Project No. LDA-1502

Feasibility Study of 89 Shrewsbury Street

Worcester, Massachusetts

A Major Qualifying Project

Submitted to the Faculty of

Worcester Polytechnic Institute

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

in

Civil Engineering

By

____

Matthew Deptula

____

Sara Beth Leach

____

Benjamin Morse

Date: 3/26/2015

Project Advisor:

____

Professor Leonard Albano, Advisor

Table of Contents

Table of Figures

Table of Tables

Abstract

This project performs a feasibility study of a residential design and a commercial design to retrofit the existing brick mill building at 89 Shrewsbury Street in Worcester, MA. Each design includes structural modifications, an automatic sprinkler system, and compliance to building codes including egress methods, accessibility, and fire protection. Each design is suited with recommended sustainable design aspects to promote green building, sustainability, and potential cost-saving benefits. A cost analysis compares both proposed alternatives and recommends which will be the better option in terms of return on investment. This project's intent is to form a methodology for future renovations of similar buildings by using 89 Shrewsbury Street as a case study.

Authorship Page

The team worked evenly on the project design. Benjamin Morse was primarily responsible for the fire protection system design and analysis of steel members. Sara Beth Leach was primarily responsible for the wood analysis, masonry wall analysis, and structural modifications. Matthew Deptula was primarily responsible for sustainability design and cost estimation. All members contributed evenly to the drafting and editing phases of the paper.

Capstone Design Statement

Worcester Polytechnic Institute's (WPI) Major Qualifying Project (MQP) involves the application of a student's skills acquired through their academic course work while applying engineering standards and realistic constraints. This MQP performs a feasibility study on two proposed designs to be retrofitted to 89 Shrewsbury Street in Worcester, MA. The two proposed designs are a residential building and a commercial office building. This study focuses on specific design aspects including structural modifications to the existing building, compliance with local building codes, addition of an automatic sprinkler system, and inclusion of sustainability elements. This project provides recommendations as to which design is more favorable for a potential purchaser through a cost analysis that compares both designs to constructability costs and potential return on investment. This MQP applies realistic constraints that include economics, constructability, ethics, environment and sustainability, as well as health and safety.

Economics and Constructability

Each proposed design involved modifying the existing plans with architectural and structural elements to ensure structural integrity as well as compliance to code. Throughout this process, economic feasibility was considered. In determining the selection of building materials and members, the lowest cost solution was chosen. Different materials and member sizes were analyzed and selected based on cost effectiveness to ensure both designs have the lowest constructability costs. Material takeoff was performed to determine the quantity of materials and known material costs were utilized either on a square footage or a quantity basis to determine the best design option for the building.

These choices also reflect the easiest and most efficient methods for construction. This concept of constructability goes hand in hand with economics in terms of labor costs and item availability. These two concepts combine to ensure the construction is as inexpensive and efficient as possible.

Environment and Sustainability

This project is designed with consideration to the environment as well as sustainable design methods. Potential sustainable technology aspects are investigated and applied to each design if determined to be feasible. Technologies such as energy reduction through efficient lighting and appliances and rainwater management are investigated. These systems provide reasonable and sustainable methods that, along with the reuse of an existing building, will promote green building and sustainability in the civil engineering field in the future.

Health and Safety

One of the most important aspects of this project is safety. Safety of the occupants is essential in building design and the safety aspects within the scope of our design were adhered to through building code compliance. Standards written by the International Code Council and the National Fire Protection Association were followed to incorporate egress methods, accessibility, and fire protection systems. Following these standards provides a safe living environment that is crucial to potential future buyers and inhabitants. Furthermore the adherence to codes and standards such as *ASCE 7* and the *Massachusetts State Building Code* ensured that the structural modifications would provide reasonable safety and well-being to the inhabitants.

Ethics

It is implied throughout the course of this project that the ASCE Code of Ethics will be abided by strictly. Ethics are and should be considered in every decision a civil engineer makes throughout his or her career. As stated directly in the ASCE Code of Ethics, these moral values "uphold and advance the integrity, honor, and dignity of the engineering profession," and will constitute our entire thought process through honesty, professionalism, and dignity. Examples include performing our design analysis to the upmost of our abilities and providing recommendations which will further sustainability efforts for future renovation projects.

Professional Licensure

Professional licensing is the process of receiving accreditation from the licensing board of the intended State of practice validating the qualifications of a professional service. The major federal organization for licensure oversight is the National Council of Examiners for Engineering and Surveying (NCEES). As part of their duties, the NCEES creates the study materials, performs credentials evaluations, and develops and grades the licensing examinations. Each state along with the territories of the United States has members on the NCEES's council. Aside from this national advisory council, the individual states establish the requirements for licenses, which includes the application and approval process.

The Commonwealth of Massachusetts requires four main steps in the application process for registration of a professional license. They are as follows:

1. Meet all the requirements of law (character references, experience, etc.)
2. Pass the required examinations
3. Receive Board review and approval
4. Pay the registration fee

A table produced on the Massachusetts government website concerning licensing summarizes the necessary requirements for certification. The following excerpted section is the one most applicable to our specific experience:

250 CMR 3.04(4): Table I Engineering Application Requirements

Education Requirements	Engineering Experience	FE Exam	PE Exam	Interview	Reference
A Bachelor of Science degree in engineering from an ABET accredited program.	4 years	Yes	Yes	No	M.G.L.c. 112, § 81J (1)(b)

After completion of the items in the above table, the appropriate application forms must be completed and sent to the local licensing board. After review of the documents, work experience, and interviews the individual will hear of their acceptance or rejection status.

As stated on the NCEES website, the purpose behind professional licensure is to provide for the public health, safety, and welfare. As with a driver's license, a professional license states that an individual or company has been deemed both qualified and technically competent enough to practice within the state. This certification is extremely important to the public since it guarantees a safe and complete professional service. Similarly, the process of accreditation through professional licensure is important to the profession and industry itself. By ensuring that only competent individuals are allowed to practice, the field, as a whole, is much more reputable. Employers also have a more comprehensive screening process due to licensure, since those without the proper background will not be state certified. Finally, the professionals themselves can also expect greater rewards for their services since they have bolstered qualifications through state accreditation.

Our MQP required finding solutions to problems in a similar manner that we will have to in our future professions. The team performed engineering calculations for structural strength in a similar fashion to professional engineers. We also had to exercise judgment based upon these calculations to determine if the structure was safe or needed renovation and reinforcement. Along these same lines, the team was expected to “overcome engineering challenges” such as determining rainwater management systems, fire protection design, and code compliance. Much like a professional practitioner, these judgments had to be made with safety, affordability, and responsibility in mind.

Chapter 1: Introduction

Close to one-trillion dollars is spent on construction in the United States per year, approximately six percent of the total US economy. Of this, over two-thirds of these expenditures come from the private sector (Census). The industry is directly responsible for employing over six million people (BLS), close to 4% of the current available workforce. And with these numbers being tabulated during one of the worst recessions in American history, it is safe to assume that the totals will only rise, making the industry all the more important. With construction being such an influence on the economy of the country, it is important that the industry is efficient.

The path to efficiency in the construction industry is not always clear. Deciding between building a new structure and retrofitting/renovating an existing building depends on numerous factors. Recently, the trend has leaned toward renovation. There are several reasons that restoration has become the choice of developing business owners. Whenever the construction process includes demolition, removal, and new construction, it is significantly less friendly to the environment. According to the National Trust for Historic Preservation, it takes twenty to thirty years for a new building to compensate for its initial impact. The Trust goes on to state that in some cases, it make take up to eighty years for a building to "overcome…the climate change impacts created by its construction" (NTHP). In extreme circumstances, this time needed to reach equilibrium of efficiency is longer than the lifespan of the building. All this information is crucial to developers, since there are many incentives for green building including tax deductions, subsidies and low interest loans.

Furthermore, in older and densely populated cities, such as those found in the Northeast, space to build is all but extinct. In 2008, only 1.8% of the total commercial building area for the country was from new construction (Energy.gov). This low amount of new construction shows how a majority of businesses are looking for existing buildings to retrofit.

Worcester, Massachusetts is an example of one of these industrialized New England cities. Worcester was incorporated as a city in 1848. Just fewer than 200,000 people live inside the city limits, which is approximately 765 people per square mile. With such a high population density, finding room to build is near impossible. The alternative is to utilize the space currently available in an existing building. Having its roots in manufacturing and industry, Worcester has many such structures that can be renovated for business.

From here, the problem lies in the renovation process. Worcester, being diverse, has many different building types. Due to their age, many of the old mill and textile buildings are not compliant with modern codes. Furthermore, every building was constructed in a different manner, leaving no "secret formula" for retrofitting and modernization. The engineer's job is to manipulate the current structure into its best possible future. This means taking into account several key factors, including sustainability, code compliance, and usage.

Sustainability is a growing factor in new development. Many old buildings, especially those built during the early part of the 20th century, may not have been constructed with environmental friendliness in mind. With new incentives being offered for meeting green building standards, it is in the best interest of the owner to ensure that the building is up to date and green.

Another continuing concern is the need for safety. Building codes and the associated engineering standards are in a constant state of updating. The engineer must understand all aspects of this code and be ready to accommodate them in the design of the building. Some examples include fire protection, size restrictions, and means of egress. Land developers and entrepreneurs are interested in making the most profit. This often means that the engineer must examine multiple uses. The city of Worcester currently has hundreds of restaurants, hotels, and business spaces converted from its old buildings. However, there is no science to determine whether an old building should be converted for one use versus another.

This project examines a specific building in Worcester. The design of an existing, outdated, and non-compliant building is used to develop a methodology that can determine ways to best renovate such buildings. These renovations look to make the building into one that is sustainability oriented, safe, profitable, and a possible example for building renovations in the future.

Chapter 2: Background

Included throughout this section is information pertaining to general concepts that will be referenced throughout the methodology, result, and future sections. These concepts were all known, and established prior to the completion of any work on the project.

2.1 Selected Aspects of the Construction Industry

The two fields of civil engineering and construction are tightly related. The engineer must have a firm understanding of the building process when designing the structure, in order to make sure that the plan is feasible. Hence, a brief background of some important features of the construction industry is included in the following sections.

2.1.1 Economic Scale of the Construction Industry

The construction industry is a large, ever growing, and influential American industry. The United States census tallies monthly the total expenditures in the construction industry. A condensed and reproduced table is included below.

Table 1: Value of Construction Put in Place

Type of Construction	2014 Seasonally Adjusted Annual Rate (millions of dollars)
Total Construction	**$960,958**
Residential	357,234
Non Residential	603,724
Commercial	54,599
Manufacturing	57,004
Total Private Construction	**$685,025**
Residential	351,968
Non Residential	333,327
Commercial	52,773
Manufacturing	56,314

As can be seen, close to one trillion dollars is spent per year on construction. Of this sum, over two-thirds are spent by the private sector, and all of these expenditures are occurring in an economy that is just beginning to muddle out of recession.

The non-residential sector accounts for nearly two thirds of the industry. Renovation and retrofitting of existing buildings comprises a large majority of this cash flow. At the end of 2008, there was approximately 78 billion square feet of commercial building space in the United States. Only 1.8% of this total was new growth (Energy.gov).

2.1.2 Trends to Renovation

The reason behind the large push towards renovation stems from a lack of space to build. With a majority of business in the United States being conducted in cities and with very little room to develop inside city limits, fixing up older or abandoned buildings is the most viable option in establishing a new business. Cost is also a large reason why many business owners choose to remodel existing buildings. The process of demolishing, removing, and rebuilding a large structure could be extremely expensive due to the urban environment. Some of the most costly items of new construction in urban areas are listed below:

- Architectural and engineering costs for new building design
- Cost of demolition
- Cost to remove debris/old structure
- Need to block roadways to perform construction
- Delivery of new materials
- Storage/materials areas need to be off sight

2.1.2.1 Designing Renovation

Like new construction, a renovation must be drawn out and planned. To do this, many different software programs can be used. Highlighted in the project are a few of these. Below are brief descriptions of the ones that were utilized.

2.1.2.2 Building Information Modeling

Building information modeling (BIM) is an emerging technology that started becoming popular in the early 2000s. It is a program that electronically represents the systems and components involved in building. By doing this, it greatly contributes to integrating the design and construction process. It is important to note the difference between BIM and computer-aided design (CAD); BIM also includes elements such as estimating, cost, and project management. Dennis Neeley of SmartBIM states that BIM will catch on much quicker within the construction and engineering industry than CAD and believes the decade leading up to 2020 "will be the most exciting and transitional decade in the history of [the] building industry" (American Architectural Mechanical Association, 2012).

BIM provides the benefits of computer-aided design in addition to its own unique aspects. It allows any changes made in the drawings to be reflected in all other views and associated schedules. It also allows MEP components to be integrated with structural components in one all-inclusive design. It can incorporate time and dollar costs in creating 4D and 5D models to aid in construction project management and to predict and reduce construction costs. BIM also improves collective understanding during the design and construction process by increasing shared knowledge among architects, engineering project managers, and subcontractors. In particular, Autodesk's *Revit* is one of the most well-known BIM software programs on the market today.

2.1.2.3 Structural Design

In modern day building projects structural design practice involves following the building code requirements and the standards set by national organizations. These organizations are separated by material, each providing a set of specifications for the design of specific members made of that material. For example the American Institute of Steel Construction has been publishing specifications for structural steel buildings since June 1, 1923 (American Institute of Steel Construction). Today the nation's industry follows specifications and standards set by the American Institute of Steel Construction, American Concrete Institute, Precast Concrete Institute, and American Wood Council. These standards guide design requirements, are incorporated within building codes, and are central to the process that must be followed to ensure the safety of the building for both existing and new designs. Equations to check means of failure for specific types of members are provided along with any other information that may be necessary. These equations provide the designer with the maximum loadings members can have. This analysis is applicable to individual members of the design and can be used with existing and new building members. The specification and building code provisions do not specify which member is the best option from an economical or project standpoint, this is up to the designer.

2.1.2.4 Block Diagrams

In architectural design, a common tool utilized to lay out the basic plan for a building is a block diagram. The purpose behind it is to lay out a basic overview of the floor plan of a building and give general dimensions for the interior structure. It is important to note that the actual layout of the rooms is not included since this is a separate diagram from the architect.

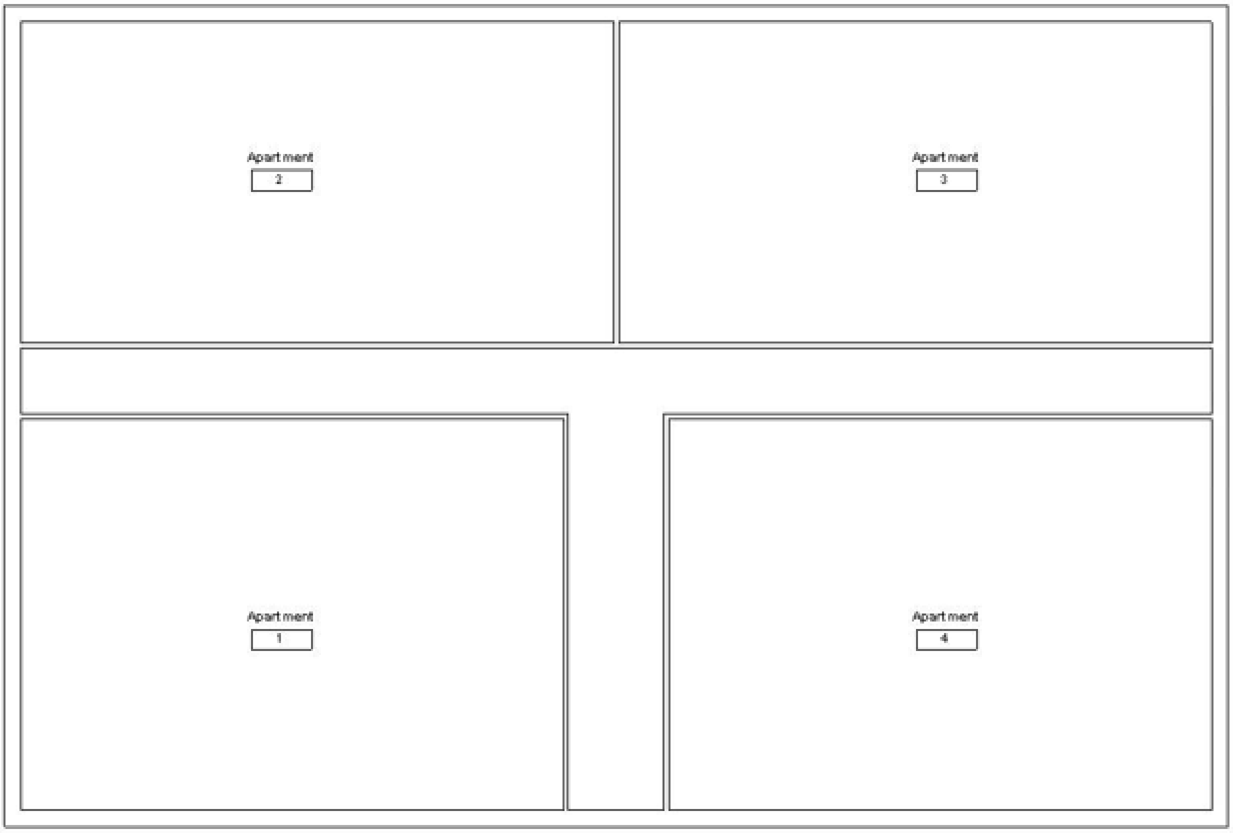


Figure 1: Example Block Diagram

2.1.3 Building Codes

Early in American construction, there were no regulations on building. It was the common practice for people to build their own one or two-story homes. However, when cities began to grow in size, health and safety issues began to arise due to the large numbers of people confined into such small areas of land. New regulations needed to be introduced to ensure safety.

2.1.3.1 History of Building Codes

The first examples of building codes can be traced back over 4,000 years. In Hammurabi's Code, a builder who constructed a building that did not stand up or caused an accident would be punished. Although not providing for exact building requirements, it established the first set of regulations for construction and liability (Tyree & Pitts, 2014).

In the United States, the first known building codes were established in colonial Boston in 1631. Boston outlawed chimneys made with wood in order to protect both the structure's inhabitants and neighbors. During the construction of the District of Columbia, George Washington recommended that height and area limitations be implemented for structures within the city limits.

During the early 1900's, the first building safety codes were being written on a national level. The first organization with the intention of writing these codes was developed in 1915. From here, the main set of building codes started to be written on a more regular basis. Currently, codes are edited very frequently to account for new and ever-changing technologies.

2.1.3.2 International Code Council

The International Code Council was founded in 1994 as a not-for-profit organization that focused on the development of codes designed for construction. It is a collective of officials from three earlier organizations: Building Officials and Code Administrators International (BOCA), International Conference of Building Officials (ICBO), and the Southern Building Code Congress International (SBCCI). Originally, these three organizations had created three separate sets of codes for contractors to follow. However, with regional development, codes were becoming unresponsive to the country's needs, and a single national code without regional limits was created.

As per its website, the purpose of the ICC is to "protect the health, safety, and welfare of people by creating safe buildings and communities." To do this, over one dozen different codes have been written to provide specifications for any construction scenario. Some examples are listed below:

- *International Building Code (IBC)*
- *International Fire Code (IFC)*
- *International Mechanical Code (IMC)*
- *International Plumbing Code (IPC)*
- *International Residential Code (IRC)*
- *International Zoning Code (IZC)*

Many federal and state organizations have adopted the I-series. A list of examples is included below (ICC Safe):

- All 50 States and District of Columbia
- National Park Service
- Department of State
- US Forest Service
- Architect of the Capitol
- Veterans Administration

International Building Code

The *International Building Code* is a guideline created by the International Code Council to develop a national code for building construction. The task was begun by breaking the code up into five technical code development committees. These committees are listed, and their responsibilities briefly described in Table 2.

Table 2: International Building Code Committees

Committee Name	Description of Responsibilities
Structural	General rules regarding design, inspections, and foundation requirements
Occupancy	Use groups, height and area requirements,
Fire Safety Committee	Sprinkler, alert systems, “most-restrictive”
Means of Egress	Exit locations, stairway sizes, illumination
General	Definitions, citations

The *IBC* has been adopted by a majority of the global community. Massachusetts is included in this listing. However, the state legislature has edited a few items throughout the code. When analyzing a building for renovation or construction, the *IBC* is the code to reference and a particular state’s modifications will be considered. The code itself will be specifically utilized for this project to identify the legal requirements for the building. Since the project will also be a comparison between different possible uses of the building, different occupancies requirements will be considered and examined.

2.1.3.3 National Fire Protection Association (NFPA)

Like the ICC, the NFPA was established as an international non-profit organization. Their goal, as found on their website, “is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training and education.” Being established in 1896, the organization has been around significantly longer than the ICC.

The NFPA focuses their codes on fire protection systems, as the name implies. The majority of their codes are suited to things such as sprinkler installation, fire rating tests, and other features and technologies relevant to fire safety. Their most prominent code, *NFPA 101*, commonly referred to as the *Life Safety Code*, is often referenced for the design of fire protection systems. The NFPA has developed its own building code, *NFPA 5000*. This code has been adopted by very few organizations, and will not come into prominence during the majority of the project.

2.2 Sustainability

In modern construction, one of the most important aspects is sustainability. Being able to design a structure or implement technologies that help save energy, reduce water consumption and have an overall smaller impact on the Earth’s environment is becoming more and more important to clients and the engineering profession as a whole.

2.2.1 Rainwater Management

Rainwater management is the ability to collect, recycle, and reuse naturally occurring rainwater. The concept is becoming more and more common in urban areas. Roofs and gutter systems already installed on buildings serve as the perfect means of entrapment for rainwater.

Another reason for rainwater management's popularity is that recycling rainwater is an efficient use of water. Due to development (i.e. buildings, sidewalks, roads) there is little area for rainwater to naturally enter back into the local water table. Most is, in fact, removed via the municipal storm water system. Allowing for entrapment ensures that previously removed rainwater can be used locally.

2.2.1.1 Local Conditions

On average, Worcester receives 48.02" of rainfall per year. The chart located below shows the average precipitation totals per month that comprise this grand total.

Table 3: Worcester Monthly Rainfalls

Month	Rainfall Accumulation (inches)	Month	Rainfall Accumulation (inches)
January	3.5	July	4.21
February	3.23	August	3.7
March	4.21	September	3.94
April	4.09	October	4.69
May	4.17	November	4.29
June	4.17	December	3.82

Conditions will vary from year to year, but these values allow for a good starting point when determining several factors of the rainwater management system (U.S. Climate Data).

2.2.1.2 General Water Requirements

The Unites States is one of the highest water consumers in the world. The average family of four will utilize 400 gallons of water per day. A breakdown of this daily use into percentages is shown in the pie chart below.

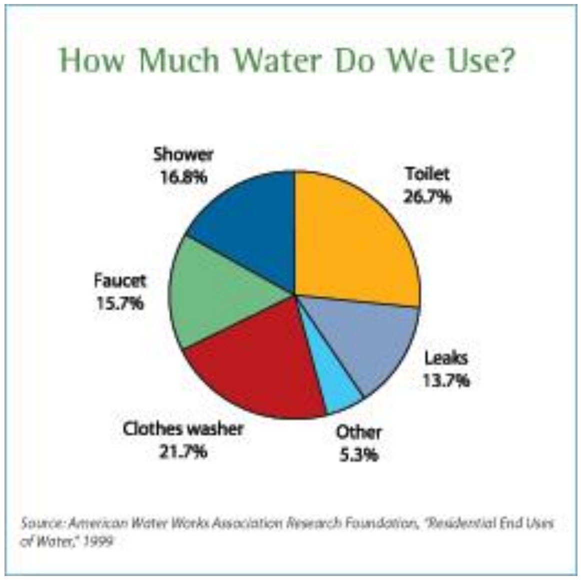


Figure 2: American Water Usage

As can be seen, the majority of water usage occurs from the bathroom of our homes which include the toilet, showers, and some faucets. Included below is a table showing the amount of water used by some general in-home water features.

Table 4: Water Users Values

Feature	Water Used
Toilet	1.6 gal/ flush
Showerhead	2.5 gal/ min
Faucet	2 gal/ min
Washing Machines	27 gal/ load

2.2.1.3 Water Regulation

The Commonwealth of Massachusetts encourages the use of rainwater harvesting on its official website. Stated in the briefing released to the public in 2004 entitled *Massachusetts Water Policy*. The Massachusetts Executive Office of Environmental Affairs states ten basic recommendations to be followed to promote effective water conservation. The applicable points to rainwater management are included below:

- Promote storm water recharge close to its site of origin
- Advance effective management of water supplies
- Promote sustainable development, timely maintenance of old infrastructure, and the protection of priority water resources
- Develop clear guidance and planning materials to help municipalities, developers, and consultants advance development that reduces negative impacts on the environment

As far as regulations on the recycling of roof collected precipitation are concerned, the MassDEP sites in *314 CMR 20: Reclaimed Water Permit Program and Standards* that a rainwater recycling system for toilet use of uncontaminated water on a non-metal roof does not require a permit (Division of Water Pollution Control, 2009). Uncontaminated water is defined in *314 CMR* 20 as:

> "…water which does not contain dredge spoil, solid waste, incinerator residue, garbage, sewage, sludge, munitions, chemical wastes, biological waste materials, radioactive materials, wrecked or discarded equipment, cellar dirt, industrial, municipal or agricultural waste, or any other material upon which discharge could cause or contribute to a violation of the Massachusetts Surface Water Quality Standards or interfere with the actual or potential use of ground water as a source of potable water."

2.2.1.4 Systems

All rainwater management systems follow a general "blue-print." The first step in any system is to establish the downspouts collection points. Collection points are the areas on the surface of the building or surrounding area that take in the rainwater and funnel it into the storage tank. These downspouts can be located throughout the roof or on the gutters. Generally, they offer the first phase of filtration as well. Heavy debris such as leaves, twigs and large collections of sediment are removed in this first step filters inside the downspouts.

The next point the rainwater enters is the tank. Tanks can be stored either underground or inside the structure. Along with simply storing the water, tanks also allow for further filtration by allowing sediments in the water to settle to the bottom of the tank. In some cases, a water smoothing inlet is required to ensure no turbulence disturbs the settled particles. Tanks are sized based on several factors. The first is the location of the project. Dependent on geography, some areas of the United States will be subjected to higher amounts of rainfall and thus have larger storage requirements. Secondly, the size of the building affects the tank size since a larger building with a larger roof area will collect and channel more water downwards into the tank. Finally, the usage by the occupants will affect the sizing since high usage may lead to a smaller amount of "long-term" stored rainwater. In general, the smallest sized tank is desirable in order to ensure cost and space efficiency.

The final step is the pressure device. Unlike a municipal water supply, tanks do not add pressure to pump water throughout a system. Therefore, an external source such as a pump or bladder must be used. Both solutions to the pressure problem are viable in most cases and have their own sets of advantages and challenges. Pumps function quite well and are easier to maintain, but can be noisy and cause sporadic pressure when turning on and off. Bladders cause a more stabilized pressure, but if damaged are tough to repair. Either way, the pressure caused by the device forces the water through the pipes and into the desired locations (whether it be the toilet, the HVAC system, etc.). The only caveat to a rainwater management system is that the piping to these appliances must be on its own loop; therefore new piping must be supplied to these locations separate from any other municipal or well water system.

Although on its own separate loop, the rainwater management system still needs to have a back-up supply in the case of an extended dry spell, various types of regulators are available to serve this purpose. Some electrical controls can be set remotely, but are often the priciest to purchase and install. The most commonly used regulator uses the pressure from the municipal water supply and the rainwater management system to control a flap which allows for an intake of water.

2.2.2 Energy Efficiency

Energy efficient is a growing trend for American homes and businesses. To combat the ever changing effects of a large energy demand, various energy reduction techniques are being employed regularly. The government has also begun to back these effort with subsidies and grants to help promote businesses to invest in energy reduction.

Several different commercial program including Energy Star and LEED have emerged to offer certifications and standardization energy reduction. Based upon the companies point totals and rankings, the company is given its specified tax reduction or incentive.

2.2.3 LEED Requirements

The United States Green Building Council (USGBC) was founded in 1993. Its mission is to promote sustainability in the building and construction industry. The nonprofit organization currently has over 181,000 professionals working in the field (USGBC).

The USGBC's most prominent, and relevant, creation is the Leadership in Energy and Environmental Design (LEED) certification. LEED certification is currently the nationally recognized benchmark for green buildings. The system works by assigning point values for different sustainability aspects. For example, maintaining 50%, by surface area, of an existing abandoned building earns six points. These points, when totaled can lead to a platinum, gold, or silver rating.

There are many incentives to designing a new structure or formatting an old one with LEED in mind. A list with brief description of these incentives is produced below as per the LEED website:

- Expedited Review/ Permit Processes: municipalities will prioritize buildings designed with the intention of a high LEED rating
- Density and Height Bonuses: municipalities will allow for an increase in the floor area ratio upon certification
- Tax Credit: municipalities intending to promote new policies can reduce overall payment on taxes
- Fee Reduction: permitting fees and other processing fees may be reduced or waived

- Grants: municipal or state government may help subsidize building or certification cost
- Revolving Loan Fund: special low interest loan programs designed to assist in the construction process

This project does not include exact measures to qualify the building for LEED certification. However, all of the design features incorporated for sustainability have a direct LEED correlation which is described in the appropriate sections.

2.3 Worcester

In construction, like real estate, location is extremely important. The main focus of the project will be on a building located at 89 Shrewsbury Street Worcester, Massachusetts. Shrewsbury Street is one of the main streets in Worcester for restaurants, shops, and night life.

2.3.1 Demographics

The City of Worcester has a population of just under 200,000 people inside an area of just under 40 square miles. The residents of the area average a relatively high income, just over $79,600. The city is also a large establishment for education, having 13 colleges in the general area and having more than 30,000 students living in the Greater Worcester area.

The business community is spurned on by this high influx of income and large population of young people. The average cost to rent office space falls inside the range of $11 to $22 per square foot. This means any new renovations would be completed with this being the goal rent for future occupants. Also important to the business community is the large amount of downtown office space, which totals close to 4.5 million square feet. The city also features a commuter rail into Boston (Worcester Regional Resource Bureau).

2.3.2 History

The City of Worcester was first settled under the Native American name Quinsigamond in 1673. It was settled twice more, with the final name of "Worcester" being adopted and finalized in 1713. Worcester, meaning "War-Castle," was incorporated as a town in 1722 and finally as a city in 1848.

Worcester was originally an unlikely place for an industrial town. When the only way to have a successful mill was to have a large flow of water; Worcester did not have the river to power any buildings. Therefore, its manufacturing background began in 1828, when the Blackstone Canal first opened. In 1835, the first railroad connecting Worcester and Boston opened, making the city a crossroad for trade.

After the Civil War, the true industrial age swept through the Northeast. The population of Worcester saw close to a 240% increase prior to the turn of the century. The amount of output from mills and factories established Worcester as a manufacturing power in the thriving New

England economy. It was during this time period that the building of focus was first built as a manufacturing building on Shrewsbury Street (Worcester Historical Museum).

2.3.3 89 Shrewsbury Street

The existing building was built to be approximately 4,600 sq. ft. per floor and is three stories tall. The outer walls are entirely brick and the inner support structure is a combination of heavy timber and steel members. The original building had no sprinkler system, HVAC, or other mechanical systems. The steel members were also made before the current sizing charts were created. Therefore, many assumptions were made throughout the methodology and structural chapters for loading.

The structure has already undergone a renovation from its original purpose. It currently has the restaurant, Via Italian Table, and several of the upper floors are office spaces. For this project, the newly renovated aspects of the building will be ignored and only the aspects labeled existing will be taken into account. For example, the old plans include an existing storage room, elevator and structural support members.

Seeing as how the building is located in Worcester, it is crucial to keep the locale in mind. Determining return on investments for potential renovation occupancies will help to establish what the ideal future occupancy type of the building should be.

Chapter 3: Methodology

This project is intended to assist the retrofitting process of non-compliant buildings. This will be achieved by performing a feasibility study of 89 Shrewsbury St. comparing residential and commercial options for its renovation design. The primary objectives of this project are as follows:

1. To develop structural modifications to the existing building
2. To bring certain elements of the building into compliance within the *IBC*'s provisions
    a. Structural Design
    b. Automatic Sprinkler Systems
    c. Accessibility and Means of Egress
3. To incorporate water reuse sustainable design aspects
4. To provide recommendations as to which building design is more profitable based on a return on investment cost analysis

Objectives 1-3 will be completed individually for a residential and commercial design. Objective 4 will bring the two designs together in a life-cycle cost analysis. Table 5 shows the MQP project completion schedule, and displays a visual overview of the project tasks that will be accomplished.

Table 5: MQP Schedule

	B-Term (in weeks)							C-Term (in weeks)						
Activity (with primary student)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Structural Design (SL)														
Initial Revit Drawings														
Block Diagrams														
Current Structural Analysis														
Write Analysis Methodology and Results														
Necessary Structural Modifications														
Final Revit Drawing														
Modifications Writing														
Fire Protection (BM)														
Modifications to Accessibility														
Modifications to Means of Egress														
Sprinkler System Design														
Code Analysis Writing														
Sustainable Design (MD)														
Rainwater Management Design														
Rainwater Impacts														
Sustainable Design Writing														
Cost Analysis (MD, SL, BM)														
Overall Cost														
Return on Investment Analysis														
Comparison of Designs														
Cost Analysis Writing														
Compile Final Designs														
Final Draft for Paper														
Final Paper Complete														
Poster														

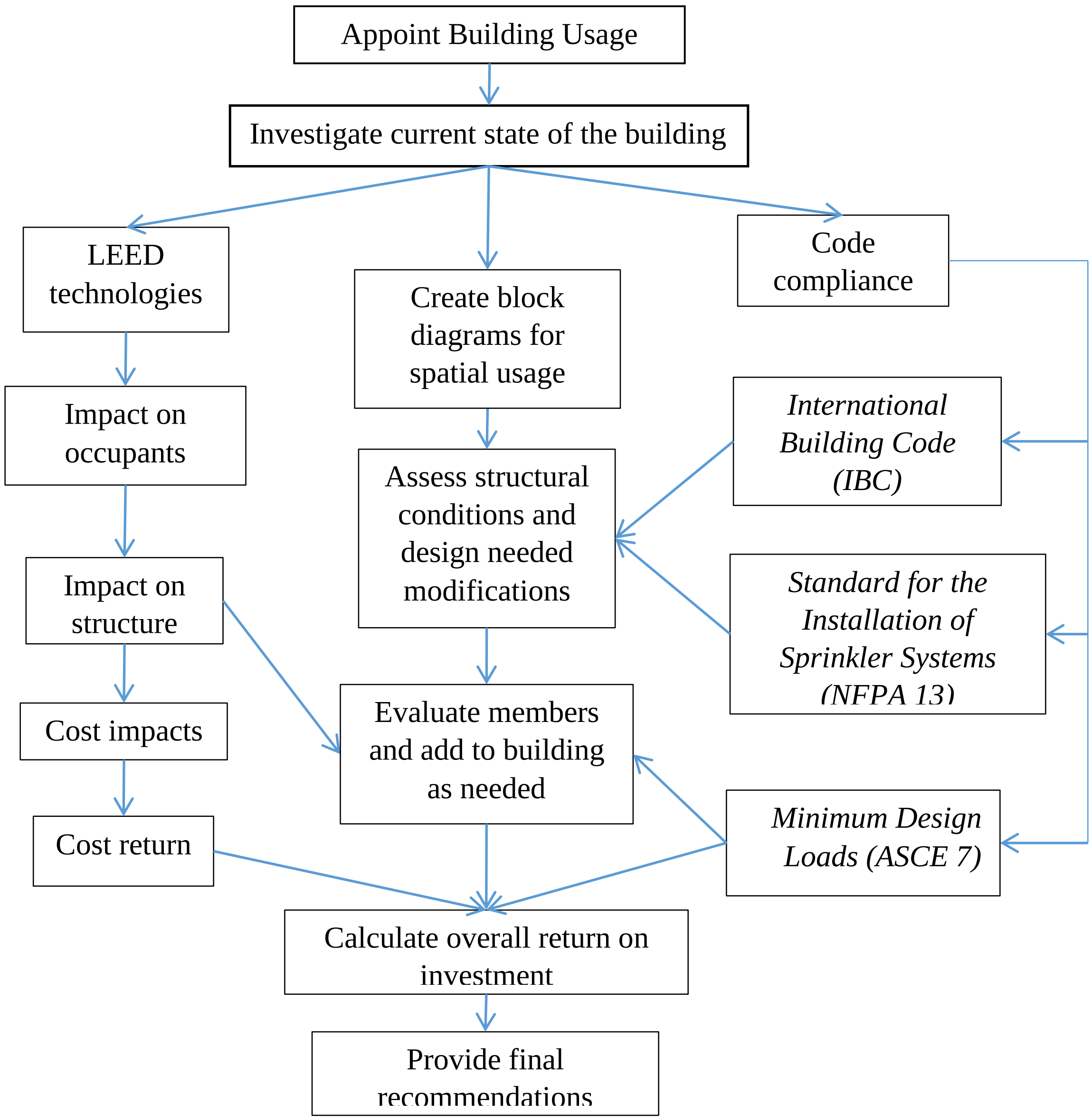


Figure 3: Concept Map for Retrofitted Building Design

3.1 Structural Modifications

The first objective is to assess current structural conditions of the building and to then develop any needed structural modifications to ensure it will comply with modern day design loadings. The first step in assessing structural conditions is to obtain floor plans, sections, and layout for the building and learn about the state of the existing building. The 2005 building plans are the newest plans that were obtained, and these plans show the state of the building before any modern renovations were made. The hard copy drawings were converted into a 3D building information model (BIM) using Autodesk *Revit*. Scanned plans were copied into *Revit* to measure dimensions using the provided scale. Having the building model in *Revit* facilitated a visual interpretation of the drawings and provided a better understanding of what currently exists in the building. Additionally, *Revit* allows the drawings to be quickly edited and added to, which will be extremely beneficial later in the project.

For each proposed use, a block diagram was drawn for each floor to determine egress means and verify the design meets occupancy limits. These limits are 100 gross sf per occupant for business areas and 200 gross sf per occupant for residential areas, which can be found in Table 1004.1.2 of the *IBC*. Hard constraints such as stairways and the elevator shaft are also incorporated into the design as moving these components would be costly and unfeasible.

Once the building has a general layout and hard constraints for each of the two usages, the design loads must be determined. These design loads can be found in *ASCE 7*. The design live load for commercial office space is 50 psf for uniform loads and 2000 lbs for concentrated loads. Residential must be designed to support a uniform load of 40 psf. Both have a roof live load of 20 psf. In both cases, snow loadings will also be considered for the northeast region. Similarly, dead loads, wind loads, and seismic loads are the same for residential and commercial use, and can be found in *ASCE 7*.

These design loadings are used in conjunction with the provisions of the *National Design Specification for Wood Construction (NDS)* and the *American Institute of Steel Construction, Steel Construction Manual (AISC Manual).* Existing wood members were evaluated based on the *NDS* to determine if their capacity will allow for renovated building use. When the wood members were found to fail under the current loadings, steel plates were used to reinforce the wood beams. Steel beams were evaluated for bending, deflection, shear, and buckling. Both wood and steel columns were also evaluated for buckling

3.2 Building Compliance

Upon completion of block diagrams and appropriate selection of structural modifications to 89 Shrewsbury Street, the building must comply with the fire safety conditions of the 2009 edition of the *International Building Code* along with the Massachusetts amendments as stated in the current version of the *Massachusetts State Building Code*. This involves a properly designed automatic fire suppression system, an evaluation of the proposed egress methods, and general building heights and area. Due to the limited scope of this study, not all areas of the *IBC* were inspected for compliance.

The first main area of compliance that was addressed was whether or not an automatic sprinkler system will be required. The 2009 edition of the *International Building Code* provides the criteria for establishing the presence of a sprinkler system. *NFPA 13* is the standard used for sprinkler system installation and has been adopted by the *International Building Code*. The sprinkler systems were designed accordingly based off of the completed block diagrams and details specific to each building use. Although there were different requirements for commercial and residential uses of this building, similar aspects such as required number of sprinkler systems, temperature rating of sprinklers, and spacing of branch lines are defined in accordance with *NFPA 13* for each use.

With the completion of the sprinkler system design for both intended uses, means of egress, general building heights and area, and accessibility of both building designs were consulted in the *IBC* to verify that both the residential and commercial designs satisfied the *Massachusetts State Building Code*. Appropriate changes to the block diagram were made if certain means of egress or other requirements were not met. The addition of the sprinkler system typically makes most of these requirements more lenient, allowing these designs to more easily meet the requirements of the *IBC*.

3.3 Sustainability

To incorporate sustainable designs, potential methods were evaluated based on feasibility and benefits. Renovation of an abandoned building is already a large step towards achieving a green building; however, this project investigates and develops other methods. The area of design that was investigated is rainwater management.

The first step was to determine which technologies would provide a sustainable design while still within the context of the scope. The technology's effect on the structural integrity of the building was also evaluated. Any added weight to the design loads, particularly on upper floors or the roof, required that structural members to be reevaluated to verify the structural integrity of the members. Any required changes to the structural modifications beyond those necessitated by the design loadings were added into the design cost estimate. This cost estimate includes structural modifications and cost of the technology. Finally, the return on investment was evaluated to compare the cost with the benefits.

3.4 Provide Recommendations

Once all designs were completed, a cost analysis was performed on each intended building use to provide a base for which design option will be more profitable in the long term. The building information model was used to perform a quantity take-off of items modified in this project. For these known materials, parametric estimates were used based on RSMeans item data. For unknown items, RSMeans square foot costs were utilized to provide a representative estimate. In addition, average incomes from both residential apartments and office buildings in the Worcester area were obtained based on state and city averages to establish an average owner yearly income from the building space, based on an assumed vacancy rate. Sustainable design implications were analyzed to determine their worth for the building designs. Based on these figures, a return on investment was calculated to compare which of these two development options would be the most cost effective. With this analysis, recommendations are provided to suggest which intended use would be the best choice and what sustainable objectives to pursue if someone were to purchase and retrofit this existing building on 89 Shrewsbury Street.

Chapter 4: Proposed Layout

Proposed layouts for both intended designs were created to meet occupancy and means of egress requirements. These requirements address important safety issues for the building and must be followed before any structural modifications can be performed. With this in mind, the block diagrams for building usage were created and used to design the automatic sprinkler system and implement a structural analysis.

4.1 Occupancy Requirements

To determine which requirements in the code would be applicable, the occupancy type and construction type were first established. Based upon the appropriate sections of the Section 602.4 of the *IBC*, it was determined that the building is of Type IV construction, since the building is made of non-combustible exterior walls and the interior framing is solid wood. From here, two occupancy types were assigned based upon their future use. From Chapter 3 of the *IBC*, the designed office plan for the building would be considered a Group B occupancy and for apartments, it is a Group R-2 occupancy.

4.2 Means of Egress

The *IBC* 2009 edition lays out a comprehensive set of code requirements for a building's means of egress. The sections that are relevant to the scope of the project are summarized and included in the following table.

Table 6: Means of Egress Requirements

Section of *2009 IBC*	What is Stated
Table 1004.1.1	Occupant load factors for residential and business occupancies: 200 gross and 100 gross respectively
1004.4.4	Where exits serve more than one floor, only the occupant load of each floor will be considered in determining required capacity of egress system
1005.3.1	Where the stairways serve more than one story, only the occupant load of each story individually shall be used
1009.4	Exception 1: Stairway serving less than 50 people has a minimum width of 36"
1014.3	The common path of egress travel shall not exceed 75'
1015.1	Only one exit necessary from dwelling units with less than 10 people
Table 1021.2(1)	Less than 4 dwelling units per floor only requires one exit

4.3 Block Diagrams

After consultation with the *IBC*, block diagrams were designed to meet egress and exit standards and to provide suitable accommodations for the intended residential and commercial designs. Multiple sources of typical apartment and office square footage such as Voke Lofts of Worcester and Ramtech Building Services were used as a basis for the design of the block diagrams for 89 Shrewsbury Street. Typical apartments vary from about 500 to 1,200 square feet depending on the number of bedrooms and occupants that will live in each dwelling. General office floor plans and areas can have a large variability, depending on a company's needs and size.

The block diagrams that are described below pertain to both the second and third floor of 89 Shrewsbury Street. The first floor design varies to include an entrance lobby and does not exactly the match the figures seen below. The resulting block diagram for the residential design incorporates five individual apartments per floor, ranging from almost 450 to a little over 900 square feet per unit. This will provide flexibility to accommodate one-, two-, and potentially three-bedroom apartments that can suit various types of living situations. Based on Table 6 above on egress requirement from the *International Building Code,* only one exit is required for less than four dwelling units. In this case, the dwelling units 1 and 2 have access to the northern stairwell and units 3, 4, and 5 have access to the southern stairwell. Figure 4 below shows the proposed residential block diagram.

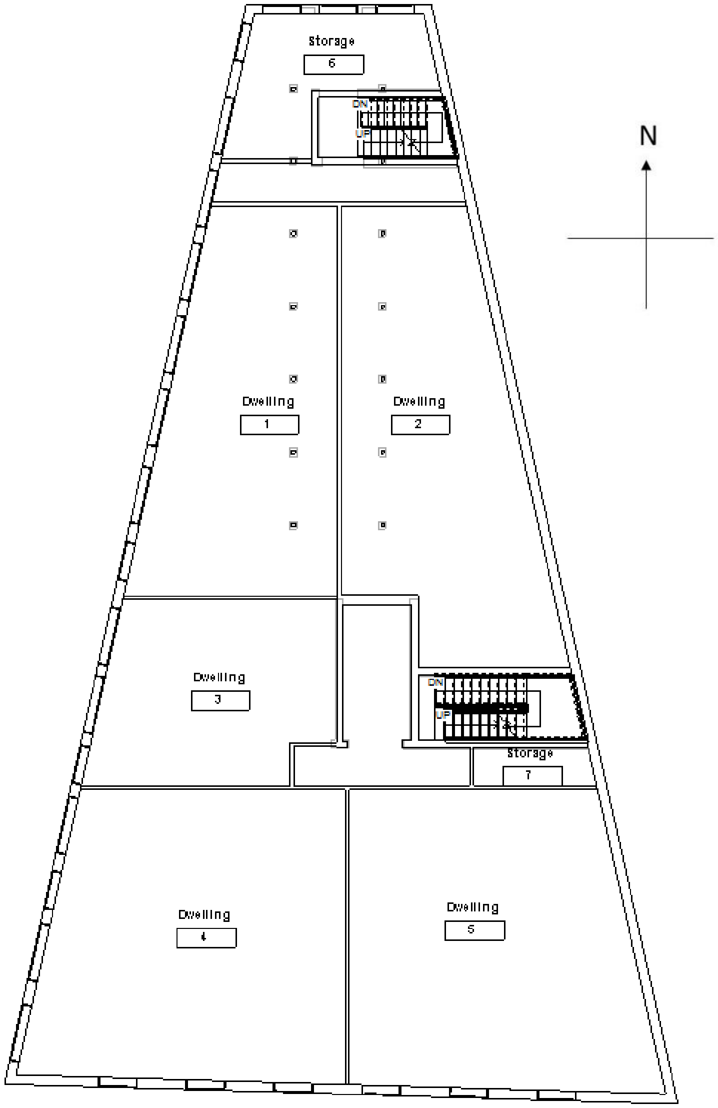


Figure 4: Residential Block Diagram

The proposed commercial office block diagram includes one large office area per floor, providing ample spaces for offices, conference rooms, break room, and an open plan area that can be utilized for cubicles or other uses. This provides versatility that will comfortably suit the needs of most companies. Figure 5 illustrates the proposed block diagram for the commercial design.

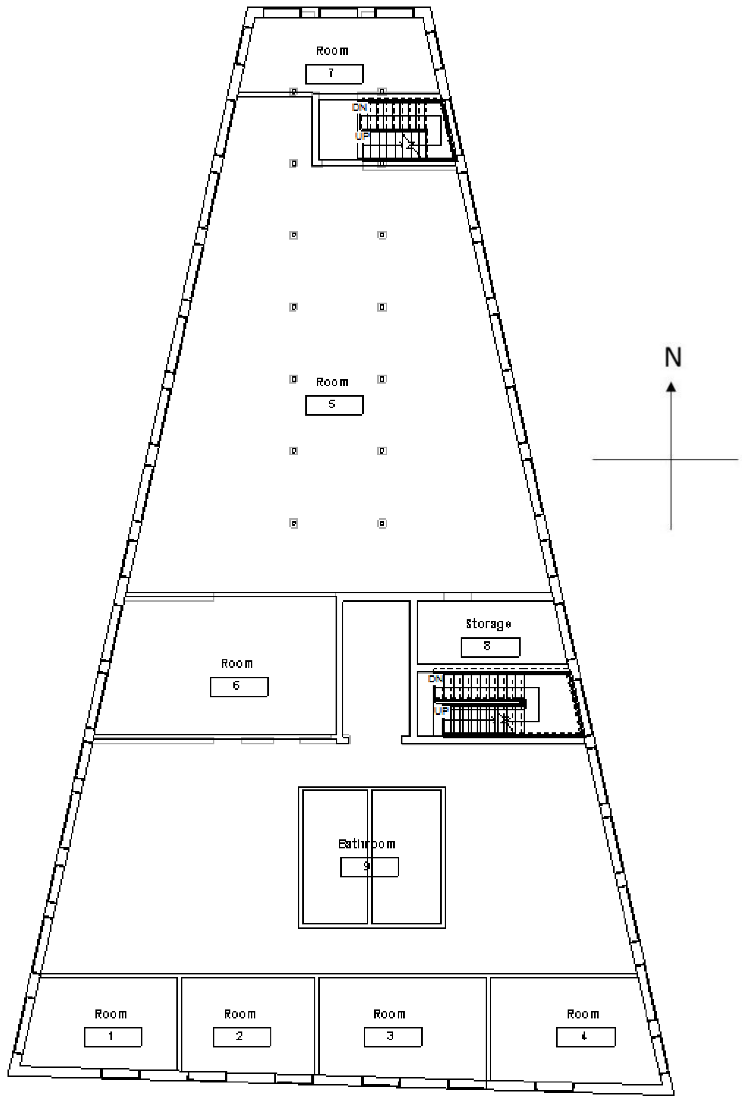


Figure 5: Commercial Block Diagram

4. 4 Automatic Sprinkler System Requirements

For residential and commercial designs to be implemented at 89 Shrewsbury Street, an evaluation of the building's fire protection needs was performed in accordance with the 8th edition *Massachusetts Building Code* which references the *2009 International Building Code*. These codes utilize *NFPA 13: Standard for the Installation of Sprinkler Systems* for the design and implementation of automatic sprinkler systems, while the information in the *IBC* determines whether or not a system is required. In accordance with Section 903.2 of the *2009 IBC*, an automatic sprinkler system is only required for the intended residential design and not the commercial option. Although a sprinkler system may not be required by the state building code for the intended commercial design, another third-party, such as an insurance company or potential buyer of the property, may want the added protection benefits of a sprinkler system.

Both the residential and commercial design are considered a light occupancy hazard as defined by *NFPA 13*, Section 5.2 as an occupancy "where the quantity and/or combustibility of contents is low and fires with relatively low rates of heat release are expected." This occupancy allows the lowest design density flow and greatest spacing for sprinkler heads, making it simpler and less costly to design than other occupancy classifications. This building space will also utilize a wet pipe automatic sprinkler system because ambient temperatures in the building will not drop below 40°F, and it is the simplest, most reliable, and lowest costing system. Additionally, since the area of each floor does not exceed 52,000 ft^2, the sprinkler system will only require one system riser according to Section 8.2.1(1) of *NFPA 13*.

Table 7 below summarizes all of the requirements that must be considered in designing and installing an automatic wet pipe sprinkler system for 89 Shrewsbury Street.

Table 7: Automatic Sprinkler System Requirements

Category	Requirement	*NFPA 13* Section
Design Density/Area	0.10 gpm/ft^2 over 1,500 ft^2	11.2.3.11
Minimum Sprinklers for Design Area	5	11.2.3.2.3.2
Minimum Operating Pressure	7 psi	22.4.4.10.1
Minimum K-Factor	5. 6	8.3.4.1
Temperature Rating	Ordinary	8.3.2.1
Response Type	Quick Response	8.3.3.1
Sprinkler Orientation	Upright or Pendent	8.4.1.1
Max Protection Area	225 ft^2	8.6.2.2.1(a)
Maximum Spacing between Sprinklers	15 ft.	8.6.2.2.1(a)
Minimum Spacing between Sprinklers	6 ft.	8.6.2.2.1(a)
Maximum Distance from Walls	7 ft. 6 in	8.6.3.2.1
Minimum Distance from Walls	4 in	8.6.3.3

For a wet pipe system to work properly, certain components are required to be installed and maintained as per *NFPA 13*. Each plays a vital role in the successful automatic activation of the sprinkler system, and they are described below in Table 8. This table also provides a proposed solution for the fire protection system identifying brand and model number of the necessary components.

Table 8: System Components for Wet Pipe System

Required Component per *NFPA 13*	Proposed Model and Number	Component Description
Alarm Check Valve	Tyco Model AV-1-300	The alarm check valve maintains the system water pressure at a constant level and prevents water from leaking back into the water supply. It also has a port for the attachment of the alarm. This model also includes both system and supply side water pressure gauges, a shutoff valve for alarm tests, and a main drain valve.
Retard Chamber	Tyco Model RC-1	A retard chamber is a device used to prevent false alarms due to varying water pressures, usually associated with public water supplies.
Control Valve	Viking Model H-1	It assists the automatic sprinkler on/off control within the check valve
Control Valve Tamper Switch	Potter PCVS-1	This tamper switch monitors the position of fire sprinkler control valves and sends an electronic alert when they have been partially or fully closed
OS&Y Gate Valve	UWP Model 2030	An OS&Y gate valve allows the system to have a shut-off valve and is a quick indicator if the system is open or closed
OS&Y Gate Valve Tamper Switch	Potter OSYSU-1	The switch monitors the position of fire sprinkler gate valves and sends an electronic alert when they have been partially or fully closed
Water Motor Alarm	Tyco Model WMA-1	The water motor alarm is a sound warning device activated by water flow to notify occupants that the sprinkler system is operating. This model includes an alarm line strainer, which is designed to filter any obstructions that may be in the water supply before reaching the water motor alarm.
Automatic Drip Valve	Tyco Model AD-2	An automatic drip valve is intended to automatically drain water for the fire protection equipment supply connections that are to be maintained normally dry.
Fire Department Connection	Guardian Model 6014	The fire department connection is used as an auxiliary connection through which the fire department can pump water to supplement existing water supplies
Check Valve for FDC	Viking Model D-1	A check valve prevents water from back flowing from system out to the fire department connection
Alarm Water Flow Pressure Switch	Potter Model PS10-2	Pressure switches are used to detect changes to the normal system water pressure and will also notify when the sprinkler system is activating
Backflow Preventer	Ames 2000SS	A backflow preventer blocks the potential backflow of polluted water in the sprinkler system into the potable water supply
Post Indicator Valve	Nibco Model NIP-1AJ	Post indicator valves are used to open or close the water supply to the building for the fire protection system and to indicate whether or not the valve is open

Chapter 5: Structural Analysis

Once block diagrams were defined for each of the proposed occupancy types it became possible to determine the design and occupancy loadings the structure would be required to support. With these loads established the existing structure needed to be analyzed for the structural integrity.

5.1 Loadings

To begin the structural analysis, loadings were determined for the intended use of each design. Both development options are required to carry uniform distributed loads from snow, flooring, roofing, ceiling, mechanical, electrical, and plumbing (CMEP), and a roof live load. Figure 6 and Figure 7 show typical cross sections of the proposed floor and roof construction. The building is also required to support lateral wind and seismic loads. The design loads and references are summarized in Table 9.

Table 9: Design Loadings for both Commercial and Residential

Loading Type	**Loading**	**Reference**	
Snow	55 psf	*Massachusetts Building Code*, Table 1604.11	
Floor Dead Load (proposed)	8.1 psf	2”x10” Wood Beams, 16” o.c.	2.9 psf
		3/8” Plywood Sheathing	1.2 psf
		Hardwood Floor	4.0 psf
CMEP	20 psf	Estimated Value	
Roof Dead Load (proposed)	6.55 psf	Metal Deck	2.5 psf
		1” Rigid Insulation	1.5 psf
		0.05” PVC Membrane	0.35 psf
		2”x10” Wood Beams, 16” o.c.	2.9 psf
Roof Live Load	20 psf	*International Building Code*, Table 1607.1	
Seismic Base Shear	443.3 kips	*ASCE 7 -10*	
Wind Base Shear	11.0 psf	*ASCE 7-10*	

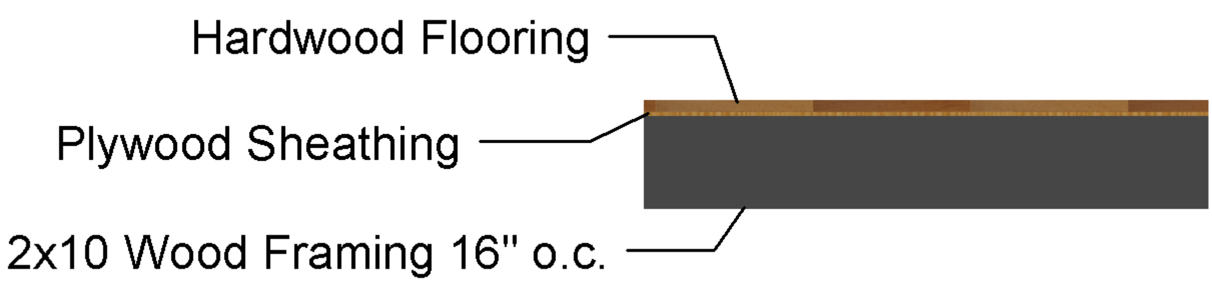


Figure 6: Typical Cross Section for Proposed Flooring

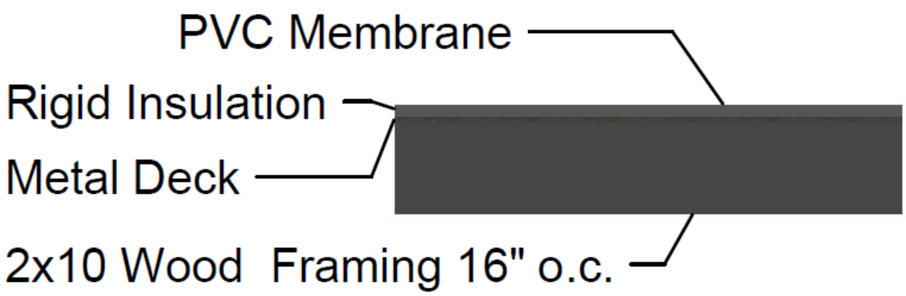


Figure 7: Typical Cross Section for Proposed Roof

The proposed floor joists were analyzed for the building and load capacities required. In both design occupancy types, 2"x10" wood beams placed 16" on center were found to be sufficient for the span lengths required by the initial framing plan for the 2nd Floor, 3rd Floor, and Roof. Figure 8 shows a full framing plan of the 3rd Floor including the existing beams, girders, and floor joists.

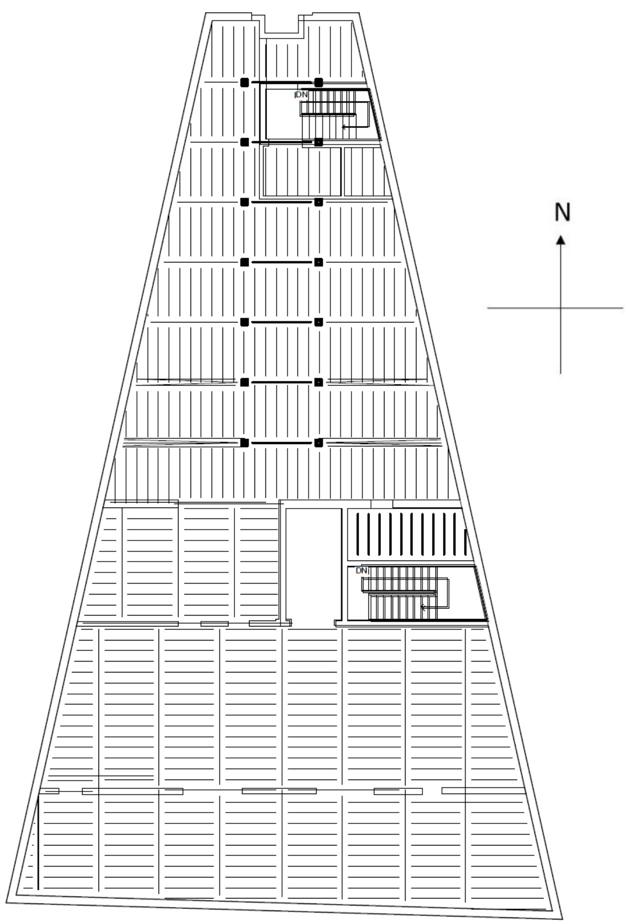


Figure 8: Complete Framing Plan, 3rd Floor

Initial occupancy live loads were also determined for both of the intended uses. These loadings were found in Table 1607.1 of the 2009 *International Building Code (IBC)*, and are summarized in Table 10. The partition uniform live load is found in Section 1607.5 of the *IBC*. This takes into account the location of partitions changing which is common in office space where cubicles may be added, removed, or relocated throughout the lifetime of the building.

Table 10: Proposed Live Load Based on Occupancy

Occupancy type		**Loading**
Office	Uniform	50 psf
	Concentrated	2,000 lbs
	Partition Uniform Load	15 psf
	Stairs and Exits	100 psf
	Lobbies and First Floor Corridors	100 psf
Residential	Private rooms and corridors serving them	40 psf
	Stairs and Exits	100 psf

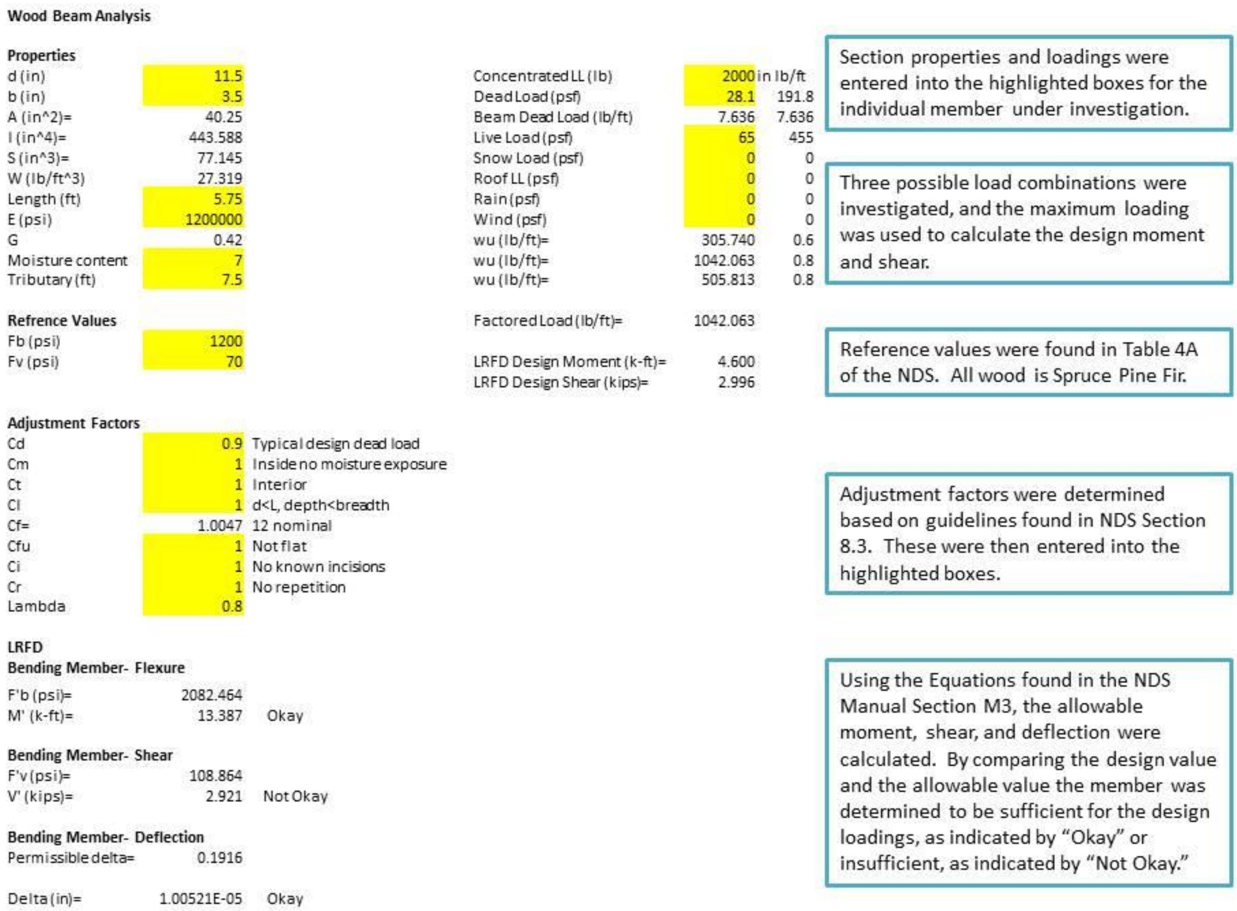
These loads were input into the basic load combinations as described in Section 1605.2.1 of the *IBC*. These combinations were used in the structural analysis when required by a Load and Resistance Factor Design (LRFD) approach, as described in the following two sections.

5.2 Existing Wood Beams

The building's existing wood members were analyzed as specified in the American Wood Council's *National Design Specification for Wood Construction (NDS)*. Wooden beams were found in the north half of the 2nd Floor, 3rd Floor, and Roof framing plan. There was no information given on the 1st Floor framing plan and therefore it was assumed that all framing members were sufficient for the given loads. The beams were determined to be bending members due to the evenly distributed loading along the length of the member. These bending members were checked for their flexural capacity, shear capacity, and permissible deflection using the LRFD method. Although the NDS does not specify a permissible deflection, a commonly accepted value of the member length over 360 was used.

Due to the number of members in the building, a Microsoft Excel sheet was created to minimize repetitive calculations. Figure 9 displays a sample spreadsheet that was used to analyze the wood beams. The blue dialogue boxes on the right side of the diagram provide explanations of the calculation process.

The beam sizes specified in the plans provided were assumed to be nominal. The wood is Spruce Pine Fir, as designated on the structural plans. The minimum allowable stress reference values used were the values specified in the structural plans. Section 2303.1.1 of the *IBC* requires load bearing sawn lumbar to be graded and identified to determine the properties of the wood. It is assumed this inspection resulted in the stress value provided in the structural plans. These values were slightly lower for moment and significantly lower for the shear stresses as compared to the values specified in the *NDS.* The lower value could be attributed to shrinkage cracks, thermal cracks, or splitting in the wood.



Wood Beam Analysis

Properties		
d (in)	11.5	
b (in)	3.5	
A (in^2)=	40.25	
I (in^4)=	443.588	
S (in^3)=	77.145	
W (lb/ft^3)	27.319	
Length (ft)	5.75	
E (psi)	1200000	
G	0.42	
Moisture content	7	
Tributary (ft)	7.5	
Refrence Values		
Fb (psi)	1200	
Fv (psi)	70	
Adjustment Factors		
Cd	0.9	Typical design dead load
Cm	1	Inside no moisture exposure
Ct	1	Interior
Cl	1	d<L, depth<breadth
Cf=	1.0047	12 nominal
Cfu	1	Not flat
Ci	1	No known incisions
Cr	1	No repetition
Lambda	0.8	
LRFD		
Bending Member- Flexure		
F'b (psi)=	2082.464	
M' (k-ft)=	13.387	Okay
Bending Member- Shear		
F'v (psi)=	108.864	
V' (kips)=	2.921	Not Okay
Bending Member- Deflection		
Permissible delta=	0.1916	
Delta (in)=	1.00521E-05	Okay

Concentrated LL (lb)	2000	in lb/ft
Dead Load (psf)	28.1	191.8
Beam Dead Load (lb/ft)	7.636	7.636
Live Load (psf)	65	455
Snow Load (psf)	0	0
Roof LL (psf)	0	0
Rain (psf)	0	0
Wind (psf)	0	0
wu (lb/ft)=	305.740	0.6
wu (lb/ft)=	1042.063	0.8
wu (lb/ft)=	505.813	0.8
Factored Load (lb/ft)=	1042.063	
LRFD Design Moment (k-ft)=	4.600	
LRFD Design Shear (kips)=	2.996	

Section properties and loadings were entered into the highlighted boxes for the individual member under investigation.

Three possible load combinations were investigated, and the maximum loading was used to calculate the design moment and shear.

Reference values were found in Table 4A of the NDS. All wood is Spruce Pine Fir.

Adjustment factors were determined based on guidelines found in NDS Section 8.3. These were then entered into the highlighted boxes.

Using the Equations found in the NDS Manual Section M3, the allowable moment, shear, and deflection were calculated. By comparing the design value and the allowable value the member was determined to be sufficient for the design loadings, as indicated by "Okay" or insufficient, as indicated by "Not Okay."

Figure 9: Sample Spreadsheet for Wood Beam Analysis

5.3 Existing Steel Beams

Most of the southern portion of the floor framing is supported by existing steel beams and girders. These steel beams and girders were found in the 2nd Floor, 3rd Floor, and Roof framing plan. There was no information given on the 1st Floor framing plan, and therefore it was assumed that all framing members were sufficient for the given loads. As this building was constructed in the early 20th century, all of these members are not defined by the standardized steel notation used today and are only noted in the drawings by their depth and flange width. With only these dimensions, additional information was required to perform bending and shear calculations. In order to obtain these missing details, historical members that best represented the existing members' dimensions were chosen through consultation with the *AISC Rehabilitation and Retrofit Guide*. This guide provides thousands of historical discontinued steel members and their section properties dating back to 1873. Relating the existing members to designated steel members provided all the necessary design properties such as weight, flange thickness, plastic section modulus, and moment of inertia. Table 11 below shows the existing steel members along with their corresponding designated members and their properties.

Table 11: Designated Steel Members and Their Properties

Existing Member	Designated Member	W (lb/ft)	b_f (in)	A (in^2)	d (in)	t_w (in)	t_f (in)	Z_x (in^3)	I_x (in^4)	r_y (in)
WF 24 (bf 9 7/8)	CB242	85	9.797	24.99	24.154	0.452	0.74	227.84	2457	2.16
WF 24 (bf 9 1/2)	B24a	84.5	9.5	24.75	24	0.46	0.759	225. 5	2380	1.97
WF 24 (bf 9)	CB241N	74	9	21.77	24	0.412	0.68	195. 51	2088	1.95
WF 20 (bf 8)	CB201N	55	8	16.19	20	0.37	0.565	120.78	1076	1.73
WF 18 (bf 11 7/8)	18WF, CB183	124	11.889	36.45	18.64	0.651	1.071	268.01	2227	2.78
WF 18 (bf 11 3/4)	18WF, CB183	96	11.75	28.22	18.16	0.512	0.831	204.04	1675	2.71
WF 18 (bf 8 7/8)	B18a	74	8.77	21.79	18.12	0.44	0.819	154	1249	1.95
WF 18 (bf 7 1/2)	18WF, CB181	50	7.5	14.71	18	0.358	0.57	99.954	800.6	1.59
WF 15 (bf 7 1/2)	CB152N	60	7.5	17.63	15	0.442	0.765	101.72	680.7	1.75
WF 15 (bf 7)	B15a	54.5	7	15.88	15	0.41	0.739	92.421	610	1.55
WF 15 (bf 6 3/4)	CB151N	39	6.75	11.47	15	0.3	0.53	66.341	448.8	1.54
WF 15 (bf 6 11/16)	B15	38	6.66	11.27	15	0.29	0.543	66.275	442.6	1.44
WF 14 (bf 7)	B14	42	6.825	12.46	14.25	0.34	0.578	68.468	436 5	1. 48
WF 12 (bf 6 3/8)	B12a	36. 5	6.38	10.6	12	0.31	0.567	50.443	269 2	1. 44
WF 12 & WF 12 (bf 6 1/2)	12WF, CB121	28	6.5	8.23	12	0.24	0.42	39.086	213.5	1.46
WF 10 (bf 8)	10WF, CB102	41	8	12.06	10	0.328	0.558	48.621	222.4	1. 99

The structural steel members were then analyzed for their bending and shear capacity and allowable deflection based on each building design's anticipated loads. As with the wood members, a deflection limit of the member length divided by 360 was used. The equations and factored design loads were calculated using Load and Resistance Factor Design (LRFD). This method utilizes various load factors to increase initial design loads, and a resistance factor to decrease the member's theoretical strengths. A Microsoft Excel sheet was created as a calculator to automatically verify if each steel member passed the criteria mentioned above. Figure 10 below shows an example calculation for a steel beam from the second floor of the proposed office building.

Steel Beam Analysis

Properties

Beam Type	B15a	
A	15.9	in^2
d	15	in
t_w	0.41	in
t_f	0.74	in
b_f	7	in
W	54.5	lb/ft
L	12.667	ft
Tributary Width	5.25	ft
F_y	36	ksi
z_x	92.4	in^3
E	29000	ksi
I_x	610	in^4
h/t_w	29.9	
$bf/2t_f$	4.739	
r_y	1.6	in

BENDING

Plastic Section modulus		
Phi	0.9	
z_x (in^3)=	4.921	Okay

Load Buckling of the Compression Flange		
$b_f/2t_f$	4.74	
0.38 sqrt(E/F_y)	10.785	Okay

Load Buckling of the Web		
h/tw	29.9	
3.76 sqrt(E/F_y)	106.717	Okay

Concentrated LL	2000	lb
Dead Load	28.1	psf
Beam Dead Load	54.5	lb/ft
Live Load	50	psf
Snow Load	0	psf
Roof LL	0	psf
Rain	0	psf
Wind	0	psf
w_u	282.835	lb/ft
w_u	662.43	lb/ft
w_u	373.68	lb/ft
Factored Load	662.43	lb/ft
Design Moment	13.286	k·ft
Design Shear	4.196	k·ft

DEFLECTION

50% LL	10.9375	lb/in
Delta max	0.004298	in
L/360	0.422233	Okay
50% LL+DL	27.773	lb/in
Delta max	0.010913	in
L/240	0.63335	Okay

Shear

2.24 sqrt(E/Fy) =	63.57638	
Phi	1	
cv	1	
phi V_n	132.84	k
V_u (kips)=	4.1955	Okay

Section properties and loadings were entered into the highlighted boxes for the individual member under investigation.

Three possible load combinations were investigated, and the maximum loading was used to calculate the design moment and shear.

Section properties were obtained from the *AISC Rehabilitation and Retrofit Guide* that most closely reflected the existing members' given properties from Table 8.

Using the Equations found in the *AISC Steel Construction Manual*, the allowable moment, shear, and deflection were calculated. By comparing the design value and the allowable value the member was determined to be sufficient for the design loadings, as indicated by "Okay" or insufficient, as indicated by "Not Okay."

Figure 10: Sample Spreadsheet for Steel Beam Analysis

5.4 Existing Wood and Steel Column Analysis

For the wood columns throughout the building, the same loadings that were used for the beam analysis were utilized again. Along with this loading, the weight of the beams themselves was taken into account to provide an accurate dead load total. The columns were checked for their buckling capacity. Since all the columns were found to be the same size, the one of focus was the column with the largest tributary area located on the first floor of the building. This one would be the member with the highest loading and since it was found to be compatible, all the others could be assumed to be compatible as well. Figure 11 below shows the Microsoft Excel calculator that was created to determine the maximum allowable load for a wood column considering strength and buckling. An 11.5"x11.5" wooden column was determined to be sufficient for the size and strength required.

Buckling Analysis					
	(input cell) <= input cells				
				F_c	E_{min}
F_c	825	psi			
E_{min}	1,200,000	psi	C_M	1.0	1.0
ℓ	11.75	ft	C_t	1.0	1.0
K_e	2.1		C_F	1.0	
ℓ_e	24.675	ft	C_i	1.0	1.0
d	11.5	in	C_T		1.0
b	11.5	in			
ℓ_e/d	25.7		c	0.8	
A_{net}	132.3	in^2			

LRFD	Time Effect				
KF 2012 Definitions					
Compression		Stability		Time Effect	
ϕ_c	0.90	ϕ_s	0.85	λ	0.8
KF	2.40	KF	1.76		
F_{cn}	1,980	psi			
$E_{min\ n}$	2,112,000	psi			
$E_{min\ n}'$	1,795,200	psi			
ℓ_e/d	25.7				
$F_{cE\ n}$	2,226	psi	(1+FcE/F*c)/(2c)		1.600856
$F^*_{c\ n}$	1,426	psi	(FcE/F*c)/c		1.951713
C_P	0.819				
F'_{cn}	1,168	psi			
P_n	154,443	lb			

	DESIGN LOAD, LRFD		
1.2D+1.6L	141,161.90	lb	okay

Figure 11: Wood Column Analysis

For the steel columns, there was no information given as to the actual size of the members themselves. Therefore, the size of member necessary to support the overlying load was the target of investigation. A steel member sized W10x54 was found to be an appropriate strength and size. This member would be able to support the weight of the beams and also the given loadings. Like the beams, a Microsoft Excel sheet, seen in Figure 12, was used to check the buckling and load bearing analysis. Similar to wood columns, the column with the largest tributary area to support was used to ensure that it would work for all other column loadings.

Columns													
Properties						in lb						**Beams**	
Beam Type	W10x54			Dead Load (psf)	82.75	35996.25							
				Roof Dead Load (psf)	26.55	11549.25						Beam 1	
A (in^2)	15.8			Steel Dead Load (psf)	13.13182	5712.341						Weight 1 (lb/ft)	54.5
d (in)	10.1			Live Load (psf)	100	43500		***50 psf for Office				Tributary Width 1	10
tw	0.37			Snow Load (psf)	55	23925		***40 psf for Residential					
tf	0.615			Roof LL (psf)	20	8700						Beam 2	
bf	10			Rain (psf)	0	0						Weight 2	54.5
Stories	1			Wind (psf)	0	0						Tributary Width 2	10
W (lb/ft)	54			wu (lb)=	58392.03								
L (ft)	11.75			wu (lb)=	145471.9							Beam 3	
Tributary Area (ft^2)	435			wu (lb)=	110080.3							Weight 3	84.5
Fy (ksi)	50											Tributary Width 3	11
zx (in^3)	66.6			Factored Load (lb)=	145471.9								
E (ksi)	29000						41.70859					Beam 4	
I (in^4)	303											Weight 4	84.5
h/tw	21.2											Tributary Width 4	11
bf/2tf	8.15												
rx (in)	4.37											Beam Weight (psf)	13.13182
ry (in)	2.56												
							Column Effective Length factor K						
0.56 sqrt(E/Fy)	13.48659						k=1.0	pinned ends, rotation of joints					
bf/2tf	8.15	:]					k=0.5	fixed ends, no rotation at ether end					
							k=2.0	one fixed end, one free end					
1.49 sqrt(E/Fy)	35.88395												
h/tw	21.2	:]											
k	1												
kL/r	55.07813		Fe=	94.34946324									
4.71 sqrt(E/Fy)	113.4318		Fcr=	40.05343582	Inelastic								
Fcr (kips)=	40.05344		Fcr=	82.74447926	Elastic								
Load Capacity (kips)=	569.5599												
Service Load (kips)=	145.4719	:]		Aim to choose beam with smallest rx/ry.									

Figure 12: Steel Column Analysis

5.5 Lateral Loading Analysis

The building was also analyzed for its sufficiency against lateral loadings. The loadings investigated were seismic and wind forces. For wind and seismic analysis, both residential and commercial buildings fall into Risk Category II, as described in the *IBC* Table 1604.5. This risk category is the only place where the occupancy of the building factors into the wind and seismic loads. Since both occupancy types were subject to the same loadings, the analysis was done once for both modification plans.

5.5.1 Seismic Analysis

The seismic loads defined in Table 9 were calculated as specified in *ASCE 7-10*. Table 12 presents key parameters and values that were used in calculating the Seismic Base Shear. These values are used with the process laid out in *ASCE 7-10* Section 12.8.1. The base shear was distributed between the 2nd Floor, 3rd Floor, and Roof following the calculations specified in *ASCE 7-10*. These loadings were determined for the project east wall to be conservative. This is conservative because of the geometry of the building.

ASCE 7-10 Section 12.5.2 describes the direction of loading criteria for Design Category B taking into account the nonparallel system irregularity that is seen in the building. This nonparallel system irregularity occurs "where vertical lateral force-resisting elements are not parallel to the major orthogonal axes of the seismic force-resisting system" as described in Table 12.3-1 of *ASCE 7-10*. Each wall faces the same loadings however the length of the wall affects the amount of shear load it can carry.

The east wall is the longest and therefore it will be capable of supporting the largest loads; the north, south, and west walls are shorter and therefore will be capable of supporting a smaller load. The seismic load from the east wall will be carried through the north and south walls as a shear load and will be the most conservative. The lateral load at each floor is presented in Table 12, and Figure 13 presents a free body diagram of the story forces.

Table 12: Key Parameters and Values for Seismic Load Analysis

Item	**Value**		**Process**
Spectral Response Acceleration Parameter "S_{DS}"	0.193g		*ASCE 7-10* Section 11.4.4, based on building location and soil site class
Response Modification "R"	1.50		*ASCE 7-10* Table 12.2-1 A.11 based on bearing wall system, ordinary plan masonry shear walls
Over strength Factor "Ω_o"	2.50		*ASCE 7-10* Table 12.2-1 A.11 based on bearing wall system, ordinary plan masonry shear walls
Importance Factor "I_e"	1.00		*ASCE 7-10* Section 11.5.1, based on use and occupancy, Risk Category II
Base Shear "V"	443.431 kips		*ASCE 7-10* Section 12.8.1 Use above parameters to evaluate
	2nd Floor Shear	90.9 kips	Floor values are distributed based on weight and height of the floor
	3rd Floor Shear	187.1 kips	
	Roof Shear	165.8 kips	
Masonry Wall Shear Strength	80 psi		*IEBC* Section A108.1, this value was chosen conservatively based on minimum allowable compressive strength of masonry

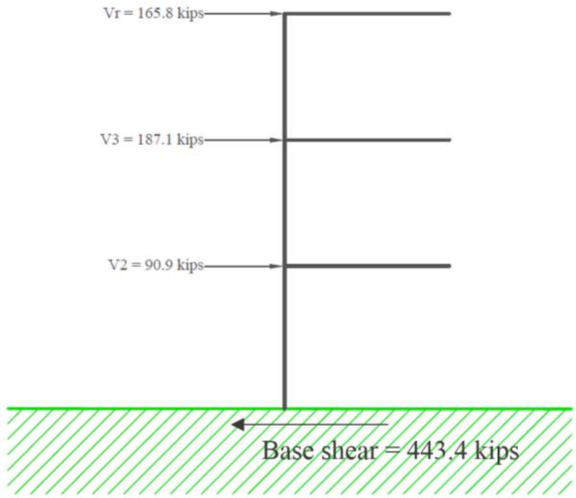


Figure 13: Seismic Lateral Loadings by Floor

While the east wall is subject to the largest lateral loads, the transverse walls, the north and south walls, must carry the shear as shown in Figure 14. Each transverse wall carries an amount of shear proportional to its rigidity. Due to the fact that the north was is significantly shorter than the south wall, the north wall is less rigid. Based on the rigidity of the north and south wall, the north wall will absorb approximately 20% of the seismic lateral forces, and the south wall will absorb approximately 80% of the seismic lateral forces. Table 12.3-1 of *ASCE 7-10* presents Horizontal Structural Irregularities including a nonparallel system. This takes into account the torsion created by the uneven forces as described in Section 12.5.3 for Design Category B. Both the north and south walls have a number of windows creating piers which must carry the shear loads. In both the north and the south walls, the piers in the center of wall were uniform and the outer piers were also uniform. The capacity of each pier was calculated by multiplying the area of the pier by the masonry shear stress. The design loads in each pier were calculated by following the load path through the wall. Figure 15 shows an example of following the load path through the north wall to the second floor piers. The results from the analysis sampled in Figure 15 are shown in the Design Shear columns of Table 13.

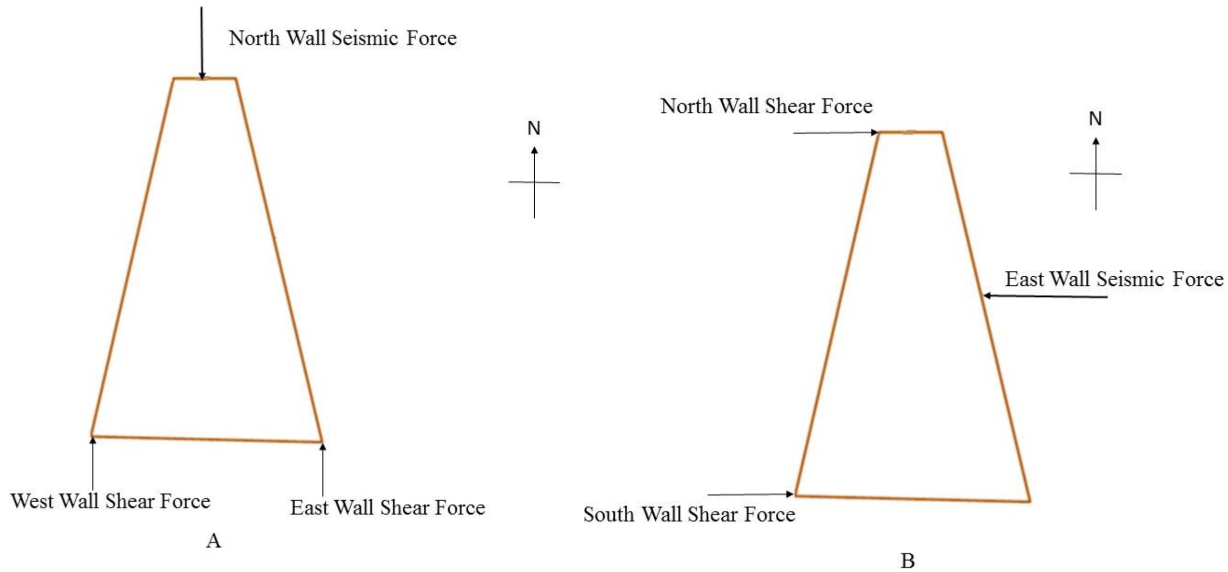


Figure 14: Seismic Forces Distribution into Transverse Walls, Plan View

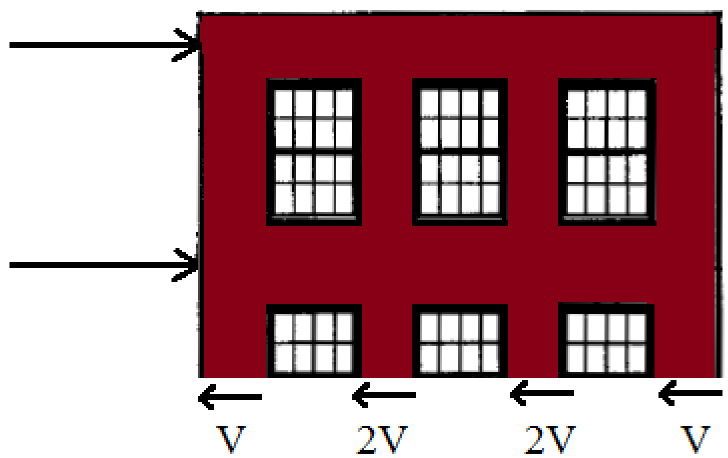


Figure 15: Example Free Body Diagram Following the Load Path through Transverse Wall

Table 13: Breakdown of Lateral Loadings in Transverse Walls

		Center Piers		**Outer Piers**		Wall Analysis Outcome
		Shear Capacity (in kips)	Design Shear (in kips)	Shear Capacity (in kips)	Design Shear (in kips)	
North Wall	3rd Floor	30.7	10.4	28.2	5.2	Sufficient
	2nd Floor	30.7	22.1	28.2	11.1	Sufficient
	1st Floor	58.9	27.9	37.1	13.9	Sufficient
South Wall	3rd Floor	79.4	22.4	148.5	11.2	Sufficient
	2nd Floor	79.4	47.8	148.5	23.9	Sufficient
	1st Floor	553.0	180.1	414.7	180.1	Sufficient

5.5.2 Wind Loadings

Lateral wind loadings were determined from *ASCE 7-10*, as referenced in Table 9. Table 14 provides a summary of key parameters and values that were used in the calculation of the design wind loadings. The loadings were determined using the main wind force-resisting system directional procedure, as laid out in Chapter 27 of *ASCE 7-10.* The base loading was multiplied by the tributary width and height for each wall to acquire the individual wall values given in Table 14. The project east wall is subject to the largest wind loads the building will need to support. This maximum loading is significantly less than the seismic loadings. The building was determined to be sufficient for the given seismic loads, and therefore it is sufficient for the given wind loads.

Table 14: Summary of Wind Loading Key Parameters and Values

<table>
<tr><th>Item</th><th colspan="2">Value</th><th>Process</th></tr>
<tr><td>Basic Wind Speed “V”</td><td colspan="2">100 mph</td><td>ASCE 7-10 Figure 26.5-1A, based on building location</td></tr>
<tr><td>Wind Directionality Factor “K_d”</td><td colspan="2">0.85</td><td>ASCE 7-10 Table 26.6-1, based on structure type, Main Wind Force Resisting System</td></tr>
<tr><td>Exposure Category</td><td colspan="2">B</td><td>ASCE 7-10 Section 26.7, building is located in downtown Worcester, an urban area</td></tr>
<tr><td>Topographic Factory “K_{zt}”</td><td colspan="2">1.00</td><td>ASCE 7-10 Section 26. 8, based on surrounding topography</td></tr>
<tr><td>Gust Effect Factor “G”</td><td colspan="2">0.850</td><td>ASCE 7-10 Section 26.9.1, building is rigid</td></tr>
<tr><td>Enclosure Classification</td><td colspan="2">Enclosed</td><td>ASCE 7-10 Section 26.10, based on building design and outer walls</td></tr>
<tr><td rowspan="5">Base Shear “V”</td><td colspan="2">11.0 psf</td><td>ASCE 7-10 Chapter 27, followed steps in Table 27.2-1 to determine wind loads</td></tr>
<tr><td>North Wall</td><td>7.7 kips</td><td rowspan="4">Individual wall values are distributed based on tributary width and height of the wall</td></tr>
<tr><td>East Wall</td><td>46.8 kips</td></tr>
<tr><td>South Wall</td><td>28.1 kips</td></tr>
<tr><td>West Wall</td><td>45.9 kips</td></tr>
<tr><td>Masonry Wall Shear Strength</td><td colspan="2">80 psi</td><td>IEBC Section A108.1, this value was chosen conservatively based on minimum allowable compressive strength of masonry</td></tr>
</table>

5.5.3 Analysis

The seismic and wind loadings were then used to analyze the existing structure with the unreinforced masonry shear wall providing lateral resistance. The *International Existing Building Code (IEBC)* was used to determine the shear strength of the existing wall. The floors are also required to carry the shear, and the joists are to be rigidly attached to the walls and the supporting framing.

Assumptions had to be made about the physical properties of the building, due to the lack of information on the structural properties of the unreinforced masonry wall in the plans given. Had information on the mortar shear strength or the tensile-splitting strength been provided, the procedure outlined in the *IEBC* section A108.2 would have been followed. In lieu of this information the shear strength of the wall was assumed to be 80 psi. Section A108.2 provides Equation A1-6 using the compressive strength of masonry, f'_{m}. Masonry compressive strength typically ranges from 1,000 psi to 4,000 psi as suggested by the Portland Cement Association. To take a conservative estimate, 1,000 psi was used in Equation A1-6a) resulting in 80 psi. This is significantly less than A1-6b) of 200 psi, and less than A1-6c) of 233.1 psi, when the minimum allowable v is assumed. Additionally, assumptions were made with regards to the rigidity of the building. The modulus of elasticity of the masonry wall was assumed to be 495 ksi, based on typical modulus of elasticity for masonry walls. The shear forces across each pier in the north and south wall were calculated by following the load path through the structure. These design values were then compared to the pier capacity.

The west and east walls were not analyzed. Although the east and west walls are subject to the largest seismic loads, they do not carry the largest lateral shear forces. The largest lateral shear is carried through the transverse walls, an example of which is seen in Figure 14. The amount of shear being carried through the east and west walls is minimal, because the north and south walls are subject to a smaller loading due to the area of the walls. The shear lateral forces in the east and west walls will not exceed that in the north and south walls and therefore they are found to be sufficient.

5.6 Structural Analysis Results

Each of the existing members was analyzed with the methods above. Figure 16 shows the results from the gravity load analysis based on the proposed residential loadings. Figure 17 shows the results based on the proposed commercial loadings. All steel beams, girders, and columns were found to be sufficient. Approximately one third of the wood beams fail under the proposed residential loadings, and approximately one half of the wood beams fail under the proposed commercial loadings. The wooden members failed in shear. Section 5.2 discusses the use of the reference values found in the structural plan over the reference values found in the *NDS*. The specified allowable shear stress is significantly lower than the value specified in the *NDS*. The lower allowable shear value is the reason that the beams reached their shear capacity before reaching their flexure capacity.

All columns in the existing plans were unlabeled. Wood columns were assumed to be 12”x12” nominal and found to be sufficient. Similarly, steel columns were assumed to be W10x52, and found to be sufficient.

For seismic and wind loadings the north and south masonry walls were determined to be sufficient. The west and east walls were not analyzed. Based on the geometry of the building, the north and south walls will have to carry the greatest shear loads as shown in Figure 14. Table 13 presents the breakdown of shear forces in the north and south walls and their sufficiency. The seismic and wind loadings in the east and west walls will not exceed those in the north and south walls. This means the design stress will be lesser than the design stress in the north and south walls. Also, the shear capacity will be greater than the north and south wall given the wall properties are consistent for each wall. Due to this fact, the west and east walls were judged to be sufficient

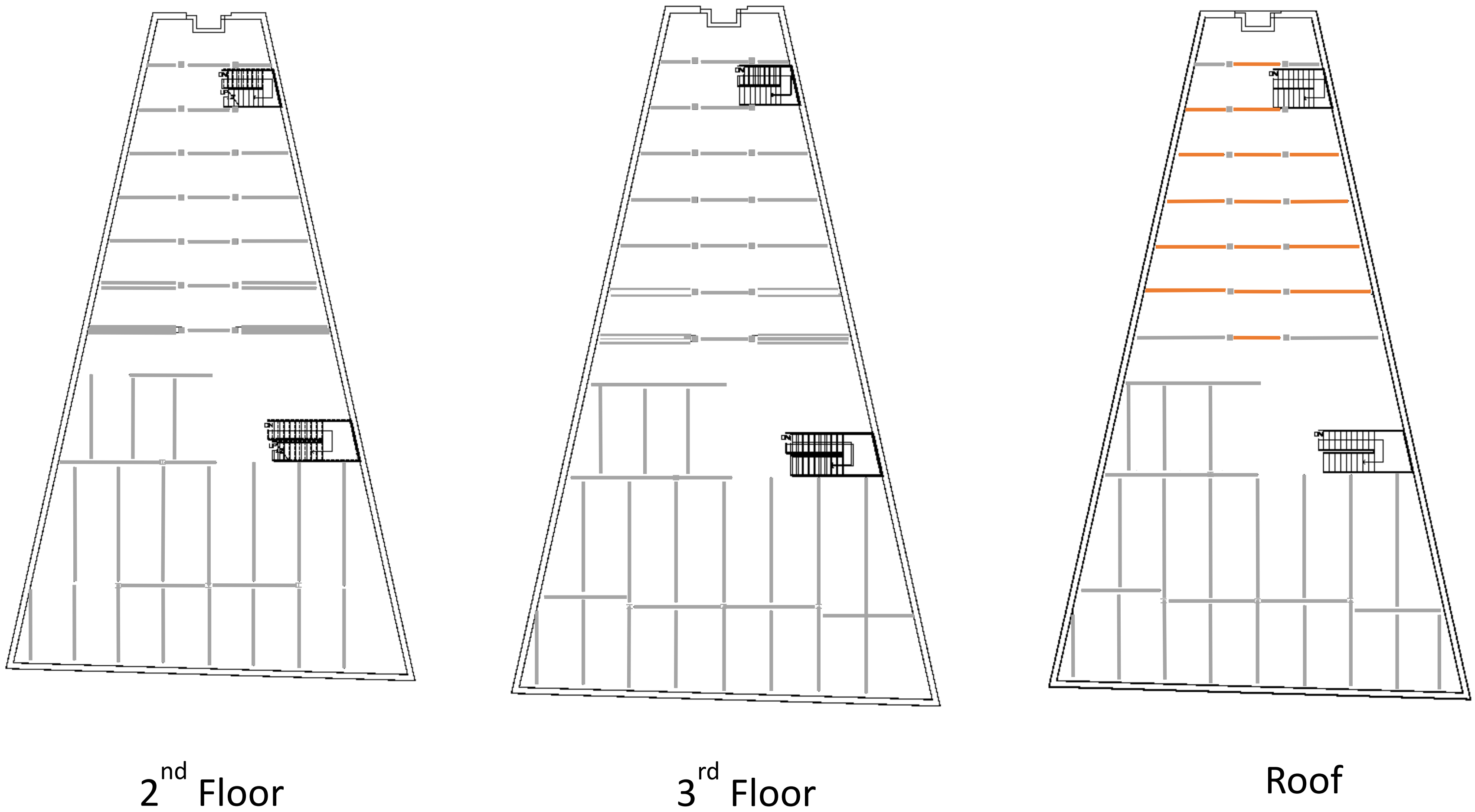


Figure 16: Residential Design Member Failure

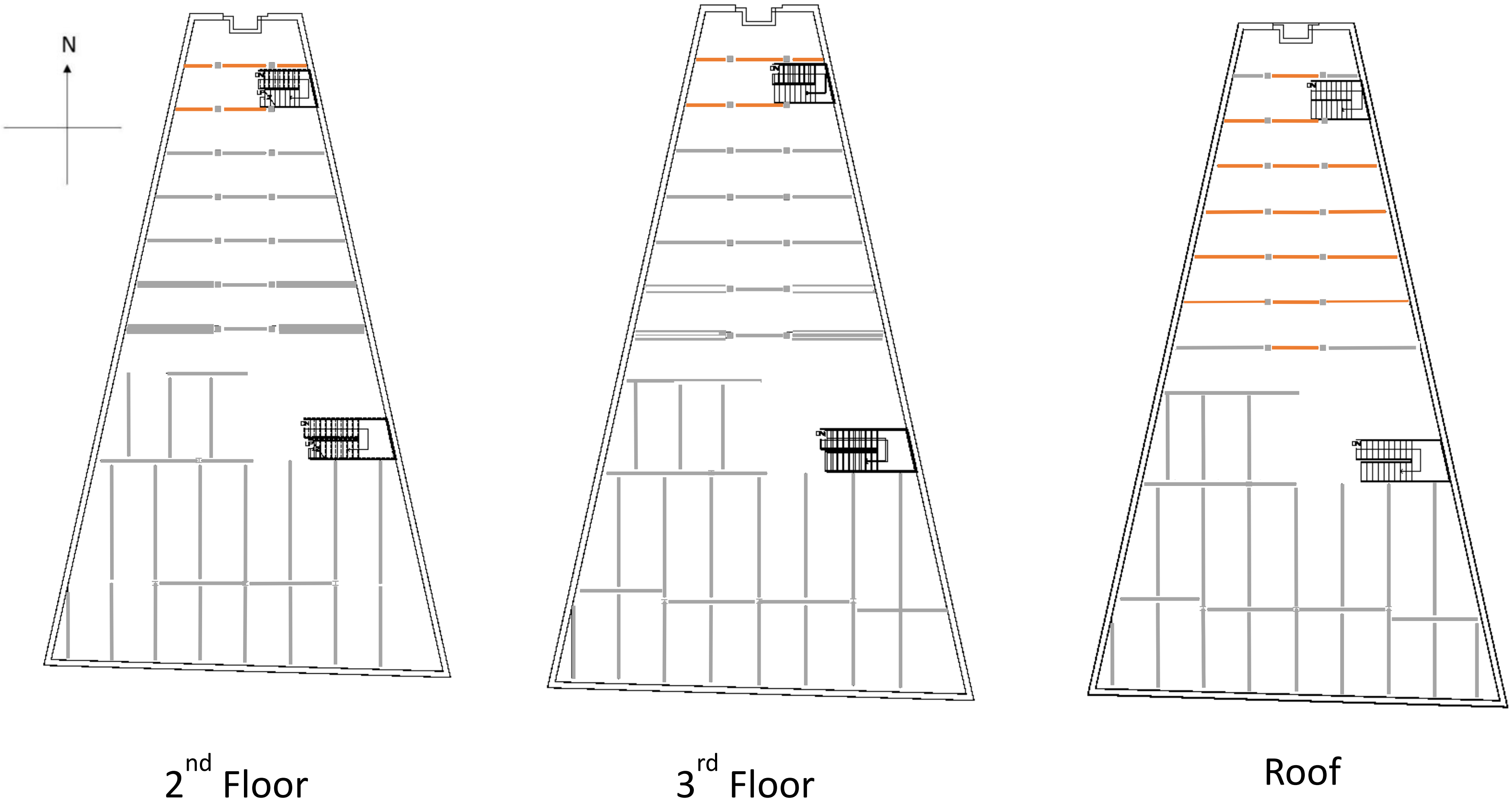


Figure 17: Commercial Design Member Failure

Chapter 6: Residential Modifications

Following the analysis of the existing members for a residential occupancy loading, all steel members were found to be sufficient while sixteen individual wood members failed. Due to the repetition of members, only seven different beam sizes failed and needed to be modified. These members need to be reinforced in a way that minimizes cost, construction time, and modifications to the space.

6.1 Potential Reinforcement Methods

Various methods to reinforce the beams and prevent failure were considered. One method of reinforcing the floor was to add more wooden members. This would decrease the tributary area of each member and reduce the amount of load that each would carry. Although this method would be simple to develop and add to the current members, the number of members would nearly double to support the roof. Given that the existing members primarily failed due to shear stresses, the size and number of members necessary would cause this method to become very costly.

Due to the shear failure of the members the addition of knee braces to reduce the reaction forces in the insufficient members was considered as a possible solution. Figure 18 shows a diagram of a potential knee brace connection. The wood beam attaches directly into the wood column, and the knee brace is placed at an angle, connecting the wood members. This solution addresses the beams' failure in shear as it directs a portion of the shear flow from the wood beam into the column, decreasing the total shear in the end of the beam. The shear flow is shown in Figure 18, moving from the center of the wood beam to the right of the diagram towards the column and splitting as it moves into the knee brace.

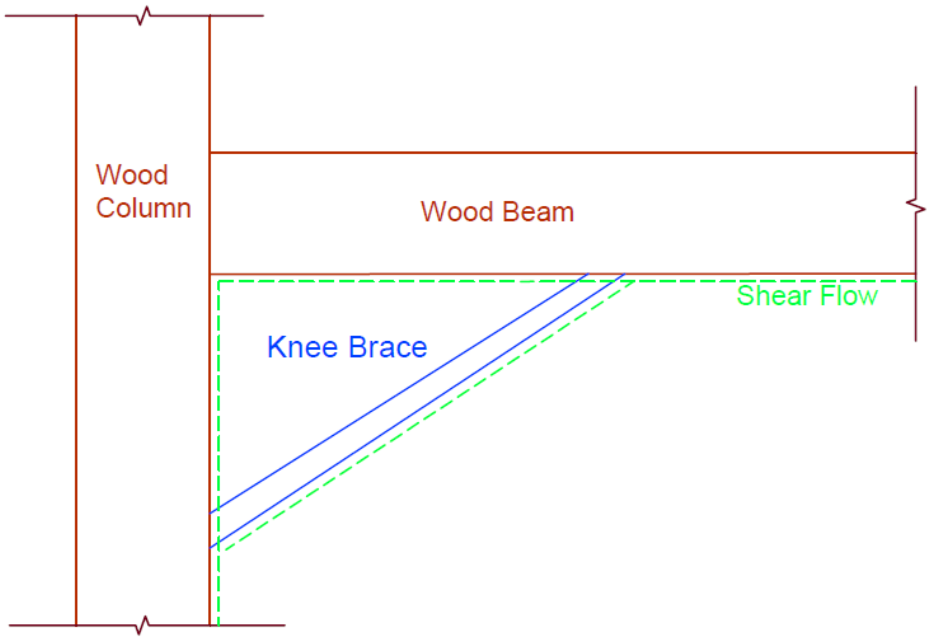


Figure 18: Shear Flow through Knee Brace Connecting Wooden Members

Additional benefits of knee braces include the increased lateral bracing they provide. Despite these benefits, knee braces were not chosen. One constraint opposing the use of knee braces is the loss of overhead space due to the bracing. While the knee brace can provide a particular ambiance with the proper architectural design, the loss of space within those rooms due to these members extending down from the ceiling was not worth the architectural appeal. This architectural appeal would also not be consistent across the building, as the residential design only had members in the roof fail. From a structural standpoint the addition of knee braces would require the columns and walls to have extra reinforcement to allow them to support the force from the brace coming in at an angle. This additional reinforcement and bracing would require extra work and materials increasing the cost.

The third and final option considered was to transform the wood members into a composite section with the addition of a steel plate on the beam's bottom face as seen in Figure 19. This allows for the shear capacity to increase with the transformed area lowering the neutral axis of the entire member, providing a larger moment of inertia to resist shear, as given by the equation, $\tau = {}^{VQ}/_{It}$. The steel plate is only necessary on the section of the wood member which is not sufficient alone, which means that the steel plates on the wooden members often do not need to run along the entire length of the beam. This saves time and money as it requires less installation and less materials. The addition of a steel plate to the bottom of wood members is a relatively simple modification from the construction standpoint. It also does not create a loss of space or a modification to the architectural feel of the building. The material costs of the modifications are minimal due to the thickness of the steel plates which is most often 3/16 in. This option was chosen due to the cost and constructability of the modifications.

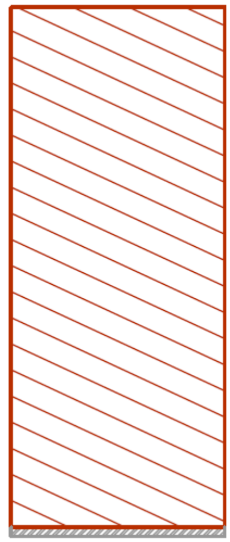


Figure 19: Example Composite Section of Wood Beam

6.2 Modification Analysis

To determine the necessary modifications the composite members were analyzed using the Allowable Stress Design (ASD) methods. They were checked for bending moment and shear in both the wood and steel sections of the member. Additionally the number of bolts necessary to attach the steel plate to the wood beam was determined using the shear flow in the composite member. Similar to the existing member analysis, a Microsoft Excel spreadsheet was created to minimize repetitive calculations. To analyze the composite section, transformed moment of inertia and transformed section modulus were found. ASD was then used to check the member design for its moment and shear capacity. The transformed properties were used with the allowable stress and allowable shear stress of wood and steel to check the capacities. Figure 20 provides a sample spreadsheet used. The blue dialogue boxes on the right side of the figure provide explanation of the calculation process.

The length of the steel plate to be attached to each end of the wooden beams was then determined. Shear diagrams were created to compare to the amount of shear the wooden beam could support to the amount of shear in the beams. Where the amount of shear in the beam exceeded the allowable shear was chosen as the critical location, as seen in Figure 21. The length of the steel plate was the distance from the critical point to the end of the member; these lengths were rounded up to the nearest half foot for constructability.

Composite Beam Analysis

Properties		
d (in)	11.5	
b (in)	3.5	
A (in^2)=	40.25	
I (in^4)=	443.589	
S (in^3)=	77.146	
W (lb/ft^3)	27.320	
Length (ft)	7.417	
Ec (psi)	1200000	
G	0.42	
Moisture content	7	
Tributary (ft)	7.5	
Fy (ksi)	60	
Es (psi)	29000000	
n=	24.16666667	
Steel Thickness (in)	0.19	
Steel Weight (pcf)	490	
Transformed A (in^2)	56.109	
y bar (in)	7.402	
Transformed I (in^4)	832.143	
Transformed S (in^3)	112.425	
σ all Steel (ksi)	36	
σ all Wood (ksi)	1.2	
τ all Steel (ksi)	24	
τ all Wood (ksi)	0.07	
Stud Size	3/4" Lag bolt	
Stud Shear Capacity (ksi)	54	
Allowable Moments		
Mmax Steel	24.103	Okay
Mmax Wood	11.243	Okay
Allowable Shear		
Vmax Steel	192.826	Okay
Vmax Wood	7.870	Okay
Steel Length		
V all Wood (kips)	2.921	
Length (ft)	0.523	
Length on each side (ft)	1.000	
Shear Studs		
Shear Flow (k/in)	0.246	
3/4" Lag bolt capacity (k)	0.98	
Spacing (in)	3.000	
Number of Bolts	8	

Concentrated LL (lb)	0	in lb/ft
Dead Load (psf)	27.25	185.85
Beam Dead Load (lb/ft)	9.869	9.869
Live Load (psf)	0	0
Snow Load (psf)	55	385
Roof LL (psf)	20	140
Rain (psf)	0	0
Wind (psf)	0	0
wu (lb/ft)=	292.592	0.6
wu (lb/ft)=	463.343	0.8
wu (lb/ft)=	917.093	0.8
Factored Load (lb/ft)=	917.032	
Design Moment (k-ft)=	6.306	
Design Shear (kips)=	3.401	

Section properties and loadings were entered into the highlighted boxes for the individual member under investigation.

Three possible load combinations were investigated, and the maximum loading was used to calculate the design moment and shear.

The allowable stress and shear stresses were found in Table 4A of the NDS for wood members and the AISC Steel Construction Manual for steel members.

The maximum allowable moment and shear were found based on the allowable stresses in steel and wood. These were compared to the design values to determine the sufficiency of the member. The steel plate properties were entered and the thickness was modified such that a sufficient allowable shear and moment were found.

The necessary length of the steel plate was determined using a shear diagram as shown in the following figure. The length is the length from the beam to wall connection to the critical point.

Shear flow was found at the bottom of the wood member where it attaches to the steel plate. The capacity of a ¾" lag bolt was found in Table 11K of the NDS. These values were used to determine the spacing and number of bolts necessary to attach the steel plate to the wood beam.

Figure 20: Composite Section Analysis Spreadsheet

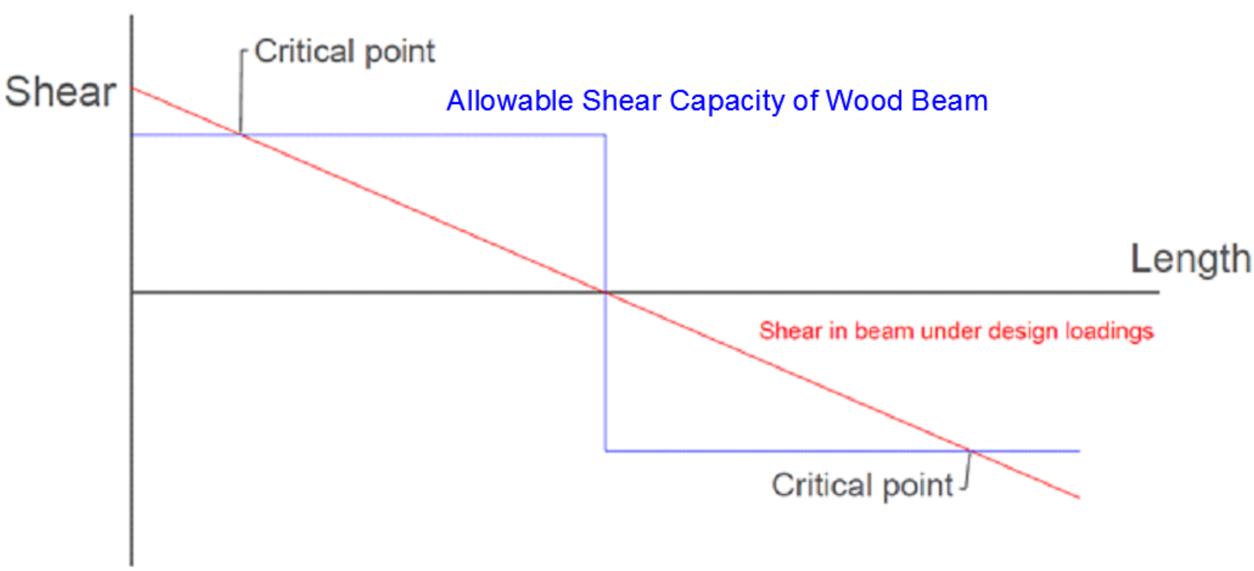


Figure 21: Shear Diagram

6.3 Residential Modification Results

Table 15 presents the necessary modifications that were made to the existing building to support the residential design loadings. Each steel plate as designated in column three of Table 15 will completely cover the width of each wood member. The steel plates are to be attached to the underside of the wood beams as shown in Figure 19. ¾" lag bolts will be used to secure the steel plates to the wood beams at the spacing given below in column four.

Table 15: Residential Member Modifications

Location	Wood Beam Size (width x height x length)	Steel Plate on Each Side (width x thickness x length)	Bolt Spacing	Bolts Used per Plate
Roof	3.5" x 11.5" x 7.4'	3.5" x 3/16" x 1.0'	3.0"	8
Roof	4.5" x 11.5" x 9.1'	4.5" x 3/16" x 0.5'	3.0"	4
Roof	4.5"x11.0" x 9.1'	4.5" x 3/16" x 1.0'	3.0"	8
Roof	4.5" x 11.0" x 9.0'	4.5" x 3/16" x 1.0'	3.0"	8
Roof	4.5" x 11.0" x 10.3'	4.5" x 3/16" x 1.5'	3.0"	18
Roof	5.5"x11.0" x 12.4'	5.5" x 5/16" x 1.5'	4.0"	10
Roof	7.5"x11.0" x 13.9'	7.5" x 5/16" x 1.0'	2.0"	12

6.4 Residential Sprinkler System Design

Following the requirements specified in *NFPA 13* for automatic sprinkler system design, sprinkler heads were located to provide sufficient coverage of floor area for the proposed residential design. Sprinkler and branchline placement were designed to meet minimum and maximum spacing requirements while utilizing cost-effective procedures to minimize the amount of sprinklers and pipe used. The sprinklers chosen for the residential design are quick-response pendent sprinklers that provide an area coverage of 225 square feet. Figure 22 below shows the intended design of the floor's crossmain, branchlines, and sprinklers. All floors are identical in the residential design so this schematic can be used for all three floors.

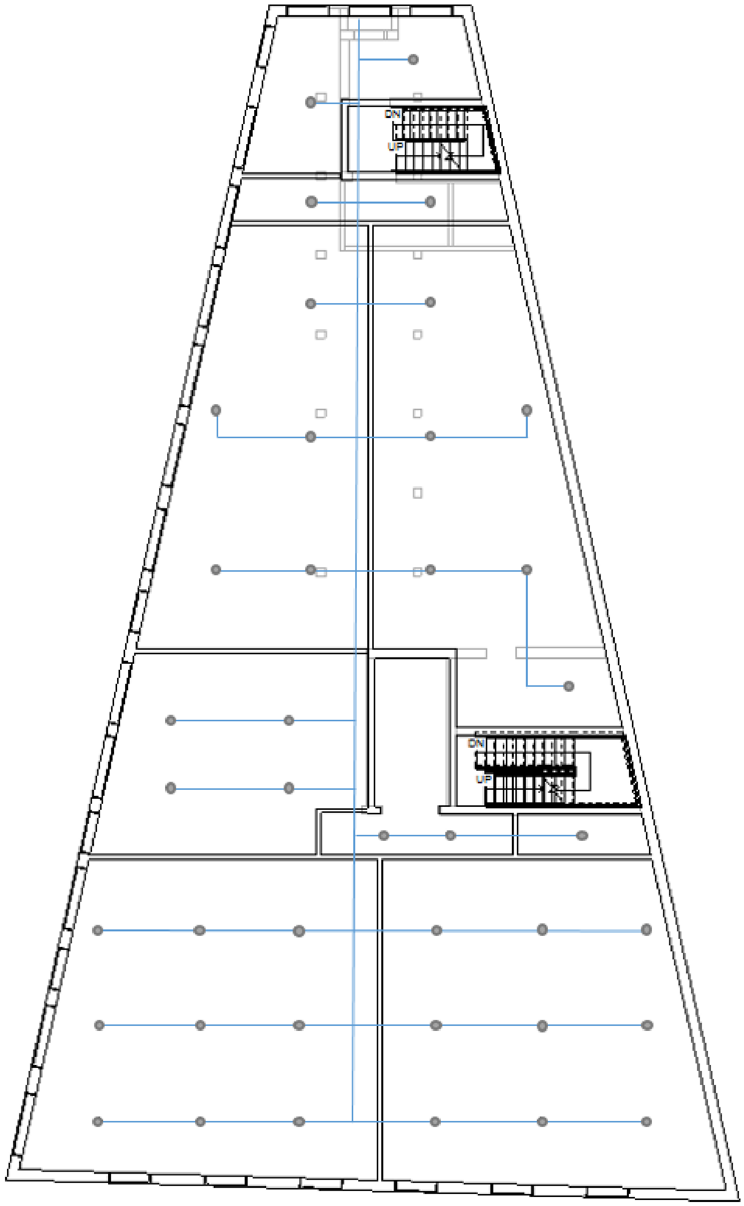


Figure 22: Sprinkler Layout for Residential Design

To determine if the available city water supply is sufficient to properly meet the flow and pressure demands of the system, hydraulic calculations were performed on third floor, the most hydraulically demanding floor due to loss in pressure over elevation change. A design area was created to occupy at least 1,500 square feet and at least 5 sprinklers as shown below in Figure 23. From the design area, the demand was calculated to determine the pressure and flow requirements as if all sprinklers in the design area were to activate at the same time. The density/area method is one of the three methods allowed to determine system water demand stated by *NFPA 13*. Figure 24 shows an example hydraulic calculation sheet that was created in Microsoft Excel that requires input of the initial required pressure and flow at the most remote sprinkler, the sprinklers K-factor, actual diameter, C-value, and length of the pipe, and any changes in elevation. This example shows the primary path from the most remote sprinkler to the bottom of the riser. Equivalent K-values were calculated to simulate the flow and pressure demand of branch lines not on the primary path. After calculations, the system is required to have at least 251 gpm at 67.22 psi.

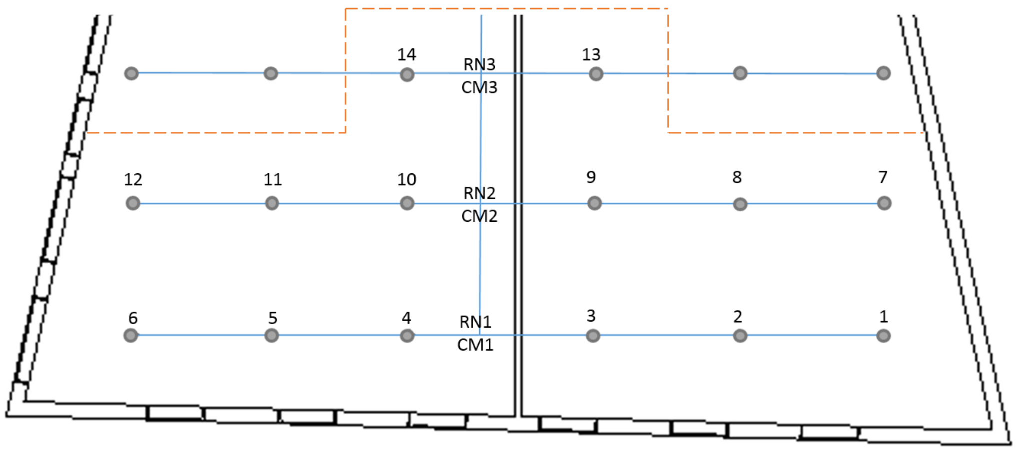


Figure 23: Design Area for Residential Design

Node	K-Factor	Nominal	Friction Loss *psi/ft*	Fittings	Length *ft*	Pt *psi*	Elevation Change *ft*
	q *gpm*	ID *inches*			Fittings *ft*	Pf *psi*	
Description	**Q** *gpm*	**C-Factor**			**Total** *ft*	**Pe** *psi*	
1	5.6	1			10	7.00	
2	14.8	1.05	0.074	-		0.74	
5.6K Spr	**14.8**	120			10	0.00	
2	5.6	1			10	7.74	
3	15.6	1.05	0.281	-		2.81	
5.6K Spr	**30.4**	120			10	0.00	
3	5.6	1			7.5	10.56	
RN1	18.2	1.05	0.669	1T	5	8.37	
5.6K Spr	**48.6**	120			12.5	0.00	
RN1	11.7	1.5			1	18.92	
CM1	50.8	1.61	0.314	1T	8	2.82	1
AP1	**99.4**	120			9	0.43	
CM1		2.5			9	22.18	
CM2	0.0	2.469	0.039	-		0.35	
	99.4	120			9	0.00	
CM2	21.1	2.5			9	22.53	
CM3	100.0	2.469	0.142	-		1.28	
AP3	**199.4**	120			9	0.00	
CM3	10.6	2.5			86.25	23.81	
TOR	51.6	2.469	0.217	1E	6	20.02	
AP5	**251.0**	120			92.25	0.00	
TOR		2.5			36	43.82	
BOR	0.0	2.469	0.217	-	0	7.81	36
	251.0	120			36	15.59	
						67.22	

Required Flow	251.0 gpm
Required Pressue	67.22 psi

Determine the minimum flow (Q) in gpm that is required: Q=(d)(A), where d is the required density (gpm/ft^2) and a is the assigned area (ft^2)

Determine the minimum pressure (P) that will be required: P=$\frac{Q^2}{K^2}$, where Q is the required flow (gpm) and K is the sprinkler's or attachment path's K-factor

Determine the C factor for the piping to the next node and the total amount of pipe lengths including fittings until next node

Calculate friction loss per foot: $P_f = \frac{4.52Q^{1.85}}{C^{1.85}D^{4.87}}$, where Q is required flow (gpm), C is the pipe C factor, and D is the pipe's internal diameter (in.)

Calculate the total friction loss in to the next node and calculate any pressure losses or gains due to elevation

Add the pressure column ($P_t + P_e + P_f$) to establish a new required pressure (P_t) at the next node

Repeat the process for flowing and nonflowing nodes back to the source node

Figure 24: Hydraulic Calculation for Primary Path of Residential Design

Using known values of the City's static pressure, residual pressure, and flow at the closest hydrant to 89 Shrewsbury Street, a water supply curve, seen in Figure 25, was drawn to determine if the city supply is adequate for the proposed fire protection system. Because the total system demand is below the water supply curve, the available water supply will provide enough flow and pressure for the system to operate properly. Different pipe sizes were sampled to see if the diameter size could be reduced and still maintain pressure and flow under the curve. The smaller the diameter size, the lower the cost of the fire protection system.

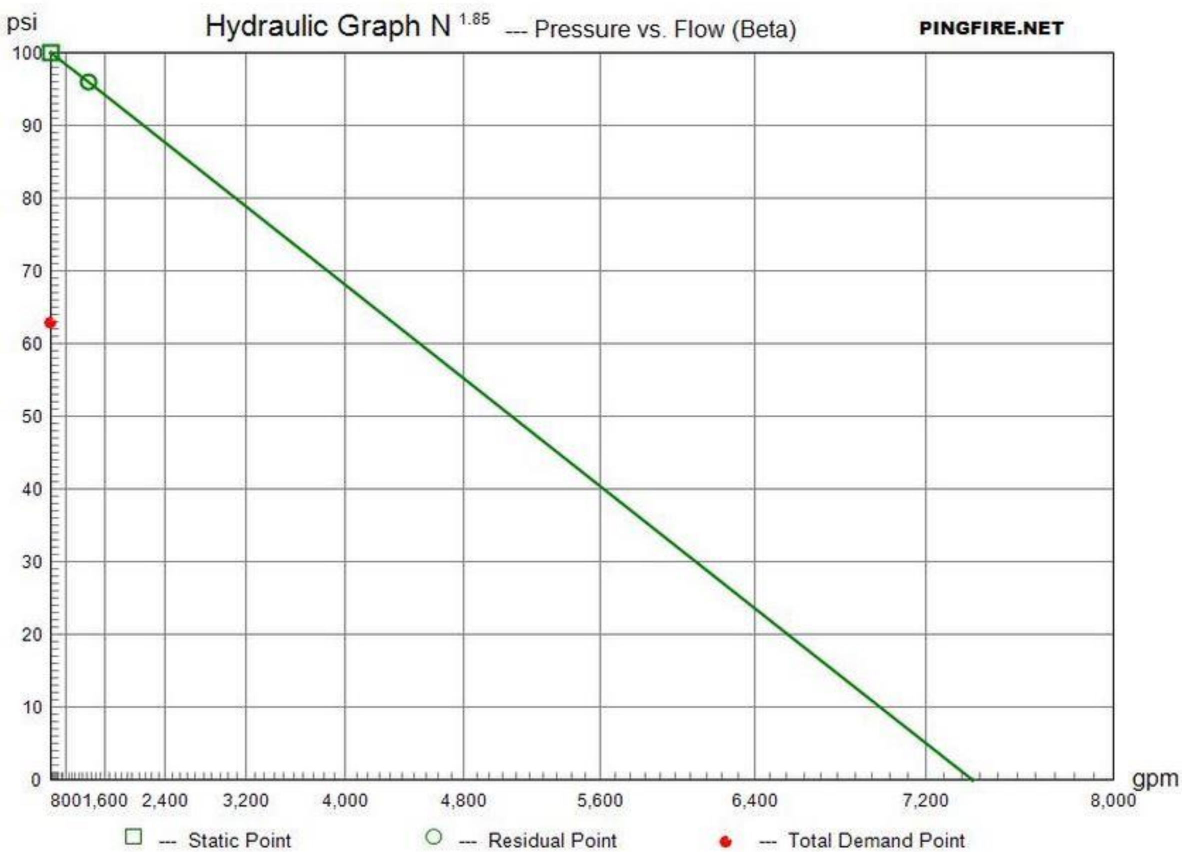


Figure 25: Water Supply Curve and System Demand for Residential Design

6.5 Cost Analysis

The cost of the modifications discussed in this chapter is outlined in

Table 16. This cost estimate was determined using *RSMeans Building Construction Cost Data 2014*. This resource provides a unit cost line for various individual construction items. This cost line provided a unit cost for the items based on material, labor, equipment, and overhead and profit costs. This unit cost was used in column four of

Table 16 and can be seen for each item. Column two is the quantity of each item in the modified plans. These two columns, the item quantity and the item unit cost, are multiplied together to determine the total cost of that item. The structural items are summed to determine the total structural costs and the sprinkler system items are summed to find that total as well. The structural and sprinkler system totals are added together to calculate the final cost for the suggested modifications for this section.

Table 16: Cost Analysis Breakdown

Item	Quantity	Unit	Unit Cost	Total
3/4" Bolt	304	Bolt	$ 6.85	$ 2,085
3/16" Steel Plates	1272	Sq. ft.	$ 11.15	$ 100
5/16" Steel Plate	756	Sq. ft.	$ 18.68	$ 100
Joist Framing	5201.67	MBF	$ 1,500.00	$ 7,805
Metal Decking	4596	Sq. ft.	$ 2.55	$ 11,720
Rigid Insulation	4596	Sq. ft.	$ 0.83	$ 3,815
Plywood	9192	Sq. ft.	$ 1.88	$ 17,285
Structural Total				**$ 42,910**
1" Pipe	961.9375	LF	$ 18.20	$ 17,510
1. 5" Pipe	36	LF	$ 23.00	$ 830
2. 5" Pipe	348.75	LF	$ 40.50	$ 14,125
Pipe Total				**$ 32,465**
Fittings			30% of Pipe Cost	$ 9,740
Sprinklers	120	Sprinkler head	$ 58. 00	$ 6,960
Sprinkler System Total			**$ 49,165**	
Modifications Total			**$ 92,075**	

Chapter 7: Commercial Modifications

Following the analysis of the existing members for a commercial occupancy loading, all steel members were found to be sufficient while twenty-seven individual wood members failed. Due to the repetition of members, only ten different beam sizes failed and needed to be modified. These members need to be reinforced in a way that minimizes cost, construction time, and modifications to the space.

7.1 Potential Commercial Reinforcement Methods

Various methods to reinforce these beams and prevent failure were considered. The methods considered for reinforcement in the commercial design are the same as those for the residential design. These methods have been described in Section 6.1 Table 17 summarizes the thought process for identifying the best method for reinforcing the wood members.

Table 17: Potential Commercial Modification Methods

Method	Description	Decision Points
Additional Members	Decreases tributary area and the amount of load each member supports.	Easy development and addition to design, however does not specifically address the failure of beams in shear making this method require a large number of beams.
Knee Braces	Directs a portion of the shear flow from the wood beam into the column decreasing the total shear in the end of the beam. This method also provides additional lateral bracing.	Knee braces create a loss of space and do not fit the architectural design for the office space. Additional support and bracing on the columns and walls would be required.
Composite Section	Attach a steel plate to the bottom of the wood members using ¾” lag bolts where necessary. This increases the shear capacity by increasing the transformed area and lowering the neutral axis.	Easily constructible and cost efficient modification. Additionally there is very little loss of space and no changes to the architectural feel of the building.

The use of a composite section was chosen based on its easy constructability as well as its minor effect on other disciplines within the building.

7.2 Modification Analysis

Just as in section 6.2 which defined the composite members for a residential design, the necessary modifications for the commercial design were defined using ASD methods. They were checked for bending moment and shear in both the wood and steel sections of the member. Additionally the number of bolts necessary to attach the steel plate to the wood beam was determined using the shear flow in the member. The same spreadsheet that was used to analyze the residential modifications was used for the commercial modifications, and a sample is shown in Figure 26. Different loadings were entered, along with different beam properties for each member. The structural analysis remained the same, using the same method of creating a transformed section to determine the allowable moments and shear. The length of the steel plate to be attached to each end of the wooden beam was defined using the same process as in the residential modifications. Shear diagrams such as the example provided in Figure 27 show where the amount of shear in the beam exceeds the allowable shear creating a critical location. The length of the steel plate was the distance from the critical point to the end of the member; these lengths were rounded up to the nearest half foot for constructability.

Composite Beam Analysis

Properties		
d (in)	11.5	
b (in)	3.5	
A (in^2)=	40.25	
I (in^4)=	443.589	
S (in^3)=	77.146	
W (lb/ft^3)	27.320	
Length (ft)	5.750	
Ec (psi)	1200000	
G	0.42	
Moisture content	7	
Tributary (ft)	7.5	
Es (psi)	29000000	
n=	24.16666667	
Steel Thickness (in)	0.19	
Steel Weight (pcf)	490	
Transformed A (in^2)	56.109	
y bar (in)	7.402	
Transformed I (in^4)	832.143	
Transformed S (in^3)	112.425	
σ all Steel (ksi)	36	
σ all Wood (ksi)	1.2	
τ all Steel (ksi)	24	
τ all Wood (ksi)	0.07	
Allowable Moments		
Mmax Steel	24.103	Okay
Mmax Wood	11.243	Okay
Allowable Shear		
Vmax Steel	192.826	Okay
Vmax Wood	7.870	Okay
Steel Length		
V all Wood (kips)	2.921	
Length (ft)	0.079	
Length on each side (ft)	0.500	
Shear Studs		
Shear Flow (k/in)	0.217	
3/4" Lag bolt capacity (k)	0.980	
Spacing (in)	4.000	
Number of Bolts	4	

Concentrated LL (lb)	2000	in lb/ft
Dead Load (psf)	28.1	191.8
Beam Dead Load (lb/ft)	9.869	9.869
Live Load (psf)	65	455
Snow Load (psf)	0	0
Roof LL (psf)	0	0
Rain (psf)	0	0
Wind (psf)	0	0
wu (lb/ft)=	301.517	0.6
wu (lb/ft)=	1038.443	0.8
wu (lb/ft)=	502.193	0.8
Factored Load (lb/ft)=	1038.443	
Design Moment (k-ft)=	9.200	
Design Shear (kips)=	3.004	

Section properties and loadings were entered into the highlighted boxes for the individual member under investigation.

Three possible load combinations were investigated, and the maximum loading was used to calculate the design moment and shear.

The allowable stress and shear stresses were found in Table 4A of the NDS for wood members and the AISC Steel Construction Manual for steel members.

The maximum allowable moment and shear were found based on the allowable stresses in steel and wood. These were compared to the design values to determine the sufficiency of the member. The steel plate properties were entered and the thickness was modified such that a sufficient allowable shear and moment were found.

The necessary length of the steel plate was determined using a shear diagram as shown in the following figure. The length is the length from the beam to wall connection to the critical point.

Shear flow was found at the bottom of the wood member where it attaches to the steel plate. The capacity of a ¾" lag bolt was found in Table 11K of the NDS. These values were used to determine the spacing and number of bolts necessary to attach the steel plate to the wood beam.

Figure 26: Composite Section Analysis Spreadsheet

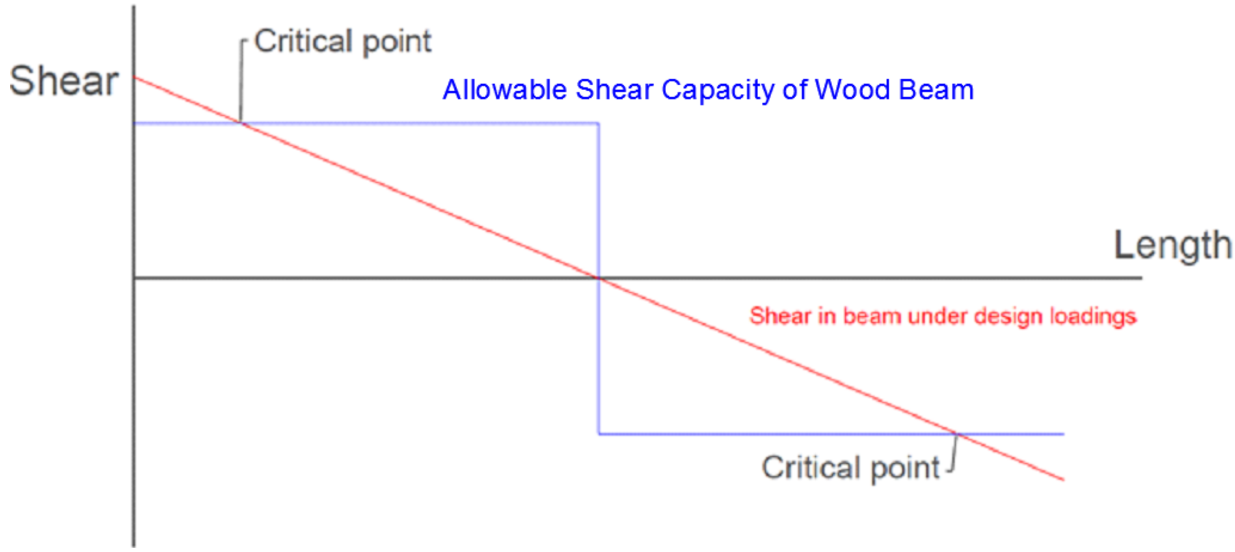


Figure 27: Shear Diagram

7.3 Required Commercial Modifications

Table 18 provides the necessary modifications that were made to the existing building to support the residential design loadings after being analyzed as described in Section 7.2. Each steel plate will completely cover the width of each wood member. Table 18 presents the size of the plate to be attached to each wood beam, along with the number of ¾" lag bolts required to attach the beam at the spacing necessary.

Table 18: Commercial Member Modifications

Location	Wood Beam Size (width x height x length)	Steel Plate Size on Each Side (width x thickness x length)	Bolt Spacing	Bolts Used per Plate
2nd and 3rd	3.5" x 11.5" x 5.8'	3.5" x 3/16" x 0.5'	4.0"	4
2nd and 3rd	3.5" x 11.5" x 7.4'	3.5" x 5/16" x 1.0'	5.0"	6
2nd and 3rd	4.5" x 11.5" x 9.1'	4.5" x 1/4" x 1.0'	3.0"	8
2nd and 3rd	7.0" x 15.0" x 15.8'	7.0" x 5/8" x 1.0'	6. 0"	4
Roof	3.5" x 11.5" x 7.4'	3.5" x 1/4" x 1.0'	5.0"	6
Roof	4.5" x 11.5" x 9.1'	4.5" x 1/4" x 0.5'	4.0"	4
Roof	4.5" x 11.0" x 9.1'	4.5" x 5/16" x 1.0'	5.0"	6
Roof	4.5" x 11.0" x 9.0'	4.5" x 5/16" x 1.0'	5.0"	6
Roof	4.5" x 11.0" x 10.3'	4.5" x 5/8" x 1.5'	12.0"	4
Roof	5.5" x 11.0" x 12.4'	5.5" x 9/16" x 2.5'	9.0"	8
Roof	7.5" x 11.0" x 13.9'	7.5" x 1/4" x 1.0'	2.0"	12

7.4 Commercial Sprinkler System Design

Similar to the residential sprinkler system discussed in Chapter 6, the commercial fire protection system has a maximum square footage protection area of 225 square feet and a maximum of 15 foot spacing. Figure 28 below shows the proposed sprinkler system, including branchlines, crossmain, and sprinklers for all floors of the commercial design.

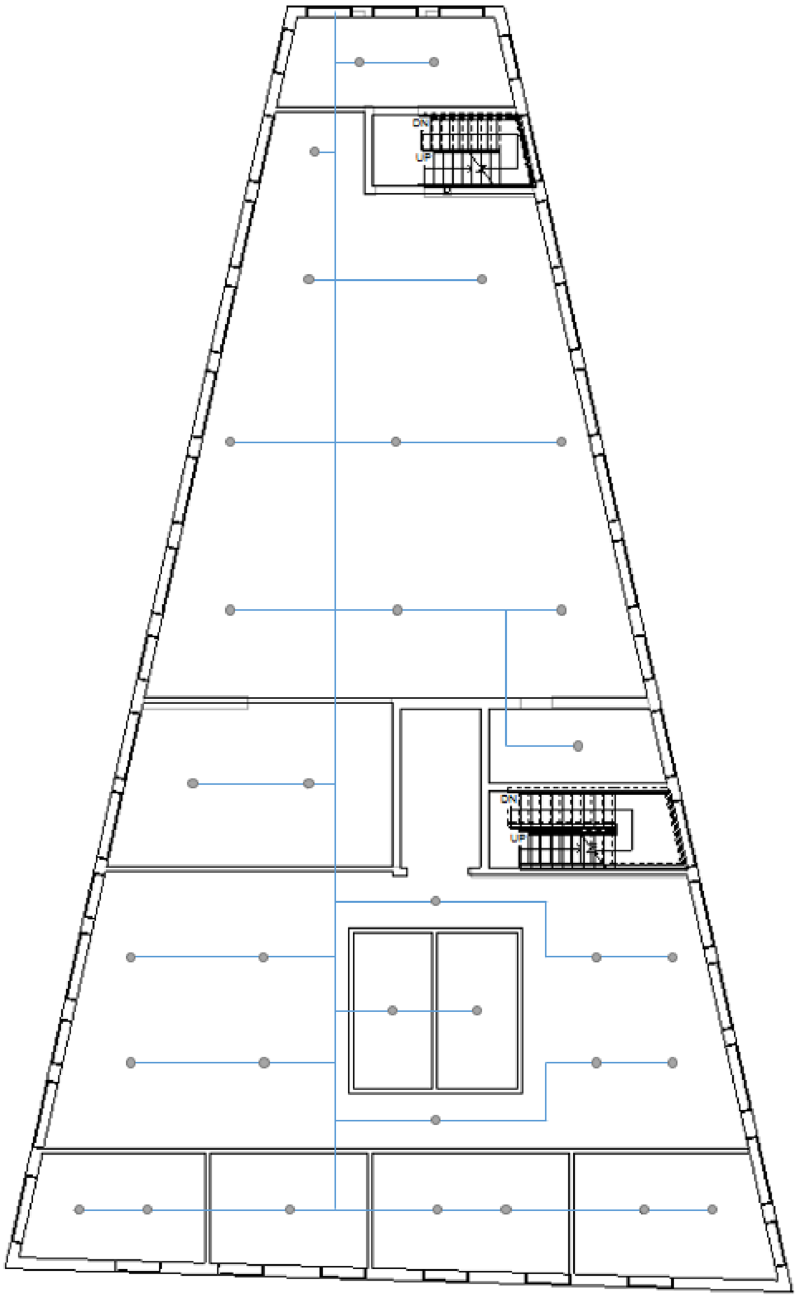


Figure 28: Sprinkler Layout for Commercial Design

The design area was again created to encompass the most hydraulically demanding sprinklers over 1,500 square feet, seen in Figure 29. The area/density method from *NFPA* 13 is one of three methods used to determine a system's water demand. The design area differed from that of the residential design due to the fact there are different floor plans for each design, requiring different sprinkler placement and spacing. Hydraulic calculations, seen in Figure 30, require the system to have at least 354.2 gpm at 75.65 psi. Because of the different design area that is encompassed for the calculations, it actually required slightly larger piping for the crossmain to lower the amount of pressure loss throughout the system. Though the commercial design requires more flow at a higher psi, it is significantly below the water supply curve for 89 Shrewsbury Street, indicating that the City's water supply is sufficient, and the system will not require a fire pump. The water supply curve, along with the system's demand is shown below in Figure 31.

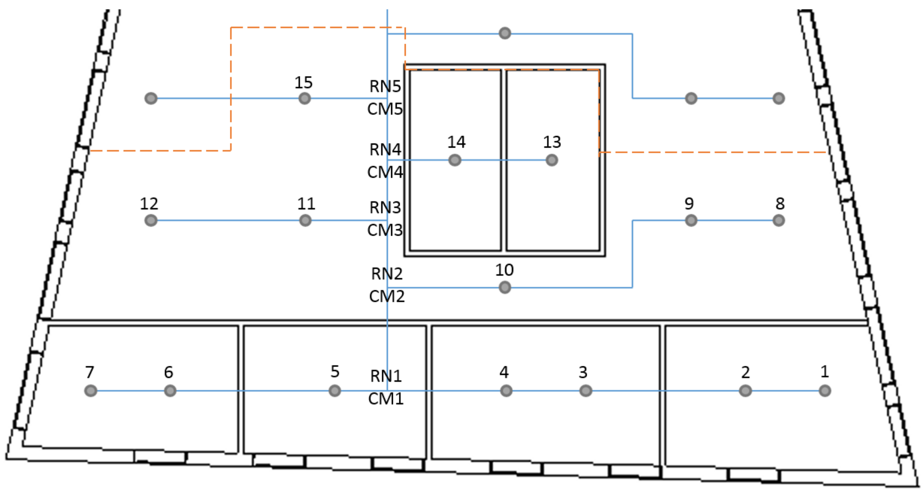


Figure 29: Design Area for Commercial Design

Node	K-Factor	Nominal	Friction Loss psi/ft	Fittings	Length *ft*	Pt *psi*	Elevation Change *ft*
	q *gpm*	ID *inches*			Fittings *ft*	Pf *psi*	
Description	Q *gpm*	C-Factor			Total *ft*	Pe *psi*	
1	5.6	1			6	7.00	
2	14.8	1.05	0.074	-		0.45	
5.6K Spr	**14.8**	120			6	0.00	
2	5.6	1			12	7.45	
3	15.3	1.05	0.276	-		3.31	
5.6K Spr	**30.1**	120			12	0.00	
3	5.6	1			6	10.76	
4	18.4	1.05	0.666	-		4.00	
5.6K Spr	**48.5**	120			6	0.00	
4	5.6	1			9.5	14.75	
RN1	21.5	1.05	1.314	1T	6	20.37	
5.6K Spr	**70.0**	120			15.5	0.00	
RN1	11.7	1.5			1	35.12	
CM1	69.3	1.61	0.586	1T	8	5.27	1
AP1	**139.3**	120			9	0.43	
CM1		3			7.75	40.83	
CM2	0.0	3.068	0.025			0.20	
	139.3	120			7.75	0.00	
CM2	9.9	3			5	41.03	
CM3	63.5	3.068	0.051	-	0	0.25	
AP2	**202.8**	120			5	0.00	
CM3	8.8	3			4.75	41.28	
CM4	56.7	3.068	0.080	-	0	0.38	
AP3	**259.5**	120			4.75	0.00	
CM4	8.9	3			4.75	41.66	
CM5	57.3	3.068	0.116	-		0.55	
AP4	**316.8**	120			4.75	0.00	
CM5	5.8	3			82.25	42.21	
TOR	37.4	3.068	0.142	1E	7	12.72	
AP5	**354.2**	120			89.25	0.00	
TOR		3			36	54.93	
BOR	0.0	3.068	0.142	-		5.13	36
	354.2	120			36	15.59	
						75.65	

Required Flow	354.2 gpm
Required Pressue	75.65 psi

Figure 30: Hydraulic Calculation for Primary Path of Commercial Design

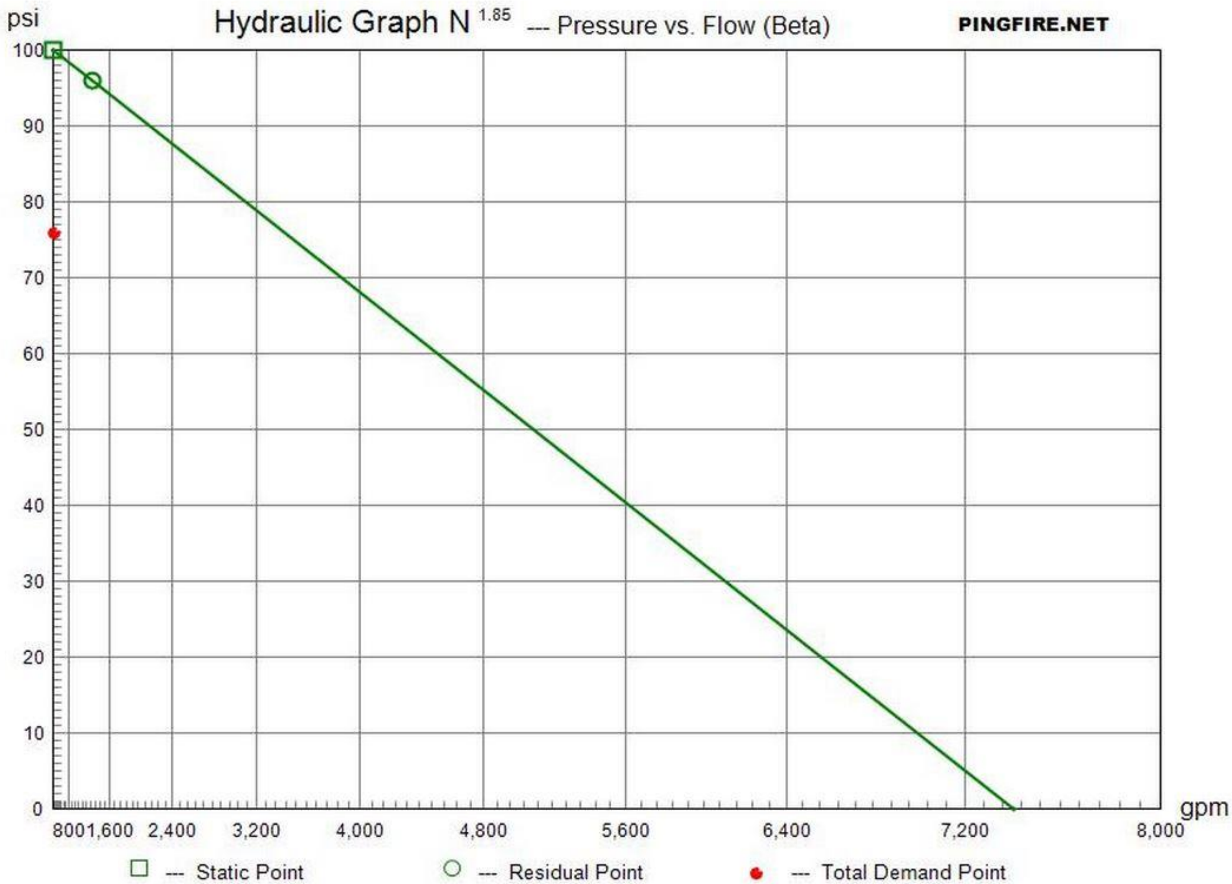


Figure 31: Water Supply Curve and System Demand for Commercial Design

7.5 Cost Analysis

The cost of the modifications discussed in this chapter is outlined in Table 19. This cost estimate was determined using *RSMeans Building Construction Cost Data 2014*. This resource provides a unit cost for each construction item that is based on material, labor, equipment, and overhead and profit costs. This unit cost was used in column four of Table 19. The quantity of each item was determined from the modifications made to the existing building. These two columns are used to determine the total cost for each item. The sum cost of structural modifications and sprinkler modifications are provided. These two sub costs are then summed together to determine the total cost of the modifications.

Table 19: Cost Analysis Breakdown

Item	Quantity	Unit	Unit Cost	Total Cost
3/4" Bolt	360	Bolt	$ 6.85	$ 2,470
3/16" Steel Plate	168	Sq. ft.	$ 11.15	$ 15
1/4" Steel Plate	984	Sq. ft.	$ 14.85	$ 105
5/16" Steel Plate	924	Sq. ft.	$ 18.68	$ 120
9/16" Steel Plate	580.8	Sq. ft.	$ 33.00	$ 135
5/8" Steel Plate	996	Sq. ft.	$ 36.50	$ 255
Joist Framing	5201.67	MBF	$ 1,500.00	$ 7,805
Metal Decking	4596	Sq. ft.	$ 2.55	$ 11,720
Rigid Insulation	4596	Sq. ft.	$ 0.83	$ 3,81
Plywood	9192	Sq. ft.	$ 1.88	$ 17,280
Structural Total				**$ 43,720**
1" Pipe	848.9375	LF	$ 18.20	$ 15,455
1. 5" Pipe	36	LF	$ 23.00	$ 830
3" Pipe	349.5	LF	$ 49.00	$ 17,125
Pipe Total				$ 33,415
Fittings			30% of Pipe Cost	$ 10,025
Sprinklers	99	Sprinkler head	$ 58.00	$ 5,745
Sprinkler System Total				**$ 49,185**
Modifications Total				**$ 92,910**

Chapter 8: Sustainable Design

89 Shrewsbury Street was built long before any concept of sustainable construction had been investigated. Since then, many new regulations, guidelines, and incentives have been implemented in order to ensure that development minimizes its impact on the planet. This includes systems designed to reduce water consumption.

8.1 Rainwater Management System

Given the area of the roof being approximately 4,600 sq. ft. and the Worcester rainfall totals, average rainfall collections on the order of approximately 137,000 gallons annually can be expected. Although seeming like a large total, this value is only a fraction of the municipal water actually consumed by the occupants of the structure.

The system would be based upon collection from the roof. Serving as the mouth of a funnel, the water will be directed from the down spouts and already existing gutter system to the intake for the tank. By doing this, we ensure that the majority of the rainwater that falls on the property will be recycled and not disposed of by the municipal storm water system.

In both cases, the WISY 4 step system as suggested by the company Rainwater Management Solutions was implemented. The system itself includes what is called a "vortex filter." This vertical filter is designed to remove large debris, such as leaves and twigs, from the collected rainwater. This same filtration system also will filter out particles down to 280 microns before the water enters the tank. From here, both the filtration process and smoothing inlet allow for highly oxygenated water to enter the tank, allowing for a healthy tank environment. Naturally occurring bacteria will develop along the top of the water and the sides of the tank. However, these bacteria are necessary for a healthy tank environment and will feed on unhealthy, foul-smelling microorganisms. Furthermore, this biofilm is not disturbed during rain events because of the installed smoothing inlet and water is pumped out of the tank several inches below the biofilm layer. At this point several inches below the surface, the water have settled and no biofilm exists. Between all of this, the requirement for "uncontaminated water" has been met and it is adequate to use in toilet systems. It is not however adequate for potable water. (Rainwater Management Solutions, 2015).

For both occupancy types, the main focus for estimating water cost and supply was based upon the toilet usage. In both the cases of residential and commercial, the water needed to supply the toilets would not be met by rainwater alone. This ensures that there is no need for connecting the rainwater recycling scheme to multiple plumbing systems. However, the rainwater system also requires a backup feed. Adding a pressure regulated flap will allow for the municipal water supply to be utilized in the cases of a prolonged dry spell.

8.1.1 Residential Design

Based upon the designed layout of the residential occupancy, the maximum amount of building tenants as per the *IBC* is 69. This is the number to be utilized when conducting all sizing calculations for the tank, piping, use etc. According to the software utilized by Rainwater Management Solutions of Salem, Virginia, the following tank sizes will supply the given water totals to the building designed for residential use.

Table 20: Residential Tank Sizing

Tank size (gallons)	Overflow days (per year)	"Dry" days (per year)	Overflow volume per year (thousands of gallons)	Supplied volume per year (thousands of gallons)	% of demand met by rainwater	Savings from water use ($)	Savings from stormwater ($)	Savings from sewer fees ($)	Overflow from design storm (% of volume)
100	0	365	107	11	4	0	0	0	0
1,100	41	309	52	65	27	0	0	0	28
2,100	23	277	31	87	36	0	0	0	9
3,100	14	254	20	98	40	0	0	0	5
4,100	10	245	14	104	43	0	0	0	3
5,100	6	238	9	108	44	0	0	0	2
6,100	5	234	7	111	45	0	0	0	2
7,100	4	231	6	112	46	0	0	0	1
8,100	3	229	4	113	46	0	0	0	1
9,100	2	228	4	114	46	0	0	0	1
10,100	2	227	3	114	47	0	0	0	1
11,100	1	227	3	115	47	0	0	0	1
12,100	1	226	3	115	47	0	0	0	1
13,100	1	226	3	115	47	0	0	0	1
14,100	1	225	2	116	47	0	0	0	0
15,100	1	225	2	116	47	0	0	0	0
16,100	1	224	2	116	47	0	0	0	0
17,100	1	224	2	116	47	0	0	0	0

As can be seen, at approximately the 4,000 gallon tank size, the % met by rainwater begins to level out at around 45%. The increase in "demand percentage met" increases very slowly from here, reaching an asymptote at around 47%. Therefore, the decision was made to invest in a tank in the 5,000 to 6,000 gallon range. At this size, an estimated value of 5,000 to 8,000 gallons of water would be lost. This is a cost differential of around $50.

Due to the fact the building the tank would need to service is already constructed, the decision was made to purchase two smaller tanks to ensure they fit in through the doors. Thus, two 2,500 gallon capacity tanks were selected. From here, the total cost for all parts and piping would be approximately $3,800-$4,300 as per the Rainwater Management Solutions WISY 4 system (Rainwater Management Solutions). Overall, this system would provide approximately 45% of the toilet water consumption. An example system, with cost, material and equipment data is included in the table below.

Table 21: Residential Rainwater Management System Design

Component	Details	Cost/Item	# of Items	Total
Tank	2500 gallon tanks	~$1,250-$1,500	2	$2,500-$3,000
Filter	WISY Medium Capacity Vortex Fine Filter	$800	1	$800
Smoothing Inlet	WISY 4” Smoothing Inlet	$125	1	$125
Floating Filter	1 ¼” Coarse Floating Filter	$100	1	$100
Overflow Device	WISY 4” Overflow Device	$315	1	$315
TOTAL				$3,840-$4,340

8.1.2 Commercial

Based upon the designed layout of the commercial occupancy, the maximum amount of building tenants as per the *IBC* is 140. This is the number to be utilized when conducting all sizing calculations for the tank, piping, use etc. According to the software utilized by Rainwater Management Solutions of Salem, Virginia, the following tank sizes will supply the given water totals to the building designed for residential use.

Table 22: Commercial Tank Sizing

Tank size (gallons)	Overflow days (per year)	"Dry" days (per year)	Overflow volume per year (thousands of gallons)	Supplied volume per year (thousands of gallons)	% of demand met by rainwater	Savings from water use ($)	Savings from stormwater ($)	Savings from sewer fees ($)	Overflow from design storm (% of volume)
100	0	365	107	11	3	0	0	0	0
1.100	12	327	53	65	16	0	0	0	8
2,100	22	296	29	89	22	0	0	0	7
3,100	12	293	17	100	25	0	0	0	3
4.100	8	284	11	107	27	0	0	0	2
5.100	4	281	7	110	28	0	0	0	1
6,100	3	280	6	112	28	0	0	0	1
7,100	2	278	4	113	28	0	0	0	1
8.100	1	277	4	114	29	0	0	0	0
9.100	1	276	3	115	29	0	0	0	0
10,100	1	276	2	115	29	0	0	0	0
11,100	1	276	2	116	29	0	0	0	0
12,100	0	276	2	116	29	0	0	0	0
13.100	0	275	2	116	29	0	0	0	0
14,100	0	275	2	116	29	0	0	0	0
15,100	0	275	1	117	29	0	0	0	0
16,100	0	275	1	117	29	0	0	0	0
17.100	0	275	1	117	29	0	0	0	0

Based upon the totals supplied to the team, it was recommended to install a tank that once again was between 5,000 and 6,000 gallons of storage for the same reasoning as can be seen in the residential section of this same chapter. This tank would supply the facility with approximately 28% of its toilet water requirement. The total cost to install such as a system would once again be approximately $3,800-$4,300, not including installation.

8.1.3 Justification of Cost

Assuming that the system will save an estimated 110,000 gallons of water from the municipal supply annually, the facility will cut its water cost by about $500 per year. Although a relatively small number, this cost saving is only a minor contributor towards the importance of the system. Currently, the world community is facing a water supply shortage; therefore any water that is recycled and reused will greatly benefit the overall community.

Installing a rainwater system for this particular building overlaps with several LEED requirements. The first is the installation of a rainwater management system, which earns the owner three points toward certification. The other is a reduction in the Indoor Water Use, which can lead to 6 points toward accreditation.

8.2 Energy Efficiency

One of the easiest and most effective sustainability options is to reduce the consumption of electricity. Currently on the market are hundreds of possible implementations that can be utilized to make cost and sustainable changes possible. Some of the possible implementations are discussed in the following section.

8.2.1 Possible Implementations

The Environmental Protection Agency recommends an energy audit by a private company be completed in order to ensure the best possible savings. Several possible ways of reducing the energy usage of the building are stated below. The suggestions are located on the website Environmental Protection Agency. They are listed and described as follows:

- Energy Efficient Lighting- LED and energy reducing fluorescent bulbs can be easily installed at no additional cost. Since the fixtures and interior needs to be completely redone, the cost will be similar to the one in RSMeans.
- ENERGY STAR- the Energy Star rating is used on appliances that require less energy to power and operate. Under these categories specifically are lighting, heating and cooling equipment, and commercial appliances. Once again, since the space needs a full renovation, new appliances with the Energy Star tag can be purchased.

8.2.2 Justification of Cost

Similar to the rainwater management system, the amount of energy to be saved could result in effective cost savings. However, the real savings stem from the sustainability certifications. The LEED and Energy Star requirements being met are the largest benefits. By being rated by either of these two entities, the company can be given certain discounts and tax rebates. According to the LEED standards, reducing energy savings can be worth up to 18 points, almost half reaching the first level of certification.

Chapter 9: Comparison of Occupancy Types

In designing the fire protection systems, structural modifications, and looking into sustainability options the two occupancy types were found to differ. These differences contribute to a difference in costs for the complete renovation for each occupancy option. The following chapter will look at the differences found through analysis, research, and cost estimation.

9.1 Fire Protection

In the design of the fire protection systems for the both the commercial and residential designs, a light occupancy hazard was used based on the intended uses of the building. According to *NFPA 13*, a light hazard occupancy called for a design density of 0.10 gpm/ft^2 and a design area of 1,500 ft^2. Despite both designs having the same the occupancy hazard, different designs were required based on space requirements. The fire protection system is required to have complete coverage, meaning sprinklers heads need to be placed in specific places for floor area coverage. This resulted in different sprinkler placement, different size piping, and different system water demands for each design. The table below summarizes the two distinct fire protection systems and allows an easy comparison between the two.

Table 23: Comparison of Fire Protection System Demands

Fire Protection System Design	Residential	Commercial
Required Flow (gpm)	251	354.2
Required Pressure (psi)	67.22	75.65
Number of Sprinkler Heads	120	99

Due to different space requirements for each design, the residential and commercial fire protection systems each required a different amount of sprinkler heads and piping. The commercial system requires a larger flow and pressure than the residential system, but requires less sprinkler heads. It also requires larger pipe diameters to reduce friction losses from the riser to the design area. These differences stem from a different design area, piping lengths, and sprinkler head placement. Although the commercial design has greater system demands than the residential system, the demands of both systems are far below what is supplied by the city water supply. The city water supply will supply sufficient flow and pressure to each system, and the installation of a fire pump or gravity tank is not required.

9.2 Structural

In the structural analysis, the commercial plan required the existing structure to sustain a larger design load than the residential plan. This load caused ten more wooden members to fail in the commercial plan than in the residential plan. All steel members were sufficient for both commercial and residential.

For wind and seismic analysis, both residential and commercial buildings fall into Risk Category II, as described in the *IBC* Table 1604.5. The risk category of a building is the only factor that takes occupancy type into consideration when determining wind and seismic loads.

Since the occupancy categories were the same, the building was subject to the same lateral loadings whether it was a commercial or a residential building. The analysis was preformed once and the existing masonry shear walls were found to be sufficient to carry the loads.

9.3 Sustainability

In the implementation of sustainability features in both occupancy types was very similar. For both, the rainwater management system most effectively serviced the toilet water needs of the facility and utilized the roof as the collection point. The systems themselves were also designed the same since the occupancy type had no effect on the size of the storage tank. The only differences were in how the system would impact the water use of the structure. A summary table of these differences is included below:

Table 24: Comparison of Rainwater Management System

Characteristic	Residential Value	Commercial Value
Demand met by rainwater	~44%	~27%
"Dry" Days	238 days/year	281 days/year
Overflow Days	6 days/year	4 days/year

As can be seen, the impact of the rainwater management system was much greater for the residential building. In this sense, the residential building is the better value, but ultimately this has very little impact on the decision for which structure to construct.

9.4 Cost Analysis

The final comparison is the overall cost of creating the structure. This determining factor is a good indication of which structure to ultimately choose. Below is a comparison in the pricing of all the components of the structural modifications for both occupancy types.

Table 25: Residential Structural Modifications Anticipated Costs

Line Item	Amount	Cost	Total
¾" Bolts	304	$6.85	$2,084
3/16" Steel Plates	1272	$11.15	$100
5/16" Steel Plates	756	$18.68	$100
Joist Framing	5202	$1500	$7,805
Metal Decking	4596	$2.55	$11,720
Rigid Insulation	4596	$0.83	$3,815
Plywood	4596	$1.88	$17,285
TOTAL			**$42,910**

Table 26: Commercial Structural Modifications Anticipated Costs

Line Item	Amount	Cost	Total
¾" Bolts	360	$6.85	$2,470
3/16" Steel Plates	168	$11.15	$15
¼" Steel Plates	984	$14.85	$105
5/16" Steel Plates	924	$18.68	$120
9/16" Steel Plates	581	$33.00	$135
5/8" Steel Plates	996	$36.50	$255
Joist Framing	5,202	$1500	$7,805
Metal Decking	4,596	$2.55	$11,720
Rigid Insulation	4,596	$0.83	$3,815
Plywood	4,596	$1.88	$17,285
TOTAL			**$43,725**

The following tables are cost estimates for the sprinkler system for both occupancy types.

Table 27: Residential Fire Protection System Anticipated Costs

Line Item	Amount	Cost	Total
1" Pipe	962 ft.	$18.20	$17,510
1.5"Pipe	36 ft.	$23.00	$830
2.5" Pipe	349 ft.	$40.50	$14,125
Pipe Total			**$32,465**
Fittings		30%	$9,740
Sprinklers	120	$58.00	$6,960
TOTAL			**$49,165**

Table 28: Commercial Fire Protection System Anticipated Costs

Line Item	Amount	Cost	Total
1" Pipe	849 ft.	$18.20	$15,455
1.5"Pipe	36 ft.	$23.00	$830
3" Pipe	350 ft.	$49.00	$17,130
Pipe Total			**$33,415**
Fittings		30%	$10,025
Sprinklers	99	$58.00	$5,745
TOTAL			**$49,185**

The final cost comparison stems from the furnishing of the occupancies and the interior systems (mechanical, HVAC, wiring, etc.)

Table 29: Anticipated Interior Construction Costs for Residential Option

Line Item	Amount	Cost	Total
MEP	4,596	$19.60	$90,082
Finishes	4,596	$10.65	$48,947
Equipment	4,596	$3.63	$16,683
TOTAL			**$467,137**

Table 30: Anticipated Interior Construction Costs for Commercial Option

Line Item	Amount	Cost	Total
MEP	4,596	$31.50	$144,774
Finishes	NA	NA	NA
Equipment	4,596	$2.11	$9,698
TOTAL			**$463,415**

The total cost for both occupancies are presented in Table 31 below.

Table 31: Final Construction Costs

Aspect	Residential Cost	Commercial Cost
Structural Modifications	$42,910	$43,725
Fire Protection System	$49,165	$49,185
Interior Construction	$467,137	$463,415
Rainwater System	$4,000	$4,000
GRAND TOTAL	**$563,212**	**$560,325**

As can be seen, the total costs are very similar, causing the choice to be complicated further. It therefore comes down to the overall profitability of the occupancies to determine in which way it is best to use the structure.

9.5 Profitability of Occupancy

The occupancies themselves are intended to generate revenue for the owner/developer of the building. To calculate the average income from the building, local area data on renting/leasing was used to create estimated revenues. These estimated revenues would be considered "low" for the Worcester area, in order to ensure that cost analysis was conservative and reasonably justified. Also included is the vacancy rate. This rate assumes that not all the rooms or space will be filled in the structure, giving a more reasonable rate of return on investment (Reis Reports and Department of Numbers for Worcester).

Table 32: Expected Revenue by Occupancy Type

Residential				Commercial	
Apartment	#/Floor	Rent	Units	Lease Rate	Unit
2 Bedroom	3	$1400	Monthly	$12	sf. /year
1 Bedroom w/ Den	1	$1000	Monthly		
1 Bedroom	1	$900	Monthly		
Subtotal					
$219,600/year				**$165,456/year**	
Assumed Vacancy Rate					
7%				18%	
GRAND TOTAL					
$204,288/year				**$135,674/year**	

Table 33 presents the profitability in terms of the years to the breakeven point. The occupancy type with the shorter breakeven point will be more profitable. Once hitting the breakeven point the owner has made back the money that has been spent on construction and can begin to use revenue to cover operation and maintenance as well as begin to make a profit. The residential design had a shorter breakeven point and therefore would be more profitable.

Table 33: Profitability of Occupancy Types

	Residential	Commercial
Construction Cost Estimate	$563,212	$560,325
Expected Annual Revenue	$204,228	$135,674
Predicted Years to Breakeven Point	2.75 years	4.13 years

Based upon this profitability study, the more profitable option would be to create a residential structure. However, any changes in the layout of the apartments would cause a differentiation in pricing. Furthermore, rent costs fluctuate from year to year; therefore rent may increase or decrease. Finally, the utility cost to run the facility was not included; it was just assumed that energy costs would be similar, or at least comparable enough.

Chapter 10: Conclusions

This project examines a specific building in Worcester. The design of this building is used to develop a methodology that can determine ways to best renovate such buildings. To determine the feasibility of redesigning an existing, non-compliant building, the methodology can be divided into four categories; sprinkler system design, structural analysis, sustainability research, and cost analysis. The following chapter summarizes the work performed in each category, presents key findings, discusses limitations, and proposes ideas to further the project.

10.1 Summary of Work

To begin the design of the fire protection system, conceptual layouts, often referred to as block diagrams, of the building spaces had to be defined. The block diagrams were designed for the building based on the egress and occupancy requirements. These requirements are laid out in Chapter 10 of the *IBC*. Section 903.2 of the *IBC* required the sprinkler be designed for the residential plan but not the commercial plan. However, a sprinkler system was designed for the commercial plan as well due to its safety appeal to potential customers and due to insurance factors. The automatic wet pipe sprinkler system was designed for these light occupancy hazards based on requirements described in *NFPA 13*. The number of sprinkler heads and required water pressure for each occupancy type can be found in Table 35.

Once the occupancy types were chosen and the initial block diagrams were constructed, the existing structure was analyzed for its capacity to support the new loadings. Design loadings for each occupancy type were found in *ASCE 7-10*. These loadings were used with structural analysis and both LRFD and ASD methods to determine the adequacy of the wood and steel beams and girders, wood and steel columns, and the masonry shear wall. These processes were followed as laid out in the *AISC Steel Construction Manual* for steel members and the *National Design Specification for Wood Construction* for wood members. Through this analysis process, assumptions had to be made as summarized in Table 36. The results of this analysis are summarized in Table 35.

To create a more sustainable design, rainwater management systems were researched with relevance to 89 Shrewsbury St. The most applicable rain water management system was to collect the rainwater and connect it to supply the toilet system. Occupancy maximums were determined and used to calculate the estimated toilet water usage for each occupancy type. This amount was compared to the expected annual rainfall collection. From these numbers a tank size was chosen based on efficiency, spatial needs, and cost. The cost of installing the rainwater systems was justified by comparing the annual savings to the overall cost. However, this system will provide benefits in addition to cost savings such as benefits to the community by minimizing the facility's draw on the water supply and contributing to some LEED requirements. The result of these calculations and research are summarized in Table 35.

The cost of the investigated modifications and the structural and sprinkler system designs were calculated using *RSMeans Building Construction Cost Data, 2014*. Unit costs for each item were found and used to get a more accurate price estimate. For modifications that will be required but were not specifically investigated, such as finishes, equipment, and MEP, *RSMeans Square Foot Cost Data* were used. These costs were compared to typical rents and vacancy rates for residential and office space in Worcester, MA to estimate a yearly income and a breakeven point for the owner. These results are summarized in Table 35.

10.2 Key Findings

Key findings from the procedure summarized above can be found in Table 35. From this analysis it can be seen that a commercial renovation will cost less overall, but more for the specific modifications discussed in Chapter 6 and 7, and summarized in Table 34. This is likely because there are more structural members that need to be reinforced due to the heavier loads the members will support. The commercial design requires less sprinkler heads than residential; however, it requires more piping, bringing the sprinkler system cost to be $20 more than the residential system. The total commercial renovation costs less because the building will not require finishes, and it will not require as much equipment such as kitchen appliances. A residential renovation will require finishes, such as flooring, molding, and walls to be installed by the owner as well as some appliances. Based on data found for Worcester, MA, the residential renovation will bring approximately $70,000 more than a commercial renovation on a yearly basis, as seen in Table 35. When comparing construction costs to yearly predicted income, a residential renovation will hit a breakeven point 2.7 years after construction finishes, and a commercial renovation will hit a breakeven point in 4.1 years. Based on this information a residential renovation would likely be a better investment. Taxes would not impact this cost since both structures fall under the commercial category financially (Worcester Assessors Office 2015).

Table 34: Final Construction Costs

	Residential Costs	**Commercial Costs**
Structural Modifications	$42,910	$43,720
Sprinkler Modifications	$49,165	$49,185
Interior Construction	$467,137	$463,415
GRAND TOTAL	**$559,212**	**$556,325**

Table 35: Key Findings for Each Occupancy Type

		Residential	Commercial
Fire Protection System	Sprinkler Heads	Quick response pendent sprinklers, 225 sq. ft. area coverage, 120 heads required	Quick response pendent sprinklers, 225 sq. ft. area coverage, 99 heads required
	Required Water Pressure	251 gpm at 67.22 psi Sufficient	354.2 gpm at 75.65 psi Sufficient
Structural Analysis	Wooden Members	16 members failed in shear Steel plates attached to bottom of beams to reinforce wood members	26 members failed in shear Steel plates attached to bottom of beams to reinforce wood members
	Steel Beams and Girders	Sufficient	Sufficient
	Columns	Sufficient	Sufficient
	Lateral Loads	Sufficient	Sufficient
Sustainability	Tank Size	5,000-6,000 gal	5,000-6,000 gal
	Toilet Water Provided	46%	28%
	Total Cost to Install	$1,340	$1,340
	Total Yearly Savings	$500	$500
Cost	Total Cost to Build	$563,212	$560,325
	Yearly Income	$204,228	$135,674
	Years to Breakeven	2.8 years	4.1 years

10.3 Limitations of Work

During the execution of this project limitations were faced both due to the scope of work and due to the initial information provided. The scope of work limited the detail that could be put into the drawings as well as the cost estimate. The schedule of construction was not considered and therefore limited the detail that could be put into the cost analysis. Additionally, very few aspects of the architectural design of the building were considered. Costs such as finishes, equipment, and partitions were taken into account using *RSMeans Square Foot Cost Data*, which limits the accuracy of the final cost estimate.

The initial plans given on the existing building also posed some limitations. While the plans provided many details, some were missing and assumptions had to be made. These assumptions are summarized in Table 36. These assumptions are limiting to the project as they cannot be confirmed to be correct or incorrect. Confirmation would require access to the building as it was when the plans were drawn and in some cases, the ability to test the materials.

Table 36: Assumptions Made During Project

Topic	Assumption
Steel Members	Closest historic beam size
Columns	10”x10” wooden columns B12a steel columns
Roofing	Roof would have to be replaced with 2”x10” wood framing 16” o.c. supporting metal decking, 1” rigid insulation, and 0.05” PVC membrane
Flooring	Floor would have to be replaced with 2”x10” wood framing 16” o.c. supporting 3/8” plywood sheathing, and hardwood floor
First Floor Framing Plan	Sufficient for current loads
Masonry Wall Strength	80 psi, based on a minimal allowable compressive strength for masonry of 1,000 psi

10.4 Future Work

This project evaluated the structural, sprinkler system, and sustainability options for the retrofit of 89 Shrewsbury Street. This project can be further investigated by looking into the architectural aspects, construction plans and detailing, and further developing fire protection and structural solutions that were used in this project.

This project also offers others the ability to follow through the process of analyzing a different building using the methods provided. Following the method provided, a non-compliant, existing, and outdated structure can be brought to compliance with aspects of the *International Building Code*. This methodology will be sufficient for buildings with only wood members, only steel members, or a combination of wood and steel. This process also outlines methods to determine cost of such a renovation using RSMeans data. From the methodology provided, users will be able to determine the best use for an existing building. Factors that should be considered include those that affect the return on investment for a particular area such as vacancy rates, rent rates, and operational costs. Other factors that can be considered that were not investigated in this project include architectural details and construction schedules. These factors can affect the decision on what is the best use of an existing building depending on the owner’s needs and constraints.

Bibliography

American Architectural Mechanical Association. (2012). *BIM: An Accelerating Game Changer*. Retrieved 9/24/2014, from: http://www.aamanet.org/news/2/10/42/western-region/763/bim-an-accelerating-game-changer

American Institute of Steel Construction. (2014). *Historic Standards*. Retrieved 10/15/2014, from http://www.aisc.org/content.aspx?id=2870

American Society of Civil Engineers. (2014). *Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10).*

American Institute of Steel Construction. (2011). *Steel Construction Manual* (Fourteenth ed.)

American Society of Civil Engineers. *Code of Ethics*. Retrieved 10/16/2014, from http://www.asce.org/Ethics/Code-of-Ethics/

American Wood Council. (2012). *National Design Specification for Wood Construction*.

Bureau of Labor Statistics. (2014). *Workforce Statistics*. Retrieved 10/15/2014, from http://www.bls.gov/iag/tgs/iag23.htm#workforce

City of Worcester, MA. (2015). *Cost of Living*. Retrieved 2/28/2015, from http://www.worcesterma.gov/living-working/cost-of-living

Environmental Protection Agency. (2014). *What You Can Do: At the Office*. Retrieved 2/7/2015, from http://www.epa.gov/climatechange/wycd/office.html

Federal Emergency Management Agency. (2000). *FEMA 356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings*: Federal Emergency Management Agency.

Gagnon, R. (2005). *Designer's Guide to Automatic Sprinkler Systems*. Quincy, MA: National Fire Protection Association.

Hibbeler, R.C. (2011). *Structural Analysis* (8th ed.). Upper Saddle River, NJ: Prentice Hall.

"History of Fire and Fire Codes." *Iowa Department of Public Safety*. State of Iowa. Retrieved 10/16/2014, from http://www.dps.state.ia.us/fm/inspection/history/History_of_Fire_and_Fire_Codes.pdf.

International Code Council. *About ICC*. Retrieved 10/10/2014, from http://www.iccsafe.org/abouticc/Pages/default.aspx

International Code Council. (2009a). *International Building Code*

International Code Council. (2009b). *International Existing Building Code*

Massachusetts Executive Office of Environmental Affairs. (2004). Massachusetts Water Policy. Retrieved 1/31/2015, from http://www.mass.gov/eea/docs/eea/water/waterpolicy-2004.pdf

Massachusetts State Building Code. (2010). 8th Edition. Retrieved 10/16/2014, from http://www.mass.gov/eopss/consumer-prot-and-bus-lic/license-type/csl/8th-edition-base-code.html

Massachusetts State Legislature. (2009). Reclaimed Water Permit Program and Standards. Retrieved 2/4/2015, from http://www.mass.gov/courts/docs/lawlib/300-399cmr/314cmr20.pdf

McCormac, J., & Csernak, S. (2012). *Structural Steel Design* (Fifth ed.). Upper Saddle River: Prentice Hall.

McGraw-Hill Construction. (2011). *Business Case for Energy Efficient Building Retrofit and Renovation*. from http://energy.gov/sites/prod/files/2013/12/f5/business_case_for_energy_efficiency_retrofit_renovation_smr_2011.pdf

National Fire Protection Association. (2007). *NFPA 13: Standard for the Installation of Sprinkler Systems* (2007 ed., pp. 454): National Fire Protection Association.

National Fire Protection Association. (2012a). *NFPA 101: Life Safety Code*. Quincy, MA: National Fire Protection Association.

National Fire Protection Association. (2012b). *NFPA 5000: Building Construction and Safety Code*. Qunicy, MA: National Fire Protection Association.

National Trust for Historic Preservation. (2012). *The Environmental Value of Building Reuse*. from http://www.preservationnation.org/information-center/sustainable-communities/green-lab/valuing-building-reuse.html#.VDPemvldV8E

Rainwater Management Solutions. Retrieved 2/3/2015, from http://www.rainwatermanagement.com/index.html

ReisReports. (2015). *Commercial Real Estate Report - Worcester, MA*. Retrieved 3/7/2015, from https://www.reisreports.com/markets-classic/massachusetts/worcester/office/

United States Census Bureau. (2014). *Construction Management*. Retrieved 10/10/2014, from http://www.census.gov/construction/c30/c30index.html

U.S. Climate Data (2015). Climate - Worcester, Massachusetts. Retrieved 2/19/2015, from http://www.usclimatedata.com/climate/worcester/massachusetts/united-states/usma0502

U. S. Green Building Council. (2014). *Good to know: Green Building incentive strategies*. Retrieved 10/10/2014, from http://www.usgbc.org/articles/good-know-green-building-incentive-strategies-0/

Tyree, D. & Pitts, D. *The International Building Code and International Residential Code and Their Impact on Wood-Frame Design and Construction*. Retrieved 10/06/2014, from http://www.awc.org/Publications/papers/ASCEIBC-IRC.pdf

Value of Construction Put in Place - Seasonally Adjusted Annual Rate. (2014). Retrieved 10/08/2014, from http://www.census.gov/construction/c30/pdf/totsa.pdf

Worcester Historical Museum. *Worcester History*. Retrieved 10/09/2014, from http://www.worcesterhistory.org/worcesters-history/.

Worcester, Massachusetts Residential Rent and Rental Statistics. (2013). Retrieved 2/23/2015, from http://www.deptofnumbers.com/rent/massachusetts/worcester/

Worcester Polytechnic Institute. *Energy & Water Conservation*. Retrieved 2/3/2015, from http://www.wpi.edu/about/sustainability/conservation. html

Worcester Regional Research Bureau. (2013). *Demographics & Census Information*. Retrieved 10/02/2014, from http://www.worcestermass.org/home/about-worcester/special-events/demographics-census-information

Appendix A: Sample Structural Beam Calculations

Table 37: Steel Beam Commercial Analysis Sufficient

Beam Calculations					
Properties			Concentrated LL	2000	in lb/ft
Beam Type	B15a		Dead Load (psf)	28.1	214.2625
A (in^2)	15.9		Beam Dead Load (lb/ft)	54.5	54.5
d (in)	15		Live Load (psf)	50	381.25
tw	0.41		Snow Load (psf)	0	0
tf	0.74		Roof LL (psf)	0	0
bf	7		Rain (psf)	0	0
			Wind (psf)	0	0
W (lb/ft)	54.5		wu (lb/ft)=	376.2675	
L (ft)	14.333		wu (lb/ft)=	932.515	
Tributary (ft)	7.625		wu (lb/ft)=	513.14	
Fy (ksi)	36				
zx (in^3)	92.4		Factored Load (lb/ft)=	932.515	
E (ksi)	29000				
I (in^4)	610		Design Moment (k-ft)=	23.946	
h/tw	29.9		Design Shear (kips)	6.683	
bf/2tf	4.739				
ry (in)	1.6				
BENDING					
Plastic Section modulus					
Phi=	0.9				
zx (in^3)=	8.869033	OK			
Ignore weight of beam to approximate section modulus.					
Choose beam and update properties.					
Load Buclking of the Compression Flange					
bf/2*tf	4.74				
0.38 sqrt(E/Fy)	10.8528	OK			

Load Buckling of the Web					
h/tw	29.9				
3.76 sqrt(E/Fy)	106.7175	OK	If flange is non-compact can't use Mu and must perform extra calculations.		
DEFLECTION					
50% LL (lb/in)=	15.88542				
Delta max (in)=	0.010233				
L/360	0.477767	OK			
50% LL+DL (lb/in)=	38.28229				
Delta max (in)=	0.024659				
L/240	0.71665	OK			
Shear					
2.24 sqrt(E/Fy) =	63.57638				
Phi =	1				
cv	1				
phi Vn (kips)=	132.84				
Vu (kips)=	6.682869	OK	Check wu of shear and bending when designing.		

Table 38: Steel Beam Residential Analysis, Sufficient

Beam Calculations						
Properties						in lb/ft
Beam Type	CB151N			Dead Load (psf)	28.1	196.7
A (in^2)	11.5			Beam Dead Load (lb/ft)	39	39
d (in)	15			Live Load (psf)	40	280
tw	0.3			Snow Load (psf)	0	0
tf	0.53			Roof LL (psf)	0	0
bf	6.75			Rain (psf)	0	0
				Wind (psf)	0	0
W (lb/ft)	39			wu (lb/ft)=	329.98	
L (ft)	20.75			wu (lb/ft)=	730.84	
Tributary (ft)	7			wu (lb/ft)=	422.84	

Fy (ksi)	35					
zx (in^3)	66.3			Factored Load (lb/ft)=	730.84	
E (ksi)	29000					
I (in^4)	448.8			Design Moment (k-ft)=	39.334	
h/tw	43.1			Design Shear (kips)	7.582	
bf/2tf	6.368					
ry (in)	1.5					
BENDING						
Plastic Section modulus						
Phi=	0.9					
zx (in^3)=	14.9844	OK				
Ignore weight of beam to approximate section modulus.						
Choose beam and update properties.						
Load Buclking of the Compression Flange						
bf/2*tf	6.37					
0.38 sqrt(E/Fy)	10.93827	OK				
Load Buckling of the Web						
h/tw	43.1					
3.76 sqrt(E/Fy)	108.2313	OK		If flange is non-compact can't use Mu and must perform extra calculations.		
DEFLECTION						
50% LL (lb/in)=	11.66667					
Delta max (in)=	0.044868					
L/360	0.691667	OK				
50% LL+DL (lb/in)=	31.30833					
Delta max (in)=	0.120405					
L/240	1	OK				

Shear						
2.24 sqrt(E/Fy) =	64.47821					
Phi =	1					
cv	1					
phi Vn (kips)=	94.5					
Vu (kips)=	7.582465	OK		Check wu of shear and bending when designing.		

Table 39: Wood Beam Commercial Analysis, Sufficient

Wood Beam Analysis					
Properties					
d (in)	15		Concentrated LL (lb)	2000	in lb/ft
b (in)	11		Dead Load (psf)	28.1	196.7
A (in^2)=	165		Beam Dead Load (lb/ft)	31.3038	31.3038
I (in^4)=	3093.75		Live Load (psf)	65	455
S (in^3)=	412.5		Snow Load (psf)	0	0
W (lb/ft^3)	27.31968123		Roof LL (psf)	0	0
Length (ft)	12.41666667		Rain (psf)	0	0
E (psi)	1200000		Wind (psf)	0	0
G	0.42		wu (lb/ft)=	338.8753	0.6
Moisture content	7		wu (lb/ft)=	1070. 65	0.8
Tributary (ft)	7.5		wu (lb/ft)=	534.2146	0.8
			Factored Load (lb/ft)=	1070.465	
			LRFD Design Moment (k-ft)=	20.630	
			LRFD Design Shear (kips)=	6.645801	
Adjustment Factors			**Reference Values**		
Cd	0.9	typical design dead load	Fb (psi)	1200	

Cm	1	Inside no moisture exposure	Fv (psi)	70	
Ct	1	Inside			
Cl	1	d<L, depth<breadth			
Cf=	0.975511112	Height is nominal			
Cfu	1	Not flat			
Ci	1	No known incisions			
Cr	1	No repetition			
Lambda	0.8				
LRFD					
Bending Member-Flexure					
F'b (psi)=	2021.883351				
M' (k-ft)=	69.5022402	OK			
Bending Member-Shear					
F'v (psi)=	108.864				
V' (kips)=	11.97504	OK			
Bending Member-Deflection					
Permissible delta=	0.413888889				
Delta (in)=	6.95E-06	OK			

Table 40: Wood Beam Commercial Analysis, Insufficient

Wood Beam Analysis					
Properties					
d (in)	11.5		Concentrated LL (lb)	2000	in lb/ft
b (in)	3.5		Dead Load (psf)	28.1	196.7
A (in^2)=	40.25		Beam Dead Load (lb/ft)	7.63623	7.63623
I (in^4)=	443.588541		Live Load (psf)	65	455
S (in^3)=	77. 458333		Snow Load (psf)	0	0
W (lb/ft^3)	27.3196812		Roof LL (psf)	0	0
Length (ft)	7.41666667		Rain (psf)	0	0

E (psi)	1200000		Wind (psf)	0	0
G	0.42		wu (lb/ft)=	305.7407	0.6
Moisture content	7		wu (lb/ft)=	1042.063	0.8
Tributary (ft)	7.5		wu (lb/ft)=	505.8135	0.8
			Factored Load (lb/ft)=	1042.063	
			LRFD Design Moment (k-ft)=	7.165	
			LRFD Design Shear (kips)=	3.864319	
Adjustment Factors			**Reference Values**		
Cd	0.9	typical design dead load	Fb (psi)	1200	
Cm	1	Inside no moisture exposure	Fv (psi)	70	
Ct	1	Inside			
Cl	1	d<L, depth<breadth			
Cf=	1.004740045	Height is nominal			
Cfu	1	Not flat			
Ci	1	No known incisions			
Cr	1	No repetition			
Lambda	0.8				
LRFD					
Bending Member-Flexure					
F'b (psi)=	2082.46441				
M' (k-ft)=	13.387787	OK			
Bending Member-Shear					
F'v (psi)=	108.864				
V' (kips)=	2.921184	Not OK			
Bending Member-Deflection					

Permissible delta=	0.24722222				
Delta (in)=	1.68256E-5	OK			

Table 41: Composite Wood and Steel Beam Analysis, Commercial

Composite Beam Analysis					
Properties					
d (in)	11.5		Concentrated LL (lb)	2000	in lb/ft
b (in)	3.5		Dead Load (psf)	28.1	196.7
A (in^2)=	40.25		Beam Dead Load (lb/ft)	11.358	11.358
I (in^4)=	443.589		Live Load (psf)	65	455
S (in^3)=	77.146		Snow Load (psf)	0	0
W (lb/ft^3)	27.320		Roof LL (psf)	0	0
Length (ft)	7.417		Rain (psf)	0	0
Ec (psi)	1200000		Wind (psf)	0	0
G	0.42		wu (lb/ft)=	310.951	0.6
Moisture content	7		wu (lb/ft)=	1046.530	0.8
Tributary (ft)	7.5		wu (lb/ft)=	510.280	0.8
Es (psi)	29000000				
n=	24.16666667		Factored Load (lb/ft)=	1046.53	
Steel Thickness (in)	0.31				
Steel Weight (pcf)	490				
Transformed A (in^2)	66.682		Design Moment (k-ft)=	11.867	
y bar (in)	8.091		Design Shear (kips)=	3.881	
Transformed I (in^4)	1000.366				
Transformed S (in^3)	123.636				
σ all Steel (ksi)	36				
σ all Wood (ksi)	1.2				
τ all Steel (ksi)	24				
τ all Wood (ksi)	0.07				
Allowable Moments					
Mmax Steel	33.371	OK			
Mmax Wood	12.364	OK			
Allowable Shear					
Vmax Steel	266.967	OK			
Vmax Wood	8.655	OK			

Steel Length					
V all Wood (kips)	2.921				
Length (ft)	0.917				
Length on each side (ft)	1.000				
Shear Studs					
Shear Flow (k/in)	0.165				
3/4" Lag bolt capacity (k)	0.980				
Spacing (in)	5.000				
Number of Bolts	6				

Table 42: Wood Beam Residential Analysis, Sufficient

Wood Beam Analysis					
Properties					
d (in)	15				in lb/ft
b (in)	7.5		Dead Load (psf)	28.1	196.7
A (in^2)=	112.5		Beam Dead Load (lb/ft)	21.3435	21.343 5
I (in^4)=	2109.375		Live Load (psf)	40	280
S (in^3)=	281.25		Snow Load (psf)	0	0
W (lb/ft^3)	27.319681		Roof LL (psf)	0	0
Length (ft)	9		Rain (psf)	0	0
E (psi)	1200000		Wind (psf)	0	0
G	0.42		wu (lb/ft)=	324.930 9	0.6
Moisture content	7		wu (lb/ft)=	758.512 2	0.8
Tributary (ft)	7.5		wu (lb/ft)=	428.512 2	0.8
			Factored Load (lb/ft)=	758.512 2	
			LRFD Design Moment (k-ft)=	7.680	
			LRFD Design Shear (kips)=	3.41330 5	

Adjustment Factors			**Reference Values**		
Cd	0.9	typical design dead load	Fb (psi)	1200	
Cm	1	Inside no moisture exposure	Fv (psi)	70	
Ct	1	Inside			
Cl	1	d<L, depth<breadth			
Cf=	0.97551111	Height is nominal			
Cfu	1	Not flat			
Ci	1	No known incisions			
Cr	1	No repetition			
Lambda	0.8				
LRFD					
Bending Member- Flexure					
F'b (psi)=	2021.8833				
M' (k-ft)=	47.387891	OK			
Bending Member- Shear					
F'v (psi)=	108.864				
V' (kips)=	8.1648	OK			
Bending Member- Deflection					
Permissible delta=	0.3				
Delta (in)=	3.79256E-6	OK			

Table 43: Wood Beam Residential Analysis, Insufficient

Wood Beam Analysis					
Properties					
d (in)	11.5				in lb/ft
b (in)	4.5		Dead Load (psf)	27.25	190.75

A (in^2)=	51.75		Beam Dead Load (lb/ft)	9.81801	9.81801
I (in^4)=	570.32812		Live Load (psf)	0	0
S (in^3)=	99.1875		Snow Load (psf)	55	385
W (lb/ft^3)	27.319681		Roof LL (psf)	20	140
Length (ft)	9.083333		Rain (psf)	0	0
E (psi)	1200000		Wind (psf)	0	0
G	0.42		wu (lb/ft)=	299.870	0.6
Moisture content	7		wu (lb/ft)=	463.281	0.8
Tributary (ft)	7.5		wu (lb/ft)=	917.031	0.8
			Factored Load (lb/ft)=	917.031	
			LRFD Design Moment (k-ft)=	9.458	
			LRFD Design Shear (kips)=	4.164852	
Adjustment Factors			**Reference Values**		
Cd	0.9	typical design dead load	Fb (psi)	1200	
Cm	1	Inside no moisture exposure	Fv (psi)	70	
Ct	1	Inside			
Cl	1	d<L, depth<breadth			
Cf=	1.0047400	Height is nominal			
Cfu	1	Not flat			
Ci	1	No known incisions			
Cr	1	No repetition			
Lambda	0.8				
LRFD					
Bending Member- Flexure					
F'b (psi)=	2082.4644				
M' (k-ft)=	17.212869	OK			
Bending Member- Shear					

F'v (psi)=	108.864				
V' (kips)=	3.755808	Not OK			
Bending Member-Deflection					
Permissible delta=	0.302777				
Delta (in)=	1.72738E-5	OK			

Table 44: Composite Wood and Steel Beam Analysis, Residential

Composite Beam Analysis					
Properties					
d (in)	11.5		Concentrated LL (lb)	0	in lb/ft
b (in)	4.5		Dead Load (psf)	27.25	190.75
A (in^2)=	51.75		Beam Dead Load (lb/ft)	12.689	12.689
I (in^4)=	570.328		Live Load (psf)	0	0
S (in^3)=	99.188		Snow Load (psf)	55	385
W (lb/ft^3)	27.320		Roof LL (psf)	20	140
Length (ft)	9.083		Rain (psf)	0	0
Ec (psi)	1200000		Wind (psf)	0	0
G	0.42		wu (lb/ft)=	303.890	0.6
Moisture content	7		wu (lb/ft)=	466.727	0.8
Tributary (ft)	7.5		wu (lb/ft)=	920.477	0.8
Es (psi)	29000000				
n=	24.16666667		Factored Load (lb/ft)=	920.4769	
Steel Thickness (in)	0.19				
Steel Weight (pcf)	490				
Transformed A (in^2)	72.141		Design Moment (k-ft)=	9.493	
y bar (in)	7.402		Design Shear (kips)=	4.180	
Transformed I (in^4)	1069.898				
Transformed S (in^3)	144.547				
σ all Steel (ksi)	36				
σ all Wood (ksi)	1.2				
τ all Steel (ksi)	24				
τ all Wood (ksi)	0.07				
Allowable Moments					

Mmax Steel	30.990	OK			
Mmax Wood	14.455	OK			
Allowable Shear					
Vmax Steel	247.919	OK			
Vmax Wood	10.118	OK			
Steel Length					
V all Wood (kips)	3.756				
Length (ft)	0.461				
Length on each side (ft)	0.500				
Shear Studs					
Shear Flow (k/in)	0.302				
3/4" Lag bolt capacity (k)	0.980				
Spacing (in)	3.000				
Number of Bolts	4				

Table 45: Analysis of Wood Joists used for Roof Framing

Framing Analysis					
Properties					
d (in)	10		Concentrated LL (lb)	0	in lb/ft
b (in)	2		Dead Load (psf)	26.55	185.85
A (in^2)=	20		Beam Dead Load (lb/ft)	3.7944	3.7944
I (in^4)=	166.6666		Live Load (psf)	0	0
S (in^3)=	33.33333		Snow Load (psf)	55	385
W (lb/ft^3)	27.31968		Roof LL (psf)	20	140
Length (ft)	16.83333		Rain (psf)	0	0
E (psi)	1200000		Wind (psf)	0	0
G	0.42		wu (lb/ft)=	54.8721	0.6
Moisture content	7		wu (lb/ft)=	83.6999	0.8
Tributary (ft)	1.333333		wu (lb/ft)=	164.366	0.8
			Factored Load (lb/ft)=	164.366	
			LRFD Design Moment (k-ft)=	5.822	
			LRFD Design Shear (kips)=	1.38341	
Adjustment Factors			**Reference Values**		
Cd	0.9	typical design dead load	Fb (psi)	1200	
Cm	1	Inside no moisture exposure	Fv (psi)	70	
Ct	1	Inside			
Cl	1	d<L, depth<breadth			
Cf=	1.0204645	12 is nominal			
Cfu	1	Not flat			
Ci	1	No known incisions			
Cr	1	No repetition			
Lambda	0.8				
LRFD					
Bending Member-Flexure					
F'b (psi)=	2115.055				

M' (k-ft)=	5.875154	OK			
Bending Member- Shear					
F'v (psi)=	108.864				
V' (kips)=	1.45152	OK			
Bending Member- Deflection					
Permissible delta=	0.561111				
Delta (in)=	3.6386E-5	OK			

Table 46: Analysis of Wood Joists used for Commercial Framing

Framing Analysis					
Properties					
d (in)	10		Concentrated LL (lb)	2000	in lb/ft
b (in)	2		Dead Load (psf)	25.2	176.4
A (in^2)=	20		Beam Dead Load (lb/ft)	3.7944	3.794
I (in^4)=	166.6666		Live Load (psf)	50	350
S (in^3)=	33.33333		Snow Load (psf)	0	0
W (lb/ft^3)	27.31968		Roof LL (psf)	0	0
Length (ft)	8.75		Rain (psf)	0	0
E (psi)	1200000		Wind (psf)	0	0
G	0.42		wu (lb/ft)=	52.3521	0.6
Moisture content	7		wu (lb/ft)=	151.539	0.8
Tributary (ft)	1.333333		wu (lb/ft)=	78.2066	0.8
			Factored Load (lb/ft)=	151.539	
			LRFD Design Moment (k-ft)=	7.000	
			LRFD Design Shear (kips)=	1.6	
Adjustment Factors			**Reference Values**		
Cd	0.9	typical design dead load	Fb (psi)	1250	
Cm	1	Inside no moisture exposure	Fv (psi)	135	

Ct	1	Inside			
Cl	1	d<L, depth<breadth			
Cf=	1.02046	Height is nominal			
Cfu	1	Not flat			
Ci	1	No known incisions			
Cr	1.15	No repetition			
Lambda	0.8				
LRFD					
Bending Member- Flexure					
F'b (psi)=	2533.66				
M' (k-ft)=	7.037945	OK			
Bending Member- Shear					
F'v (psi)=	209.952				
V' (kips)=	2.79936	OK			
Bending Member- Deflection					
Permissible delta=	0.29166				
Delta (in)=	9.064E-6	OK			

Table 47: Analysis of Wood Joists for Residential Framing

Wood Beam Analysis					
Properties					
d (in)	10		Concentrated LL (lb)	0	in lb/ft
b (in)	2		Dead Load (psf)	25.2	176.4
A (in^2)=	20		Beam Dead Load (lb/ft)	3.7944	3.794
I (in^4)=	166.6667		Live Load (psf)	40	280
S (in^3)=	33.33333		Snow Load (psf)	0	0
W (lb/ft^3)	27.31968		Roof LL (psf)	0	0
Length (ft)	8.75		Rain (psf)	0	0
E (psi)	1200000		Wind (psf)	0	0
G	0.42		wu (lb/ft)=	52.352	0.6
Moisture content	7		wu (lb/ft)=	130.20	0.8
Tributary (ft)	1.333333		wu (lb/ft)=	71.5395	0.8

			Factored Load (lb/ft)=	130.20	
			LRFD Design Moment (k-ft)=	1.246	
			LRFD Design Shear (kips)=	0.5696	
Adjustment Factors			**Reference Values**		
Cd	0.9	typical design dead load	Fb (psi)	1250	
Cm	1	Inside no moisture exposure	Fv (psi)	135	
Ct	1	Inside			
Cl	1	d<L, depth<breadth			
Cf=	1.020464	Height is nominal			
Cfu	1	Not flat			
Ci	1	No known incisions			
Cr	1.15	No repetition			
Lambda	0.8				
LRFD					
Bending Member- Flexure					
F'b (psi)=	2533.660				
M' (k-ft)=	7.037945	OK			
Bending Member- Shear					
F'v (psi)=	209.952				
V' (kips)=	2.79936	OK			
Bending Member- Deflection					
Permissible delta=	0.291666				
Delta (in)=	7.78824E-06	OK			

Appendix B: Sample Structural Column Calculations

Table 48: Analysis of Steel Columns

Properties	
Beam Type	W10x54
A (in^2)	15.8
d (in)	10.1
tw	0.37
tf	0.615
bf	10
Stories	1
W (lb/ft)	54
L (ft)	11.75
Tributary Area (ft^2)	435
Fy (ksi)	50
zx (in^3)	66.6
E (ksi)	29000
I (in^4)	303
h/tw	21.2
bf/2tf	8.15
rx (in)	4.37
ry (in)	2.56

0.56 sqrt(E/Fy)	13.48659	
bf/2tf	8.15	OK

1.49 sqrt(E/Fy)	35.88395	
h/tw	21.2	OK

Fe=	94.34946	
Fcr=	40.05344	Inelastic
Fcr=	82.74448	Elastic

k	1

Pinned Ends, Rotation of Joints

kL/r	55.07813
4.71 sqrt(E/Fy)	113.4318
Fcr (kips)=	40.05344

Load Capacity (kips)=	569.5599	
Service Load (kips)=	145.4719	OK

Beams

Beam 1	
Weight 1 (lb/ft)	54.5
Tributary Width 1	10

Beam 2	
Weight 2	54.5
Tributary Width 2	10

Beam 3	
Weight 3	84.5
Tributary Width 3	11

Beam 4	
Weight 4	84.5
Tributary Width 4	11

Beam Weight (psf)	13.13182

		in lb
Dead Load (psf)	82.75	35996.25
Roof Dead Load (psf)	26.55	11549.25
Steel Dead Load (psf)	13.13182	5712.341
Live Load (psf)	100	43500
Snow Load (psf)	55	23925
Roof LL (psf)	20	8700
Rain (psf)	0	0
Wind (psf)	0	0
wu (lb)=	58392.03	
wu (lb)=	145471.9	
wu (lb)=	110080.3	
Factored Load (lb)=	**145471.9**	

Table 49: Analysis of Wood Columns

Buckling Analysis					
				(input cell)	<= input cells
F_c	825	psi		F_c	E_{min}
E_{min}	1,200,000	psi	C_M	1.0	1.0
ℓ	11.75	ft	C_t	1.0	1.0
K_e	2.1		C_F	1.0	
ℓ_e	24.675	ft	C_i	1.0	1.0
d	11.5	in	C_T		1.0
b	11.5	in			
ℓ_e/d	25.7		c	0.8	
A_{net}	132.3	in^2			

LRFD	Time Effect				
KF 2012 Definitons					
Compression		Stability		Time Effect	
ϕ_c	0.90	ϕ_s	0.85	λ	0.8
KF	2.40	KF	1.76		
F_{cn}	1,980	psi			
$E_{min\ n}$	2,112,000	psi			
$E_{min\ n}'$	1,795,200	psi			
ℓ_e/d	25.7				
$F_{cE\ n}$	2,226	psi	(1+FcE/F*c)/(2c)		1.600856
$F^*_{c\ n}$	1,426	psi	(FcE/F*c)/c		1.951713
C_P	0.819				
F'_{cn}	1,168	psi			
P_n	154,443	lb			
	DESIGN LOAD, LRFD				
1.2D+1.6L	141,161.90	lb	okay		

Appendix C: Sample Wind and Seismic Calculations

Table 50: Excel Calculations of MWFRS Wind Loads

Basic Parameters			
Risk Category	II		Table 1.5-1
Basic Wind Speed, V	100 mph		Figure 26.5-1A
Wind Directionality Factor, K_d	0.85		Table 26.6-1
Exposure Category	B		Section 26.7
Topographic Factor, K_{zt}	1.00	Assumed, lack of info	Section 26.8
Gust Effect Factor, G or G_f	0.850		Section 26.9
Enclosure Classification	Enclosed		Section 26.10
Internal Pressure Coefficient, GC_{pi}	+/- 0.18		Table 26.11-1
Terrain Exposure Constant, α	7.0		Table 26.9-1
Terrain Exposure Constant, z_g	1,200 ft		Table 26.9-1
Wall Pressure Coefficients			
Windward Wall Width, B	115 ft		
Side Wall Width, L	44 ft		
L/B Ratio	0.38		
Windward Wall Coefficient, C_p	0.80		Figure 27.4-1
Leeward Wall Coefficient, C_p	-0.50		Figure 27.4-1
Side Wall Coefficient, C_p	-0.70		Figure 27.4-1
Roof Pressure Coefficients			
Roof Slope, θ	0.0°		
Median Roof Height, h	37 ft		
Velocity Pressure Exposure Coef., K_h	0.74		Table 27.3-1
Velocity Pressure, q_h	16.1 psf		Equation 27.3-1
h/L Ratio	0.83		
Windward Roof Area	0 ft²		
Roof Area Within 18 ft of WW Edge	0 ft²		

Location	*Min/Max*	*Horiz. Distance From Windward Edge*			
		0 ft	*18 ft*	*37 ft*	*73 ft*
Windward Roof Coefficient	Min	-1.17	-1.17	-0.63	-0.57
Normal to Ridge, C_p	Max	-0.18	-0.18	-0.18	-0.18
Leeward Roof Coefficient	Min	-1.17	-1.17	-0.63	-0.57
Normal to Ridge, C_p	Max	-0.18	-0.18	-0.18	-0.18
Roof Coefficient	Min	-1.17	-1.17	-0.63	-0.57
Parallel to Ridge, C_p	Max	-0.18	-0.18	-0.18	-0.18

Figure 27.4-1

<table>
<tr><th rowspan="3">Height, z</th><th rowspan="3">K_z</th><th rowspan="3">q_z</th><th colspan="4" rowspan="2">Walls</th><th colspan="3">Roof</th><th colspan="2" rowspan="2">Internal</th></tr>
<tr><th colspan="2">Normal to Ridge</th><th rowspan="2">Parallel to Ridge</th></tr>
<tr><th>WW</th><th>LW</th><th>WW + LW</th><th>Side</th><th>WW</th><th>LW</th><th>Positive</th><th>Negative</th></tr>
<tr><td>0 ft</td><td>0.57</td><td>12.5 psf</td><td>8.5 psf</td><td rowspan="11">-6.9 psf</td><td>15.4 psf</td><td rowspan="11">-9.6 psf</td><td rowspan="5">Min: -16.0 psf</td><td rowspan="5">Min: -16.0 psf</td><td rowspan="5">Min: -16.0 psf</td><td>2.3 psf</td><td rowspan="11">-2.9 psf</td></tr>
<tr><td>4 ft</td><td>0.57</td><td>12.5 psf</td><td>8.5 psf</td><td>15.4 psf</td><td>2.3 psf</td></tr>
<tr><td>7 ft</td><td>0.57</td><td>12.5 psf</td><td>8.5 psf</td><td>15.4 psf</td><td>2.3 psf</td></tr>
<tr><td>11 ft</td><td>0.57</td><td>12.5 psf</td><td>8.5 psf</td><td>15.4 psf</td><td>2.3 psf</td></tr>
<tr><td>15 ft</td><td>0.57</td><td>12.5 psf</td><td>8.5 psf</td><td>15.4 psf</td><td>2.3 psf</td></tr>
<tr><td>18 ft</td><td>0.61</td><td>13.2 psf</td><td>9.0 psf</td><td>15.9 psf</td><td rowspan="6">Max: -2.5 psf</td><td rowspan="6">Max: -2.5 psf</td><td rowspan="6">Max: -2.5 psf</td><td>2.4 psf</td></tr>
<tr><td>22 ft</td><td>0.64</td><td>14.0 psf</td><td>9.5 psf</td><td>16.3 psf</td><td>2.5 psf</td></tr>
<tr><td>26 ft</td><td>0.67</td><td>14.6 psf</td><td>9.9 psf</td><td>16.8 psf</td><td>2.6 psf</td></tr>
<tr><td>29 ft</td><td>0.70</td><td>15.1 psf</td><td>10.3 psf</td><td>17.2 psf</td><td>2.7 psf</td></tr>
<tr><td>33 ft</td><td>0.72</td><td>15.7 psf</td><td>10.7 psf</td><td>17.5 psf</td><td>2.8 psf</td></tr>
<tr><td>37 ft</td><td>0.74</td><td>16.1 psf</td><td>11.0 psf</td><td>17.8 psf</td><td>2.9 psf</td></tr>
</table>

Seismic Load Calculations

ASLE 7-10 12.7.2

$V = C_s W$

$C_s = \frac{S_{DS}}{R/I}$ $I \rightarrow 11.5.1$ $I = 1$ $R = 1.5$

$S_s = 0.181g$ $S_1 = 0.066g$
$S_{MS} = 0.289g$ $S_{M1} = 0.158g$
$S_{DS} = 0.193g$ $S_{D1} = 0.105g$

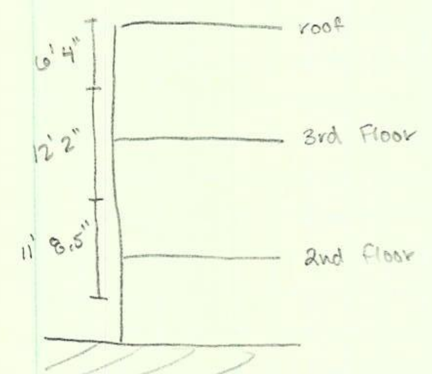
89 Shrewsbury St. Worcester MA
Site class D - "stiff soil"
Risk Category II

$W = DL + 0.2S + \text{partition weight}$
$= 3 \cdot 28.1\ lb/ft^2 \cdot 4596\ ft^2 + 26.55\ lb/ft^2 \cdot 4596\ ft^2 + 2678819.97\ lb + 4596\ ft^2 \cdot 0.2\,(55\ psf)$
$+ 15\ psf \cdot 3(4596\ sf)$
$= 3445662.570\ lb$

$V = \frac{0.193g \cdot 3445662.570\ lb}{1.5/1} = \boxed{443{,}341.917\ lb}$ ← Base shear

Distribute Base Shear to floors

$V = \frac{\Sigma w_i h_i}{\Sigma w_x h_x}$



$w_{t2} = 998349.584\ lb$
$h_2 = 11' 9"$

$w_{t3} = 1032400.989\ lb$
$h_3 = 23' 5"$

$w_{tr} = 592210.615\ lb$
$h_r = 36' 1"$

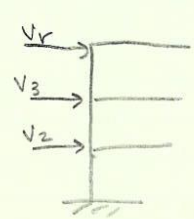
$\Sigma wh = 57274930.467$

$C_2 = \frac{998349.584\ lb \cdot 11' 9"}{57274930.469} = 0.205$

$C_3 = \frac{1032400.989\ lb \cdot 23' 5"}{57274930.5} = 0.422$

$C_r = \frac{592210.6 \cdot 36' 1"}{57274930.5} = 0.374$

$V_2 = C_2 V = 90.9^k$
$V_3 = C_3 V = 187.1^k$
$V_r = C_r V = 165.8^k$



Siesmic Analysis

International Existing Building Code
A108.2

Equation A1-6, unreinforced masonry shear strength is lesser of:

a) $2.5\sqrt{f'_m}$

b) 200 psi

c) $v + 0.75 \frac{P_D}{A}$

a) f'_m range is 1,000 psi to 4,000 psi
use 1,000 psi

$V_m = 80$ psi ← lowest value governs

b) 200 psi $= V_m$

c) $V_m = 25 \text{ psi} + 0.75 \frac{P_D = 120 \text{ lb/ft}^3 \cdot 37' \cdot A}{A = A}$
$= 233.1$ psi

use $V_m = 80$ psi under the asumption that f'_m, the compressive strength of masonry is 1,000 psi.

Rigidity

flexural deflection may be ignored IEBC A112.2.1

$$k = \frac{1}{\Delta v} = \frac{E_v A}{1.2 V h} = \qquad [k] = {}^{k}/_{in}$$

$E_v = 0.4 E_m \rightarrow$ modulus rigidity
↳ shear modulus
$= 0.4$

A = horizontal cross section wall
I = horizontal I in direction of bending

E_m assumed
$= 495000$ psi

$E_v = 198$ ksi

$$k_{north} = \frac{198\text{ksi}\,(16'' \cdot 19' \cdot 12''/_1)}{1.2\ V\ (37' \cdot 12''/_1)} = \frac{1355.67}{V}\ {}^{k}/_{in}$$

$$k_{south} = \frac{198\text{ksi}\,(16'' \cdot 69' \cdot 12''/_1)}{1.2\ V\ (37' \cdot 12''/_1)} = \frac{5846.35}{V}\ {}^{k}/_{in} \qquad \frac{k}{in^2}\ \frac{(in^2)}{in} \qquad \frac{k}{in}$$

$$\frac{k_n}{k_n + k_s}(V_{base\ shear}) = V_{north} = \frac{\frac{1355.67}{V}}{\frac{7202.02}{V}}(V_{3rd} = 165.8^k) = 31.209^k$$

$$V_{north\ 2nd} = 0.188(187.1^k) = 35.219^k$$

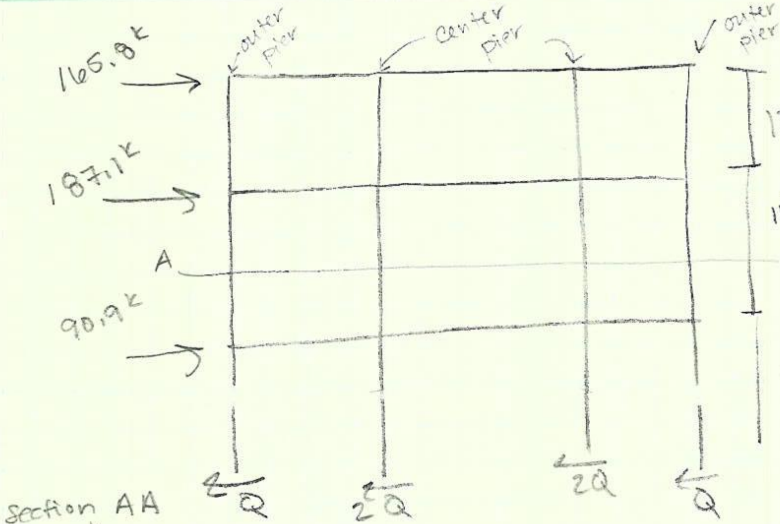
$$V_{north\ 1st} = 0.188\,(90.9^k) = 17.111^k$$

$$V_{south} = \frac{k_s}{k_n + k_s}(V_{shear}) = 0.812(V_{3rd} = 165.8^k) = 134.591^k$$

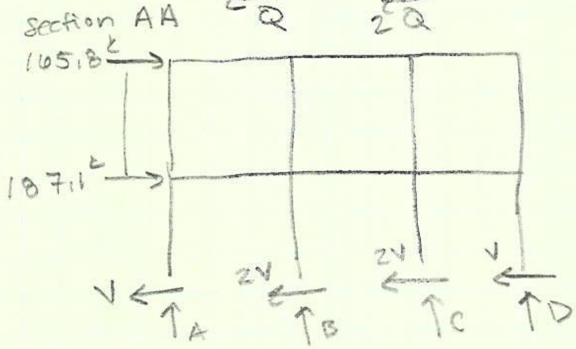
$$V_{south\ 2nd} = 0.812(187.1^k) = 151.881^k$$

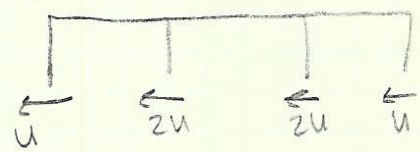
$$V_{south\ 1st} = 0.812\,(90.9^k) = 73.789^k$$

Siesmic → North Wall



Seismic (1.0) > wind (1.6)
use seismic load for analysis



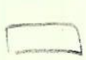


Allowable in each pier:

3rd + 2nd Floor → center piers

A = 384 in²
V = 125 psi
Vall = 48 k

outer piers



A = 352 in²
V = 125 psi
Vall = 44k

1st Floor → center piers

A = 736 in²
V = 125 psi
Vall = 92 k
Vcp =

outer piers

A = 464 in²
V = 125 psi
Vall = 58 k

Shear - North Wall

3rd Floor :

$$\Sigma F_x = 0 = 31.209^k - 6U$$
$$U = 5.202^k$$

2nd Floor :

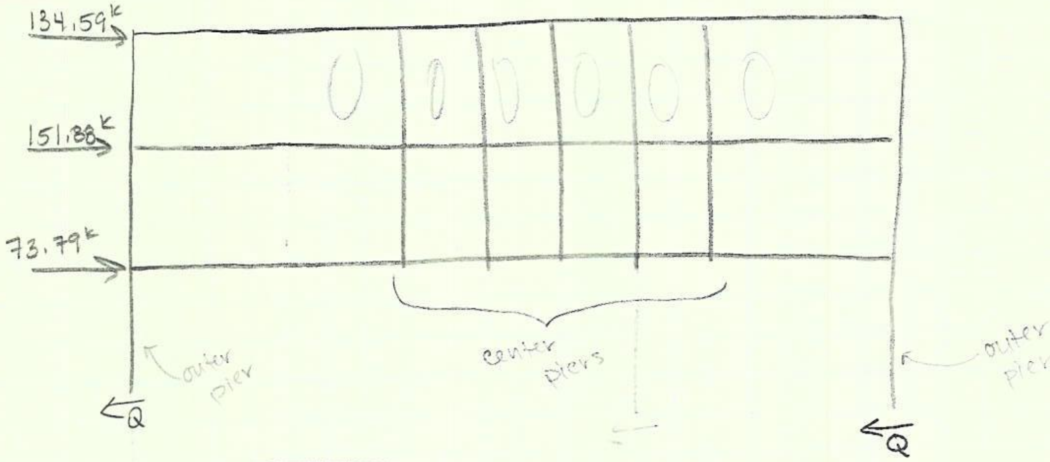
$$\Sigma F_x = 0 = 31.209^k + 35.219^k - 6V$$
$$V = 11.071^k$$

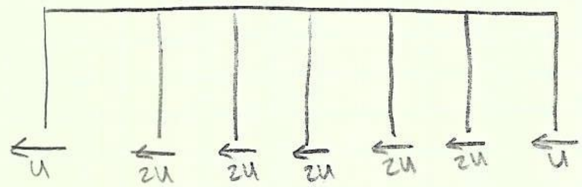
1st Floor :

$$\Sigma F_x = 0 = 31.209^k + 35.219^k + 17.111^k - 6Q$$
$$Q = 13.923^k$$

Center Piers	Outer Piers
capacity : 48^k design : 10.404^k ✓	capacity : 44^k design : 5.202^k ✓
capacity : 48^k design : 22.142^k ✓	capacity : 44^k design : 11.071^k ✓
capacity : 92^k design : 27.846^k ✓	capacity : 58^k design : 13.923^k ✓

Shear - South Wall





3rd

$\Sigma F_x = 0 = 134.59^k - 12U$

$U = 11.216^k$

2nd floor

$\Sigma F_x = 0 = 134.59^k + 151.88^k - 12V$

$V = 23.873^k$

First floor

$\Sigma F_x = 0 = 134.59^k + 151.88^k + 73.79^k - 2Q$

$Q = 180.13^k$

Interior Piers	Outer Piers
capacity: 16" · 62" · 125 psi = 124k Design = 22.432k ✓	capacity = 16" · 116" · 125 psi = 232k design = 11.216k ✓
capacity = 124k Design = 47.746k ✓	capacity = 232k design = 23.873k ✓
West Pier Capacity = 16" · 36' · 125 psi = 864k design = 180.13k ✓	East Pier Capacity = 16" · 27' · 125 psi = 648k Design = 180.13k ✓

Appendix D: Sample Hydraulic Calculations

Table 51: Hydraulic Calculations Attachment Path 1

Node / Description	K-Factor / q gpm / Q gpm	Nominal / ID inches / C-Factor	Friction Loss psi/ft	Fittings	Length ft / Fittings ft / Total ft	Pt psi / Pf psi / Pe psi	Elevation Change ft	Notes
6	5.6	1	0.074	-	9.5	7.00		Q = kvP
5	14.8	1.05				0.71		
5.6K Spr	**14.8**	120			9.5	0.00		
5	5.6	1	0.280	-	9.5	7.71		
4	15.5	1.05				2.66		
5.6K Spr	**30.4**	120			9.5	0.00		
4	5.6	1	0.664	1T	5.25	10.37		
RN1	18.0	1.05			5	6.81		
5.6K Spr	**48.4**	120			10.25	0.00		
				-		17.18		11.67674589

Table 52: Hydraulic Calculations Attachment Path 2

Node / Description	K-Factor / q gpm / Q gpm	Nominal / ID inches / C-Factor	Friction Loss psi/ft	Fittings	Length ft / Fittings ft / Total ft	Pt psi / Pf psi / Pe psi	Elevation Change ft	Notes
7	5.6	1	0.074	-	10	7.00		Q = kvP
8	14.8	1.05				0.74		
5.6K Spr	**14.8**	120			10	0.00		
8	5.6	1	0.281	-	10	7.74		
9	15.6	1.05				2.81		
5.6K Spr	**30.4**	120			10	0.00		
9	5.6	1	0.669	1T	7.5	10.56		
RN2	18.2	1.05			5	8.37		
5.6K Spr	**48.6**	120			12.5	0.00		
						18.92		11.17172832
						0.00		
						0.00		

Table 53: Hydraulic Calculations Attachment Path 3

Node	K-Factor	Nominal	Friction Loss *psi/ft*	Fittings	Length *ft*	Pt *psi*	Elevation Change *ft*	Notes
	q *gpm*	ID *inches*			Fittings *ft*	Pf *psi*		
Description	Q *gpm*	C-Factor			Total *ft*	Pe *psi*		
12	5.6	1	0.074	-	9.5	7.00		Q = kvP
11	14.8	1.05				0.71		
5.6K Spr	**14.8**	120			9.5	0.00		
11	5.6	1	0.280	-	9.5	7.71		
10	15.5	1.05				2.66		
5.6K Spr	**30.4**	120			9.5	0.00		
10	5.6	1	0.664	1T	5.25	10.37		
RN2	18.0	1.05			5	6.81		
5.6K Spr	**48.4**	120			10.25	0.00		
RN2	11.2	1.5	0.287	1T	1	17.18	1	K_{eq} from AP2
CM2	46.3	1.61			8	2.58		
AP2	**94.7**	120			9	0.43		
						20.20		21.074083
						0.00		
						0.00		

Table 54: Hydraulic Calculations Attachment Path 4

Node	K-Factor	Nominal	Friction Loss *psi/ft*	Fittings	Length *ft*	Pt *psi*	Elevation Change *ft*	Notes
	q *gpm*	ID *inches*			Fittings *ft*	Pf *psi*		
Description	Q *gpm*	C-Factor			Total *ft*	Pe *psi*		
13	5.6	1	0.074	1T	7.5	7.00		Q = kvP
RN3	14.8	1.05			5	0.93		
5.6K Spr	**14.8**	120			12.5	0.00		
						7.93		5.262766517

Table 55: Hydraulic Calculations Attachment Path 5

Node	**K-Factor**	**Nominal**	**Friction Loss** *psi/ft*	**Fittings**	**Length** *ft*	**Pt** *psi*	**Elevation Change** *ft*	**Notes**
	q *gpm*	**ID** *inches*			**Fittings** *ft*	**Pf** *psi*		
Description	**Q** *gpm*	**C-Factor**			**Total** *ft*	**Pe** *psi*		
14	5.6	1	0.074	1T	10	5.25		Q = kvP
RN3	14.8	1.05			5	1.12		
5.6K Spr	**14.8**	120			15	0.00		
RN3	5.3	1.5	0.030	1T	1	6.37	1	
CM3	13.3	1.61			8	0.27		
AP4	**28.1**	120			9	0.43		
						7.07		10.56626571

Table 56: Hydraulic Calculations Primary Path

Node / Description	K-Factor / q *gpm* / Q *gpm*	Nominal / ID *inches* / C-Factor	Friction Loss *psi/ft*	Fittings	Length *ft* / Fittings *ft* / Total *ft*	Pt *psi* / Pf *psi* / Pe *psi*	Elevation Change *ft*	Notes
1	5.6	1	0.074	-	10	7.00		Q = kvP
2	14.8	1.05				0.74		
5.6K Spr	**14.8**	120			10	0.00		
2	5.6	1	0.281	-	10	7.74		
3	15.6	1.05				2.81		
5.6K Spr	**30.4**	120			10	0.00		
3	5.6	1	0.669	1T	7.5	10.56		
RN1	18.2	1.05			5	8.37		
5.6K Spr	**48.6**	120			12.5	0.00		
RN1	11.7	1.5	0.314	1T	1	18.92	1	
CM1	50.8	1.61			8	2.82		
AP1	**99.4**	120			9	0.43		
CM1		2.5	0.039	-	9	22.18		
CM2	0.0	2.469				0.35		
	99.4	120			9	0.00		
CM2	21.1	2.5	0.142	-	9	22.53		
CM3	100.0	2.469				1.28		
AP3	**199.4**	120			9	0.00		
CM3	10.6	2.5	0.217	1E	86.25	23.81		
TOR	51.6	2.469			6	20.02		
AP5	**251.0**	120			92.25	0.00		
TOR		2.5	0.217	-	36	43.82	36	
BOR	0.0	2.469			0	7.81		
	251.0	120			36	15.59		
						67.22		

Required Flow	251.0 gpm
Required Pressure	67.22 psi

Appendix E: Proposal

Project No. LDA-1502

Worcester Polytechnic Institute

Feasibility Study of 89 Shrewsbury Street
Worcester, Massachusetts

Major Qualifying Project Proposal

Submitted by:
Matthew Deptula
Sara Beth Leach
Benjamin Morse

Project Advisor:
Professor Leonard Albano

Date Submitted:
October 16, 2014

Table of Contents

Abstract

This project will perform a feasibility study of a residential design and a commercial design to retrofit the existing building at 89 Shrewsbury Street in Worcester, MA. Each design will include structural modifications, an automatic sprinkler system, and compliance to building codes including egress methods, accessibility, and fire protection. Each design will also be suited with recommended LEED design aspects to promote green building, sustainability, and potential cost-saving benefits. A cost analysis will compare both potential designs and recommend which will be the best design in terms of return on investment.

Capstone Design Statement

WPI's Major Qualifying Project (MQP) is the application of a student's skills acquired through their academic course work while also applying engineering standards and realistic constraints. This proposal and future MQP will perform a feasibility study on two proposed designs to be retrofitted to 89 Shrewsbury Street in Worcester, MA. The two proposed designs are a residential building and a commercial office building. This study will focus on specific designs aspects including structural modifications to the existing building, compliance with local building codes, addition of an automatic sprinkler system, and inclusion of LEED elements. This project will provide recommendations to which design is more favorable for a potential purchaser through a cost analysis that will compare both designs to constructability costs and potential return on investment. This MQP will apply realistic constraints that includes economics, environment and sustainability, and safety.

Economics and Constructability

Each proposed design will involve modifying the existing plans with architectural and structural elements to ensure structural integrity as well as compliance to code. Throughout this process, economic feasibility will be considered. In determining the selection of building materials and members, the lowest cost solution will be chosen. Different materials and member sizes will be analyzed and selected based on cost effectiveness to ensure both design have the lowest constructability costs.

These choices will also reflect the easiest and most efficient methods for construction. This concept of constructability goes hand in hand with economics in terms of labor costs and item availability. These two concepts combine to ensure the construction is as inexpensive and efficient as possible.

Environment and Sustainability

This project will be designed with consideration to the environment as well as sustainable design methods. Potential Leadership in Energy and Environmental Design (LEED) technology aspects will be investigated and applied to each design if determined to be feasible. Technologies such as daylighting, water reuse, and rainwater management will be investigated. These systems provide reasonable and very sustainable methods that, along with the reuse of an existing building, will promote green building and sustainability in the civil engineering field in the future.

Health and Safety

One of the most important aspects of this projects is safety. Safety of the occupants is essential in building design and most safety aspects within the scope of our design will be adhered to through building code compliance. Standards written by the International Code Council and the National Fire Protection Association will be followed to incorporate egress methods, accessibility, and fire protection system design. Following these standards provides a safe living environment that is crucial to potential future buyers and inhabitants.

Ethics

It is implied throughout the course of this project that the ASCE Code of Ethics will be abided by strictly. Ethics are and should be the considered in every decision a civil engineer makes throughout his or her career. As stated directly in the ASCE Code of Ethics, these moral values "uphold and advance the integrity, honor, and dignity of the engineering profession," and will constitute our entire thought process through honesty, professionalism, and dignity.

Chapter 1: Introduction

Close to one-trillion dollars is spent on construction in the United States per year, approximately six percent of the total US economy. Of this, over two-thirds of these expenditures come from the private sector (Census). The industry is directly responsible for employing over six million people (BLS), close to 4% of the current available workforce. And with these numbers being tabulated during one of the worst recessions in American history, it is safe to assume that the totals will only rise, making the industry all the more important. With construction being such an influence on the economy of the country, it is important that the industry is efficient.

The path to efficiency in the construction industry is not always clear. Deciding between building a new structure and retrofitting/renovating an existing building depends on numerous factors. Recently, the trend has leaned toward renovation. There are many incentives for green building including tax deduction, subsidizing and low interest loans, and whenever the construction process includes demolition, removal, and new construction, it is significantly less friendly to the environment. According to the National Trust for Historic Preservation, it takes twenty to thirty years for a new building to compensate for its initial impact. The Trust goes on to state that in some cases, it make take up to eighty years for a building to "overcome…the climate change impacts created by its construction" (NTHP). In extreme circumstances, this time needed to reach equilibrium of efficiency is longer than the lifespan of the building.

Furthermore, in older and densely populated cities, such as those found in the Northeast, space to build is all but extinct. In 2008, only 1.8% of the total commercial building area for the country was from new construction (Energy. gov). This low amount of actual construction shows how a majority of businesses are looking for existing buildings to retrofit.

Worcester, Massachusetts is an example of one of these industrialized New England cities. Worcester was incorporated as a city in 1848. Just fewer than 200,000 people live inside the city limits. This is approximately 765 people per square mile. With such a high population density, finding room to build is near impossible. The alternative is to utilize the space currently used by an existing building. Having its roots in manufacturing and industry, Worcester has many such structures that can be renovated for the new commercial business interested.

From here, the problem lies in the renovation process. Worcester, being diverse, has many different building types. Due to their age, many of the old mill and textile buildings are not compliant with modern codes. Furthermore, every building will be constructed in a different manner, leaving no "secret formula" for retrofitting. The engineer's job is to manipulate the current structure into its best possible future. This means taking into account several key factors, including sustainability, code compliance and usage.

Another developing concern is the need for safety. Building codes are in a constant state of updating. The engineer must understand all aspects of this code and be ready to accommodate them in the design of the building. Some examples include fire protection, size requirements, and means of egress. Land developers and entrepreneurs are interested in making the most profit. This often means that the engineer must examine multiple uses. The city of Worcester currently has hundreds of restaurants, hotels and business spaces converted from its old buildings, and each one would require its own unique methodology for recycling.

This project will examine a specific building in Worcester. We will take the designs of the existing, outdated, and non-compliant building and attempt to develop a methodology that can determine by what means these buildings can be renovated. Different ways to make the building into one that is energy conscious, safe, and profitable so that an example method of recycling buildings can be analyzed.

Chapter 2: Background

Included throughout this section is information pertaining to general concepts that will be referenced throughout the methodology, results and other future sections. These concepts were identified and investigated in the literature, and established prior to any work being completed on the project.

2.1 Selected Aspects of the Construction Industry

The field of civil engineering often coincides with the construction industry. The engineer must have a firm understanding of the building process when designing the structure, in order to make sure that the plan is feasible. Hence, a brief background of some important features of the construction industry is included in the following sections.

2.1.1 Economic Scale of the Construction Industry

The construction industry is a large, ever growing, and influential American industry. The United States census tallies a numerical data monthly of total expenditures in the construction industry. A condensed and reproduced table is included below.

Table 2.1.1: Value of Construction Put in Place

Type of Construction	Seasonally Adjusted Annual Rate (millions of dollars)
Total Construction	**960,958**
Residential	357,234
Non Residential	603,724
Commercial	54,599
Manufacturing	57,004
Total Private Construction	**685,025**
Residential	351,968
Non Residential	333,327
Commercial	52,773
Manufacturing	56,314

As can be seen, close to one trillion dollars is spent per year on construction. Of this sum, over two-thirds are spent by the private sector, and all of these expenditures are occurring in an economy that is just beginning to muddle out of recession.

The non-residential sector accounts for nearly two thirds of the industry. Renovation and retrofitting of new buildings comprises a large majority of this cash flow. At the end of 2008, there was approximately 78 billion square feet of commercial buildings in the United States. Only 1. 8% of this total was new growth (Energy. gov).

2.1.2 Trends to Renovation

The reason behind the large push towards renovation stems from a lack of space to build. With a majority of business in the United States being conducted in cities and with very little room to develop inside city limits, fixing up older or abandoned buildings is the most viable option in establishing a new business. Cost is also a large reason why many business owners choose to remodel existing buildings. The process of demolishing, removing, and rebuilding a large structure could be extremely pricey.

2.1.2.1 Building Information Modeling

Building information modeling (BIM) is an emerging technology that started becoming popular in the early 2000s. It is a system that electronically represents all systems and components involved in building and greatly contributes to the design and construction process. It is important to note the difference between BIM and computer-aided design (CAD); BIM also includes elements such as estimating, cost, and project management. Dennis Neeley of SmartBIM states that BIM will catch on much quicker within the construction and engineering industry than CAD and believes the decade leading up to 2020 “will be the most exciting and transitional decade in the history of [the] building industry. ”

BIM provides the benefits of computer-aided design in addition to its own unique aspects. It allows any changes made in the drawings to be reflected in all other views and associated schedules. It also allows MEP components to be integrated with structural components in one all-inclusive design. It can incorporate time and dollar costs in create 4D and 5D modeling to aid in construction project management and to predict and reduce construction costs. BIM also improves collective understanding during the construction process by increasing shared knowledge among architects, project managers, and subcontractors. In particular, Autodesk’s Revit is one of the most well-known BIM software programs on the market today.

2.1.2.2 Structural Design

In modern day building projects structural design involves following the standards set by national organizations. These organizations are separated by material, each providing a set of codes for the design of specific members made of that material. For example the American Institute of Steel Construction has been publishing specifications for structural steel buildings since June 1, 1923 (American Institute of Steel Construction). Today the nation’s industry follows specifications, codes, and standards set by the American Institute of Steel Construction, American Concrete Institute, Precast Concrete Institute, and American Wood Council. These standards and codes guide design requirements and the process that must be followed to ensure the safety of the building for both existing and new designs. Equations to check means of failure for specific types of members are provided along with any other information that may be necessary. These equations provide the designer with the maximum loadings members can have. This analysis is applicable to individual members of the design and can be used with existing and new building members. The codes do not specify which member is the best option from an economical or project standpoint, this is up to the designer.

2.1.2.3 Block Diagrams

In architectural programming, a common tool utilized to define the basic plan for a building is a block diagram. The purpose behind it is to lay out a basic overview of the floor plan of a building and give general dimensions for the interior structure. It is important to note that the actual design of the rooms is not included since this is a separate diagram from the architect.

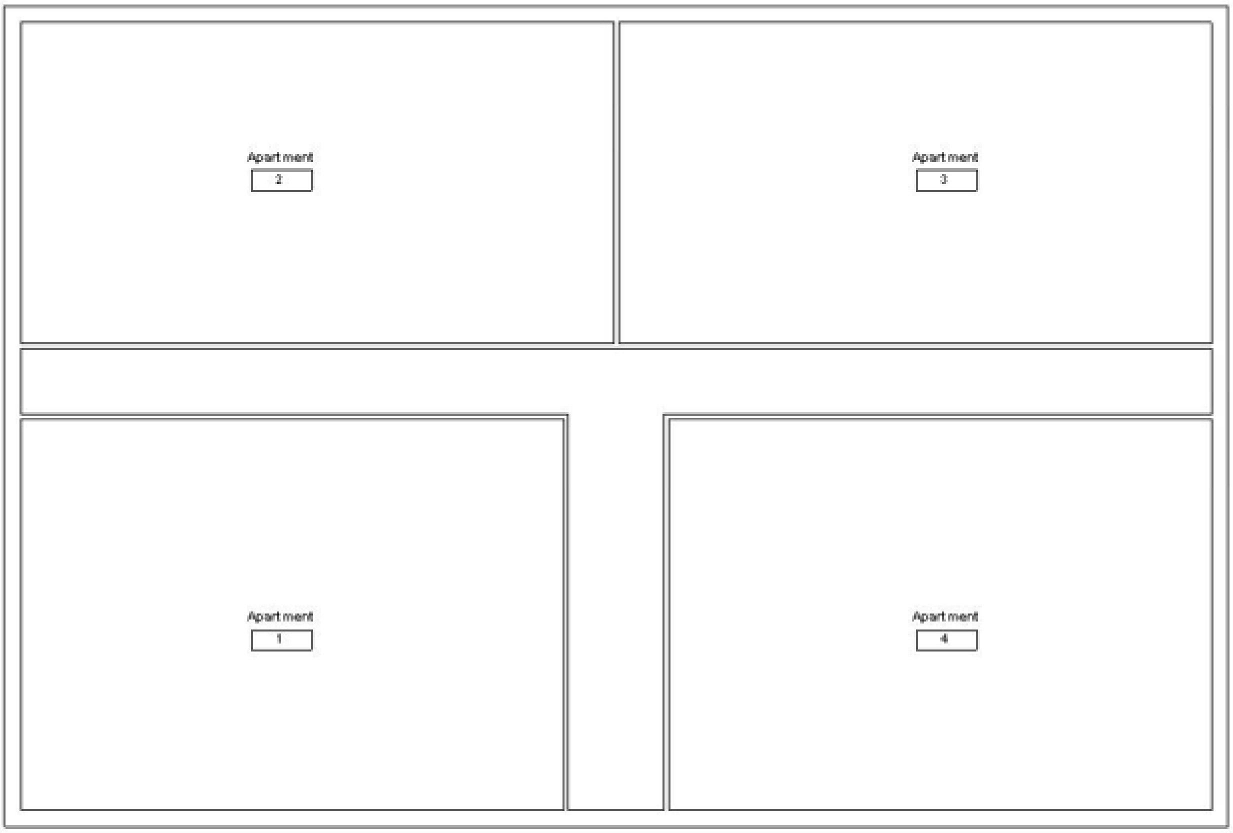


Figure 2.1.2.3: Example Block Diagram

2.1.3 Codes

Early in American construction, there were no regulations on building. With so many people living on the frontier, there were very few rules on how homes and structures were to be built. However, when cities began to grow in size and issues began to arise due to the increasing amount of people, new regulations needed to be introduced to ensure safety.

2.1.3.1 History of Building Codes

The first examples of building codes can be traced back over 4000 years. In Hammurabi's Code, a builder who constructed a building that did not stand up or caused an accident would be punished. Although not providing for exact building requirements, it established the first set of regulations for construction.

In the United States, the first known building codes were found in 1625, when the materials for roof coverings were limited to promote higher fire safety. Locally, Boston outlawed chimneys made with wood in order to protect both the structure's inhabitants and neighbors. During the construction of the District of Columbia, George Washington recommended that height and area limitations be implemented for structures within the city limits. The first formal building code was written in 1788.

During the early 1900's, the first building safety codes were being written on a national level. The first organization with the intention of writing these codes was developed in 1915. From here, the main set of building codes started to be written on a more regular basis. Currently, codes are edited very frequently to account for new and ever-changing technologies.

2.1.3.2 International Code Council

The International Code Council was founded in 1994, as a not for profit organization that focused on the development of codes designed for construction. It is a collective of officials from three earlier organizations: Building Officials and Code Administrators International (BOCA), International Conference of Building Officials (ICBO), and the Southern Building Code Congress International (SBCCI). Originally, these three organizations had created three separate sets of codes for building design and construction. However, with regional development codes becoming unresponsive to the country's needs, a single national code without regional limits was created.

As per its website, the purpose of the ICC is to "protect the health, safety, and welfare of people by creating safe buildings and communities." To do this, over one dozen different codes have been written to provide specifications for any construction scenario. Some examples are included below:

- *International Building Code* (*IBC*)
- *International Fire Code* (IFC)
- *International Mechanical Code* (IMC)
- *International Plumbing* Code (IPC)
- *International Residential Code* (IRC)
- *International Zoning Code* (IZC)

This "I-series" has been widely adopted by both federal and state organizations. A list of examples is included below (ICC Safe):

- All 50 States and District of Columbia
- National Park Service
- Department of State
- US Forest Service
- Architect of the Capitol
- Veterans Administration

2.1.3.2.1 International Building Code

The *International Building Code* was project undertaken by the International Code Council to develop a national code for structure construction. The task was begun by breaking the code up into five technical code development committees. These committees are listed, and briefly described in Table 2.1.3.2.1:

Table 2.1.3.2.1: *IBC* Committees

Committee Name	**Description**
Structural	General rules regarding design, inspections, and foundation requirements
Occupancy	Use groups, height and area requirements,
Fire Safety Committee	Sprinkler, alert systems, “most-restrictive”
Means of Egress	Exit locations, stairway sizes, illumination
General	Definitions, citations

The *IBC* has been adopted by a majority of the global community. Massachusetts is included in this listing. However, the state legislature has edited a few items throughout the code. When analyzing a building for renovation or construction, the *IBC* is the code to reference. The code itself will be specifically utilized for this project to identify how we can legally change the structure of the building. Since the project will also be a comparison between different possible uses of the building, different occupancies requirements will be considered and examined.

2.1.3.3 National Fire Protection Association (NFPA)

Like the ICC, the NFPA was established as an international non-profit organization. Their goal, as found on their website, “is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training and education.” Being established in 1896, the organization has been around significantly longer than the ICC.

The NFPA focuses their codes on fire protection systems, as the name implies. The majority of their codes are suited to fire safety systems and acceptable construction techniques such as sprinkler installation, fire rating tests, etc. Their most prominent code, *NFPA 101*, commonly referred to as the Life Safety Code, is often referred to for the design of fire protection systems. The NFPA has developed its own building code, *NFPA 5000*. This code has been adopted by very few organizations, and will not come into prominence during the majority of the project.

2.1.3.4 LEED Requirements

The United States Green Building Council was founded in 1993. Its mission is to promote sustainability in the building and construction industry. The nonprofit organization currently has over 181,000 professionals working in the field (USGBC).

The USGBC's most prominent, and relevant, creation is the Leadership in Energy and Environmental Design certification. LEED certification is currently the nationally recognized benchmark for green buildings. The system works by assigning point values for different sustainability aspects. For example, maintain 50%, by surface area, of an existing abandoned building earns six points. These points, when totaled can lead to a gold, silver or bronze rating.

There are many incentives to designing a new structure or formatting an old one with LEED in mind. A list with brief description of these incentives is produced below:

- Expedited Review/ Permit Processes: municipalities will prioritize buildings designed with the intention of a high LEED rating
- Density and Height Bonuses: Municipalities will allow for an increase in the floor area ratio upon certification
- Tax Credit: municipalities intending to promote new policies can reduce overall payment on taxes
- Fee Reduction: permitting fees and other processing fees may be reduced or waived
- Grants: municipal or state government may help subsidize building or certification cost
- Revolving Loan Fund: special low interest loan programs designed to assist in the construction process

2. 2 Worcester

The main focus of the project will be on a building located at 89 Shrewsbury Street Worcester, Massachusetts. Shrewsbury Street is one of the main streets in Worcester for restaurants, shops and night life.

2.2.1 Demographics

The city of Worcester has a population of just under 200,000 people inside an area of just under 40 square miles. The residents of the area average a relatively high income, just over $79,600. The city is also a large establishment for education, having 13 colleges in the general area and having more than 30,000 students living in the Greater Worcester area.

The business community is spurned on by this high influx of income and large population of young people. The average cost to rent office space falls inside the range of $11 to $22 per square foot. Also important to the business community is the large amount of downtown office space, which totals close to 4. 5 million square feet. The city also features a commuter rail into Boston, which only takes a 65 minute commute.

2.2.2 History

The city of Worcester was first settled under the Native American name Quinsigamond in 1673. It was settled twice more, with the final name of "Worcester" being adopted and finalized in 1713. Worcester, meaning “War-Castle,” was incorporated as a town in 1722 and finally as a city in 1848.

Worcester was originally an unlikely place for an industrial town. When the only way to have a successful mill was to have a large flow of water; Worcester did not have the river to power any buildings. Therefore, its manufacturing background began in 1828, when the Blackstone Canal first opened. In 1835, the first railroad connecting Worcester and Boston opened, making the city a crossroad for trade.

After the Civil War, the true industrial age swept through the Northeast. The population of Worcester saw close to a 240% increase prior to the turn of the century. The amount of output from mills and factories established Worcester as a manufacturing power in the thriving New England economy. It was during this time period that the building of focus was first built as a manufacturing building on Shrewsbury Street.

2.2.3 89 Shrewsbury Street

The existing building has already undergone a renovation from its original purpose. It currently has the restaurant, Via Italian Table, and several of the upper floors are office buildings. Drawings of the building are included in the Appendix.

For this project, the newly renovated aspects of the building will be ignored and only the aspects labeled existing will be taken into account. For example, the old plans include an existing storage room, elevator and structural support members.

Seeing as how the building is located in Worcester, it is crucial to keep the locale in mind. Knowing the needs of the city will help to establish what the ideal future occupancy type of the building should be.

Chapter 3: Scope of Work

Figure 1 below presents a map of 89 Shrewsbury St. in present day Worcester, MA. The location of the building affects the design loadings as mandated by the *Massachusetts State Building Code*. Due to these design factors, this project will be most applicable to existing mill buildings that were built in the late 1800's and early 1900's in the New England region.

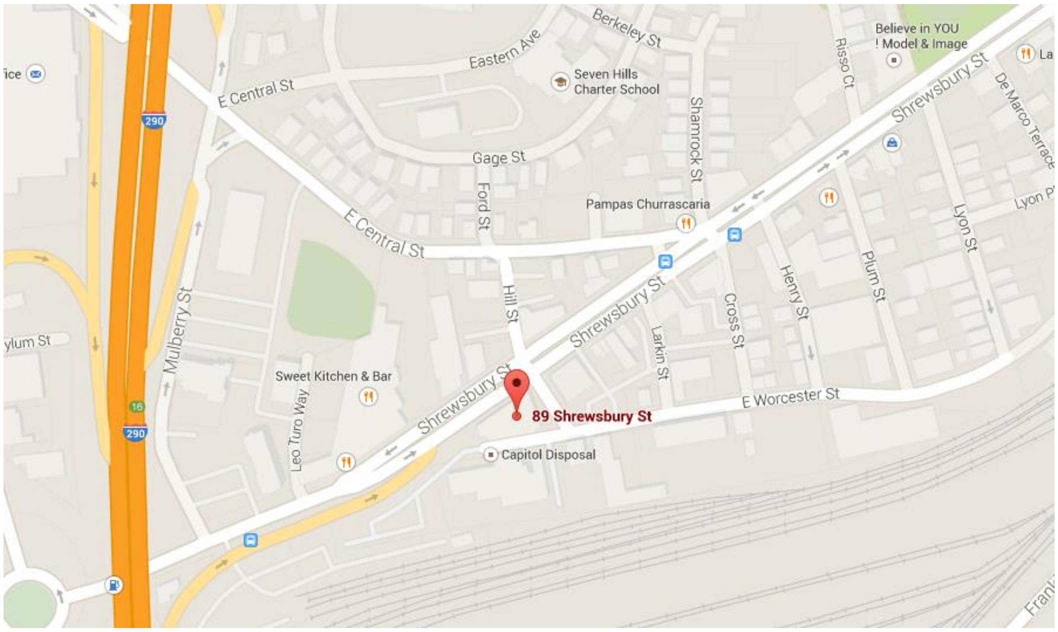


Figure 1: Location of 89 Shrewsbury St. , Worcester, MA

The scope of this study is to specifically look at the superstructure, interior, and fire protection systems of the building and propose, develop, and evaluate modifications to meet design loadings and safety requirements. The *Massachusetts State Building Code* will be used to determine the design loadings and safety requirements for the structural components and systems that will be considered for both residential and commercial designs. It encompasses the *International Building Code 2009 (IBC)*, *ASCE/SEI 7 Minimum Design Loads For Buildings and Other Structures (ASCE 7),* and the 2010 edition of *National Fire Protection Association 2013 Standard for the Installation of Sprinkler Systems (NFPA 13)*. Green building components will also be integrated into the project. LEED design methods through daylighting and water reuse will be evaluated for feasibility and potential benefits such as increased energy efficiency and reduce resources used. These big picture strategies for points will be considered, however actual certification of the building design will not be investigated.

Chapter 4: Methodology

This project is intended to assist the retrofitting process of non-compliant buildings. This will be achieved by performing a feasibility study of 89 Shrewsbury St. comparing residential and commercial retrofitted designs. The primary objectives of this project are as follows:

1. To develop structural modifications to the existing building
2. Determine the appropriate occupancy type for usage
3. To bring the building into compliance with the *Massachusetts State Building Code* based on occupancy type
    a. Structural Design
    b. Automatic Sprinkler Systems
    c. Accessibility and Means of Egress
4. To incorporate water reuse and daylighting LEED design aspects
5. To provide recommendations as to which building design is more profitable based on a return on investment cost analysis

Objectives 1-3 will be completed individually for a residential and commercial design. Objective 4 will bring the two designs together in a life-cycle cost analysis. Figure 2 displays a visual overview of the project tasks that will be accomplished.

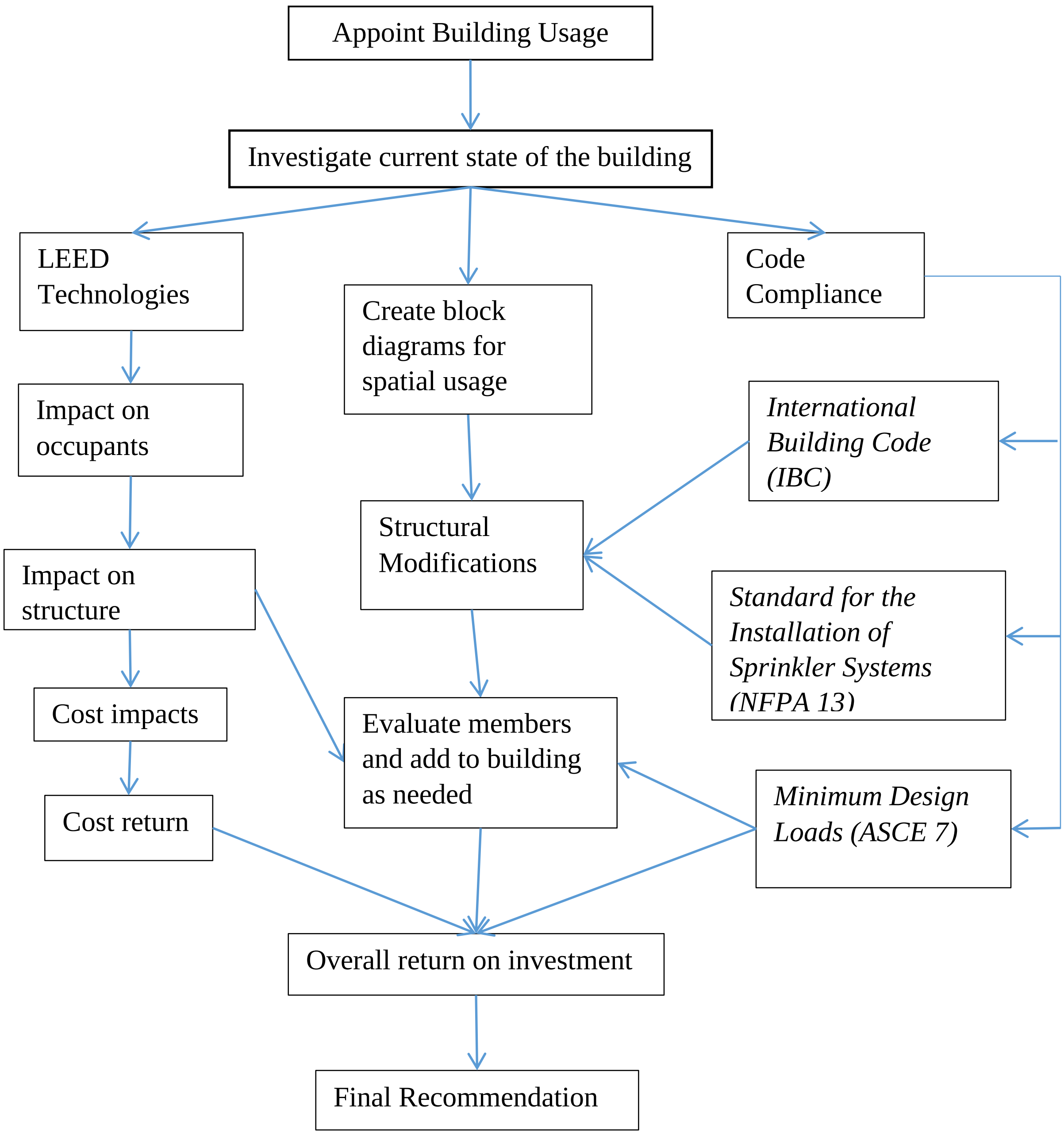


Figure 2: Concept Map for Retrofitted Building Design

4.1 Structural Modifications

Our first objective is to develop structural modifications for the existing building to ensure it will comply with modern day design loadings. The first step in structural modifications is to obtain the 2005 building plans and study them to learn about the state of the building as it was in 2005. The hard copy drawings will be converted into a 3D building information model using Autodesk *Revit*. Scanned plans were copied into Revit to measure dimensions using the provided scale. Having the building model in *Revit* will allow the team to visually interpret the drawings and get a better understanding of what currently exists in the building. Additionally, *Revit* will allow the drawings to be edited and added to, which will be extremely beneficial later in the project.

For each proposed use, a block diagram will be drawn for each floor to determine egress means and the hard constraints that must be worked into the design. This also incorporates the occupancy limits. These limits are 100 gross sf per occupant for business areas and 200 gross sf per occupant for residential areas. This information can be found in Table 1004.1.2 of the *IBC*.

Once the building has a general layout and hard constraints (existing structural members, stairs, etc.) for each of the two usages, the design loads must be determined. These design loads can be found in *ASCE 7*. The design live load for commercial office space is 50 psf for uniform loads and 2000 lbs for concentrated loads. Residential must be designed to support a uniform load of 40 psf. Both have a roof load of 20 psf. In both cases, snow loadings will also be considered for the northeast region. Similarly, dead loads, wind loads, and seismic loads are the same for residential and commercial use, and can be found in the *ASCE 7*.

These design loadings will be used in conjunction with the provisions of the *National Design Specification for Wood Construction (NDS)* and the *American Institute of Steel Construction, Steel Construction Manual (AISC Manual).* Existing wood members will be evaluated based on the *NDS* to determine if their capacity will allow for renovated building use. Steel members will be added to support or reinforce wood members which are not sufficient. The existing wood floors will also be reinforced if necessary. Steel beams will be evaluated for bending, deflection, shear, buckling, and lateral torsional buckling. Steel columns will be evaluated for buckling. Typical connections will be designed looking at welded and bolted options. These members will be chosen and placed based on a lowest cost comparison.

4.2 Building Compliance

Upon completion of block diagrams and appropriate selection of structural modifications to 89 Shrewsbury Street, the building will need to comply with the 2009 edition of the *International Building Code* along with the Massachusetts amendments. This will include involving the structural modifications and ensuring they meet the standards of implemented design loads and deflection. Due to the limited scope of this study, not all areas of the *IBC* will inspected for compliance.

The first main area of compliance that will be addressed will be an appropriately designed automatic sprinkler system. *NFPA 13* is the standard used for sprinkler system installation and has been adopted by the *International Building Code*. The sprinkler systems will be designed accordingly based off of the completed block diagrams and details specific to each building use. Although there will be different requirements for commercial and residential uses of this building, similar aspects such as required number of sprinkler systems, temperature rating of sprinklers, and spacing of branch lines will need to be defined in accordance with *NFPA 13* for each use.

With the completion of the sprinkler system design for both intended uses, means of egress, general building heights and area, and accessibility of both building designs will be consulted in the *IBC* to verify that both the residential and commercial designs will meet Massachusetts Building Code. Appropriate changes to the block diagram will be made if certain means of egress or other requirements are not met. The addition of the sprinkler system typically makes most of these requirements more lenient and will allow these designs to more easily meet the requirements of the *IBC*.

4.3 LEED

To incorporate LEED designs, potential methods will be evaluated based on feasibility and benefits. Renovation of an abandoned building is already a large step towards achieving a green building; however, this project will investigate and develop other methods. The areas of design that will be investigated include, but are not limited to rainwater management, water reuse, and use of daylighting

The first step will be to research case studies where buildings have incorporated technologies relevant to this project. This will help determine which technologies will provide a sustainable design while still within the context of the scope. Then an evaluation of the impacts of the LEED design on the occupants of the building will be conducted. This evaluation will help decide if the technology will benefit the occupants or if it will quickly become obsolete. Next, the design's effect on the structural integrity of the building will be evaluated. Added weight to the design loads, particularly on upper floors or the roof, may cause some of the members to be insufficient. Any required changes to the structural modifications beyond those necessitated by the design loadings will be added into the design cost estimate. This cost estimate will include structural modifications and cost of the technology. Finally, the return on investment will be evaluated, to compare the cost with the benefits. Nonfinancial impacts will be reviewed.

4.4 Provide Recommendations

Once all designs are completed a cost analysis will be performed on each intended building use to compare which design will be more profitable in the long term. The *Revit* building information model will be used to perform a quantity take-off of items modified in this project. For these known materials, parametric estimates will be used based on RSMeans item data. For unknown items, RSMeans square foot costs will be utilized to provide a rough estimate. In addition, average incomes from both residential apartments and office buildings in the Worcester area will be obtained based on state and city averages to establish an average owner yearly income from the building space, based on an assumed vacancy rate. LEED design implications will also be analyzed to determine their worth for the building designs. Based on these figures, a return on investment can be calculated to compare which of these two scenarios would be the most cost effective. With this analysis, recommendations will be provided to suggest which intended use would be the best choice and what LEED objectives to pursue if someone were to purchase and retrofit this existing building on 89 Shrewsbury Street.

Chapter 5: Deliverables

Topic Area	Deliverables	
Architectural	Block Diagrams*	
Structural	Initial Revit Drawings	
	Necessary Structural Modifications*	
	Final Revit Drawings*	
Fire Protection	Necessary Accessibility and Means of Egress*	
	Sprinkler System Design*	Hydraulic Calculations
		Sprinkler Placement Schematic
LEED	Rainwater Management Design*	Structural Impacts
		Economic Impacts
	Increased Water Reuse Design*	Structural Impacts
		Economic Impacts
	Increased Daylighting Design*	Structural Impacts
		Economic Impacts
Cost Analysis	Overall Cost using RSMeans Data*	
	Return on Investment Analysis*	
	Comparison of Two Designs	

*- indicates deliverable will be completed for both residential and commercial designs

Chapter 6: Schedule

	B-Term (in weeks)							C-Term (in weeks)						
Activity (with primary student)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Structural Design														
Initial Revit Drawings (SL)														
Block Diagrams (BM)														
Current Structural Analysis (MD)														
Write Analysis Methodology and Results (SL)														
Necessary Structural Modifications (SL)														
Final Revit Drawing (BM)														
Modifications Writing (MD)														
Fire Protection														
Modifications to Accessibility (SL)														
Modifications to Means of Egress (MD)														
Sprinkler System Design (BM)														
Code Analysis Writing (MD)														
LEED Design														
Rainwater Management Design (MD)														
Rainwater Impacts (MD)														
Increased Water Reuse Design (SL)														
Water Reuse Impacts (SL)														
Increased Daylighting Design (BM)														
Daylighting Impacts (BM)														
LEED Writing (SL)														
Cost Analysis														
Overall Cost (SL)														
Return on Investment Analysis (BM)														
Comparison of Designs (BM)														
Cost Analysis Writing (MD)														
Compile Final Designs														
Final Draft for Paper														
Final Paper Complete														
Poster														

Chapter 7: Conclusions

The deliverables from this project will meld together many aspects of the civil engineering field. Structural engineering will be used to evaluate the current integrity of the building and make the necessary modifications for structural safety. The final result will give the reader a full overview of the changes required based on the loadings for each design. In addition block diagrams will give a rough outline of the architectural design. Fire protection engineering will play its role as the sprinkler system is designed along with accessing the means of egress and accessibility. Sustainability aspects will be incorporated into the design as green engineering technologies are evaluated for their constructability and economic impact. The cost estimate of the design will also be provided and the return on investment analysis will guide the recommendation as to which design is more profitable. The final report will guide the reader through the design process and aspects of the design which were considered. This will allow the reader to gain knowledge of the retrofitted design of 89 Shrewsbury St.

Bibliography

American Institute of Steel Construction. (2014). *Historic Standards*. Retrieved 10/15/2014, from http://www.aisc.org/content.aspx?id=2870

American Society of Civil Engineers. *Code of Ethics*. Retrieved 10/16/2014, from http://www.asce.org/Ethics/Code-of-Ethics/

Bureau of Labor Statistic. (2014). *Workforce Statistics*. Retrieved 10/15/2014, from http://www.bls.gov/iag/tgs/iag23.htm#workforce

International Code Council. *About ICC*. Retrieved 10/10/2014, 2014, from http://www.iccsafe.org/abouticc/Pages/default.aspx

Massachusetts State Building Code. (2010). 8th Edition. Retrieved 10/16/2014, from http://www.mass.gov/eopss/consumer-prot-and-bus-lic/license-type/csl/8th-edition-base-code.html

McGraw-Hill Construction. (2011). *Business Case for Energy Efficient Building Retrofit and Renovation*. From http://energy.gov/sites/prod/files/2013/12/f5/business_case_for_energy_efficiency_retrofit_renovation_smr_2011.pdf

National Trust for Historic Preservation. (2012). *The Environmental Value of Building Reuse*. from http://www.preservationnation.org/information-center/sustainable-communities/green-lab/valuing-building-reuse.html#.VDPemvldV8E

Tyree, D. & Pitts, D. *The International Building Code and International Residential Code and Their Impact on Wood-Frame Design and Construction*. Retrieved 10/06/2014, from http://www.awc.org/Publications/papers/ASCEIBC-IRC.pdf

United States Census Bureau. (2014). *Construction Management*. Retrieved 10/10/2014, from http://www.census.gov/construction/c30/c30index.html

U. S. Green Building Council. (2014). *Good to know: Green Building incentive strategies*. Retrieved 10/10/2014, from http://www.usgbc.org/articles/good-know-green-building-incentive-strategies-0/

Value of Construction Put in Place - Seasonally Adjusted Annual Rate. (2014). Retrieved 10/08/2014, from http://www.census.gov/construction/c30/pdf/totsa.pdf

Worcester Historical Museum. *Worcester History*. Retrieved 10/09/2014, from http://www.worcesterhistory.org/worcesters-history/

Worcester Regional Research Bureau. (2013). *Demographics & Census Information*. Retrieved 10/02/2014, from http://www.worcestermass.org/home/about-worcester/special-events/demographics-census-information