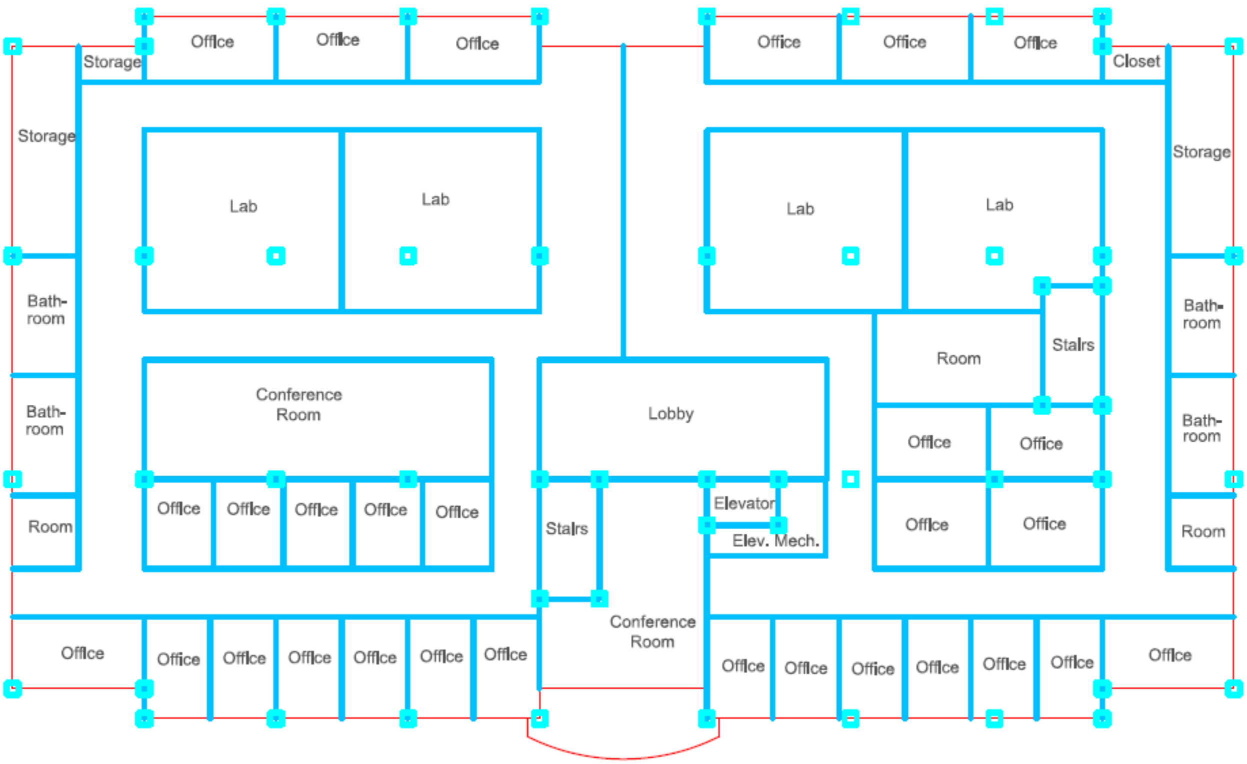
WPI Biomanufacturing Education and Training Center



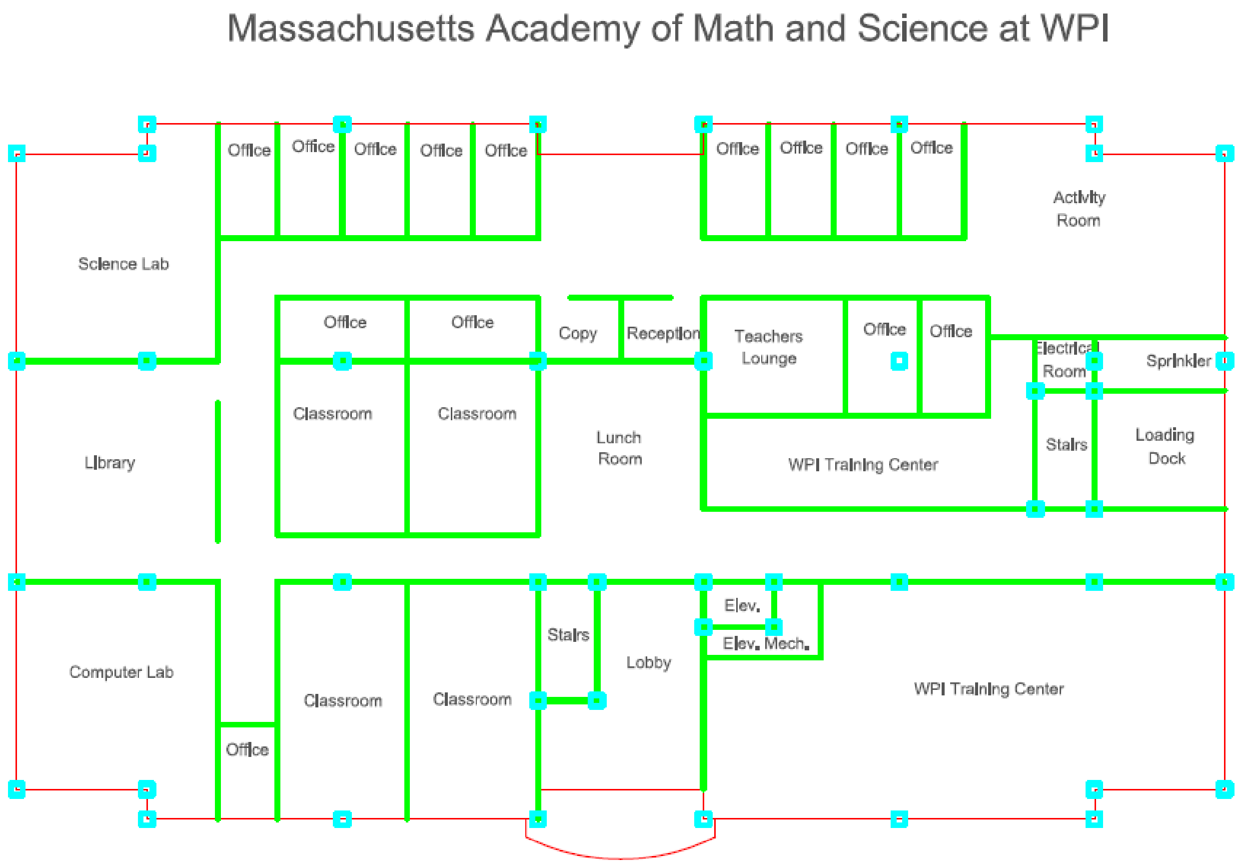
WPI Department of Fire Protection Engineering



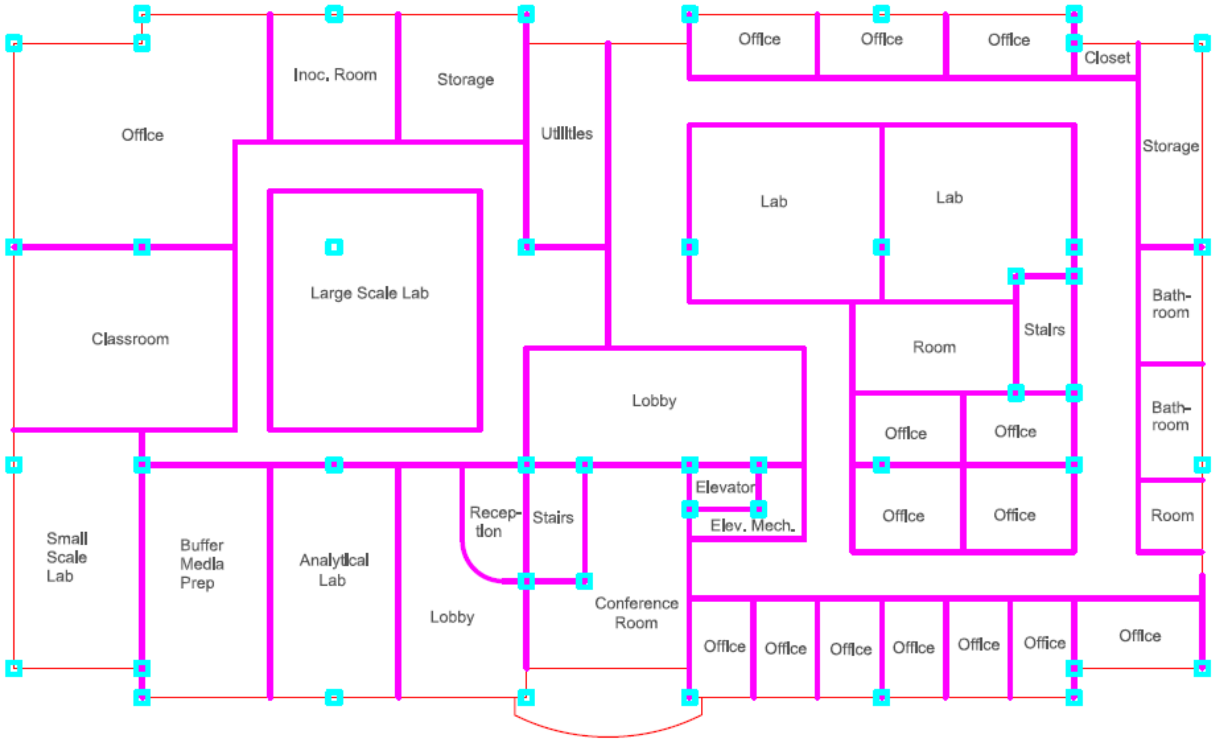
BioTech Companies



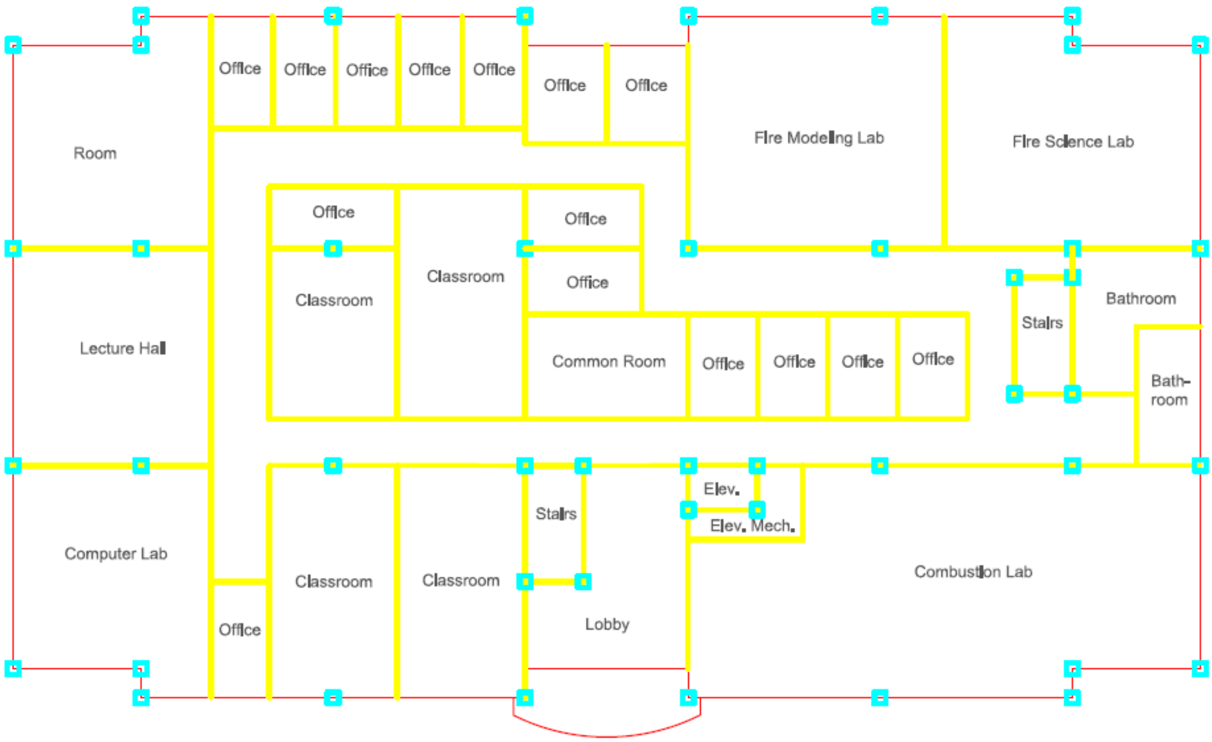
B.2 Large Bay Design



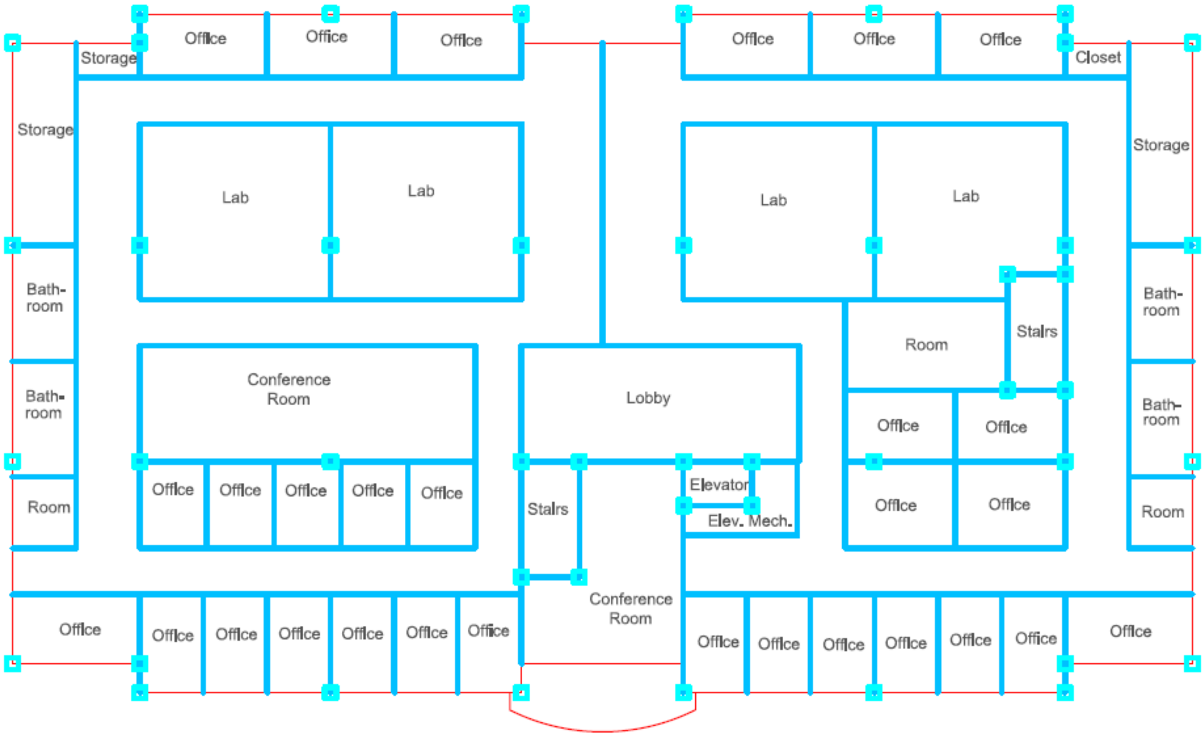
WPI Biomanufacturing Education and Training Center



WPI Department of Fire Protection Engineering



BioTech Companies



Appendix C: Steel Calculations

Appendix C.1 Beam and Girder Design

Large Beam Design #1

Bay Size 35' x 22'

3 Filler Beams Spanning 35'

			E	29000	k/in^4
Beam Length	35	ft	fy	50	ksi
Tributary width	5.5	ft	f'c	3	ksi
Slab thickness	3	in	fu	65	ksi

Dead Loads	PLF	**Live Loads**	PLF
Concrete Slab (3", 145pcf)	219.31	Occupancy (100psf)	550
Decking (3 psf)	16.50		
MEP and Ceiling (8 psf)	44.00		
Total	279.81	***Total***	550

Loading Combinations

Factored	PLF	
Wu=1.4D	391.74	
Wu=1.2D+1.6L	1215.78	Governs

Critical Moment Mu	ft-kips
Mu = (Wu*L²)/8	186.17

Effective Flange Width (AISC I3.1)

be	105	
be	66	Governs

Select W section

Ycon	4 1/2	in
Y2 (assume a=2in)	3.5	in

Try 14 X	**34**	
Area	10	in^2
Ix	340	in^4
d	14	in
tw	0.285	in
Qn (kips)	500	

a (in)	2.97	Ok < 4.5
Y2	3.01	

ϕb*Mn (AISC tbl 3-19)		
Y2=3.5	393	
Y2=3	375	
ϕb*Mn (ft-kips)	392.46	186.17
With weight of Beam		220.17

Design of Studs		
fc	3024.21	ksi
Asc	0.44	
Qn (kips)	21.04	
Qn (kips)	17.23	Governs
Number of Studs	58.04	
Use 59 - (3/4") studs		

Investigate strength of wet conc.

Dead Loads	PLF	**Live Loads**	PLF
Beam wt	34	Wet Concrete	110
		Slab	219.31
Total	34	***Total***	329.31

Loading Combinations		
Factored	PLF	
Wu=1.4D	47.60	
Wu=1.2D+1.6L	567.70	Governs

Critical Moment Mu	ft-kips
Mu = (Wu*L²)/8	86.93

Check for deflection during const.

w	253.31	lbs/ft
Δ (in)	0.867	ok < 1in

Check Beam Shear (AISC table 3-6)

Wu	1.26	k/ft
Vu	21.99	kips
ϕVn (table 3-6) kips	120	> Vu

	OK

Large Beam Design #1

Bay Size 40' x 33'

4 Filler Beams Spanning 35'

			E	29000	k/in^4
Beam Length	40	ft	fy	50	ksi
Tributary width	6.6	ft	f'c	3	ksi
Slab thickness	3	in	fu	65	ksi

Dead Loads	PLF	**Live Loads**	PLF
Concrete Slab (3", 145pcf)	263.18	Occupancy (100psf)	660
Decking (3 psf)	19.80		
MEP and Ceiling (8 psf)	52.80		
Total	335.78	***Total***	660

Loading Combinations

Factored	PLF	
Wu=1.4D	470.09	
Wu=1.2D+1.6L	1458.93	Governs

Critical Moment Mu

	ft-kips
Mu = $(Wu*L^2)/8$	291.79

Effective Flange Width (AISC I3.1)

be	120	
be	79.2	Governs

Select W section

Ycon	4 1/2	in
Y2 (assume a=2in)	3.5	in

Try 18 X	**60**	
Area	17.6	in^2
Ix	984	in^4
d	18.2	in
tw	0.415	in

Qn (kips)	880	
a (in)	4.36	Ok < 4.5

Y2	2.32	
ϕb*Mn (AISC tbl 3-19)		
Y2=2	735	
Y2=2.5	768	
ϕb*Mn (ft-kips)	725.1	291.79
With weight of Beam		351.79

Design of Studs		
fc	3024.21	ksi
Asc	0.44	
Qn (kips)	21.04	
Qn (kips)	17.23	Governs
Number of Studs	102.15	
Use 103 - (3/4") studs		

Investigate strength of wet conc.

Dead Loads	PLF	**Live Loads**	PLF
Beam wt	60	Wet Concrete	132
		Slab	263.18
Total	60	***Total***	395.18

Loading Combinations		
Factored	PLF	
Wu=1.4D	84.00	
Wu=1.2D+1.6L	704.28	Governs

Critical Moment Mu	ft-kips
Mu = (Wu*L²)/8	140.86

Check for deflection during const.

w	323.18	lbs/ft
Δ (in)	0.652	ok < 1in

Check Beam Shear (AISC table 3-6)

Wu	1.53	k/ft
Vu	30.62	kips
ϕVn (table 3-6) kips	248	> Vu OK

Large Girder Design #1

Bay Size 35' x 22'

3 Filler Beams Spanning 35'

			E	29000	k/in^4
Beam Length	22	ft	fy	50	ksi
Tributary width	35	ft	f'c	3	ksi
Slab thickness	3	in	fu	65	ksi

Dead Loads	PLF	**Live Loads**	PLF
Concrete Slab (3", 145pcf)	1395.63	Occupancy (100psf)	3500
Decking (3 psf)	105.00		
MEP and Ceiling (8 psf)	280.00		
Beam Weight (4EA 35lbs/ft)	162.27		
Total	1942.90	***Total***	3500

Loading Combinations

Factored	PLF	
Wu=1.4D	2720.06	
Wu=1.2D+1.6L	7931.48	Governs

Critical Moment Mu

	ft-kips
Mu = (Wu*L²)/8	479.85

Effective Flange Width (AISC I3.1)

be	66	Governs
be	420	

Select W section

Ycon	4 1/2	in
Y2 (assume a=2in)	3.5	in

Try 21 X	**50**	
Area	14.7	in^2
Ix	984	in^4
d	20.8	in
tw	0.38	in

Qn (kips)	735	
a (in)	4.37	Ok < 4.5

Y2	2.32	
ϕb*Mn (AISC tbl 3-19)		
Y2=2	685	
Y2=2.5	712	
ϕb*Mn (ft-kips)	685.81	479.85
With weight of Beam		529.85

Design of Studs		
fc	3024.21	ksi
Asc	0.44	
Qn (kips)	21.04	
Qn (kips)	17.23	Governs
Number of Studs	85.32	
Use 86 - (3/4") studs		

Investigate strength of wet conc.

Dead Loads	PLF	**Live Loads**	PLF
Beam wt	50	Wet Concrete	700
		Slab	1395.63
Total	50	***Total***	2095.63

Loading Combinations		
Factored	PLF	
Wu=1.4D	70.00	
Wu=1.2D+1.6L	3413.00	Governs
Critical Moment Mu	ft-kips	
Mu = (Wu*L²)/8	206.49	

Check for deflection during const.

w	1445.63	lbs/ft
Δ (in)	0.267	ok < 1in

Check Beam Shear (AISC table 3-6)

Wu	7.99	k/ft
Vu	87.91	kips
ϕVn (table 3-6) kips	252	> Vu OK

Large Girder Design #1

Bay Size 40' x 33'

4 Filler Beams Spanning 35'

			E	29000	k/in^4
Beam Length	33	ft	fy	50	ksi
Tributary width	40	ft	f'c	3	ksi
Slab thickness	3	in	fu	65	ksi

Dead Loads	PLF	**Live Loads**	PLF
Concrete Slab (3", 145pcf)	1595.00	Occupancy (100psf)	4000
Decking (3 psf)	120.00		
MEP and Ceiling (8 psf)	320.00		
Beam Weight (4EA 35lbs/ft)	290.91		
Total	2325.91	***Total***	4000

Loading Combinations

Factored	PLF	
Wu=1.4D	3256.27	
Wu=1.2D+1.6L	9191.09	Governs

Critical Moment Mu	ft-kips
Mu = $(Wu*L^2)/8$	1251.14

Effective Flange Width (AISC I3.1)

be	99	Governs
be	480	

Select W section

Ycon	4 1/2	in
Y2 (assume a=2in)	3.5	in

Try 24 X	**76**	
Area	22.4	in^2
Ix	2100	in^4
d	23.9	in
tw	0.44	in

Qn (kips)	1120	
a (in)	4.44	Ok < 4.5

Y2	2.28	
ϕb*Mn (AISC tbl 3-19)		
Y2=2	1250	
Y2=2.5	1300	
ϕb*Mn (ft-kips)	1251.5	1251.14
With weight of Beam		1327.14

Design of Studs

fc	3024.21	ksi
Asc	0.44	
Qn (kips)	21.04	
Qn (kips)	17.23	Governs
Number of Studs	130.01	
Use 131 - (3/4") studs		

Investigate strength of wet conc.

Dead Loads	PLF	**Live Loads**	PLF
Beam wt	76	Wet Concrete	800
		Slab	1595.00
Total	76	***Total***	2395.00

Loading Combinations

Factored	PLF	
Wu=1.4D	106.40	
Wu=1.2D+1.6L	3923.20	Governs

Critical Moment Mu	ft-kips
Mu = (Wu*L²)/8	534.05

Check for deflection during const.

w	1671.00	lbs/ft
Δ (in)	0.732	ok < 1in

Check Beam Shear (AISC table 3-6)

Wu	9.28	k/ft
Vu	153.16	kips
ϕVn (table 3-6) kips	375	> Vu OK

Short Beam Design #2

Bay Size 40' x 22'

2 Filler Beams Spanning 40'

			E	29000	k/in^4
Beam Length	40	ft	fy	50	ksi
Tributary width	7.3	ft	f'c	3	ksi
Slab thickness	3	in	fu	65	ksi

Dead Loads	PLF	**Live Loads**	PLF
Concrete Slab (3", 145pcf)	291.09	Occupancy (100psf)	730
Decking (3 psf)	21.90		
MEP and Ceiling (8 psf)	58.40		
Total	371.39	***Total***	730

Loading Combinations

Factored	PLF	
Wu=1.4D	519.94	
Wu=1.2D+1.6L	1613.67	Governs

Critical Moment Mu	ft-kips
Mu = (Wu*L²)/8	322.73

Effective Flange Width (AISC I3.1)

be	120	
be	87.6	Governs

Select W section

Ycon	4 1/2	in
Y2 (assume a=2in)	3.5	in

Try18 X	**46**	
Area	13.5	in^2
Ix	712	in^4
d	18.1	in
tw	0.36	in

Qn (kips)	675	
a (in)	3.02	Ok < 4.5
Y2	2.99	

ϕb*Mn (AISC tbl 3-19)		
Y2=3	585	
Y2=3.5	611	
ϕb*Mn (ft-kips)	585.78	322.73
With weight of Beam		368.73

Design of Studs

fc	3024.21	ksi
Asc	0.44	
Qn (kips)	21.04	
Qn (kips)	17.23	Governs
Number of Studs	78.35	
Use 79 - (3/4") studs		

Investigate strength of wet conc.

Dead Loads	PLF	**Live Loads**	PLF
Beam wt	46	Wet Concrete	146
		Slab	291.09
Total	46	***Total***	437.09

Loading Combinations

Factored	PLF	
Wu=1.4D	64.40	
Wu=1.2D+1.6L	754.54	Governs

Critical Moment Mu

	ft-kips
Mu = (Wu*L²)/8	150.91

Check for deflection during const.

w	337.09	lbs/ft
Δ (in)	0.940	ok < 1in

Check Beam Shear (AISC table 3-6)

Wu	1.67	k/ft
Vu	33.38	kips
ϕVn (table 3-6) kips	120	> Vu OK

Short Girder Design #2

Bay Size 40' x 22'

2 Filler Beams Spanning40'

			E	29000	k/in^4
Beam Length	22	ft	fy	50	ksi
Tributary width	40	ft	f'c	3	ksi
Slab thickness	3	in	fu	65	ksi

Dead Loads	PLF	**Live Loads**	PLF
Concrete Slab (3", 145pcf)	1595.00	Occupancy (100psf)	4000
Decking (3 psf)	120.00		
MEP and Ceiling (8 psf)	320.00		
Beam Weight (5EA 50lbs/ft)	167.27		
Total	2202.27	***Total***	4000

Loading Combinations

Factored	PLF	
Wu=1.4D	3083.18	
Wu=1.2D+1.6L	9042.73	Governs

Critical Moment Mu	ft-kips	
Mu = $(Wu*L^2)/8$	547.09	

Effective Flange Width (AISC I3.1)

be	66	Governs
be	480	

Select W section

Ycon	4 1/2	in
Y2 (assume a=2in)	3.5	in

Try21 X	**44**	
Area	13	in^2
Ix	843	in^4
d	20.7	in
tw	0.35	in

Qn (kips)	650	
a (in)	3.86	Ok < 4.5

Y2	2.57	

ϕb*Mn (AISC tbl 3-19)		
Y2=2.5	625	
Y2=3	649	
ϕb*Mn (ft-kips)	625.72	547.09
With weight of Beam		591.09

Design of Studs		
fc	3024.21	ksi
Asc	0.44	
Qn (kips)	21.04	
Qn (kips)	17.23	Governs

Number of Studs	75.45
Use 76 - (3/4") studs	

Investigate strength of wet conc.

Dead Loads	PLF	**Live Loads**	PLF
Beam wt	44	Wet Concrete	800
		Slab	1595.00
Total	44	***Total***	2395.00

Loading Combinations		
Factored	PLF	
Wu=1.4D	61.60	
Wu=1.2D+1.6L	3884.80	Governs

Critical Moment Mu	ft-kips
Mu = (Wu*L²)/8	235.03

Check for deflection during const.

w	1639.00	lbs/ft
Δ (in)	0.353	ok < 1in

Check Beam Shear (AISC table 3-6)

Wu	9.10	k/ft
Vu	100.05	kips
ϕVn (table 3-6) kips	375	> Vu OK

Appendix C.2 Column Design

C.2.1 Large Bay Design- Load Combination 1

Column Design

Load Comb.	U = 1.2D + 1.6(Lror S or R) + (0.5LL or 0.8W)			
Column Load Effects from Analysis				
	Exterior		Interior	
P_{nt}	152	kips	484	kips
P_{lt}	18	kips	14	kips
M_{nt}	251	ft-k	512	ft-k
M_{lt}	179	ft-k	182	ft-k

Amplifier B_2				
	Exterior		Interior	
$\sum P_{e2}$	29206.77	kips	29206.77	kips
$\sum P_{nt}$	1216	kips	3872	kips
B_2	1.04		1.15	

Amplifier B_1				
	Exterior		Interior	
M_1	0	ft-k	0	ft-k
M_2	251	ft-k	512	ft-k
Curvature:	Single		Single	
C_m	0.6		0.6	
P_r	171	kips	501	kips
$\sum P_{e1}$	52572.19	ft-k	52572.19	ft-k
B_1	0.60	≤1.0	0.61	≤1.0
	Use	1.0	Use	1.0

Required Second-Order Strength Values				
	Exterior		Interior	
P_r	171.20	kips	500.60	kips
M_r	437.78	ft-k	721.82	ft-k

Interaction Equations				
Pr/Pc	0.18	<0.2	0.38	>0.2
	Use Inter. Eq. H1-1b		Use Inter. Eq. H1-1a	
h/tw	49.6 <90.5	ok	49.6 <90.5	ok
bf/2tf	6.89 <9.2	ok	6.89 <9.2	ok
Lp	8.9 <13	ok	8.9 <13	ok
ΦMn	1106.65	ft-k	1106.65	ft-k
Interaction Eq.	0.48	≤1.0	0.983	≤1.0

w30x108 is acceptable for both interior and exterior columns

C.2.2 Large Bay Design- Load Combination 2

Column Design

Load Comb.	U = 1.2D + 1.6W + 0.5L + 0.5S			
Column Load Effects from Analysis				
	Exterior		Interior	
P_{nt}	202	kips	564	kips
P_{lt}	9	kips	7	kips
M_{nt}	291	ft-k	599	ft-k
M_{lt}	89.5	ft-k	91	ft-k

Amplifier B_2				
	Exterior		Interior	
$\sum P_{e2}$	29206.77	kips	29206.77	kips
$\sum P_{nt}$	1616	kips	4512	kips
B_2	1.06		1.18	

Amplifier B_1				
	Exterior		Interior	
M_1	0	ft-k	0	ft-k
M_2	291	ft-k	599	ft-k
Curvature:	Single		Single	
C_m	0.6		0.6	
P_r	212	kips	572	kips
$\sum P_{e1}$	52572	ft-k	52572	ft-k
B_1	0.60	≤1.0	0.61	≤1.0
	Use	1.0	Use	1.0

Required Second-Order Strength Values				
	Exterior		Interior	
P_r	212	kips	572	kips
M_r	386	ft-k	707	ft-k

Interaction Equations				
Pr/Pc	0.22	>0.2	0.35	>0.2

	Use Inter. Eq. H1-1b		Use Inter. Eq. H1-1a	
h/tw	49.6 <90.5	ok	49.6 <90.5	ok
bf/2tf	6.89 <9.2	ok	6.89 <9.2	ok
Lp	8.9 <13	ok	8.9 <13	ok
ΦMn	1106.65	ft-k	1106.65	ft-k
Interaction Eq.	0.53	≤1.0	0.92	≤1.0

w30x108 is acceptable for both interior and exterior columns

C.2.3 Small Bay Design- Load Combination 1

Column Design

Load Comb.	U = 1.2D + 1.6(Lror S or R) + (0.5LL or 0.8W)			
Column Load Effects from Analysis				
	Exterior		Interior	
P_{nt}	171	kips	382	kips
P_{lt}	4	kips	2	kips
M_{nt}	179	ft-k	171	ft-k
M_{lt}	94	ft-k	85	ft-k

Amplifier B_2				
	Exterior		Interior	
$\sum P_{e2}$	23652.91	kips	23652.91	kips
$\sum P_{nt}$	1366	kips	3052	kips
B_2	1.06		1.15	

Amplifier B_1				
	Exterior		Interior	
M_1	0	ft-k	0	ft-k
M_2	179	ft-k	512	ft-k
Curvature:	Single		Single	
C_m	0.6		0.6	
P_r	175	kips	383	kips
$\sum P_{e1}$	42575.24	ft-k	42575.24	ft-k
B_1	0.60	≤1.0	0.61	≤1.0
	Use	1.0	Use	1.0

Required Second-Order Strength Values				
	Exterior		Interior	
P_r	175.36	kips	383.22	kips
M_r	278.15	ft-k	268.76	ft-k

Interaction Equations				
Pr/Pc	0.19	<0.2	0.42	>0.2

	Use Inter. Eq. H1-1b		Use Inter. Eq. H1-1a	
h/tw	49.6 <90.5	ok	49.6 <90.5	ok
bf/2tf	6.89 <9.2	ok	6.89 <9.2	ok
Lp	8.9 <13	ok	8.9 <13	ok
ΦMn	424.56	ft-k	424.56	ft-k
Interaction Eq.	0.75	≤1.0	0.98	≤1.0

w27x102 is acceptable for both interior and exterior columns

C.2.4 Small Bay Design- Load Combination 2

Column Design

Load Comb.	U = 1.2D + 1.6W + 0.5L + 0.5S			
Column Load Effects from Analysis				
	Exterior		Interior	
P_{nt}	171	kips	382	kips
P_{lt}	8	kips	4	kips
M_{nt}	179	ft-k	171	ft-k
M_{lt}	188	ft-k	170	ft-k

Amplifier B_2				
	Exterior		Interior	
$\sum P_{e2}$	23652.91	kips	23652.91	kips
$\sum P_{nt}$	1368	kips	3056	kips
B_2	1.06		1.15	

Amplifier B_1				
	Exterior		Interior	
M_1	0	ft-k	0	ft-k
M_2	179	ft-k	171	ft-k
Curvature:	Single		Single	
C_m	0.6		0.6	
P_r	179	kips	387	kips
$\sum P_{e1}$	42575	ft-k	42575	ft-k
B_1	0.60	≤1.0	0.61	≤1.0
	Use	1.0	Use	1.0

Required Second-Order Strength Values				
	Exterior		Interior	
P_r	179	kips	387	kips
M_r	379	ft-k	366	ft-k

Interaction Equations				
Pr/Pc	0.20	>0.2	0.42	>0.2

	Use Inter. Eq. H1-1a		Use Inter. Eq. H1-1a	
h/tw	49.6 <90.5	ok	49.6 <90.5	ok
bf/2tf	6.89 <9.2	ok	6.89 <9.2	ok
Lp	8.9 <13	ok	8.9 <13	ok
ΦMn	424.56	ft-k	424.56	ft-k
Interaction Eq.	0.89	≤1.0	0.97	≤1.0

w27x102 is acceptable for both interior and exterior columns

Appendix C.3 Concrete Slab and Steel Decking Design

Appendix C.4 Green Roof Design

Appendix C.5 Base Plate Design

Small Bay Design		
Column	27 x 102	
Area	30	in^2
bf	10	in
d	27.1	in
bf*d	271	in^2
Pu	382	kips
X=sqrt(A1/A2)	2	
f'c	3	ksi
ϕ	0.6	
Fy	50	ksi
A1=Pu/(φ*.85*f'c*X)	124.84	
Use A1=	271	
sqrt(A1)	16.46	
Δ	8.87	
N	25.33	
B	10.70	
φPp = φ.85*f'c*A1*X	829.26	>Pu
m= (N-.95*d)/2	-0.21	
n = (B - .8bf)/2	1.35	
n' = sqrt(d*bf)/4	4.12	
l (largest m,n,n')	4.12	
t = l*sqrt((2*Pu)/(.9Fy*B*N))	1.03	in

Base plate area cannot be less then bf*d

Large Bay Design		
Column	30 x 108	
Area	31.7	in^2
bf	10.5	in
d	29.8	in
bf*d	312.9	in^2
Pu	484	kips
X=sqrt(A1/A2)	2	
f'c	3	ksi
ϕ	0.6	
Fy	50	ksi

Base plate area cannot be less then bf*d

A1=Pu/(φ*.85*f'c*X)	158.17	
Use A1=	312.9	
sqrt(A1)	17.69	
Δ	9.96	
N	27.64	
B	11.32	
φPp = φ.85*f'c*A1*X	957.474	>Pu
m= (N-.95*d)/2	-0.33	
n = (B - .8bf)/2	1.46	
n' = sqrt(d*bf)/4	4.42	
l (largest m,n,n')	4.42	
t = l*sqrt((2*Pu)/(.9Fy*B*N))	1.16	in

Appendix C.6 Connections

C.6.1 Single Angle Connections

Single Angle Connection				
Investigate Design Load				
Live Load	455	lb/ft		
Dead Load	560	lb/ft		
Total	1015	lb/ft		
Load Combinations				
1.2D + 1.6 L	1400	lb/ft		
Mu	190.58	ft-k		
Vu	23.10	kips		
ΦVn	167	kips	≥ Vu = 23.10 kips	ok
Establish Number of Bolts				
ΦRn	15.9	kips/bolt in single shear		
n (#bolts)	1.45	bolts		
	2	bolts		
Establish Connection Geometry				
Dist. between bolts	3	inches		
Dist. between edge and bolt	2	inches		
Establish Angle Thickness				
Lc	1.56	inches		
ΦRn	1.404	t		
ΦRn	1.35	t		
Total Bearing Capacity	0.125	≤	t	
Angle Shear Rupture				
ΦRn	0.146	≤	t	
Angle Shear Yield				
ΦRn	0.176	≤	t	
Check Bearing on Girder Web				
ΦRn	61.857	kips	≥ Vu = 23.10 kips	ok

C.6.2 Double Angle Connections

Double Angle Connection				
Investigate Design Load				
Live Load	3300	lb/ft		
Dead Load	2724	lb/ft		
Total	6024	lb/ft		
Load Combinations				
1.2D + 1.6 L	8548.8	lb/ft		
Mu	1163.71	ft-k		
Vu	141.06	kips		
ΦVn	167	kips	≥ Vu = 141.06 kips	ok
Check Girder Shear Capacity				
for w24 x 84				
h/tw	49.6	≤	53.95	ok
ΦVn	339.81	kips	≥ Vu = 141.06 kips	ok
Establish Number of Bolts				
ΦRn	31.809	kips/bolt in double shear		
n (#bolts)	4.4	bolts		
	5	bolts		
Establish Connection Geometry				
Dist. between bolts	3	inches		
Dist. between edge and bolt	1.5	inches		
Establish Angle Thickness				
Lc	2.563	inches		
ΦRn	2.306	t		
ΦRn	1.35	t		
Total Bearing Capacity	0.300	≤	t	
Angle Shear Rupture				
ΦRn	0.3045	≤	t	
Angle Shear Yield				
ΦRn	0.363	≤	t	

Check Bearing on Girder Web				
ΦRn	173.31	kips	≥ Vu = 141.06 kips	ok

C.6.3 Fillet Welds

Fillet Weld			
Yield on Gross Area			
Tu	≤	97.2	kips
Target Capacity of weld			141.06 kips
Weld Size (table AISC J2.4)			
Minimum	1/8	inches	
Minimum	3/16	inches	
Fillet Weld Capacity			
Rn	0.13		
Weld Metal Strength			
Use E70 electrodes			
fw	5.57	k/in.	
Base Metal Strength			
Shear Yield			
Rn	5.4	k/in.	
Shear Rupture			
Rn	8.7	k/in.	
Design Strength			
ΦRn	4.05	k/in.	
Required Weld Length			
Lw	17.4	inches	

Appendix D: Concrete Calculations: Beam & Girder Method

Concrete Design | LRFD | Short Span / Long Span

Trib 35 x 22' D = 271.91 plf L = 550 plf w_u = 1.2D + 1.6L = 1215.78 plf

f_y = 60 Ksi f'_c = 4 Ksi E_s = 29000 K/in² M_u = 186.17 ft-Kips

ρ = .011 ϕ = .9

Determine R_n

$m = f_y / .85 f'_c = \frac{60}{.85(4)} = 17.65$ $R_n = \rho f_y (1 - .5 \rho m)$

R_n = .011(60000)[1 - .5(.011)(17.65)] = 596 psi

$M_n = M_u / \phi = \frac{186.17}{.9}$ = 206.86 ft-Kips

$bd^2 = \frac{M_n}{R_n} = \frac{206.86(12000)}{596}$ = 4114.83 in³

Choose Beam Size

b	d
8	22.81
10	20.41
12	18.63 ⇐ Use

h = d + 2.5 h = 21.13 ⇒ 22 in Size 12 in x 22 in d' = 3 in

Steel Calc T = C_c + C_s T = $f_y A_s$ C_c = .85 f'_c b a C_s = (f_y - .85 f'_c) A'_s

[illegible] c_{max} = .4286(d) = 8 in a = β_1(c_{max}) = .8(8) = 6.4 in

C_c = .85(4)(6.4)(12) = 265.2 Kips ∴ A_s = C/f_y = 4.42 in² + $M_n = \frac{C(d - a/2)}{12}$ = 341 ft-K

ϕ = .82 Req M_n = 341/.82 = 415.85 ft-Kip ΔM_n = 74.85 ft-K

$C_s = \frac{\Delta M_n (12)}{d - d'}$ = 57.67 Kips $A'_s = \frac{(f_y - .85 f'_c)}{C_s}$ = .98 in²

T = C_c + C_s = 322.83 A_s = T/f_y = 5.38 in²

Concrete Beams | LRFD | Short Span / Long Span

Bay = 35x22' Beam on outside so only half Trib width

$35/2 = 17.5'$ $D_{slab} = \frac{150\,pcf\,(1.83\,ft)(17.5\,ft)(3)}{5.5\,ft} = 2620.22$

$D = 4400.46$ plf $L = 3500$ plf $W_u = 1.2D + 1.6L = 10881.03$ plf

$M_u = 658.3$ Ft kips

$R_n = 596$ psi $M_n = M_u/.9 = 731.4$ FtK

$bd^2 = M_n/R_n = \frac{731.4(12000)}{596} = 14,727.05\,in^3$

b	d
16	30.34 ← use
18	28.60
20	27.14

$h = d + 2.5$ $h = 32.84 \Rightarrow 33$ in Size 16 in x 33 in $d' = 3$ in

Steel Calc Assume same as before

ϵ $C_{tmax} = .4286(d) = 13$ in $a = B_1(c_{tmax}) = .8(13) = 10.4$ in

$C_c = .85(7)(10.4)(16) = 565.76$ Kips $\therefore$ $A_s = T/f_y = 9.43\,in^2$

req $M_n = M_u/.92 = 1445.45$ FtKips $M_n = \frac{C(d - a/2)}{12} = 1185.27$ Ft Kips

$\Delta M_n = 260.18$ Ft kips

$C_s = \frac{\Delta M_n(12)}{d - d'} = 119.2$ Kips $A_s' = \frac{(f_y - .85f'_c)}{C_s} = .5\,in^2$

$T = C_c + C_s = 674.96$ kips $A_s = T/f_y = 11.33\,in^2$

Girder Design | LRFD | Long Span

Bay 40' x 33' D = 335.78 plf L = 660 plf W_u = 1.2D + 1.6L = 1455.93 plf

M_u = 291.79 ft-kip f_y = 60 ksi f'_c = 4 ksi E_s = 29000 ksi ρ = .01 ϕ = .9 d' = 3 in

Determine R_n

Same as previous R_n = 596 psi

$M_n = M_u/\phi$ = 324.21 ft-kip $bd^2 = M_n/R_n = \frac{324.21(12000)}{596}$ = 6527.74 in³

Choose Beam Size   b d

10 25.55
12 23.32 ← Use
14 21.59

h = d + 2.5 h = 25.82 → 26 in   Size 12 in x 26 in

Steel Area same as before $x@c_{max}$ = .4286(d) = 10 in a = .8(10) = 8 in

C_c = .85(4)(8)(12) = 326.4 kips ∴ A_s = 5.44 in² M_n = 525.5 ft-kip

ϕ_r = .82 req $M_n = M_u/\phi_r$ = 640.86 ft-kip ΔM_n = 115.36 ft-kip

$C_s = \frac{\Delta M_n(12)}{d-d'}$ = 68.13 kip $A'_s = \frac{(F_y - .85f'_c)}{C_s}$ = .83 in²

$T = C_c + C_s$ = 394.53 kip $A_s = T/F_y$ = 6.58 in²

Concrete Design | LRFD | Long Span

Girder Design B_4 40' x 33'

$$D_w = \frac{150\,pcf(2.17)(40)(4)}{6.6} = 7890.91\ plf$$

$D = 4425.91$ plf $L = 4000$ plf $W_u = 1.2D + 1.6L = 14311.1$ plf

$V_u = 2442.6$ ftkips $M_u = wl^2/8 = 2769.55$ ftkips

$$bd^2 = \frac{M_u}{R_n} = \frac{2769.55(1000)}{546} = 55762.8\ in^3$$

b	d
25	47.23 ← use
27	45.45
29	43.85

$h = d + 2.5$ $h = 49.73 \rightarrow 50$ Size 25×50 in $d = 47$ in

Steel Calc Assume Single Reinforced

#9 @ 4 in = .4286(d) = 20.27 in $a = A_s(+f_y) \ldots = 16.14$ in

$C_c = .85(4)(16.14)(25) = 1376.51$ kips $A_s = C/f_y = 22.94\ in^2$

$$M_n = \frac{C(d - a/2)}{12} = 4030.3\ \text{ftkips}$$

Req $M_n = M_u/\phi = 4915$ ftkips $\Delta M = 884.7$ ftkips

$$C_s = \frac{\Delta M_n(12)}{d - 3'} = 240.01\ \text{kips} \quad A_s' = \frac{(f_s - .85 f_c)}{C_s} = .24\ in^2$$

$T = C_s + C_c = 1616.52$ kips $A_s = T/f_y = 26.97\ in^2$

Girder Des | LRFD | Short Span

70'x22' W_D = 331.39 plf L = 730 plf W_u = 1.2D + 1.6L = 1612.67 plf

M_u = 322.73 ft kips

R_n = 596 (previous)

M_n = M_u/ϕ = 358.59 ft kips bd^2 = M_n/R_n = $\frac{358.59(12000)}{596}$ = 7219.96

b	d
10	26.87
12	24.53
14	22.71 ≤ use

h = d+3.5 h = 25.21 → 26 in   Size 14 in x 26 in

Steel Calc Assume Sec Tension

Max c = .42(d) = 9.73 in   a = .85(9.73) = 7.79 in A_s = 6.18 in^2

C_c = .85(4)(7.79)(14) = 370.65 kips ; M_n = 591.15 ft kips

req M_n = $M_u/.72$ = 708.72 ft kips ΔM_n = 127.57 ft kips

C_s = $\frac{\Delta M_n(12)}{d - d'}$ = 77.67 kips A_s' = .73 in^2

T = $C_c + C_s$ = 444.72 kips A_s = 7.47 in^2

Concrete Design | LRFD | Short Span

Girder 40'x22' $W_{wall} = \frac{150(3.53)(40)(2)}{7.3} = 4157.9$ plf

$D = 6193.9$ plf $L = 4000$ plf $W_u = 1.2D + 1.6L = 13832.65$ plf

$R_n = 596$ psi $M_u = 536.88$ ft-kips $M_n = wl^2/24 = 924.98$ ft-k

$bd^2 = M_u/\phi R_n = \frac{424.86(12000)}{596} = 18722.1$ in³

b	d
16	34.21
18	32.25 ← Use
20	30.6

$h = d + 2.5 = 34.75 \rightarrow 35$ in   Size = 18x35 in

Steel Calcs   from seismic factors

$X\bar{C}_{max} = .4286(32) = 13.82$ in $a = .5(13.82) = 11.46$ in

$C_c = .85(4)(11.46)(18) = 676.82$ kips $A_s = 11.28$ in²

$M_n = 1507.17$ ft-kips

req $M_n = M_u/.82 = 1838.01$ $\Delta M_n = 330.84$ ft-kips

$C_s = \frac{\Delta M_n(12)}{d - d'} = 135.73$ kips $A_s' = .42$ in²

$T = 812.6$ kips $A_s = 13.54$ in²

Appendix E: Concrete Calculations: One-Way Slab System

	Beam Design							
	Bay Size 35' x 22'							
	3 Filler Beams Spanning 35'							
	Beam Length	22	ft	fy	60	ksi		
	Tributary width	8.75	ft	f'c	4	ksi		
	ACI-Table 9.5a		min h	T/24	4.38	in		
			min h	T/28	3.75	in		
	Slab thickness (t)	4.5	in					
	b	12	in					
	Dead Loads	PSF		**Live Loads**	PSF			
	Concrete Slab (4.5", 150pcf)	56.25		Occupancy	100			
	MEP and Ceiling (8 psf)	8.00						
	Total	64.25		***Total***	100			
	Loading Combinations			**Clear Span**				
	Factored	KSF		Span: T-1ft	7.75	ft		
	Wu=1.4D	0.090						
	Wu=1.2D+1.6L	0.237	Governs					
	Bending Moment Check							
	Mu max = ((Wu)(Span)^2)/10	1.42	ft-kips/ft					
	Use p = .010 and Rn = 530 psi							
	req d = sqrt(Mu*12000/(.9*Rn*b))	1.73	in					
	Assume .75 in cover and db = .625							
	req h =	2.79	in					
	Use original t							
	d = t -.75-.31	3.44	in					
	Shear w/o stirrups Vc=.75*(2*sqrt(f'c))*b*d	3.92	kip/ft					
	Max Vu = 1.15*Wu(Span)/2	1.06	kip/ft					
	Stirrups Needed?	NO						
	Reinforcement of One-Way Slab							
	Line Number		S1			S2/S3		
		Support	Middle	Support	Support	Middle	Support	Unit
1	ACI moment coeff.	- 1/24	1/14	- 1/10	- 1/11	1/16	- 1/11	
2	Mu = **1***Wu*(Span)^2	-0.59	1.02	-1.42	-1.29	0.89	-1.29	ft-kips/ft
3	req Rn = (**2***12000)/(.9*b*d^2)	56	96	134	122	84	122	psi
4	req p = **3**/51456	0.0011	0.0019	0.0026	0.0024	0.0016	0.0024	
5	req As = **4***b*d (min req As = 0.12)	0.12	0.12	0.12	0.12	0.12	0.12	sq in/ft
6	Provided As	#4@16st	#4@16st	#4@16st	#4@16st	#4@16st	#4@16st	

1

	T Beam (Exterior Design)								
1	be = b + L/12	34	Use						
2	be = b + 6t	39							
3	be = b + Span/2	105							
	Determine h from a = t								
	C = .85*f'c*be*a	520.20	kips						
	As = C/fy	8.67	sq in						
	Because a is within the flange, beam operates like a rectangular beam								
	Use p = .011 and Rn = 596 psi								
	Mu =	14.34	ft-kips						
	Mn = Mu/.9	15.94	ft-kips						
	bd^2 = Mn/Rn	320.91	in^3						
	req d =	5.17	sq in						
	For As use 7 #10	8.89	sq in						
	Ad =	1.27	in						
	h min =	7.94	in						
	use h =	8.00	in						

2

Girder Design					
Bay Size 35' x 22'					
3 Filler Beams Spanning 35'					
Beam Length	22	ft	fy	60	ksi
Tributary width	8.75	ft	f'c	4	ksi
Slab thickness (t)	4.5	in			
b	12	in			
Dead Loads	PSF	PLF	**Live Loads**	PSF	PLF
Concrete Slab (t, 150pcf)	56.25	1968.75	Occupancy	100	3500
MEP and Ceiling (8 psf)	8.00	280.00			
T Beams (12in*8in, 150pcf)		400.00			
Total	64.25	2648.75	***Total***	100	3500
Loading Combinations					
Factored	KLF				
Wu=1.4D	3.708				
Wu=1.2D+1.6L	8.779	Governs			
Interior Girder Design					
Mu=	531	ft-kips			
Mn=Mu/.9	590	ft-kips			
Use p = .011 and Rn = 596 psi					
bd^2 = Mn/Rn	11,881.41	in^3			
d= about 2b	b	d			
	11.00	32.87			
	13.00	30.23			
	15.00	28.14	Use		
h=d+2.5	31.00	in			
Use 15in x 31in					
d'=3in					
Steel Calcs					
x@etmin= .4286(d)	12.06	in			
a= .8*(x@etmin)	9.65	in			
Cc=(.85)(f'c)(a)(b)	492.15	kips			
req Mn= Mn/.82	719.65	ft-kips			
Mnn=(Cc(d-a/2))/12	956.38	ft-kips			
ΔMn=	236.74	ft-kips			
Cs=(ΔMn)(12)/(d-d')	112.98	kips			
As'=(fy-.85f'c)/Cs	0.50	in^2			
T=Cc+Cs	605.14	Kips			
As=T/Fy	10.09	in^2			

3

	Short Beam Design							
	Bay Size 40' x 22'							
	4 Filler Beams Spanning 22'							
	Beam Length	22	ft	fy	60	ksi		
	Tributary width	8	ft	f'c	4	ksi		
	ACI-Table 9.5a		min h	T/24	4.00	in		
			min h	T/28	3.43	in		
	Slab thickness (t)	4	in					
	b	12	in					
	Dead Loads	PSF		**Live Loads**	PSF			
	Concrete Slab (t, 150pcf)	50.00		Occupancy	100			
	MEP and Ceiling (8 psf)	8.00						
	Total	58.00		***Total***	100			
	Loading Combinations			**Clear Span**				
	Factored	KSF		Span: T-1ft	7.00	ft		
	Wu=1.4D	0.081						
	Wu=1.2D+1.6L	0.230	Governs					
	Bending Moment Check							
	Mu max = ((Wu)(Span)^2)/10	1.13	ft-kips/ft					
	Use p = .010 and Rn = 530 psi							
	req d = sqrt(Mu*12000/(.9*Rn*b))	1.54	in					
	Assume .75 in cover and db = .625							
	req h =	2.60	in					
	Use original t							
	d = t -.75-.31	2.94	in					
	Shear w/o stirrups Vc=.75*(2*sqrt(f'c))*b*d	3.35	kip/ft					
	Max Vu = 1.15*Wu(Span)/2	0.92	kip/ft					
	Stirrups Needed?	NO						
	Reinforcment of One-Way Slab							
	Line Number	S1			S2/S3			
		Support	Middle	Support	Support	Middle	Support	Unit
1	ACI moment coeff.	- 1/24	1/14	- 1/10	- 1/11	1/16	- 1/11	
2	Mu = 1*Wu*(Span)^2	-0.47	0.80	-1.13	-1.02	0.70	-1.02	ft-kips/ft
3	req Rn = (2*12000)/(.9*b*d^2)	60	103	145	131	90	131	psi
4	req p = 3/51456	0.0012	0.0020	0.0028	0.0026	0.0018	0.0026	
5	req As = 4*b*d (min req As = 0.12)	0.12	0.12	0.12	0.12	0.12	0.12	sq in/ft
6	Provided As	#4@16st	#4@16st	#4@16st	#4@16st	#4@16st	#4@16st	

	T Beam (Exterior Design)							
1	be = b + L/12	34						
2	be = b + 6t	36	Use					
3	be = b + Span/2	96						
	Determine h from a = t							
	C = .85*f'c*be*a	489.60	kips					
	As = C/fy	8.16	sq in					
	Because a is within the flange, beam operates like a rectangular beam							
	Use p = .011 and Rn = 596 psi							
	Mu =	13.89	ft-kips					
	Mn = Mu/.9	15.43	ft-kips					
	bd^2 = Mn/Rn	310.76	in^3					
	req d =	5.09	sq in					
	For As use 7 #10	8.89	sq in					
	Ad =	1.27	in					
	h min =	7.86	in					
	use h =	10.50	in					

Short Girder Design					
Bay Size 40' x 22'					
4 Filler Beams Spanning 22'					
Beam Length	22	ft	fy	60	ksi
Tributary width	8	ft	f'c	4	ksi
Slab thickness (t)	4	in			
b	12	in			
Dead Loads	PSF	PLF	**Live Loads**	PSF	PLF
Concrete Slab (t, 150pcf)	50.00	1750.00	Occupancy	100	4000
MEP and Ceiling (8 psf)	8.00	280.00			
T Beams (12in*10.5in, 150pcf)		525.00			
Total	58.00	2555.00	***Total***	100	4000
Loading Combinations					
Factored	KLF				
Wu=1.4D	3.577				
Wu=1.2D+1.6L	9.466	Governs			
Interior Girder Design					
Mu=	573	ft-kips			
Mn=Mu/.9	636	ft-kips			
Use p = .011 and Rn = 596 psi					
bd^2 = Mn/Rn	12,811.92	in^3			
d= about 2b	b	d			
	13.00	31.39			
	15.00	29.23	Use		
	17.00	27.45			
h=d+2.5	32.00	in			
Use 15in x 31in					
d'=3in					
Steel Calcs					
x@etmin= .4286(d)	12.53	in			
a= .8*(x@etmin)	10.02	in			
Cc=(.85)(f'c)(a)(b)	511.06	kips			
req Mn= Mn/.82	776.01	ft-kips			
Mnn=(Cc(d-a/2))/12	1,031.28	ft-kips			
ΔMn=	255.28	ft-kips			
Cs=(ΔMn)(12)/(d-d')	116.81	kips			
As'=(fy-.85f'c)/Cs	0.48	in^2			
T=Cc+Cs	627.87	Kips			
As=T/Fy	10.46	in^2			

6

	Long Beam Design							
	Bay Size 40' x 33'							
	4 Filler Beams Spanning 33'							
	Beam Length	33	ft	fy	60	ksi		
	Tributary width	8	ft	f'c	4	ksi		
	ACI-Table 9.5a		min h	T/24	4.00	in		
			min h	T/28	3.43	in		
	Slab thickness (t)	4	in					
	b	12	in					
	Dead Loads	PSF		**Live Loads**	PSF			
	Concrete Slab (t, 150pcf)	50.00		Occupancy	100			
	MEP and Ceiling (8 psf)	8.00						
	Total	58.00		***Total***	100			
	Loading Combinations			**Clear Span**				
	Factored	KSF		Span: T-1ft	7.00	ft		
	Wu=1.4D	0.081						
	Wu=1.2D+1.6L	0.230	Governs					
	Bending Moment Check							
	Mu max = ((Wu)(Span)^2)/10	1.13	ft-kips/ft					
	Use p = .010 and Rn = 530 psi							
	req d = sqrt(Mu*12000/(.9*Rn*b))	1.54	in					
	Assume .75 in cover and db = .625							
	req h =	2.60	in					
	Use original t							
	d = t -.75-.31	2.94	in					
	Shear w/o stirrups Vc=.75*(2*sqrt(f'c))*b*d	3.35	kip/ft					
	Max Vu = 1.15*Wu(Span)/2	0.92	kip/ft					
	Stirrups Needed?	NO						
	Reinforcment of One-Way Slab							
	Line Number		S1			S2/S3		
		Support	Middle	Support	Support	Middle	Support	Unit
1	ACI moment coeff.	- 1/24	1/14	- 1/10	- 1/11	1/16	- 1/11	
2	Mu = **1***Wu*(Span)^2	-0.47	0.80	-1.13	-1.02	0.70	-1.02	ft-kips/ft
3	req Rn = (**2***12000)/(.9*b*d^2)	60	103	145	131	90	131	psi
4	req p = **3**/51456	0.0012	0.0020	0.0028	0.0026	0.0018	0.0026	
5	req As = **4***b*d (min req As = 0.12)	0.12	0.12	0.12	0.12	0.12	0.12	sq in/ft
6	Provided As	#4@16st	#4@16st	#4@16st	#4@16st	#4@16st	#4@16st	

	T Beam (Exterior Design)							
1	be = b + L/12	45						
2	be = b + 6t	36	Use					
3	be = b + Span/2	96						
	Determine h from a = t							
	C = .85*f'c*be*a	489.60	kips					
	As = C/fy	8.16	sq in					
	Because a is within the flange, beam operates like a rectangular beam							
	Use p = .011 and Rn = 596 psi							
	Mu =	31.25	ft-kips					
	Mn = Mu/.9	34.73	ft-kips					
	bd^2 = Mn/Rn	699.20	in^3					
	req d =	7.63	sq in					
	For As use 7 #10	8.89	sq in					
	Ad =	1.27	in					
	h min =	10.40	in					
	use h =	10.50	in					

Long Girder Design					
Bay Size 40' x 33'					
4 Filler Beams Spanning 35'					
Beam Length	33	ft	fy	60	ksi
Tributary width	8	ft	f'c	4	ksi
Slab thickness (t)	4	in			
b	12	in			
Dead Loads	PSF	PLF	**Live Loads**	PSF	PLF
Concrete Slab (t, 150pcf)	50.00	1750.00	Occupancy	100	4000
MEP and Ceiling (8 psf)	8.00	280.00			
T Beams (12in*10.5in, 150pcf)		525.00			
Total	58.00	2555.00	***Total***	100	4000
Loading Combinations					
Factored	KLF				
Wu=1.4D	3.577				
Wu=1.2D+1.6L	9.466	Governs			
Interior Girder Design					
Mu=	1289	ft-kips			
Mn=Mu/.9	1432	ft-kips			
Use p = .011 and Rn = 596 psi					
bd^2 = Mn/Rn	28,826.83	in^3			
d= about 2b	b	d			
	17.00	41.18			
	19.00	38.95	Use		
	21.00	37.05			
h=d+2.5	42.00	in			
Use 15in x 31in					
d'=3in					
Steel Calcs					
x@etmin= .4286(d)	16.69	in			
a= .8*(x@etmin)	13.36	in			
Cc=(.85)(f'c)(a)(b)	862.77	kips			
req Mn= Mn/.82	1,746.02	ft-kips			
Mnn=(Cc(d-a/2))/12	2,320.39	ft-kips			
ΔMn=	574.37	ft-kips			
Cs=(ΔMn)(12)/(d-d')	191.72	kips			
As'=(fy-.85f'c)/Cs	0.30	in^2			
T=Cc+Cs	1,054.49	Kips			
As=T/Fy	17.57	in^2			

Appendix F: Foundation Design

F.1 Small Bay Spread Footing Design

Footing Design Small Bay			
f'c	3000	psi	
Column	27 X 102		
Column Area	1.88	ft^2	
Net Soil Pressure	5.2	ksf	
Pu	382	kips	
Req A	73.46	ft^2	
sqr(A)	8.57		
One side	8.75	ft	
8.75ft x 8.75ft	76.5625	ft^2	
Pnet	4.99	ksf	
Two-way Action			
Avg d	20	in	
Four sided critical section			
Vu	372.62	kips	
Bo	188		
Bo/d	9.4		< 20 ok
Vc	823.77	kips	
ϕVc	617.831	kips	>Vu ok
One-way action			
Vu	68.98	kips	
Vc	230.04	kips	
ϕVc	172.53	kips	>Vu ok
Bending moment strength			
Mu	230.56	ft-kips	
d	25.50		
Req Rn	45.03	psi	
Req p	0.000909		
Req As	2.43	in^2	
pg	0.002		
min As	5.25	in^2	
provided As	6.32	in^2	
Use 8 - #8 bars			
Ld	36.5	in	
Actual embedment	37		>Ld ok

Pn	690.34	kips		
Pu	382	kips		
ϕPn	448.7184	kips	>Pu ok	
Req As	1.3536	in^2		
Req As per bar	0.3384	in^2		
Ldc	18.25742	in		
Ldc	15	in	< slab thick ok	

F.2 Large Bay Spread Footing Design

Footing Design Large Bay			
f'c	3000	psi	
Column	30 X 108		
Column Area	2.17	ft^2	
Net Soil Pressure	5.2	ksf	
Pu	484	kips	
Req A	93.08	ft^2	
sqr(A)	9.65		
One side	9.75	ft	
9.75ft x 9.75ft	95.0625	ft^2	
Pnet	5.09	ksf	
Two-way Action			
Avg d	20	in	
Four sided critical section			
Vu	472.95	kips	
Bo	200		
Bo/d	10		< 20 ok
Vc	876.36	kips	
ϕVc	657.2671	kips	>Vu ok
One-way action			
Vu	97.30	kips	
Vc	256.33	kips	
ϕVc	192.25	kips	>Vu ok
Bending moment strength			
Mu	327.06	ft-kips	
d	31.50		
Req Rn	37.56	psi	
Req p	0.000757		
Req As	2.79	in^2	
pg	0.002		
min As	5.85	in^2	
provided As	6.32	in^2	
Use 8 - #8 bars			
Ld	36.5	in	
Actual embedment	37		>Ld ok

Pn	796.82	kips		
Pu	484	kips		
ϕPn	517.9356	kips	>Pu ok	
Req As	1.5624	in^2		
Req As per bar	0.3906	in^2		
Ldc	18.25742	in		
Ldc	15	in	< slab thick ok	

Appendix G: Square Foot Estimate

Square Foot Cost Estimate Report

Estimate Name: **MQP Square Foot**

Building Type:	**Office, 5-10 Story with Face Brick with Concrete Block Back-up / Steel Frame**
Location:	WORCESTER, MA
Stories Count (L.F.):	**5.00**
Stories Height	**13.00**
Floor Area (S.F.):	**24,276.00**
LaborType	**Union**
Basement Included:	No
Data Release:	**Year 2011**
Cost Per Square Foot	**$264.04**
Total Building Cost	**$6,410,000**

Costs are derived from a building model with basic components. Scope differences and market conditions can cause costs to vary significantly.

		% of Total	Cost Per SF	Cost
A Substructure		**3.5%**	**7.00**	**$170,000**
A1010	**Standard Foundations**		**2.76**	**$67,000**
	Strip footing, concrete, reinforced, load 11.1 KLF, soil bearing capacity 6 KSF, 12" deep x 24" wide			
	Spread footings, 3000 PSI concrete, load 600K, soil bearing capacity 6 KSF, 10' - 6" square x 33" deep			
A1030	**Slab on Grade**		**1.13**	**$27,500**
	Slab on grade, 4" thick, non industrial, reinforced			
A2010	**Basement Excavation**		**0.06**	**$1,500**
	Excavate and fill, 10,000 SF, 4' deep, sand gravel, or common earth, on site storage			
A2020	**Basement Walls**		**3.05**	**$74,000**
	Foundation wall, CIP, 4' wall height, direct chute, .148 CY/LF, 7.2 PLF, 12" thick			
B Shell		**46.8%**	**93.18**	**$2,262,000**
B1010	**Floor Construction**		**18.76**	**$455,500**
	Steel column, W5, 25 K, 16' unsupported length, 16 PLF			
	Steel column, W8, 125 KIPS, 16' unsupported height, 40 PLF			
	Steel column, W10, 150 KIPS, 16' unsupported height, 45 PLF			
	Steel column, W12, 300 KIPS, 16' unsupported height, 72 PLF			
	Steel column, W12, 400 KIPS, 16' unsupported height, 87 PLF			
	Steel column, TS14, 500 KIPS, 16' unsupported height, 109 PLF			
	Floor, composite metal deck, shear connectors, 5.5" slab, 20'x25' bay, 21.5" total depth, 75 PSF superimposed load,			
	Fireproofing, sprayed fiber, 1.5" thick, 8" steel column, 2 hour rating, 6.3 PLF			
	Fireproofing, sprayed fiber, 1.5" thick, 10" steel column, 2 hour rating, 7.9 PLF			
	Fireproofing, sprayed fiber, 1.5" thick, 14" steel column, 2 hour rating,10.8 PLF			
B1020	**Roof Construction**		**1.26**	**$30,500**
	Floor, steel joists, beams, 1.5" 22 ga metal deck, on columns, 20'x25' bay, 20" deep, 40 PSF superimposed load, 60			
B2010	**Exterior Walls**		**55.96**	**$1,358,500**
	Brick wall, composite double wythe, standard face/CMU back-up, 8" thick, perlite core fill			
B2020	**Exterior Windows**		**15.01**	**$364,500**
	Windows, aluminum, sliding, insulated glass, 5' x 3'			

1

		% of Total	Cost Per SF	Cost
B2030	**Exterior Doors**		0.29	$7,000
	Door, aluminum & glass, with transom, narrow stile, double door, hardware, 6'-0" x 10'-0" opening			
	Door, steel 18 gauge, hollow metal, 1 door with frame, no label, 3'-0" x 7'-0" opening			
B3010	**Roof Coverings**		1.89	$46,000
	Roofing, asphalt flood coat, gravel, base sheet, 3 plies 15# asphalt felt, mopped			
	Insulation, rigid, roof deck, composite with 2" EPS, 1" perlite			
	Roof edges, aluminum, duranodic, .050" thick, 6" face			
	Flashing, aluminum, no backing sides, .019"			
C Interiors		16.7%	33.30	$808,500
C1010	**Partitions**		9.04	$219,500
	Metal partition, 5/8" water resistant gypsum board face, no base layer, 3-5/8" @ 24" OC framing ,same opposite face			
	1/2" fire ratedgypsum board, taped & finished, painted on metal furring			
C1020	**Interior Doors**		2.86	$69,500
	Door, single leaf, kd steel frame, hollow metal, commercial quality, flush, 3'-0" x 7'-0" x 1-3/8"			
C1030	**Fittings**		0.80	$19,500
	Toilet partitions, cubicles, ceiling hung, plastic laminate			
C2010	**Stair Construction**		2.86	$69,500
	Stairs, steel, cement filled metal pan & picket rail, 16 risers, with landing			
C3010	**Wall Finishes**		1.13	$27,500
	Painting, interior on plaster and drywall, walls & ceilings, roller work, primer & 2 coats			
	Vinyl wall covering, fabric back, medium weight			
C3020	**Floor Finishes**		8.63	$209,500
	Carpet, tufted, nylon, roll goods, 12' wide, 36 oz			
	Carpet, padding, add to above, minimum			
	Vinyl, composition tile, maximum			
	Tile, ceramic natural clay			
C3030	**Ceiling Finishes**		7.97	$193,500
	Acoustic ceilings, 3/4"mineral fiber, 12" x 12" tile, concealed 2" bar & channel grid, suspended support			
D Services		33.0%	65.79	$1,597,000
D1010	**Elevators and Lifts**		14.93	$362,500
	Traction, geared passenger, 3500 lb, 8 floors, 12' story height, 2 car group, 200 FPM			
D2010	**Plumbing Fixtures**		2.51	$61,000
	Water closet, vitreous china, bowl only with flush valve, wall hung			
	Urinal, vitreous china, wall hung			
	Lavatory w/trim, vanity top, PE on CI, 20" x 18"			
	Service sink w/trim, PE on CI,wall hung w/rim guard, 24" x 20"			
	Water cooler, electric, wall hung, 8.2 GPH			
	Water cooler, electric, wall hung, wheelchair type, 7.5 GPH			
D2020	**Domestic Water Distribution**		1.71	$41,500
	Gas fired water heater, commercial, 100< F rise, 200 MBH input, 192 GPH			
D2040	**Rain Water Drainage**		0.29	$7,000
	Roof drain, CI, soil,single hub, 5" diam, 10' high			
	Roof drain, CI, soil,single hub, 5" diam, for each additional foot add			
D3050	**Terminal & Package Units**		17.16	$416,500
	Rooftop, multizone, air conditioner, offices, 25,000 SF, 79.16 ton			
D4010	**Sprinklers**		3.01	$73,000
	Wet pipe sprinkler systems, steel, light hazard, 1 floor, 10,000 SF			
	Wet pipe sprinkler systems, steel, light hazard, each additional floor, 10,000 SF			
	Standard High Rise Accessory Package 8 story			
D4020	**Standpipes**		1.92	$46,500

		% of Total	Cost Per SF	Cost
	Wet standpipe risers, class III, steel, black, sch 40, 4" diam pipe, 1 floor			
	Wet standpipe risers, class III, steel, black, sch 40, 4" diam pipe, additional floors			
	Fire pump, electric, with controller, 5" pump, 100 HP, 1000 GPM			
	Fire pump, electric, for jockey pump system, add			
D5010	**Electrical Service/Distribution**		**6.41**	**$155,500**
	Service installation, includes breakers, metering, 20' conduit & wire, 3 phase, 4 wire, 120/208 V, 1600 A			
	Feeder installation 600 V, including RGS conduit and XHHW wire, 60 A			
	Feeder installation 600 V, including RGS conduit and XHHW wire, 200 A			
	Feeder installation 600 V, including RGS conduit and XHHW wire, 1600 A			
	Switchgear installation, incl switchboard, panels & circuit breaker, 1600 A			
D5020	**Lighting and Branch Wiring**		**12.25**	**$297,500**
	Receptacles incl plate, box, conduit, wire, 16.5 per 1000 SF, 2.0 W per SF, with transformer			
	Miscellaneous power, 1.2 watts			
	Central air conditioning power, 4 watts			
	Motor installation, three phase, 460 V, 15 HP motor size			
	Motor feeder systems, three phase, feed to 200 V 5 HP, 230 V 7.5 HP, 460 V 15 HP, 575 V 20 HP			
	Motor connections, three phase, 200/230/460/575 V, up to 5 HP			
	Motor connections, three phase, 200/230/460/575 V, up to 100 HP			
	Fluorescent fixtures recess mounted in ceiling, 1.6 watt per SF, 40 FC, 10 fixtures @32watt per 1000 SF			
D5030	**Communications and Security**		**4.49**	**$109,000**
	Telephone wiring for offices & laboratories, 8 jacks/MSF			
	Communication and alarm systems, fire detection, addressable, 100 detectors, includes outlets, boxes, conduit and \			
	Fire alarm command center, addressable with voice, excl. wire & conduit			
	Internet wiring, 8 data/voice outlets per 1000 S.F.			
D5090	**Other Electrical Systems**		**1.11**	**$27,000**
	Generator sets, w/battery, charger, muffler and transfer switch, diesel engine with fuel tank, 100 kW			
	Uninterruptible power supply with standard battery pack, 15 kVA/12.75 kW			
E Equipment & Furnishings		**0.0%**	**0.00**	**$0**
E1090	**Other Equipment**		**0.00**	**$0**
F Special Construction		**0.0%**	**0.00**	**$0**
G Building Sitework		**0.0%**	**0.00**	**$0**
Sub Total		**100%**	**$199.27**	**$4,837,500**
Contractor's Overhead & Profit		**25.0%**	**$49.82**	**$1,209,500**
Architectural Fees		**6.0%**	**$14.95**	**$363,000**
User Fees		**0.0%**	**$0.00**	**$0**
Total Building Cost			**$264.04**	**$6,410,000**