GATEWAY BUILDING 2012: ALTERNATIVE DESIGNS & USE
OF BUILDING INFORMATION MODELING TOOLS
A Major Qualifying Project Proposal
Submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
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Degree of Bachelor of Science
In Civil Engineering
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Abstract

This project proposes two alternative designs of the structural frame of the Gateway Park Phase II using a cast-in-place concrete sway frame and a redesign of the existing steel building to incorporate lateral bracing. The work flow and design process incorporated modern Building Information Modeling (BIM) tools, for which the logistics of interoperability were explored and documented. The programs utilized were Scia Engineer, Revit Structures, Revit Architecture, and Robot.

Acknowledgements

Capstone Design Statement

To assess the actual capabilities of the various programs two alternate structural designs were compared to the original designed building. The buildings were initially proportioned through hand calculations and further analyzed with computer software to ensure adequate strength. The software packages used were Revit Architecture, Revit Structures, Robot Structural Analysis and Scia Engineer. In order to find the most economically competitive structure a cost estimate was created for each structure using RS Means. Additionally preliminary schedules were created to determine any possible savings which may become available due to simplified construction. A set of guidelines for the design and analysis process were created to aid in the use of the analysis programs and to serve as a starting point for any future projects. The entire process culminated in the creation of a full set of structural drawings for the newly designed building layout to demonstrate the coordination available within the programs as well as represent the end of the design stage.

Economics

Costs have a great impact on the selection of a building type. By studying the differences in labor, material, and construction costs between steel frames and cast-in-place concrete buildings we were able to design a more economical building. Building Information Modeling software was the primary tool used to perform quantity take-offs to determine material quantities and the amount of labor that was required to construct different structural systems.

Environmental and Sustainability

Environmental and sustainability constrains were also addressed in this project. By redesigning the existing building we were able to decrease the amount of material needed for the construction of the steel frame, the height of the building and in turn decreased the volume needing to be heated or cooled.

Constructability

One of the primary considerations for the structural designs was constructability. For the concrete design a major focus was uniform, square member sizes. This allowed for faster construction speeds and reuse of formwork. For the laterally braced steel design special
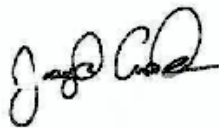
consideration was given in to the reduction of field welds as well as smaller member sizes resulting from the removal of the moment frames.

Social and Political

This project is directly involved with Gateway Park Phase II, which will house WPI's Fire Protection Engineering Department, Graduate Business Program, a new Biomanufacturing Education and Training Center, along with two companies: Blue Sky Biotech and the Massachusetts Biomedical Initiative. When completed, this building will provide valuable research and office space and will also provide positive social and political impacts by generating jobs for people in surrounding areas

Authorship Page

The division of labor for this project was broken down into three main components which each person completed and documented in the paper. The structural designs and analyses were completed by Aaron Na, the cost estimates were prepared by Artur Lebedev, and the Scheduling was prepared by Joseph Angulo. The exploration of interoperability was completed in equal parts by Artur Lebedev and Aaron Na. The Revit Structures model was completed by Artur Lebedev and the Revit Architecture Model was completed by Joseph Angulo and Aaron Na.

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1.0 Introduction

Structural engineering "is a systemic and iterative process" in which the engineer must explore various choices in materials of construction and the structural framing plan to determine the most economical and safe solution (Varma 2011). For example the materials of construction could be steel or concrete whereas the structural framing plan could consist of a moment frame, laterally braced frame, or a great deal more. To accomplish their work structural engineers have many formulas, guides, established procedures, and innovative tools at their disposal. Building Information Modeling (BIM) software programs are powerful emerging tools in the AEC industry which could drastically change the manner in which analysis, modeling, and documentation is completed in construction projects.

Despite having the potential for such a powerful impact on the industry issues such as interoperability have led to only half of the industry in North America incorporating BIM or BIM related tools (Mc-Graw Hill Construction, 2010). Interoperability is the "ability to manage and communicate electronic product and project data between collaborating firms and within individual companies, design, construction, maintenance, and business process systems" (Pniewski 2011). It is currently estimated that $15.8 billion are lost annually due to a lack of interoperability and data management in AEC industry. The AEC industry's highly fragmented characteristics in combination with a growing number of BIM programs being developed and available make interoperability a huge hurdle.

The main goal of our project is to learn and experience the systematic and iterative process a structural engineer experiences while implementing BIM tools and to explore and understand the issues of interoperability. The Gateway Park Phase II building reaching 4 stories, occupying 92,000 square feet, and designed with steel moment frames was chosen as the facility which would provide the opportunity to explore these topics. In order to accomplish our goal our project objectives were determined as the following:

1. Design two economically competitive alternate structural systems with minimal architectural impacts to the original design.

2. Accurately evaluate each structural system in terms of cost and scheduling.

3. Incorporate several BIM software packages for modeling, analysis, and documentation in the project workflow.

To achieve these objectives the building was redesigned with a cast-in-place structural frame and a laterally braced steel frame. Each redesign was initially proportioned through hand calculations and further analyzed with computer software to ensure it is compliant with design codes. The software packages that were implemented in the project work flow were Revit Architecture, Revit Structures, Robot Structural Analysis and Scia Engineer. In order to find the most economically competitive structure cost estimates were created for each structure using RS Means. Additionally preliminary schedules were created to determine if any possible savings may be available due to simplified construction and reduced quantity of materials. A set of guidelines for the design and analysis process were created to aid in the use of the analysis programs and to serve as a reference for future projects. Then to demonstrate the coordination available within the programs as well as represent the end of the design portion a full set of structural drawings were created for each alternative designs. The structural concrete redesign resulted in a 6% saving in costs and an early construction finish 23 days ahead of the original steel building. The lateral braced frame resulted in a 7% saving in costs and an early construction finish 6 days ahead of the original steel moment frame building.

Our study of interoperability provided valuable insights into the realities of implementing various BIM packages. While it has been acknowledged as an invaluable aspect of any project, there are certain realities that must be associated with BIM. Without a working understanding of the intricacies of BIM, development of an exportable structural model will be a process filled with many challenges. While there is an undeniable learning curve, much of the

learning process is mitigated by frequent export checks. These consistent checks provide an overall time savings and will develop good modeling habits.

Overall our project provided insight into the duties associated with an architect, structural engineer, and project manager while the implementation of BIM tools allowed us to create building designs with greater efficiency once proper guidelines were developed.

2.0 Background

This chapter introduces the historical, technical, and non-technical information needed to establish a foundation of reference and understanding for the findings and procedures of this project. The history of Gateway Park and its Phase II building is introduced; as well as an overview concerning the software and technical components applied and used in this project

2.1 Growth District Initiative: Gateway Park

In an effort to stimulate economic growth the Commonwealth of Massachusetts has established a Growth District Initiative involving 16 areas around the state. The Executive Office of Housing and Economic Development will work within each district to facilitate the permitting process, site preparation, infrastructure improvements, and marketing (Commonwealth of Massachusetts 2011). Designated for life sciences and related economic development, Gateway Park (see Figure 1) is the anchor of what is designated the first Growth District, "Innovation Square" (WPI 2010). The Gateway Park Phase II building occupies the area labeled 2 in Figure 1. The other labeled areas refer to potential projects that could be developed throughout the next five to twenty years.
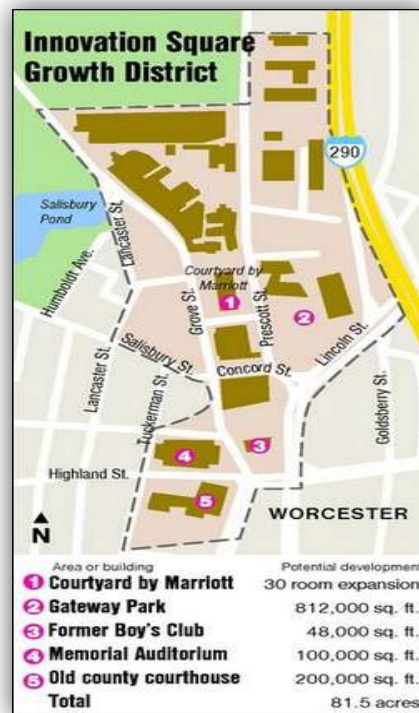
Figure 1 Innovation Square Growth District
(Luttrell 2008)

2.1.1 Gateway Park: Phase II

Gateway Park will include the construction of five buildings to attract and accommodate the development of academic and research programs as well as commercial businesses (WPI 2011b). The park to date has already constructed a 660 space parking garage and erected its first of five building, the Life Sciences and Bioengineering Center (WPI 2011b). The project naming convention "Phase II" was adopted from the DOC construction documents.

Originally, the Worcester Business Development Corporation (WBDC) and Worcester Polytechnic Institute (WPI) formed a joint venture to develop Gateway Park. In 2010, WPI then continued to acquire the WBDC interests to obtain full ownership while maintaining the WBDC as a consultant (WPI 2011a).

Worcester Polytechnic Institute with exclusive property ownership entered in an agreement with the O'Connell Development Group (ODG), based in Holyoke, MA, to finance, develop, and construct the Phase II building (WPI 2011b). Located at 50 Prescott Street in Worcester, MA this building will contain academic and corporate office space, as well as laboratories. Designed by the architectural firm Perkins + Will the building in its entirety will cover 92,000 square feet, reach four stories high, and is expected to achieve LEED certification (WPI 2011b). It is expected it will take 18 months to complete this building, from the start of design of criteria development on February 01, 2011 until beneficial occupancy on August 11, 2012 (Exhibit 'N' from Project Manual Vol. 1). The project will also approximately cost $30 million dollars to construct (WPI 2011a).

WPI will occupy the first floor of the building with an expanded Fire Protection Engineering Department, Graduate Business Program, and on the second floor a new Biomanufacturing Education and Training Center (BETC) (WPI 2011b). Two life science companies will also be moving and occupying the 2nd floor of the building. Blue Sky Biotech will be moving in from WPI's Life Sciences and Bioengineering Center and the Massachusetts Biomedical Initiative (MBI) will lease space to develop an incubator to support future life sciences companies (WPI 2011b). The two life science companies and three WPI programs only occupy half of the building, leaving room for future tenants. It is expected this building will facilitate and hold a 140 permanent jobs and 120 construction jobs (WPI 2011b). Overall, "the Gateway Park project has been recognized as a national model of environmental stewardship

and urban redevelopment," earning numerous awards, recognition, and attracting great attention (WPI 2011b).

2.1.2 Developer and Construction Manager

The development of Gateway Park Phase II has been awarded to the O'Connell Development Group (ODG) from Holyoke, Massachusetts. Their subsidiary company Daniel O'Connell Sons, Inc. (DOC) is the Construction Manager for the project. This organization has been in business since 1879 and their expertise lie in budgeting, design, and project planning (The O'Connell Companies 2011a).

With offices in Franklin, MA, New Haven, CT, and Nashua, NH ODG employs 60 salaried professionals and 100 field personnel (The O'Connell Companies 2011a). Over 30 of their employees are trained engineers and among them is a chief engineer introducing and utilizing advance technologies (The O'Connell Companies 2011b). Incorporating BIM in their many projects they have invested in all Revit Products for Structural, MEP, and Architectural applications. Despite this they have not been utilizing BIM on this project.

Throughout New England this company has offered its services in many diverse sectors of construction. The ODG has partaken in the financing, management, and development of projects in sectors such as industrial, retail, office, housing, and infrastructure. They manage and own several hydroelectric plants and are the 2nd largest recyclers of human waste in the U.S. (The O'Connell Companies 2011c). Some of the signature projects the ODG have been involved in are the Memorial Bridge, MIT Simmons Hall, US Federal Courthouse, and the Bard College Center for Science and Computation (The O'Connell Companies 2011d). Being a member of the U.S Green Building Council many of their projects involve LEED certifications and implementation of sustainable design.

2.1.3 Architect

Established in 1935 the architectural firm, Perkins + Will (P+W), based in Chicago, Illinois, is an innovative organization dedicated to sustainability and design with an interdisciplinary approach. Contracted to design Gateway Park Phase II, P+W offers services in the disciplines of "architecture, branded environments, interior design, planning and strategies, preservation and reuse, and urban design" (Perkins + Will 2010a). Their work and experience

encompass projects in a variety of sectors such as corporate, commercial, transit, civic, and healthcare. Highly recognized and merited, they have received numerous awards from such organizations as the National Building Museum, Architect magazine, Building Design + Construction Magazine, and the American Institute of Architects (Bernstein 2011 and Perkins + Will 2010b). Committed to innovation and moving the AEC industry forward P+W conducts research in various AEC industry topics. They have created an Innovation Incubator program that provides their staff members with "micro grants of money and time" (Perkins + Will 2010c) to conduct research. Their novel findings are then highlighted and published in biannual research journals which contain articles such as "Building Commissioning Strategies, Criteria, and Applications" by Ajla Aksamija in Perkins + Will Research Journal (Aksamija and Kuttaiah 2009). By incorporating this research in their designs they further promote sustainability practices and LEED certifications in their client's and own facilities. For example in 2005 Perkins + Will developed a Green Operations Plan providing guidelines and provisions for the firm's facilities to monitor and reduce their energy consumption and emissions (Perkins + Will 2010e). Furthermore, with over 1,000 LEED accredited professional employees (Bernstein 2011) they design and renovate all their offices to LEED Platinum standards. In 2011, the firm celebrated its 100th LEED certified building (Interiors and Sources 2011).

Strongly driven with a holistic approach in their design they envision and incorporate deep social purposes in their work. In 2007 the firm created a continuing comprehensive pro bono program offering 1% of their company time and resources to either communities or organization that would not have access otherwise (Perkins + Will 2010d). 1% of their resources translates to a 15 employee staffed firm working full time on pro bono projects (Perkins + Will 2010d).

P+W implement a multifaceted approach to architectural design in order to service not only their clients' needs but also issues that arise in the architectural world on a larger scale. Their emphasis on social applications as well as research allows them to implement new technologies in both the public and private sectors. P+W has developed and established the Building Technology Laboratory, a continuing research program, dedicated to monitoring, reviewing, analyzing, and circulating emerging technologies in materials, building systems, and

information technologies (Aksamija 2011). Using BIM in many of its project, P+W delivered the Rush University Medical Center, representing the firm's largest health sector project completed with BIM (Espinal 2010). The 14 floor, $575-million, 806,000-square-foot building was designed using Autodesk Revit Architecture as the primary platform for design and production (Espinal 2010). By beginning their search for improvement internally they create an environment which fosters growth for themselves and the AEC industry. BIM models were developed for the Gateway Park Phase II building.

2.2 BIM Interoperability and the AEC Industry

The construction industry, unlike other industries utilizing information technologies has not been able to increase its productivity (see Figure 2). The AEC industries overall slow progress in implementing information technologies has had substantial negative effects (Mitropoulos 1999).
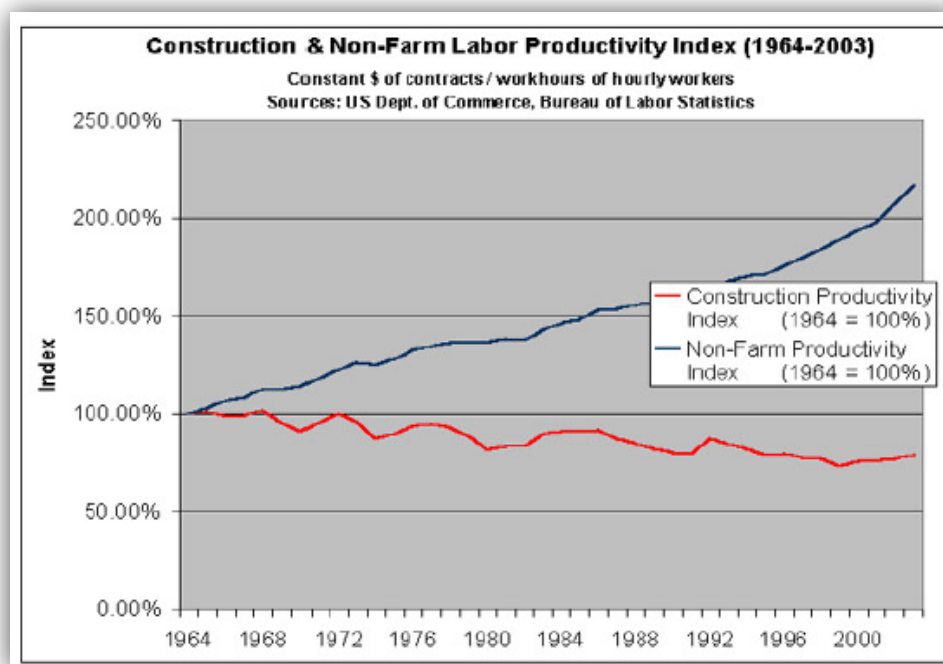
Figure 2 Labor productivity index for the US construction and all non-farm industries (McManus 2011)

The AEC industry has long been fragmented by the number of small firms increasing while their average size decreases (Alashwal et al 2011). Accounting for over 6.44% of the

Gross Domestic Product (1997), 69% of the comprising companies contain less than 100 people (1996) (Case and Griffith 2011). Fragmentation is further increased since in the AEC industry every project undertaken is unique in terms of scope, budget, and schedule. For most projects the companies and teams that interact and work together are never the same. This frequent change in the process of information flow and group dynamics leads to great unfamiliarity among the project teams. As a result "multiple, non-hierarchical teams from different organizations find themselves with little incentive to share knowledge or methodologies" (Sabol 2007). Fragmentation truly impedes the sharing of mutual knowledge in the industry and communication (Alashwal et al 2011). This characteristic is a major obstacle the AEC industry must overcome to improve efficiency.

BIM is defined by the American Institute of Architects as "a model-based technology linked with a database of project information" (Sabol 2007). It involves the creation of a 3d geometric model that can produce and manage building information throughout the life cycle of the project (Eastman 2009). Generating information by delineating the geometry and spatial relationship of its building elements BIM offers a great number of benefits. With BIM it is possible to calculate material take-offs, conduct clash detections, assign a schedule, or analyze the properties of the elements depending on the program. BIM greatest benefits are from the manner it integrates different disciplines and facilitates an integrated design process. Although it provides a wide range of benefits in the AEC industry, its adoption and implementation has been hindered due to the industries' fragmented characteristics and interoperability issues.

Interoperability is defined as the "ability to manage and communicate electronic product and project data between collaborating firms and within individual companies, design, construction, maintenance, and business process systems" (Pniewski 2011). Programs which support and facilitate interoperability in the industry are created with the intent to save time and money. However, in 2004, the National Institute of Standards and Technology conducted a study which estimated that the technical issues of interoperability led to an estimated S15.8 billion annual loss in the industry (Mc-Graw Hill Construction 2010). The interoperability issues stem from multiple software vendors creating BIM programs with their own proprietary file formats. Consequently, issues such as interoperability have led to only half of the industry in

North America incorporating BIM or BIM related tools (Mc-Graw Hill Construction, 2010).BIM has the potential to revolutionize the AEC industry if issues of interoperability are addressed.

2.2.1 Autodesk

Autodesk Inc. is an American corporation based in San Rafael, California that currently develops different software products including AutoCAD (Walker 1994). With over 110 software products available the software ranges in application from BIM platforms that manage 3D building models to digital media creation software packages (Autodesk 2012b). Since its initial launch in 1982, Autodesk's flagship program, AutoCAD, has become the most widely used 2D computer aided design software (Wright 2004). Some of the more specialized design platforms were internally developed, such as Autodesk Inventor, while others such as Revit were acquired from other companies.

2.2.2 Nemetschek

The Nemetschek Group is the leading software vendor in Europe for AEC industry computer programs. Established in 1963 and comprising of the following four business segments Build, Manage, Multimedia, and Design the company employs 1,064 people around the world (Nemetschek 2009a). Nemetschek Aktiengesellschagt (Nemetschek AG) is the parent company of the 10 smaller product based sub companies. The majority of their companies are based in the design business segment where they develop Computer Aided Drafting and Computer Aided Engineering programs focused on 2D or 3D parametric oriented design. The Nemetschek group is comprised of the product based companies Allplan, Graphisoft, Vectorworks, Frillo, Auer, Bausoftware, Crem, Maxon, and Scia (Nemetschek, 2011c).

2.2.3 Revit

Autodesk currently releases three programs under the Revit title: Revit Architecture, Revit Structure, and Revit MEP. Each program focuses on a different subset of design disciplines and construction applications but allows for multiple models to be combined into a single coordinated model. Various Revit models can be linked across programs and viewed throughout the design phase or at its completion.

All three BIM programs use a 3D parametric object-oriented based modeling approach. Parametric components, also known as families, contain physical and analytical properties as

well as graphical representations of objects in a central location. When modeling within a parametric framework, edits are made to an entire model rather than individual views. This means that it is unnecessary to manually update components within views (Autodesk 2010a). Figure 3 shows an example of the properties tab where elements may be given parametric constraints such as lower and upper levels, offsets, basic phasing, and load applications.
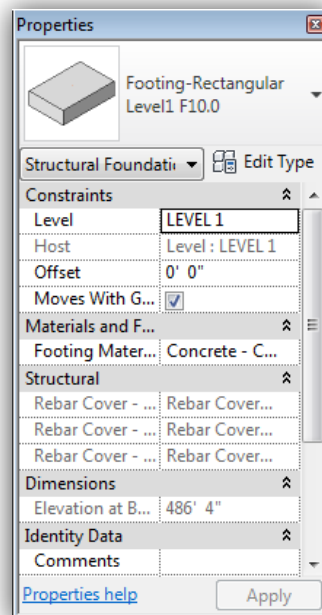
Figure 3 Typical Revit Family

2.2.4 Revit Architecture

Revit Architecture is one of the many BIM tools developed by Autodesk. The primary function of Revit Architecture is to facilitate the development of high quality architectural designs and design documents. Revit Architecture does not create analytical models but instead offers other design tools, such as massing and energy analysis tools. The massing tools allows architects to create conceptual masses such as building shells or sections while the energy analysis tools can provide a detailed analysis into potential energy consumption. These tools grant the architect insight into the building at a level previously unavailable.

Revit Architecture also incorporates basic aspects of other disciplines, the majority being structural tools, to create a more unified building modeling environment. Multiple Revit models, from different Revit packages such as Revit Structures or Revit MEP, can be combined

into a single unified model. Interference checks and material take-offs allow information exchanged between architects, project managers and other design participants to be accurate and up to date. This breakaway from the traditional 2D design flow allows architects to focus on the needs of the client and helps to eliminate miscommunications between involved parties.

2.2.5 Revit Structure

Revit Structure is a software package which can be used to design steel, cast-in-place and precast concrete, masonry, and wooden structures. The main purpose of this software is to provide modeling tools for structural design, analysis, and construction documentation. Autodesk Revit Structures takes advantage of the same parametric framework found in other Revit programs which included wall systems, beam systems, columns, slabs, and foundations to ensure compatibility (Autodesk 2011).

In the traditional method for structural design, the structural engineer must interpret architectural drawings to create a structural design model. Once the design model is completed, a set of analytical models are generated in a number of different software packages to run structural analysis, such as gravity, seismic, and wind. After the analytical model has been finalized, the structural engineer is responsible for generating construction documents. This traditional workflow requires continuous manual updating of all involved models to avoid errors and duplication of work throughout the synchronizing phase Overall, interoperability issues can compromise the integrity and accuracy of analytical models or construction documents (Autodesk 2011).

The major advantage of Autodesk Revit Structure compared to other structural software packages is the integration of the structural and analytical models into one unified system. When a structural engineer creates a building model in Revit Structure, the software then automatically generates a synchronized analytical model to be used for analysis. Loads and material properties, as well as other parameters, can then be added to the integrated model. This analytical model can be exported into third-party software, such as Autodesk Robot or SE, for a more in-depth structural analysis. Changes to the analytical model made in the analysis software can then be imported back into Revit Structure to update the design model. This is extremely important for the creation of consistent construction documents. Information for 2D

drawing sheets, 3D views and schedules are pulled directly from the integrated model and are automatically synchronized within views. With the integrated model approach that Autodesk Revit Structure offers, all drawings, construction documents and models stay "coordinated, consistent, and complete" (Autodesk 2007b).

2.2.6 Robot Structural Analysis

Autodesk ROBOT Structural Analysis is a program that attempts to minimize the errors typically involved in structural analysis associated with manual updating. Unlike most structural analysis software packages, Robot Structural Analysis not only develops typical analytical models but also 3D representations of the design model, much like Revit Structures. Additionally ROBOT Structural Analysis supports multiple materials, including reinforced concrete, steel and timber, in addition to design functionality (Autodesk 2010b).

A typical workflow would begin with the structural engineers interpreting architectural drawings and creating analytical models and design documents. The analytical models must match the architectural layout and need to be updated frequently with corresponding design documents. Once the models are created they are then run through structural analysis software and acceptable member sizes are found. The engineer must then go back to the model and update the documentation to reflect the current design. This must be done for the entire structure, possibly multiple times depending on the type of project. In addition to consuming a great amount of time any errors between analysis and updating documents creates potential liability risks. ROBOT Structural Analysis attempts to streamline the process by performing not only the structural analysis but also updating the Revit Structural model, minimizing the potential for error due to manual updating (Autodesk 2010b).

Furthermore, the coordinated interoperability between Revit Structure and Robot Structural analysis enables a more efficient structural analysis. For instance the engineer can export separate models for the gravity load analysis and the lateral load analysis or even specific elements of interest. Or if the engineer wants to test multiple loadings, ROBOT allows the engineer to create and analyze multiple loading scenarios. Additionally there are ROBOT extensions available should the engineer wish to perform some preliminary analysis directly in Revit Structure (Autodesk 2010b).

2.2.7 Scia Engineer

Managed and developed by the Nemetschek Scia company, the program SE is a BIM program with the capability to model, analyze, and design a variety of structures. This Nemetschek subsidiary with a presence already in Europe, the Middle East, and Brazil took its first steps into the American market with its product in 2009 (Nemetschek 2009b). Despite a strong presence in Europe SE is not well known in the U.S (Khemlani 2010). Its current unfamiliarity in the U.S market is a major factor that has driven the choice to explore its interoperability with other BIM packages.

Developed to provide high end engineering solutions the program has the capacity to create models up to 4D in a wide range of structures in various sectors of construction. SE can model projects like bridges, train stations, high rise buildings, pipelines, containment vessels, and a great deal more. Figure 4 shows a comprehensive list of the many types of projects and sectors of construction in which SE can be used. Figure 5 displays 3D views of design and analytical models of sample building structures developed in SE. The program provides the user the option to create these structures in concrete, aluminum, timber, steel, or composite materials (Nemetschek 2011b).

**Figure 4 Scia Projects
(Nemetschek 2011b)**
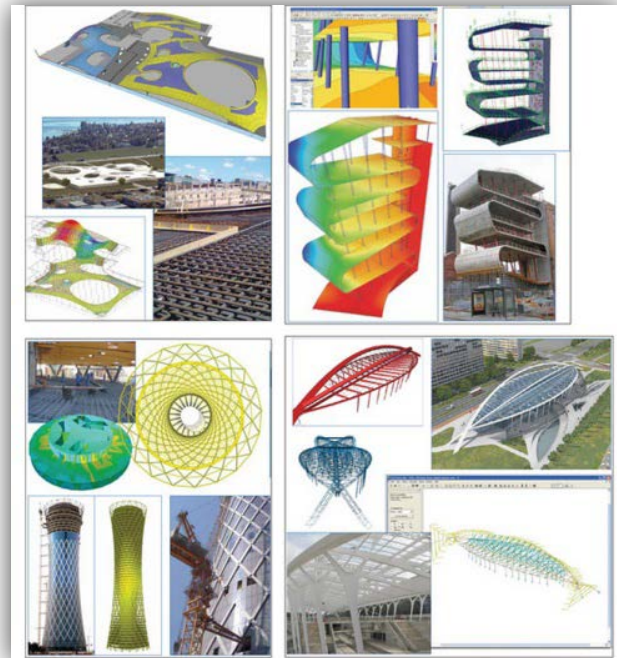
**Figure 5 Structures Developed in Scia Engineer
(Nemetschek 2011b)**

Projects modeled and developed in SE are able to undergo a variety of structural analyses that can be directly checked against building codes and standards. The software has standards and code checks available for the International Building Code, Eurocodes, British Standards, National Annexes, and many more (Nemetschek 2011b). In conjunction with the standards and code checks SE contains optimization tools that will adjust the project elements to meet the necessary requirements.

In SE two basics types of models are created a structural design model and an analysis model. The analysis model is developed first and then the design model is automatically generated by the program. This characteristic separates SE from the Autodesk software programs used in the redesign of the Phase II structure as well as many other currently available BIM packages. Figure 6 shows three types of models of the same structure in which the top image illustrates the analytical model, the middle depicts the cross sectional volume of the building members, and the bottom displays the design model after generation (Khemlani 2010).
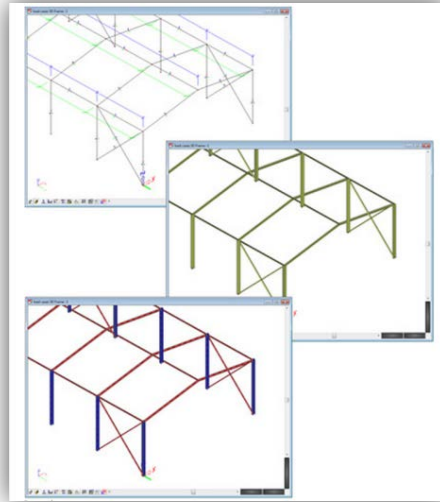
Figure 6 Scia's Modes for Structural Model
(Khemlani 2010)

By creating the analytical model first SE follows a more traditional structural though process. The analysis model can perform stability, nonlinear, static, dynamic, or Finite Element Mesh (FEM) analysis (Nemetschek 2011b).

There are 4 available editions of SE; the Concept edition, Professional Edition, Expert Edition, and the Structural edition (see Table 1) (Nemetschek 2011b). Each edition is tailored to a specific target group of users and the features offered are accordingly constrained. The Concept edition is targeted towards engineers modeling and analyzing conventional structures. The Professional Edition is more suitable for engineers encountering complex designs and analyses. In this edition stability, earthquake, dynamic, and non-linear calculations capabilities are provided. Engineers designing the most challenging and difficult structure would find the Expert edition the most appropriate. It has the capability to perform calculations on soil-structure interaction and analyze building elements such as membranes and cables (Nemetschek 2011a). Lastly, the Structural edition is aimed at users who will not perform any analyses but instead create models for documentation. In the chart below a more detailed list of the differences between the editions is illustrated. For this report the student edition of SE, available off their website, was used since it contains all the analysis and design modules from the latest released program versions (Nemetschek 2011a).

Table 1 SE Edition Comparison Chart
(Nemetschek 2011b)

	Concept	Professional	Expert	Structural
Modeller				
Modeller, Productivity toolbox with active document, IFC, DWG, DXF, VRML	X	X	X	X
BIM engineering toolbox, parametric modelling, general cross-section, Allplan, Tekla, ETABS interface		X	X	X
Clash check detection - collision check			X	X
Link to Revit Structures; Free-form modeller				X
Load generators				
Load generator: wind, snow, plane load generator	X	X	X	
3D wind load generator, Mobile load		X	X	
Advanced mobile loads, Train loads			X	
Analyser				
Linear static analysis	X	X	X	
Non-linear static analysis (tension only members, pressure only supports), Geometrical non-linearity	X	X	X	
Advanced non-linear static analysis (springs and gaps for beams, pressure only slabs), Stability analysis, Dynamic analysis (eigenmodes, harmonic, seismic, general dynamic load)		X	X	
Advanced calculations: Soil interaction, Cables, Non-linear stability, Membranes, Sequential analysis, Friction springs			X	
Linear and non-linear construction stages			X	
Pre-stressed structures, Time Dependent Analysis			X	
Steel designer				
Steel code check - incl. optimisation of cross-sections	X	X	X	
Fire resistance check, Cold-formed sections check, Plastic analysis		X	X	
Steel connections modeller		X	X	X
Steel connections checks		X	X	
Concrete designer				
RC design and check, Punching shear check, Code dependent deformations	X	X	X	
Input of practical reinforcement	X	X	X	X
Fire resistance check for RC beams		X	X	
Pre- and post-tensioned members: design and check; Input of prestressing cables			X	
Detailer				
Automated General Arrangement Drawings		X	X	X
Detailed connections drawings		X	X	X
Foundations				
Pad foundations		X	X	

SE is a versatile program supporting open BIM collaboration which involves "the exchange of data between different applications through a versatile and open data file" (Nametschek 2011b). It is the first Computer Aided Engineering program that has obtained Industry Foundation Class (IFC) 2x3 certification (Nemetschek 2011b). IFC is an open file format, independent of any commercial software vendors, created by the international organization Building SMART. This open file format has been adopted and implemented by many software programs, including Revit, thus expediting and facilitating data collaboration with different programs. There are a total of 133 applications by 92 developers that support IFC files; SE is capable of exchanging data with these programs (Building SMART 2011). In addition to IFC files SE can support other file formats like DWG, DXF, VRML, and SDNF (Nemetschek 2011b). The program also provides direct links to Revit Structures, Tekla Structures, ETabs, and Allplan. SE

IFC capability and bidirectional links to other BIM software programs permits a multi-disciplinary BIM workflow to occur.

To conclude SE's capability to model and analyze structures in the same package, its current unfamiliarity in the U.S, and enabled interoperability with so many BIM packages make it an interesting program to explore its level of interoperability

2.3 Comparison of Steel and Concrete as Structural Building Materials

There are various factors which determine the choice of building material. Numerous studies have been performed all over the world to determine which material is better during particular scenarios. In order to compare the two materials we can look at a number of categories, such as safety, cost, material availability, construction scheduling, environmental impacts, and design possibilities (Madsen 2005).

Safety is an important factor to consider for any structure. In terms of safety, concrete not only offers exceptional fire resistance, but can also endure explosions and impacts. Unlike steel, concrete can withstand much higher temperatures without loss of structural integrity. Although steel alone is not as safe a building material as concrete, with the aid of passive fireproofing systems and effective designs, steel can be used to create structurally sound and safe buildings. According to Larry Williams, president of the Washington, D.C.-based Steel Framing Alliance: "Steel framing does very well under high [wind] loads because it is ductile, which means it has the ability to bend without breaking and absorb that kind of energy" (Madsen 2005). Concrete can also perform well in areas prone to seismic activity because with proper design and construction techniques, even rigid concrete structures can exhibit high ductility.

Cost is one of the main driving forces in the selection of building materials. Reinforced concrete buildings usually have a relatively higher cost early on in the construction process in comparison to steel framed buildings. While steel buildings can be cheaper to build, insurance companies usually recognize benefits of concrete structures because of their increased safety and structural integrity. This can lead to annual savings of up to 25% for property insurance (Madsen 2005).

Some experts say that even though the price of steel framing systems have gone up in recent decades the cost of reinforced concrete systems showed the same price escalation pattern due to steel reinforcement. Identifying which material is more cost effective should be done on project-by-project basis as there are a number of factors that can influence prices, such as availability of materials, labor costs, schedule constraints, etc. (Madsen 2005).

Cement is one of the primary ingredients of concrete and during 2004, a number of states were reporting shortages of cement. This was attributed mainly to hurricanes in Florida. Rising shipping rates due to limited availability of cement transport ships put an additional strain on concrete supply, which in return, caused a higher demand. Steel experienced the same availability shortages due to expansion and economic growth of large countries, such as China. Experts in the steel industry are trying to dismiss the myths that there is a shortage of steel. John Cross, Vice President of Marketing for the American Institute of Steel Construction, stated: "There is no shortage. The United States' structural steel industry has the capacity to produce 6 million tons of structural steel per year. In 2004, our usage was about 4 million tons of wide-flange structural products, which means there is certainly adequate capacity to meet any growth in the foreseeable future. Structural steel is readily available" (Madsen 2005).

When it comes to construction schedules, Alfred G. Gerosa, President of the Concrete Alliance Inc., stated: "Buildings with concrete can almost always be built faster. When compared to structural steel, sometimes twice as fast. It is not uncommon for cast-in-place reinforced concrete buildings to raise one floor every other day. Developers can finish jobs faster, earn a profit, recoup capital, and move on to the next project." The construction process which allows for fast construction of cast-in-place buildings is called the 2-day cycle. With this method is it possible to pour up to 20,000 sq. ft. of concrete flooring every 2 days. This method is very beneficial when the building needs to be completed as soon as possible in order for the owner to occupy the building, yet it is highly labor intensive. Steel buildings can also be built at fast rates, but unlike concrete, steel requires off-site fabrication (Madsen 2005).

In order to identify environmental impacts, the study titled "Comparison of Environmental Effects of Steel – and Concrete-Framed Buildings" (Guggemos and Horvath 2005) performed life-cycle assessments for concrete and steel buildings by quantifying energy

use and environmental emissions during a number of life-cycle phases. Phases that were considered in the study are: materials-manufacturing, construction, use, maintenance, and end-of-life. The study found that if all phases were considered, the differences of environmental impacts for the two frame types were not substantial. During the construction phase, concrete frames require much more energy and generate a greater amount of emissions, but these numbers are offset by steel's intense energy requirements and large emissions during the building life-cycle.

Compared to a number of construction materials, steel has one of the highest strength to weight ratio (Madsen 2005). This allows steel buildings to be designed with extremely long spans, compared to concrete. Concrete, on the other hand can be much more suitable for tall buildings, where floor-to-floor height is important. Cast-in-place buildings can typically fit more floors than steel buildings of the same height due to shallower floor systems (Madsen 2005).

Table 2 summarizes advantages and disadvantages of both concrete and steel as building materials.

Table 2 Advantages and Disadvantages of Concrete vs. Steel Construction

Category	Concrete	Steel
Safety	Fire Resistant Impact and Explosive Resistant Withstand Height Temperatures	Wind Resistant
Cost	High Initial Cost Potential Insurance Savings	Potentially Cheaper to Build
Material Availability	Stable Price Escalation	Experience High Price Escalation
Construction Scheduling	Faster Construction Speed	
Environmental Impacts	Greater Emissions Early on Greater Energy Expended Early on	Intense Energy Requirements Large Emissions during Building Life Cycle
Design Possibilities	Lower Floor-to-Floor Heights	Higher Strength to Weight Ratio

2.4 Gateway Park Phase II Originally Designed Structural System

Gateway Park Phase II is a steel building which incorporates the use of both a moment frame and a simple frame. Located on the South East side of the building is a two story annex designed with a moment frame. The main building's average column-to-column spacing on the

North to South and East to West sides are approximately 30' 6" and 22' 0", respectively. The building columns and beams are comprised of W-shape sections. Beam depths vary anywhere Beam depths vary anywhere from 8 inches to 30 inches (Figure 7).
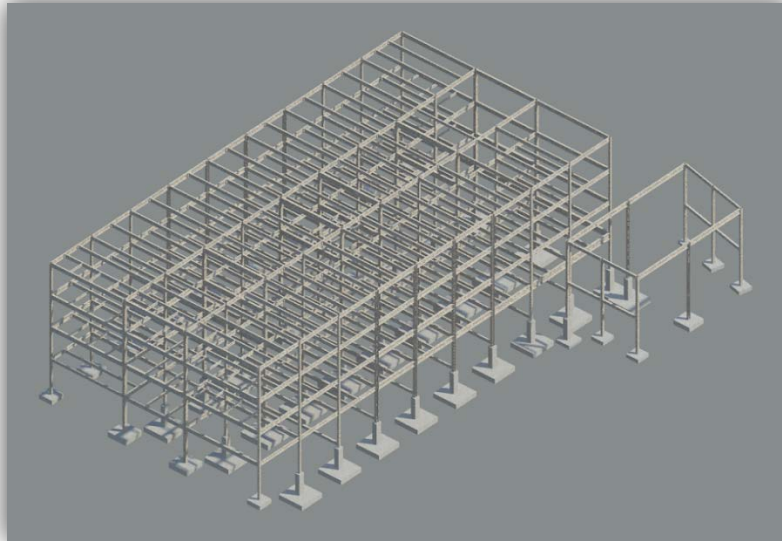
Figure 7 Gateway Park Phase II Structural Frame

A composite beam and girder system were chosen for this building. Metal decking provides the necessary formwork for concrete while shear connectors provide composite action for the entire system. The thickness of the reinforced concrete slab is 7 ½". Most beams in the system contain positive camber at mid span, which is indicated on construction plans.

The building is supported by a spread footing foundation with footing sizes ranging from 7.0'x7.0'x20" to 13' 6"x13' 6"x30". Footings are located below both the basement and first floor since the basement does not encompass the full footprint of the building. It took approximately 163 days to construct the steel frame.

2.5 Project Layout

The project was completed and documented to follow a traditional design timeline with the incorporation of BIM tools. Two alternative designs were proportioned after which an interoperability study was completed. The results from the study were used to create Revit models and assess the proposed alternative designs for structural integrity as well as any architectural impacts. Once the structural systems were finalized a baseline estimate was

prepared for the as designed steel frame and compared to estimates prepared for the laterally braced steel frame and concrete sway frame. The estimates were then used to prepare a preliminary schedule to determine construction speed and create a timeline.

3.0 Proposed Alternative Structural Designs

One of the main components of the project was to perform a structural design of a building. Numerous structural systems, which can be found in Appendix A, were considered. The steel moment frame system was replaced with a cast-in-place concrete system and a laterally braced steel system. The structural systems were chosen to minimize architectural impacts and so bay sizes were kept consistent. The elements were designed to resist gravity and lateral loads combined according to ASCE 7. Elements of the structural frame were selected based on optimizing inter-story heights, material availability, cost, and constructability. The calculations for the preliminary designs were completed using a combination of hand calculations and computer aided tools such as Microsoft Excel and Matlab. The design was further analyzed using 3D structural analysis software which will be discussed in the Chapter 6.

3.1 Alternative Steel Lateral Bracing System

Since the existing steel building was designed to utilize a steel moment frame an alternate design using a laterally braced steel frame was explored. Immediately a few constraint issues arose as to the placement of the actual bracing. To minimize any architectural impacts and structural irregularities the placement of the lateral braces were placed along column lines 4 and 9 (Figure 8). Due to the position of the doors along column line 4 as well as constructability issues a vertical k truss was used instead of the usual diagonal members between floors.

Figure 8 Typical Floor Plan with Lateral Bracing

The initial bracing members chosen were HSS 5"x5"xv.25"and would connect in the mid span of the beam above. The frames were initially analyzed using the Robot 2d frame analysis for the internal member forces, which can be seen in Figure 9 and Figure 10.
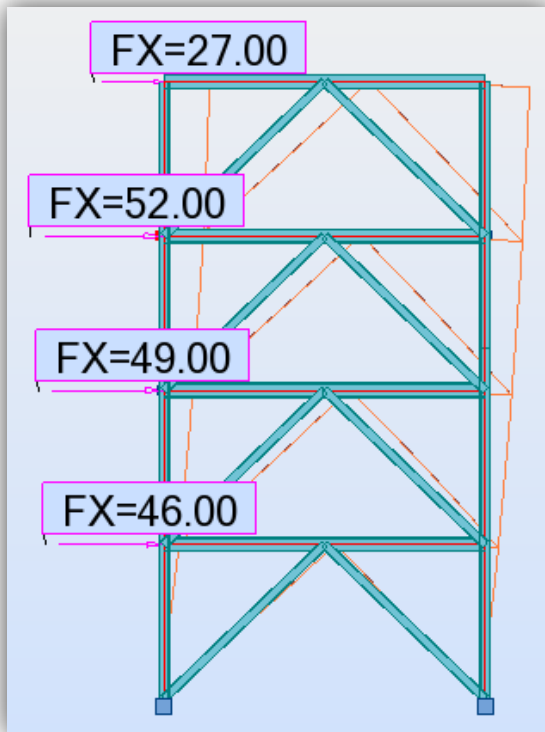
Figure 9 Laterally Braced Frame Robot Analysis

Bar/Node/Case			FX (kip)	FZ (kip)	MY (kip-ft)
1/	1/	1	-106.54	3.59	-34.88
1/	2/	1	-10.86	0.75	-1.30
2/	2/	1	-10.86	0.75	-1.30
2/	3/	1	-0.05	0.07	1.81
3/	4/	1	120.47	2.43	-23.74
3/	5/	1	15.89	0.44	-0.29
5/	5/	1	15.89	0.44	-0.29
5/	6/	1	0.12	-0.00	0.69
6/	7/	1	105.25	-1.18	16.28
6/	16/	1	-62.73	-1.15	-12.91
7/	9/	1	87.17	-0.64	9.56
7/	18/	1	-39.81	-0.45	-5.86
8/	11/	1	63.86	-0.35	5.51
8/	12/	1	-13.95	-0.24	-2.54
9/	3/	1	26.93	-0.05	1.81
9/	6/	1	-0.00	-0.12	-0.69
10/	1/	1	-114.75	0.57	-4.03
10/	15/	1	-115.27	0.03	2.27
11/	4/	1	117.75	-0.02	2.06
11/	15/	1	117.23	-0.56	-4.11
12/	16/	1	89.87	0.25	-1.99
12/	17/	1	89.35	-0.29	-2.32
13/	7/	1	-86.45	0.11	2.10
13/	17/	1	-86.97	-0.43	-1.21
14/	18/	1	55.63	0.24	-1.40
14/	19/	1	55.11	-0.30	-2.05
15/	9/	1	-52.38	0.18	0.72
15/	19/	1	-52.90	-0.36	-1.16
16/	12/	1	20.21	0.25	-1.13
16/	20/	1	19.69	-0.29	-1.62
17/	11/	1	-17.22	0.18	0.39
17/	20/	1	-17.74	-0.36	-1.60

Figure 10 Results for Laterally Braced Frame Robot Analysis

The steel members were selected from rectangular hollow sections according to the AISC code requirements and placed into the Robot 2D frame analysis for code verification. Pre-tensioning was not considered due to Robot's inability to model the pre-tensioned members which resulted in larger sections than would typically have been necessary. Once the frame was deemed to be of sufficient strength the moment frames from the previously made steel model was removed and were changed back to the typical gravity frame members, which can be seen in Figure 11. See Appendix L for more detailed structural analysis of the laterally braced framing system.
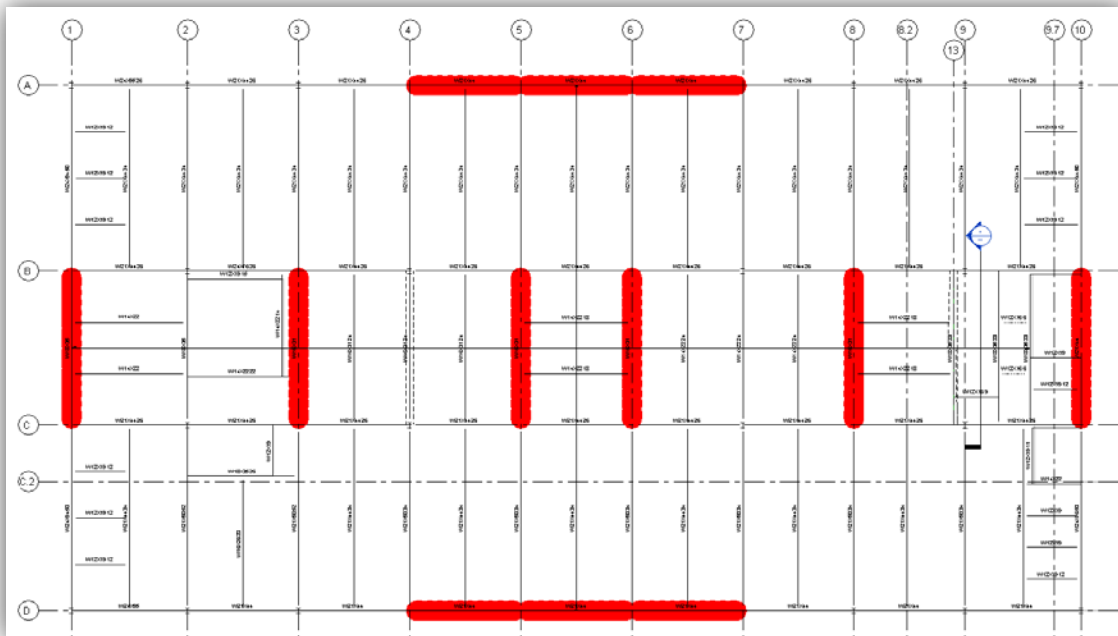
Figure 11 Locations of Moment Frames

3.2 Alternative Cast-in-Place Concrete Design

A single typical bay of a reinforced concrete frame was designed and analyzed through hand calculations. Each bay had a superimposed dead load of 30 pounds per square foot for mechanical systems and partitions. Due to the nature of the building a 100 pound per square foot live load was used for a mixed use office and classroom space. Based on local building material costs, which can be seen in Table 3, 5000 psi concrete was selected with 60 ksi reinforcing bars.

Table 3 Local Concrete Costs

Concrete Strength (psi)	Typical Cost Per C.Y.
3000	$95
4000	$98
5000	$101
6000	$110

3.2.1 Gravity System Design

Several options were explored based on building proportions, design loads, and architectural constraints. A typical beam system, one way joist system and flat plate design were all considered and proportioned. Based on the concept of economic, structural, and

constructible feasibility a flat plate system was selected. Despite the fact that there would be a greater amount of concrete required to construct the system when compared to a system using beams or waffle slabs, the cost would be offset a shorter building height and faster construction speed compared to the alternate systems. Additionally a system which would utilize a moment frame instead of a lateral brace was chosen due to the architectural constraints.

3.2.2 Column and Slab Design

Once the flat plate system was selected we proportioned the building using the direct design method. The initial calculations led to a 13 inch plate which we determined was too costly based on material prices. Additionally the added self-weight of the plate created an extremely high load demand for the columns. We then chose to change our structural system to include drop panels which allowed for increased shear strength, negative moment capacity and stiffness of the slab. This allowed us to reduce our slab to 10.5 inches, which can be seen in Figure 12. This also reduced the loading on our columns allowing us to decrease both the size of the column as well as the required area of steel. The drop panels were set to minimize the amount of work needed to frame them and so were set to a depth of 3½ inches and extended 10 feet in both directions.
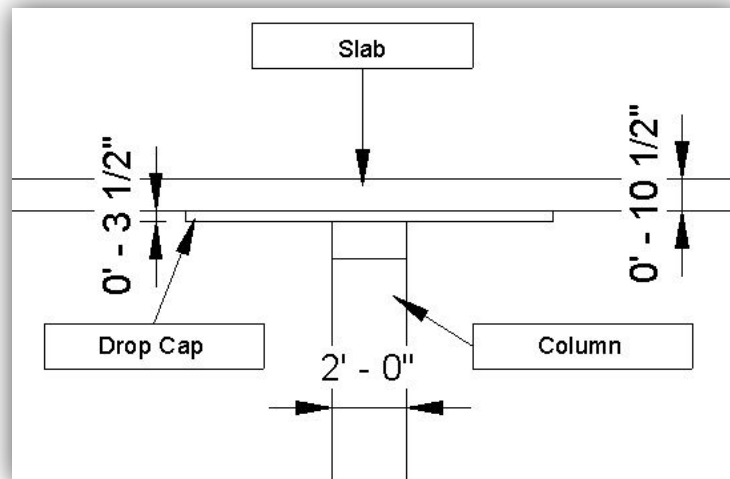

Figure 12 Typical Interior Column with Drop Panel

A general bay was designed with the premise of using a 20 inch square column as support with our typical drop panels. Since our building passed the requirements for analysis by coefficients we used the direct design method to distribute portions of the total design

moments to column and middle strips. The critical shear sections were then calculated for a column supported slab. Once it was determined that the slab was of adequate capacity the required steel reinforcement was determined for column strips, middle strips and exterior strips. The equations for the slab requirements were then input into an excel spreadsheet so that calculations did not have to be repeated depending on the new column sizes.

The columns were initially estimated to be 20 inch square columns with 1% steel based on design charts. Once the basic gravity and lateral effects were analyzed we found that we would need at least 22½ inch square columns in order to meet structural requirements. Based on construction standards we increased the size to 24 inch square columns which would be one continuous stack the entire height of the building. The exterior and corner columns were proportioned to 16 inch square columns and checked to ensure that the shear capacity of the slab would not be exceeded by the smaller column. Based on the initial proportions simplified design charts were created for typical column cross sections for each level to ensure that the lateral and gravity loads would not exceed the limitations of the columns. This process was scripted into Matlab for repeatability should any of the columns fail the load requirements. Once it was determined that the columns were of adequate capacity the steel reinforcement was designed with a focus on constructability rather than completely minimizing the material used.

3.2.3 Diaphragm

Since the concrete columns were designed to resist the lateral forces as well as the gravity forces the slab had to be able to transfer the forces into the columns. Once the initial slab dimensioning was completed a 2d frame analysis was run using Robot Structural Analysis to find the moments within the floor. These moments were then added into the loading combinations and the slab analysis was redone with new checks for critical transfer sections of shear. Each loading was reversed to check for wind load reversals and the slab was designed for the governing scenario. The reinforcement was designed to be placed in large uniform sections to optimize placement rather than optimized material costs.

3.2.4 Foundation

Since the concrete framing system introduced a significant increase in the magnitude of the dead load forces the foundations were redesigned to provide adequate support for the building. The geotechnical report was obtained from Daniel O'Connell and Sons and the soil bearing capacities were used to design minimum sized foundations. Since the bearing capacity increased significantly at a slightly deeper depth the foundations were placed lower than the original design foundations. The added capacity was enough to justify the higher labor costs associated with the added excavation and backfill.

The column loads were recalculated for unfactored values and designed according to ACI 318-08. Based on the axial loads the depth of the spread footings were set to required values and dimensions of the footing were kept to square sections to speed formwork placement. For the basement level the size of the interior column spread footing was larger than the bay size and so was changed to a pad footing extending to the necessary width, which can be seen in Figure 13. Calculations for foundation design can be found in Appendix J.
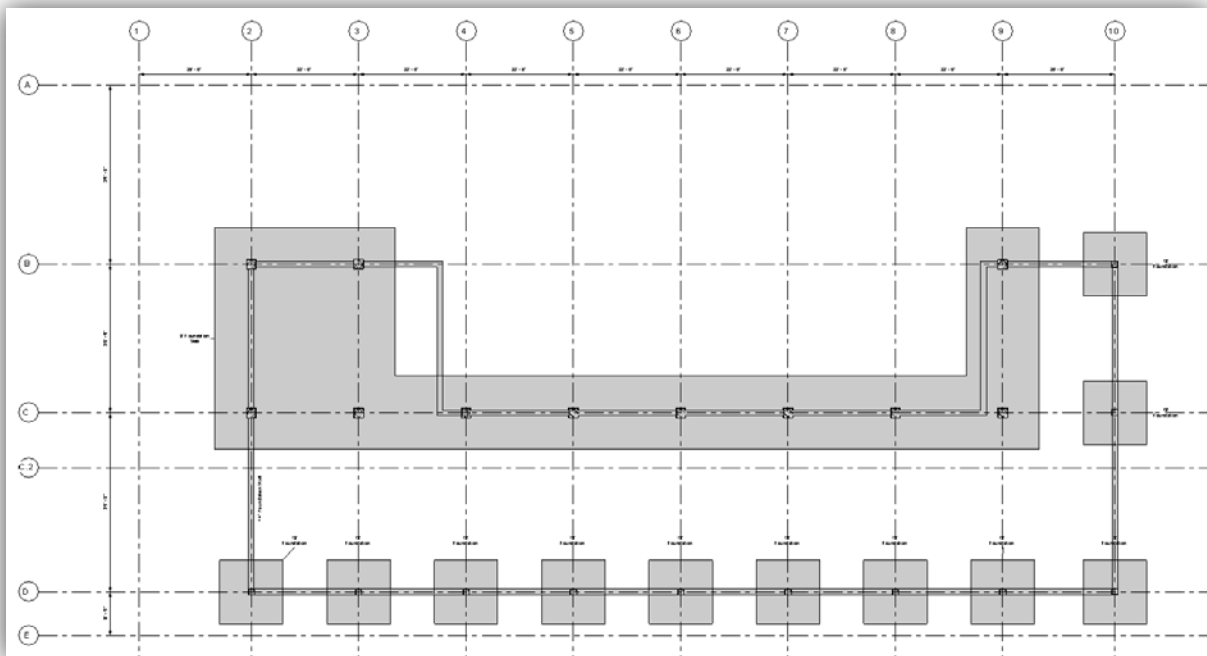

Figure 13 Cast-in-Place Concrete System Foundation Plan View

4.0 Interoperability

Four main software packages were used to explore interoperability, Revit Structures, Revit Architecture, Scia Engineer and Robot Structural Analysis. The entire process was designed to replicate the interactions between multiple parties involved in a project by following a typical design flow for building. A basic overview to Revit model creation is provided as well as the linking process between the Revit platforms. The export process for the analytical model into Robot Structural Analysis and Scia Engineer are also outlined along with common issues, key components of a successful export and a set of guidelines for model development.

4.1 Steel Model Development

The first set of models developed were the as designed steel moment frame architectural and structural models. These models served as a baseline for the next sets of models developed and allowed for the focus to shift from design to modeling by using professionally stamped designs. Additionally this would facilitate the development of a baseline estimate with which to compare the alternative proposals and ensure proficiency with the software packages.

4.1.1 Architectural Model

Since projects begin with an architect creating a conceptual design which drives the placement of basic structural members, such as beams and columns, an architectural model was developed in Revit Architecture (see Figure 14) which would establish the constraints of the structural model.
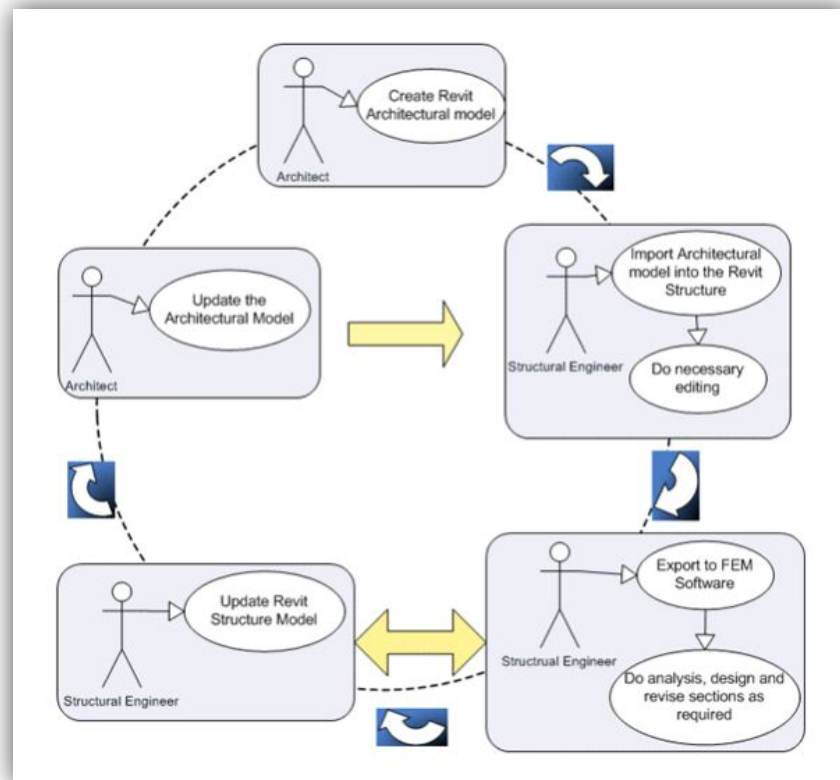
Figure 14 High Level Flow between BIM and FEM Software
(Nemetschek 2012)

The gridlines and elevations were based off the projects drawings, found on the Daniel O'Connell's website. The first step was to place the grid lines and elevations in their respective views. In some gridlines were added for elements that would be placed in the structural model so that there would be a level of consistency between the architectural and structural models.

The main architectural elements modeled were the exterior brick facade, curtain walls, interior partitions, stairwells, doors windows and ceilings. The architectural model was created with enough detail so that a clash detection could be run with a linked Revit Structural model. Often times this meant creating new families for doors, exterior walls and interior partitions. Figure 15, Figure 16, and Figure 17 show different views of the architectural model. Figure 18 shows a 3D rendering of the building. Step-by-step instruction which outline the creation of the architectural model can be found in Appendix D.

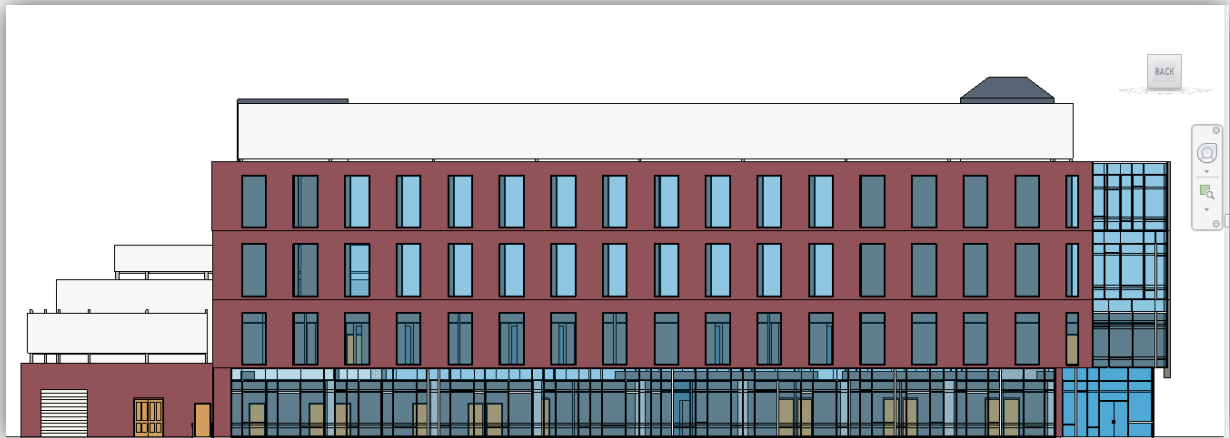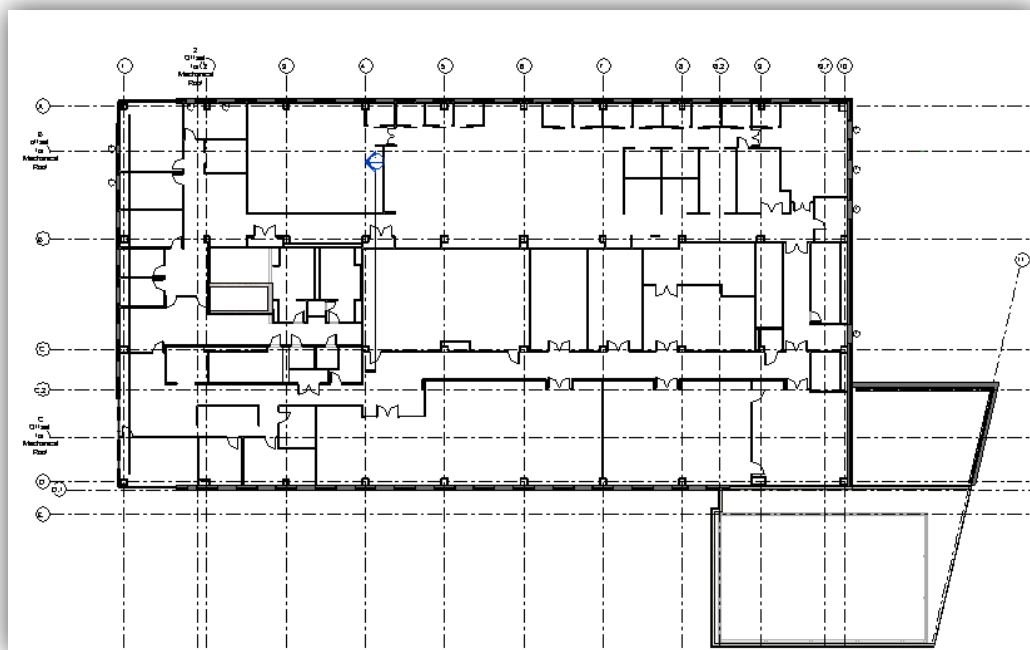**Figure 15 West Elevation View of Exterior facade**

Figure 16 Level 2 Plan View

Figure 17 Building Section view @ Grid Line 4

Figure 18 3D Rendering of Gateway Phase II Building

4.1.2 Structural Model

The structural model began by using the linking function within Revit. The architectural model was linked and the gridlines and elevations were copied to ensure consistency. The

elevations were then offset by the depth of the slab so that the framing could be placed at the proper elevations. The structural levels would be at different elevations compared to the Architectural level elevations hence, it was important that the elevations were copied and not monitored to make sure the architectural model would not be impacted. The model was then developed from the bottom up with exact dimensions and element types. In some cases this required modifying or even creating new families with a higher level of detail that was allowed with the default families than what was available in the software. The completed structural model was then exported to Robot Structural analysis and Scia Engineer. The detailed process of the structural model development can be found in Appendix E.

4.1.3 Model Export to Structural Analysis Software

The structural model was exported to Robot using the Revit Extensions for Revit Structures released by Autodesk, and to Scia using a Revit Add-on released by Nemtetschek, see Figure 19 and Figure 20 below. These extensions allow for both export into Robot and Scia for initial analysis as well as import from Robot and Scia should any changes be applied within the analysis packages. Step-by-step instructions on how to export models to ROBOT and Scia can be found in Appendices F and G respectively.
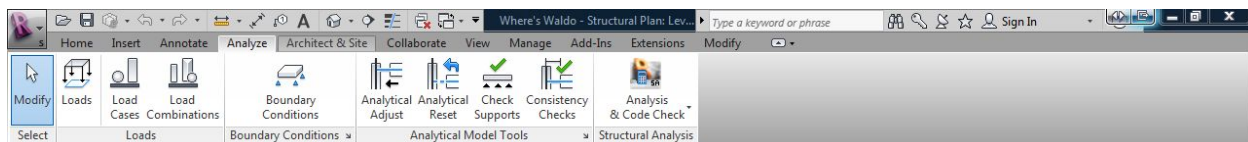
Figure 19 Robot Exporter
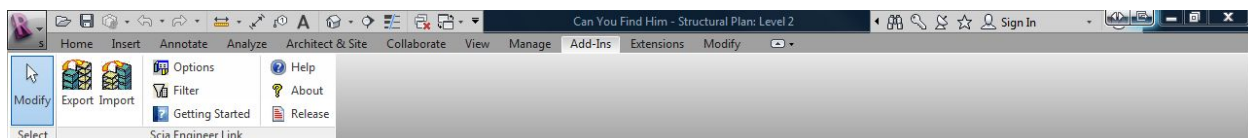
Figure 20 Scia Exporter

The export process into ROBOT ran smoothly however the Scia export resulted in numerous errors. The exported model was missing several structural elements of various types, boundary conditions, unknown material properties and unknown cross sections, one example is shown in Figure 21. A similar material type in Scia was selected as an alternative so an initial analysis could run but it resulted in an access denied message. Our temporary solution was to

attempt to export the members as unknown cross sections and unknown materials which would later be adjusted in Scia.
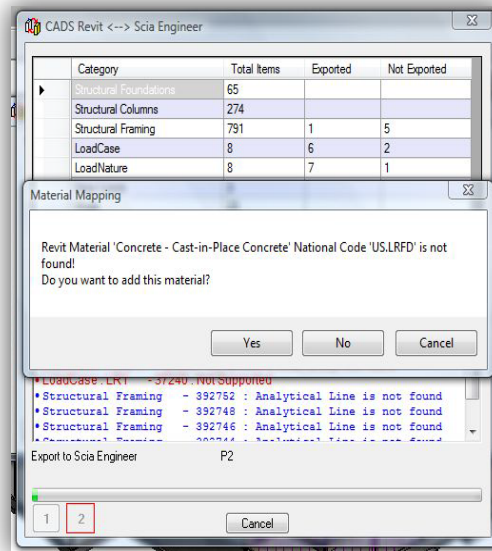
Figure 21 Scia Exporter - Unknown Material

Once the models were fully exported into both Robot and Scia initial calculations were run to determine the deflections and required member sizes. The initial analysis resulted in unrealistic deflections (Figure 22) and deformations with multiple instabilities found in both the Scia Engineer and Robot Structural Analysis models. Problematic members were identified and corrections were attempted. However after numerous failed attempts the process was restarted and analyzed in half story sections. This reduced the number of members to work with allowing the errors to be explored on a more manageable scale. As a result five major categories which every model requires for export and analysis were identified.
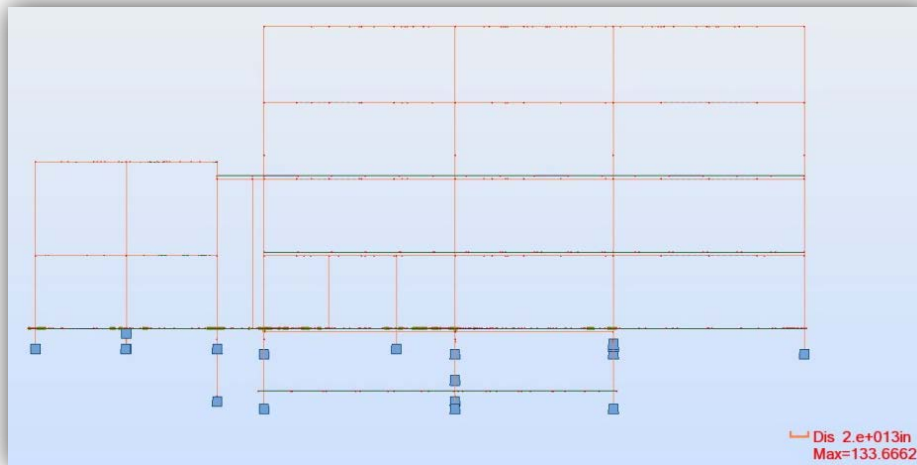
Figure 22 Robot Structural Analysis with Unrealistic Deflections

4.2 Key Export Components

Based off the errors encountered during the export process, five main criteria which were crucial for a successful export of Revit models into structural analysis packages were identified. These criteria must be successfully met before any analysis can be accurately completed. After defining five major criteria each criterion was explored in detail to identify and document any potential issues. The five main criteria are boundary conditions, material mapping, connection types, load exports and rebar placement. The following sections elaborate on the definitions and the level of support that each analysis package provides. More detailed descriptions of each criterion can be found in Appendix I.

4.2.1 Material Mapping

Material mapping allows for materials defined within Revit Structure to be exported as the best matching material in the analysis software (Autodesk 2012a). Instead of using material properties from Revit Structure, each structural software package has an internal database with materials and properties. During the export, material mapping is applied to each element which may be selected based on closest matching material properties, or material names. This can become an issue when working with materials not in the Revit database as properties designated in Revit will not carry over into the analysis packages. As such it is usually necessary to create the material again in the analysis programs. The method for changing material

properties in Scia and Robot as well as selecting closest value unknown materials is covered in Appendix I.

4.2.2 Loads and Load Combinations

Revit Structures has the ability to create loads and apply them to any point in the analytical model. The loads can be point loads, linear loads or surface loads that can either be placed spatially in the model or hosted on an element. Loads which are placed spatially will not adjust to changes in the model and will remain in the same location, regardless of what is nearby. Hosted loads are fixed on an element and will automatically adjust to changes made to the element. Additionally users can set what type of load will be applied as well as apply factors to create ASCE load combinations, though most structural analysis packages will generate the combinations automatically based on the type of analysis that will be used. It is generally recommended that unfactored hosted service loads be applied in the appropriate places in Revit and that combinations be created within the analysis program instead of within Revit.

Since the loads are created and hosted analytically Scia and ROBOT will export loads and place them in the model for analysis. Robot will read each parameter of the load and, if selected, automatically apply load factors and create the appropriate combinations. Scia will do the same for however roof live loads and thermal loads are currently unsupported. A ticket was logged with Scia customer service but they were unable to resolve the issue and this remains an unsupported portion of the Revit Scia link.
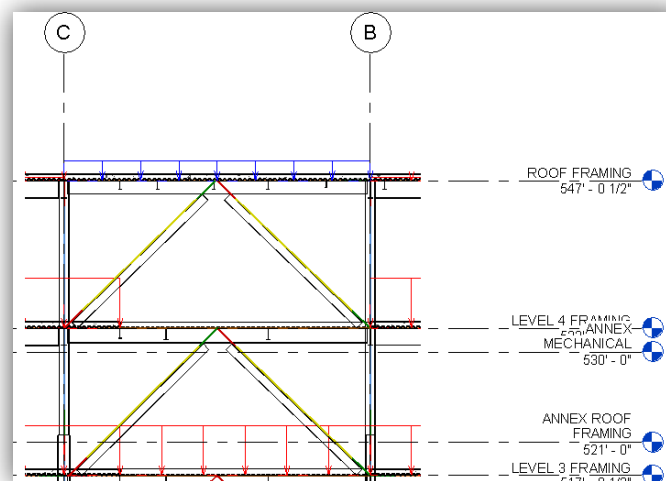

Figure 23 Missing Nodes at Column-Slab Intersection

4.2.3 Boundary Conditions and Foundations

Boundary conditions are treated as fixed points or areas within the structural analysis programs. Revit currently has three different types of boundary conditions, points, lines and surfaces which are applied to different types of structural elements. It is important to make sure that the lowest points of every structure, usually the columns, receives a boundary condition to ensure proper structural analysis (Figure 24). Missing even one can result in instabilities within nodes which will result in extremely high deflections in the structure. Both Robot and Scia automatically replace spread footings with boundary conditions so it is usually not necessary to place separate boundary conditions however the model should be checked after successful export to ensure that the boundary conditions were placed.
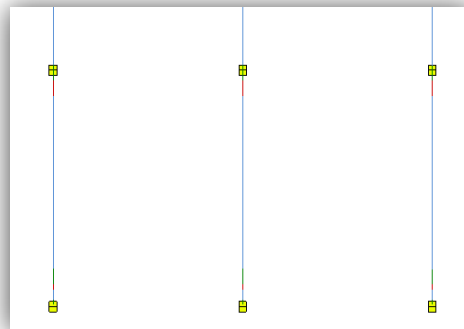
Figure 24 Columns with Boundary Conditions

4.2.4 Steel Member Connections

There are a number of types of connections that steel structures can have. Primarily, attention was paid to pinned and moment connections. Moment connections are important because they are used to create moment frames to resist lateral forces on structures. Pinned connections, on the other hand are used to resist vertical forces. In Revit, member connections can be adjusted through the analytical model for analysis purposes and through the plan views for documentation purposes. The Robot exporter will either choose to ignore steel connection types or will export connections depending on the option selected (Figure 25 (a)). It is important to realize that if the connection types are ignored ROBOT will treat each connection as a moment connection. Scia has a similar option however it is currently a place holder for a future development so each connection is exported as a moment connection (Figure 25 (b)).

Scia does support pin connections but they must be manually placed within the Scia model. This has been confirmed by Scia Support.

a   b

Figure 25 Export Options (a) Robot, (b) Scia

4.2.5 Concrete Reinforcement

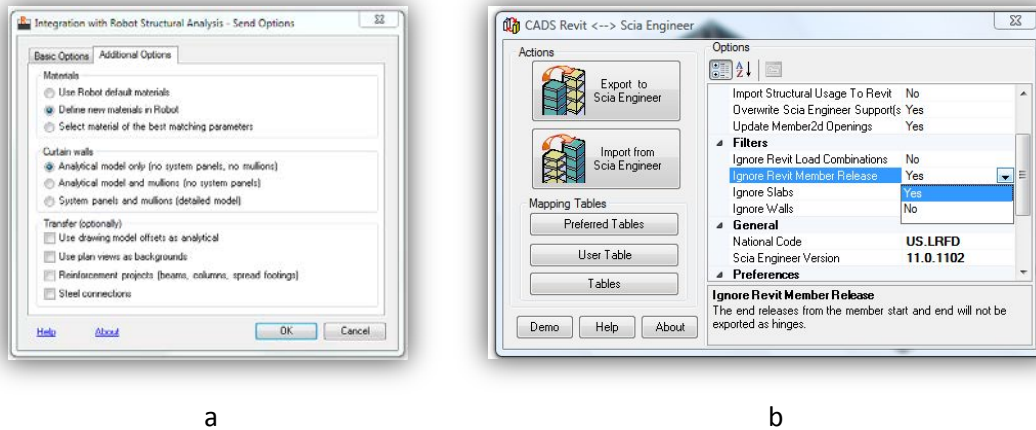The final key component of a successful export would be concrete reinforcement export. With the new addition of Revit Extensions 2012 reinforcement can be modeled to a higher level of accuracy. The Revit extension also includes a ROBOT Structural Analysis Code check which analyzes one reinforced concrete member and perform code checks on existing rebar or analyze and design rebar for the member. Scia currently does not support rebar export from Revit but analyzes and designs rebar for the entire building.

4.3 Interoperability Issues

Throughout the model export process there were a number of issues that arose. A number of flaws within the programs were found which had to be addressed prior to an analysis of the building could be completed. The issues that arose with the software were addressed either by reaching out to the software companies or through our own attempts to work through the issues. Detailed descriptions of numerous interoperability issues could be found in Appendix H.

4.3.1 Missing Nodes

The one issue that arose with the Revit-Robot link was a slab connected to a column with no beams placed underneath. Since the slab on grade was not treated as a boundary condition to get initial results for slab deflections this became an issue in the basement which

has concrete columns extending three feet below the surface. Since the column does not end at the slab Revit does not treat the intersection as one element ending on another and therefore does not create a node, which can be seen in Figure 26.
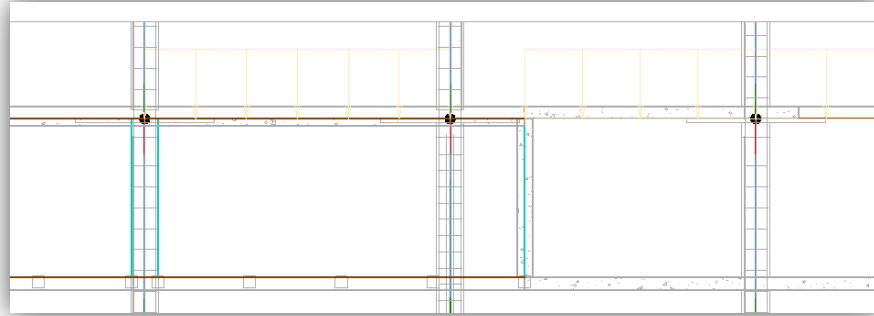
Figure 26 Missing Nodes at Column-Slab Intersection

After exploring ways to have Revit place nodes automatically it was decided that it would be more time efficient to manually place nodes in ROBOT. This was also a very unique situation since the slab would typically be turned into a boundary condition or the columns would typically end on the floor system. Since Scia requires a correction to be applied to any Revit model this was not an issue.

4.3.2 Disappearing Columns

When the model was created structural foundation walls were included for accuracy however upon exporting the model into Scia all of the columns were missing (Figure 27). The Robot model was complete with the analytical walls and columns so it was concluded that it was not an issue with the Revit model.

a   b   c

Figure 27 Figure BB Basement Level Foundation Walls and Columns:
(a) Revit Analytical Model, (b) Revit Structural Model, (c) Scia Engineer Structural Model

Our initial thought was that Scia would create the analytical model and then generate the physical model based on the analytical unlike Robot which most likely generated the analytical model based off physical properties. This would result in any encased members being ignored from the model. Our next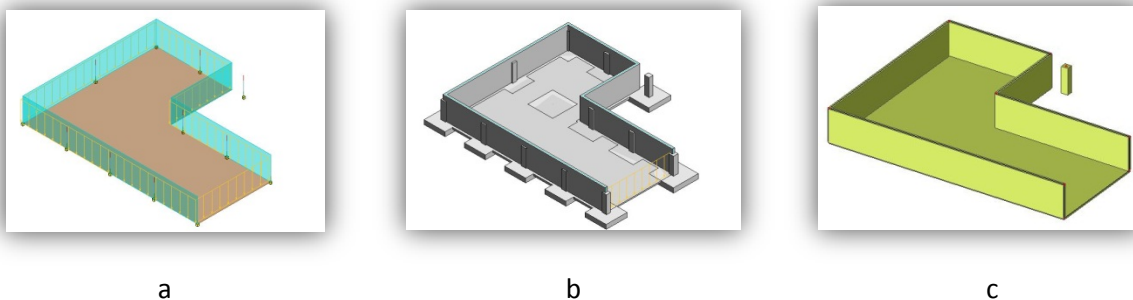 step was to ignore structural walls during the export process however this still resulted in all encased columns being ignored. Deleting structural walls would allow for all columns to successfully export however the exact problem was never found.

When the entire basement level was exported random columns were ignored instead of only the encased columns. Since columns which were previously being ignored were now appearing numerous different scenarios were explored to see if there was a system behind which columns would or would not export. After attempting numerous unsuccessful fixes and logging tickets with Scia support it was decided that the best course of action would be to wait for the developers to respond. Unfortunately a response was never received and this remains a problem between the Revit-Scia link.

4.3.3 Material Mapping

During our exploration of the export process in Scia there was still the issue of unknown cross sections and materials. One common feature that each element that failed to export had was that they were all concrete elements. During the export different methods of manually mapping the "unknown material" to the proper concrete in the export process were attempted. However manually mapping the material brought up the error "Access to the path is denied" (Figure 28). Since only the concrete members were an issue the first option explored was to alter material properties within Revit to one that Scia would recognize. Upon selecting the concrete type it was noticed that the concrete was set to a generic Cast-in-Place instead of the 4,000 psi concrete specified. Once this was changed the material mapping was successful however the manual mapping method was still explored should it be necessary later on.
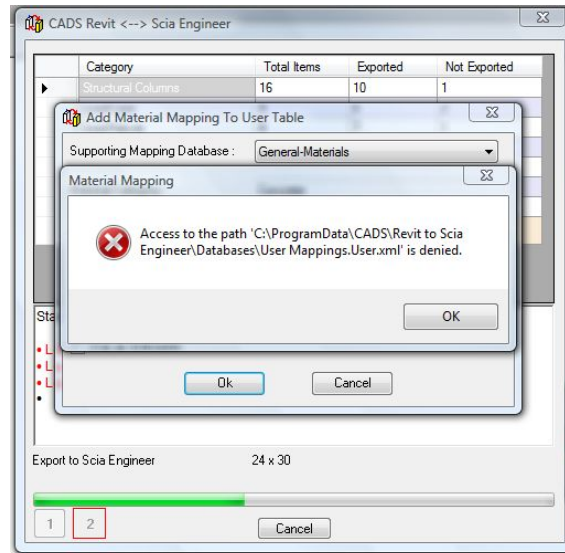
Figure 28 Access to User Mapping Denied

Upon reaching out to Scia regarding this issue customer support said the issue was a lack of administrative privileges to access the mapping database and sent a solution along with a screenshot of how to perform it. Unfortunately their solution did not work but once the administrative privileges were mentioned Revit Structures was run in administrator mode which allowed for proper material mapping.

4.4 Proper Model Development Guidelines

Based on the findings of the previous section, a set of guidelines for proper export ready model development was developed. Special attention should be given to the five aspects covered in the previous sections as they arise. Structural Analysis should also be performed at regular intervals so any underlying issues can be addressed as they arise. This guide also assumes that certain aspects of the project will be constrained based on the architectural requirements.

In general, when working with any new structural analysis software packages the first step should be to use all published material regarding the software. Many internal errors can be addressed using available material and introductory tutorials and will save time later on. Additionally understanding the basics of the structural analysis software will save time in the event that unusual deflections do arise. Any software which generates a finite element mesh will inherently be different from other analyses so minor discrepancies should be expected.

This first and most important step in the model creation process is to link the existing architectural model. The grid lines and basic elevations will be set forth by the architect and therefore should be copied directly from the architectural model. It is likely that the elevations may change due to the MEP and framing system needs so the elevations should be monitored to ensure consistency. Once these have been completed the modeling can begin.

Every member placed in Revit Structures will be given an analytical model. The analytical member has properties associated with it so it is important that member properties be specified in advanced. Material properties should be set in advanced for families, eliminating the need to reselect and correct the members. Member end releases should be set once a reasonable amount of elements with identical connection types have been placed. Boundary conditions can be created at the end of a sections completion but must be verified through export and basic analysis.

Any spread footings placed under columns will automatically be turned into boundary conditions so it is unlikely that separate boundary conditions need to be added however it should be verified through initial exports. In general boundary conditions should only be applied to the lowest point of the structure, meaning any slab on grade should not be turned into a boundary condition but should be separately analyzed. Should any boundary conditions be required they should be made immediately after the element is created.

Revit Structures automatically creates an analytical model which is associated with the physical model. At times the analytical model can become misaligned and will require adjustment. Typically the model becomes misaligned when attached elements, such as walls or columns, are shifted in the model. Revit view properties usually disables the analytical model in plan views however enabling the analytical model is a simple way to keep track of all the analytical models and ensure they align with the physical model.

Using the following steps a reasonable portion of the building should be built, usually half a floor will suffice, and then exported for a preliminary analysis. Before an analysis is performed a handful of members should be checked to ensure that the correct properties have been applied. Once they have been verified for a random selection of members analysis can begin. Based on the preliminary results the model may need adjusting. If they are minor

adjustments they may be made in Robot and updated in Revit through the use of the Revit Extension when possible however most adjustments will likely have to be made within Revit Structures. Once the model has been verified the modeling process can continue with less frequent exports, however the model should still be verified at least once per modeled floor for low rise structures or every few floors for high rise structures. This process, though time consuming, will eventually lead to a proper model development which accounts for a majority of potential errors prior to a finalized model. The interoperability study culminated in the creation of a set of structural plans for both alternative designs which can be seen in Appendices R and S

5.0 Design Assessment: Structural Analysis

Two new designs were proposed, one being a laterally braced steel frame and the other a reinforced concrete moment frame. The structural analyses and designs were multistep processes which involved initial hand calculations, simplified model calculations and verifications, Revit documentation and eventually complete model analysis. Each section will detail the extent of the required steps for the eventual full scale analysis and design of the proposed structural systems.

5.1 Software Calculation Verification

One of the most important steps of software calculations is the initial verification to ensure that the results are reliable. Simply supported steel wide flange beams were analyzed in both Robot Structural Analysis and Scia Engineer and compared to an expected hand calculated results. The summary of these results can be found in Table 4 and Table 5. Complete calculations can be found in Appendix B.

<div align="center">Table 4 Deflection & Rotation Results for W12x24 Beam with 2kip Load (pin-pin)</div>

	Hand Calculations	RISA 2D	Scia Engineer	Robot Structural Analysis
Deflection (in)	-0.0974	-0.122	-0.101	-0.0974
Rotation (deg)	-0.069	-0.0871	-0.070	-0.069

<div align="center">Table 5 Deflection & Rotation Results for W12x24 Beam with 2kip Load (moment-pin)</div>

	Hand Calculations	RISA 2D	Scia Engineer	Robot Structural Analysis
Deflection	-0.024	-0.03	-0.028	-0.0243

Once the initial calculations were completed the sample models were turned into simple frames and analyzed in Robot and Scia to ensure the results from both programs would be comparable and accurate. Since Robot and Scia were developed for different regions certain material properties were not consistent and so had to be changed. The Robot materials were altered due to write permissions placed in the student version of Scia. The exact method for this is located within Appendix B. Once the program and project settings were coordinated the results were verified full scale models were analyzed.

5.2 Existing Steel Model

The primary purpose of documenting and analyzing the steel structural model for the as designed building was to ensure our competency with the documentation and analysis software. After resolving the issues discussed previously in the interoperability chapter the existing steel model passed the analysis and code checks located within the programs. There were certain limitations built into the program and so we were unable to analyze the building as it would have been created.

5.2.1 Limitations

There were several limitations placed on the level of analysis in the project. Some of the issues did not affect the structural analysis while others resulted in compromises as to the level of detail. One such limitation of the software analysis programs was the inability to model composite decking. While ROBOT can model the metal decking and trapezoidal concrete it cannot model the shear studs to create composite decking. As such the floors were not modeled as concrete slab on metal decking but instead were treated as a flat slab system.

There were additional obstacles within the modeling and analysis programs which were outlined in detail in Appendix H. These were generally minor details which were either resolved or worked around with minimal to no impacts on the analysis.

5.2.2 Results

Once the analysis was complete the model was put through the Robot Steel Member Design Module. This allowed us to check the viability of each steel member. However there were certain checks that had to be compromised due to the inability to model everything exactly as it was designed. Since composite beam design was such a large aspect of the structural framing the design module results were completed to check for usability rather than structural verification.

The member verification outputs a summary table showing which sections pass and which ones have insufficient capacities (Figure 29). Calculation notes are also created for each member and can be opened by clicking on members. While there were beams that failed the code checks they were all due to the inability to perform composite deck calculations.

Figure 29 Member Verification Summary Table

5.3 Alternate Steel

Once the steel model was modified to the laterally braced frame the model was analyzed in Robot Structural Analysis in the same manner as the original steel model. The model was analyzed for the structural forces and then put through the steel member design module. The same principles which were applied to the steel moment frame were applied to the laterally braced frame design as far as member verification for the gravity members.

The structural steel verification was run mainly for the braced frame and the members which were previously located in the moment frame. The moment frames were changed to match the typical framing plans and so were expected to pass the member verification with the same alterations to the analysis that were applied to the previous model. The laterally braced frame was designed to withstand the wind forces so the verification was to ensure that the addition of the gravity loads would not result in critical buckling. A portion of a typical bracing member's calculation note can be found below in Figure 30.

STEEL DESIGN

CODE: ANSI/AISC 360-05 An American National Standard, March 9,2005
ANALYSIS TYPE: Member Verification

CODE GROUP:
MEMBER: 14 Column_14   POINT: 3   COORDINATE: x = 1.00 L = 21.16 ft

LOADS:
Governing Load Case: 1 WIND1

MATERIAL:
STEEL   Fy = 36.00 ksi   Fu = 58.00 ksi   E = 29000.00 ksi

SECTION PARAMETERS: HSRE 10x6x0.375
d=10.00 in   Ay=3.457 in2   Az=6.249 in2   Ax=10.400 in2
b=6.00 in   Iy=137.000 in4   Iz=61.800 in4   J=139.000 in4
tw=0.35 in   Sy=27.400 in3   Sz=20.600 in3
tf=0.35 in   Zy=33.800 in3   Zz=23.700 in3

MEMBER PARAMETERS:

Ly = 21.16 ft   Lz = 21.16 ft
Ky = 1.00   Kz = 1.00   Lb = 21.16 ft
KLy/ry = 69.95   KLz/rz = 104.16   Cb = 1.00

INTERNAL FORCES: NOMINAL STRENGTHS:
Pr = 55.11 kip   Fic*Pn = 190.35 kip
Mry = -2.05 kip*ft   Fib*Mny = 91.26 kip*ft
                Vrz = -0.30 kip   Fiv*Vnz = 121.48 kip

SAFETY FACTORS:
Fib = 0.90   Fic = 0.90   Fiv = 0.90

SECTION ELEMENTS:
UNS = Compact   STI = Compact

VERIFICATION FORMULAS:
Pr/(Fic*Pn) + 8/9*Mry/(Fib*Mny) = 0.31 < 1.00 LRFD (H1-1a) Verified
Vrz/(Fiv*Vnz) = 0.00 < 1.00 LRFD (G2-1) Verified
Ky*Ly/ry = 69.95 < (K*L/r),max = 200.00   Kz*Lz/rz = 104.16 < (K*L/r),max = 200.00   STABLE

LIMIT DISPLACEMENTS

Deflections Not analyzed

Displacements
vx = 0.1359 in < vx max = L/150.00 = 1.6927 in   Verified
Governing Load Case: 1 WIND1
vy = 0.0000 in < vy max = L/150.00 = 1.6927 in   Verified
Governing Load Case: 1 WIND1

Section OK !!!

Figure 30 Member Calculations Note

Once the steel members passed the code checks within Robot they were taken into the connection design module. Intersecting members can be selected and a basic connection type will automatically be selected. The connection can be designed as a bolted or welded connection depending on the requirements needed. Because the member selected was a 3/8th inch section, the number of bolts required to fully transfer the forces would have resulted in

large reinforcing plates needing to be added. Instead of choosing this option the members were simply designed for welded connections. For hollow sections Robot automatically designs full perimeter welds and automatically runs capacity verifications for each member being welded. A portion of a typical connection is shown below in Figure 31.
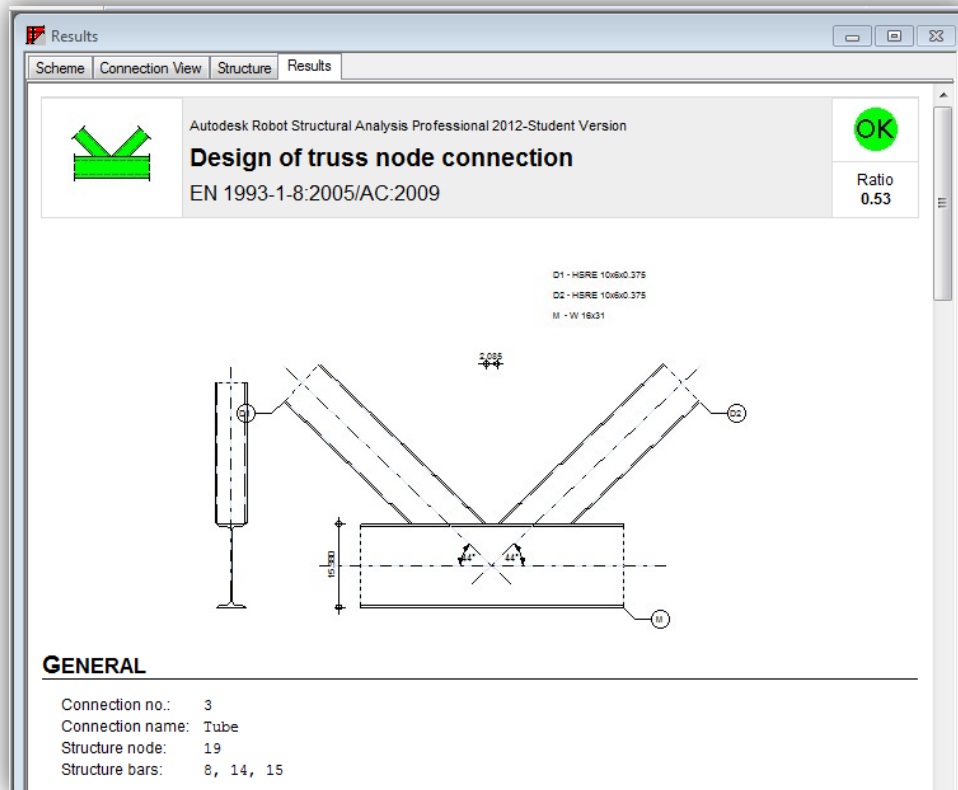
Figure 31 Bracing connection

5.4 Alternate Cast-in-Place

The cast-in-place concrete system was created in Revit structures according to the hand proportioning completed prior. Rebar was not placed in the slab or the columns but was kept as a guide for verification in case any of the results were too low in comparison. The analytical model was then exported to Robot for detailed analysis. A 3D view of the building can be found in Figure 32 below.
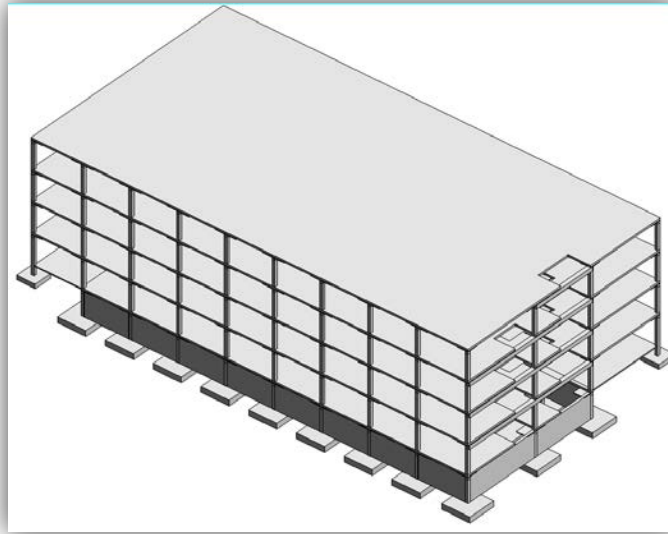
Figure 32 Revit Structure 3D Concrete Model

Once the model was imported into Robot basic load combinations were created as per ASCE 7. Four critical loading types were identified, three of which were doubled to change the wind direction between lateral and transverse loading. The model was then analyzed according to the seven load combinations identified summarized below in

Table 6.

Table 6 Load Combinations

Combinations	Name	Analysis type	Combination type	Definition
10 (C)	9-3T	Linear Combination	ULS	1*1.20+2*1.60+9*0.80
11 (C)	9-4T	Linear Combination	ULS	1*1.20+2*1.60+9*1.00
12 (C)	9-6T	Linear Combination	ULS	1*0.90+9*1.60
18 (C)	9-2	Linear Combination	ULS	1*1.20+2*1.60
19 (C)	9-3	Linear Combination	ULS	1*1.20+2*1.60+3*0.80
20 (C)	9-4	Linear Combination	ULS	1*1.20+3*1.60+2*1.00
21 (C)	9-6	Linear Combination	ULS	1*0.90+3*1.60

The results from the analysis were then used to calculate the required reinforcement as well as perform code checks. The slabs were calculated first to ensure adequate punching capacity which would have resulted in columns needing to be resized. The slab code check performs punching shear calculations and required reinforcement for the sections through the

use of the slab required reinforcement module which is located below in Figure 33. Once the calculations were performed for each slab the provided reinforcements were calculated.
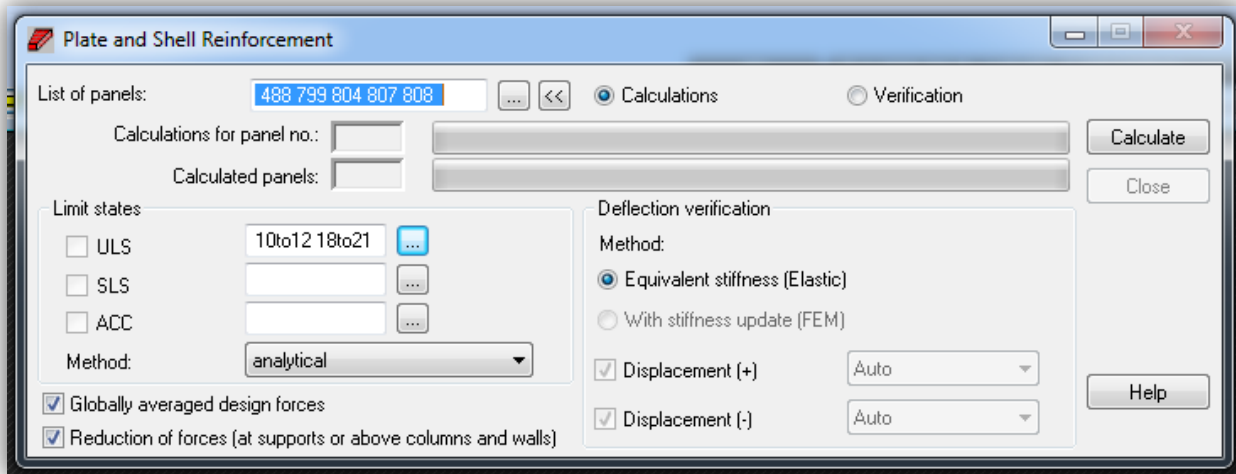
Figure 33 Robot Slab and Reinforcement Module

The column and beam reinforcements were calculated in a similar manner but were also summarized in a table output by the design module. One example can be found below in Table 7. The reinforcement information was then used to calculate the provided reinforcement according to different options needed according to the project. Figure 34 shows the different types of calculation options available for ACI 318.

Table 7 Column and Beam Reinforcement

Bar	Required reinforcement along b (in2)	Reinforcement along b - distribution	Required reinforcement along h (in2)	Reinforcement along h - distribution	Transversal reinforcement - type/distribution
490	0.8	2#8	0.48	2#8	2#4 30@7.00
498	0.8	2#8	0.48	2#8	2#4 30@7.00
499	0.8	2#8	0.48	2#8	2#4 30@7.00
500	0.8	2#8	0.48	2#8	2#4 30@7.00
501	0.8	2#8	0.48	2#8	2#4 30@7.00
508	0.8	2#8	0.48	2#8	2#4 19@7.00
509	0.8	2#8	0.48	2#8	2#4 19@7.00
510	0.8	2#8	0.48	2#8	2#4 19@7.00
511	1.14	2#8	0.14	2#8	2#4 19@7.00
512	0.12	2#8	1.16	2#8	2#4 19@7.00
513	1.27	2#8	1.61	3#8	2#4 16@11.00
514	1.8	3#8	1.08	2#8	2#4 19@11.00
515	1.8	3#8	1.08	2#8	2#4 19@11.00
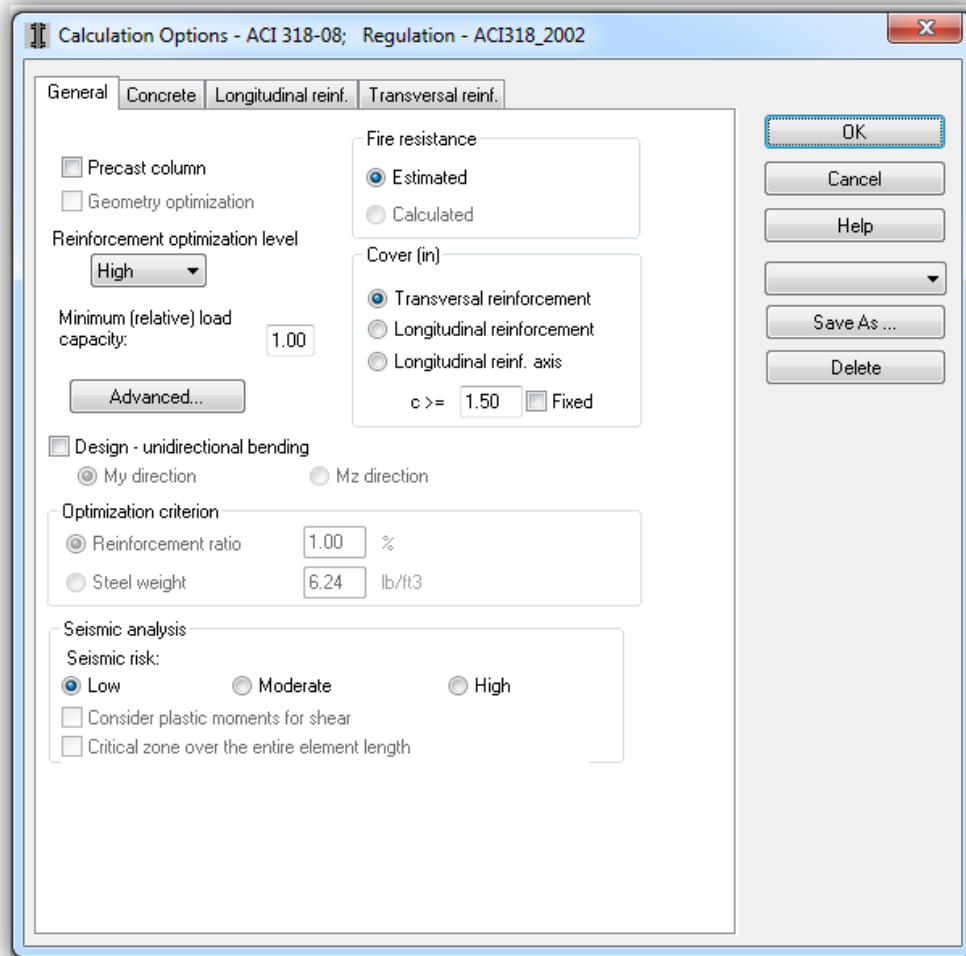
Figure 34 Robot Design Options per ACI 318-08

The provided reinforcement module also prepares calculation notes for every member designed and specification drawings for selected members. The calculation notes allow for manual verification of calculations providing material surveys, geometry, load combinations accounted for as well as which codes were used for calculations, reinforcement ratios and print outs of all factors applied to each column. A sample results portion of a single columns calculation note is provided below in Figure 35

2.5 Calculation results:

2.5.1 ULS Analysis
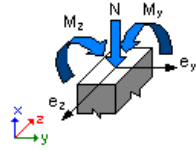
Design combination: 9-4T (A)
$\phi = 0.65$
Internal forces:
N = 273.78 (kip) My = 234.09 (kip*ft)   Mz = 23.29 (kip*ft)

Design forces:
Upper node
N = 273.78 (kip) My = 234.09 (kip*ft)   Mz = 23.29 (kip*ft)

2.5.1.1 Detailed analysis-Direction Y:

2.5.1.1.1 Critical force

Pc = 2141.01 (kip)   (10-13)
   k*lu = 13.58 (ft)
    EI = 40024.97 (kip*ft2)   (10-14)
     βd = 1.00
     Ec = 4300.62 (ksi)
     Es = 29000.02 (ksi)
     Ig = 5461.33 (in4)
     Ise = 235.51 (in4)

2.5.1.1.2 Slenderness analysis

Non-sway structure

l_u (ft)	k	k^*l_u (ft)
13.58	1.00	13.58

k*luy/ry = 35.29 < 40.00   Short column   (10-7)

2.5.1.1.3 Buckling analysis

M1 = -209.82 (kip*ft)   M2 = 234.09 (kip*ft)
Case: Cross-section at the column end (Upper node), Slenderness not taken into account
M = 234.09 (kip*ft)
Mc = M = 234.09 (kip*ft)

2.5.1.2 Detailed analysis-Direction Z:

M1 = 2.64 (kip*ft)   M2 = 23.29 (kip*ft)
Case: Cross-section at the column end (Upper node), Slenderness not taken into account
M = 23.29 (kip*ft)
Mc = M = 23.29 (kip*ft)

2.5.2 Reinforcement:

Ratio: $\mu = Asr/Ag = 3.52\%$

Figure 35 Concrete Column Results

Once the entire structure is finalized the Robot extension in Revit Structures can be used to update the entire project with any changes that may have been made during the course of the Robot analysis and design. Depending on the options selected aspects of the project which were not presented prior to export, namely the newly added structural rebar, can be added to

the project. Figure 36 below shows an updated Revit Structures model for a concrete building with the newly added rebar.
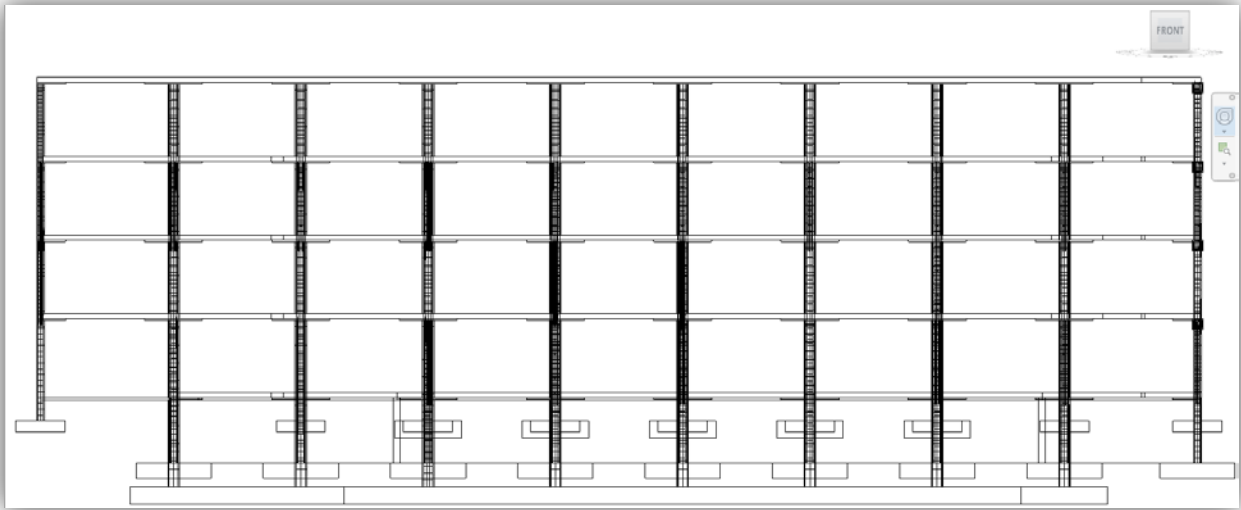
Figure 36 Concrete Model with Added Rebar

6.0 Design Assessment: Architectural Impacts

One of the measures of each structural design was the impacts it would have on the architectural layout of the building. Since the architectural constraints needed to be minimized any system designed would have to be feasible not only structurally but also architecturally. Additionally any needs of the developer and eventual tenants would also be an aspect of the flexibility of the design.

6.1 Alternative Steel

The laterally braced steel frame design was a system which was a much more structurally conservative system when compared to the steel moment frame. Building costs were generally lower and resulted in a more economically competitive design. There were however, some aspects of the design which could have resulted in an eliminating the design depending on the needs of the building.

6.1.1 Addition of Permanent Walls

One of biggest alterations to the architectural model was the addition of walls. These walls would close in the lateral bracing structure thereby being a permanent aspect of the building, though the walls themselves need not be structural. One set of bracing was already placed in a shaft structure used to run mechanical systems between the floors and did not need to be enclosed. Figure 37 shows the third floor architectural plan view showing the added wall enclosure for the lateral bracing.

a   b
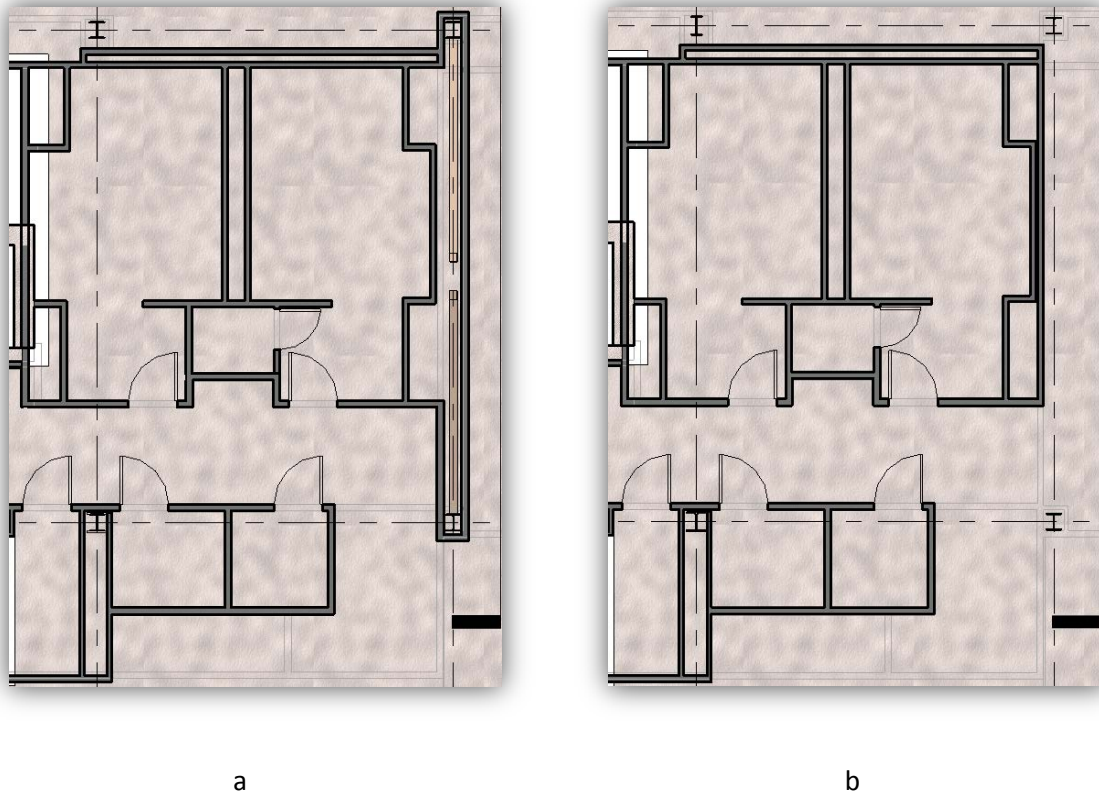
Figure 37 Architectural Model with (a) Steel Moment Frame (b) Laterally Braced Frame

6.1.2 Movement of Doors

In one instance the laterally braced frame required moving the location of one door so that it would not conflict with the location of the bracing. Shown below in Figure 38, the laterally braced frame places the door on the opposite side of the room. This was a relatively small impact since the room was designated as closet space.
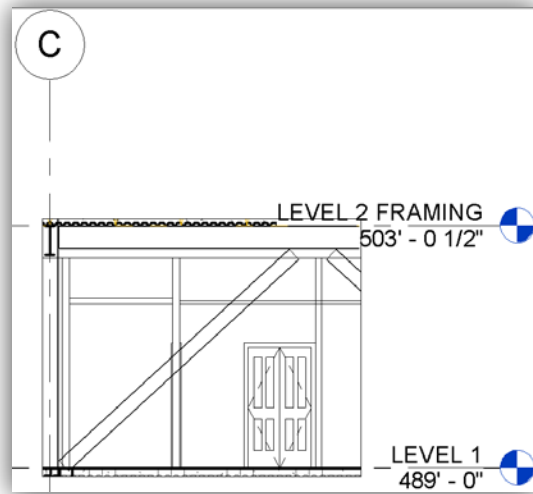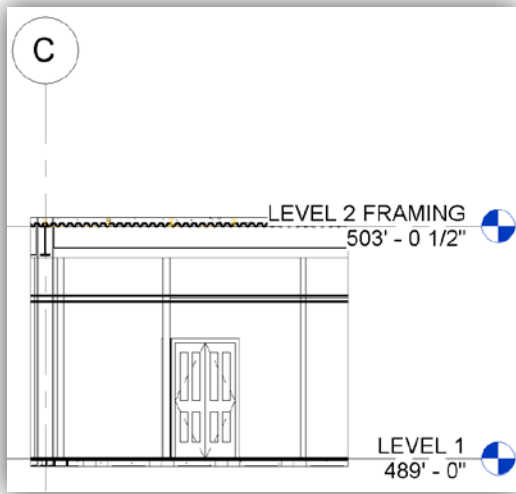
a   b

Figure 38 Door Placement for (a) Moment Frame (b) Laterally Braced Frame

6.2 Alternative Concrete

The proposed concrete sway frame had one main architectural impact which resulted in fairly significant modifications. Additional steps could be taken to elements of the building to mitigate these impacts but were outside the scope of work of this project.

6.2.1 Architectural Impacts

Because of the removal of the steel beams the floor to floor heights were dropped by 13". Calculations for minimum floor-to-floor heights can be found in Appendix C. Since the floor to ceiling heights remained the same the clearances were not an issue nor were the placement of interior partitions. What was affected by the change in height was the number of windows that could be placed in one of the offices. The elevation of the third floor was dropped 26" while the annex height remained unchanged. The original view from the office had the annex roof at 4' 3.5", as shown in Figure 39, above the 3rd story finish floor which would be above eye level for most people. Once the elevations were dropped the annex roof was located 6' 5.5" above the finish floor height, above the average person's height as shown in Figure 40. As such it was decided that the windows would be removed from the model.

Figure 39 Original Model Elevation Difference

Figure 40 Dropped Model Elevation Difference
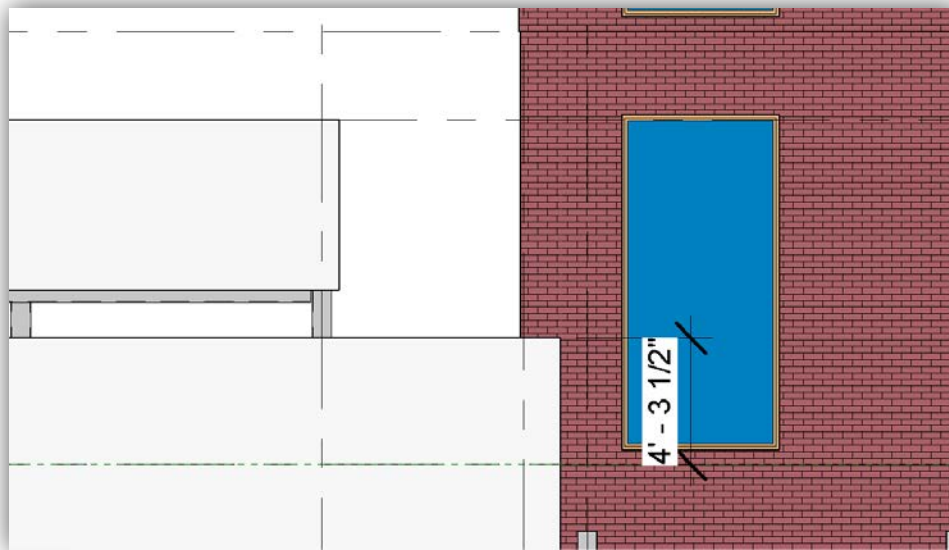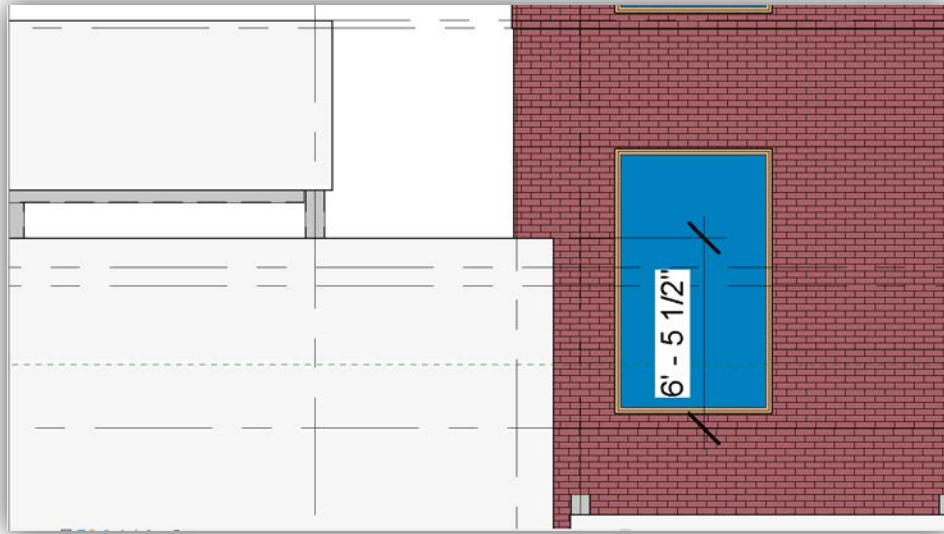
7.0 Estimate

To evaluate the feasibility of our alternative designs 3 different estimates, one for the existing structure to serve as a baseline and two for the newly proposed structures, using R.S. Means cost data and CSI Master Format divisions. Although a rough cost for the core and shell was obtained from the project manager of the actual building a baseline estimate was created to ensure consistency between each type of estimate. Since the midpoint of the project was in mid-December 2011 we chose to use the 2011 cost data. Additionally the Costworks 2011 software was used to simplify the estimate creation since it used the 2011 R.S. Means cost database, broke down items according to Master Format and automatically applied location adjustments for unit prices. The Revit Architectural and Structural models were used to perform quantity take-offs for the items to be estimated. For simplified comparison the estimate was broken down into 5 categories: foundations, columns, horizontal framing system, curtain wall & brick veneer and miscellaneous.

7.1 Baseline Estimate

The baseline schedule of the existing structure was generated in order to accurately compare and contrast the costs of the newly redesigned systems. This allowed us to stay consistent with the RS Means cost data and not introduce any new variables due to local market conditions since we could not receive bids from contractors to make comparisons. Detailed baseline estimate can be found in Appendix N.

The Revit Structures model was used to perform quantity take-offs which were applied to the RS Means database to calculate costs. The structural model included spread footing foundations, steel beams, columns, a composite metal deck and basic steel connections. The fireproofing was applied using Revit values but was not modeled directly. While performing the cost estimate for the beams and columns we found that RS Means Construction Cost database does not contain prices for certain beams used on the project. Based on the existing values we extrapolated the costs for materials, labor, and equipment for each steel member, which could be seen in the following graph for a 12 in deep Wide Flange beam.

Table 8 Relation Between Depth and Cost for W12 Beam
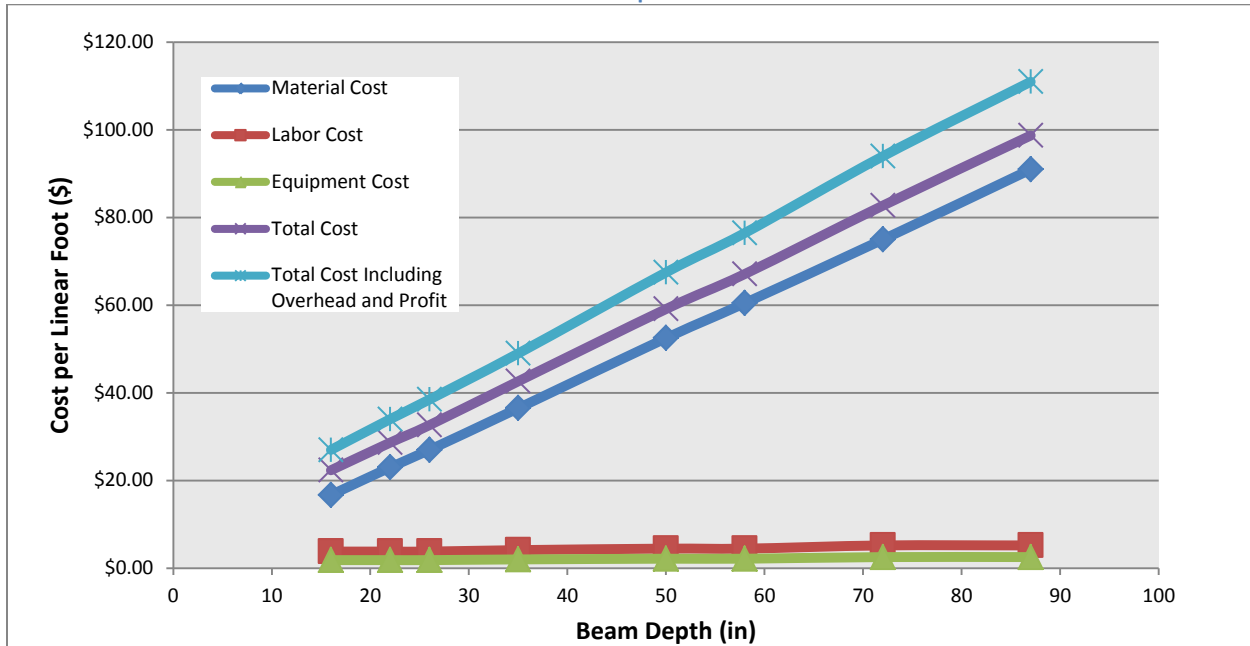
Additionally since the slab was resting on corrugated metal decking we found dimensions for a typical metal deck from DEK-Ing Specialty Warehouse Inc (Figure 41). These dimensions were used to adjust the actual value of concrete required for our slab.
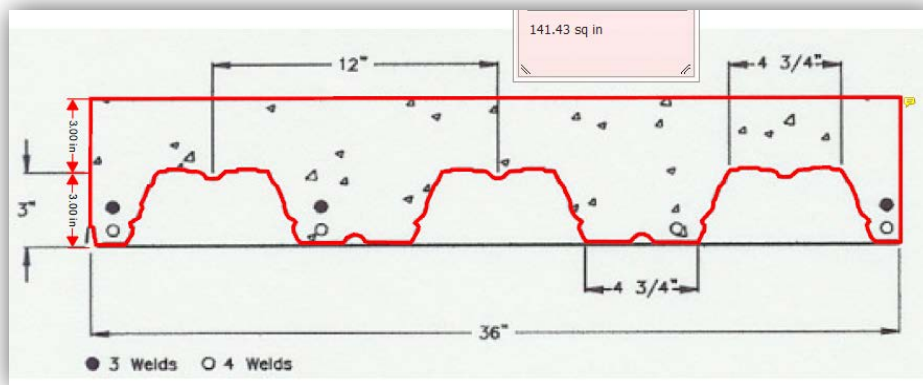
Figure 41 3" Composite Cellular Galvanized Steel Decking (DEK-Ing Specialty Warehouse Inc)

From our calculations we found that approximately 1561.6 cubic yards of concrete was required for the slab on metal decking. Quantities and prices for wire fabric and metal decking were also estimated based on the RS means cost data

The fireproofing for beams and columns were calculated by determining the surface area of the exposed steel members. The project manual also stated that the annex would only be fireproofed to 20 feet above the grade. This helped reduce the cost by eliminating the need to fireproof the entire underside of the annex roof.

Due to the architectural constraints presented the structural engineers chose to create a moment frame steel system. This type of framing is typically the costlier option when compared to a lateral bracing system due to the need to field weld moment resisting connections as well as the larger steel sections required for the frames. Since RS Means assumes bolted connections additional steps had to be taken to ensure that the field welds and column plate stiffeners were fully accounted for. This would allow us to create an accurate comparison of the two different types of systems.
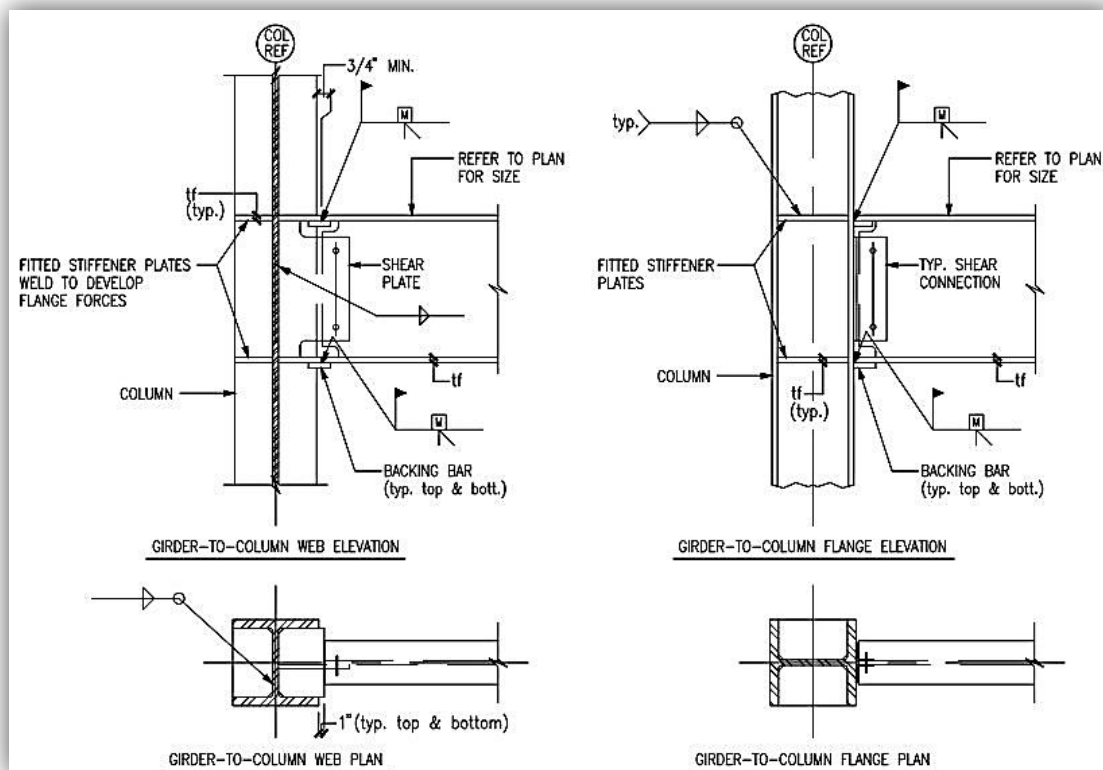
Figure 42 Typical Moment Connection Details
(McNamara/Salvia Inc., S-402)

There were a total of 110 moment connections in the entire structure which consisted of two types of moment connections: girder to column web and girder to column flange. Each

moment connection weld required the use of a backing bar which was temporarily welded to the bottom of each connecting flange with a 5/16 in fillet weld. The flanges of the girders were then welded to the columns by a complete joint penetration weld and the backing bars then removed. This was followed by another 5/16 in fillet weld pass to complete one connection. Column web stiffeners, which would allow for full development of the flange forces, were to be shop welded to the column as continuations of the attaching girder flanges. Unfortunately since RS Means does not include shop welds we decided to exclude the cost of the backing bars to account for the additional cost of filed welding the web stiffeners. Since the depth of the welds and web stiffeners varied depending on the size of the member each connection was referenced against an AISC Steel Construction Manual for flange thicknesses. This also meant that some values for welds had to be extrapolated from existing values available in RS Means. The cost of welds did not increase in a linear fashion and Microsoft Excel "Trend line" function was used to derive equations to estimate weld prices. This can be seen in Table 9.

Table 9 Cost of Field Welds vs Weld Thickness
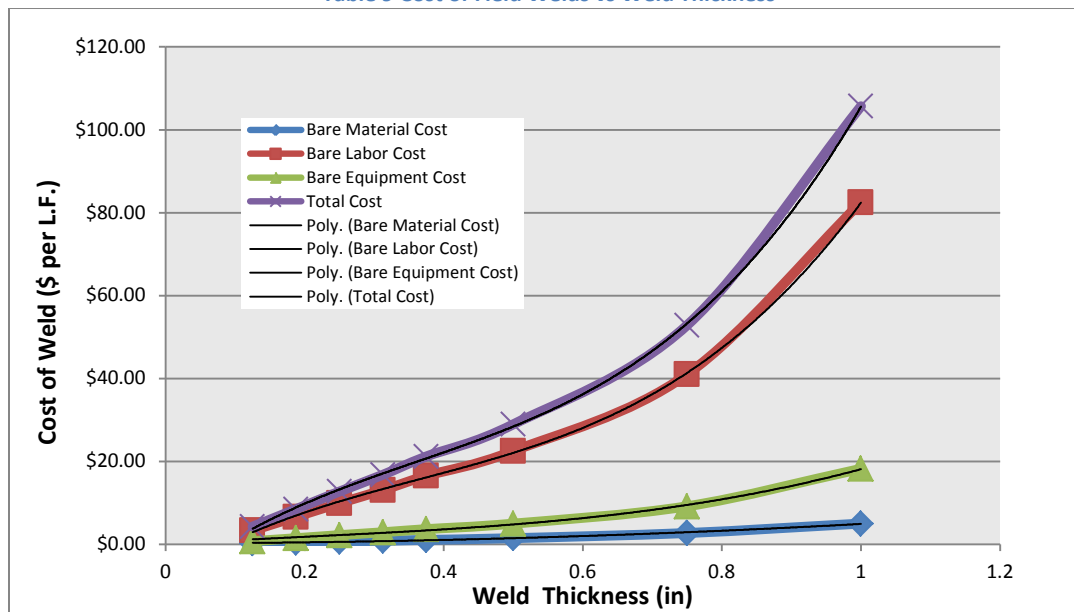
A detailed table containing weld thickness, web stiffener areas and other values used in calculating the weld costs can be found in Appendix M.

7.2 Alternative Lateral Bracing System Estimate

The estimate for the laterally braced steel frame was identical to the steel sway frame estimate. The few differences were the quantities of steel due to the removal of the moment frame steel and replacing them with typical gravity frames and the addition of new HSS members for the lateral braces. The quantity of fireproofing was also updated based on the new surface area of the steel frame. Field welds were completely removed and replaced with newly sized welds based on the Robot Structural Analysis software results. All other quantities remained unchanged. Detailed estimate for Alternative Lateral Bracing System can be found in Appendix O.

7.3 Cast-in-Place Estimate

The cost estimate for the cast-in-place concrete was performed in a similar manner to the steel frame, but was a much simpler process. The quantities of concrete were extracted from the Revit Structural model based on the usage, resulting in separate take-offs for columns, slab and foundations. Since a material cost was obtained from a local supplier for 5,000 psi concrete the line item for concrete was split between labor and material costs. A detailed estimate for the cast-in-place structural system can be found in Appendix P.

Since there were separate line items depending on the size of the concrete column the take-off was separated based on size, namely the interior and exterior columns. Once the columns were separated according to size the contact square footage and volumes for the columns were input to estimate labor and formwork for each type. The rebar values for the columns were exported from the Robot Structural Analysis model into the Revit model and estimated according to the tonnages required.

The slab values were broken down into contact square footage for formwork costs as well as volume for labor and material costs. Since the rebar quantities for the slab could not be exported back into the Revit model the quantities were taken directly from Robot Structural Analysis and input into the prepared template. Since the drop panel quantities were not estimated with the columns they were isolated and estimated as 3.5 inch slabs. The foundations were estimated as single items depending on whether they were mat foundations or spread footings.

7.4 Brick Veneer & Curtain Wall

The Architectural model was used to prepare a quantity take off for the exterior façade of the building. The brick veneer was estimated according to the components which were specified in the architectural plans as shown in Figure 43. These elements were combined into a total cost per square footage which was then applied to the total square footage to estimate the cost. The same was done for the curtain wall system and the two estimates were added to create an estimate for the exterior façade. Once the architectural model for the steel moment frame was completed another model was created with lowered inter-story heights. The square footages of each model were applied to the prepared templates to find the façade costs for each type of system, summarized below in
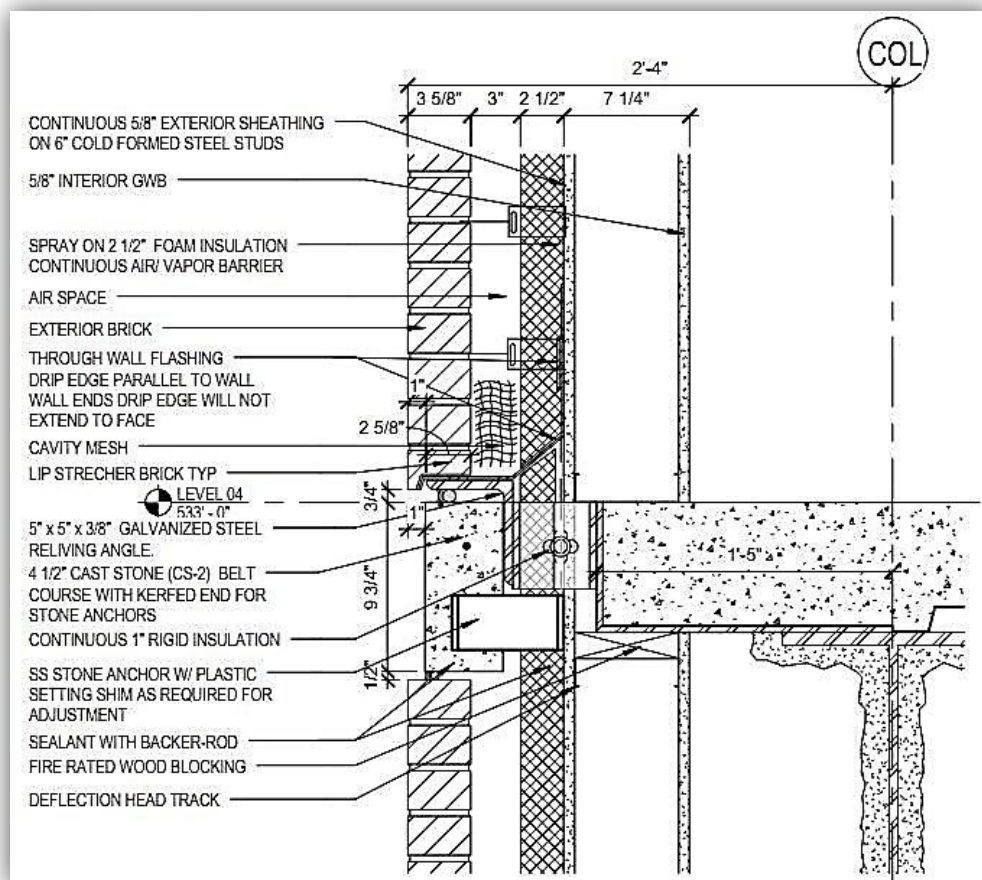
Table 10, Table 11, and Table 12.

Figure 43 Slab Edge Detail @ Exterior Wall
(Perkins + Will, A-420)

Table 10 Brick Veneer Cost

Description	Cost (per sq.ft.)
Metal stud partition, non-load bearing, galvanized, 12'high, 6" wide, 20 gauge, 16" O.C., includes top & bottom track	$2.69
Oversized brick, veneer, 4" x 2.25" x 16"	$16.10
Sheathing, plywood on walls, CDX, 5/8" thick	$1.99
Insulation, polyurethane foam, 2#/CF density, 2" thick, R13, sprayed	$1.74
Total	**$22.52**

Table 11 Curtain Wall Cost

Description	Cost (per sq.ft.)
Curtain wall, aluminum, stock, double glazed, including glazing, average	$86.50
Total	**$86.50**

Table 12 Quantities from Revit for Brick Veneer & Curtain Wall

	Brick Veneer Area (sq.ft.)	Curtain Wall Area (sq.ft.)
Moment Frame Steel	25,436.00	8,051.00
Laterally Braced Steel	25,436.00	8,051.00
Cast-in-Place Reinforced Concrete	23,516.00	7,231.00

7.5 Comparison and Conclusions

The various portions of the estimates were combined into the three estimates, one for each type of proposed system. The items included in each estimate were grouped according to the five different categories previously created. A summary of what was included in each is located below in Table 13. The total cost of structural system and exterior façade were combined into a total cost in Table 14 below.

Table 13 Estimate Categories[1]

	Moment Frame Steel & Laterally Braced Steel	Cast-in-place Reinforced Concrete[2]
Foundations	Spread Footings	Spread Footings Foundation Mat
Columns	Steel Columns	Concrete for Columns Columns Steel Reinforcement
Horizontal Framing System	Steel Beams and Girders Metal Decking Concrete for Slabs Slab Wire-Mesh Shear Studs Field Welds	Concrete for Slabs Slab Reinforcement
Miscellaneous	Sprayed Cementitious Fireproofing	Formwork
Curtain Wall & Brick Veneer	Brick Veneer System Curtain Wall	

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[1] Other items such as material delivery and placement were also included in the estimate.
[2] Cast-in-Place Concrete Estimate also includes the cost of the annex which is constructed out of structural steel.

<div align="center">Table 14 Estimate Comparison</div>

	Moment Frame Steel	Laterally Braced Steel	Cast-in-place Reinforced Concrete
Foundations	$ 203,962.34	$ 203,962.34	$ 290,167.92
Columns	$ 306,138.52	$ 219,509.06	$ 232,034.99
Horizontal Framing System	$ 1,634,399.57	$ 1,543,072.71	$ 1,046,475.34
Miscellaneous	$ 290,617.62	$ 209,253.26	$ 767,109.78
Curtain Wall & Brick Veneer	$ 1,269,230.22	$ 1,269,230.22	$ 1,155,061.82
Total	**$ 3,704,348.27**	**$ 3,445,027.59**	**$ 3,490,849.85**

Both alternate structural systems were more economical when compared to the original estimate. Overall the laterally braced frame was 7% cheaper than the steel moment frame with a savings of approximately $259,000 while the concrete was 5.8% cheaper with a savings of approximately $213,000. Based purely on cost the steel lateral frame would be the best framing option, however there are numerous factors which could play an important decision on framing type. One important aspect of the estimate is that it does not reflect current market prices. The actual labor and material costs could vary depending on the region, time and market trends and so should be estimated based on bid packages.

The prices for each structural system were compared to a UniFormat cost based on square footages, framing type, bay size, and loading. The costs were then adjusted for location and multiplied by the square footage of the entire building. The cost per square foot for the reinforced concrete system was adjusted to $20.81 and the steel frames, both the sway and laterally braced frame, were adjusted to $24.34. A summary of the cost comparisons are located in Table 15. Because of this we can expect overall that a structural system construction utilizing cast-in-place concrete to be more economical than a system constructed out of structural steel.

<div align="center">Table 15 Comparison of MasterFormat and UniFormat Costs</div>

	MasterFormat	UniFormat
Moment Frame Steel	$2,231,155.71	$2,239,574.4
Laterally Braced Steel	$1,971,835.03	$2,239,574.4
Cast-in-Place Reinforced Concrete	$2,045,620.11	$1,914,556.80

8.0 Scheduling

Project scheduling is vital and directly associated with project planning and direct/indirect costs. It involves the anticipation and identification of all the work required to construct the project and is driven by the owner's need. It provides a baseline to measure progress throughout the project and monitor material quantities and costs. Three schedules were developed for this project in order to accurately evaluate the structural systems designed. All durations for major work activities and packages were based off RS Means work item descriptions and values. The material quantities were obtained from Autodesk Revit Architecture and Revit Structures in the same manner as the estimate, but were further grouped and sorted by floor. The software program Primavera version 6 was used to develop the schedules. Following the original schedule provided by DOC the structural frame construction was scheduled to start May 18th 2011 in each schedule. The annex frame was not included in the any of the scheduling since it was maintained as a steel frame building in each design and was not altered.

8.1 Concrete Schedule

The conventional metal formwork system was chosen despite typically having higher initial costs because of the number of times they could be reused when compared to wooden forms. It was assumed that the high initial cost would be offset by the high number of reuses in conjunction with the building's repetitive member sizes and uniform spacing.

Table 16 displays generic cost deduction factors based on the number of formwork reuses.

Table 16 Effect of Reuse of Concrete Formwork
(Adapted from Hanna 1999, P 152)

Number of Uses	Cost per Square Foot of Contact Area[3]	Cost per Square Meter of Contact Area
One	1.00	10.76
Two	0.62	6.67
Three	0.5	5.38
Four	0.44	4.74
Five	0.4	4.31
Six	0.37	3.98
Seven	0.36	3.88
Eight	0.35	3.77
Nine	0.33	3.55
Ten	0.32	3.44

To develop a more accurate construction floor cycle in the building it was decided to incorporate and account for re-shoring in the schedule. Re-shores are vertical supporting members placed underneath structural elements such as slabs where large areas of formwork have been stripped; the structural element must deflect and support its self-weight and construction live loads prior to re-shore installation (ACI 2005, P 3). The combination of shores and re-shores in the construction of the floor slabs allow more trades greater flexibility to move and work.

ACI recommends formwork can be safely stripped for slab spans over 20 feet between 7 to 10 days (ACI 2004, P 14). Since re- shoring is installed once the poured slab has had sufficient time to cure and obtain a substantial portion of its design strength it was assumed that at the time of stripping formwork re-shoring could promptly begin. Re-shoring in the schedule was placed with a 5 day lag after slab pours since Primavera schedules standard 5 day work weeks. The concrete Gant chart and list of activities with durations is shown in Figure 44. The breakdown of major building elements by item description with their respective calculated durations can be found in Appendix Q.

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[3] Cost based on one use equal to 1.00
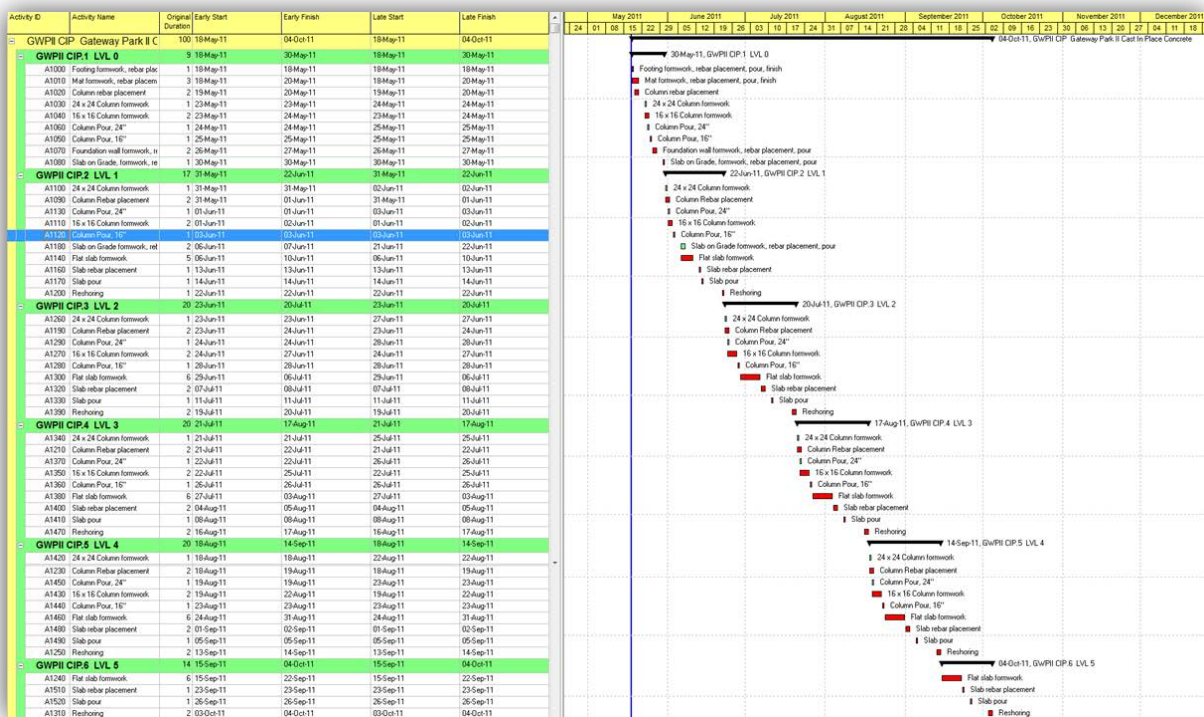
Figure 44 Cast In Place Concrete Building Gant Chart and Activities

8.2 Steel Frame Schedule

The DOC provided the original schedule sent for bidding but it was decided to construct a schedule for the original steel frame building based of RS Means values to ensure compatibility and consistency between work items and values used. The moment frame design in comparison to the laterally braced design comprised of the same major work items differing greatly in the durations of field welds and fire proofing. The steel moment frame and laterally braced frame schedules are displayed in Figure 45 and Figure 46 respectively. Breakdown for both schedules can be found in Appendix Q.
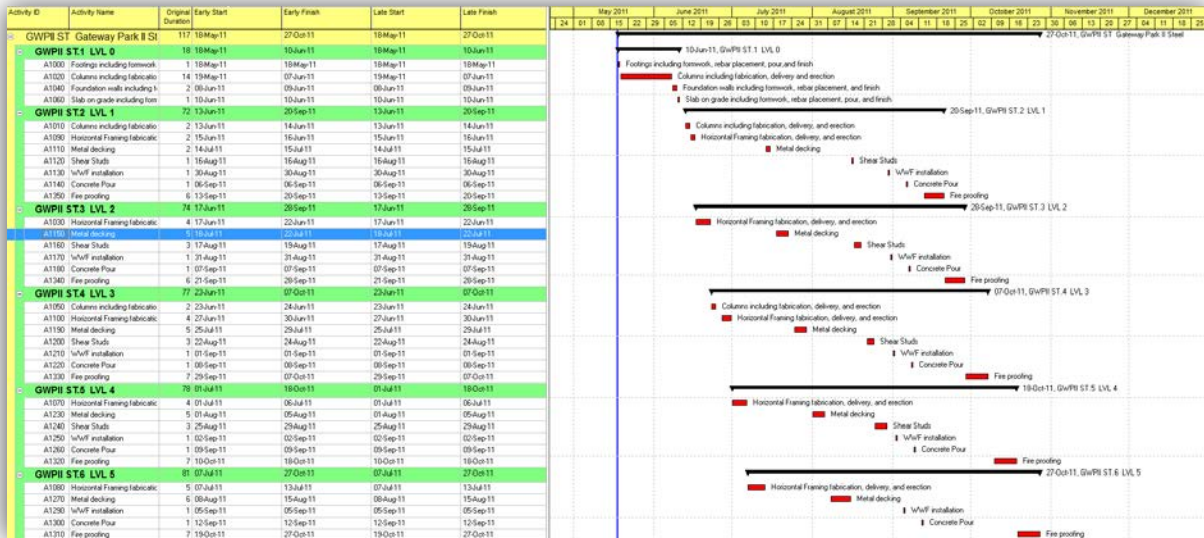
Figure 45 Steel Moment Frame Gant Chart and Activities
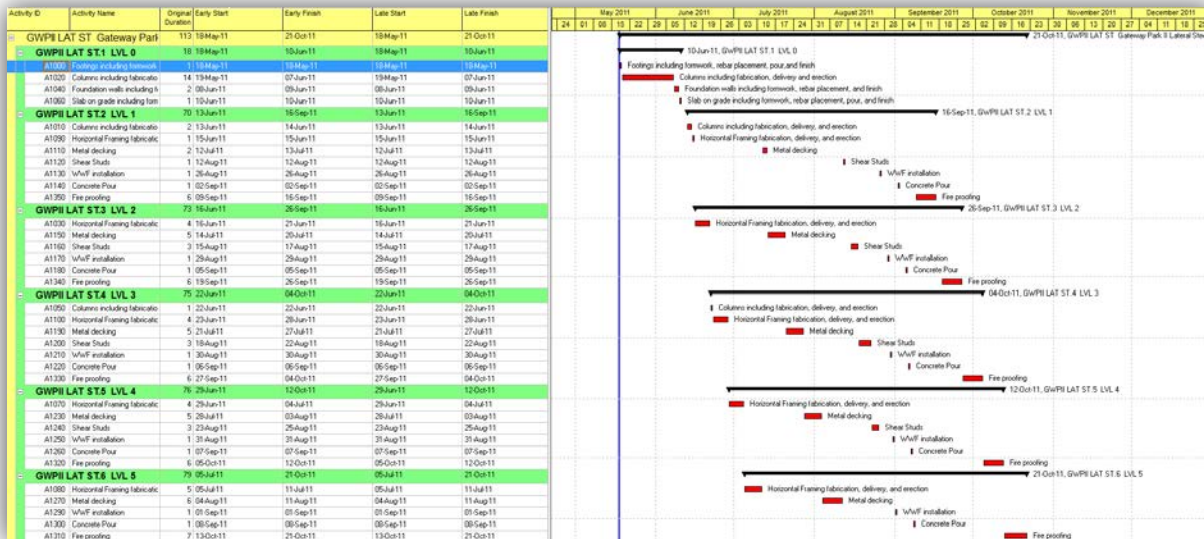
Figure 46 Laterally Braced Steel Frame Gant Chart and Activities

8.3 Schedule Summaries

Comparing all three schedules the shortest construction duration was obtained with the cast-in-place concrete building. A shorter schedule was able to be developed for the following reasons:

1. Concrete has a shorter material procurement time in comparison to steel construction

2. The building was designed with uniform column and drop panel dimensions to facilitate construction speed
3. There was no need for fire proofing.

The laterally braced frame and moment steel frame were very similar in schedule only differing in the time allocated for field wields and spray on fire proofing. As a result the laterally braced designed building trimmed 6 days of the completion date since it contained less of latter work items mentioned. The final completion dates for each schedule are shown below in.

Figure 47: Construction Schedule Comparison

9.0 Conclusion of Report and Recommendations

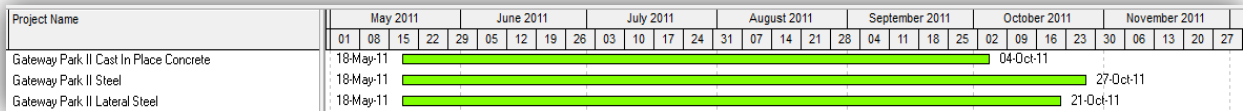The project investigated two alternate structural designs that maintained the layout and the building, with prepared cost estimates and schedules for both design. Each structural design included building proportioning, individual member sizing, foundation design, and impacts on architectural elements. Estimates for each framing plan were prepared based on Masterformat values using CostWorks software. These were compared to a baseline estimate prepared in the same manner to ensure consistency and accuracy. Schedules for each system were created based on the estimate line items and submitted as a portion of the deliverable. Additionally a set of guidelines were developed regarding modeling practices for the development of a Revit Structures model with the intent of exporting the model for analysis into a building analysis software package.

The structural design involved a multi-step process which involved both material and framing selection, building proportioning conforming to building and design codes, modeling of the proposed structure, and software analysis of the completed building. Both building designs were taken to the same stage of completion after which cost estimates were prepared.

The cost estimates were prepared to determine how economically feasible each design would be. A baseline estimate was prepared instead of using the values provided by Daniel O'Connell Sons Inc. to ensure the estimates would be comparable. The cost estimates showed that the core and shell cost would range from $3.4 million to $3.7 million depending on the type of frame used.

The estimates were then used to prepare preliminary schedules which were compared to a developed baseline schedule of the steel moment frame building. The initial schedule showed that the concrete moment frame would be a framing system which would provide the shortest construction time and grant the most control to the project managers. The results from all three components were then combined to make a final recommendation as to which framing type should be used.

On a purely economic basis the most efficient design would be the laterally braced steel frame saving approximately 7% of the core and shell costs of the building. However once the use of the building was taken into account as well as the fact that the top two stories are

currently unoccupied both the originally designed steel moment frame and the redesigned cast-in-place concrete system would provide more flexible and adaptable space. Based on the estimates a concrete framing system would be the most economical and flexible option. The only issue which could affect the feasibility of the framing system would be the availability of contractors who could handle the scope of work involved.

Another significant portion of the project was the use of BIM tools and the development of a set of guidelines. The guidelines were prepared using the information gathered during the duration of the project and allowed for a much more in-depth analysis than a typical Major Qualifying Project. While there are evident flaws in the software packages themselves as well as the flow of information connecting various programs, the overall effect of using BIM tools provided a great benefit to the entire design and analysis process.

The large scope of work involved in the project resulted in several issues being unresolved. While Scia engineer is an excellent tool with the current lack of support for American codes it is not fully prepared for an American market. One area that was not explored was the ability to produce shop drawings for fabricators. While structural plans were created, Revit also boasts the ability to create detail drawings which was not explored. The flow of information between Robot, Revit and the programs typically used by fabricators such as Tekla is one that would truly benefit the AEC industry.

This project was an excellent culmination of the education provided by WPI and the Civil Engineering program. The focus on information flow and communication through the entire project emulated real-world work scenarios and shifted the focus from individual work to interdisciplinary collaboration. The scope of work was also very broad encompassing large aspects of building design without sacrificing the level of detail that each aspect could be explored in, enabled by the usage of software and close communication between project parties.

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11.0 Schedule

TASK	A Term (Week) 1	2	3	4	5	6	7	B Term (Week) 1	2	3	4	5	6	7	C Term (Week) 1	2	3	4	5	6	7	D Term (Week) 1	2	3	4	5	6	7	COMPLETED BY[4]
Determine Scope of Work	■	■	■	■	■	■																							L, N, A
Identify BIM Packaged	■	■	■	■	■	■																							L, N, A
Background Research	■	■	■	■	■	■																							L, N, A
Proposal																													
Proposal First Draft		■	■	■	■																								L, N, A
Proposal Final Draft						■																							L, N, A
Models																													
Revit Architecture	■	■	■	■	■	■	■	■	■	■																			L, N
Steel Revit Structure	■	■	■	■	■	■	■	■	■																				L, N
Concrete Revit Structure											■	■	■	■	■	■	■												L, N
Alternative Steel Revit Structure																					■	■	■						N
Software Analysis of Models																													
Existing Steel Model											■	■																	L, N
Concrete Model															■	■	■												L, N
Alternative Steel Model																						■	■						N
Design																													
Concrete Model										■	■	■	■		■	■	■												L, N, A
Alternative Steel																						■	■						N, L
Interoperability Issues																													
Revit Structure model → Scia								■	■	■	■	■			■	■													L, N
Revit Structure model → ROBOT								■	■	■	■	■			■	■	■												A, N
PM Portion																													
Material Take offs in Revit Structure															■	■	■	■	■		■								L
Estimates																		■	■			■	■						L
Construction Schedule Comparison																			■	■		■	■						A
Results and Conclusion																		■	■	■									L, N, A
MQP Report First Draft																		■	■	■									L, N, A
MQP Report Final Draft																									■	■	■		L, N, A
Complete Poster																								■	■				L, N, A

12.0 Appendices