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(Review Article)

A culminating senior design capstone project on a residential building in engineering education

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Abstract

A study was conducted based on the theoretical construction of a three-story residential house from beginning to end, that included the following considerations: architectural, structural, environmental, and cost analyses; additionally, a commentary as to educational benefits to be gained by such an undertaking is also offered. Regarding the environment, the study considered LEED aspects and their impact in association with the design of the building. Among the efforts to make the building green are the calculation of associated costs that were likewise taken into consideration together with the savings in energy to ultimately be realized with the implementation of LEED features.

Keywords: Architectural; Structural; LEED; Sustainable; Cost

1. Introduction

The future in terms of building stewardship is in sustainability. Tomorrow advocates for more environmentally friendly innovations and designs. But a question confronting engineers is how to continually promote and innovate such sustainability features in all their construction efforts? The team of student researchers at California State University, Northridge began this project by creating a design of a home within a city in Los Angeles County. Due to seismic activity within this region, the project displays characteristics and designs pertaining to this region's building code. The project was completed through the following steps: site plan, floor plan, elevation views, design of beams, columns, beam-to-column connections, and the foundation. Once designed with their respective structural plan, seismic calculations were implemented following AISC 341 and then modeled through the software program, RAM structural analysis. Upon completion, researchers continued with the implementation of Leadership in Energy and Environmental Design (LEED) certification, which was the final step of the cost analysis for this project.

Students of the University of Oklahoma as well as California State University, Northridge have similarly translated their senior studies into research in order to examine their findings alongside other researchers. Through the use of research, students who have already completed their undergraduate studies are able to further develop their knowledge of real-world applications within engineering. Lemley et al. [1] emphasized the importance of recognizing design aspects within research projects and provided examples of research projects that can incorporate engineering design. Incorporating LEED features and conducting a detailed cost analysis enabled the student researchers a view into the benefits of proposing a green building design versus a more traditional approach. Hopkins [2] reiterated this through the study of LEED within college campuses with the comparison of the cost versus building life cycles.

The main components of this undertaking focused on the architectural, structural, and environmental aspects of the proposed building design. Researchers worked to execute a fully functional home designed from start to finish by replicating real-world processes vying for the attention of professional engineers on a daily basis. Under the auspices

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of the yearlong Senior Design capstone course, students from the civil engineering major were able to aggregate all that they had learned throughout their many years of study. Along with structural and architectural considerations, the home to be designed by the team of student researchers was to intentionally incorporate LEED aspects to allow for a more environmentally friendly and energy efficiently functioning house. Barshilia [3] conducted a study on LEED (and Green Rating Integrated Habitat Assessment GRIHA) innovation in design, which analyzed buildings with LEED certification and the qualifying sustainable features. Selected environmentally friendly features mentioned by Barshilia [3] were incorporated into the house's design to achieve LEED certification alongside architectural goals of being aesthetically pleasing.

2. Architectural Features

The project consists of a three-floor residential home, situated on a 0.4-acre lot, and located in the Beverly Hills area of Southern California. Composed of steel, the building was stipulated to have a 2,000 square foot area per floor. In terms of aesthetics, the home designed considered a completely symmetrical exterior, with a 45' × 45' perimeter and a 15' × 13' interior opening. This 15' × 13' exterior area included a garden atrium with an opening on the roof to be able to capture both morning dew as well as rainwater. For enhancing the environmental synergy of the house and garden, the exterior of the home utilized sage glass for maximizing the amount of natural sunlight exposure. The home was configured with the main entrance to be in a westward direction thus rendering a back entrance to the east for allowing longer durations of sunlight throughout the day. Speaking of lighting, using sage glass also allows for auto and remote dimming whenever desired or deemed necessary. Solar panels installed on the roof also allow for enhanced green energy efficiency.

The home consists of nine bedrooms, six bathrooms, and an atrium visible from each story. Figure 1 depicts the layout of this residential home with suggested uses of the rooms and floor space. The kitchen has an entrance from the east and south direction, with the south opening having easier access to the garage. Alongside the kitchen's east entrance, the living room was to have an entrance on the opposite end, making for 2 backyard openings. Figure 2 depicts the second and third story layouts. The home is designed to have stately grand entrance rising 32' in height and is key for allowing the garden its needed egress of light that then permeates to the remainder of the home.

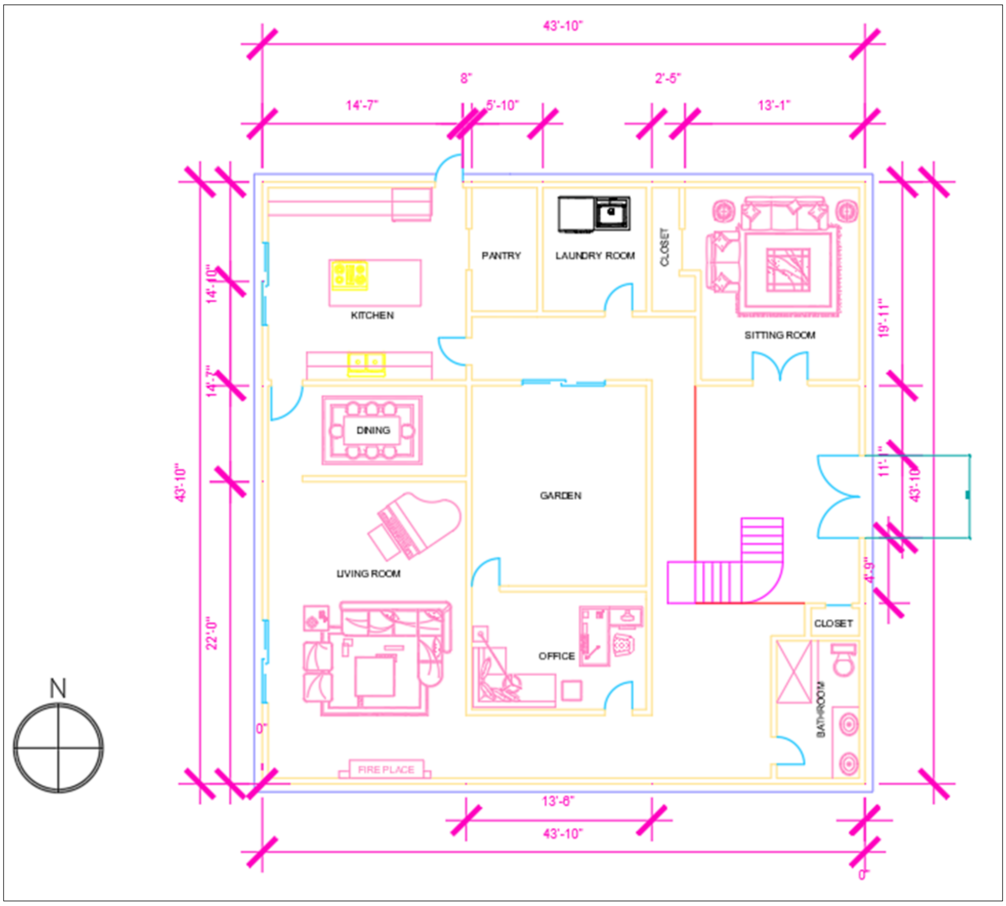

Figure 1 First floor plan

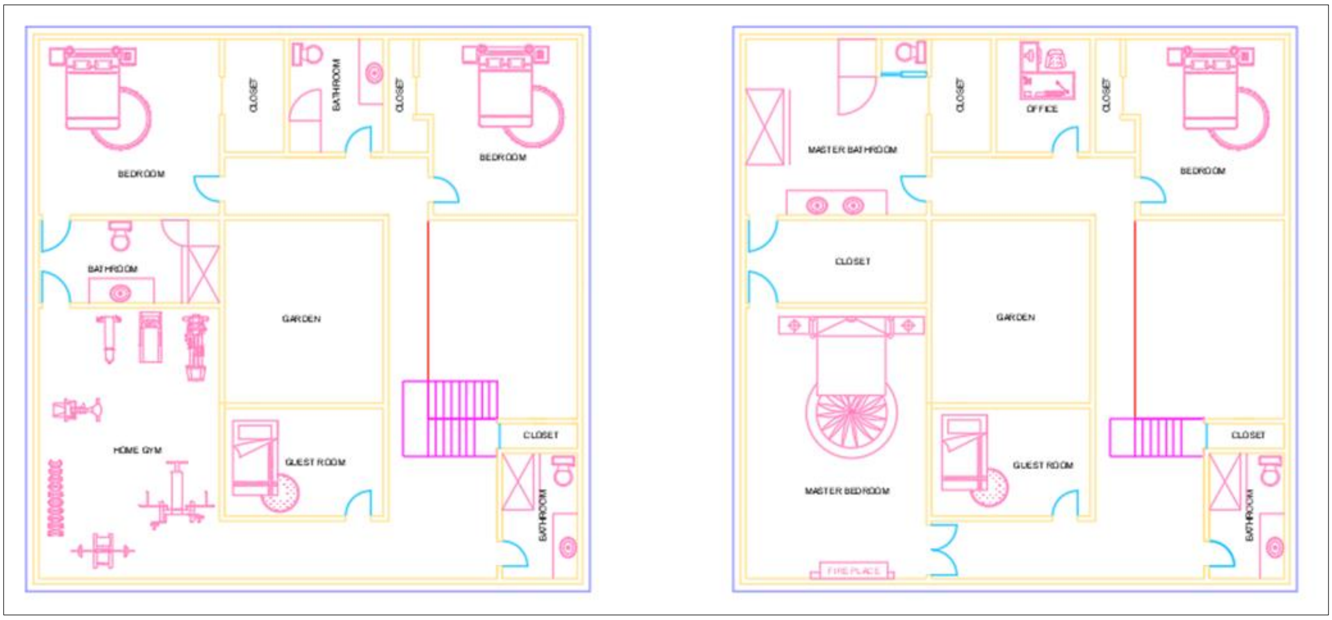

Figure 2 Left to right, second and third floor plan

3. Structural Design

The building was designed using standard structural codes such as ASCE 7-16 and the International Building Code. In this process, the team of student researchers gained knowledge in structural design methods conforming to code while being able to express and incorporate innovative ideas through a variety of energy saving LEED features into the building's performance. The material aspects of this building utilized structural steel girders and columns in its construction, with concrete being used for the foundation and decking system.

Table 1 Summary of the results for structural design [4]

Structural Element	Design	Notes
Beams	W10 × 12, W12 × 16	W10 × - Gravity W12 × Moment
Columns	W8 × 35, W12 × 79	W8 × - Gravity W12 × - Moment
Foundation	10' × 10' × 2'-6", 6' × 6' × 2'-6" 6-#8 @ 9" O.C. (T&B) TYP. with #3 Stirrups @ 9" O.C. 10" J-Bolts 4 Places, TYP. w/ ¾" × 14" × 14" Base Plate	Soil Bearing Capacity: 4 ksi

The building design commenced by first manually calculating required sizes of the girders and columns before using computer software such as commercially available finite element packages. To this end, codebooks by those of the American Institute of Steel Construction (AISC 341 & 360) as well as the American Concrete Institute (ACI 3-18) were used in determining the adequate sizes of members for withstanding the anticipated loads being applied and borne by the structure. The order of design considered a top-down approach in contrast to the actual construction which begins and progresses in bottom-up fashion. After roof loads and the beams needed for support, then consideration is given to columns, followed by beam-column connections, the lateral bracing system, and, finally, the foundation. Shown below in Table 1 are the beam, column, and foundation sizes chosen once calculations were cross-checked and updated. The calculated sizes of all structural aspects were determined using the Load Resistance Factor Design (LRFD) method, in which all the loads are increased by a multiplicative factor in order to utilize the full strength of the structural member up until the point of yielding. As stated by Galambos [5], the LRFD design approach ensures that the strength of structural members is utilized to their full capacity rather than relying on lesser, elastic-based, factors as used in methods like that of its predecessor known as the Allowable Stress Design (ASD).

4. Design for Sustainability and LEED Certification

As Abair [6] mentioned, nearly 30% of the United States' carbon dioxide emissions, 40% of its Ozone pollution, and 35% of municipal solid waste come from construction-related activities. For such reasons, it is absolutely crucial to incorporate LEED and environmentally-friendly methods into modern day construction projects. Designing a three-story, fully glass curtain wall building with sustainability and LEED features requires consideration of various factors such as material selection, indoor air- and environment-quality, and the overall savings in costs to be gained by using an enhanced energy efficient structure. Some of the LEED features incorporated into the design of this building, include:

- *Sage Glass:* The exterior of the building is to be designed with glass using electrochromic technology that allows the glass to automatically tint or clear in response to changing external weather conditions, such as to varying intensities of sunlight and heat. Based on the information found on Sage Glass Website [7], Sage Glass reduces the need for artificial lighting and heating by dynamically adjusting the amount of sunlight entering the building, resulting in lower energy consumption.
- *Solar Panels:* Operating solar panels for the electrical system of the building has great advantages, such as utilizing renewable energy, reducing energy costs, promoting environmental sustainability, and contributing to LEED certification. Solar panels produce clean electricity without emitting greenhouse gases or air pollutants which lead to a greener and more sustainable future. Utilizing a solar panel system also helps in fulfilling the renewable energy goals of LEED and contributes to the earning of credits in the Energy and Atmosphere category.
- *Atrium:* The proposed indoor atrium allows natural light to penetrate deep into the building, thus reducing the need for artificial lighting during the day. It also helps to increase the sustainability of building vegetation. Incorporating plants and greenery within the indoor atrium that can absorb sunlight and release moisture through a process known as transpiration, helps to offset localized pockets of higher temperature known as the heat island effect.
- *Porous (a.k.a. Permeable) Pavement:* Sorvig [8] explained about the benefits of using porous pavements in designs and pointed out that utilizing such a permeable medium allows for rainwater to infiltrate through the surface and into the underlying layers, thus reducing stormwater runoff. This earns the required LEED credits in the Sustainable Sites category, specifically for Stormwater Management. Moreover, using a permeable pavement supports the water efficiency goal by allowing rainwater to infiltrate into the ground in order to replenish the groundwater and reduce a higher demand for irrigation water, as aligned with LEED's objectives in the Water Efficiency category. Once again, the urban heat island effect is also reduced by allowing rainwater to infiltrate into the ground, which cools the pavement surface and contributes to the earning of LEED credits in the Sustainable Sites category for Heat Island Reduction.

Integrating the aforementioned LEED features into the building's design as well as considering other LEED grading factors, the building is expected to pass LEED requirements with a minimum of 50 points, which will classify the house's design at a LEED rating of Silver.

5. Cost Analysis

An estimated cost analysis was performed to evaluate the expense associated with the design, construction, operation, and maintenance of this three-story building. To analyze the cost of a conventional building with that of a LEED featured one, all additional expenses related to incorporating LEED features and the potential cost savings or benefits associated with those features have been taken into consideration.

Table 2 shows associated cost estimates and details of structural members, e.g. beams, columns, and concrete footings. Based on the collected data and estimates from two local contractors, the estimated design and construction cost of this building has been determined to be ~\$3.2M with an average of ~\$550 per square foot. As demonstrated in Table 3, incorporating all proposed LEED features and certification will cost an additional 23% in associated design and construction fees rendering a total cost of ~\$3.9M.

Table 2 Summary of estimated costs of structural elements/construction

Labor Estimated Cost I		**Labor Estimated Cost II**
(Pre Covid-19) $1,999,500		*(Post Covid-19) $4,500,000*
Item	Price	Quantity
W24 x 94 (Columns)	$85,205	Qty. 32 - 20' Lengths
W 21 x 44 (Girders)	$36,048	Qty. 35 - 16' Lengths
W18 x 35 (Joists)	$85,500	Qty. 60 - 16' Lengths
Footing Concrete	$17,280	95 Cy of Concrete
Fabrication/Welding	$40,000	
Machinery for Construction	$840,000	Crane Rentals, Lifts, etc.
Rebar	$6,000	$1,063.00/38 - 20' lengths
Deck	$25,000	
Labor Cost	$61,920	4 people @ $90/hr 8hr/day
Total Construction Cost	*$3,196,395*	

Table 3 Summary of LEED features estimated costs

Feature/ Item	**Price / Quantity**	**Total Cost**	**Note(s)**
Sage Glass	$800/m^2	$512,000	Roughly 7,000 sf of glass
Solar Panels	Lump Sum	$17,078	
Atrium Design/ Construction Costs	Lump Sum	$80,000	
LEED Certification/ Review Costs	Lump Sum	$25,000	
Landscaping	Lump Sum	$1,800	
Porous Pavement	$30/ft^2	$108,000	
	LEED Total Cost	$743,878	
Total Cost With Proposed LEED Features: $3,940,273			
Cost Increase for LEED Features: 23%			

6. Educational Objectives

In addition to the aforementioned design, cost analyses, and LEED considerations for the building, another significant objective to have been fulfilled from this research undertaking was for the team of student researchers to have gained an educational introspection from their various interactions with faculty, industry professionals, and collaborations between their fellow classmates. Evan et al. [9] assert the importance of faculty guiding students, as in a senior design class, on research undertakings with an educational bent for producing more well-rounded engineers in the future. The research was conducted through a series of presentations prepared by student teams to teach their classmates about the various aspects of design: from architectural to structural plans, to LEED considerations and its affects towards the overall longevity of such buildings. As per a preset schedule, the team of student researchers would prepare and learn as much as they could about a particular aspect in the design and construction of their building. Essentially exercises as these simulated real-world design situations in which deadlines, dealings with contractors, and stringent working regulations and conditions could be appreciated. Another benefit gained by the teams of student researchers throughout this process was in appreciating the importance of teamwork and collaborating with people of different backgrounds and abilities.

This method of researching and presenting thus serves to enable student researchers to translate what they have learned in the classroom and apply it to real-world applications before, or, as in some cases, even in tandem with, their commencing with their own personal industry-related work experiences post-graduation.

7. Conclusion

This student-led research effort was initiated to simulate the diverse processes involved in the design of an actual structure, from start-to-end. The location of the property chosen was in the city of Beverly Hills within the county of Los Angeles, having a 0.4-acre footprint, and involving a three-story residential home using structural steel. Cost was an important factor of consideration throughout the project, even if these savings were to be realized over the course of time due to the implementing of LEED features that begin with higher front-end costs. The most notable LEED features in the design, involved using: Sage Glass, solar panels, porous pavements, the design of a high-ceiling atrium with indoor vegetation, and landscaping. The design methodology utilized ASCE-7 and the International Building Code, in conjunction with tips from practitioners in the field. In the design process, the student researchers determined the ideal dimensions of structural members to withstand the anticipated loads in accordance to the aforementioned codes together with steel and concrete specifications as published in the handbooks by the American Institute of Steel Construction (AISC 341 & 360) and the American Concrete Institute (ACI 3-18), respectively. The total cost of this project came to an estimated ~$3.9M which included the total LEED feature costs of ~$750k. With such LEED additions, the building received a minimum of 50 points, which would grant the building a Silver classification. In addition to the benefits gained by the team of student researchers regarding the design component of this project, they also made great strides educationally and academically by the well-rounded learning experience afforded them by the unique setup of this capstone, senior design class, culminating in the publication of this present journal article.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors of this paper have NO affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

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