Sustainable Modular Home Design

A Major Qualifying Project Report:

submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

By

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Date: March 5, 2010

Approved:

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Abstract

The focus of this project was to create a sustainable modular home design that makes a small impact on the environment both during construction and throughout its lifetime in Southern California. This project includes the structural design and layout of a sustainable modular home. It also focuses on incorporating environmentally friendly structural materials that were chosen through a series of tests. A cost analysis for the home's structure was performed at the conclusion of design activities.

Acknowledgements

We would like to acknowledge the contributions of the following people. The success of this project would not have been possible without their assistance.

Professor Leonard Albano
Donald Pellegrino
Dean Daigneault
Professor Tahar El-Korchi

Authorship

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

Stephanie Schultz: Home Systems, Structural Design, Cost Estimate

Carly Willmott: Site Design, Layout Design, Materials Testing

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Capstone Design Statement

In order to fulfill the Capstone Design degree requirement, this Major Qualifying Project considered several real world constraints. This project addresses economic, environmental, sustainability, constructability/manufacturability, health and safety, social, and political design considerations.

Economic

The economic portion of the capstone design consists of a cost estimate for the structural materials needed for the construction of the home. A chart was created to comprehensively outline the costs of the major materials selected. The cost of this design was compared to the framing costs of a traditionally constructed home. A goal of the project is to design a high-quality home that is within the price range of a typical middle class family.

Environmental

The environmental component of the design addresses factors that impact the environment during the actual construction of the home. Reduction of site impact during construction was vital in order to meet environmental goals.

Sustainability

The sustainability portion of the design addresses the impacts of material choice and efficiency of resource consumption throughout the life of the home. Extensive research and testing was completed on traditional as well as new eco-friendly materials. The home was designed to enhance energy efficiency and use the selected environmentally friendly materials. Charts, graphs, and computer models of the home were developed in order to show how the materials were used in the design.

Constructability/Manufacturability

The constructability/manufacturability considerations of the design address how the home is to be constructed. One inherent advantage of modular housing is that homes are easily assembled and produced in a factory using an efficient manufacturing process. Once this process is completed, prefabricated sections of the home are shipped to the site, limiting the amount of work required on site.

Health and Safety

The health and safety component of the capstone design addresses how the region's geo-hazards, such as earthquakes and wildfires, were considered in the design of the home. The design will be based on California Building Standards. This section also discusses the health-related properties of the materials, such as their potential to release chemical and particulate matter into the environment, compared with traditional materials.

Social

The social portion of the design mainly pertains to the functional design and layout of the home. It explains the reasoning behind certain elements of the design and their social impact on the residents. Considerations for certain lifestyles, needs, or current trends in home design, such as number of bedrooms, room functions, and dimensions were addressed.

Political

The political portion of the capstone design addresses the home's adherence to certain standards such as title 24, The California Green Building Code, as well as the ASTM standards. This section also touches on how the design of the home reflects recent movements and designs of green buildings.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

For centuries people have been relatively unaware of the harm and strain that their levels of resource consumption put on the global environment. Only recently have people been searching for ways to slow or reverse this resource-depleting trend. The problem is so immense that isolated, small-scale efforts will not be enough to combat it. Therefore, in order to achieve any significant results, conservation must be incorporated into the everyday lives of consumers. To maximize the impact of this conservation movement, strategies should target an element within people's lives that is responsible for high energy and resource consumption. The prime candidates for this attention are private homes. The residential sector consumes over 20% of the energy in the United States (Energy Information Administration, 2009), and in response to this statistic, new designs and efforts are being developed in order to lower it.

Most traditional homes were designed and built long before anyone was concerned about the impact they would have on the environment. Natural resources have been greatly depleted due to short-sighted construction practices, over-extraction, and the long period of time required for them to regenerate. In addition to the unsustainable extraction of natural resources, many established construction materials have a high embodied energy, meaning that they require large amounts of energy to manufacture. Others are often treated with chemicals that are harmful to human health as well as the environment. These are the three principle issues with traditional materials that the development of new, environmentally friendly materials is attempting to address.

Environmentally friendly housing has been around for quite some time, especially in California, but its popularity has increased in recent years. Throughout the past few decades, new research has helped consumers to understand their impacts on the environment and the harm they are causing. This has created a consumer demand for the construction industry to incorporate more responsible practices, to which they have responded with increased efforts in efficient resource use. This renewed interest has also inspired the ingenuity to find new sustainably produced materials that can be incorporated into the construction of homes.

During the design process of a house, numerous elements need to be considered and altered in order to limit the home's impact on the environment. For example, what types of materials are suitable for high quality, environmentally friendly design? How can material usage be lessened? How can these goals be achieved while keeping the home affordable for the middle class? Additionally, in order for an environmentally-conscious housing movement to be successful, these homes need to be high quality and aesthetically appealing to potential homebuyers.

The aim of this project is to incorporate the eco-friendly materials and design and construction practices into the design of a one-story modular home located in Southern California. Environmentally conscious design strategies, including site design, layout design, and incorporation of home systems, were investigated in order to apply the sustainability goals of the project to the major aspects of the home's design. Laboratory testing was completed on construction materials that were researched and determined to have a less significant environmental impact than conventional materials. The home's structure was then designed using materials chosen based on laboratory testing results and a simple cost estimate performed to be used in comparison with a traditional stick-built house. All of these activities contributed to the design of a home with significantly reduced environmental impact.

Chapter 2: Background

In order to establish a basis for the activities of this project, the basics of sustainable construction practices were investigated. Research into modular construction, which is the method used in this project was completed, and comparisons were drawn between this approach and traditional stick-built construction. Additionally, further background information is provided in the appropriate sections.

"Green" Building

"Green" building is a trend whose popularity has grown rapidly in recent years in response to the more widespread recognition of the global environmental crisis. "Green buildings are designed, constructed, and operated to boost environmental, economic, health, and productivity performance over that of conventional building" (Building Momentum, 2003). According to the United States Green Building Council, the "built environment" is a huge resource consumer in the United States. The estimated 81 million residential and commercial buildings in the United States are responsible for 72% of electricity consumption, 39% of energy use, and 38% of all carbon dioxide emissions. They can also claim 40% of raw material use, 30% of waste output, and 14% of potable water consumption (USGBC, 2009).

Green building strategies benefit the environment by protecting ecosystems, improving air and water quality, reducing solid waste, and conserving natural resources. Green building can benefit even those whose chief concerns are not environmental, but rather financial. Much of the time, green buildings can be constructed at a cost lower than or equal to conventional buildings. Because resource efficiency is a focus of the design, mechanical, electrical, and structural systems are often downsized to the point where they effectively accomplish their purpose, but are not wastefully overdesigned.

Unfortunately, the integration of high-performance elements can sometimes increase the initial cost of the building by an average of 2 to 7 percent (Building Momentum, 2003). Even though these costs can be recovered rather quickly during operations, decisions are often made without looking that far ahead. The ability of these high-performance elements to pay for themselves is even more evident when considering that, of the total amount of money that the owner will spend in a building's lifetime, the initial cost of the building will only account for 5 to 10 percent of that cost (Building Momentum, 2003). On the other hand, operations and maintenance take up 60 to 80 percent of the total life-cycle costs. Therefore, life-cycle cost information can be a valuable tool in promoting these building techniques (Building Momentum, 2003).

Green building practices also benefit the health of building occupants by creating improved air, thermal, and acoustic environments (USGBC, 2009). The air inside of a building can contain many chemical and biological substances that can be harmful to human health. These substances include volatile organic compounds, mold, allergens, and infectious agents. According to the EPA, indoor air quality is one of the top five environmental health risks. Concentrations of air pollutants can average 2 to 5 times higher than the air outdoors (Building Momentum, 2003). However, by choosing materials that resist growth of mold and allergens, do not contain harmful chemicals, and are made from natural or renewable products, buildings can be designed with consideration for the health of both people and the environment.

Stick-Built Homes vs. Modular Homes

In light of the growing concern for energy and resource consumption, home design and construction are being closely examined in order to find components and methods with which to improve sustainability. Traditional, or stick-built, homes are the first thing that comes to mind for most people when thinking about building a new house. Though efforts are being made to make these homes more environmentally friendly, they may not be the best option available to achieve that goal, and also may not be the most financially appealing. Though they have the advantage of being fully customizable and the most available/common method of construction, there are many downsides.

As a building that is constructed entirely on site, materials for each stick-built home must be ordered solely for that individual home, unless the builder has a large warehouse to store materials in order to take advantage of economies of scale. Another disadvantage of on-site construction is weather exposure, which damages materials, and this early damage is shown to necessitate more maintenance throughout the life of the building. All of these ruined materials and repairs not only cost money, but waste natural resources. This early weather exposure and other factors make this method the most costly.

Because nearly the entire stick-built house is custom constructed, more workers are required to complete the project, and more time is needed because the process is not streamlined by repetition, since each project is unique and workers may be involved in various construction activities at the same time. Weather delays, in addition to damage, run up the project's cost. Another disadvantage of this method is the six to twelve month construction period. Because all work is done on site, the critical path is lengthened, since certain activities cannot be completed until the previous is finished.

It is possible to increase the energy efficiency of these homes by improving insulation or incorporating energy efficient systems. These efforts have been made, but the lack of economies of scale makes their price tags unattractive to homebuyers. Therefore, other methods of construction are being looked to as a solution.

One way to increase the efficiency of the construction process is to build with prefabricated, modular units. Though often confused with mobile homes, which carry the negative stigma of being low-quality and non-customizable, modular homes are considerably different. Modular homes do not have axels like mobile homes and, once placed on the construction site, they are permanently affixed to a foundation. These buildings can take the shape of multi-story or single-story apartment style, multi-family, or single family dwellings. It is also possible for the homebuyer to customize their home and end up with a high-quality, visually appealing home.

The central principle of modular construction is that the sections of the home are built in a controlled factory environment, transported to the site once completed, then connected and placed on the foundation. One of the key advantages of these homes is that the efficient factory construction process reduces the amount of waste material generated during construction. Also, non-traditional (renewable/recycled) materials and energy-saving systems can be incorporated to achieve eco-friendly design. These eco-friendly materials, which can often be difficult to procure and deliver to a construction site, can be ordered in bulk, stored in or near the factory, and incorporated into the design of several projects. This reduces prices by taking advantage of economies of scale and also cuts back on construction delays due to material unavailability. But before manufacturing can begin, the materials' suitability for modular design in the areas of structural integrity, human health risks, cost, projected lifespan/durability, etc. must be evaluated.

Because modular homes are built in a factory, they are not exposed to weather damage and construction is not delayed by weather. The home is also easily assembled on-site, cutting construction time nearly in half. This is because, while the home is being constructed in a factory, the site and foundation work can be completed. Once the home is fabricated, it is sent to the site and assembled (Pelletier, 2007). This reduces the amount of construction equipment needed and vehicular traffic to and from the site, cutting down on the carbon emissions associated with these activities, which is a goal of sustainable construction practices. The reduced the amount of time that machines are needed on site also lessens the physical impact on the site from issues like erosion (Finish Werks, 2008).

Chapter 3: Methodology

Eco-friendly projects are becoming the norm in the 21st century, although most existing homes cannot claim such a distinction. The modular home presented in this project represents an attempt to reduce the impact of a new home on the environment.

Background

Research was done in order to gain a background understanding of the environmental impacts of construction. Statistics for resource consumption of buildings, particularly the residential sector, was used to emphasize the impact that could be made by altering conventional construction practices. Both the benefits and drawbacks of these strategies were also explored.

Keeping the goal of environmentally-conscious design in mind, extensive research was completed on the topic of modular homes and their construction. A comparison was made with traditional, stick-built homes, which addressed the differences between the two methods in terms of customizability, material costs, waste and damage, labor costs, duration of project, and energy and resource efficiency.

Site Design

One goal of this project was to incorporate strategies to reduce the impact of construction on the surrounding environment. Research was done on the conventional approach to site development, and then on newer approaches which aim to preserve natural elements of the site from the beginning of construction continuing through the service life of the building. These topics ranged from ways of clearing and grading the site to the materials and vegetation used in final landscaping.

Layout

The layout of the home was designed to be both appealing to a modern family and environmentally friendly. Incorporating ideas from a variety of modular homes was key to the design process, as these designs have already been proven successful by their acceptance by actual homebuyers. Research into strategies that help a building take advantage of natural lighting and heating was completed. Also, regional considerations for Southern California and the methods used to accommodate them were taken into account, such as the effect of warm climate and the region's various natural hazards.

Once environmental design aspects were identified, the social implications of a home's layout were investigated. While designing the layout of the modular home it is important to keep in mind modern expectations for room sizes as well as trends in room function, arrangement, and social atmosphere.

Once this research was completed, an architectural model was created using Autodesk Revit 2010. The Revit model functioned as a method to visually communicate the results of the design decisions made in both a two-dimensional layout and a three-dimensional view of the home's exterior.

Home Systems/Exterior Finishes

Another objective in this project was to select eco-friendly in-home systems such as insulation, heating, and cooling to contribute to the overall "greenness" of the home. Significant research was done on these in-home systems to guarantee that they are environmentally friendly and reduce the overall cost of heating and electricity. The goal is to make this modular home as eco-friendly as possible without spending a great deal money.

Materials Testing

The materials testing component of the project was divided into two sections corresponding to the type of material investigated. The two categories of materials were wood and concrete. For both, the impacts that the traditional forms of these construction materials have on the environment were researched. Once this research was completed, inquiry into alternatives to conventional wood and concrete construction materials was conducted through trade publications, online resources and journal articles. For wood, these alternatives consisted of engineered lumber while concrete alternatives focused on cementitious materials that could be substituted for portions of Portland cement in the mix design. The benefits and drawbacks of all of the alternatives were identified, and in the end, three types of wood and three types of cement replacements were chosen for testing. Their selection was based on their ability to meet the engineering requirements of the design and their classification as an environmentally friendly material.

The first materials to be tested were the wood specimens. Douglas fir was chosen to serve as the traditional construction material to which the two types of engineered lumber, laminated veneer lumber (LVL) and wooden I-beams, were compared. The Douglas fir was subjected to tests for three-point bending strength and compression strength perpendicular and parallel to the grain. The LVL was subjected to tests for three-point bending strength, compression strength perpendicular and parallel to the grain, and tensile strength parallel to the grain. The wooden I-beams were only tested for three-point bending strength. All tests were conducted in accordance with ASTM D198 for wood testing.

Once these tests were completed, the test values were compared to the design values provided by the LVL and I-beam manufacturer, Georgia-Pacific Wood Products LLC, and values for Douglas fir published by the U.S. Department of Agriculture's Forest Products Laboratory. The manner of failure was also noted and practical implications of these results to actual home construction were explored. Finally, after weighing the qualitative and quantitative advantages and negative aspects of the three types of wood, one was chosen for use in the design of the modular home.

Before any testing began, the concrete mixes for replacement of a portion of Portland cement with fly ash, blast furnace slag, and silica fume were designed based on an existing mix design. Modifications were made to the Portland cement content of the design, with the chosen percent substitutions removed from the cement content and replaced with the alternative cementitious materials. Research on the concrete additives provided a guideline on the amount of Portland cement that could be replaced by an alternative cementitious material. Based on this research, it was determined that 15% and 25% replacement was an accepted amount, and 35% would be used to test the limits. Therefore, mix designs for each amount of replacement and each material were done, giving eight mix designs (a limited amount of blast furnace slag only allowed for a 25% and 35% mix).

It was decided that three cylinders would be tested for compressive strength and one for split tensile strength for each mix design. Therefore, the each mix of concrete was batched, mixed, and molded into four 6"x 12" cylinders according to ASTM C192. All eight batches of concrete were mixed within a period of three consecutive days. 74 days after the first batch was mixed, all of the cylinders from the eight mix designs were tested. Compression testing was carried in accordance with ASTM C39 and split tensile testing adhered to ASTM C496.

Based on the results gathered in testing, conclusions were drawn regarding the strength characteristics of the different mixes. In order to determine whether the different levels of percent substitution of fly ash, slag, or silica fume for Portland cement produced significantly stronger concrete, the Student's t-test was performed for each set of compressive strength data. Because the data sets were so small, a statistical p-value of 0.15 was used. If the p-value of a two particular sets of data was less than 0.15, then they were concluded to be significantly different.

All specimens had their qualitative benefits and drawback, but the tests completed on them provided quantitative data to aid in the process of choosing the correct concrete mix for the home. Comparisons were made between different mixes through the use tables and graphs. By assessing the relative importance of each of the different mix designs' properties, one design was chosen to be used in the design of the modular home.

Structural Design

Once tests were completed and materials identified, the structural design process began. The frame of the home was designed around *ASCE 7-05* (ASCE, 2006) which is the minimum design loads for buildings and other structures. All loading combinations were examined in order to provide the home with sufficient support. Different options for foundations were researched and designed. Materials for the foundation were chosen based on the test data for the alternative concrete mix designs and the overall eco-friendliness of the material. The frame of the home was represented in a series of AutoCAD drawings in order to effectively communicate dimensions. Research was also completed on a variety of materials for the interior and exterior, keeping in mind that the selection of materials to be used could aid in the heating and cooling of the home.

Cost Estimate

One goal of the project was to design a home that could be considered an economically feasible option for a middle-class family. To determine whether this goal was met, a cost analysis was completed for the modular home and then compared to the typical cost of a traditionally constructed home. The items in this estimate included the costs of the foundation, footings, floor joists, subflooring, walls, roof rafters, girders, and roof covering.

Chapter 4: Environmentally Conscious Design Strategies

A holistic approach to improving the environmental quality of the entire project was taken, with efforts made to lessen the environmental impacts of the major, non-structural aspects of the project. These topics consisted of the site design, layout design, and choice of home systems.

Site Design

The purpose of sustainable site design is to preserve the site's characteristics both during and after construction so that it remains as close to its pre-construction state as possible. The major strategy in this type of design is Low Impact Development (LID), which refers to sustainable storm water management practices that work with nature by managing and keeping storm water as close to its source as possible (Guillette, 2008). Water management practices are a major concern in arid regions like Southern California, where water is a precious and scarce resource.

When a site is undeveloped, its area is essentially 100% pervious and plant and animal habitats are allowed to function normally. When the site is developed, the natural balance is disrupted by the addition of man-made elements and activities. This occurs most dramatically during construction, but also continues throughout the entire duration of the site's use, as it is maintained and prevented from returning to its natural conditions.

The most dramatic case of site alteration is taking an undeveloped, vegetated parcel of land and building on it. Traditionally, the site would be stripped of vegetation and graded with large machinery. This greatly disturbs the environment, destroys habitats, and leads to erosion. When the principles of LID are implemented, measures such as use of a site sedimentation and erosion control plan are implemented during construction. Heavy equipment can also do a lot of damage and greatly disturb a site, so access of this machinery can be limited ("Sustainable Site Design", 2003).

One of the largest impacts of building on a site is the creation of a large impervious area, which does not allow water to infiltrate the soil. Conventionally, handling storm water consists of directing it as quickly as possible to a storm drain or a large retention pond. The most direct way to reduce this impact is to make the building footprint as small as possible while maintaining functionality ("Sustainable Site Design", 2003). In addition to the building itself, paved surfaces are large impervious areas which can be reduced in area or made with more permeable materials so that they permit water infiltration to the underlying soil. Paved areas can also be broken up with landscaping. This landscaping can be either preserved natural vegetation or new plants, with the goal that it will slow runoff, filter out pollutants, and help the water to infiltrate and recharge the groundwater supply (Guillette, 2008).

Disturbing the existing vegetation is also a consequence of land development. If the vegetation cannot be relocated, plant life can be reintroduced once construction is complete. The all-encompassing recommendation regarding planting is to use native species, which are the types of vegetation which grow naturally in the region or climate. Because they are intended to grow in this environment, they need less intervention when it comes to survival since they have evolved to survive the soil and climate conditions. They will also require less water and fertilizer, be more resistant to local pests and diseases than non-native plants, and provide habitats for native wildlife (Guillette, 2008).

Layout Design

Once a general site design is established, the orientation of the building on the site should be decided upon. In order to save on heating costs in the winter, passive heating can be implemented by orienting the house along an east-west axis, with windows concentrated on the south side to let more sunlight in. Electricity costs for lighting can also be cut down by the increased amount of light entering the home. To make the most of this effect, a general rule that can be applied to all climate regions is to design the house in the shape of a long rectangle (Minnesota, 2007).

The design of a home's floor plan is an architectural matter mainly grounded in social, rather than engineering, issues. The layout should be designed while keeping in mind the intended occupants, in this case a family. When designing without a specific client in mind, the layout should be shaped around the needs of a modern lifestyle, as well as current trends in home design, while keeping the design flexible. A house that can accommodate a variety of lifestyles and types of households is much less likely to require remodeling later on (Edminster, 2008).

This home was designed in this way, taking into consideration trends in modern homes in addition to environmentally friendly design elements. One contemporary trend in home design that was not applied to this home is the preference for large houses, as such large spaces are inefficient to heat and cool and consume more resources in construction. Over the last three decades, the average house size in America has increased while the number of people per household has decreased. The average floor area per person rose from 427 to 756 square feet, which is a 77 percent jump (Edminster, 2008). The modular home was designed to have an approximate area of 2000 square feet, so that it is a comfortable size, but not so large to be wasteful of material and energy resources (Figure 1)(Adler, 2006).

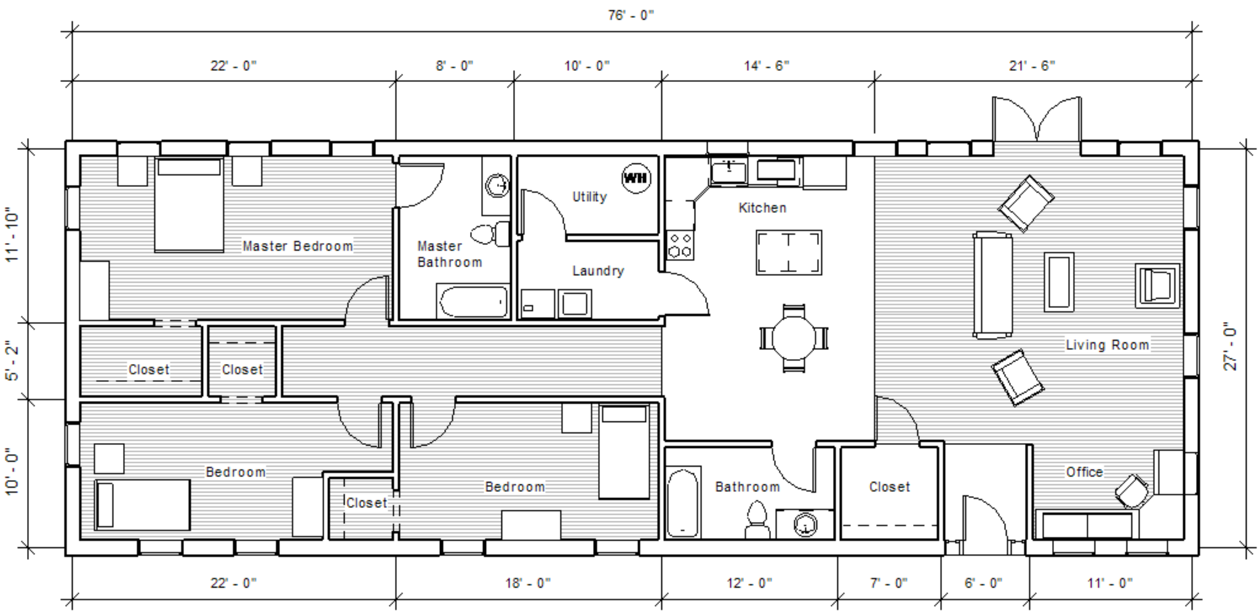

Figure 1: Modular home layout

The most prominent feature of the floor plan is the main living area, which is comprised of the kitchen, eating area, and living room. A large multipurpose common area is a desirable feature in modern homes, as it enables family members engaged in various activities to relax, reconnect, and take a break from their busy daily routine. The main entrance of the home opens into this space, making it an ideal setting for receiving guests and holding large group gatherings and social events. The kitchen and dining areas were combined into one space because, in modern homes, separate formal dining rooms are often wasted space. In this layout, the three functional spaces may be superficially separated from each other with finish work, such as furniture arrangement, wall finishes, and flooring material, rather than interior walls. There is extensive use of windows in this space to achieve as much natural lighting as possible to lower electricity consumption and to give the room an open and spacious feeling.

Connected to the common area of the home by a central hallway are the bedrooms. The master bedroom is located at the opposite end of the house from the living area to provide privacy and reduce noise. It is designed to have an area of about 250 square feet, which is within the typical range of 168 to 384 square feet. In addition to this area, attached are a master bathroom and walk-in closet, which have come to be expected features in modern homes. The full bathroom's 88 square feet of area is within the average range of a full bathroom which is 54 to 96 square feet (Room Sizes, 1999).

With the average American family having two children, two secondary bedrooms are designed so that each child gets their own room (U.S. Census, 2000). This type of arrangement is another expectation of modern homes. The bedrooms are designed to have an area of about 180 square feet, which is within the standard limits of 100 to 224 square feet. Each bedroom has its own closet space and is located across the central hallway from the full bathroom for convenience. The bathroom is situated in the center of the home so that it is also accessible from the living area for use by guests. Its 78 square feet of area fits within the typical range of a full bathroom which is 54 to 96 square feet (Room Sizes, 1999).

One feature of a modern home is an office area that serves as a workspace set aside from the rest of the house, but still connected so as to avoid isolation. As of 2007, 70 percent of households owned a computer, indicating that it is reasonable for a homeowner to expect a place to house this equipment (National Statistics, 2008). An office is also used as a space to organize and store a family's important personal and financial information and other documents.

The laundry room is located off of the kitchen to unify the 'working areas' of the home. It is large enough to fit a washing machine, dryer, and any required storage space. The adjacent mechanical room serves as a place to put systems like a water heater, which would normally be located beneath the living space in a basement.

The basement is one notable omission from the design. Though common in much of the United States, basements are often avoided in home construction in Southern California. Some reasons for this include the danger of collapse during an earthquake in this seismically active region and the high construction cost due to California's strict building codes (Sims, 2001). Deep foundations are also unnecessary in this region because the ground doesn't freeze, so there is no need to extend footings below the frost line to prevent heaving (Sims, 2001). Basements also present the risk of several health hazards that would be reduced in the home if it is simply constructed on a slab on grade. Some of these potential hazards include mold, mildew, and harmful pests (Minnesota, 2007).

Another recent trend in home design has been increasing the height of ceilings. Aesthetically, it creates a more spacious, airy feel in a home, and makes smaller homes feel larger. Though increasing ceiling height also adds to the amount of materials used in walls, studs, insulation and siding, it can raise a home's energy efficiency. Because warm air rises, in climates where cooling is the primary concern, like in Southern California, high ceilings can make economic sense. Therefore, in this home, ceilings are designed to be nine feet high, rather than the traditional standard of eight feet (Williams-Tracy, 2004). An exterior rendering of the Revit model can be seen in Figure 2.

Figure 2: Exterior rendering of modular home

Home Systems

Additional factors that can greatly increase a home's energy efficiency are the home systems that are incorporated. The proposed modular home is in Southern California, where temperatures during the summer months can get well above 100 degrees and dip down to cooler temperatures during the winter months. Water resources in this particular area also diminish faster than any other area in the United States due to high demand and extremely low amounts of rainfall. Keeping the area of Southern California in mind, proper home systems must be chosen in order to fit the building's needs, reduce harmful emissions, and protect the environment.

Home systems contribute to the environmental friendliness of the home in many ways. It is important to select heating and cooling systems that decrease energy consumption and expenses while also reducing the total harm to the environment. Some of the home systems included in the modular home are insulation, kitchen appliances, heating, cooling, and bathroom fixtures.

Insulation comes in many varieties and forms, and choosing an inadequate one could cost hundreds in heating and cooling costs. It is important to choose the correct insulation not only to reduce energy costs but also to reduce the harmful effects on the environment through the manufacturing process. The U.S. Department of Energy requires a specific R-value, which is a measure of thermal resistance, for new wood framed homes. The required R-Value for the California area is R-2.5 -5 for in home insulation (U.S. Department of Energy, 2009).

The insulation used for the modular home will be contained within the walls of structural insulated panels. The structural insulated panels will form the frame of the home and will be discussed in detail in the structural design section. The insulation sandwiched between the inner and outer walls is a rigid core of foam plastic insulation. This foam insulation is a major contributor to the overall "greenness" of the home, and consists of 98% air, and non-cfc blowing agents are used to set the foam in place. This type of foam insulation can provide high levels of thermal protection with and R-value ranging from R-14 to R-19 and is extremely airtight, reducing heating and cooling costs by up to 50% (Structural Insulated Panel Association, 2010). Because a major producer of greenhouse gases is the energy used to heat and cool a home and reduced emissions is a goal of this project, the installation of the structural insulated panels would reduce the impact this modular home has on the ecosystem.

While insulation helps with the heating throughout the cool winter months, other environmentally friendly components should be chosen for the home, since even small details can contribute to the overall energy efficiency. Windows, for instance, can make a sizeable impact on a home's energy consumption. Windows should be placed to take full advantage of the sunlight during the winter months and reduce passive solar gain during the summer months. High performance, energy efficient windows are widely available. Additionally, in order to cut back on air leakage, a glazing system can be applied to the window itself reducing heat loss, air leakage, condensation and improve comfort. This new innovative glazing system applies double or triple glazing and insulating gas between the panes (Ander, 2008).

To control the amount of light that enters the house, roof eaves can be used to shade out the sun in the summer, or to allow the lower angled winter sun to shine through. Southern California is an extremely hot and dry place during the summer with temperatures reaching well above one-hundred. Placement of windows can help reduce energy costs but, unfortunately, will not make a significant impact on cooling the home. Consequently, an air conditioning system is needed in order to provide a comfortable living environment. Air conditioners can be responsible for emitting up to 1.34 pounds of carbon dioxide for every kilowatt-hour used. Despite not being known for their energy saving abilities, new eco-friendly options have become available to reduce both monetary and environmental costs (Haworth, 2008).

One newer method for cooling the modular home is a rooftop pond. The idea behind this is to put six to twelve inches of water in a large plastic or fiberglass container covered by glazing. This container is placed on a recessed portion of the roof. A cover is placed over the water throughout the day allowing heat to rise from the home and collect in the solar pond. At night the cover is opened and the heat is then evaporated. The water cools down and the process begins again. The water cools significantly at night which allows cool air to descend into the home during the day (Calfinder Contractors, 2009). Earth Tubes work very similarly to the rooftop pond. Large circular metal tubes are placed in the ground at an average depth of about six feet. The idea is to circulate the warm air from the home down into the earth tube where it is considerably cooler. The air is then brought back into the home (US Department of Energy, 2008). Both of these ideas for cooling the home are very creative but unfortunately are not practical for this project. They are both significantly expensive and will add to the overall cost of the home, which is one thing we are trying to reduce.

Though both of these ideas are very innovative and environmentally friendly, their significant price tags and status as a new and relatively untested product make them impractical for this project. Therefore, the most viable option is an Energy Star air conditioning system. This type of air conditioner uses up to 14% less energy than standard cooling units and consequently saves the same amount on energy costs and pollution that a conventional air conditioner would generate (Energy Star, 2010). Energy Star heating will also be used throughout the home, though it wouldn't be needed for much of the year due to the region's mild winter temperatures.

Energy Star is a valuable resource for eco-friendly ideas for a home, especially in terms of kitchen appliances. The refrigerator is required by the United States Department of Energy to use 20% less energy than your standard refrigerator, saving the homeowner upwards of $165 during the lifetime of the appliance (Energy Star, 2010). All other appliances throughout the kitchen have the same specifications.

This particular modular home is designed to be located in Southern California, where water resources are in high demand and extremely limited. Water consumption in the region is unsustainable, and new water supply options can be extremely expensive and possibly unavailable altogether. Water conservation methods must be used in order to cut back on the amount of water consumed in the home. The modular home will be outfitted with water efficient water fixtures, which include ultra low-flow toilets, low-flow sinks, low-flow showerheads, and water-efficient dishwashers and washing machines. Because of the location of the home, landscaping will contain native plants that do not require a considerable amount of water, therefore eliminating the use of a sprinkler system. Through the implementation of these technologies and practices, water usage is greatly reduced (Bourg, 2009).

The amount of artificial lighting used throughout the home will be much lower than in a traditional home, partly due to the extent of natural lighting designed into the house. However, the light fixtures that will be used are to be fluorescent lamps, which are 3 to 5 times more efficient than the standard incandescent bulb and can last 10-20 times longer. These types of bulbs do however contain small amounts of mercury. However home based fluorescent bulbs are not legally considered hazardous waste according to federal solid waste rules, but it still important to dispose of a bulb properly. The proper way of doing this is to place the bulb in a sealed plastic bag and dispose just like you would with a car battery (Environmental Protection Agency, 2010). Electric lighting controls can also be utilized throughout the home. This system possesses such features as automatically dimming lights during peak demand periods or turning them off when not in use. This automatic system cuts back on the total amount of electricity consumed, subsequently reducing the total electricity bill (Nelson, 2009).

Table 1 below summarizes the elements that will be used throughout the home.

Table 1: Summary of home systems

Major Group Elements	Group Elements	Individual Elements
Interior	Lighting	Fluorescent lamps Automatic lighting system
	Cooling	Energy Star air conditioner
	Heating	Energy Star heating system
	Insulation	Structural insulated panels Foam Plastic
	Water fixtures	Low-flow water fixtures
	Appliances	Energy Star appliances
Exterior	Windows	Energy Star windows
	Roof overhangs	Sufficient to provide sunlight in the winter and limit access in the summer

Chapter 5: Construction Materials Testing

Testing of construction materials was performed in order to gain an understanding of the specimens' properties and behavior in failure. In the category of wood, Douglas fir, laminated veneer lumber, and wooden I-beams were tested. For concrete, different mix designs involving
the use of fly ash, blast furnace slag and silica fume were investigated. All materials had their qualitative benefits and drawbacks, but the tests completed on them provided quantitative data to aid in the process of choosing the correct material for the home's structural design.

Wood Testing

Wood is one of the most common building materials used in construction. Over the next several decades, wood consumption is expected to double, placing a huge strain on the world's already depleted forest resources (Edminster, 2008). Forests provide clean air, clean water, and crucial wildlife habitats. This high demand also translates into an effect on the quality of wood being used for construction. As wood becomes a scarcer resource, the quality declines, forcing builders to use wood that contains higher levels of imperfections, such as knots and warping. This makes the material more difficult to work with, so construction professionals have begun to turn to types of lumber that have more consistent properties and more reliable quality (Edminster, 2008).

Engineered lumber is a product that is fabricated by adhering wood strands, veneers, or other forms of wood fiber together to produce a larger composite unit. This unit is stronger and stiffer than its individual components and is often superior in strength and easier to install than traditional sawn lumber. It is also more dimensionally stable since it is manufactured using wood which is already dry, so the product does not warp or shrink. Engineered wood products are more environmentally friendly than sawn lumber, since large members can be made from small pieces of wood. In the past, to get a sawn piece of lumber or structural timber of significant size, a large tree that had taken decades to grow would have to be cut down. The components of engineered lumber can be harvested from much smaller trees in a sustainable manner, lowering the time that it takes a forest to recover drastically (Russelburg, 2006). In this project, the team performed testing on different types of engineered wood products, in addition to a traditional species of sawn lumber.

The first engineered product investigated, laminated veneer lumber, or LVL, is the composite of thin layers of wood glued together with a strong adhesive. The wood grain in all of the veneers runs parallel to the length of the beam. LVL has been shown to be stronger and more dimensionally stable than sawn beams of equivalent dimensions. Because an LVL beam consists of many layers of veneer, any defects in the wood will be confined to that one layer, reducing its impact on the strength of the member (Georgia Pacific LVL, 2008). LVL can accommodate a wide range of applications, including joists and girders in floor framing; columns, studs and beams in walls; and rafters in roof framing (Austin Energy, 2010).

The second engineered wood product was wooden I-beams. The I-beams tested were composed of solid sawn lumber flanges attached to an oriented strand board web. Because they are an engineered product, their tolerances for stability and strength are more precise than for sawn lumber, and these properties are more consistent throughout the span. Wood I-beams are most commonly used as floor joists and rafters in roof construction (Austin Energy, 2010). I-beams also require less material to achieve a desired strength, and the particular I-beams tested in this project use 45% to 70% less wood fiber than comparably sized traditional lumber joists. Due to their high strength, rafters or joists can be spaced further apart than ordinary lumber, saving material and installation costs (Georgia Pacific I-Beam, 2008).

In order to have a base for comparison, Douglas fir, one of the most common species of wood used in home construction, was also studied. Douglas fir is North America's most plentiful species of softwood. It also has the highest strength properties of any western softwood (WWPA, 1996). In addition, Douglas fir is also grown all along the U.S. west coast, making it locally available for a project in Southern California (Miller, 1999).

Wood specimens are tested in order to obtain data that can be compared with other data, either of the same species or a different one, and to establish the material's mechanical strengths to be used as design values. It is important to be able to determine, with confidence, that a certain species of wood will be able to meet the needs of a design.

Being able to intelligently select materials for construction enhances not only the safety, but also the economy of a construction project.

Laminated Veneer Lumber Test Results

The first test performed on the laminated veneer lumber was a three-point bending test. In this investigation, a simply-supported beam is subjected to a vertical load at midspan, which is allowed to increase until failure. During a three-point bending test, the beam experiences compressive, tensile, and shear forces at various locations along its span. In short beams, shear failure may occur, though the 12 foot span of the beams used in these tests was chosen so that this would not be a concern. Generally, a beam in bending is much more likely to fail initially in the compression zone (top of the beam where the load is being applied), and then the tension side (underside) of the beam experiences failure as the tensile strength is reached (Flaherty, 1998). Two beam sizes, four with a 1 ¾"x 11 ⅞" cross section and three with a 1 ¾"x 9 ½" cross section, were used in this assessment. The data collected consisted of load and deflection values, which were then used to calculate the average bending stress and strain for each size beam. The bending stress, or modulus of rupture, is an accepted measure of strength in wood specimens (Green, 1999).

The tensile strength of the LVL parallel to the grain was then tested, with the result based on the average strengths of three test specimens. Wood is an anisotropic material, meaning that its properties differ depending on the axis of loading. Because of this, the direction must be specified when identifying what strength property is being tested. The tensile specimens were cut from an LVL beam and machined to have a reduced section in order to control the location of failure.

Finally, the compressive strength of the LVL along two axes was assessed. The first was compression parallel to the grain, where a 1 ½"x 1 ½"x 6" specimen was loaded parallel to the length of the block until failure. In solid sawn pieces of wood, this type of failure is initiated by yielding of the structural fibers in the wood, causing wrinkling on the surface of the specimen. The second test was for compression perpendicular to the grain, where a 1 ½"x 1 ½"x 4" specimen was loaded perpendicular to its length. The goal of this test is to observe deformation, not failure (Flaherty, 1998).

The specimens tested were beams of GP Lam® GP 2.0E, which are manufactured by Georgia-Pacific Wood Products LLC. An APA product report, produced by the Engineered Wood Association, supplied published values of design properties for the specific product being tested (APA GP LVL, 2008). These design values can be seen in Table 2 alongside the values obtained during experimental testing. Full testing results for all wood specimens can be found in Appendix B.

Table 2: Average test values vs. APA product report design values for LVL

Laminated Veneer Lumber (GP 2.0E LVL)				
Property	Average Test Values (psi)		APA Product Report Design Values (psi)	
Bending Strength	1 ¾"x 9 ½"	1 ¾"x 11⅞"	1 ¾"x 9 ½"	1 ¾"x 11⅞"
	5522	6173	2987	2900
Tension Parallel to the Grain	7640		1825	
Compression Parallel to the Grain	9203		2600	
Compression Perpendicular to the Grain	6546		845	
Modulus of Elasticity	1.30×10^6		2.0×10^6	

The primary mode of failure in both sizes of LVL beams was by lateral torsional buckling, as can be seen in Figure 3. Lateral torsional buckling (LTB), occurs when beam deformation includes in-plane deformation (about the strong axis), out-of-plane deformation (about the weak axis), and twisting. This tendency for loading to cause lateral instability is influenced by loading and support conditions, member cross section, and the beam's unbraced length (American Wood Council, 2003). Load was applied to the beam at midspan through a metal plate that was welded to two additional vertical plates which acted to stabilize the beam. The ends of the beam were unbraced, allowing them to rotate.

Figure 3: Lateral torsional buckling in an 1 ¾"x 11⅞" LVL beam

LTB failure occurred in all but one of the LVL beams, and this one exception was observed to have defects before loading, so it will be discounted as an unusual case. For the remaining six specimens, LTB was observed as the mode of failure. As the beam was loaded and beginning to twist, the sound of layers delaminating was heard, though once the load was removed, the beam returned to its original shape without any signs of damage. Since the top of the beam was somewhat braced at midspan, the unbraced length can be taken to be approximately 6 feet in these tests.

The average test values for the bending strength are nearly double the expected values. This discrepancy can mostly be explained as a factor of safety imposed so that those using the lumber in practical applications do not risk allowing it to reach its actual capacity. These published design values also could have been obtained using a four-point bending test, which lowers the moment capacity of the beam, and therefore the bending strength. The test values can be seen plotted in Figure 4 with error bars that display the standard deviation of the test values for each beam size.

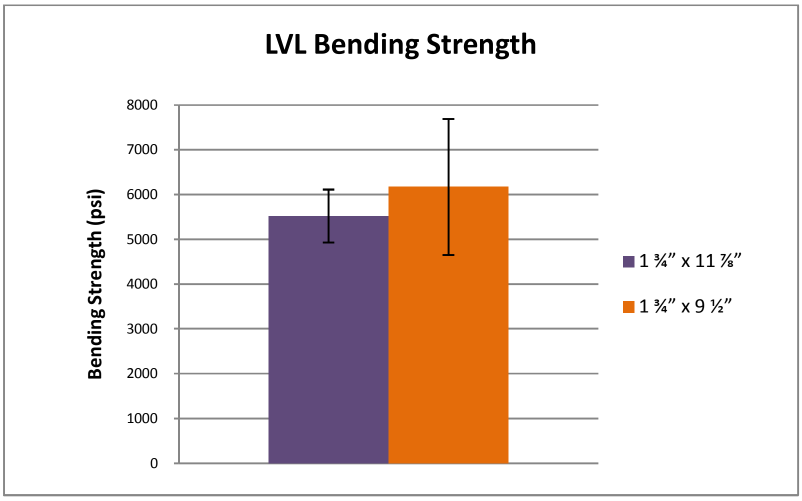

Figure 4: Bending Strength of LVL

When the wood fails in tension, it is the bonds in the wood fibers that break, not the glue that holds them together (Flaherty, 1998). LVL, however, is held together by both the natural glue within the wood of the veneers and the adhesive that bonds the veneer layers. When the LVL tensile bars failed, the layers of veneer delaminated, leaving long fractured layers of veneer (Figure 5). The tensile strength of the LVL test specimens was approximately four times the value predicted by the APA product report. This could be explained by the fact that design values for the tensile strength parallel to the grain are typically given to be much lower than the actual tensile strength. This is done because, though tensile strength in clear, straight-grained wood is the strongest property of the specimen, variables and imperfections such as knots and the slope of the grain must be taken into account to give a more realistic expectation for possible fracture (Flaherty, 1998).

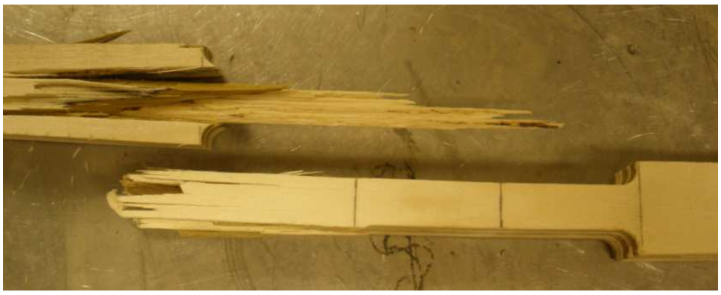

Figure 5: Typical failure pattern in an LVL tensile specimen

The manner of failure for the compression parallel to the grain specimens was similar to the expected behavior of sawn lumber, with layers of veneer wrinkling outward, which can be seen in Figure 6. The sample mainly failed along the glue lines between layers of veneer, which was anticipated to be the weak point in the specimen. The calculated compressive strength was over three times as large as the expected strength given by the product report design values, which could be explained as a factor of safety built into the published values.

Figure 6: Typical failure in compression parallel to the grain of an LVL specimen

In the test of compressive strength perpendicular to the grain, failure did not occur because the goal was to only achieve a deformation of 0.1 inches. Based on the test results, the compressive strength perpendicular to the grain of the LVL was over seven times larger than the anticipated value, which could, once again, be attributed to a built-in factor of safety.

Modulus of elasticity, calculated as the slope of the elastic (linear) portion of a stress-strain graph, indicates the wood's tendency to experience non-permanent deformation when subjected to a load. The higher the modulus of elasticity, the more resistant a material is to deformation. The calculated value for modulus of elasticity was lower than the published value by approximately 700,000 psi.

Wooden I-Beam Test Results

The only test performed on the wooden I-beams was a three-point bending test. Compression and tensile tests would have been impractical since the beam is not made of one consistent material and does not have a rectangular cross section from which to cut samples. The APA product report also gave design values for bending moment, rather than bending strength, so the former was calculated from the test results to allow for comparison. The test results can be seen along the APA design values in Table 3 (APA GP I-Beam, 2008).

Table 3: Average test values vs. APA product report design values for I-beam

Wooden I-Beam (GPI 40)				
Property	Average Test Values		APA Product Report Design Values	
Maximum Bending Moment (ft-lb)	1 ¾"x 9 ½"	1 ¾"x 11⅞"	1 ¾"x 9 ½"	1 ¾"x 11⅞"
	10855	9310	3090	3990
Modulus of Elasticity (psi)	3.22×10^6	2.18×10^6	2.99×10^6	2.56×10^6

The calculated bending moment of both wooden I-beams was about three times greater than the APA values. This discrepancy could be attributed to a built-in factor of safety, or the grade of lumber may have been different for the two separate design values. The test values can be seen plotted in Figure 7 with error bars that display the standard deviation of the test values for each beam size. The modulus of elasticity for both beam sizes was reasonably close to the expected values.

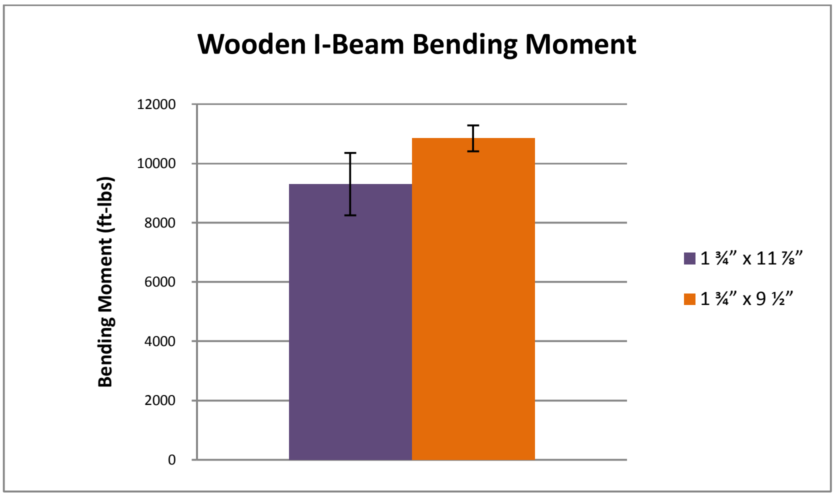

Figure 7: Bending strengths of wooden I-beam

The primary mode of failure was lateral torsional buckling, as was the case with the LVL beams. In two of the 1 ¾"x 11⅞" beams, failure occurred when the sheets of oriented strand board in the web split along the glued vertical seams connecting each sheet. In both cases, this failure occurred within 2 feet of the end support, and the resulting bending moment values do not differ greatly for the others which failed due to LTB. Since the other 1 ¾"x 11⅞" beam failed by LTB, it can be assumed that these two exceptions would have done the same had there not been a weak bond in the web. Therefore, if an I-beam is expected to experience loads that would produce a bending moment anywhere near those resulting in these tests, considerations should be made regarding the unbraced length of the beam and attention paid to the quality of glued seams in the web.

Douglas Fir Test Results

Douglas fir was chosen as the conventional type of structural wood to be tested. Three 2"x 4" beams and four 4"x 6" beams were tested in three-point bending and several specimens were tested for compressive strength both parallel and perpendicular to the grain. Results are shown alongside published design values in Table 4 (Green, 1999).

Table 4: Average test values vs. published design values for Douglas fir

Douglas Fir			
Property	Average Test Values (psi)		APA Product Report Design Values (psi)
Bending Strength	2”x 4”	4”x 6”	12800
	6852	7453	
Compression Parallel to the Grain	6913		7260
Compression Perpendicular to the Grain	2793		870
Modulus of Elasticity	1.33×10^6		1.97×10^6

In bending, the manner of failure was sudden failure in the tension region at approximately midspan of the 10 foot beams (Figure 8). The test values can be seen plotted in Figure 9 with error bars that display the standard deviation of the test values for each beam size. There were two exceptions to this trend however: two of the 4”x 6” beams cracked, not in the tension region, but horizontally through knots that were located near the center of the span. These, consequently, were the two 4”x 6” beams with the lowest bending strength. Nonetheless, the bending strength of both the 2”x 4” and the 4”x 6” beams was significantly lower than the values published by the U.S. Forest Products Laboratory. Once again, a different grade of lumber may have been used, so if a higher grade was used in the testing that yielded the published data, those values would be higher.

Figure 8: Typical bending failure in a Douglas fir 2"x 4" beam

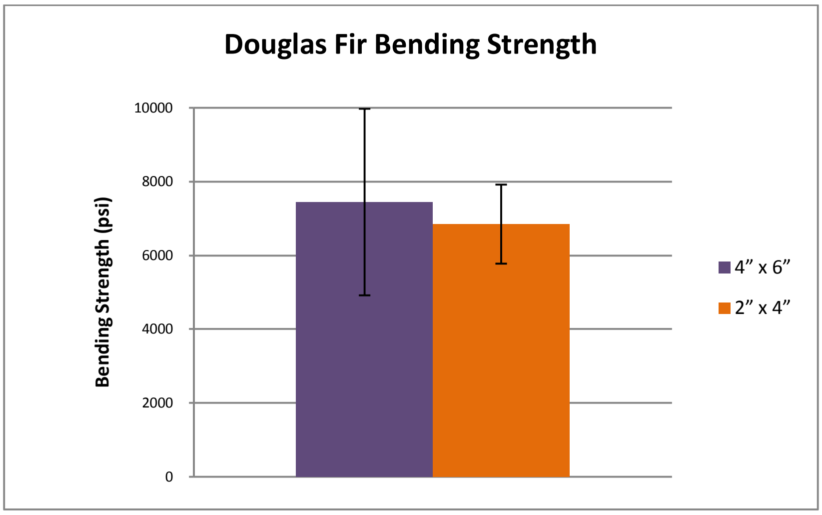

Figure 9: Bending strength of Douglas fir

In the test for compressive strength parallel to the grain, the specimens failed in the expected manner of sawn lumber, with layers of veneer wrinkling outward as the structural fibers of the wood yielded. The test values for this strength were very close to the value anticipated by the published data.

For the compression perpendicular to the grain, once again, the goal of the test was to achieve a deformation of 0.1 inches, rather than failure of the specimen. The stress required to achieve this deformation was over three times as large as the recognized value. In tests such as compression where the specimens are so small, the grade of lumber may not matter because clear test specimens can be readily chosen. Therefore, the higher test value would be reduced by a factor of safety imposed for practical design applications.

Concrete Testing

Concrete is an exceedingly popular material that is used to some extent in practically every modern construction project, with nearly 10 billion tons of it produced worldwide every year (Meyer, 2009). It is also a very energy-intensive product to create, and therefore has an incredibly large carbon footprint. Cement manufacturing facilities alone produce 5% of all carbon dioxide emissions resulting directly from human activities (Habert, 2009). Studies have shown that cement fabrication is the process which is responsible for over 80% of the carbon dioxide emissions attributed to concrete (Habert, 2009). Therefore, if concrete is to be made more environmentally friendly, incorporating an alternative to Portland cement into the mix design would be the most effective strategy.

Three different supplementary cementitious materials were investigated as potential partial replacements to cement. The first was fly ash, which is a byproduct of coal combustion. As its name indicates, fly ash refers to the small particles of ash that are captured by the scrubbers in power plant smokestacks. Normally, this ash would have to be disposed of in a landfill at great cost to the power plant (Meyer, 2009). Therefore, even though burning coal is an environmentally harmful practice, if it has to be done, this resource consumption ought to be made as efficient as possible by using even the waste products. This diverts material from the waste stream and helps to cut back on the consumption of another harmful product, cement.

In a typical hydration reaction with Portland cement, tricalcium silicate reacts with water to form calcium silicate hydrate (C-S-H) and calcium hydroxide. C-S-H is the desired cementitious product of the reaction, with calcium hydroxide being a relatively useless product. Fly ash is a pozzolan, which is a siliceous material that will react with calcium hydroxide in the presence of moisture to form a cementitious material. This makes the hydration more efficient and produces a stronger paste (Kosmatka, 2002). Thus, concrete produced with fly ash can have enhanced strength and durability properties versus concrete made with just Portland cement. It also has a lower heat of hydration, which is beneficial in large scale projects. Fly ash is also available wherever coal is burnt and is generally less expensive than Portland cement. On the down side, fly ash concrete gains strength slower than normal concrete, though admixtures are available to speed up the hydration process if necessary. Fly ash also has the problem of quality control, with the physical and chemical properties varying greatly depending on the power plant it came from and the source of the coal. However, the fly ash industry has recently developed quality control measures to reduce the variability of properties (Meyer, 2009).

The second potential supplement to cement that was investigated was ground granulated blast furnace slag. Slag, also a pozzolan, is a byproduct of steel manufacturing and is formed when molten blast furnace slag is rapidly chilled. Blast furnace slag, like fly ash, has beneficial effects on concrete strength, durability, and lowers the heat of hydration of the concrete. Generally, the unit cost of slag is about equal to that of Portland cement, and oftentimes its environmental benefit tip the scales in its favor. Slag is also a waste material, which would otherwise be deposited in a landfill or used as road base in construction projects. These disposal techniques are environmentally harmful because slag contains toxic metals that could seep into groundwater supplies. When used in concrete, however, these harmful materials are trapped and safely incorporated into the products of the chemical hydration process (Meyer, 2009).

The final pozzolan used was silica fume, which is a byproduct of producing silicon metals and alloys. To manufacture these metals, quartz, coal, and wood are burned in an electric furnace and the resulting smoke, which is the silica fume, is collected. Silica fume predominantly consists of particles of amorphous silica dioxide, which are much smaller than cement particles. This gives a large surface area, which along with the high silica dioxide content, makes it a very reactive pozzolan (Silica Fume Association, 2007). It adds exceptional strength and durability to concrete; so much so that it is used extensively in nearly all high performance concrete mixes (Meyer, 2009).

Eight concrete mixes were designed based around the percent of Portland cement to be replaced by one of the supplementary cementitious materials and can be seen in Appendix C. Three mixes were prepared for fly ash and silica fume, each with 15%, 25%, and 35% substitution. Due to material shortages, only two mixes using blast furnace slag were done, with 25% and 35% substitution. Each mix produced four cylinders of 6 inch diameter by 12 inch height. Three cylinders from each mix were tested in compression and one in tension. Full results of these tests can be found in Appendix D.

Fly Ash Concrete Test Results

The first test performed on the 6 inch by 12 inch cylinders was a compression test. The 15% and 25% concrete cylinders had been allowed to cure for 72 days and the 35% for 73 days. During this investigation load was applied evenly to the upright cylinder over its 6 inch diameter base until failure occurred. From the load and deformation data collected by the testing machine, the compressive strength of the concrete cylinders was calculated and averaged for the three cylinders of each mix of different percent substitution of fly ash.

In order to obtain the tensile strength of the concrete, a split tensile test was performed on one cylinder of each mix design. Tensile strength in concrete is low compared to its compressive strength. Load was applied uniformly along a metal plate which was placed on top of the cylinder laid its side. The results of the compression and split tensile tests can be seen in Table 5 for each mix design for fly ash concrete. The compression test values can be seen plotted in Figure 10 with error bars that display the standard deviation of the test values for each mix design.

Table 5: Compressive and tensile strengths of concrete with 15%, 25%, and 35% replacement of Portland cement with fly ash

Fly Ash			
(units of psi)	15% (72 day)	25% (72 day)	35% (73 day)
σ_{c1}	5240	5926	5392
σ_{c2}	5444	5893	5682
σ_{c3}	5217	5408	5677
$\sigma_{c\ AVE.}$	5300	5742	5584
σ_t	399	437	395

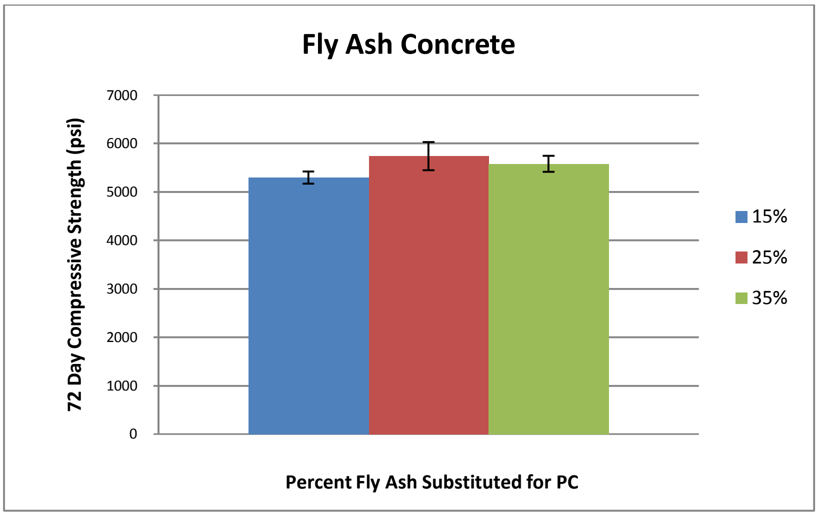

Figure 10: Compressive strength of fly ash concrete

According to the data, the 25% fly ash substitution mix appeared to perform best in both compressive and tensile strength, and a visual representation of this data can be seen in Figure 6. However, by statistically analyzing the data using a t-test, the 25% fly ash mix was shown to not be significantly stronger than the 35% fly ash mix, though it was significantly stronger than the 15% fly ash concrete. A t-test only indicates whether or not the null hypothesis (that the means of the two data sets are equal) can be rejected, not whether it is proven. In the case of the 25% versus the 35% fly ash concretes, it cannot be rejected, though it is not proven that they are equal. In order to be more confident in that conclusion, a larger data set would be needed.

All of the fly ash specimens failed splitting cleanly with small amounts of crumbling. Most often, pieces representing less than half of the cylinder broke off of the sides; however, there were several cases of the cylinder splitting diagonally from top to bottom (Figure 11). A loud pop was heard when the cylinders failed, indicating that the failure occurred mainly through the aggregate, which would mean that the mortar was the stronger component of the two.

Figure 11: Compression failure in a fly ash concrete cylinder

Blast Furnace Slag Concrete Test Results

Compression and tensile tests were performed in the same manner as for the fly ash concrete mix designs. However, slag concrete mixes were only completed for 25% and 35% substitution. Compression tests were still done on three cylinders and a split tensile test on one. The results of these tests can be seen in Table 6.

Table 6: Compressive and tensile strengths of concrete with 25% and 35% replacement of Portland cement with slag

Blast Furnace Slag		
(units of psi)	25% (73 day)	35% (73 day)
σ_{c1}	5736	6203
σ_{c2}	8627 (not included in average)	6044
σ_{c3}	6035	5885
$\sigma_{c\ AVE.}$	5886	6044
σ_t	382	415

The average compressive strength of the 25% slag mix does not include the value for cylinder 2, due to the fact that it is perceived to be an outlier. It is difficult to statistically determine whether or not a number is an outlier when the data set only contains three values, so it was determined that the compressive strength for the 25% cylinder 2 is an outlier because it is greater than one standard deviation from the mean of the three values. Excluding this value, a t-test indicates that the 35% slag substitution mix is not significantly stronger in compression than the 25% mix. The compression test values can be seen plotted in Figure 12 with error bars that display the standard deviation of the test values for each mix design.

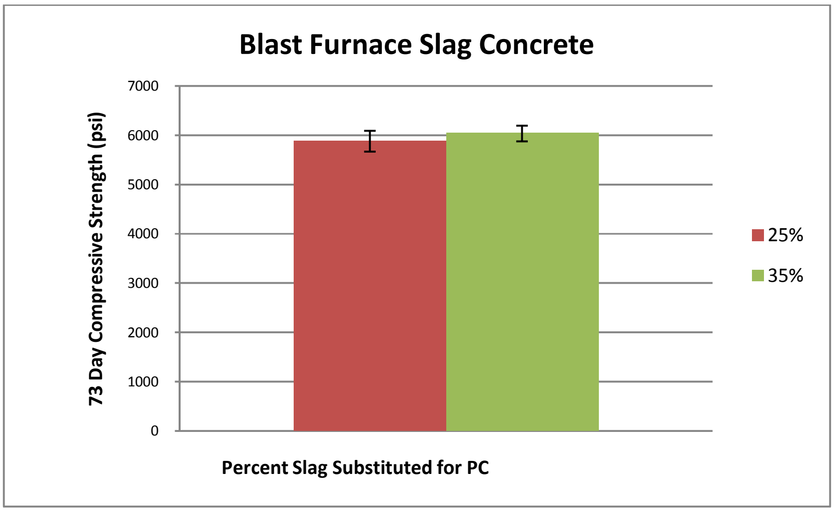

Figure 12: Compressive strengths of blast furnace slag concrete

Failure of the slag cylinders was in a similar manner to the fly ash cylinders. A loud pop was also heard when the cylinders failed, indicating that the failure occurred mainly through the aggregate, which would mean that the paste was the stronger component of the two.

Silica Fume Concrete Test Results

Compression and tensile tests were performed in the same manner as for the fly ash concrete mix designs. Compression tests were done on three cylinders and a split tensile test on one. The results of these tests can be seen in Table 7.

Table 7: Compressive and tensile strengths of concrete with 15%, 25%, and 35% replacement of Portland cement with silica fume

Silica Fume			
(units of psi)	15% (74 day)	25% (74 day)	35% (74 day)
σ_{c1}	4694	3819	3387
σ_{c2}	4572	3735	3528
σ_{c3}	4700	3561	3303
$\sigma_{c\,AVE.}$	4655	3712	3406
σ_t	335	289	-----*

The tensile strength of the 35% silica fume mix was not recorded due to a machine malfunction. Even without this value, the data indicates that the 15% silica fume substitution mix is stronger in compression than both the 25% and 35% mixes, and stronger in tension than the 25% mix. According to a statistical t-test, the average compressive strengths of the three mixes are significantly different, so the 15% silica fume mix can be considered the strongest of the three. The compression test values can be seen plotted in Figure 13 with error bars that display the standard deviation of the test values for each mix design.

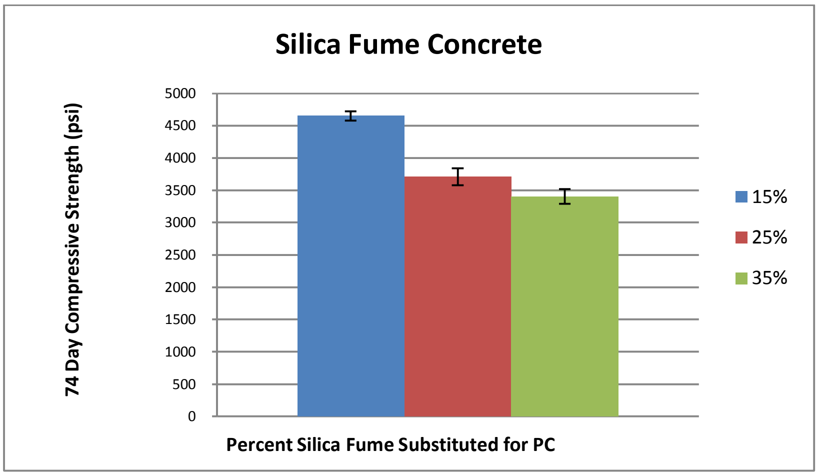

Figure 13: Compressive strength of silica fume concrete

Failure of the silica fume concrete cylinders was different from that of the fly ash and slag. Once the concrete reached the maximum load, it quietly crumbled into small pieces, indicating that the paste was the weaker component instead of the aggregate (Figure 14).

Figure 14: Compression failure in a silica fume concrete cylinder

Materials Selection

The choice of materials for the design of the modular house was based, not only on strength, but also on environmental impact and other qualitative factors. The three options for wood were laminated veneer lumber, wooden I-beams, and Douglas fir. Douglas fir was tested in order to be used as a base case for comparison with the two engineered types of lumber. Since it is a conventional building material that does not possess significant environmentally redeeming qualities, it was not considered for design.

The 1 ¾"x 9 ½" LVL beam was chosen to be used in the design of the floor and roof structure. The LVL beam with a 1 ¾"x 11 ⅞" cross section was not only larger and more expensive, but it provided less bending strength. When compared with the I-beams, the LVL beams are inferior in strength and cost twice as much. Values for the bending strength per dollar are shown in Table 8. However, the LVL was chosen because of its lower modulus of elasticity, giving it a greater capacity to deform and flex in response to earthquake loads, which is a major concern is Southern California.

Table 8: Bending strength per unit cost

	Span	Cost/Beam	Average Bending Strength	Strength/$1.00
LVL 1 ¾" x 11⅞"	12'	$58.89	5521.61 psi	93.76 psi/$
LVL 1 ¾" x 9 ½"	12'	$48.44	6173.43 psi	127.44 psi/$
I Beam 1 ¾" x 11⅞"	12'	$20.54	4486.02 psi	218.40 psi/$
I Beam 1 ¾" x 9 ½"	12'	$19.67	7961.17 psi	404.74 psi/$
DF 2" x 4"	10'	$2.38	6851.78 psi	2878.90 psi/$
DF 4" x 6"	10'	$20.89	7452.93 psi	356.77 psi/$

The silica fume mixes were disqualified from consideration due to their poor performance in compressive and tensile strength tests compared with the fly ash and slag mixes. Though the 35% blast furnace slag mix was significantly stronger than the fly ash concrete, it was not selected because it exhibited substantial workability issues when it was mixed and molded. Its superior strength was not judged to be an important enough factor to overcome the difficulty that would be added to placing the concrete during construction.

35% fly ash concrete was chosen to be used for the concrete foundation of the house, which includes footings, foundation walls, and a slab. This mix design was workable during mixing and molding and demonstrated higher compressive and tensile strengths in than the 15% fly ash mix. Though the 25% fly ash mix appeared to be stronger, statistical analysis did not indicate that its compressive strength was significantly larger than the 35% mix's. Therefore, because it replaces a larger quantity of Portland cement and shared the distinction of being the strongest fly ash mix, the 35% mix was chosen.

Chapter 6: Structural Design

The common factor throughout the design process of this home was to ensure that it incorporated environmentally friendly products and practices. A major project goal was to design the home to have as little impact on the environment as was feasible, as well as reduce energy consumption. Materials and resources must also be conserved throughout construction in order for the home to be considered eco-friendly. This particular structural design kept in mind that the home must produce a healthy indoor environment which means it must be mold and pollutant free with large open spaces to allow for extensive natural lighting. The structure was designed with these factors in mind.

Structural Loading

The first step in designing the structure was to determine the dead and live loads acting upon it. The dead load included the weights of the materials permanently attached to the structure, which comprise the roof and floor covering, framing, insulation, sheathing, and any other permanent materials. The weight of the in-home systems is also considered when determining the dead load. Roof and floor dead loads are calculated separately and are then applied to the tributary width of a structural member. The tributary width of the member can be defined as the distance from midpoint of the beam spacing on one side to midway of the beam spacing on the other of the beam being evaluated. Live load on the other hand can change over time. It can be evaluated as the loads associated with maintenance of the roof, wind loads, and earthquake loads. Like the dead loads, live loads are applied to the tributary width of the member being analyzed. Once all loads are considered and applied to the structure, the design can begin. Calculations for dead and live loads can be found in Appendix E.

The design of the structure is different and quite unique compared to traditional homes. Stick-built homes are designed as one entire structure, while a modular home is designed as separate pieces. For this particular design, the modular home was broken down into four separate structures so that it can be transported from the factory to the site (Figure 15). Splitting the home along the center wall makes the on-site assembly process easier. Each of the four pieces will act as separate structures until they are assembled.

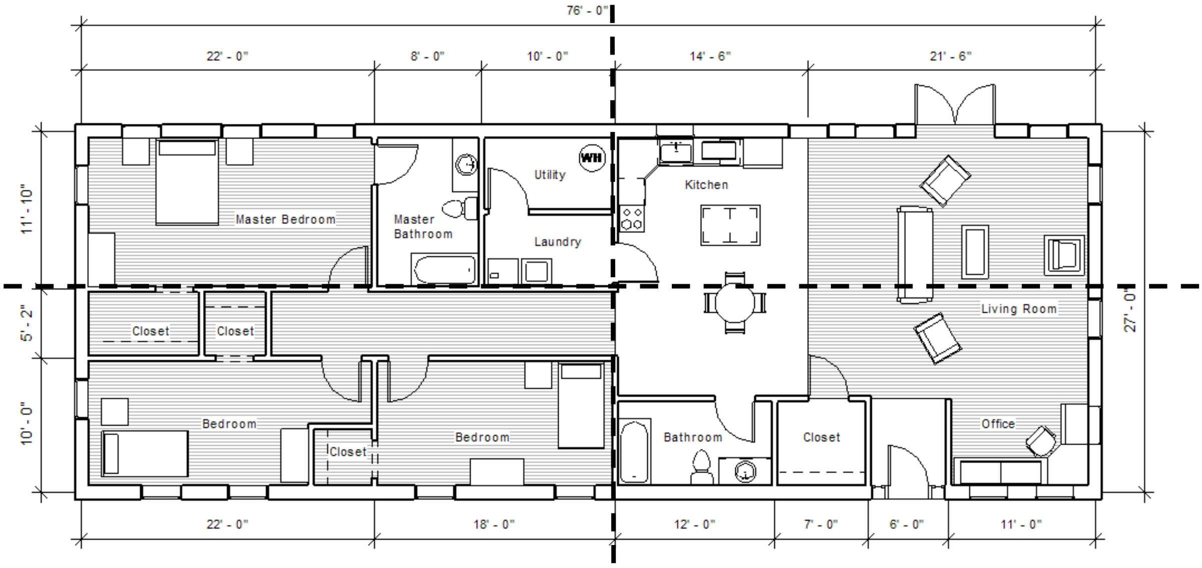

Figure 15: Dissection of modular home

Foundation Design

Before the sections can be placed on the site, a foundation must first be poured and set in place. The design for the foundation, as shown in Figure 16, uses the 35% fly ash concrete mix, which is both low cost and eco-friendly. The fly ash concrete had a compressive strength of about 5600 psi, which is more than adequate for this type of project. The main benefit of fly ash, compared with Portland cement, is that it reduces the amount of non-durable calcium hydroxide and instead converts it to calcium silicate hydrate. The calcium silicate hydrate is considered to be the strongest portion of the cement paste. Concrete produced with fly ash will typically be lower in strength at the 28-day cure time than typical concrete mixtures. However, after a year's time, the fly ash concrete with fly ash is significantly stronger than conventional concrete. The unit weight of fly ash is also much greater than that of typical concrete, therefore increasing the workability and making it easier to pump because it's a heavier mixture. This will reduce the amount of time trucks spend on site. The use of fly ash in the foundation and footings significantly reduces the depletion of natural resources while conserving landfill space (Headwaters Resources, 2005).

The width of the footing was determined to be four feet wide with three number four bars running the length of the footing (see calculations in Appendix F). Number five bars spaced at 6 ½ inches on center will also run the length of the footing perpendicular to the number four bars. The reinforcement bars, or rebar, are used in order to give the concrete a higher flexural strength. Concrete is extremely strong in compression but weak in tension, so the reinforcement bars are cast into the concrete to carry the tension loads.

The foundation wall is 27 inches tall with a width of 12 inches. This height allows for a crawl space beneath the home. If flooding occurs, though it is extremely rare in Southern California, the home will be elevated rather than sitting directly on a slab. Square footings also run down the spine of the home and are spaced evenly as shown in Figure 17. The purpose of the square footing is to support the girders that run down the spine of the home. This footing consists of five number three bars, running in each direction within the footing.

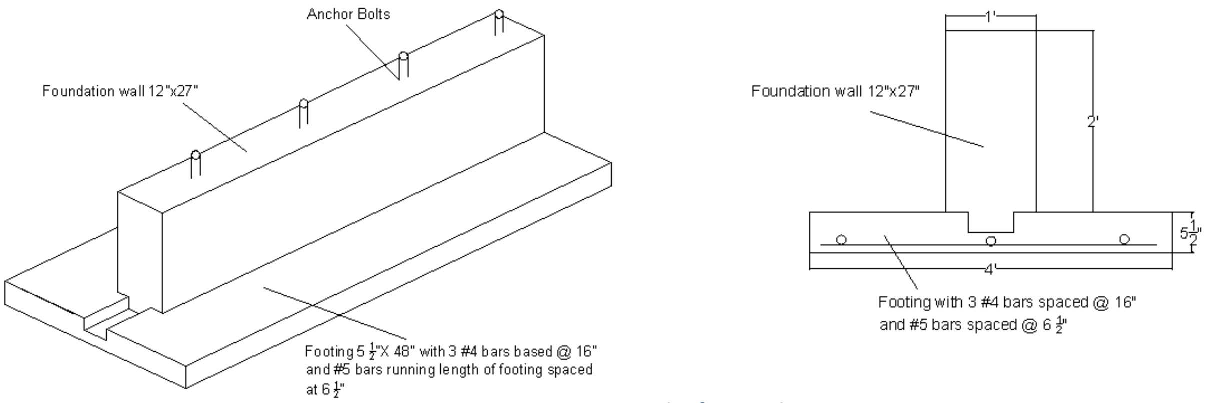

Figure 16: Rectangular footing design

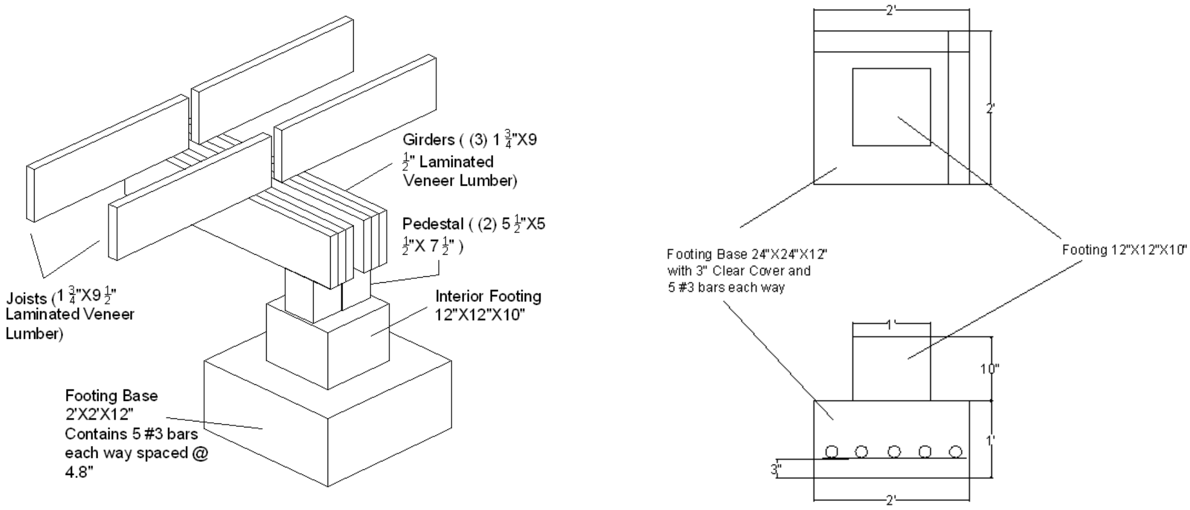

Figure 17: Square footing design

Floor Design

When assembled, each module rests on the exterior foundation as well as one of the interior footings. Each module connects securely to the others, creating a tight, energy saving seal. Figure 18 shows how a typical module connects to the foundation wall and footings. The floor joists of the home consist of 1 ¾"x 9 ½" laminated veneer lumber beams at a length that is precut to the length of the given module. From testing observations, it was noticed that the LVL beams were very flexible, and therefore able to absorb large amounts of energy. This would be beneficial during an event such as an earthquake, which is a concern in this region. The subflooring consists of 1 ½" thick plywood.

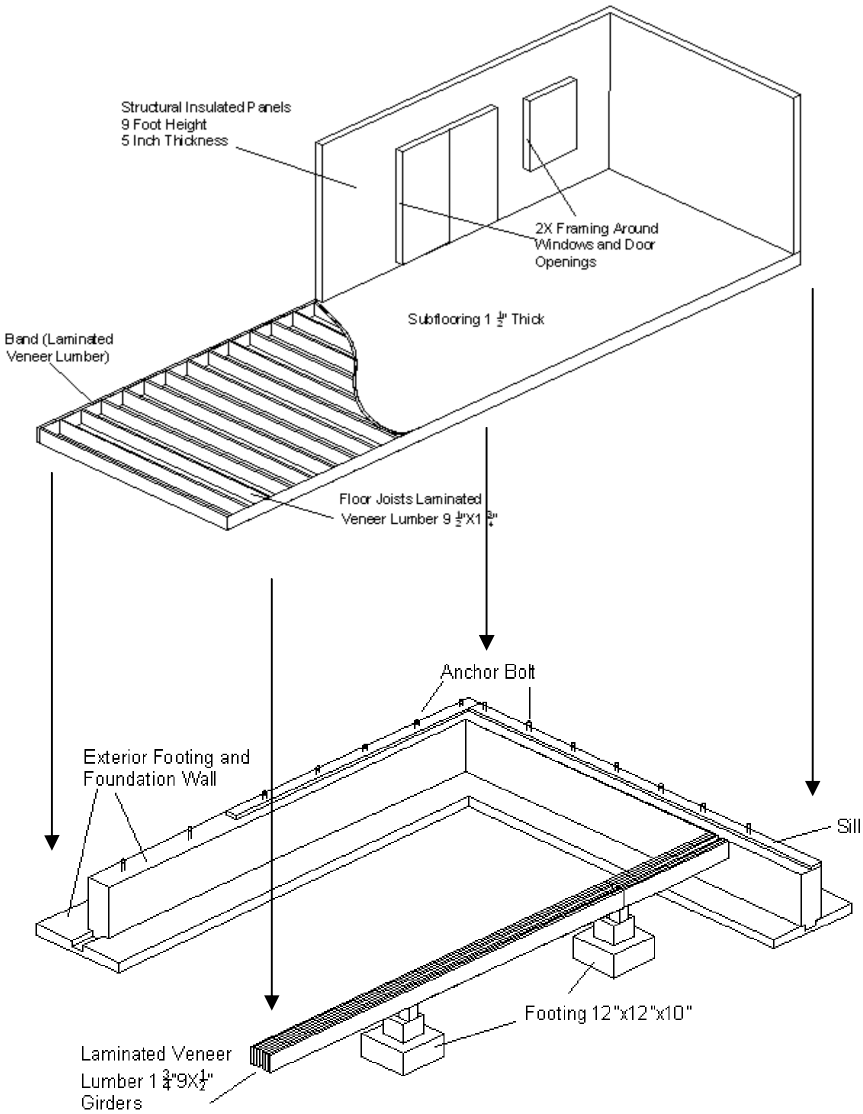

Figure 18: Floor plan and footing design

Wall Design

The walls of the home are built from structural insulated panels, which are high performance building materials comprised of a rigid core of foam plastic insulation sandwiched between two sheets of plywood. These customizable engineered panels can be used as the walls of the home and are produced and manufactured in a controlled setting. Structural insulated panels are as strong, if not stronger, than a typical stick-built wall and are considered to be very energy efficient. Generally, homes built with structural insulated panels are constructed at a faster rate than traditional stick built homes due to the fact that installation requires fewer materials and less labor, which also saves money. An entire wall can be erected very quickly which reduces the dry-in time of the wall. Further reducing construction times are the precut door and window openings.

Structural insulated panels are also considered to be one of the most environmentally friendly building materials in construction. The foam between the panels is a major contributor to the overall "greenness" of the system. The foam is a rigid foam plastic consisting of 98% air and is set in place with a non-cfc blowing agent. This type of insulation provides high levels on protection and is extremely airtight, reducing heating and cooling costs by approximately 50%. Structural insulated panels also meet fire safety requirements, and can even be manufactured to greatly exceed the minimum required fire resistance. This is an important quality for a building located in Southern California, since this region is very prone to wildfires. In addition to their energy saving and fire safety qualities, these panels have also been shown to be quite structurally sound. Significant testing has been done on them and experts have found that their structural capacity is comparable to that of a steel I-beam. They also stand alone, reducing the amount of additional framing and therefore, total material (Structural Insulated Panel Association).

Below, in Figure 19, are examples from the Structural Insulated Panel Association of typical details for fastening a structural insulated panel to the floor and then to the foundation wall. A treated sill plate is fastened to the foundation with an anchor bolt, which is further driven through to the floor joist. A wooden band is nailed to the outside of the floor joist to protect it from the elements. The structural insulated panel is then nailed directly to the top of the floor joist. The interior walls of the home are also constructed with the structural insulated panels, which provide support for the roofing system. Panels can be cut to size and interlocked at various points to obtain a single wall structure as shown in Figure 19 (Structural Insulated Panels Association, 2010).

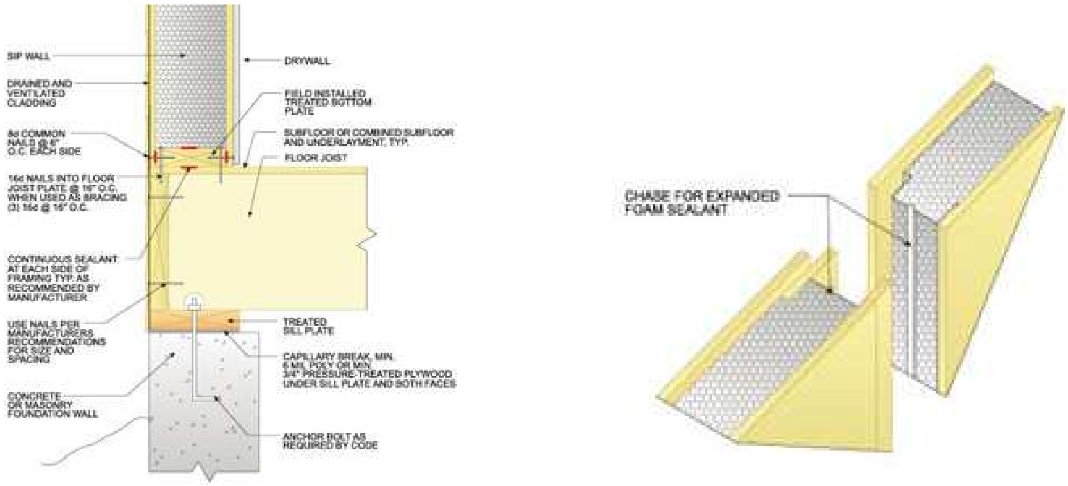

Figure 19: Structural insulated panels

A unique feature of structural insulated panels is the width options that they are available in. More insulation is provided in thicker walls, therefore increasing the R-value of the wall. For this particular design the wall will be five inches thick, which will provide an R-value of around 14. Extensive testing has been done on structural insulated panels, and a panel with an R-value of 14 was shown to outperform 2"x 6" wall with R-19 fiberglass insulation (Structural Insulated Panel Association, 2010).

Roof Design

The final step in the structural design of the home is the roof. Two different styles of roofing were considered during the design process, which were sloped and flat. Both have their advantages and disadvantages but a flat roof design proved to be the superior. It not only reduces the amount of material needed for the roof, therefore saving money, but it is also more easily accessible for repairs or the possible future installation of solar panels or a green roof. The flat roof design shown in Figure 20 sits directly on top of the structural insulated panels. The rafters consist of 1 ¾"x 9 ½" laminated veneer lumber spaced 16 inches O.C., and the trimmer is two of the same size laminated veneer lumber. Plywood and shingles would then be nailed to the top of the roof structure, finishing off the design.

Because this is a modular home, the roof structure is also separated into four modules. Each roof segment is attached to a specific module and assembled on site.

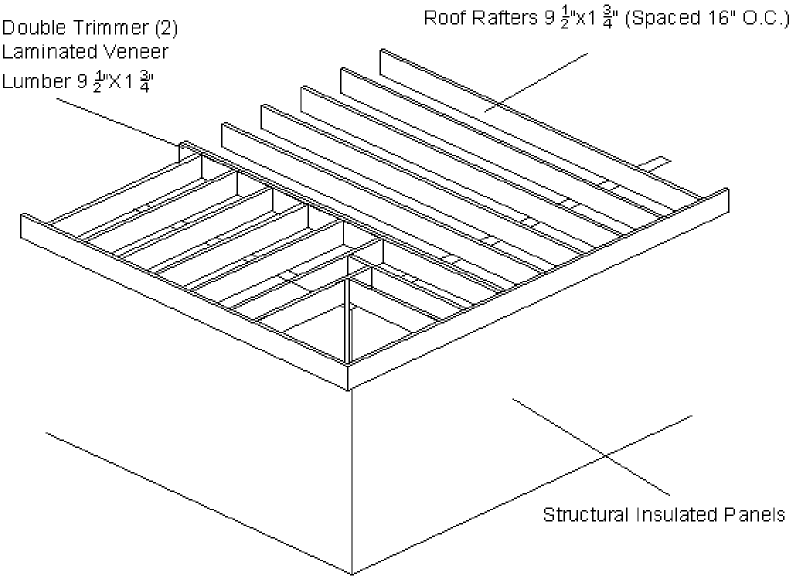

Figure 20: Roof design

One of the main concerns when designing the roof was the length of the overhang. The home should take advantage of passive solar heating during the winter months, but the amount of sunlight and heat entering the home should be reduced during the summer. The angle of sunlight must be determined in order to design for the roof overhang. The number of heating degree days, which is how many days the outside air temperature dips below a certain level, must first be calculated. A useful tool, called degreedays.net (DegreeDays.net, 2010), was used in order to determine the number of heating degree days that occur in Southern California. Using the output data, it was determined that there are approximately 1285 heating degree days that occur in Southern California. This information helped to determine that, in order to find the sun angle, the shadow line at the window sill occurring on the summer solstice, must be located (U.S. Department of Energy, 2009). Using a tool called sundesign.com the coordinates of the location are input, along with the date of the summer solstice, elevation and time (Gronbeck, 2009). In this case, the location was Southern California, or to be more specific San Diego and the date was June 21.

The resulting output is the sun angle, which is also known as the altitude angle. For this particular location the input data yielded a sun angle of 80.69°, which is shown in Figure 21. With this critical angle, the amount of overhang needed on the structure could be determined. This was calculated to be approximately three feet of overhang in order to provide the home with sufficient sunlight in the winter while decreasing the amount of sunlight and heat in the summer.

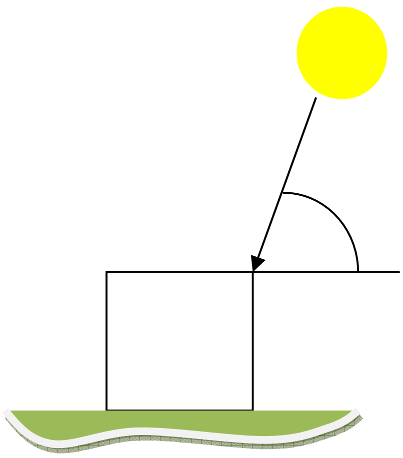

Figure 22: Sun Angle

Another concern with the structure of the roof was that it must span the entire width of the living room. Once the modules are assembled the roof would be at a length of twenty seven feet with no support. Therefore, a Douglas fir column should be erected at the center of the living room to provide support for a girder that runs the length of the room. The girder is to be constructed from two LVL beams dimensioned at 1 ¾"x 9 ½", as shown in Figure 22. The roof lies directly on top of this girder and transfers loads to the girder below.

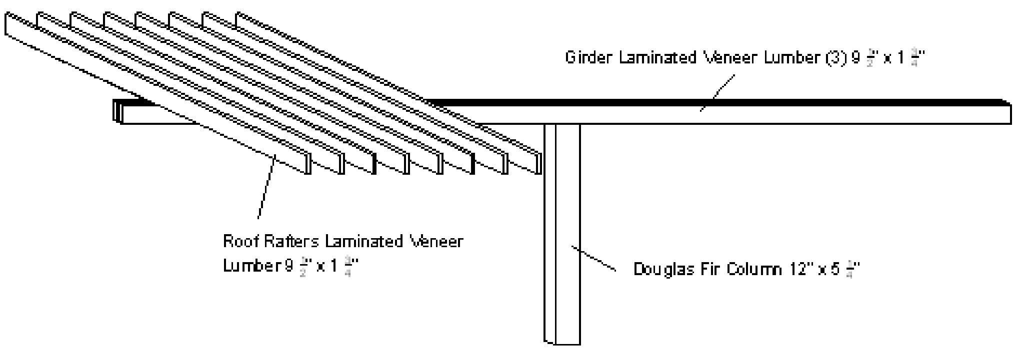

Figure 21: Living room roof support

Table 9 gives a breakdown of the elements in the structure, the material and dimensions used for that element and the details on why that material was chosen for that specific part of the structure. Following that is Table 10 which shows what type of fasteners will be used to provide proper shear strength on various parts of the structure.

Table 9: Structural elements

Element	Specifications	Details
Rectangular Footing/ Foundation wall	35% Fly Ash Footing = 4ft x 5.5 in Foundation Wall = 12ft x 27 ft	35% Fly Ash was chosen based on test data. It proved to provide superior strength while reusing resources and conserving landfill space. The particular size of the foundation wall was chosen based on calculations using loads carried by the home.
Square Footing	35 % Fly Ash Footing Base = 2ft x 2ft x 12in Footing = 12in x 12in x 10in	35% Fly Ash was chosen based on test data. It proved to provide superior strength while reusing resources and conserving landfill space. The particular size of the foundation wall was chosen based on calculations using loads carried by the home.
Floor Girders	Laminated Veneer Lumber = (3) 9 1/2" x 1 3/4" @ Various Lengths	Laminated Veneer Lumber was chosen based on test data. It provides adequate strength for home construction as well as resists earthquake loads better than typical sawn lumber. Laminiated Veneer lumber is less expensive to produce and uses less resources than most lumber types. Two sizes of this lumber were tested and although this beam is smaller it provides more than enough strength while reducing the amount of material needed. Three beams are used for the girders in order to carry the load of the modular.
Floor Joists	Laminated Veneer Lumber = 9 1/2" x 1 3/4" @ Various Lengths	Laminated Veneer Lumber was chosen based on test data. It provides adequate strength for home construction as well as resists earthquake loads better than typical sawn lumber. Laminiated Veneer lumber is less costly to produce and uses less resources than most lumber types. Two sizes of this lumber were tested and although this beam is smaller it provides more than enough strength while reducing the amount of material needed.
Subflooring	1 1/2" thick Plywood	Although no tests were done for subflooring materials, this particular size plywood is typical among homes and will adequately spread the load to the joists and girders below.
Strucutral Insulated Panels	9ft tall x 5" thick (Interior and Exterior walls)	Extensive research was conducted on structural insulated panels and they prove to be stronger than a typical frame wall. They reduce the amount of material needed for the construction of the wall and the insulation provides an R value of 14 while being mindful of the environment.
Roof Rafters	Laminated Veneer Lumber = 9 1/2" x 1 3/4" @ Various Lengths	Again Laminated Veneer Lumber was chosen for the roof rafters. Although the LVL may prove to be more than adequate to carry the load it is still more eco-friendly than typical sawn lumber. Material is not wasted during production and overall production time is reduced.
Double Trimimer	Laminated Veneer Lumber = (2) 9 1/2" x 1 3/4" @ Various Lengths	Laminated Veneer Lumber was also used for the double trimmer in the roof frame. Two LVLs will be combined to form the trimmer and will provide plently of strength to support the roof.
Roof Covering	1 1/2" thick Plywood	This size plywood is typically used for the roof. A final roof covering such as roofing shingles will be applied.

Table 10: Structural fasteners

Element	Fastener Type	Details
Foundation Wall/Sill	Anchor Bolts	Anchor Bolts will be cured into the concrete and extend upwards through the sill.
Sill/Floor Joists	Anchor Bolts	Anchor Bolts will continue up through the sill and extend upwards through the floor joists. Anchor bolts will be spaced 16" O.C. to be certain and anchor bolt is used for each floor joist.
Floor Joists/Outer Band	Top Mount Hanger	The floor joists will be fastened to the outer band using top mount hangers. The hangers will fasten directly to the band which will provide adequate shear reinforcement.
Subflooring/Floor Joists	16d Common Wire Nails	The subflooring will be fastened with 16d common wire nails which are 3 1/2" in length. This will allow for 1 1/2" of penetration through the subfloor and 2" of penetration through the floor joists.
Structural Insulated Panels/Floor Joists/Subflooring	30d Common Wire Nails	The Structural Insulated Panels will be fastened to the subflooring and then to the floor joists using 30d common wire nails which are at a length of 4 1/2". Following NDS specifications it will be nailed at an angle of 30 to the horizontal until a depth of 2L/3 has penetrated the subflooring and floor joists.
Roof Rafters/Structural Insulated Panel	30d Common Wire Nails	The roof rafters will be fastened to the structural insulated panels with 30d common wire nails. Following NDS specifications it will be nailed at an angle of 30 to the horizontal until a depth of 2L/3 has penetrated the subflooring and floor joists.
Roof Rafters/Outer Band	Top Mount Hanger	The floor joists will be fastened to the outer band using top mount hangers. The hangers will fasten directly to the band which will provide adequate shear reinforcement.
Plywood/Roof Rafters	16d Common Wire Nails	The exterior plywood will be fastened to the roof rafters using 16d common wire nails. This will allow for 1 1/2" of penetration through theplywood and 2" of penetration through the roof rafters.

Cost Estimate

A cost estimate is important to both home buyers wishing to purchase a home as well as developers. Cost estimates were performed on all parts of the structure starting from the footing and proceeding up through the structure to the roof. Table 11 below summarizes the cost of various portions of the structure. Calculation details can be found in Appendix G.

Table 11: Cost breakdown of structural materials

Element	Material	Unit Price	Total Price
Foundation	1674.4 ft^3 Portland cement	$0.40/ ft^3	$670
	901.4 ft^3 fly ash	$0.21/ ft^3	$190
Flooring/Roofing	314 LVL beams	$48.44 each	$15,210
	4104 ft^2 plywood	$32.00/4'x8' sheet	4,104
Walls	1700 ft^2 structural insulated panels	$10.00/ ft^2	$17,000
		TOTAL	$37,174

The total cost of just the structural elements of the house totals approximately $38,000. This estimate is fairly reasonable compared to traditional stick-built homes, which average a cost of about $25/$ft^2$, which only includes structural frame. This would put the price tag at $51,000 for the entire structure (Generations Timber Frame, 2009). According to this figure, the eco-friendly modular home will cost significantly less than a traditional built home, making it more marketable and desirable.

The total cost of $38,000 covers the structural elements of the home only and does not include the cost of appliances, plumbing or any other element that is put into the building after it is constructed. Although this is an estimate of the structural elements only it still gives a potential home buyer or developer information on the importance of environmentally friendly materials. This type of estimate may be better than a full home estimate because now a potential home buyer can see the base price of the home without any in-home systems. This way the buyer can put the systems they choose into the home, therefore setting the price of the home that they see fit. This not only makes the home more desirable to clients but allows the home to fall within a certain price range that can attract more buyers.

Chapter 7: Conclusions & Recommendations

Overall this project seeks to provide information on various eco-friendly materials and how they can be incorporated into the structural design of a modular home. Each step of the design process; site layout, home layout, home systems, and structural elements; focused on alternative eco-friendly practices and how they reduce the impact the home has on the environment. The ideas presented in this report demonstrate the ease with which 'green' building practices can be implemented and the extent of their economic and environmental benefits.

This project consisted of five major components: site design, layout design, selection of home systems, materials testing and selection, and structural design. Each component by itself contributes to the reduction of the home's environmental impact, from the time of harvesting the raw materials to the construction phase, and finally throughout the building's service life. The first three of these design elements were grouped under the category of environmentally conscious design strategies. These activities centered on research into ways that the environmental quality of the project could be improved by using techniques or products that fit with the project's location, intended function, and general budget.

The first major step of the project was to choose materials that are more eco-friendly than traditional materials and test them to determine their strength. This process not only provided quantitative data to use in the selection of structural materials, but it also allowed for observation into the behavior of the materials under loading and during failure. After consideration of the qualities of all the materials, laminated veneer lumber was chosen as the wood to frame the floors and roof, and the 35% fly ash concrete mix was selected for use in the home's foundation.

Once the materials were selected, the structural design was completed, taking into account the unique qualities of the region, such as climate and geo-hazards. The walls of the home are constructed out of structural insulated panels, which provide support for the roof as well as eco-friendly insulation within the panels. One of the main challenges faced during the design process was breaking down the home into its four modules so that joists would line up upon assembly, creating a tight connection and not disrupting the home's floor plan.

"Green" design elements usually have a higher initial cost, however the overall cost of this structure is significantly less than the frame of a typical stick-built home. This only includes the structural elements of the home, so once home systems, site work, and other finish work are incorporated into the home, the price would significantly increase, but should not be radically more expensive than typical homes of that size.

Less emphasis could be placed on a potentially higher initial cost if a life cycle cost analysis was performed on the home. One topic of further study would be to perform such a cost analysis on the building, which would take into account the savings on maintenance, energy and water bills, and other expenses that would be affected by the implementation of sustainable elements and practices.

The home also lacks many finish elements that need to be incorporated into the design in order for the home to be livable. Examples of this include the plumbing and electrical systems and interior and exterior finish work. Since the current cost estimate only includes structural materials, such additions would appreciably increase this estimate.

With these ideas for future investigation, the home design would attain a higher level of completion and certainly allow for a more accurate cost estimate. The most crucial parts of this project, however, are the structural materials and design of the home. This forms the necessary basis for future research and design activities. This modular home represents a cost effective, environmentally friendly option for homebuyers and serves as an example of how future, environmentally friendly homes, can be designed and constructed.

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Appendix A: Project Proposal

Problem Statement

Throughout the past century, people have been relatively unaware of the harm and strain that current levels of resource consumption put on the global environment. Only recently have people been searching for ways to slow or reverse this resource depleting trend. The problem is so immense that isolated, small-scale efforts will not be enough to combat it. Therefore, in order to achieve any significant results, conservation must be incorporated into the everyday lives of consumers. To maximize the impact of a movement, strategies should target an element within people's lives that is responsible for high energy and resource consumption, and the prime candidates for this attention are private homes. The residential sector consumes over 20% of the energy in the United States (Energy Information Administration, 2009), and in response to this statistic, new designs and efforts are being developed in order to lower it.

During the design process of a house, numerous elements need to be considered and altered in order to limit the home's impact on the environment. For example, what types of materials are suitable for high quality, environmentally friendly design? How can material usage be minimized? How can these goals be achieved while keeping the home affordable for the middle class? One method that inherently increases the efficiency of the construction process is prefabricated, modular construction. Along with this waste-limiting manufacturing process, non-traditional (renewable/recycled) materials and energy-saving systems can be incorporated to achieve eco-friendly design. But before this can be done, the materials' suitability for modular design in the areas of structural integrity, human health risks, cost, projected lifespan/durability, etc. must be evaluated. Additionally, in order for an environmentally-conscious housing movement to be successful, these homes need to be high quality and aesthetically appealing to potential homebuyers.

Introduction

Environmentally friendly housing has been around for quite some time, but its popularity has increased in recent years. Throughout the past few decades, new research has helped consumers to understand their impacts on the environment and the harm they are causing. This, in turn, has forced the construction industry to start designing homes in a way that increases the efficiency of resources use. This renewed interest has also inspired the ingenuity to find new sustainably produced materials that can be incorporated into the construction of homes.

One of many approaches to sustainable construction is modular housing. Though often confused with mobile homes, which carry the negative stigma of being low-quality and non-customizable, modular homes are considerably different. The most distinct difference is that modular homes do not have axels and, once placed on the construction site, they are permanently affixed to a foundation. These buildings can take the shape of multi-story or single-story apartment style, multi-family, or single family dwellings. It is also possible for the homebuyer to customize their home and end up with a high-quality, visually appealing home.

The central principle of modular construction is that the sections of the home are built in a controlled factory environment, transported to the site once completed, then connected and placed on the foundation. One of the advantages of these homes is that the efficient factory construction process reduces the amount of waste material generated during construction. Also, eco-friendly materials that can be difficult to procure can be ordered in bulk and incorporated into the design of several projects, reducing prices and construction delays due to material unavailability. Because modular homes are built in a factory, they are not exposed to the weather damage and construction is not delayed by weather. The home is also easily assembled on-site, cutting construction time nearly in half. This is because, while the home is being constructed in a factory, the site and foundation work can be completed. Once the home is fabricated, it is sent to the site and assembled (Pelletier, 2007). This reduces the amount of construction equipment needed and vehicular traffic to and from the site, cutting down on the carbon emissions associated with these activities, which is a goal of sustainable construction practices.

Most traditional homes were designed and built long before anyone was concerned about the impact they would have on the environment. Natural resources have been greatly depleted due to short-sighted construction practices, over-extraction, and the long period of time required for them to regenerate. In addition to the unsustainable extraction of natural resources, many modern construction materials have a high embodied energy, meaning that they require large amounts of energy to manufacture. Others are often are treated with chemicals that are harmful to human health as well as the environment. These are the three principle issues with traditional materials that the development of new, environmentally friendly materials is attempting to address.

Scope of Work / Methodology

Task	Description
Write Proposal	Each section of proposal was broken down and expanded upon. Sections were compiled and at times combined in order to better communicate the scope of work. Wording and format were addressed during the development of the proposal.
Create Layout of Modular Home	Existing layouts were investigated online and in trade publications in order to get ideas for the home's layout. Research was also conducted on room dimensions, functions, and trends in modular home designs. A discussion of the layout was provided in order to demonstrate the reasoning behind each decision.
Research Materials for Modular Home	Research on alternatives to conventional materials was conducted through trade publications, online resources, and journal articles. After careful research, the list of possible materials was narrowed-down based on material properties and requirements of the layout. Materials chosen are eco-friendly and meet testing standards. California building codes were also researched to ensure that material choices had the potential to meet the state's standards.
Select Materials for Lab Testing	Materials were selected that had been determined to work well with the design of the home and considered sustainable. The materials chosen for testing are considered environmentally friendly due to their renewable nature, recycled content, low impact on the environment during their harvest, manufacture, and assembly, and/or low maintenance/replacement requirements. Potential health concerns associated with certain materials will also be considered. See Table ___ for the list of materials selected.
Design of Experiments	Experiments and tests were designed to be conducted during B Term and are outlined in Table ___. The objective of these tests was to compare new, eco-friendly materials that perform the same function and meet the same standards as traditional materials in order to assess which are superior. The lab manager, Don Pellegrino, provided assistance in designing experiments, procuring materials, and to supervising lab testing.

Conduct Lab Tests	Tests were conducted on the chosen materials during B Term. Tests sought to investigate the 3-point bending moments, tensile, and compressive strengths of several types of wood and concrete mixes. Mixing and construction of concrete cylinders started early in B Term because of the long curing time. Testing was completed in late B Term and early C Term.
Compile Lab Results	After lab testing, comparisons were made between data obtained from the new materials and the traditional materials. Graphs and charts were created in order to compare these results.
Draw Conclusions based on Experiments	Conclusions and discussions will be prepared regarding the results of the experiments conducted and the reasoning behind final selections. Materials that performed well were compared with those that performed poorly. Materials that were researched but not tested will also be discussed concerning the reasons they were not tested and whether they were still incorporated into the design.
Design of Structure	The foundation was designed, using a mix of concrete chosen after testing. The structure was designed with the chosen materials and adheres to ASTM standards. Considerations were also made to accommodate structural requirements unique to modular homes, as well as for seismic performance. Building standards were followed and case studies of existing designs were investigated.
Revit/AutoCAD Designs	Detailed designs of the modular home were created through the use of Autodesk Revit. These designs provide a three dimensional building information model which includes interior and exterior views, layout dimensions, and additional information attached to the model. Site design is also addressed, modeling the measures employed to minimize the impact on the site.
Design Exterior, Interior, and Home Systems	Exterior and interior finishes of the home, such as siding, flooring, and roofing, were designed, keeping in mind that eco-friendly materials should be used. Home systems were also chosen and integrated into the design. These systems include heating/air conditioning, electrical, insulation, plumbing, etc.
Discussion of Revit/AutoCAD Designs	Final touchups to the designs were made. Interior and exterior views of the home from different angles were created to achieve a better visual representation of the home.

Compile Cost Estimate	Throughout the entire design process, cost estimates for materials, labor, transport, site work, and systems necessary for the construction of the home were created. Charts and graphs comprehensively outline the choices for each component of the home and their cost. A life cycle cost analysis was also performed in order to display the energy efficiency of the structure as well as any savings that may occur from the use of the eco-friendly vs. traditional materials. The ultimate goal of this cost estimate was to determine whether the home is affordable for a typical middle class family.
Outline Specifications	A brief discussion was completed to discuss the minor details of the home that were not a focus of the design, yet still needed to be addressed in order to produce an accurate cost estimate.
Review Final Design of Home	The final design of the home of all major aspects of the home was discussed, including the reasoning behind important design decisions.
Write/Finish MQP Report	All portions of project were written, combined, and edited to produce the final MQP Report.

Capstone Design

Constraint	How Constraint Will Be Addressed
Economic	The economic portion of the capstone design consists of cost estimates for materials, labor, transport, site work, and systems necessary for the construction of the home. Charts and graphs were created to comprehensively outline the costs of the major materials and components selected. A life cycle cost analysis is also part of the estimate. A goal of the project is to design a high-quality home that is within the price range of a typical middle class family.
Environmental	The environmental component of the design addresses factors that impact the environment during the actual construction of the home. Reduction of site impact during construction was vital in order to meet environmental goals. The equipment used during the transport of the modular home and in on-site construction activities was reduced in order to lower carbon emissions.
Sustainability	The sustainability portion of the design addresses the impacts of material choice and efficiency of resource consumption throughout the life of the home. Extensive research and testing was completed on traditional as well as new eco-friendly materials. The home was designed to enhance energy efficiency and use the selected environmentally friendly materials. Charts, graphs, and computer models of the home were developed in order to show how the materials were used in the design.
Constructability/Manufacturability	The constructability/manufacturability considerations of the design address how the home is to be constructed as well as what standards the design adheres to. One inherent advantage of modular housing is that homes are easily assembled and produced using an efficient manufacturing process. Once this process is completed, prefabricated sections of the home are shipped to the site, limiting the amount of work required on-site.
Health and Safety	The health and safety component of the capstone design address how the region's geo-hazards, such as earthquakes and wildfires, were considered in the design of the home. This section also discusses the health-related properties of the materials, such as their

	potential to release chemical and particulate matter, compared with traditional materials.
Social	The social portion of the design mainly pertains to the functional design and layout of the home. It explains the reasoning behind certain elements of the design and how they socially impact the family or individual living there. Considerations for certain lifestyles, needs, or current trends in home design, such as number of bedrooms, room functions, and dimensions were addressed.
Political	The political portion of the capstone design addresses how the home adheres to certain standards such as title 24, The California Green Building Code, as well as the ASTM standards. This section also touches on how the design of the home reflects recent movements and designs of green buildings. Case studies of previous green home designs that have both succeeded and failed were researched.

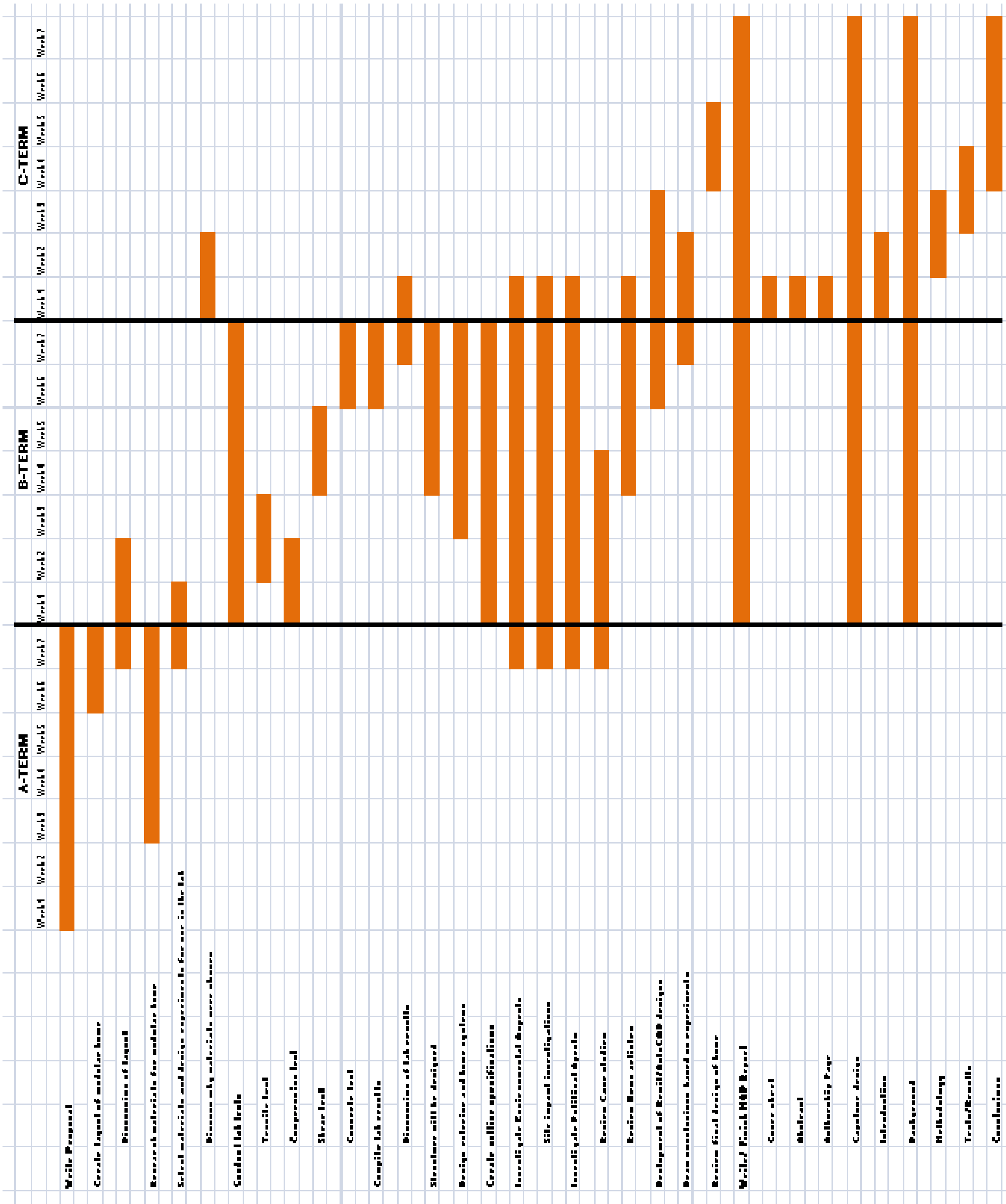
Deliverables

Deliverable	Description
Engineering/MQP Report	This document includes background research, experimental procedures, results and discussion, and recommendations based on the results.
Lab Results	Lab results consist of numerical values for the different properties of the materials tested, organized in charts and graphs.
Calculations	This document contains the calculations used during testing, which determined the proper material to use in the design of the home, as well as engineering calculations for the structural design of the modular home.
Cost Estimate	The cost estimate is a compilation of researched approximations for the cost of materials, labor, transport of materials, site work, and systems of the house. A life cycle cost analysis is also included to evaluate the total cost of the home throughout its lifetime.
Revit/AutoCAD Files	These files provide a three dimensional building information model which includes interior and exterior views, layout dimensions, and additional information attached to the model. Site design is also addressed, modeling the measures employed to reduce the impact on the site.
Outline Specifications	The outline specifications provide a brief overview of design elements that are not the focus of the project, but necessary in order to have an effective cost estimate.

Conclusion

This project aims to provide a detailed structural design and layout for a sustainable modular home. The building model, created through the use of Autodesk Revit, aims to provide a comprehensive analysis of the interior and exterior components of the modular home using various visual angles of the home and attaching information to the building components. The MQP report seeks to provide enough background research in order for the reader to understand the scope of the project. Contained in the body of the MQP report is the data obtained through extensive testing and its analysis. These tests provided a detailed breakdown of the materials tested and their various properties. Using the results of these tests as a supplement to additional research, materials were chosen and utilized in the construction of the home. Once materials were chosen and the home designed, cost estimates were conducted and compiled to provide a final cost estimate for the home. This includes rough estimates for the materials, labor, transport of materials, site work, and systems of the house. A life cycle cost analysis is also included as a way to determine the total cost of the home through its lifetime. Additionally, in order for this environmentally-conscious modular home to be successful, it was designed to be high quality and aesthetically appealing to the homebuyer.

Schedule



Appendix B: Concrete Mix Designs and Fresh Concrete Properties

Mix Design	Fly Ash			Blast Furnace Slag		Silica Fume		
	15%	**25%**	**35%**	**25%**	**35%**	**15%**	**25%**	**35%**
Cement (lb)	28.06	25.04	21.54	25.04	21.54	28.06	25.04	21.54
Alternative Cementitious Material (lb)	5.00	8.51	11.53	7.32	11.53	5.00	8.51	11.53
Coarse Aggregate (lb)	67.13	67.13	67.13	67.13	67.13	67.13	67.13	67.13
Fine Aggregate (lb)	42.55	42.55	42.55	42.55	42.55	42.55	42.55	42.55
Water (lb)	12.72	11.53	11.24	11.77	11.24	15.52	16.51	18.50
AEA (mL)	33	33	48	24	24	33	48	48
WR (mL)	33	33	63	0	0	33	48	63
Slump (in)	2.75	1.75	2.5	0.5	0.5	2.5	2.5	2.75
Unit Weight (lb/ft^3)	145.2	146.2	145.9	147.3	147.7	141.1	133.1	131.7
Pressure Meter (% air)	5.1	4.6	3.8	3.0	2.7	4.0	9.0	7.9

Appendix C: Wood Test Results

Bending Strength Results

Laminated Veneer Lumber		
(stress in psi)	**1 ¾" x 11 ⅞"**	**1 ¾" x 9 ½"**
σ_{b1}	6267.47	4448.90
σ_{b2}	5707.65	7304.89
σ_{b3}	5177.34	6766.51
σ_{b4}	4933.97	-----
$\sigma_{bAVE.}$	5521.61	6173.43

Douglas Fir		
(stress in psi)	**2" x 4"**	**4" x 6"**
σ_{b1}	6180.53	10671.67
σ_{b2}	6285.08	8008.15
σ_{b3}	8089.73	6403.31
σ_{b4}	-----	4728.59
$\sigma_{bAVE.}$	6851.78	7452.93

Wooden I-Beam		
(stress in psi)	**1 ¾" x 11 ⅞"**	**1 ¾" x 9 ½"**
σ_{b1}	4977.07	8287.83
σ_{b2}	4516.90	7945.64
σ_{b3}	3964.10	7650.04
$\sigma_{bAVE.}$	4486.02	7961.17

Bending Moment Results

Wooden I-Beam		
(ft-lb)	**1 ¾" x 11 ⅞"**	**1 ¾" x 9 ½"**
M_{b1}	10329.87	11299.92
M_{b2}	9372.00	10833.39
M_{b3}	8227.47	10430.34
$M_{bAVE.}$	9309.78	10854.55

Compression and Tensile Results

Laminated Veneer Lumber							
(units of psi)			(units of psi)			(units of psi)	
$\sigma_{c\text{-}para1}$	9310		$\sigma_{c\text{-}perp1}$	6321		σ_{t1}	8466
$\sigma_{c\text{-}para2}$	9574		$\sigma_{c\text{-}perp2}$	6771		σ_{t2}	7278
$\sigma_{c\text{-}para3}$	8725					σ_{t3}	7175
$\sigma_{c\text{-}paraAVE.}$	9203		$\sigma_{c\text{-}perpAVE.}$	6546		$\sigma_{tAVE.}$	7640

Douglas Fir				
(units of psi)			(units of psi)	
$\sigma_{c\text{-}para1}$	6813		$\sigma_{c\text{-}perp1}$	3092
$\sigma_{c\text{-}para2}$	7013		$\sigma_{c\text{-}perp2}$	2493
$\sigma_{c\text{-}paraAVE.}$	6913		$\sigma_{c\text{-}perpAVE.}$	2793

Appendix D: Concrete Test Results

Compression and Tensile Stress Results

Fly Ash			
(units of psi)	**15% (72 day)**	**25% (72 day)**	**35% (73 day)**
σ_{c1}	5240	5926	5392
σ_{c2}	5444	5893	5682
σ_{c3}	5217	5408	5677
$\sigma_{c\ AVE.}$	5300	5742	5584
σ_t	399	437	395

Blast Furnace Slag			
(units of psi)		**25% (73 day)**	**35% (73 day)**
σ_{c1}		5736	6203
σ_{c2}		8627	6044
σ_{c3}		6035	5885
$\sigma_{c\ AVE.}$		5886*	6044
σ_t		382	415

*not including σ_{c2}

Silica Fume			
(units of psi)	**15% (74 day)**	**25% (74 day)**	**35% (74 day)**
σ_{c1}	4694	3819	3387
σ_{c2}	4572	3735	3528
σ_{c3}	4700	3561	3303
$\sigma_{c\ AVE.}$	4655	3712	3406
σ_t	335	289	-----*

*machine malfunction → data not recorded

Unit Weight of Cured Cylinders Results

Fly Ash			
(weight in lbs)	**15%**	**25%**	**35%**
W_1	29.02	29.34	29.15
W_2	29.21	29.05	29.44
W_3	29.09	29.29	28.91
W_4	28.77	29.34	29.47
$W_{AVE.}$	29.02	29.25	29.24
Ave. Unit Weight (lb/ft^3)	147.80	148.99	148.93

Blast Furnace Slag			
(weight in lbs)		**25%**	**35%**
W_1		29.41	29.70
W_2		29.63	29.75
W_3		29.74	29.75
W_4		29.48	29.51
$W_{AVE.}$		29.57	29.68
Ave. Unit Weight (lb/ft^3)		150.58	151.15

Silica Fume			
(weight in lbs)	**15%**	**25%**	**35%**
W_1	28.04	26.72	26.36
W_2	28.23	26.54	26.19
W_3	27.87	26.92	26.19
W_4	28.13	26.82	26.15
$W_{AVE.}$	28.07	26.75	26.22
Ave. Unit Weight (lb/ft^3)	142.94	136.24	133.55

Appendix E: Loading Calculations

Roof Dead Load

Roofing (5-ply with gravel) Assumed………………………………………………………6.5 psf
Reroofing……………………………………………………………………………………………2.5 psf
1 ½" plywood (3psf x ½")……………………………………………………………………1.5 psf
Framing (9 ½" x 1 ¾" LVL) …………………………………………………………………3.4 psf
Ceiling……………………………………………………………………………………………………1.0 psf

Total……………………………………………………………………………………………………14.9 psf say 15 psf

Floor Dead Load

Floor Covering…………………………………………………………………………………………12.5 psf
1 1/8" plywood………………………………………………………………………………………3.4 psf
Framing (Estimate 9 ½" x 1 ¾" @ 16" O.C.)………………………………………………2.5 psf
Ceiling supports ……………………………………………………………………………………0.6 psf
Ceiling (1/2" drywall)………………………………………………………………………………2.5 psf

Total……………………………………………………………………………………………………21.5 psf say 22 psf

Earthquake Load

$V = C_s W$
$C_s = S_s/(R/I)$ R=6.5 I= 1.0 S_s=1.5g
$C_s = 2.26$
V = 2.26 (37psf, calculated from above) = 83.62 psf

Load Combinations (LRFD)

1.2D + 1.6L = 1.2(37psf) + 1.6(60psf) = 141 psf
1.2D + 1.6L = 1.2 (37psf) + 83.62psf + 60psf = 188psf Governs

Appendix F: Footing/ Foundation Designs

Square Footing design

Tributary area of 103in

Dead Load + Earthquake + Live load = 188 psf = 16.14 kips

$188(105ft)(\frac{103}{12}) = 16.14$ kips

16 in square tie column

Allowable Soil Pressure = 5000 psf (Assumed)

2 ft overburden = 100pcf

$f'_c = 5600$ psi — Footing estimated to be about 1 ft thick

$f_y = 40{,}000$ psi

a) net allowable soil pressure:

$p_{net} = 5000 - 200 - 300 = 4500$ psf

Required $A = \frac{16.14}{4.5} = 3.58 ft^2$

Try 2ft x 2ft square $A = 4 ft^2$

$P_u = 1.2(3.176) + 1.6(5.15) = 12.05$ kips

$P_{net} = \frac{12.05}{4} = 3.0125$ ksf

b) Determine depth based on shear strength, assuming a thickness of 12in

average $d = 12 - 3(cover) - 1(bar\ diameter) \approx 8in$

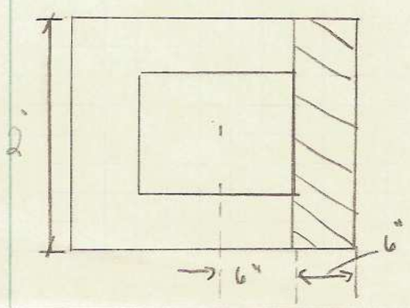
$V_u = (p_{net})(area) = 3.0125[2(2) - 1.67(1.67)] = 3.65$ Kips

$b_o/d = 4(12+8)/8 = 10 < 20$

$V_c = 4\sqrt{f'_c}\, b_o d = 4\sqrt{5600}(4(12+8))8\frac{1}{1000} = 194$ kips

$\phi V_c = 0.75(193) = 144.75$ kips $> V_u = 3.65$ kips

No shear reinforcement required



$V_u = (3.0125)(0.5)(2) = 3.0125$ kips

$V_c = 2\sqrt{f'_c}\, b_w d = 2\sqrt{5600}(2)(12)(8)\frac{1}{1000}$
$= 29.1$ kips

$\phi V_c = 0.75(29.1) = 21.8$ kips $> V_u = 3.012$ kips

No shear reinforcement required

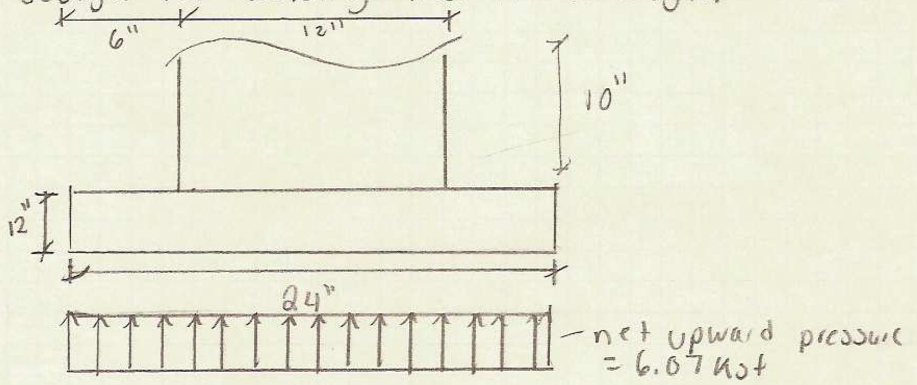
c) Check transfer of load at base of column

$\phi P_n = \phi(0.85 f'_c) A_g = 0.65(0.85(5.742))4 = 12.7$ kip

$\phi P_n > P_u = 12.05$

Thus the column load can be transferred by bearing alone

d) design for bending moment strength



$M_u = \frac{1}{2}(3.0125)(2)(6.5)^2 = 0.753$ ft-kips

Required $R_n = \frac{M_u}{\phi b d^2} = \frac{0.753(12,000)}{0.9(24)(8)^2} = 6.54$ psi

$$\rho = \frac{1}{m}\left(1 - \sqrt{1 - \frac{2mR_n}{f_y}}\right)$$

$$\rho = \frac{1}{8.2}\left(1 - \sqrt{1 - \frac{2(8.2)(6.54)}{40,000}}\right) = 0.00016$$

Required $A_s = \rho b d = 0.00016(24)(8) = 0.0307 in^2$

Min Required $A_s = 0.002(24)(10) = 0.48 in^2$

Try 5 # 3 bars $A_s = 0.55$ $d = 12 - 3 - 0.11 = 8.9$ in

$C = 0.85 f'_c b a = 0.85(5.742)(2)(12)a = 58.57a$

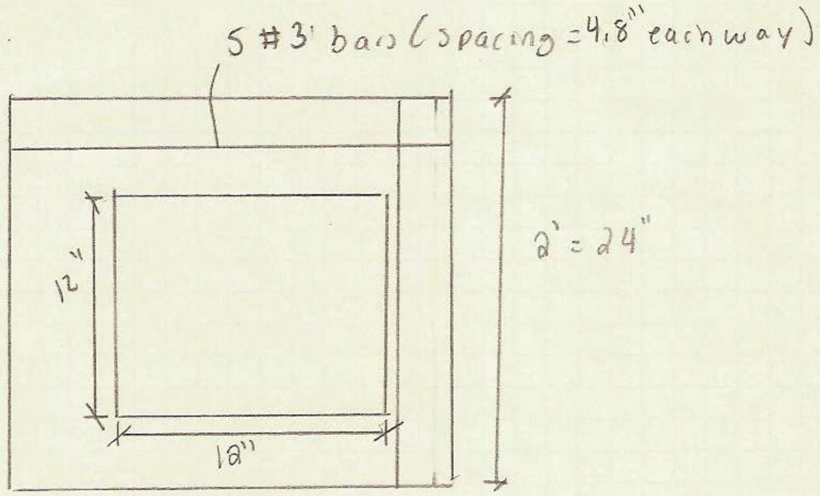
$T = A_s f_y = 0.55(40) = 22$ kips

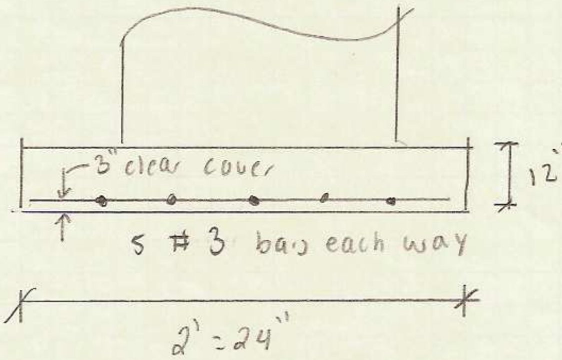
$C = T$ $a = 0.376$ in

$\phi M_n = 0.9(24)[8.9 - 0.5(0.376)]\frac{1}{12} = 15.68$ ft-kips

$\phi M_n > M_u = 0.753$ ft-kips OK

Use 5 # 3 bars ($A_s = 0.55 in^2$) each way


5 #3' bars (spacing = 4.8" each way)
2' = 24"
12"
12"


3" clear cover
12"
5 #3 bars each way
2' = 24"

Reinforced concrete Footing

12in concrete wall

Dead Load = 7.48 kips/ft including wall weight
Live Load = 2.4 kips/ft

f'_c = 5600 psi   soil pressure = 5000 psf
f_y = 40,000 psi

a) Determine footing thickness

Assume footing depth to be 10in at 125 psf
Allowable net soil pressure = 5000 − 125 = 3875 psf
Footing width = 15/3.875 = 3.87 ft. ≈ 4 ft

Apply overload factors

$$w_u = 1.2(7.48) + 1.6(2.4) = 12.816 \text{ kips/ft}$$

Net soil pressure under factored load = 12.816/4 = 3.204 ksf

When no shear reinforcement is used, the nominal strength for one-way action, using the simplified procedure is:

$$V_n = V_c = 2\sqrt{f'_c}\, b_w d$$

$$V_u = \phi V_c$$

$$3204(1.5 - d) = 0.75(2\sqrt{5600})(12)(12d)$$

$$10.22d = 1.5 - d$$

$$d = 0.133 = 1.6 \text{ in}$$

Total thickness = 1.6 + 3(cover) + 0.5(bar radius) = 5.1 in

use 5.5 in thickness

check weight = 69 psf · OK

b) reinforcement for moment strength.

$$M_u = \tfrac{1}{2}(3.204)(1.75)^2 = 4.9 \text{ ft-kips/ft}$$

$$\text{Required } R_n = \frac{4.9(12{,}000)}{0.9(12)(5.1)^2} = 209 \text{ psi}$$

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<u>use 5.5 in thickness</u>

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Appendix G: Cost Estimates

Laminated Veneer Lumber
314 beams @ $48.44 each = $15,210.16

Total Concrete = 2576 ft^3

Cement = 14% = $0.40/$ft^3$
Fly Ash = 7.5% = $0.21/$ft^3$
Course Aggregate = 44% = Free
Fine Aggregate = 27% = Free
Water = 7.5% = Free

Total cement = 1674.4 ft^3
Total Fly Ash = 901.4 ft^3

Total Cost:
Cement = $670
Fly Ash = $190