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Undergraduate Structural Design and Analysis of a LEED-Certified Residential Building

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ABSTRACT

The undergraduate research objective was to design a three-story residential steel structure with moment resisting frames and an emphasis on incorporating LEED-certified features. This model was studied by a diverse team of civil engineering undergraduate students at Cal State University Northridge in the U.S. for a senior design class project. The group of undergraduate students designed the building's vertical and horizontal structural members. The design will be presented on architectural and structural plans, which details building features based on seismic and structural designs. A LEED-certified green building, also a sustainable building, was designed to meet standards such as water, energy, and material efficiency. The implementation of LEED will reduce the negative impacts of the building on the environment. A cost analysis was conducted to obtain a comprehensive price of the building's construction. The analysis allows the students to get an extensive look into how LEED certification provides long-term annual cost savings. In this case study, the three-story structure achieves LEED certification through its architectural, structural, and green building features.

Keywords: *Civil Engineering; Green building; Structural Steel Design; Cost Analysis; Undergraduate Research*

Introduction

Leadership in Energy and Environmental Design (LEED) is a green building certification program developed by the U.S. Green Building Council (USGBC). The objective was to design a building that is environmentally friendly for a long-term period. A rating system is established for the design, construction, operation, and maintenance of green buildings, homes, and neighborhoods. LEED is a voluntary certification program applied to any building type and life cycle phase. The green building code and certification system has become increasingly popular as efforts to minimize the environmental impacts is highly encouraged.

Studies on green building technology highlighted the status of LEED certification and its future agenda. Additionally, it included the impact of climatic conditions on the effectiveness of green buildings and brought more attention to indoor environmental quality [11]. Eco-materials are known to be major factors in improving the environment and economy. For example, the eco-friendly materials are mainly used in present building construction. Alfonso Uson analyzes the possibilities for improvement and provides guidelines for materials selection in his article regarding life cycle assessment of building materials [3]. In addition, Kim Lascola, and a group of scientists had published a paper on the economic benefits of green buildings for residential buildings in the long-term period. The study was based solely on scheduling, budgeting and the long-term effects overlooking their assumption effects compared to the total cost of the green building. It is shown that life cycle energies in buildings demonstrate how much green buildings help reduce the electricity costs [8]. It is determined that high-end cost prediction of certified buildings states that the built environment has a significant impact on the economy, society, and the environment [10]. The study discusses the importance of green buildings and the eco-material that make a huge impact to improve a higher quality of life with long term considerations in the economy. For the future of the Earth, it is important to promote these building models which are environmentally friendly and sustainable in the future.

Architectural Features

The three-story building was designed to consist of three bedrooms, three bathrooms, storage, laundry room, kitchen, dining area, and living room with a minimum requirement of approximately 2000 ft^2. Fig.1 shows a typical floor plan for all three levels of the building. The total area of the typical floor plan is 3096 ft^2 with a wall height of 9 ft. The height of the building is 30 ft with the approximate dimensions of 67.5 ft by 48 ft. The lot size measured to be 8558 ft^2. The illustrations of exterior elevation views are shown in Figs. 2, 3, and 4. The east elevation view displays the front, and the west elevation displays the rear of the building. The residential building has roof access with a floor plan of solar panels and a simple arrangement of furniture and plants for a charming entertainment area. The main considerations that went into this design are appeal, simplicity, livability, and LEED features such as window placement for daylight and a rainwater system for water efficiency [5]. The simplicity and livability aspects were the focus in the design because currently, most families are spending most of their time indoors. The open floor plan was also designed with specific thermo regulated sliding doors and windows in each room to bring in natural light indoors. The sliding doors in every room go out into spacious balconies that will look over into the greenery of the nature preserving landscape.

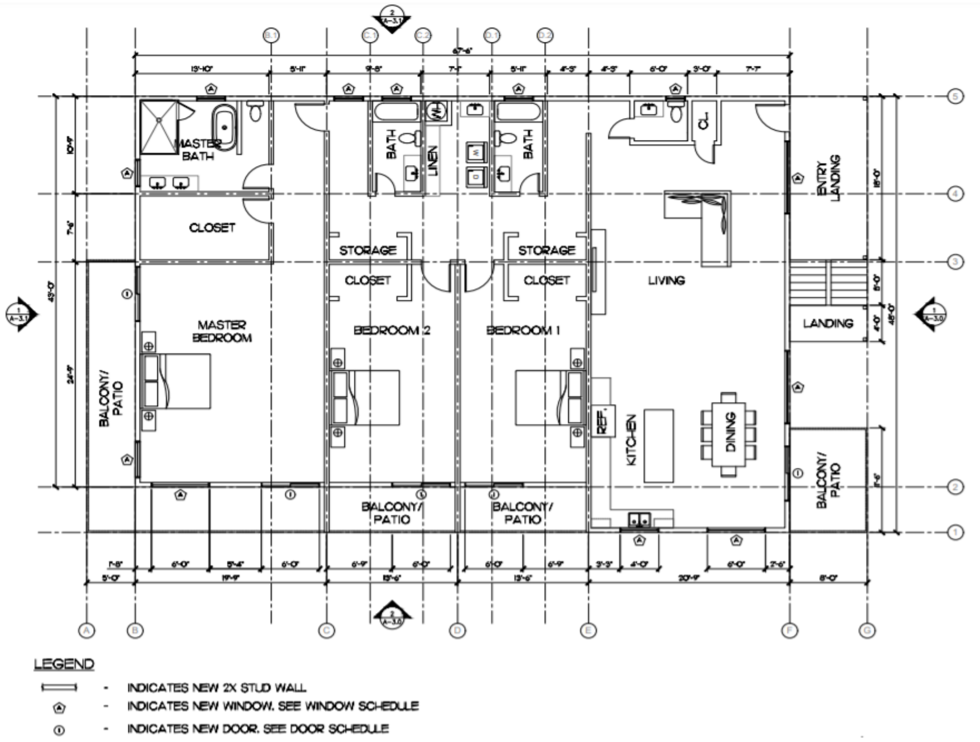

Fig1. *Typical floor plan*

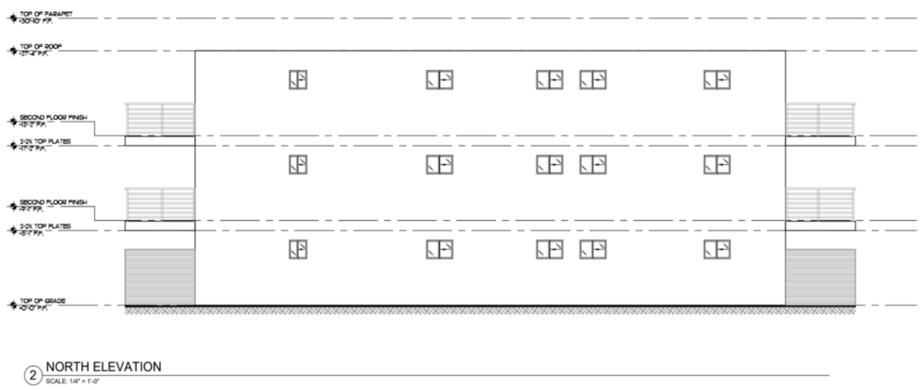

Fig2. *Exterior North Elevation View of the Building*

Fig3. *Exterior south elevation view of the building*

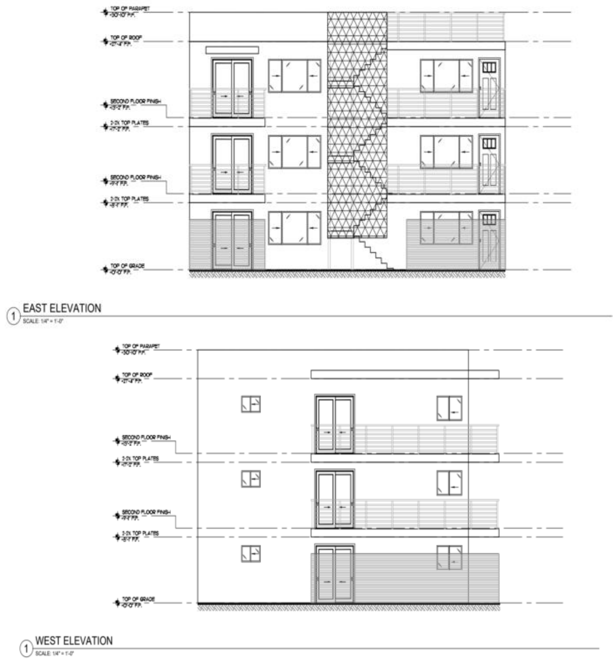

Fig4. *Exterior east and west elevation view of the building*

STRUCTURAL DESIGN

Following the architectural design and layout, the structural design of gravity load members for the building can be determined by the applied dead and live loads of the building. Structural members are placed in practical locations per the grid layout imposed on the architectural floor plan. The dead load can be determined by the material finishes selected for the building at the roof and floor level, whereas the live load was assigned by [2]. The live load can be reduced at the floor and roof level per LRFD. Steel members were determined by verifying if the deflection and bending stress met the required minimum/accepted values after gravity loads were applied [9]. By considering all beams to be simply supported, the end supports were connected to columns or exterior walls. The columns, which are pinned-pinned, have an axial load applied vertically at the center of column. The sizes were determined based on its nominal size. The axial load demand was used to check the effective slenderness and bending stress of the selected member. The design results for the beams, columns, and foundations are shown in Table 1.

The beams are attached to columns by transferring the gravity loads of the floor and roof through the beam on to the column. Fig. 5 illustrates the steel joist to steel beam connection at the roof and floor level by detailing the bolts and plate placement. To support the load applied to the column, concrete footings are added to the structural design by placing them at the interior and exterior columns [7]. The concrete footings are designed in accordance with ACI-318 to sustain the load of the roof and floors by verifying the thickness, overburden pressure, effective bearing capacity, bearing area, critical and punching shear [1]. Fig. 6 presents the building's structural composition via RAM 3D design software.

RAM was used for the analysis of the structural members and to check for failure. Fig. 7 details the steel column to concrete pad footing at the ground floor level.

Table1. *Structural Design Results*

Structural element	Design results
Beams	W12×14, W12×29, W14×22, W16×26, W16×31, W18×35
Columns	W10×33, W12×40
Foundation	[Pad] 5x5 12 #4 continuous rebars

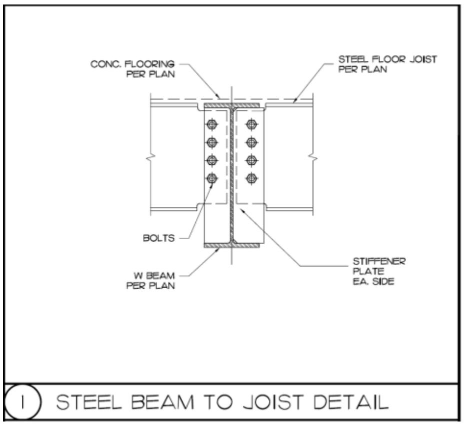

Fig5. *Joist to Steel Beam connection*

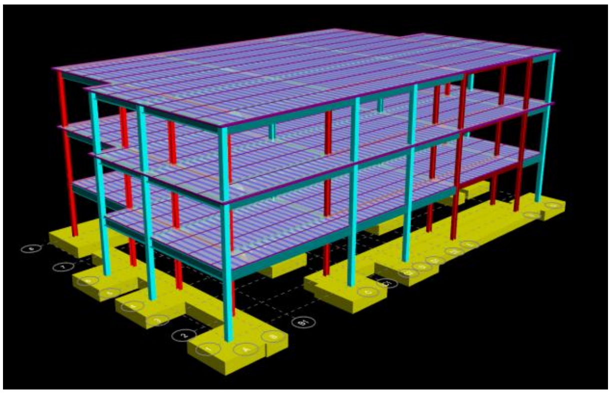

Fig6. *3D RAM Model of Structural Design*

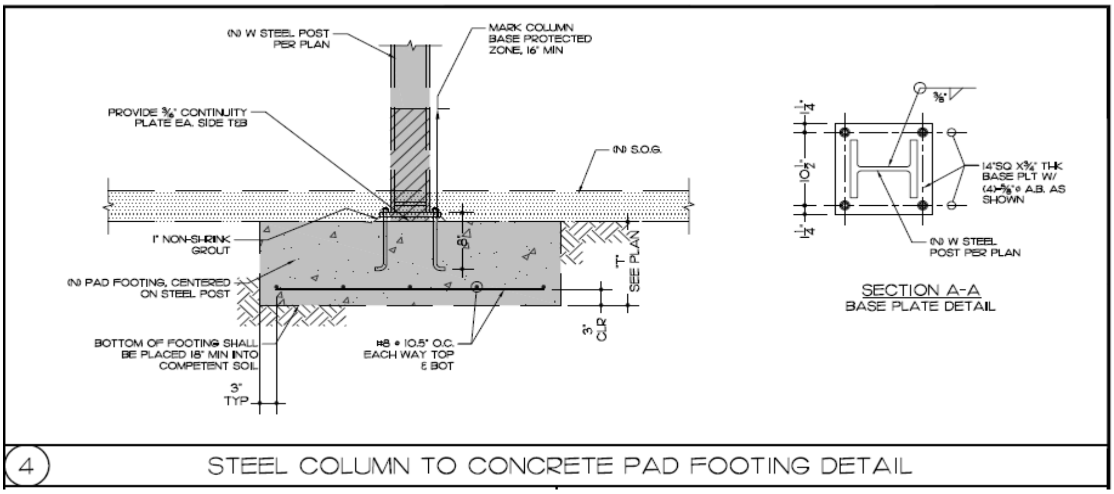

Fig7. *Foundation design*

Seismic Calculations

To counter natural disasters such as earthquakes and heavy wind forces, designing a building's lateral resisting structural components is critical to maintain the building's functional and structural stability. A lack of emphasis in this design category can result in fatal consequences. Hence, the seismic design and calculations are important key components in determining design of a building. The story shear calculations were accomplished by using Chapter 11 and Chapter 12 of the ASCE 7-16 [2]. The Seismic Design Category D and Risk Category II were selected by using the specific location of the building. The values have been determined to be S_1 = 0.686 and S_s = 2.051.

Table 2 displays how the building behaves during the large amount of the ground motion caused by the earthquake, also given by [6]. According to Chapter 11 Section 11.4-3, the values of S_{DS} and S_{D1} were calculated to check the Seismic Design Category D by comparing the values in Table 11.6-1. From Chapter 12 Section 12.8-1, the approximate fundamental period, T_a, equaled to 0.4 seconds by using the equation 12.8-7. The value of the seismic response coefficient C_s was 0.171 by using the equation 12.8-2. The maximum of Cs_{value} was 0.427 and the minimum value was 0.060. The total weight of the building totaled at 337.04 kips based on the material's weight in the construction.

Table 2. *Equivalent Lateral Force Procedure Results*

Level	W_x (kips)	h_x (ft)	$W_x h_x^k$ (k-ft)	C_{vx}	F_x (kips)
3	74	30	2220	0.363	20.921
2	126	20	2520	0.412	23.745
1	137	10	1370	0.224	12.910
∑ =	337.04		6110		57.576

The resulting base shear strength was summed to 57.634 kips by using the equation 12.8-1 in Chapter 12. The soil condition under the site was determined based from ASCE 7-16. The equations from Chapter 12, Section 12.8 Equivalent Lateral Forces (ELF) were applied to calculate the base and story shear.

Design for Sustainability and LEED Certification

The building was designed for sustainability and evaluated for LEED certification through the BD+C rating system for a new construction. The LEED certification levels possible to achieve are certified, silver, gold, and platinum. The six categories of focus from the LEED certification checklist were location and transportation, sustainable sites, water efficiency, energy and atmosphere, material and resources, and indoor environment quality [12]. When thinking about sustainable strategies to implement onto the building's design for certification, the approach taken was to put the well-being of the people and environment first. Fortunately, while designing around this approach, the features tended to create a ripple effect by benefiting many of the other credit categories besides the one intended [4]. Fig. 8 illustrates the green building features that were considered in the building's sustainability design with their corresponding benefited category to achieve LEED certification credits. Through the LEED certification checklist, this building achieved a gold level certification through reaching a total score of 69 credits.

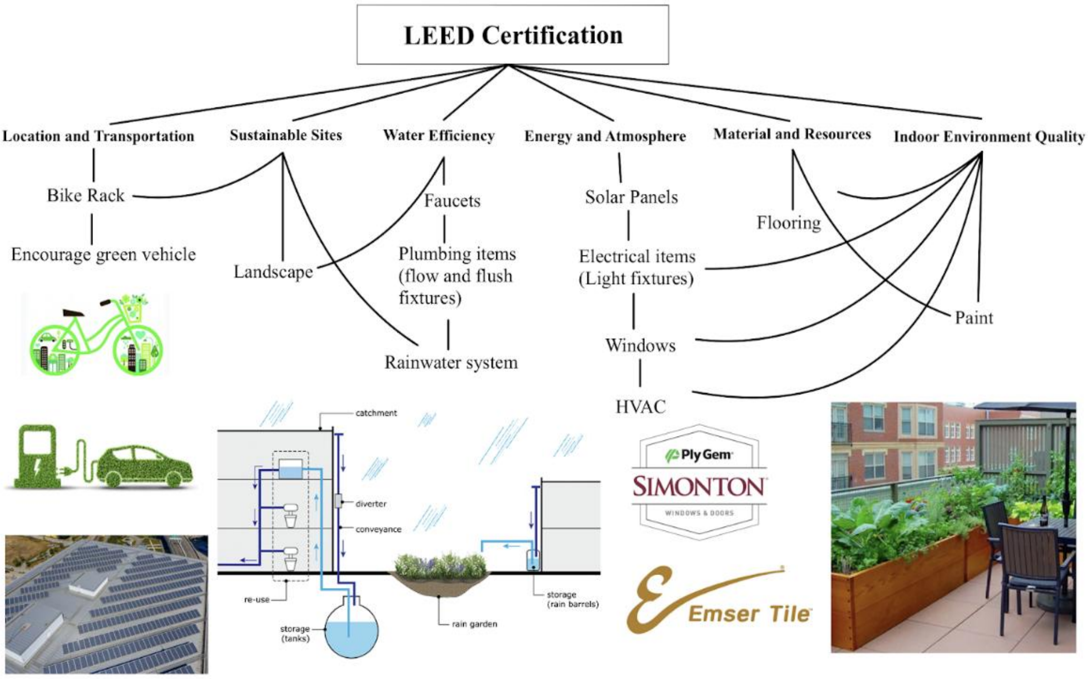

Fig8. *Features of the green building for LEED Certification*

Cost Analysis

A cost analysis was conducted to determine the total conventional and LEED cost of the building. It was shown that the LEED features are known to increase the cost of real estate compared to conventional [10]. Though, LEED allowed the annual cost of the building to decrease drastically as solar panels and rainwater catchment systems for the landscape were implemented. The return on investment was estimated to be 12 years upon completion of the construction. Table 3 shows the summarization of the building's results for cost analysis of a conventional and green building. Table 4 reviews the cost differences and future savings.

Table3. *Summary of the results for cost analysis of a conventional and green building*

Building Type	Total Cost	Total Operating Cost
Conventional	$1,929,195.42	$20,873.20
LEED	$2,132,762.33	$3,939.35

Table4. *Summary of the results for cost differences and savings*

Percent Increase	11%
Total Cost Difference	$203,566.91
Annual Cost Savings w/ LEED	$16,933.85
Time for Return on Investment	12.02 years

Educational Objectives

A LEED project research brings a lot of advantages and features to the structural design. The study aims to teach values in diversity, teamwork, women in engineering, leadership, creativity, innovation, and ethics. As the future is shifting away from fossil fuels, it is imperative to produce buildings of all types to be eco-friendly and LEED-certified to reduce its negative impacts on the environment. The benefits given in the long term significantly outweigh the drawbacks dealt with in the short term. The student-scholar model allows students to create and innovate on applying LEED-certification to a residential building. With the application of solar panels, students must demonstrate complex methods of design to accommodate such features in the structural design. The outcome upon completion of this senior design project provided the group an opportunity to work collaboratively with diverse students by improving interpersonal skills to set goals and meet the requirements of the project. Completing this senior project with an inclusive and collaborative attitude, allowed the team of students to share and acquire new knowledge. Overall, this design project reinstituted the importance to recognize the ethical and professional responsibilities one must have in engineering while considering the economy, environment, and society.

Conclusion

Leadership in Energy and Environmental Design was introduced to provide building owners a concise framework for implementing practical green building design elements. It aims to improve performance across all inflections that hold great importance such as energy savings, water efficiency, and improved indoor environmental quality that leads to higher quality of life. In this undergraduate research, the students have implemented the use environmentally friendly features such as the use of solar panels and rainwater harvesting for landscape to greatly reduce the annual costs. The application of LEED features decreased annual conventional costs by 81% as the cost of the construction increased by 11%. The educational aspect in this research achieved a practical approach to designing a residential building by exploring and developing creative engineering solutions. The group of diverse undergraduate students including first generation scholars, women in engineering, and multicultural backgrounds benefited regarding learning the constructs of working together. By implementing this student-scholar model, the students have familiarized themselves with engineering modeling and practical construction applications which will be utilized in engineering study and practice.

Acknowledgment

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