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Designing Affordable Housing in Ghana

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Abstract

Transient populations in rural areas experience a lack of available or familiar resources that make adjusting to rural life challenging. Teachers and nurses in the town of Akyem Dwenase in Southern Ghana are particularly affected by this phenomenon, but this adjustment can be supplemented through thoughtfully designed housing. This off-site project designed flexible housing units for teachers and nurses stationed in the town of Akyem Dwenase for an affordable, safe, and sustainable addition to the town. The design features Nelplast EcoBlocks, a product repurposing discarded waste plastic to reduce the cost and economic footprint of the design.

Keywords:
Ghana
Affordable Housing
EcoBlocks
Nelplast Eco, Ghana Ltd.
Sustainability
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Nelplast

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Authorship

Hannah Frieden was one of the main co-authors of this report. She contributed to the Executive Summary, Background, Methodology, Results, and Conclusions sections. While involved in all aspects of this project, her primary focus was writing and editing the written report and construction manual.

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We would also like to thank our partners in Ghana. The Chief of Akyem Dwenase, **Chief Osabarima**, greatly helped our team by explaining the needs and constraints of our project scope. Additionally, the Headmistress of L/A Junior High School in Akyem Dwenase, **Francisca Annor**, provided background information and further insight into the desired living conditions of the teachers. Further, **Nelson Boateng**, the CEO of Nelplast Eco Ghana Ltd., shared helpful information about Nelplast EcoBlocks, which greatly supplemented our design process. As an administration assistant at Nelplast Eco Ghana Ltd., **Enis Boateng** had an impact on our project as well, providing useful knowledge regarding EcoBlocks and their application. In addition, our project significantly benefited from our conversation with the Chief Linguist of Akyem Dwenase's development team, **Richmond Boadu Tinyase**.

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We greatly appreciate the endless support that our advisors and partners provided us throughout our project. Thank you.

Design Statement

ABET Criterion 5. Curriculum (2018-2019) states: "the four basic architectural engineering curriculum areas are building structures, building mechanical systems, building electrical systems, and construction/construction management. Graduates are expected to reach the synthesis (design) level in one of these areas, the application level in a second area, and the comprehension level in the remaining two areas." This team's MQP reached the design level in building structures, the application level in building mechanical systems, and the comprehension level in the remaining two areas.

The second part of the ABET criterion 5 further states that "the design level must be in a context that:

(a) Considers the systems or processes from other architectural engineering curricular areas,

(b) Works within the overall architectural design,

(c) Includes communication and collaboration with other design or construction team members,

(d) Includes computer-based technology and considers applicable codes and standards, and

(e) Considers fundamental attributes of building performance and sustainability."

The structural design took constructability into account. The ease and affordability of construction were considered and led to the decision to utilize one continuous concrete beam as the header for all windows on level 2, as described in this report. Additionally, the roof structural system was influenced by architectural aesthetics and building performance. Analysis in DesignBuilder indicated that a gable-end roof resulted in increased occupant comfort when compared to a mono-slope "shed" roof. Also, our team decided that a gable-end roof resulted in a more attractive architectural design. Thus, a structural system consisting of rafters and ceiling joists was chosen for the roof.

Our structural design also included computer-based technology and considered applicable codes and standards. Both MATLAB and Microsoft Excel were used in the structural design process. MATLAB was used to analyze concrete columns, and Microsoft Excel was used to size rafters. The 2018 American Wood Council National Design Specification and National Design Specification Supplement were used to design the roof structural system, and the 2021 International Building Code was used in the design of all structural systems.

The structural design process included contributions from all team members, and the design of each structural system was collaborative. The work performed by each individual student contributed to the overall structural design.

ABET Criterion 3 Student Outcome (2018-2019) furthermore notes that students should "attain an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors." Our overall MQP satisfied this outcome, as our team focused on providing affordable housing to serve a community in need. Public health, safety, and welfare were all considered in the overall design, as were cultural and social concerns specific to residents of Akyem Dwenase, Ghana. Additionally, environmental concerns were addressed through sustainable design strategies, and economic concerns were addressed through the use of EcoBlocks as an affordable building material.

Professional Licensure Statement

Professional licensure is important to the engineering profession as a whole, and this includes Architectural and Civil Engineering. In the United States, professional licensure results in an individual being granted the title of Professional Engineer. This allows the individual to attach their stamp or seal to drawings, calculations, letters, and other professional documentation. An Engineer's stamp of approval is required to receive a building permit in many situations, and a Professional Engineer is required in most projects in the built environment. Professional Engineers can also provide legal testimony and other related services.

In order to attain licensure, an individual must first complete an ABET-accredited degree in engineering. Substantial experience can substitute for an accredited degree in some situations, but an ABET-accredited undergraduate degree is often the first step to professional licensure. An individual must also pass the Fundamentals of Engineering (FE) exam. Requirements to sit for the exam vary by state, but individuals usually do not take it earlier than their junior year of college. After passing the FE exam, an individual needs the required work experience under a professional engineer, and to pass the Principles of Engineering (PE) exam. Required work experience varies according to education, but four years is most often required for individuals with a four-year ABET-accredited undergraduate degree. In some states, an individual can sit for the PE exam directly after graduation, while in some states experience is required before an individual can sit for the exam. Regardless of the exact timeline, acquiring the required work experience and passing the PE exam are both required to attain professional licensure. After all of these steps are completed, an individual can be licensed as a Professional Engineer. In order to maintain licensure, an individual must complete the required number of continuing education hours as specified by the state(s) they are licensed in.

Professional licensure is important to the individual, the profession, and the public. For an individual, professional licensure provides proof of their experience and capability. This can significantly benefit an individual's career. Professional licensure is important to the profession because it provides a definite standard by which we define an engineer. The profession as a whole is elevated when an engineer is defined by such stringent requirements and a high level of expertise. Professional licensure benefits the public in a similar way. It ensures that engineers who take responsibility for designs that can have a significant impact on the public are knowledgeable and qualified to take on such a responsibility.

1 *Executive Summary*

The way of life in rural Ghana is drastically different than that of urban areas. Most urban areas have grocery stores and restaurants which provide abundant and readily available food. Rural areas do not have this luxury; the land requires the utilization of raw resources for food which takes time and skill. Multi-generational homes have working adults, children, and older generations that are able to adopt the responsibility of food preparation. Smaller households have more difficulty with the rural way of life for this reason. In rural Ghanaian villages, teachers and nurses often find themselves in this situation.

The Ministry of Health and the Ministry of Education certify nurses and teachers, respectively, by stationing nurses and teachers who have been certified by larger institutions at schools and hospitals across the country (Kwansah et al., 2012). Usually, teachers have little say in their posting location. They will accept a job that's available to them, despite the multitude of logistical and personal problems involved with moving from an urban to a rural location alone.

One way to address this challenge is through reliable, inexpensive, and convenient housing. Many nurses reported that long commutes are a source of grievance in rural areas where walking is their only available mode of transportation. The walk to their place of work is long and nurses reported they were fearful of making the commute at night (Kwansah et al., 2012). In addition to transportation issues, nurses were faced with a general lack of accommodation. Some facilities have housing quarters for nurses that are congested and expensive, many force multiple nurses to share a single unit for a significant cost. In addition to these grievances, older nurses were greatly concerned about housing after retirement (Kwansah et al., 2012). Teachers in rural Ghana experience the same phenomenon as nurses. They lack adequate housing accommodations, have trouble adjusting to rural life, and are not keen to accept rural jobs.

Our project goal was to work with Nelplast Eco Ghana, Ltd. (Nelplast) to develop a prototype affordable housing unit that can be deployed in Akyem Dwenase to shelter teachers and nurses temporarily stationed in the area. To achieve this goal, we developed three overarching objectives with respective actions:

1. Identify future stakeholder needs and derive their influence on the design process.
2. Understand the building systems and material availability that inform the current infrastructure of Akyem Dwenase and their use with Nelplast EcoBlocks
3. Develop an architectural design for an affordable housing unit and present it in a format that is replicable and easily understandable.

The team conducted semi-structured interviews with stakeholders of the project to understand their goals, needs, priorities, and limitations with respect to our project and its impact on Akyem Dwenase, thus accomplishing methodology objectives 1 and 2. Interviewees included the Chief of Akyem Dwenase, the Headmistress of L/A Junior High School, and Nelplast Eco Ghana Ltd.'s CEO and Founder. Each of these stakeholders' priorities helps to define our design objectives.

With numerous interviews and inquiries regarding the necessary qualities of a teacher and nurse housing completed, we then translated their priorities into physical terms. This was done over a series of progressing design stages that resulted in a 3-dimensional rendering of our proposed model, construction documents, and a manual detailing construction methods.

Through an iterative design process, a truly affordable housing unit for teachers and nurses was developed with the goal of delivering a thermally comfortable and private living situation. Interviews, design prototype models, material testing, energy model simulations, and structural calculations were involved in the development of this housing.

2 *Background*

2.1 *History and Evolution of Urban Planning in Ghana*

The Republic of Ghana is located in Western, sub-Saharan Africa on the Gulf of Guinea. With a current population exceeding 30 million, it is the second-most populous country in West Africa, behind Nigeria (*2021 Population and Housing Census*, 2021). Ghana is divided into 16 regional provinces that collectively function under the country's unitary presidential republic under an elected president and legislative body (see Figure 1) (*Western North – National Commission on Culture*, 2022). Ghana is a multilingual nation. In addition to English, Ghana's official language, there are more than 80 indigenous languages commonly spoken in Ghana. Of the living languages, 13 are institutional and are implemented in nationwide communication with governmental recognition (Afrifa et. al, 2019).

Figure 1. Map of Ghana's 16 regions and orientation in Africa.
Source: National Commission of Culture, n.d.

Although Akans and Mole-Dagbon are Ghana's primary ethnic groups, much of Ghana's modern economic and governmental influence resulted largely from centuries of European imperialism.

The borders of modern-day Ghana are a result of the union of formerly British-governed regions: the Gold Coast and Asante colonies, and the protectorates of the Trans-Volta Togoland and the Northern Territories. The region was nicknamed the Gold Coast in reference to the region's plentiful industrial mineral wealth, coined when modern-day Ghana's rich gold deposits and access to ivory peaked Portuguese and Dutch interest in the late 15th century. This manner of imperialism incentivized by resource exportation largely defines Ghanaian history.

The British became the primary governance over the four regions in 1874. The catalyst for regional unification and eventual Ghanian sovereignty was the rapid economic expansion spurred by the heightened production of cacao. Political advancements soon followed the dramatic economic development and enabled radicalists to alter the landscape of sub-Saharan African colonialism. Led by Kwame Nkrumah and members of the Convention People's Party, Ghana gained its independence on March 6th, 1957, and became the first colony in sub-Saharan Africa to achieve sovereignty. Ghana's freedom marked the beginning of Pan-African decolonization and the final dismantling of European involvement in Africa.

A subject of European influence for over five centuries, it is no surprise that Ghana's urban landscape fell victim to Western ideology. Ghana's current capital city, Accra, is located on the southern coast and predates Ghanaian independence. At the time of its establishment in 1877, the British methodically decongested the city to make space for its own administration and facilities. This introduction of urban sprawl disrupted Accra's existing structure and established an unsustainable foundation for the city's layout.

Accra became the British colonial headquarters and the city's urban planning methods mirrored the controlling nature of Britain's relationship with the indigenous population. Lands were commonly seized for public service or sold to European capitalists for industrial use, and individual land ownership virtually disappeared (Sackeyfio, 2012). Countless barriers, including language or status, excluded indigenous populations from participating in the planning and evolution of Accra. Basic structures of land use were disrupted, including Accra's agricultural practices. Before British interference, land for agriculture in Accra was considered transitional and would rotate in cycles to promote successful crops. British planning efforts introduced permanent cultivation methods and removed Accra's transient regimes of farming. Urban planning under colonialism prioritized control and exhibited no consideration for existing social structures (Njoh, 2009).

The city's land was exploited and no master plan existed until one year after the country's independence in 1958. The master plan was proposed by the Ministry of Housing and published in a book entitled *Accra: A Plan for the Town*. The plan emphasizes Accra's need for a simple extension of existing patchwork-like infrastructure and not a complete redesign. The 150-page plan placed significant weight on the overall aesthetic nature of the city, restoration of access roads, creation of Accra's first parks, and combating Accra's overcrowded slums. In 1958, Accra's annual population increased at a rate faster than that of Ghana and early signs of severe overcrowding emerged. To combat this, the Ministry of Housing designated resources to restore neighborhoods closest to amenities such as schools, markets, or places of worship (Inkumsah & Nkrumah, 1958). Unfortunately, the plan was short-lived after Ghana's first president, Kwame Nkrumah, was overthrown in 1966. The military coup launched the country into a "silent period of spatial planning," a time in which no master plans were considered until the early 1990s (Harrison & Croese, 2022). In recent years, government bodies have proposed strategic spatial plans for Accra and the Greater Accra Metropolitan Area in an effort to develop a framework reminiscent of a "modern national capital." Despite their efforts, contrasting visions and interests regarding Accra's development have resulted in the practice of master planning being "one fraught with contestation" (Amedzro, 2021). The most recent master plan was developed by Singaporean architect and planner Dr. Liu Thai Ker and was met with heavy criticism. When considering the future of Accra, there is a disconnect between government officials and the common population. While one hopes to continue "postcolonial visions of urban modernity", the other feels the local knowledge and planning capacity of Ghanaians is being overlooked. Either way, both agree that a master plan is necessary to solve Accra's current urban crisis.

Today, Accra is one of Africa's fastest-growing cities with an annual population increase of more than 2% (*2021 Population and Housing Census*, 2021). Housing over 4 million inhabitants in 2021, Accra is set to become a mega-city with over 10 million occupants by 2050 (*Accra, Ghana*, 2022). According to the World Health Organization, Accra faces a multitude of challenges resulting from poor urban planning that must be resolved to successfully support an ever-growing population. Alongside poor waste-management practices, diminished air quality due to pollution, and inefficient public transit, Accra's housing crisis arguably poses the most looming threat to the city's future.

Traditional Ghanaian homes house generational family units, with 60% of immediate families residing in a single room. Less than a quarter of Accra's households own a home, leaving the other 75% of the population to live in the family home or rent. Renting in Accra varies drastically from typical Western-style homes to haphazardly built shelters.

Accra is the densest urban area in Ghana with an estimated 3,367 people living within a square mile (1300 people per square kilometer), far exceeding the country's average population density of 201 people per square mile (78 people per square kilometer) by a factor of 16. Despite housing approximately 13% of Ghana's total population, Accra does not sufficiently shelter the vast majority of its population and has experienced a severe housing deficit since the early 2000s (*2021 Population and Housing Census*, 2021). In 2021, 58% of Accra residents lived in informal, low-incoming housing settlements known as slums. These slum districts are overcrowded, have limited access to clean water, and have poor sanitation practices. Those living in slums are frequent victims of demolitions and displacements as the city expands to comfortably house the wealthy. The projected population growth is predicted to be absorbed almost entirely by slums, only worsening the city's overcrowding and decreasing the standard of living. Those living in slums do not necessarily embody typical stereotypes, in fact, approximately 15% of Accra's largest slum district, Old Fadama, population are working formal sector employees (Tasantab, 2018).

The housing crisis is the direct result of a lack of affordable, secure housing for the low-income population of Accra. Accra's economic climate is a paradox, where the uber-wealthy and impoverished cohabitate. A problem rooted deep in colonial times, the problem was further exacerbated when the Ghanaian government withdrew from being an "active provider of housing" after the adoption of the World Bank and International Monetary Fund's structural adjustment programs in the 1980s. The adoption of such financial programs privatized the rental housing market to create a "profit-driven housing production targeted towards high-income residents" (Tasantab, 2018). Before long, extravagant penthouses, gated communities, and high-end family homes dominated the housing market. The growth of the luxury market, rising land prices, decreased land access, and lack of housing finance services have effectively marginalized locals from obtaining secure housing.

This problem, although significant in Accra, is especially apparent in rural Ghana where individuals experience a heightened lack of accessible resources. Rural communities face financial barriers, limited access to quality building materials, and formal construction knowledge as the majority of homes are built by future occupants. Despite the rental housing market's limited success in sheltering urban Ghanaians, the rental housing market is not a prominent or sustainable source for housing in rural areas and further exaggerates these obstacles for residents (Danso-Wiredu & Poku, 2020).

2.2 *Traditional Ghanaian Living*

The largest ethnic group in Ghana is the Akan people. Currently, the group makes up around 48% of the population in the country (Salm & Falola, 2002). The Akan people have many cultural traditions regarding family structure, social networks, lifestyle, and activity systems. Amos Rapoport, an architect, and contributor to environmental behavior studies believes that the close relationship between housing and culture results in housing communicating identity (Nduom, 2018). In Ghanian rural villages, he is correct, traditional ideals influence the design and use of the home. They are present in the three common styles of housing often found in Ghana: compound housing, detached housing/bungalows, and semi-detached housing.

In 2007, around 46% of homes in Ghana were compound houses, making it the most prevalent type of housing. The second most popular was detached housing/bungalows at 25% and the third most was semi-detached at 15%. Figure 2 shows the breakdown of the distribution of housing types in Ghana.

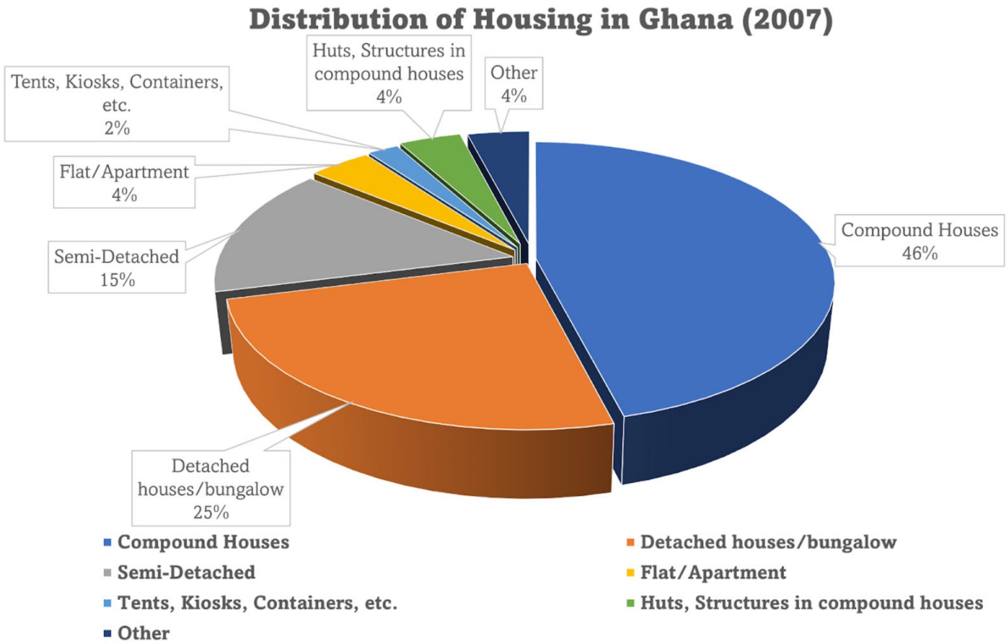


Figure 2. Distribution of Housing in Ghana in the year 2007.
Source: Bank of Ghana Report, 2007 and Adinyira et. all, 2010.

Compound houses originate back to earlier African civilizations where a husband often needed multiple bedrooms to house each of his wives (Nuser, 2022). The rooms are "typically arranged in rectilinear fashion around an open courtyard" (Afram, 2007). The courtyard acts as the center for many traditional activities in the Akan culture such as socializing, cooking, and holding family events (Ibukun, 2021). The rooms located off the courtyard primarily consist of bedrooms, a kitchen, a living room, and bathrooms (Afram, 2007). Photos of a typical compound home located in Southern Ghana can be seen in Figure 3 below.

Figure 3. Overhead view of homes in Southern Ghana demonstrating the emphasis on a central Courtyard.
Source: Google Earth

Most of the spaces in the typical compound house are shared between the residents (Ibukun, 2021). The layout provides a form of security as well as the opportunity for family members to assist others with their work life. Often, one family member will go to work while the other assists with dinner and other common house tasks. However, the rapid urbanization of Accra is leading to more cramped conditions in compound houses as the residences keep splitting the houses into smaller and smaller units (Ibukun, 2021).

The second most popular style of housing is the detached house/bungalow. This style of housing is easy to build and generally cost-effective. Typically, it is a two-to-three-bedroom house, and it is most popular among newlyweds and the working class (McGoldrick, 2022). These houses stand separately from other homes and usually contain more outdoor space than the other types (Nuser, 2022). Unlike compound-style houses, these houses are usually located in neighborhoods or areas where there is more space. The front or backyard serves as a place to hold family events or a space to socialize with others.

The third common style of housing in Ghana is the semi-detached. Semi-detached houses share one wall with another house but they are separate in living quarters and other areas of the home. It is common that teachers and nurses will get relocated for their job to an urban area as their demand is high, but the quantity is low. These houses often act as staff quarters for teachers, nurses, etc. while they work their jobs (McGoldrick, 2022).

Recently, the housing typology in the country is starting to shift from the traditional dwellings of the various ethnic groups to single-family homes and townhouses (McGoldrick, 2022). The inspiration for this shift comes from western iterations such as modern luxury high-rise and middle-income apartment dwellings. Nearly all houses in the urban areas of Ghana are constructed using the local knowledge and systems present in the area. Material cost is 80% of a typical Ghanaian home so residents commonly prefer building their own dwelling as it is cheaper, and they can utilize the resources local to the region (Nduom, 2018).

2.3 *Traditional Building Materials and Systems*

Although building materials and systems tend to vary by region, use, and socioeconomic status, there are clear prevailing methods used throughout the country. Concrete blocks account for 77.8% of building materials used in homes in both rural and urban areas. Overall, 57.5% of buildings are constructed with cement and concrete (McGoldrick, 2022). While wood is a primary export of Ghana, it is only used in about 3.4% of homes (McGoldrick, 2022). Alternatives include rammed earth or mud walls, which are generally used more in rural areas. Both concrete and earth wall systems rely on their high compressive strength to withstand vertical loads. They are generally at least 8” thick, and concrete walls usually include steel reinforcement to provide tensile strength. These wall systems act as barrier walls, with the concrete blocks or earth acting as the air, water, and vapor barrier, as well as the structural system. Different facade elements can be added to concrete masonry walls, to provide an additional layer of protection against the elements. Brick facades often accompany concrete masonry walls in western nations. These wall systems are called cavity walls and allow precipitation to enter the wall system before being redirected downward and back outside.

The main traditional construction material for roofs in Ghana is corrugated metal sheets, used in 77.8% of homes (McGoldrick, 2022). These corrugated metal sheets are relatively easy to install and can manage longer spans, however, they must be imported and can be expensive.

Access to utilities is varied throughout Ghana. In most communities, water is available from a central source and is carried to homes by underground pipes. Toilet usage, however, is far different from western standards. While toilets are common in urban Ghana, many communities in rural northern Ghana still practice open defecation to some extent (Delaire et al., 2022). Even among the households that do have toilets, many are not flushable but instead flow to a pit or latrine.

Building mechanical systems also vary throughout Ghana. Heating is not necessary, as temperatures in Ghana do not dip enough to be uncomfortable and typically range between 90°F and 75°F during the day (*Accra 2022 Past Weather (Ghana) - WeatherSpark*, n.d.). Due to consistently high temperatures, air-conditioning is often necessary. While commonly implemented for many commercial and public buildings, air-conditioning is used less in residential settings. Still, A.C.

ownership is high in certain demographics, as “household heads aged between 19 and 54 years and in full-time paid employment have high ownership of A.C.s” in urban Ghana (Sakah et al., 2019). Among air-conditioning systems that are used, 71% are non-ducted single split A.C.s, while 12% are window-type A.C.s (see Table 1).

Table 1. Types and Market Share of Air-Conditioning Equipment in Ghana *(Opoku et al., 2019).*

Type	Percentage
Non-ducted multi-split (VRF) A.C.s	4%
Non-ducted single-split A.C.s	71%
Window-type A.C.s	12%
Central A.C.s	8%
Standing and Portable A.C.s	5%

Non-ducted single-split A.C.s are often referred to as “mini-splits” in the U.S. These consist of an outdoor condenser connected to an indoor evaporator by several small pipes. Window-type A.C.s consist of a single unit containing a condenser and evaporator. Outdoor air enters the unit through an existing window, and conditioned air exits the unit into the living space.

While these types of units are generally cheap and easy to install, they are often inefficient. This is true in Ghana, where over 85% of air-conditioners exist in the lowest energy efficiency ratio category (1-star) and the remaining percentages are in the next lower categories (2 and 3-stars) (Opoku et al., 2019). While higher-efficiency air-conditioning units may be cost-prohibitive in the short-term, “total electricity cost savings potential of about US$ 1.96 billion can be achieved from the year 2018–2030 with higher EER air-conditioners in Ghana” (Opoku et al., 2019).

On the topic of energy, electricity generation in Ghana is somewhat unreliable. The nation has historically relied on hydropower as its main source of electricity generation, however recent increases in demand have resulted in electricity supply-demand margins - the difference between peak demand and available supply - falling short of the recommended range (Gyamfi et al., 2015). As a result, the country has experienced more frequent power cuts over the last decade. Low-efficiency appliances have only exacerbated this problem. Renewable energy sources could be a solution, with Ghana having strong potential for solar and wind energy generation (Gyamfi et al., 2015). In terms of residential electricity usage, higher-efficiency appliances can reduce demand while on-site renewables can increase supply. However, these solutions are often unaffordable for average citizens.

Passive design strategies can increase occupant comfort with less cost and energy consumption. In Ghana's tropical climate, passive cooling is most relevant. One common passive cooling method is evaporative cooling, where cooling is provided through natural evaporation. This strategy does not work well in southern Ghana, as this part of the country has a humid, tropical climate where the air is saturated with water and natural evaporation occurs less than in Northern Ghana's arid climate (Amos-Abanyie et al., 2009).

Choosing building materials with high or low thermal mass can also regulate temperature. Materials with high thermal mass typically absorb heat during the day and release it at night, but this is not possible in an area where temperatures remain elevated at night. In southern Ghana, incorporating low thermal mass materials will have a better effect on reducing cooling loads, as this allows the building to cool off quickly at night (Amos-Abanyie et al., 2009).

Another passive strategy that may be applicable in Ghana is passive radiative cooling. Radiative cooling naturally occurs at night as buildings and other surfaces radiate solar energy that was absorbed during the day. Specially designed paints or films can be added to the exterior of the building to allow this effect to occur during the day as well (*An Overview of Passive Daytime Radiative Cooling Materials*, 2022). Also, building energy simulation has shown that larger roof overhangs can be used to reduce cooling loads in existing buildings. Roof overhangs work to limit sun exposure in living spaces during hot days. Passive ventilation has also been effective in renovation situations, with increased ventilation providing reduced cooling loads and increased occupant comfort (*Feasibility and Retrofit Guidelines towards Net-Zero Energy Buildings in Tropical Climates*, n.d.). Overall, a number of passive strategies can be used to provide cooling and/or reduce cooling load. Specific strategies must be selected based on climate and situation.

In summation, there are clear prevailing construction materials in Ghana. Among these are concrete blocks for wall construction and corrugated metal sheets for roofing. Mini-split air-conditioning systems are most common where air conditioning is used, and plumbing access varies throughout the county. Electricity is available but not always reliable, and as a result, passive design methods should be considered. In general, a mix of traditional and non-traditional materials and methods may result in desirable outcomes.

2.4 *Significance of Housing for Teachers and Nurses*

The way of life in rural Ghana is drastically different than that of urban areas. Most urban areas have grocery stores and restaurants which provide abundant and readily available food. Rural areas do not have this luxury; the land requires you to utilize raw resources for food which takes time and skill. Multi-generational homes have working adults, children, and older generations that are able to adopt the responsibility of food preparation. Smaller households have more difficulty with the rural way of life. In rural Ghanaian villages, teachers and nurses often find themselves in this situation.

Many rural Ghanaian villages do not have institutions necessary for legally certifying nurses and teachers. Therefore, the Ministry of Health and the Ministry of Education take on this responsibility by stationing nurses and teachers who have been certified by larger institutions at schools and hospitals across the country (Kwansah et al., 2012). Usually, teachers have little say in their posting location. They will accept a job that's available to them, despite the multitude of logistical and personal problems involved with moving from an urban to a rural location alone.

In a study conducted in 2012 in conjunction with the Ghanaian Ministry of Health, many nurses express dissatisfaction and resentment due to the fact that they have little to no say in their placement and the adjustment to rural life is daunting. Many of them share the sentiment that these postings are a sacrifice, while a select few see it as their duty to the healthcare industry (Kwansah et al., 2012). Nurses who come from urban areas hope to spend 3 or 4 years at these postings before being transferred to a higher level, as the overarching goal for most nurses in this study was to advance their careers. However, many spend much longer at their posting and have to face numerous challenges in the process, such as working without lighting at night, being generally overworked, and therefore is prevented from growing within their profession. Understandably, nurses become discouraged as they do not see themselves learning and advancing their careers as they are limited by unreliable electricity, unsophisticated equipment, and a lack of running water. This lack of resources complicates their practice and livelihood.

There is an opportunity to relieve this dissatisfaction through reliable, inexpensive, and convenient housing. Many nurses reported that long commutes are a source of grievance in rural areas where walking is their only available mode of transportation. The walk to their place of work is long and nurses reported they were fearful of making the commute at night (Kwansah et al., 2012). In addition to transportation issues, nurses were faced with a general lack of accommodation. Some facilities have housing quarters for nurses that are congested and expensive, many force multiple nurses to share a single unit for a significant cost. In addition to these grievances, older nurses were greatly concerned about housing after retirement (Kwansah et al., 2012).

Teachers in rural Ghana experience the same phenomenon as nurses. They lack adequate housing accommodations, have trouble adjusting to rural life, and are not keen to accept rural jobs. Many private sector schools offer incentives to their teachers to relocate such as free healthcare, transportation, and meal allowances (Yeboah & Adom, 2016). Public schools do not have the luxury of providing the same incentives and struggle to provide accommodations to teachers. As with nurses in rural areas, housing provides an opportunity to increase the satisfaction of teachers. Increased satisfaction with job conditions has been shown to lead to enhanced job performance in numerous studies (Oswald et al., 2015). This is an adequate incentive for a village government to consider the enhancement of housing opportunities a worthwhile investment in their people.

2.5 *Local Innovation and Teacher Housing*

In this pursuit to design affordable housing units for Ghanaians, a connection was formed with a company called Nelplast Eco Ghana Ltd. Nelplast is an organization focused on increasing housing availability by repurposing plastic waste into construction materials. There are two main outputs that Nelplast creates: tiles for pavement purposes, and blocks for building wall structures (*About Nelplast Eco Ghana*, n.d.).

The Lego-like blocks produced by Nelplast are known as EcoBlocks. The process of creating these EcoBlocks is simple: in a nutshell, plastic waste is melted and mixed with river sands, and then molded into useful structural supplies. This plastic and sand mixture consists of 30% recycled plastic and 70% river sand (McGoldrick, 2022). First, plastic is collected, shredded, and washed if needed. Then, the plastic is dried and mixed with the river sand. Red, brown, or green coloring can also be added at this point. This mixture is then heated up to 220°C (428°F) to create a paste. Lastly, the paste is inserted into a mold that shapes the material into a distinct interlocking pattern to create the EcoBlocks (McGoldrick, 2022). All types of plastics (except PVC) are used to create these bricks (*Recycling Of Plastic Waste Into Building Materials*, n.d.).

Plastic waste is an issue that has plagued the Ghanaian ecosystem for years. The waste buildup has chronically polluted the landscape and its water bodies (*About Nelplast Eco Ghana*, n.d.). Nelplast's initiative has found an effective use for this excess of plastic in the country. Concurrently, the aforementioned housing crisis in Ghana became increasingly prevalent. The country's housing deficit is expected to surpass 4.2 million units by the year 2030 (McGoldrick, 2022). The creation of these EcoBlocks kills two birds with one stone: simultaneously increasing housing accessibility while decreasing environmental waste. On top of these benefits, the EcoBlocks are affordable; Nelplast products are 30% cheaper than concrete housing (*About Nelplast Eco Ghana*, n.d.).

The Nelplast EcoBlocks have a number of strengths, one of which is the sound integrity of resulting structures due to the interlocking capabilities of the bricks. Nelson Boateng, the CEO of Nelplast, has stated that "if there is any shake in the Earth, it [an EcoBlock structure] has the ability to expand itself and contract" (*Take a Look at Ghana's First Plastic House*, n.d.). The interlocking pattern diminishes the need for mortar in the wall structure, therefore preventing any permanent damage to structures in the event of an earthquake. Additionally, the blocks are specifically designed to include an interior groove that prevents heat from being trapped within EcoBlock structures (*Take a Look at Ghana's First Plastic House*, n.d.).

Since the company's foundation in 2018, there have been over 20 projects brought to completion using Nelplast EcoBlocks. Beyond the primary outcomes of reducing plastic waste output in the country and increasing the accessibility of low-income housing, the efforts of Nelplast have also resulted in the creation of a multitude of jobs. Nelplast has hired almost 80 workers directly and assisted in the employment of nearly 200 additional workers (*About Nelplast Eco Ghana*, n.d.). Nelplast's progressive intentions are clearly displayed through the company's outputs - benefiting the community and environment through the supply of sustainable housing materials. It's evident that a collaboration with Nelplast would complement our goal of improving the accessibility of affordable housing in Ghana.

There's no question that the structural, affordable, and sustainable aspects of the Nelplast EcoBlocks are beneficial. For this reason, we decided that one central goal of our project would be to utilize EcoBlocks as our primary building material. Every interior and exterior wall of our housing structure will be constructed with the EcoBlocks. Additionally, the corners/intersections will be constructed out of the column EcoBlocks, which are hollow and slightly larger than the regular EcoBlocks. The column blocks are filled with concrete and steel reinforcements to provide structural stability.

This partnership with Nelplast will help to bring our project to completion as the materials are accessible and relatively affordable at 50 cents per block. The feasibility of our housing design will be greatly supplemented by the cost-effectiveness and environmental friendliness of the EcoBlocks. With this design strategy at the forefront of our minds, the next step in our process was to gain information on the specific needs that our housing design will address. To do so, we commenced the methodology portion of our approach.

3 *Methodology*

Our project goal was to work with Nelplast to develop a prototype affordable housing unit that can be deployed in Akyem Dwenase to shelter teachers and nurses temporarily stationed in the area. To achieve this goal, we developed three overarching objectives with respective actions:

1. Understand the cultural context, building systems, and material availability that inform the current infrastructure of Akyem Dwenase.
2. Identify future stakeholder needs and derive their influence on the design process.
3. Develop an architectural design for an affordable housing unit and present it in a format that is replicable and easily understandable.

To collect accurate, relevant data for the project, we structured the approach based on Rapid Assessment Procedure and User-Centered Design.

To assess the stakeholder needs in a short period of time, the Rapid Access Procedure (RAP) will be implemented. First coined by author and anthropology professor James Beene in his 1995 publication of *Basic Concepts and Techniques of Rapid Appraisal*, RAP is a subjective, contextualized, and flexible qualitative research approach derived from ethnography. Ethnography is the scientific description in which "culture-sharing groups interpret their experiences and create meaning from their interactions" (Dharamsi & Charles, 2011). According to Beene, RAP employs "team-based qualitative inquiry" and iterative data analysis processes to "quickly develop a preliminary understanding of a situation from the insider's perspective" (Beebe, 2008). In contrast to deductive research in which inquiry is linear and pre-planned based upon prior knowledge of a system, RAP is inductive and the direction of research "depends on what was just uncovered" (Ragin et al., 2004, p. 12). This process consists of three main components: the system perspective, triangulation of data, and iterative analysis. The system perspective requires researchers to begin data collection without expectations or assumptions and to let curiosity guide their findings. Identifying where or to what factors stakeholders assign importance is discovered through semi-structured interviews and direct observation. The goal of this step is to understand the etic perspective of the topic from individuals of varying backgrounds. Next, triangulation considers multiple perceptions and opens the research to comparison. Triangulation introduces a cross-examination across research methods to ensure the data's accuracy and quality. Lastly, the iteration process compiles the data into findings and provides space for the research team to reevaluate their methods and revisit outstanding questions. This step establishes RAP as an open feedback loop where the system can be repeated and changed until satisfactory (Beebe, 2008).

To best suit RAP, we conducted semi-structured interviews to determine front-end stakeholder needs and inform design decisions. Direct observation also informed our research through picture and video analysis of existing conditions. Although fieldwork and participant observation are other important branches of RAP, these were not implemented in their entirety due to the limitations introduced by the virtual nature of our contact with stakeholders.

While RAP is the research process that guided our data collection, User-Centered Design (UCD) is what ultimately transitioned our research into the design process. User-Centered Design, or Empathic Design, in architecture or planning, is the process by which designers interact with future inhabitants to empathize with how the space impacts life experiences. Spaces designed using UCD are highly usable and accessible to the target population (Sandman et al., 2018). UCD is divided into five tasks: explore, inquire, define, co-ideate, and pilot. A flow chart for this technique is shown in Figure 4.

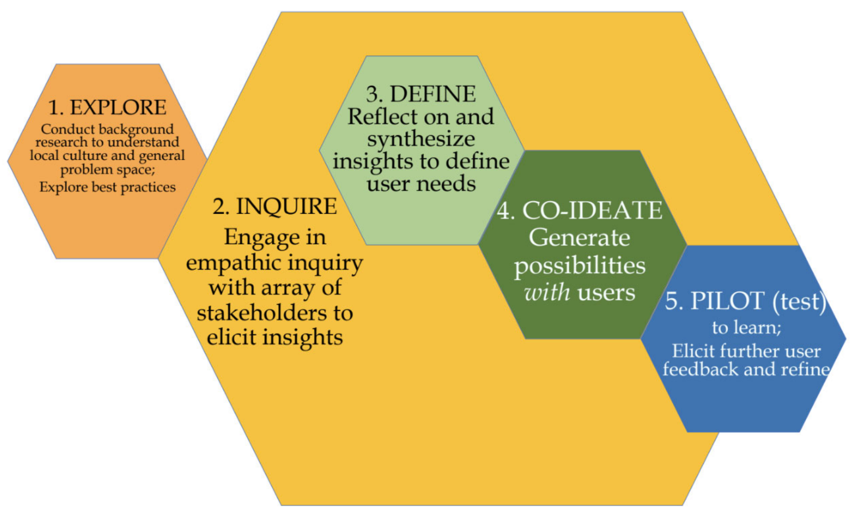


Figure 4. User-Centered Design Flowchart. *Source: Sandman et al., 2018.*

Similar to RAP, this approach requires the engineer, designer, researcher, and stakeholders to be equally involved in the project's progress. UCD prioritizes holistic sustainability and ensures pre-existing, outside biases do not interfere with the final product. Holistic sustainability encompasses human physical well-being through the built environment while considering social and economic dimensions. Sustainable development of the built environment requires the consideration of both "the natural and human systems that depend on them" (World Bank, 2021). It factors in the environmental, economic, social, and cultural implications of the development (Figure 5) and works to mitigate anticipated negative effects (Sandman et al., 2018).

Figure 5. User-Centered Design Factors. *Source: Sandman et al., 2018.*

Throughout our research and design process, aspects of both Rapid Assessment Procedure and User-Centered Design were prominent guidelines in completing our objectives.

3.1 *Objective 1: Identify future stakeholder needs and derive their influence on the design process.*

The team conducted semi-structured interviews with stakeholders of the project to understand their goals, needs, priorities, and limitations with respect to our project and its impact on Akyem Dwenase. Interviewees included Chief Osabarima of Akyem Dwenase, Headmistress of L/A Junior High School, Francisca Annor, and Nelplast Eco Ghana Ltd.'s CEO and Founder, Nelson Boateng. Each of these stakeholders' priorities helps to define our design objectives.

3.1.1 *Assess community needs and housing requirements to be integrated into the design.*

First, we began by interviewing key partners of Akyem Dwenase, starting with Chief Osabarima. The goal of interviewing Chief Osabarima was to understand the town and gain knowledge of Osabarimas's goals for the potential new housing. We conducted the interview over the phone using the messaging app called "WhatsApp" and recorded minutes during the interview. Chief Osabarima had valuable information on the type of housing they were looking for and had other contacts within the town, initiating the snowball approach of interviewing.

After interviewing Chief Osabarima, we conducted a set of semi-structured interviews with current residents in the town. The Headmistress of L/A Junior High School, Francisca Annor, was the next interviewee who explained to us the details of her and her peers' current living and what improvements could be potentially made. This information would be very valuable to aid with our design process and allow us to produce an affordable house tailored specifically to teacher needs. Some limitations to this method were the language barrier and the impersonal nature of a voice call.

In conjunction with speaking with our partners in Akyem Dwenase, we asked them to send photos and videos of their homes and of the town, which were analyzed with consideration of the following criteria:

- Home style
- Program
- Construction methods
- Materials
- Unique Preferred Features
- Areas of evident deficiency

Having studied the pictures and videos provided to us by our partners, we documented our findings and synthesized the information to determine best practices to incorporate into our design.

While our design may be unique for the area in many aspects, it was still important to retain familiarity with local practices. This helps to ensure material availability, and improves constructability, as local builders are already familiar with specific techniques and systems.

Having studied the pictures and videos provided to us by our partners, we documented our findings and synthesized the information to determine best practices to incorporate into our design.

3.1.2 *Assess Community Engagement and Town Interests*

To identify stakeholder needs and their future influence on the design process, we conducted an interview with a member of the Akyem Dwenase Development Team, Richmond Boadu Tinyase. The goal of this interview was to gain the support of the town and design a unit that was most likely to come to fruition.

3.2 *Objective 2: Understand the building systems and material availability that inform the current infrastructure of Akyem Dwenase and their use with Nelplast EcoBlocks*

To help gain a stronger understanding of the building systems and available materials of Akyem Dwenase, we conducted target interviews and analyzed pictures and videos of Ghanian homes during their construction.

3.2.1 *Evaluate current mechanical, electrical, and plumbing systems in homes.*

We conducted a semi-structured interview with Nelplast's CEO and Founder, Nelson Boateng to become more familiar with EcoBlock. Insights into how the company previously integrated building systems with the EcoBlock would benefit our understanding of building systems in Ghanaian homes.

Next, we researched the typical mechanical, electrical, and plumbing systems in homes by analyzing pictures and videos from our partners in Akyem Dwenase. After obtaining pictures and videos of Ghanaian homes, we determined the applicability of these systems to our design and returned to our contacts with follow-up questions to fully understand each system. One limitation of this method was that we could not see how each system was put together in detail or exactly how the wiring/plumbing ran inside the walls. Our limited view was required to be supplemented by reading educational journals and locating relevant Youtube videos. This assisted in the incorporation of these building systems into our final design.

3.2.2 *Identify locally accessible and affordable building materials.*

To have a strong understanding of material availability in Akyem Dwenase, we researched the most common building materials that are local to the region as well as interviewed our partners. Nelson Boateng and another member of Nelplast, Enis Boateng, were asked what construction materials they encountered through their recent work. Regional availability was to be prioritized in material selection, as it contributes to the sustainability of the project. Sources of these materials were also evaluated for the cost to accomplish the overarching goal of the project, which was that it was affordable for teachers and nurses. These materials' limitations were also identified, as some provide more strength and durability than others. Materials selections were then made based on strength, cost, and availability.

3.2.3 *Identify the structural constraints and construction methods of Nelplast's EcoBlock.*

To gain further insight into Nelplast's EcoBlock building potential, we conducted semi-structured interviews with Nelplast experts, analyzed construction videos and test reports on the EcoBlock, and conducted our own EcoBlock performance tests.

We held semi-structured interviews with Nelson and Enis Boateng to gain a more in-depth knowledge of the structural constraints and construction methods of Nelplast's EcoBlock. Nelson Boateng is the founder of the Nelplast EcoBlocks and provided a background on the company's previous prototypes and construction process. More technical information such as the process of making an EcoBlock, the material constraints, and the structural characteristics of the EcoBlocks were also inquired about. All interviews with Nelson were conducted through WhatsApp phone calls. Enis Boateng, Nelson's nephew, is also affiliated with Nelplast and is a graduate student at WPI studying material science. He was an easily accessible contact that we consulted for in-person semi-structured interviews about the construction process. By consulting both Enis and Nelson, our group was able to gain useful knowledge on EcoBlocks and the construction process.

In addition to the information from Enis and Nelson, we performed research online to find videos on the construction process of how a previous house was built using EcoBlocks. Next, we analyzed the testing data on an EcoBlock from Ghana Standards Authority (GSA). As a result of that, it helped us understand the limitations and structural constraints to accurately perform structural calculations in our design. There was however a drawback to using the results from the GSA. From the test reports we obtained, the data appeared to be only for a paver-type block that was a different shape from the EcoBlock.

To combat the discrepancy in the data about the limitations and structural constraints of the EcoBlock, we conducted performance testing using the EcoBlock here at WPI. The group contacted Russel Lang in the Kaven Hall laboratories to perform two different kinds of tests on the EcoBlock. The first was a compression test and the second one was a shear test to determine interface properties.

To calculate the compressive strength of the EcoBlock, the block was carefully cut into smaller uniform sections using a circular saw equipped with a diamond blade (Figure 6). The block was divided into 22mm x 22mm x 52.5mm sections, ensuring that each sample was complete and being careful to avoid the EcoBlocks many voids. The prepared material samples are shown in Figure 7.

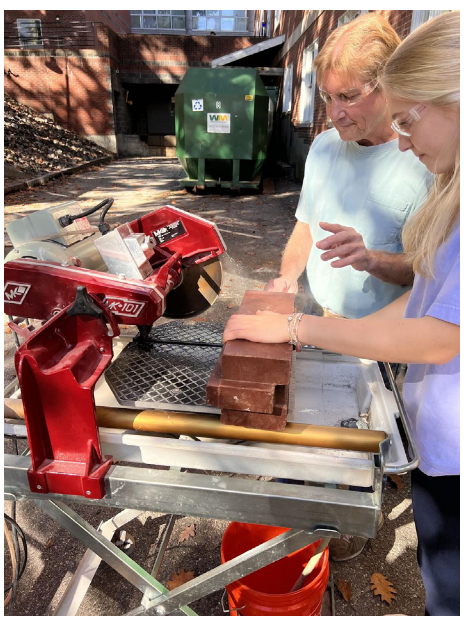


Figure 6. EcoBlock Sample Preparation for Testing

Figure 7. EcoBlock Samples #1-5 Before Compression Testing

The compressive stress tests were conducted using an Instron 5567A universal testing machine (UTM) with a loading capacity of 6,000 lbs. To conduct the compression test, the samples were placed vertically under the compression plates and the UTM's compression was set at a rate of 1.5mm per minute (Figure 8).

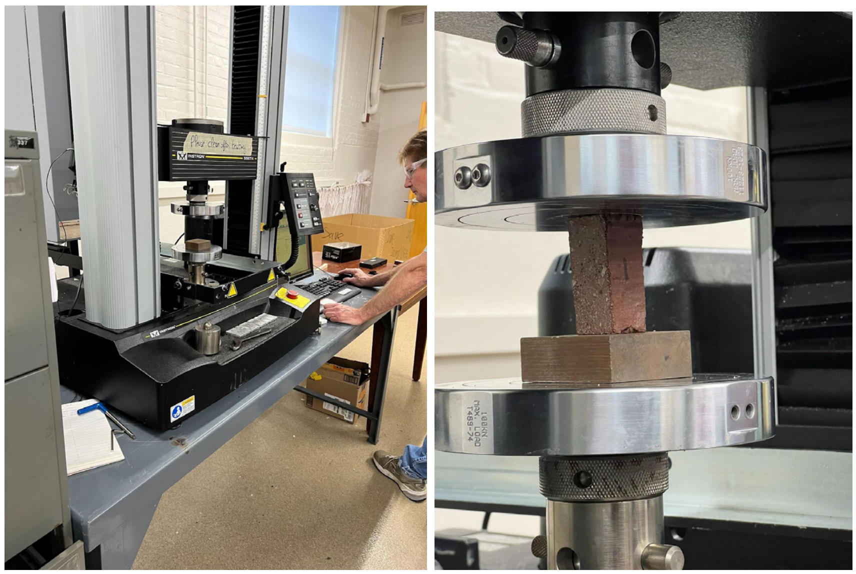


Figure 8. Universal Testing Machine Compression Testing Set-Up

Once all samples were tested, the compiled data was exported and transferred into an excel sheet for analysis. The samples themselves were also carefully inspected to identify failure patterns.

The interface shear test, conducted to better understand the EcoBlock's material bonding properties with cement, required the design and machining of a 3D mold. To determine the shear strength of the EcoBlock in relation to its interface bonding capacity with concrete, the team tested the shear strength of an EcoBlock sample bonded to freshly poured concrete. To begin, the EcoBlock was carefully cut into a sample with dimensions of 22mm x 25.5mm x 44.5mm using the identical circular saw setup. In order to bond the precisely cut EcoBlock sample with concrete, a square silicone mold was required. A mold was designed in SolidWorks and 3-D printed in polymer using an Ender-2 Extended 3-D Printer (Figure 9).

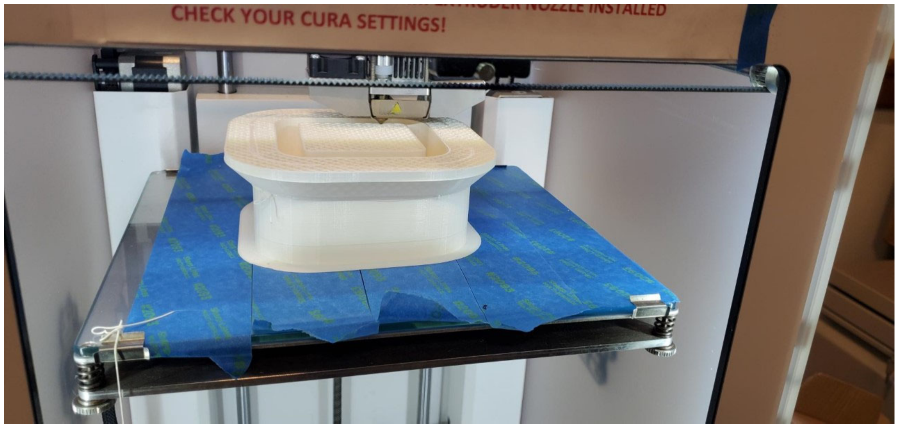


Figure 9. Plastic Mold Printing on an Ender-2 Extended 3-D Printer

The resulting plastic mold was then filled with silicone, rested on a vibration table for 15 minutes to remove trapped air bubbles, and cured for 24 hours before demolding. A basic concrete was created with a water-cement ratio of 0.45 and poured into the silicone mold. The molded concrete was placed on a vibration table for 15 minutes to remove trapped air and allowed to be set for 72 hours before testing began. The EcoBlock sample was then placed horizontally on the poured concrete and secured with duct tape to ensure a parallel attachment (Figure 10). The sample of EcoBlock material bonded to concrete is shown below in Figure 11.

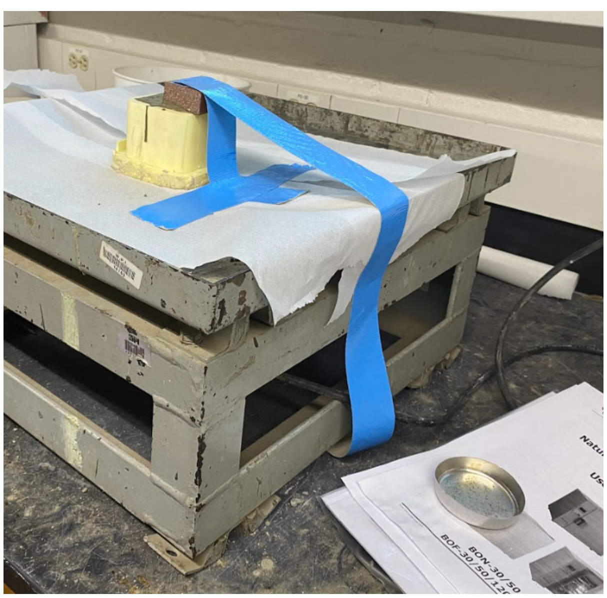


Figure 10. EcoBlock Sample Curing Process.

Figure 11. EcoBlock Sample Bonded to Concrete Before Testing.

The contact area between the EcoBlock and concrete was measured to be 1129 mm^2. Once the concrete was cured, the Instron 5567A UTM was calibrated and set to a compression rate of 1.5mm per minute. The sample was secured on the compression plate using a vice grip as shown in Figure 12.

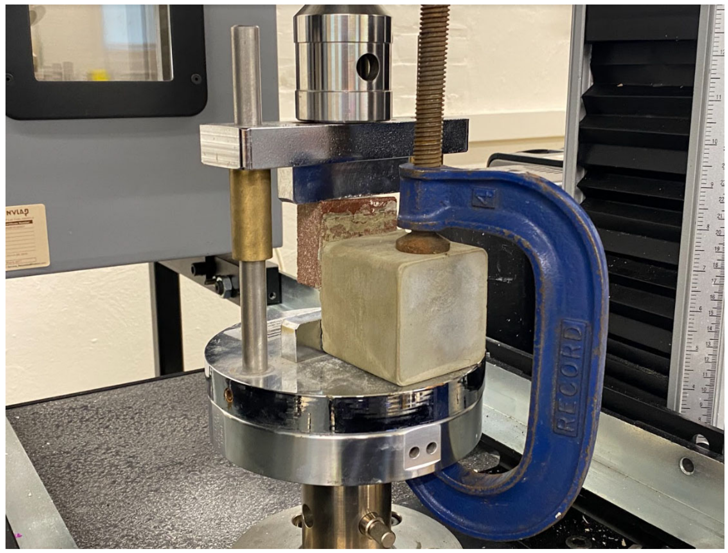


Figure 12. Universal Testing Machine Shear Strength Test Set-Up.

The shear interface test was conducted to determine the maximum compressive force the interface could withstand and the shear force was calculated by dividing the maximum compressive force by the total contact area. The final material shear strength was graphed and further analysis was implemented to inform future design decisions.

3.3 *Objective 3: Develop an architectural design for an affordable housing unit and present it in a format that is replicable and easily understandable.*

With numerous interviews and inquiries regarding the necessary qualities of a teacher and nurse housing completed, we then translated their priorities into physical terms. This was done over a series of progressing design stages that resulted in a 3-dimensional rendering of our proposed model, construction documents, and a manual detailing construction methods.

3.3.1 *Develop a sustainable and affordable housing design that employs Nelplast EcoBlocks to fulfill the needs of the town.*

The first design stage was the development of a conceptual model. The conceptual model is the inspiration that each progressing design stage drew from. This idea or thought conveys the emotions that are meant to be reflected in the building design. Program development was the next stage, which involves an analysis of how spaces relate and function with one another in the home. This phase required that requests and priorities of the budget, environment, town, and future occupants be assessed and negotiated into a physical relationship. Resulting from this design stage was a definite amount of how much square footage each space in the home should occupy and the required relationship between these spaces. From a program, the electronic modeling of the building began. The floor plan materialized the realistic needs of each stakeholder into walls and doors, therefore establishing the scale of the project. From this, a site plan, elevation drawings, section drawings, and a 3-dimensional model were designed. Every step of this design development utilized REVIT by AutoDesk.

Once an architectural model of the structure was developed, the structural design was established. The most significant system of this structure was the roofing. The roofing had to be designed using locally ready materials in order to accomplish our goals of prioritizing the environment and the town's budget. The walls of this building were designed using the Nelplast EcoBlocks building system. Supporting systems and additional support structures were designed using the known weight of the EcoBlock, the weight of the roofing, and the designed height of the building. Relevant calculations of wooden rafters, ceiling joists, and a ridge beam were assessed to ensure adequate capacity and safety of the system and materials. Once this system was designed, it was integrated into the REVIT model. For the best rendering capabilities, the exact dimensions of an EcoBlock were used to construct the model, resulting in a scaled rendering.

Proceeding structural design was the design of mechanical systems. Climate Consultant 6.0, a computer program that helps users understand their local climate, was used to perform a preliminary climate and passive design analysis. Climate Consultant was developed by the UCLA Energy Design Tools Group. The software uses weather data and a preselected comfort model as criteria to determine optimal passive and active design strategies for residential and small commercial buildings.

Weather data from Accra, Ghana, the closest city to Akyem Dwenase that had weather data available for download, was used to complete the analysis. The Adaptive Comfort Model from ASHRAE Standard 55-2010 was used as the base criteria for the analysis. The Adaptive Comfort Model assumes that occupants reside in spaces where they can open and close windows and that occupants adapt their clothing to thermal conditions and are sedentary. This method does not apply if mechanical cooling or heating systems are in operation. Climate Consultant returned a psychrometric chart detailing occupant comfort and suggested design strategies.

DesignBuilder was utilized to design mechanical systems and determine passive design strategies. It is an advanced energy-building simulation software that provides a detailed analysis of items such as thermal mass, glazing, shading, renewables, HVAC, and financial analysis (EnergyPlus Simulation, 2022). DesignBuilder allows the designer to employ various passive and active temperature and air quality regulation systems, which is how the most advantageous system was determined. We performed multiple energy analyses and used the most optimized design alternatives for our model, while also taking into account the local availability of mechanical systems in our design. This resulted in a more sustainable and well-optimized affordable housing using Nelplast EcoBlocks.

The electrical plan was then developed. This began by determining what specific electrical equipment was required, which was decided through the information collected during the inquiry phase of the project. Each of these required systems was also incorporated into the 3-dimensional REVIT model. Similarly to the electrical system, the plumbing plan was developed through information given on current plumbing systems in the town and reflected in the REVIT model.

3.3.2 *Iterate design with stakeholder and advisor feedback.*

Once the final draft of our prototype affordable housing model was completed, we shared our product with key stakeholders involved in this project. We utilized an iterative process throughout our project to arrive at a final design that is most beneficial to its future residents. To accomplish this, the plans were sent to the Chief of Akyem Dwenase, the Headmistress of L/A Junior High School, Richmond Boadu Tinyase, Chief Linguist of Akyem Dwenase, and Enis Boateng, Administrative Assistant of Nelplast who each have a wealth of knowledge about the needs of the town and the specific requirements of the future residents of this housing. Our plans were also sent to the WPI advisors of this project. The housing documentation drawing set that we are providing included a 3D REVIT model, floorplans, elevation drawings, section drawings, a roof plan, and a structural plan, as well as electrical, and plumbing plans.

Our team gave the stakeholders time to review our proposed design and provide feedback, after which we listened to their suggestions and discussed subsequent steps and iterations. Ideas that were proposed include layout improvements, equipment alternatives, or other additional developments.

With the feedback from our key stakeholders at the forefront of our minds, our final step in the co-ideation process was finalizing the prototype of our affordable housing units. To bring our project to completion, additional conversations with our stakeholders were necessary in order to review potential options and clarify best practices. Lastly, we produced our final drawing set. This documentation was then presented to our project advisors and our project partners in Akyem Dwenase.

3.3.3 *Final 3D Design Rendering and compilation of construction documents.*

We piloted the design by creating an interactive digital model, relevant construction documents illustrating the intended assembly, and a detailed construction manual explaining the specified construction methods. The goal of these materials was to provide the design of the structure with adequate detail and information to be constructed without us present. Renderings of the 3D digital model accompanied the 2D construction document to give a contextual understanding of the structure. Section models further supplement construction documents that have greater detail specifying materials, methods, assemblies, and other relevant information.

3.3.4 *Produce a detailed price breakdown for the proposed plan.*

The proposed unit design was then evaluated for cost based on recent market values. An estimator that works with Nelplast Eco Ghana Ltd. assisted with this process, as he has an understanding of the cost of an EcoBlock, as well as local labor costs. This breakdown was given to the town for their evaluation.

4 *Results*

Through an iterative design process, a truly affordable housing unit for teachers and nurses was developed with the goal of delivering a thermally comfortable and private living situation. Interviews, design prototype models, material testing, energy model simulations, and structural calculations as shown in the following section illustrate the development of this housing.

4.1 *Contextual Exploration: Key Informant Interviews*

Key informants from the town of Akyem Dwenase were interviewed with the goal of appropriately fitting an affordable housing complex into their cultural and economic context. The Chief of Akyem Dwenase, the Headmistress of the Junior High School in Akyem Dwenase, the founder of Nelplast, and the administrative assistant of Nelplast were interviewed to achieve the necessary perspective for successful design. Detailed descriptions of these interviews can be found in Appendix A., while the key findings are presented in this section.

The most popular housing style in Akyem Dwenase is a compound home.

An interview with Chief Osabarima confirmed our prior research about the prevalence of compound homes in Ghana. The town has approximately 4,300 people that live there full time, but many family members that have moved out of the town return frequently to attend marriages, funerals, and other ceremonies that occur on most Sundays. Although some of the younger generations have moved out of the village, most homes are occupied by 3 to 4 generations simultaneously. Anywhere from 4 to 10 people living in a home has contributed to the prevalence of compound homes in the village. Most homes have bedrooms, bathrooms, a communal living space, and an outdoor gated patio as we discovered from the tour of the town he gave us via video chat and a video message.

Chief Osabarima selected a site to build our housing units on it, which is conveniently located next to the town's junior high school and main road.

The plot of land he chose for this project is to the northwest of the Junior High school and the library and measures approximately 40 meters by 45 meters. Chief Osabarima sent us a list of coordinates in their town, which allowed us to utilize Google Earth and have a contextual understanding of the town and the intended construction site. The map below shows Akyem Dwenase, and the proposed teachers' quarters site is outlined in yellow. The coordinates of each location can be found in Figure 13.

Figure 13. Akyem Dwenase, Ghana Significant Locations

There are currently 20 teachers and 6 nurses working in Akyem Dwenase, many of which are unsatisfied with their current living situations and desire private housing units with no communal spaces.

Our interview with Francisa Annor, the Headmistress of L/A Junior High School gave a comprehensive understanding of the current housing situation for her colleagues in Akyem Dwanese. There are two public schools in the town; one upper school and one lower school which employ 12 teachers. However, Franciscа shared that the number of teachers will hopefully increase soon, as they hope to expand and increase the quality of their children's education. The District Education Office assigns teachers to work in towns like Akyem Dwenase, which means they hail from nearby towns and cities. They may request a transfer of location, but they can remain with one assignment for 10 or more years if they are doing a satisfactory job.

Franscisca described the current living conditions for teachers as very bad. Currently, many of the other teachers have only a single room with a veranda to themselves, and many teachers share a communal bathroom, toilet, and shower. While Franscisca was able to afford a home with a private bathroom, she frequently hears complaints that single teachers do not like sharing spaces with others. Three male teachers and two female teachers work at the secondary school alongside Franscisca, from which she has heard complaints that communal spaces between genders are unacceptable. While their accommodations are less densely packed than those of nearby towns, most homes are compound style, meaning there are many rooms and up to 6 teachers may live in them, each having one room to themselves. Most of these teachers are single, but married teachers with children find themselves in similar living situations and are further crowded. Ghanaians value their privacy and personal space, which is a value that Franscisca recommended we honor in the final design.

The most common building systems of Akyem Dwenase are designed to lower the overall cost of living, often by reducing the amount of electricity required.

We then inquired about building systems most frequently utilized by residents of the town to Chief Osabarima, he shared with us that there is a water line available that anyone may tap into, but it is very expensive to dig a connection to, so expensive that many residents opt to walk to the center of town and pay to fill their containers with water. The electricity line works the same way but is much easier to connect to and almost all homes are connected. Most homes are cooled by a ceiling fan, as electricity is costly and it is considered a luxury to have an air conditioning unit. Homes without AC compensate with a large number of windows that take advantage of the town's location in a valley where temperatures drop lower at night than in the rest of Ghana. Their plumbing systems consist of a septic system that is attached to the home and must be replaced every 2-3 years.

Nelplast's experience thus far with the EcoBlock system has established a reliable building system, but their company hopes to expand.

Nelson Botang is the founder and CEO of Nelplast. He was able to give us insight into the composition and manufacturing process for their EcoBlocks. The blocks are created beginning with the collection of discarded plastics of any variety except PVC. These are then shredded and washed if necessary. Sand and red, brown, or green dye is then mixed with the plastic and heated to 180℃ - 220℃ and extruded as a paste. The paste is put into the EcoBlock mold for 1 to 3 minutes until cured. They have 1 manufacturing facility.

They produce two types of brick products; wall and column blocks. The wall blocks only require that the first block layer be attached to the foundation using a mortar and allowed to cure for 14 days, then the other layers of blocks fit together like legos, only requiring a hammer to assemble. Nelplast is currently working on a roofing system using their plastic product, but it is not ready to be utilized in our design. They currently use a wood-framed roof with corrugated aluminum sheets atop the frame as a roofing system.

Building systems like electrical and plumbing equipment are currently placed in a notch in the wall blocks that must be cut out, then cemented over. This will then be covered with drywall and plaster. Spaces to later install windows and doors are left when building the wall, which is later screwed into the plastic.

Nelson also verified all of the certifications of the product. EcoBlocks are Ghana Building Code compliant and certified to be lived in by the Ghana Standards Authority.

4.2 *Architectural Design Process*

After developing an understanding of current home layouts, occupant needs, typical building systems, and the experiences of Nelplast, the architectural design was then established.

4.2.1 *Programming and Floor Plan Development*

A building program was developed with a consideration of the following occupant priorities:

- A **compound housing configuration** was chosen due to the popularity and functionality of the style.
- The ease of construction is complemented by the **repetition of the identical rectangular units** that form the structure.
- The affordability of the development was prioritized by **sharing as many walls as possible** between spaces.
- Francisca Annor noted that the teachers desire privacy and independence. Our design utilizes **individual units** within each structure.
- Francisca Annor and Professor Robert Krueger remarked that teachers would benefit from having a **shared common area** separate from their unit in which they can choose to congregate.
- Francisca Annor advised us to include an **outdoor kitchen/patio space** attached to each unit to align with typical practices and provide seclusion from others during the cooking process.
- There is **flexibility** in the design. Due to time or cost constraints, developers could choose to build just one rectangular unit, one floor of the structure, a complete structure with five units, or the entire project scope with all four housing structures.
- The site's **location** is ideal, being within 5-6 meters of the Junior High School. Some level of privacy for the children at school should be provided to the teachers.

The building program is shown below (Figure 14), showcasing two levels with five individual living units.

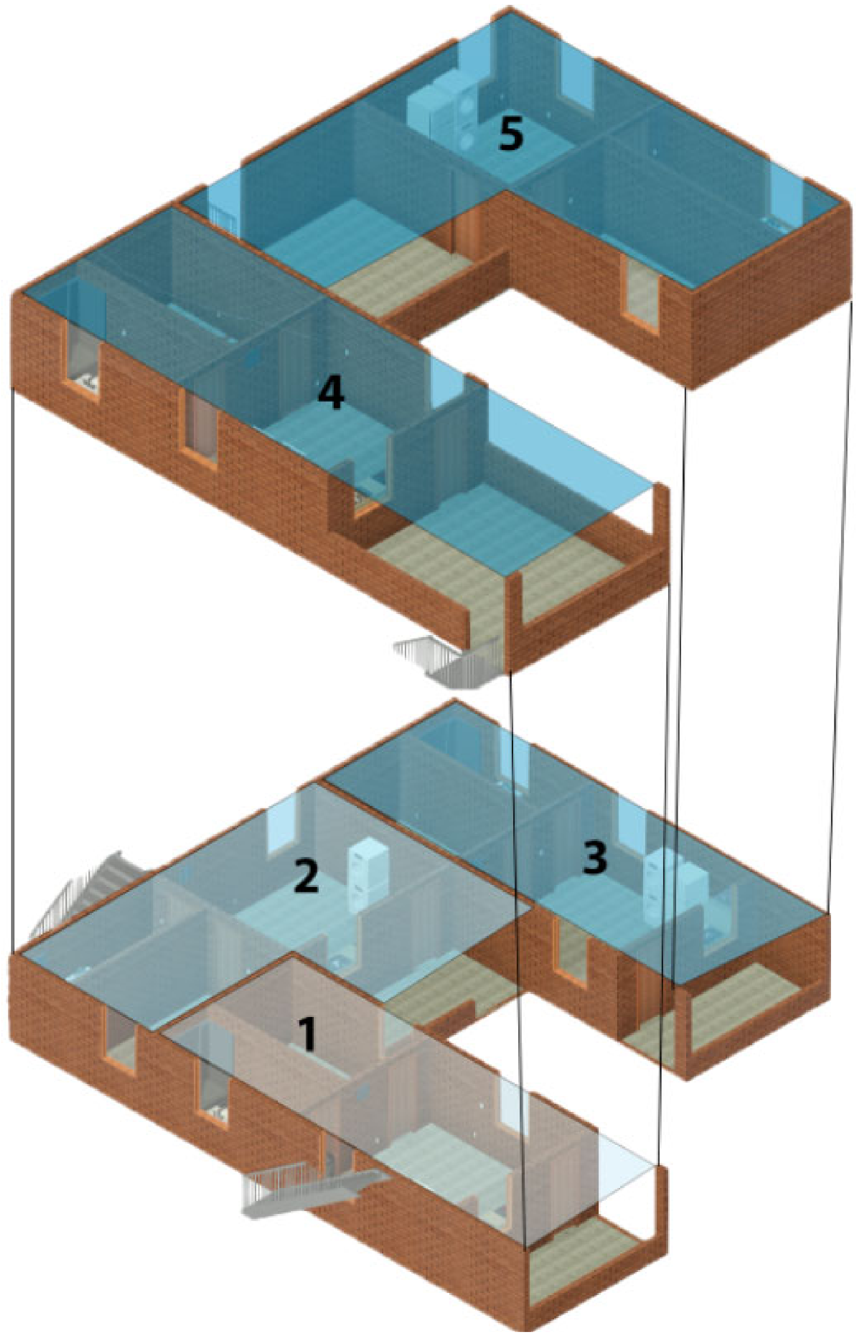
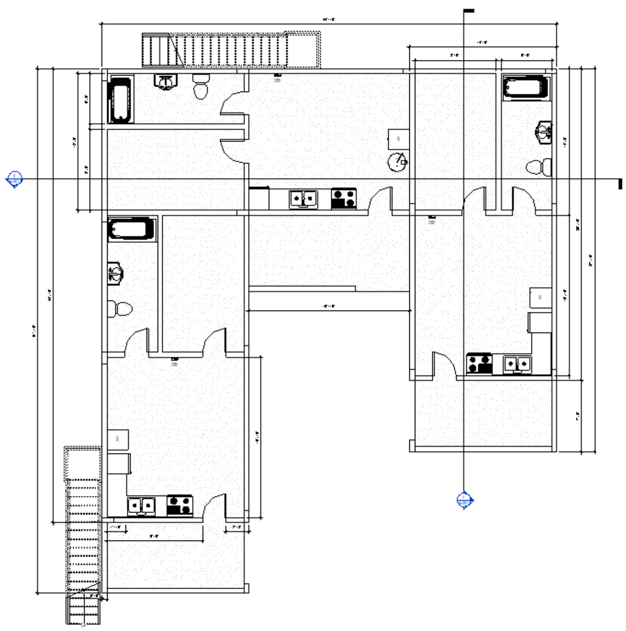


Figure 14: Architectural Program Displaying Five Units

The housing structure contains 5 units each with a bedroom, bathroom, combined living room and kitchen, and an outdoor covered patio. Floor plans detailing the dimensions of these levels are shown below in Figures 15 and 16, but can be found in greater detail in Appendix G.



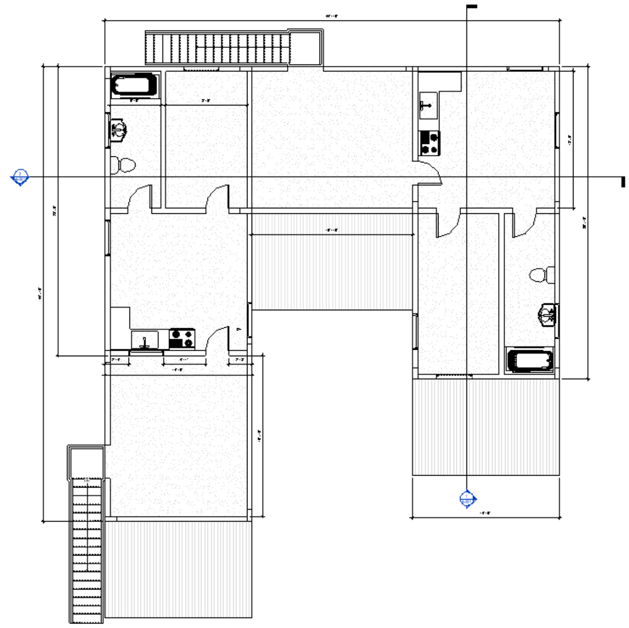


Figure 15: Level 1 Floor Plan

Figure 16: Level 2 Floor Plan

4.2.2 *Building System Design*

Building standards in Southern Ghana outlined by the 2018 Ghana Building Code were used to fit all building systems accurately for their occupants. A few factors influenced these decisions, the first being the standard of thermal comfort for occupants in Ghana. The American Society of Heating, Refrigerating and Air-Conditioning Engineers**,** known as ASHRAE, defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment". The definition of comfortable is highly variable among populations and depends heavily on one's own experience with their geographic climate. According to ASHRAE, a temperature between 67°F to 82°F and a relative humidity of less than 65% are considered to be thermally comfortable based on occupant feedback in the United States (*Thermal Environmental Conditions for Human Occupancy*, ASHRAE 55). However, a study conducted by researchers at Kwame Nkrumah University of Science and Technology and the University of Ghana investigating thermal comfort at naturally ventilated libraries in Kumasi, Ghana, found that Ghanaians accepted temperatures far exceeding those specified by ASHRAE. The study found that even when thermal comfort was defined as between 79 and 82°F with a relative humidity of less than 70%, the majority of occupants accepted thermal conditions which exceeded this standard by between 2 and 9°F. Based on collected data, the researchers concluded that individuals in tropical climates likely have a higher heat tolerance due to their natural living conditions (Mohammadpourkarbasi et al., 2022). Taking these standards into consideration, we designed the required building systems, including plumbing, electrical, and lighting. First, for the plumbing system design, the team collected a variety of information from available video resources in order to determine the contents of the system and the way in which the system is installed. All details are outlined in the plumbing plan included in the construction document set. Simplicity and functionality were prioritized in the electrical system design. Within the design, the team kept in mind the high price of electricity in comparison to the average annual income. The lighting system design process was similar. We kept the design very straightforward with only two different types of fixtures. The details of the electrical and lighting systems are outlined in the electrical plan in the construction document set.

4.2.3 *Passive Design*

Climate Consultant returned the following psychrometric chart and suggested design strategies, shown in Figures 17 and 18.

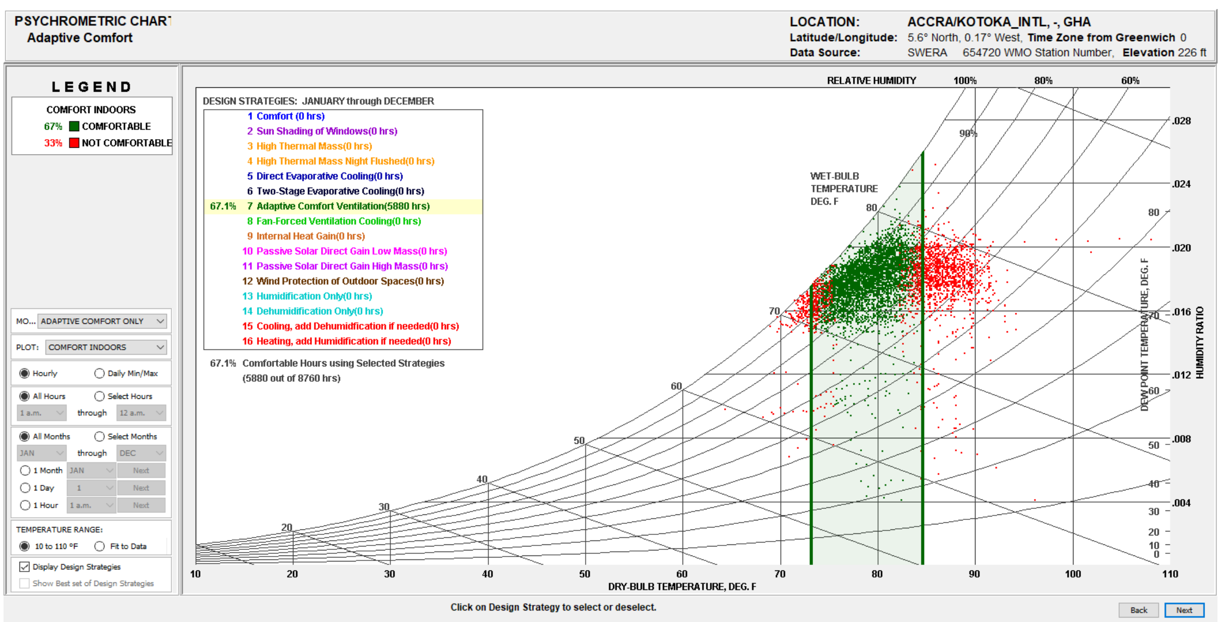


Figure 17. Psychrometric Chart with Occupant Comfort

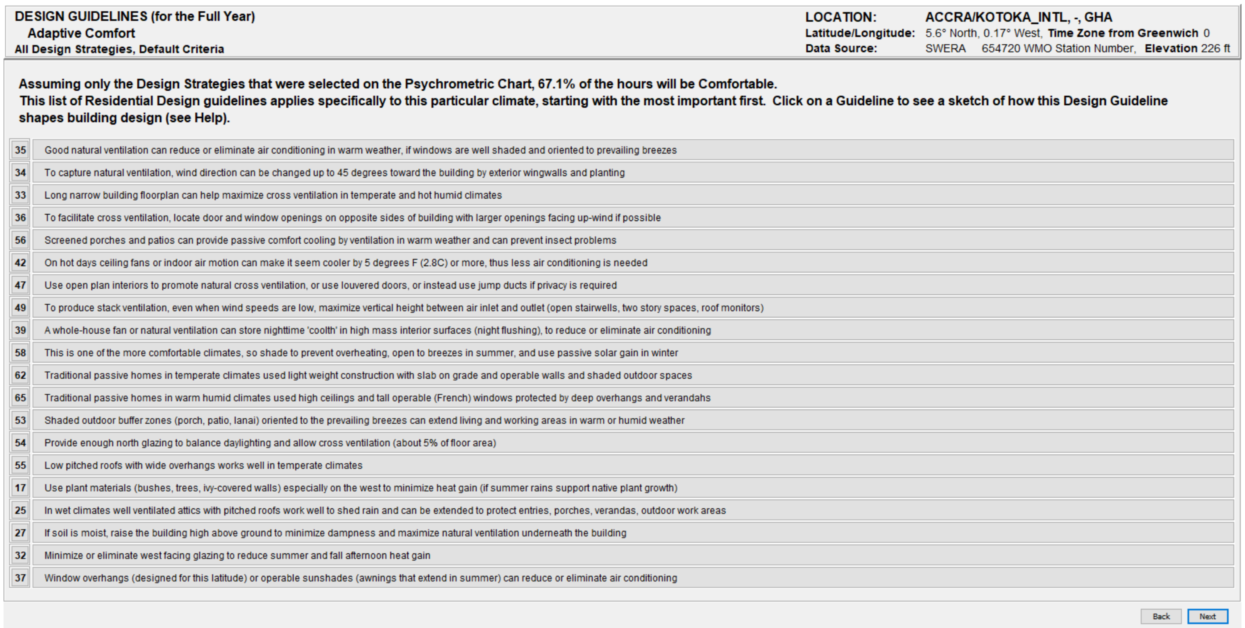


Figure 18. Climate Consultant Suggested Design Strategies

Analysis indicates that occupant comfort can be achieved 67.1% of the time if the suggested design strategies are considered and the base constraints of the Adaptive Comfort Model are honored. The suggested design strategies include natural ventilation, fan-induced ventilation, and shading to maximize occupant comfort. These strategies were incorporated into our design and tested in DesignBuilder, an energy modeling software, to verify the strategies' efficacy and produce quantifiable results.

Multiple iterations were performed and the energy analyses report from DesignBuilder was used to guide us to the most optimized design for our model. This allowed us to create a more sustainable and well-optimized affordable housing using the Nelplast EcoBlocks.

In total, there were five design iterations plus a baseline model that were explored to see how design changes affected occupant comfort. First, a baseline model was established to set the bar for comparisons. Each model was represented as a whole building average to compare the performance of each building. The limitations of this method will be explained later in this chapter.

4.2.3.1 Baseline Model

The baseline was the first iteration of the model that was the most optimized before consulting DesignBuilder. The purpose of consulting DesignBuilder was to further optimize our model for occupant comfort and make small improvements to the final design. The baseline model within DesignBuilder consisted of a 10-foot ceiling height, a gable roof with a 2-foot overhang, a baseline window placement, and utilized natural ventilation for the HVAC system. It is important to note that our findings for determining what type of HVAC system came from our discussions with local residents, Enis Boateng, Professor Robert Krueger, and further investigations that will be discussed later in this chapter. Later in this chapter will also be a summative discussion on the iteration results as well as the limitations of utilizing the DesignBuilder software. The baseline window placement consisted of window sizes being 3' wide by 8' tall. The windows were placed based on maximizing cross-wind ventilation and natural lighting. The baseline model also employs local shading in the forms of interior blinds and the use of louvers on the windows.

The construction of the model in DesignBuilder attempted to match the real-life properties of the EcoBlocks to give an accurate idea of how our building would perform. The actual properties of the EcoBlock were not obtained from Nelpast Inc., so assumptions were made based on research findings.

The thermal conductivity of the EcoBlock was based on a study that looked at the mechanical and thermal properties of interlocking blocks that utilize waste plastic. The study found that the thermal conductivity of the EcoBlock would be around 0.15 - 0.2 W/mK or 0.1012 Btu (Alaloul et al., 2020). The next property that was researched was specific heat for the EcoBlock.

A table from "The Engineering ToolBox" was utilized that listed specific heat values of common solids like brick, cement, glass, and many more materials. A combination of specific heat values was used to give an estimated specific heat value. The sand and plastics-solid categories were considered because the EcoBlock is a combination of those two materials. This gave a specific heat value of 0.3 BTU/lb-°F (Engineering ToolBox, 2003). The next property that was researched was emissivity for the EcoBlock.

A table from "ThermoWorks" was utilized that listed the infrared emissivity of common surfaces like brick, cement, glass, and many others. A combination of emissivity values was again used to obtain an estimated emissivity value for the EcoBlock. It was estimated that the EcoBlock has an emissivity of 0.81 to 0.86. A statement from ThermoWorks says that "the accuracy of the following numbers is almost impossible to guarantee as the emissivity of a surface will not only alter with regard to texture and color but also with its actual temperature at the time of measurement" (ThermoWorks, 2022). We understand that this number might not be exactly how the EcoBlock performs but we assume it is around that range.

The final property that was used for the construction of the model in DesignBuilder was density. This value was obtained by doing a density test in the Kaven Hall laboratory at WPI. A sample of the EcoBlock was weighed using a balance scale. Next, it was placed in a graduated cylinder that was filled with water. The sample weighed 95.6g and made the water rise a total of 55mL. A final density of 108.4998 lb/ft^3 was obtained.

Conversion calculations:

Density = 55mL/95.6g → 1.738g/mL → converting g/mL to lb/ft^3 → 108.4998 lb/ft^3

All of these properties are important to get an accurate measurement of how the building would perform and establish the characteristics of the baseline model.

In DesignBuilder, there is a design option called "ASHRAE Standard 55 (Adaptive Comfort Model)" that was utilized in every iteration to further increase the accuracy of the building's comfort for each simulation. The Adaptive Comfort Model is the American standard for thermal comfort in naturally ventilated buildings. Buildings reliant on natural ventilation achieve thermal comfort based heavily on the temperature difference between the indoor and outdoor environment.

Implementing the Adaptive Comfort Model was important as "people accept and even prefer a wider range of temperatures than can be explained by the PMV (Predicted Mean Vote) model". According to UC Berkeley's Center for the Build Environment, this acceptance is explained by the "psychological and behavioral adaptation" of occupants to their respective environments (Brager & Parkinson, 2019). The difference in indoor comfort level between air-conditioned and naturally ventilated buildings is shown below in Figure 19.

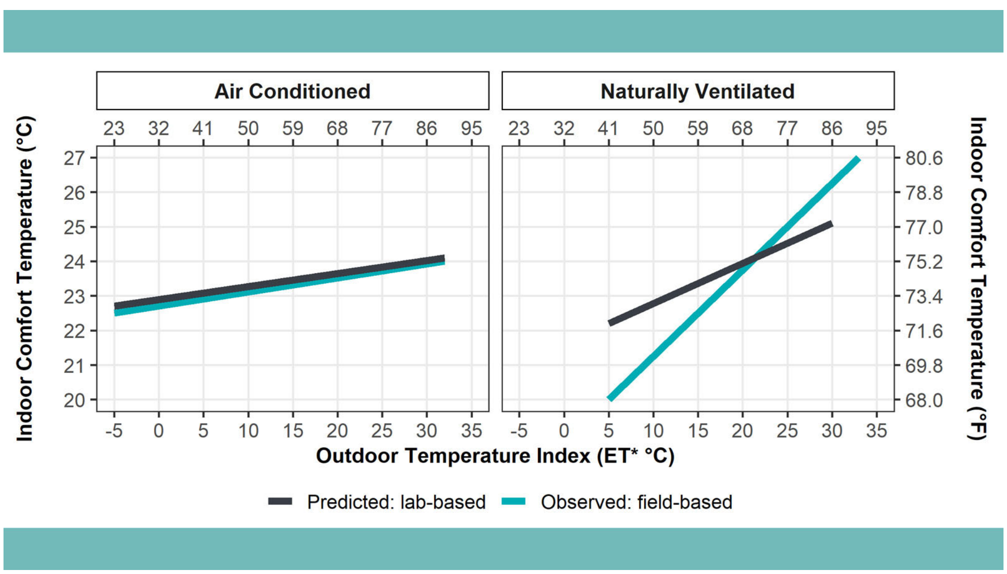


Figure 19. Adaptive Comfort Model Visualization (Brager & Parkinson, 2019).

This option was found to be useful for the model as natural ventilation was the primary method used to cool the building. The adaptive comfort model also introduced limitations in regard to its applicability to sub-Saharan Africa which is discussed later in this chapter. Figure 20 below illustrates what the baseline model looks like in DesignBuilder.

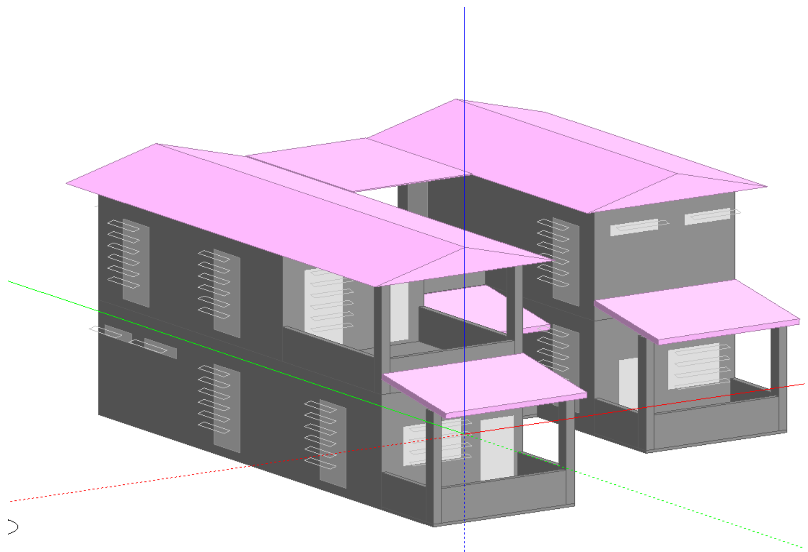


Figure 20. Baseline DesignBuilder Model

<u>4.2.3.2 Baseline Model vs. Iteration #1</u>

Iteration #1 explored how the ceiling height of the model affected occupant comfort. The height of each unit was changed from 10 feet in the baseline model to 8 feet. It was found that lowering the ceiling height increased the number of uncomfortable hours for each unit. This increase in uncomfortable hours is likely due to the stack effect. The stack effect occurs when hot air mixes with cool air more quickly due to reduced space. Lower ceilings create a more confined space which exacerbates the stack effect and requires more energy to cool the air. Lower ceilings are more energy efficient in regards to heating a space, but the opposite is true when cooling is required. Table 2 compares the average annual time in hours not meeting the adaptive comfort model standard during occupied hours in the baseline and first iterative model. On average, the housing units experienced 523.3 additional hours of discomfort due to increased ceiling heights. Figure 21 represents the building's average number (all units averaged together) of uncomfortable hours of the baseline model vs. iteration #1.

Table 2. Average Annual Time (in hours) Not Meeting the Adaptive Comfort Model Standard During Occupied Hours

	Baseline Model Building Average	**Iteration #1 Building Average**
Number of Annual Uncomfortable Hours	1968.73	2492.03
Change in Annual Uncomfortable Hours	**↑ 523.30 hours (21.00%)**	

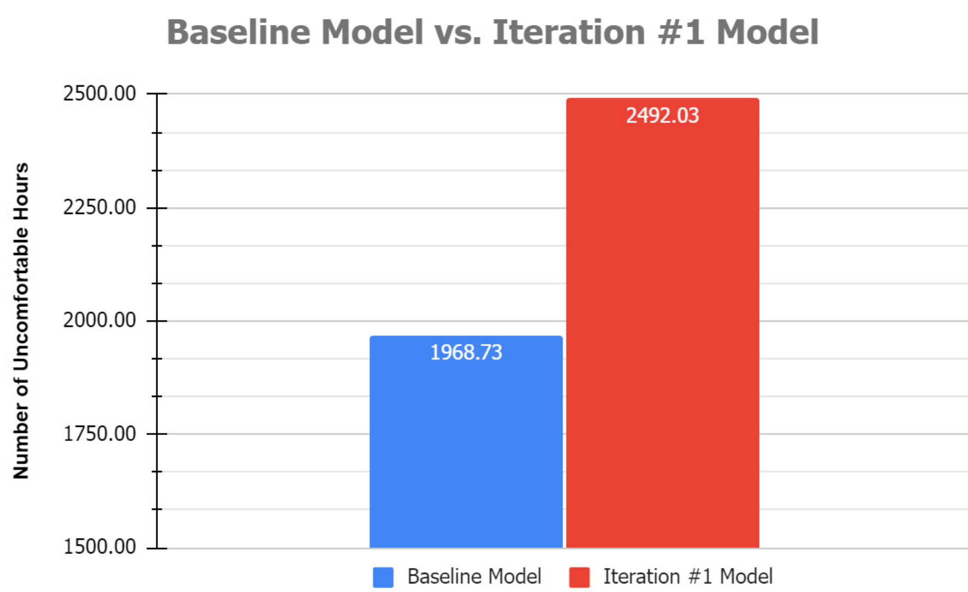


Figure 21. The building's average number of Comfort Hours Not Met (Baseline vs. Iteration #1).

4.2.3.3 Baseline Model vs. Iteration #2

Iteration #2 explored how the roof overhang length affected the building occupant comfort. The length of the roof overhang was changed to 3 feet instead of 2 feet in the baseline model. It was found that increasing overhangs only slightly decreased the number of uncomfortable hours for each unit. This minimal reduction in comfort hours after the implementation of extended roof overhangs is likely due to Ghana's geographic proximity to the equator. The solar altitude angle at the equator is significantly less varied throughout the day in regions closest to the equator. Less variation in solar altitude translates to the sun being directly overhead and fewer shadows being produced by roof overhangs. Although still a net positive addition, roof overhangs are more efficient in locations where the average solar altitude angle is smaller. Table 3 shows the average annual time in hours not meeting the adaptive comfort model standard during occupied hours. On average, the housing units experienced 41.8 fewer hours of discomfort due to increased roof overhang. Figure 22 represents the baseline model building average vs. iteration #2 building average.

Table 3. Average Annual Time (in hours) Not Meeting the Adaptive Comfort Model Standard During Occupied Hours

	Baseline Model Building Average	**Iteration #2 Building Average**
Number of Annual Uncomfortable Hours	1968.73	1926.90
Change in Annual Uncomfortable Hours	**↓ 41.83 hours (2.17%)**	

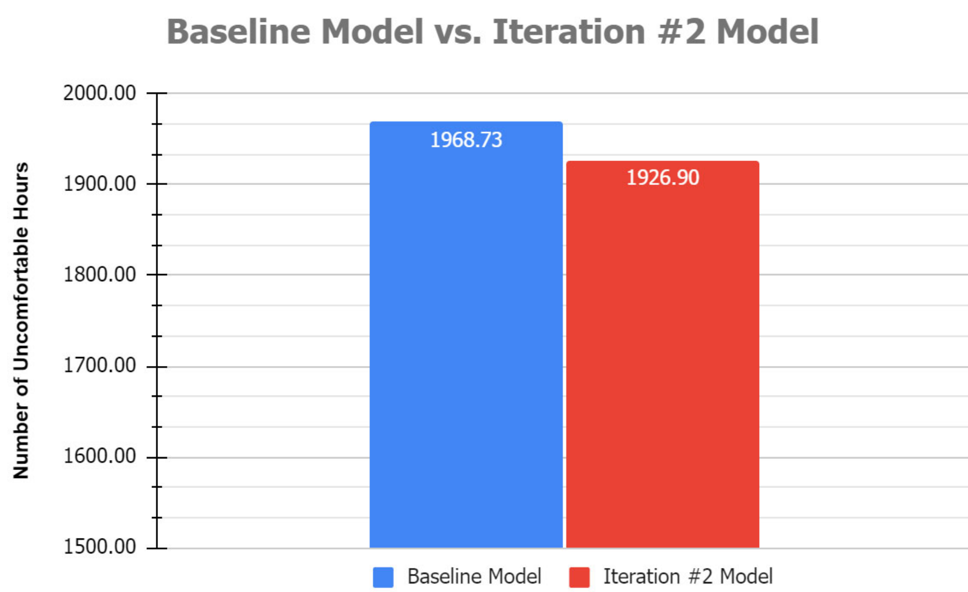


Figure 22. The number of Comfort Hours Not Met (Baseline vs. Iteration #2).

4.2.3.4 Baseline Model vs. Iteration #3

Building off of the previous iteration, Iteration #3 explored how the combination of increased roof overhang length and ceiling height affected the building occupant's comfort. The length of the roof overhang was kept at 3 feet from the previous iteration, a 1-foot increase from the baseline model. The ceiling height of each unit was changed to 12 feet rather than 10 feet in the baseline model. We found that the combination of these two had a bigger decrease in the number of uncomfortable hours for each unit. Table 4 shows the average annual time in hours not meeting the adaptive comfort model standard during occupied hours. On average, the housing units experienced 41.8 fewer hours of discomfort from increasing ceiling height and 83.6 fewer hours of discomfort due to both the ceiling height and roof overhang. Figure 23 represents the baseline model building average vs. iteration #3 building average.

Table 4. Average Annual Time (in hours) Not Meeting the Adaptive Comfort Model Standard During Occupied Hours

	Baseline Model Building Average	Iteration #3 Building Average
Number of Annual Uncomfortable Hours	1968.73	1885.17
Change in Annual Uncomfortable Hours	↓ 83.57 hours (4.43%)	

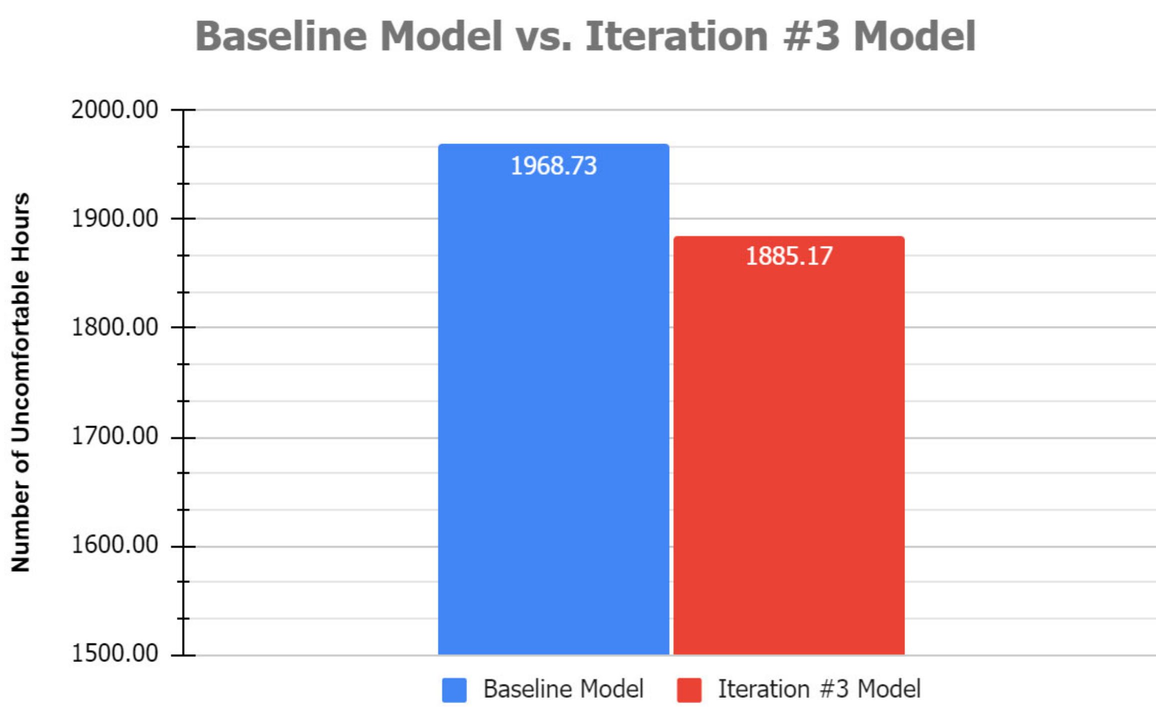


Figure 23. The number of Comfort Hours Not Met (Baseline vs. Iteration #3).

4.2.3.5 Baseline Model vs. Iteration #4

Iteration #4 explored how adjusting the building's windows and window placement affected the building occupant's comfort. In iteration #4, windows in all of the units (the first and second floors) were changed. The changes consisted of adjusting the window dimensions to make them a half foot taller and half a foot wider with the final dimensions being 3.5’ wide by 8.5’ tall. The large windows were also added to each unit’s bathroom whereas the baseline had much smaller rectangular windows at 5’ wide by 1’ tall.

It was found that the window adjustments made the number of uncomfortable hours for each unit actually increase. Table 5 shows the averages of the time in hours not meeting the adaptive comfort model standard during occupied hours per year. On average, the housing units experienced 252.6 additional hours of discomfort due to increased glazing. Figure 24 is a visual representation of the baseline model building average vs. iteration #4 building average. No further iterations of window sizing were modeled as reducing the number of windows would further reduce the occupants' experience in the space.

Table 5. Average Annual Time (in hours) Not Meeting the Adaptive Comfort Model Standard During Occupied Hours

	Baseline Model Building Average	Iteration #4 Building Average
Number of Annual Uncomfortable Hours	1968.73	2221.33
Change in Annual Uncomfortable Hours	↑ 252.60 hours (11.37%)	

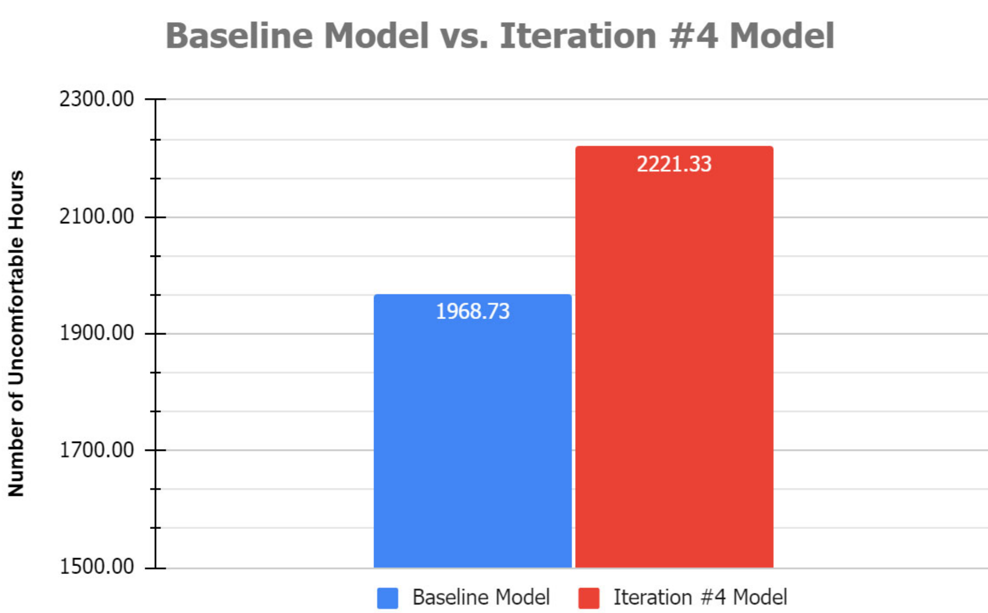


Figure 24. The number of Comfort Hours Not Met (Baseline vs. Iteration #4).

4.2.3.6 Baseline Model vs. Iteration #5

Iteration #5 explored how adding a mini-split air conditioner affected the building occupant's comfort as well as how much it would cost annually to run the air conditioner. Adding a mini-split air conditioner ultimately dropped the number of uncomfortable hours in each unit to zero for the year. This is the best option to achieve maximum occupant comfort within each unit. Table 6 shows the average annual time in hours not meeting the adaptive comfort model standard during occupied hours. On average, the housing units experienced 1968.7 fewer hours of discomfort due to the addition of a mini-split mechanical system. Figure 25 is a visual representation of the baseline model building average vs. iteration #5 building average.

Table 6. Average Annual Time (in hours) Not Meeting the Adaptive Comfort Model Standard During Occupied Hours

	Baseline Model Building Average	**Iteration #5 Model Building Average**
Number of Annual Uncomfortable Hours	1968.73	0.0
Change in Annual Uncomfortable Hours	**↓ 1968.73 hours (100%)**	

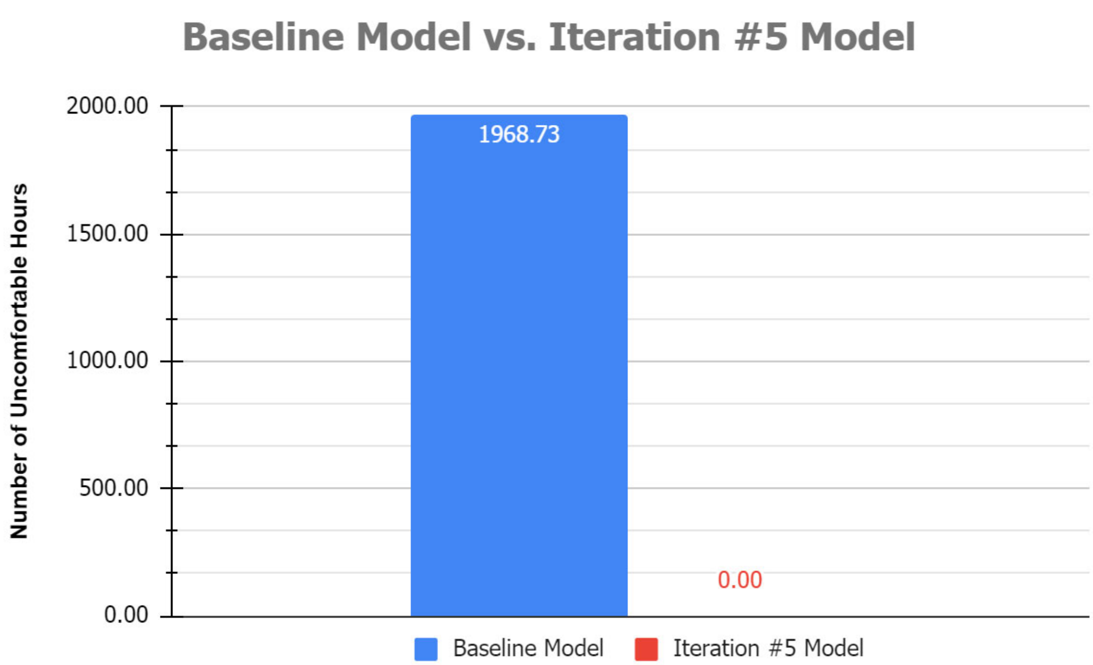


Figure 25. The number of Comfort Hours Not Met (Baseline vs. Iteration #5).

As stated above, a cost analysis was conducted on how much it would cost annually to run the air conditioner based on the end use of cooling data from DesignBuilder. Table 7 shows the cost breakdown analysis of running the mini split for the model.

Table 7. Energy Cost Analysis of Mini Split Air Conditioner

Zone	End Use of Cooling (from DesignBuilder)	Annual Energy Cost
Whole Building Combined	137998.59 kBtu (40443.39 kW·h)	$1,011.08 USD GH₵ 13,952.90*
Per Unit	27599.718 kBtu (8088.68 kW·h)	$202.22 USD GH₵ 2,790.58*

*At the time of conversion $1.00 USD → ₵14.00 GH (From Refinitiv – December 8th, 2022)

4.2.3.7 Discussion of Results and Limitations of DesignBuilder

After each iteration was completed, it was determined that some strategies were worth utilizing in our final model and some were not. For the first iteration, it was determined that decreasing the ceiling height to 8' would only increase the discomfort in each unit so a 10' ceiling height was utilized in the final design. The second iteration explored how increasing the overhangs by a foot would affect building comfort. It was found that while it did slightly increase the comfort in each unit, it is not worth the effort and construction materials that would hypothetically have to occur to have this as an option. For the third iteration, it was determined that increasing the ceiling height to 12' and also extending the overhangs by 1' did increase the comfort within each unit. However, similar to the previous statement, conclusions were made to not opt for these design options as the benefit-to-cost ratio was favored in not pursuing them. Iteration #4 looked at adjusting the window placement and size. It was concluded that the solar heat gain from enlarging the windows and adding more, decreased occupant comfort greatly. However, one benefit to this option was an increase in natural daylighting hours per year. The baseline window placement was better optimized than this new iteration so it was concluded the baseline window placement and sizing would be used. The final design iteration looked at how adding a mini-split air-conditioner to each unit affected occupant comfort. It was determined that each unit would have zero uncomfortable hours per year which made this the best option to maximize comfort. However, it was determined that utilizing natural ventilation was the best strategy to not only keep construction costs down but also simplify the construction process as well. Additionally, the yearly cost to run the mini-split was a significant portion of the average Ghanaian yearly salary so this would not be a feasible option for most residents.

Through optimizing our model and making other fine-tuning adjustments within DesignBuilder, it was concluded that our final optimized model had a 24.69% decrease in uncomfortable hours per year when compared to the original design. The final optimized model combined our findings and includes 10' ceilings, 2' roof overhangs, natural ventilation, local window shading, and a gable roof. The original model had a mono-slope "shed" roof as well as 1' foot overhangs, no local shadings, and non-optimized window placement. Figure 26 gives a visual of the old model vs. the optimized model in DesignBuilder.

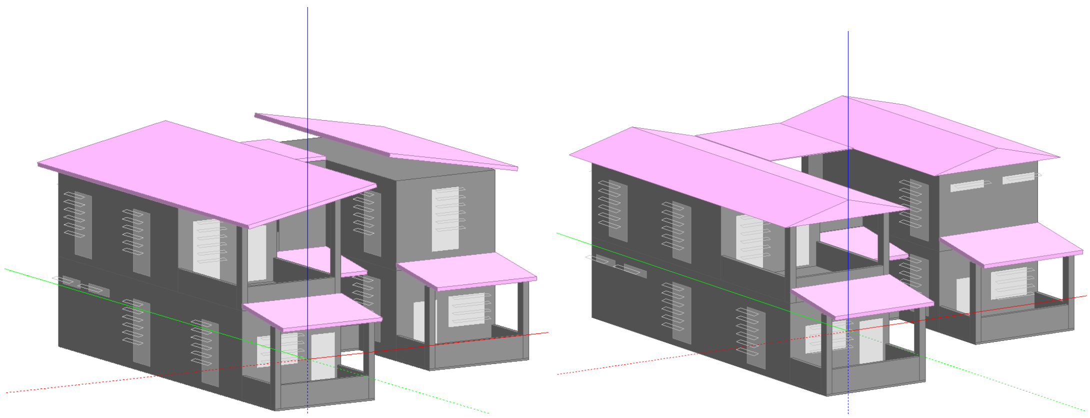


Figure 26. Non-Optimized vs. Optimized Model in DesignBuilder

Table 8. Average Annual Time (in hours) Not Meeting the Adaptive Comfort Model Standard During Occupied Hours

	Old Model Building Average	**Optimized Model Building Average**
Number of Annual Uncomfortable Hours	2417.22	1938.57
Change in Annual Uncomfortable Hours	**↓ 478.65 hours (24.69%)**	

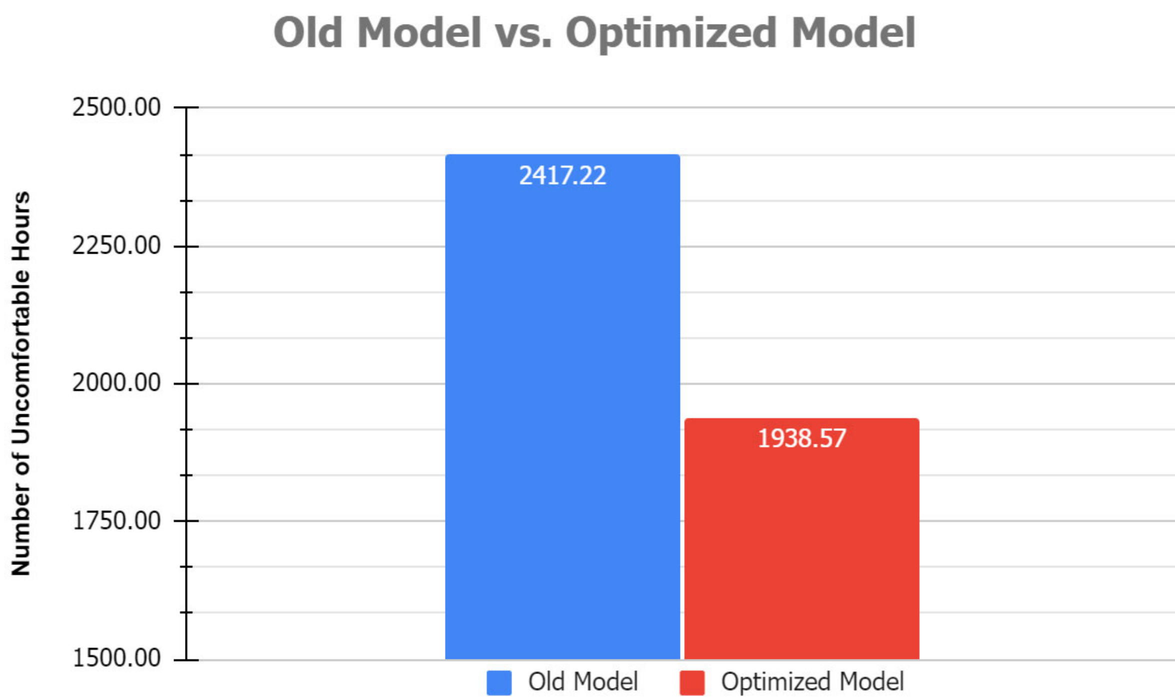


Figure 27. Optimized vs. the Non-Optimized Model Annual Comfort Hours Not Met

There are a few significant limitations to utilizing the DesignBuilder software to benchmark comfort within our model. The first limitation of the software is the reality in which DesignBuilder and the ASHRAE Standard 55 consider what a 'comfortable' temperature is. This might not match that of the Ghanaian people as seen by the study conducted by researchers at Kwame Nkrumah University of Science and Technology and the University of Ghana. Researchers found that Ghanaians accepted temperatures far exceeding those specified by ASHRAE. Furthermore, the majority of occupants accepted thermal conditions which exceeded this standard by between 2°F and 9°F (Mohammadpourkarbasi et al., 2022). This cannot be adjusted within the DesignBuilder software resulting in the simulations not being as accurate as they should be. It has been concluded that based on this study, the number of uncomfortable hours in our units would drop significantly and result in a comfortable building for most Ghanaians.

The second limitation was due to the fact that ceiling fans cannot be added to rooms within DesignBuilder. This has a significant impact on our results as an article from *DelMar Fans & Lighting* states that a ceiling fan can make a room feel up to 8°F cooler. This is due to the fact that ceiling fans reduce the perceived temperature by the method of evaporation of perspiration on the skin of the occupants (2013). Not being able to add ceiling fans within our model reduces the accuracy with which the occupant would be comfortable. Again, it has been concluded that based on this article, the number of uncomfortable hours in our units would drop significantly and result in an even more comfortable building for most Ghanaians.

The third limitation was using averages of the entire building to compare iterations. For an unknown exact reason, some units performed better than others in the number of uncomfortable hours. For example, when comparing unit #1 with unit #4 in the number of uncomfortable hours, unit #4 performed about 800 hours better. Unit #1 had 2342.3 uncomfortable hours per year compared to unit #4's 1435.67 uncomfortable hours per year. Checks were made to ensure that each unit was modeled the exact same way. Some factors that might play into this increase in uncomfortable hours could be the relative position of each unit in the building and sun exposure. Unit #1 was located on the first floor of the building whereas unit #4 is located on the second floor. Unit #4 is also shaded more by the roof due to the overhangs whereas unit #1 is mostly unshaded leaving it more exposed to the sun. Unit #4 also presumably gets more wind exposure and better cross ventilation due to it being located on the second floor. The sun exposure of unit #1 could lead to an increase in the solar heat gain resulting in higher temperatures, and increasing the number of uncomfortable hours. Overall, this variation in performance is observed but the exact reason remains unknown and is something that could be looked into for further research.

The last limitation was due to the number of assumptions made on the EcoBlock properties such as thermal conductivity, specific heat, emissivity, and density. These played a role in how our building performed when running the simulations. Having the actual properties would benefit greatly in the accuracy of the results.

Overall these limitations are something to consider when looking at the results of our model as these changes would only improve occupant comfort of our building. Due to these conditions, the predicted number of annual discomfort hours is, in reality, a conservative estimate. It can be safely assumed that the annual discomfort hours would be significantly reduced if the DesignBuilder software was completely customizable and all EcoBlock material properties were known.

4.2.4 *Iterated Design Informed by Advisor and Community Feedback*

The feedback received from our Ghanian partners in Akyem Dwenase and at Nelplast was overwhelmingly positive and the only constructive feedback was provided by Richmond Boadu Tinyase, a member of the town's development team. Any other feedback the team received was in regard to fundraising efforts for the town.

Richmond Boadu Tinyase: Member of Akyem Dwenase Development Team

Richmond Boadu Tinyase is the Chief Linguist for the town of Akyem Dwenase and serves as a member of the town's development team. We met with him with the intention of aligning our design priorities with those of the town. After presenting our floor plans, building renderings, and explaining to him our architectural design strategies for the project, he confirmed that this seems suitable for the town and the needs of the teachers. He remarked that we should reduce the size of the living area by approximately 2 feet to save materials, but this is the only physical critique of the design that he had. The design team is dedicated to furthering their town, and they deeply appreciate our efforts in contributing to the education of their children.

After our conversation with Richmond Boadu Tinyase, we took his feedback and implemented it into our design. Our living room dimensions were 14' x 18' prior to our review. Our first step was to reduce the living area by 2 feet. We then had to adjust our original dimensions to align with the dimensions of the EcoBlocks, which are 14 inches long and 6 inches wide. As a result, the final living room dimensions are 13'6" x 15'10". Thanks to the feedback we received, this new size will reduce overall construction costs and material use.

4.3 ***Structural Design Process***

The structural design process could not begin before the material properties of the Nelplast EcoBlock were understood and proper assumptions could be implemented.

4.3.1 ***Material Property Laboratory Testing***

Testing on Nelplast EcoBlocks was completed to verify the capabilities of the materials and confirm reasonable design assumptions. Two tests were completed: a comprehensive strength test and an interface test establishing the strength of the interface between concrete and an EcoBlock.

4.3.1.1 Compression Test

The maximum compressive load (N) and measured compressive stresses (MPa) of each sample were relatively consistent with the exception of sample #3. After all the data was collected, it was determined that sample #3 was an outlier as the sample failed at a compressive load of approximately 3,000 N less than the other samples. Further investigation of the sample's failure revealed a large piece of aggregate along the main source of cracking which likely contributed to the early failure of the sample. Due to this revealed condition, the third sample was considered an outlier and not analyzed with the rest of the collected data. After an investigation into each sample's failure pattern, it was found that Samples #1, 2, 4, and 5 failed in the same manner in which one corner of the sample initially cracked which was then amplified through deep, internal cracks at the samples vertical midpoint with the consistent addition of compressive stress (Figure 28).

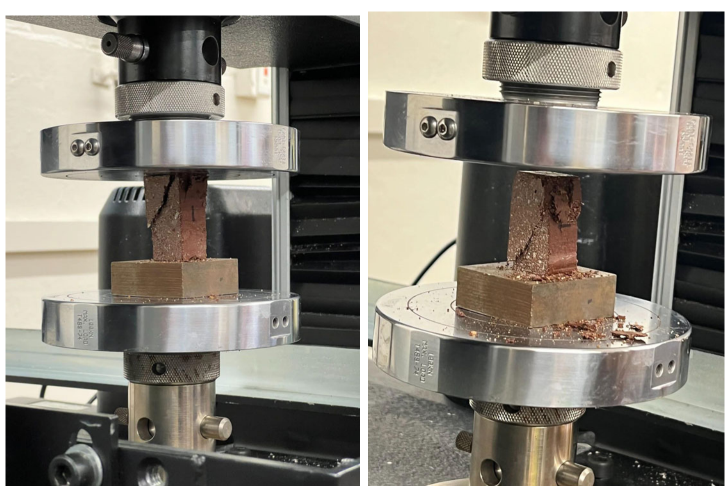


Figure 28. Manner of Failure in Sample #1

Table 9 below illustrates the results of the EcoBlock samples' compressive stress test. Figure 29 visually illustrates the measured maximum compression strength of each sample by an enlarged data point and further establishes the outlier status of Sample #3, represented by a yellow line. According to the results, the average compressive strength of the EcoBlock was 2,600 psi.

Table 9. EcoBlock Samples Compressive Stress Tests Results.

22mm x 22mm x 52.5mm EcoBlock Sample	Maximum Compressive Load [N]	Compressive Stress at Maximum Compressive Load [MPa]	Compressive Stress at Maximum Compressive Load [psi]
#1	8,552.16	16.811	2,438.23
#2	8,538.50	18.455	2,676.67
#3*	5,499.36	11.286	1,636.90
#4	8,398.42	18.180	2,636.79
#5	8,274.23	18.470	2,678.85
Average	8,440.83	17.979	2,607.63

* outlier and not considered when analyzing the data

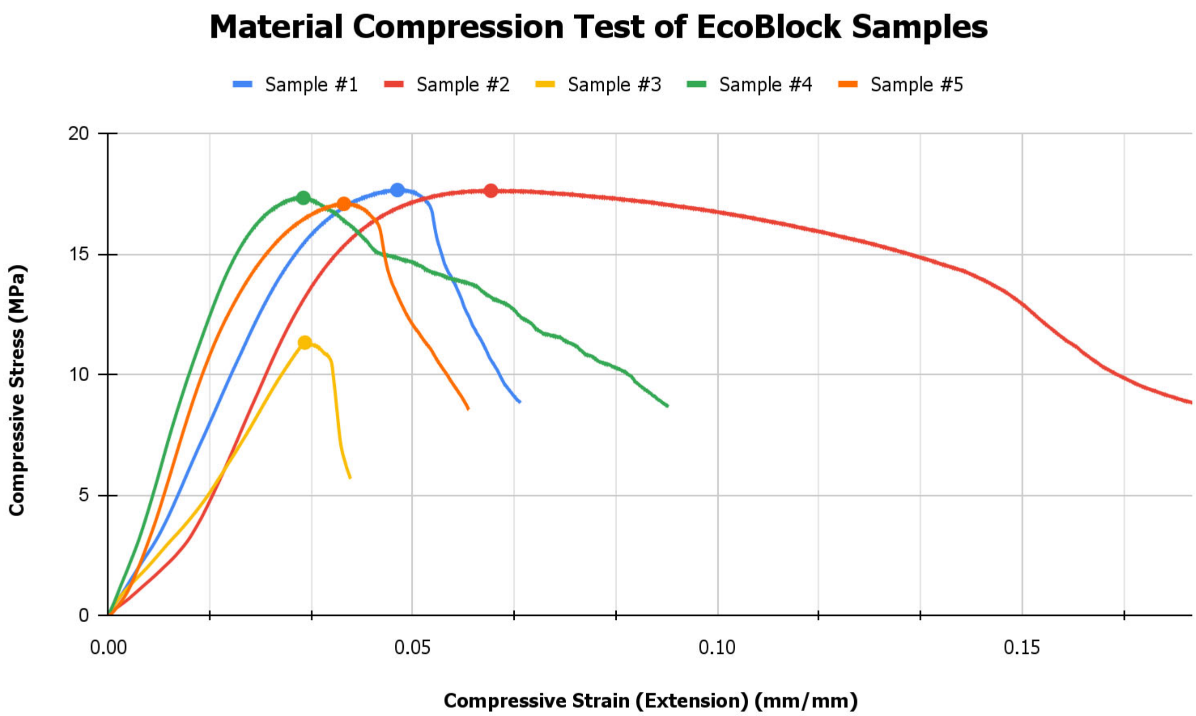


Figure 29. Compressive Stress Test Results of EcoBlock Samples

<u>4.3.1.2 Shear Interface Test</u>

Once the data from the interface test between an EcoBlock sample and concrete was collected, the compressive stress was graphed (Figure 30) and the maximum compressive load was determined to be 527.7 N, denoted by an enlarged data point. The data analysis results were presented in Table 10.

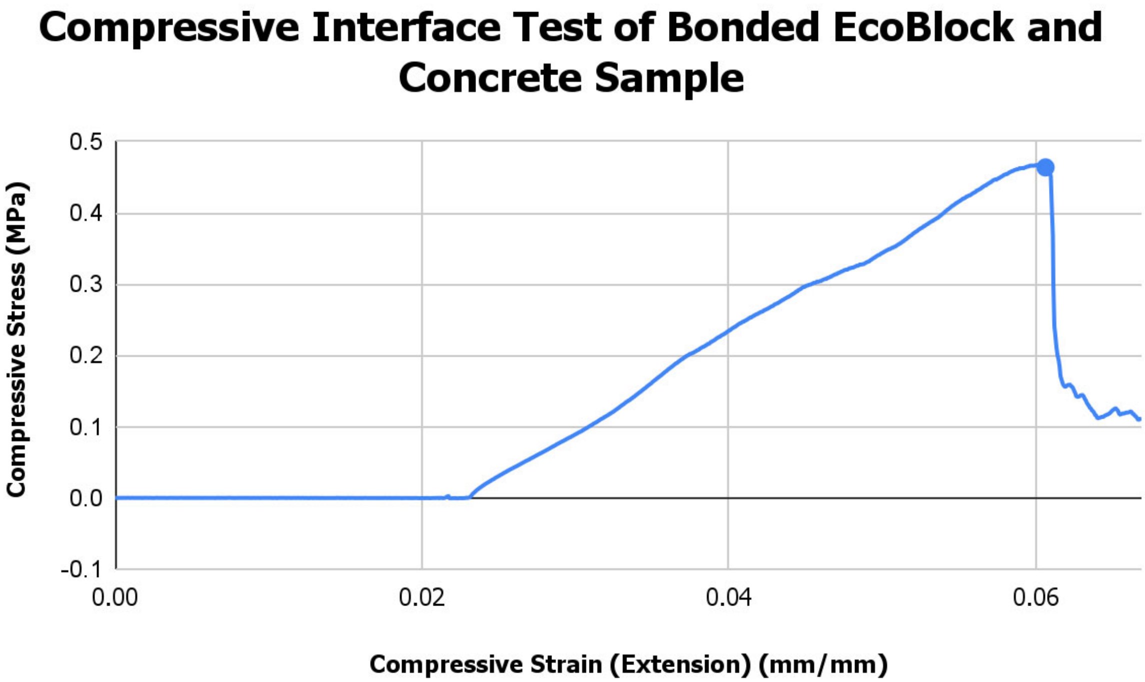


Figure 30. Compressive Stress Test Results of EcoBlock Sample Bonded to Concrete

Table 10. Interface Shear Test Results of EcoBlock Sample Bonded with Concrete

Maximum Compressive Load [N]	Compressive Stress at Maximum Compressive Load [MPa]	Shear Stress at Maximum Compressive Load [psi]
527.71	0.879	67.79

The shear stress at the maximum compressive load was calculated by dividing the maximum compressive load. 527.71 N, by the contact surface area, 1129 mm^2, between the two samples. The resulting shear strength at the maximum compressive load was found to be 67.79 psi. The minimum shear strength of concrete is $2(f'_c)^{0.5}$ and ranges between 870 psi, for an f'_c of 189 ksi and 2465 psi for an f'_c of 1519 ksi. The shear strength between the EcoBlock and concrete was measured to be significantly weaker than the shear strength of concrete. The weak interface strength between the EcoBlock and the concrete was likely due to the smooth exterior of the EcoBlock which provided the concrete with an incompatible surface to sufficiently adhere to. Seeing as the bond was significantly weak, it was decided to only implement reinforced concrete beams into our design and not invest further time exploring new beam systems which heavily rely on the unsatisfactory interface bonding between EcoBlocks and concrete. These results significantly affected the design of an EcoBlock/concrete composition section we designed in section 4.3.6. The design originally considered for this composition beam was based on the perfect bonding between concrete and EcoBlock.

4.3.2 *Design Considerations*

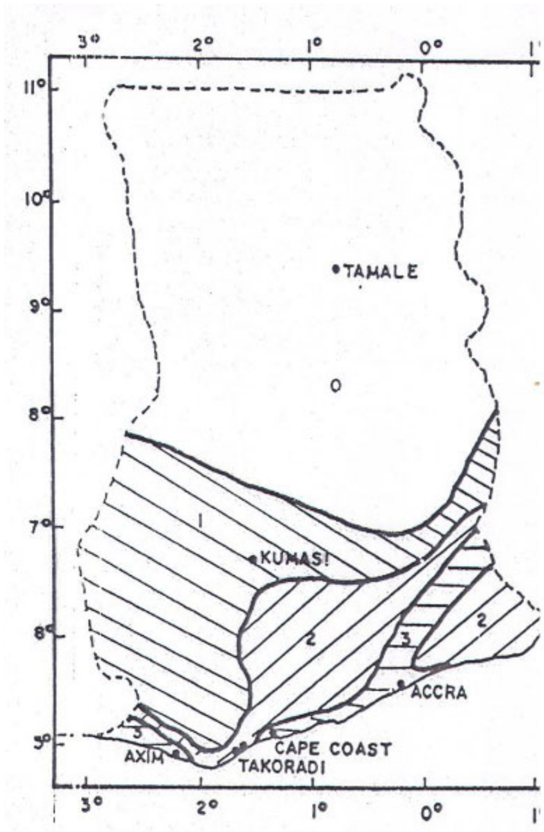
In addition to calculated results, structural properties specific to the region including soil type and seismic activity were considered.

4.3.2.1 Soil Properties

Akyem Dwenase is located in Ghana's semi-deciduous rainforest ecological zone which largely covers the country's bottom quarter of land mass, excluding the Southern coastline. Soils found in this ecological zone are defined as low-activity clays with high base saturation, with 68% of soil samples identified as lixisols by the FAO/WRB classification guidelines. Due to the lack of boring logs and soil testing, the soil conditions in Akyem Dwenase were assumed to be low-activity clay with high base saturation. The soil present on the proposed site is suitable for building as its classification indicates a limited reaction to moisture as its shrink and swell potentials are lower than that of typical cohesive soils. The most conservative clay soil-bearing capacity of 1500 psf was assumed based on the 2021 International Building Code (IBC).

4.3.2.2 Seismic Properties

It is important to consider designing for seismic activities for all buildings to ensure occupant safety as well as building rigidity. However, in this project, seismic properties were not factored into our structural design calculations. Although the country of Ghana is considered far from the major earthquake zones, further research and development of seismic properties should be considered as there have been minor earthquakes in the past century (Figure 31) (Amponsah, 2004). Seismic information in the Ghana building code was unclear and is rarely considered in local building practices. Although no formal seismic applications were introduced, supplemental design elements were implemented to increase the lateral stability of the building. A continuously reinforced concrete header, an enhanced roofing system to continuous header connection, and bent steel reinforcements at the columns all contribute to the system's lateral stability.



Seismic Zone	Assigned Horizontal Design Ground Acceleration: A (g units of gravity)
0	0
1	0.15
2	0.25
3	0.35

Figure 31. Seismic Map of Ghana. *Source: Ghana Building Code, 2018.*

4.3.3 *Footing Design*

Although the soil type can be safely assumed, the clay's actual performance and compressive capacity are unknown. To be conservative in our calculations, it was assumed that the clay soil present on the intended site was relatively poor-performing clay soil with a bearing capacity of 1500 psf from IBC 2021 Table 1806.2 *Presumptive Load-Bearing Values*. The calculations employed a total service dead load of 981.25 psf and a total service live load of 450 psf.

The footing calculations, shown in Appendix B, assume a uniform bearing pressure distribution and disregard nonuniformities present in the actual bearing pressure distribution. It is acceptable to assume a uniform bearing pressure distribution as the actual distribution is highly variable depending on the exact soil type and its influence on the magnitudes of bending moments and shear forces in a footing is relatively small. The calculations resulted in a final design of 16" below grade reinforced concrete 8" by 2' footing with #4 latitudinal reinforcements 12" on center as well as three #4 longitudinal reinforcements equally spaced with 2" clear cover. The final design is shown in Figures 32 and 33 below.

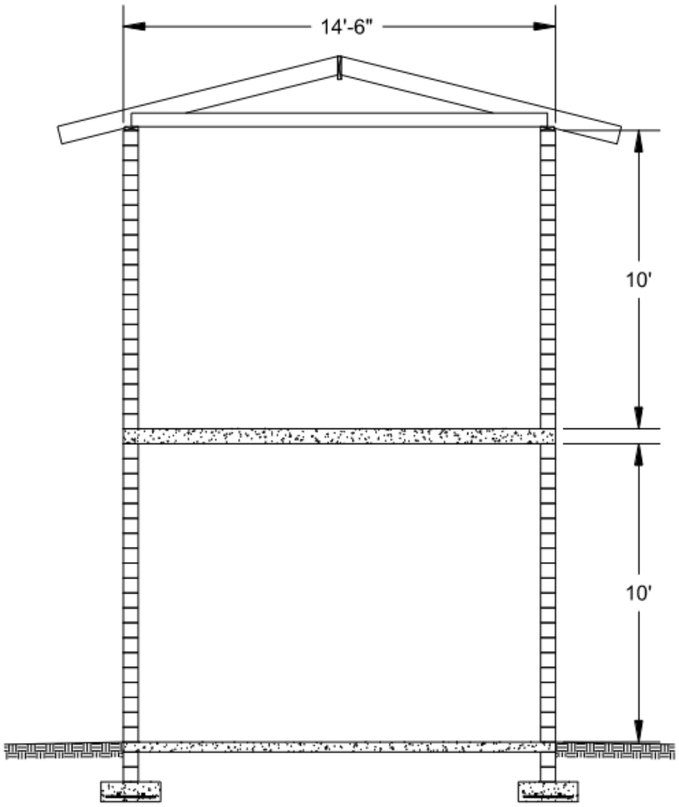


Figure 32. Scaled Cross-section of Structural Footing Design

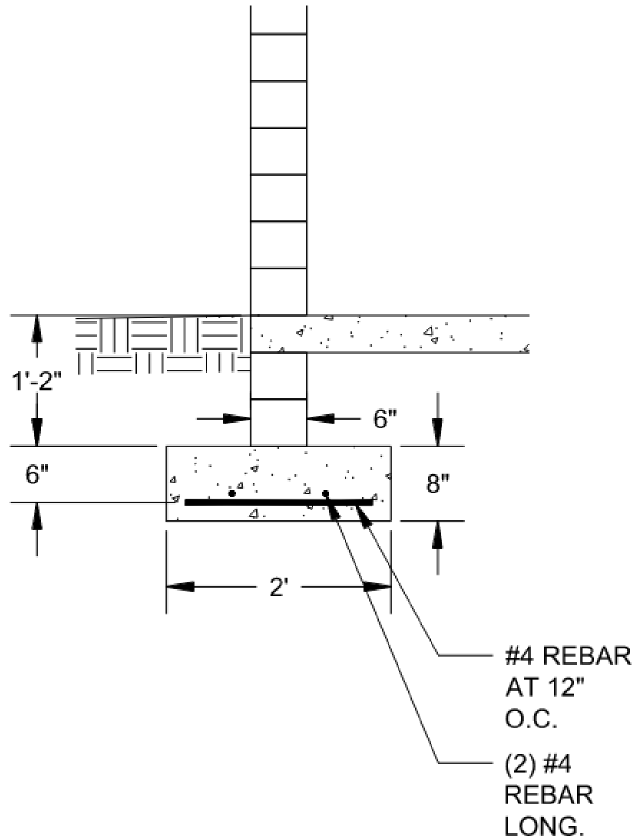


Figure 33. Final Reinforced Concrete Footing Design

4.3.4 *Slab Design*

The slab was assumed to be a one-way slab as the slab would be supported on two sides with a long-to-short span ratio of greater than 2. According to slab calculations shown in Appendix C, the simply supported slab's minimum thickness was calculated to be 8.4" which was greater than the slab's assumed thickness of 6" and therefore required deflection to be calculated. The calculated short-term deflections were within the acceptable range. The final slab design was determined to be a 6" concrete slab with #4 reinforcements uniformly spaced 10" on center (Figure 34).

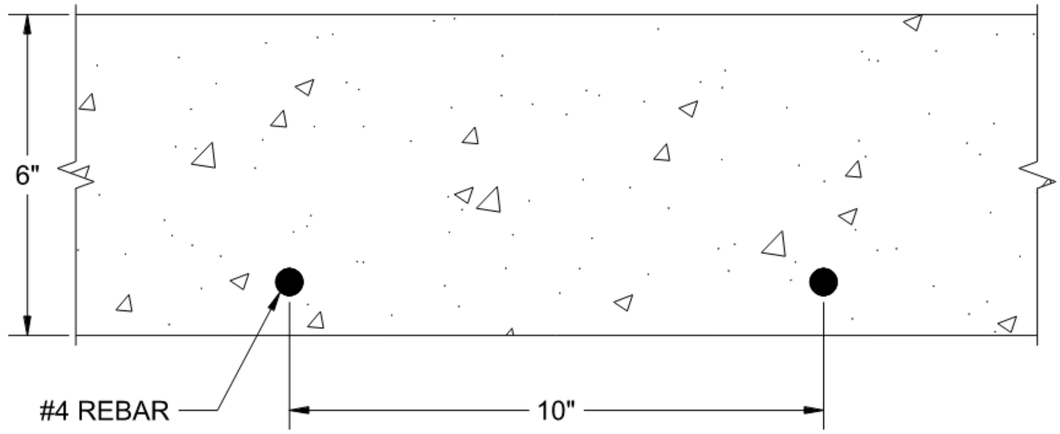


Figure 34. Final One-Way Slab Design

4.3.5 *Column Design*

The column was designed according to the column variant of the Nelplast EcoBlocks. These blocks are larger than the typical wall blocks and are filled with concrete as shown in Figure 35 below.

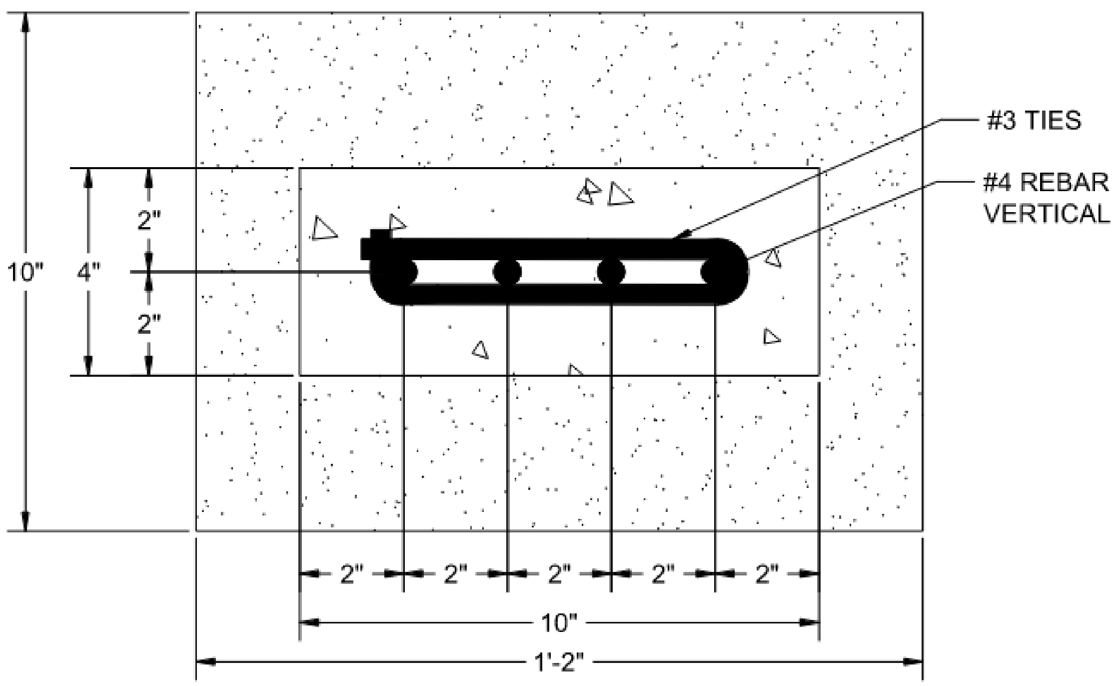


Figure 35. Final Column Design

Four #4 reinforcements were added to the column to provide reinforcement. This was the maximum amount of #4 rebar that could be included while maintaining adequate concrete cover. #3 steel reinforcement ties were also added with 8” of lateral tie spacing to provide shear support. The distance between each tie was the maximum lateral spacing as it could not exceed 16 times the ½” diameter of the #4 longitudinal bars. The column was analyzed using MatLab, with the EcoBlocks being ignored as a structural element. The MatLab code is shown in Appendix D, and the resulting interaction diagram is included in Figure 36 below.

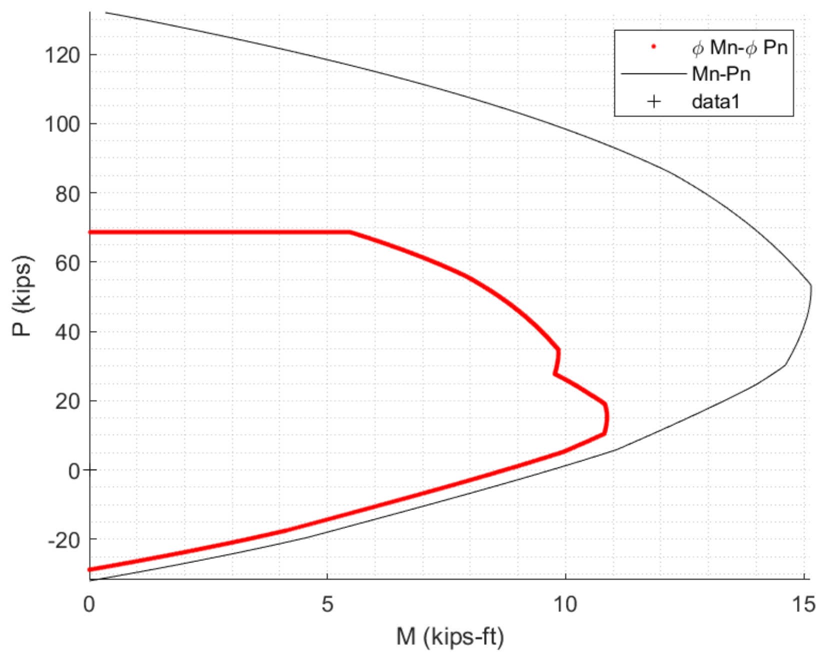


Figure 36. Column Interaction Diagram

As shown in Figure 36, the maximum compressive axial load the column can withstand with no eccentricity or added moment is slightly less than 70 kips. This capacity is much greater than any demand that will be placed in the column in this design. Even with an added moment, the column is significantly stronger than necessary.

With the capacity of the column being significantly greater than the demand, the true concern of this design is in how the column connects to the foundation. It is important that both axial and lateral loads be properly transferred from the column to the foundation. To ensure an adequate connection, there must be at least 0.5” of overlap between #4 reinforcements as shown in the detail below (Figure 37).

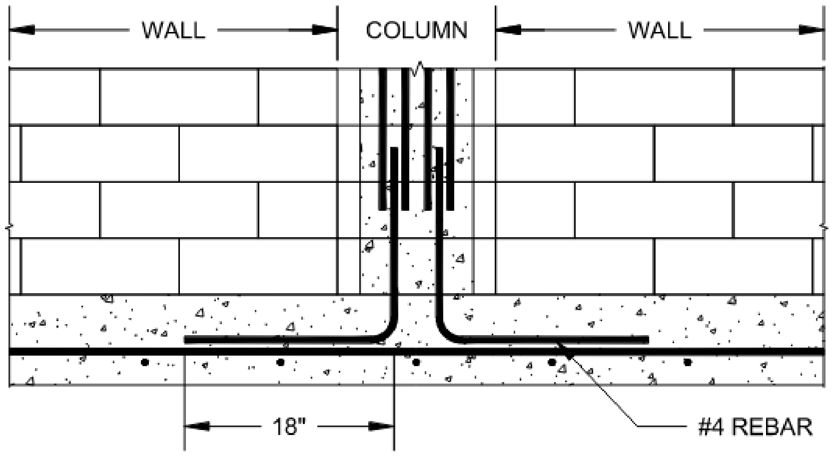


Figure 37. Column - Foundation Connection Detail

4.3.6 *Beam Design*

Designing a beam system required the team to consider the feasibility of two types of beams: a traditional concrete reinforced beam and a new beam design using prefabricated EcoBlocks to reduce concrete usage.

To design a reinforced concrete beam suited to support the proposed structure, the calculations (Appendix E) assumed the compressive strength of concrete and steel to be 3000 and 60,000 psi respectively. The assumption of concrete's compressive strength was determined by taking the most conservative compressive strength of Portland cement concrete, a cementitious building material commonly used in the United States. Portland cement concrete strength ranges from 3000 to 6000 psi based on water content and aggregate type. The lowest strength value of Portland cement concrete was selected considering the impacts of building conditions that would be present in Akyem Dwenase. In Akyem Dwenase, as is true in most of rural Ghana, concrete is mixed by hand, and aggregate is manually added. Unlike modernized building methods which include cement mixers and carefully measured material components, the consistent performance of the cement cannot be guaranteed due to the highly variable conditions of its production and therefore should be assumed to be weaker. The initial design, shown in Figure 38 was found to be a 15" by 6" poured concrete beam with three #4 reinforcements equally spaced horizontally with 2" of cover.

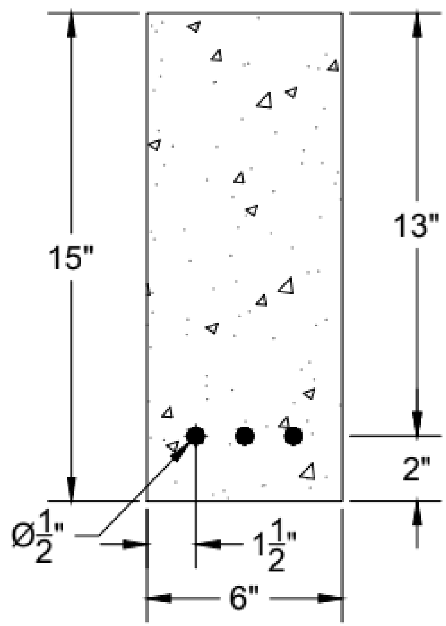


Figure 38. Cross-Section of Initial Reinforced Concrete Beam Design

Exploring new beam designs which utilized less concrete required the team to brainstorm ways in which the existing EcoBlocks could be integrated into a beam. After multiple iterations, the team settled on a conceptual design. The design employed Nelplast's hollow column EcoBlocks, concrete, and steel reinforcements. In order to be constructed, the blocks would be stacked vertically to create a hollow interior, secured with steel reinforcements, and filled with concrete. The design, shown in Figure 39, was found to be a 15" by 6" column EcoBlock filled with concrete and three #8 reinforcements equally spaced vertically with 0.5" of clear cover.

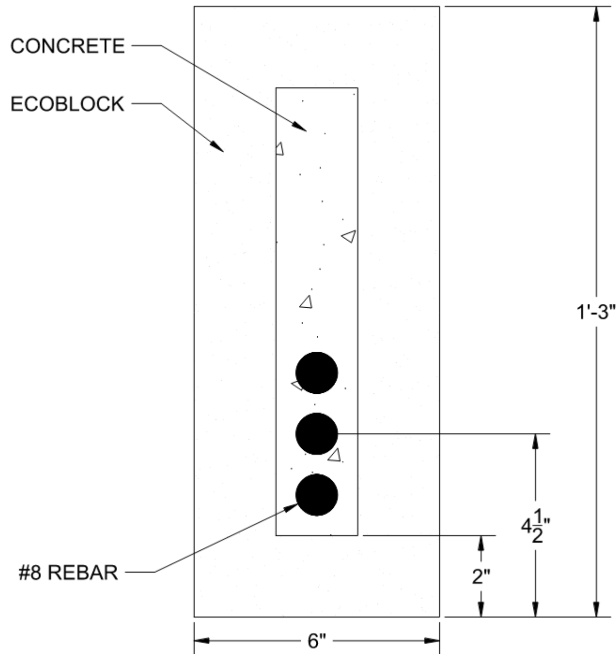


Figure 39. Cross-Section of Reinforced Concrete-Filled EcoBlock Beam Design

Based on laboratory shear testing discussed in previous sections,it was determined that the interface between concrete and EcoBlock is entirely insufficient and that any beam reliant on the bond between concrete and EcoBlock material would not be feasible. In order for a beam like this to truly function, an additional reinforcement or modification to the EcoBlock material to increase the bond between would be required. The traditional reinforced concrete beam design was ultimately chosen due to its feasibility, constructability, and ease of integration into the proposed structural system.

The oversized nature of the reinforced concrete beam (Figure 38), deemed to be 15” by 6”, was assumed for comparison purposes to the hollow column EcoBlock which shared the same dimensions and was virtually unchangeable due to financial restraints of mold expenses. Once the material composition of the beam was determined, the reinforced concrete beam design was optimized through iterative calculations shown in Appendix E. The final reinforced concrete design was decided to be a 6” by 8” concrete beam reinforced with four #4 reinforcements and 2” clear cover with #3 stirrups spaced laterally at 3” on center (Figure 40).

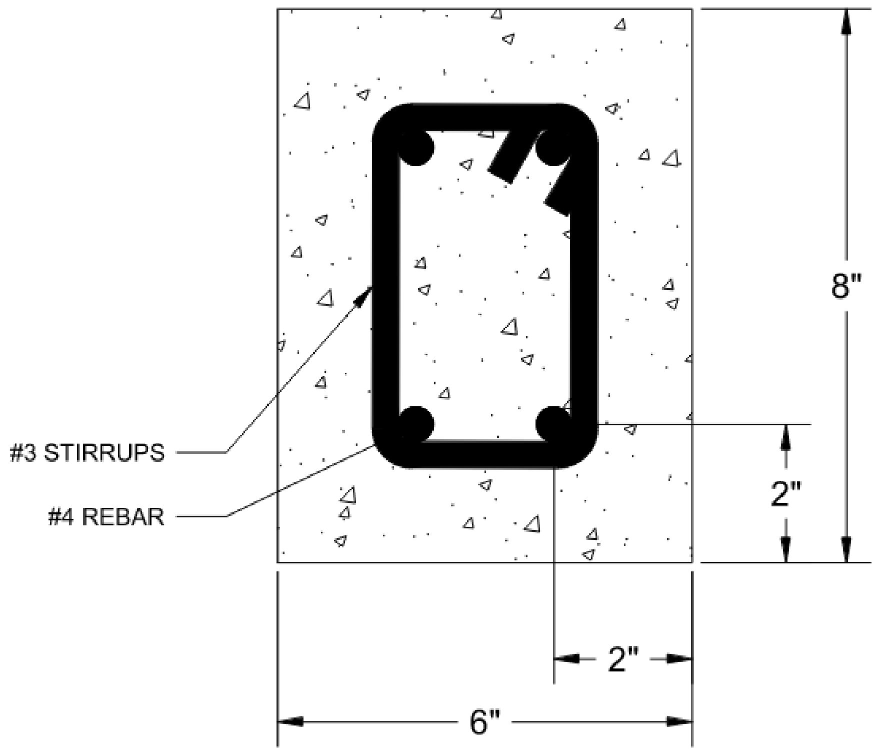


Figure 40. Cross-Section of Final Reinforced Concrete Beam Design

4.3.7 ***Roof Design***

The proposed roof system is a conventionally-framed gable wood roof with rafters, ceiling joists, and a non-structural ridge beam. This roof design was found to be the most energy-efficient option and offered easier constructability in the field. This structural system is intended to support corrugated metal panels that will serve as the final exterior roofing finish.

The rafters were designed using the American Wood Council (AWC) 2018 National Design Specification (NDS) and the 2018 NDS Supplement. The bending strength of the wood used as rafters was assumed to be 400 psi, making it a weak softwood. The live load was determined to be 20 psf from IBC 2021 Table 1607.1. The dead load was assumed to be 10 psf, as this is a common value used when exact dead loads are unknown. A 1.6L + 1.2D LRFD factored load combination was used to determine the design load. Formulas from the AWC 2018 NDS and NDS Supplement were used to determine the allowable bending strength of the rafters, as shown in the calculations in Appendix G.

The required rafter size given a 24" on-center spacing is a 2x8 inch nominal rafter. The ceiling joists must be nominal 2x6 inches or larger, as specified in IBC 2021 Table 2308.7.1. These ceiling joists make the ridge beam non-structural, although the ridge must still be a nominal 2x10 inch in order to ensure an adequate connection between the rafters and the ridge (Figure 41).

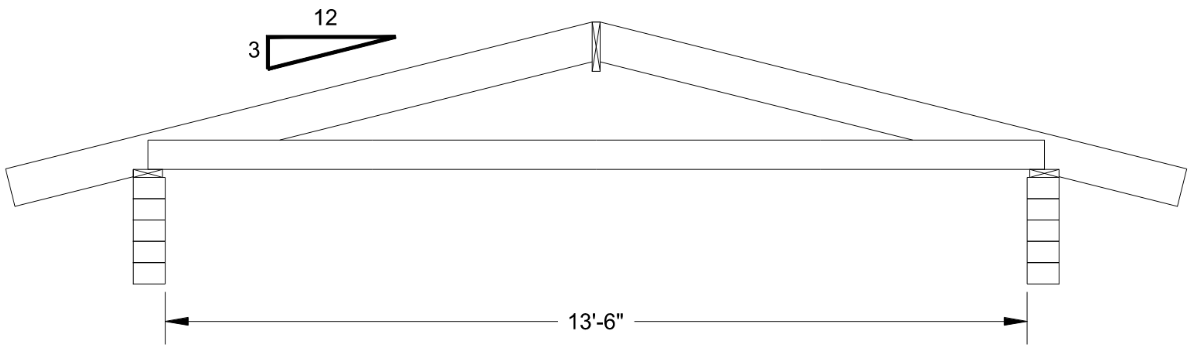


Figure 41. Scaled Cross-Section of Roofing System

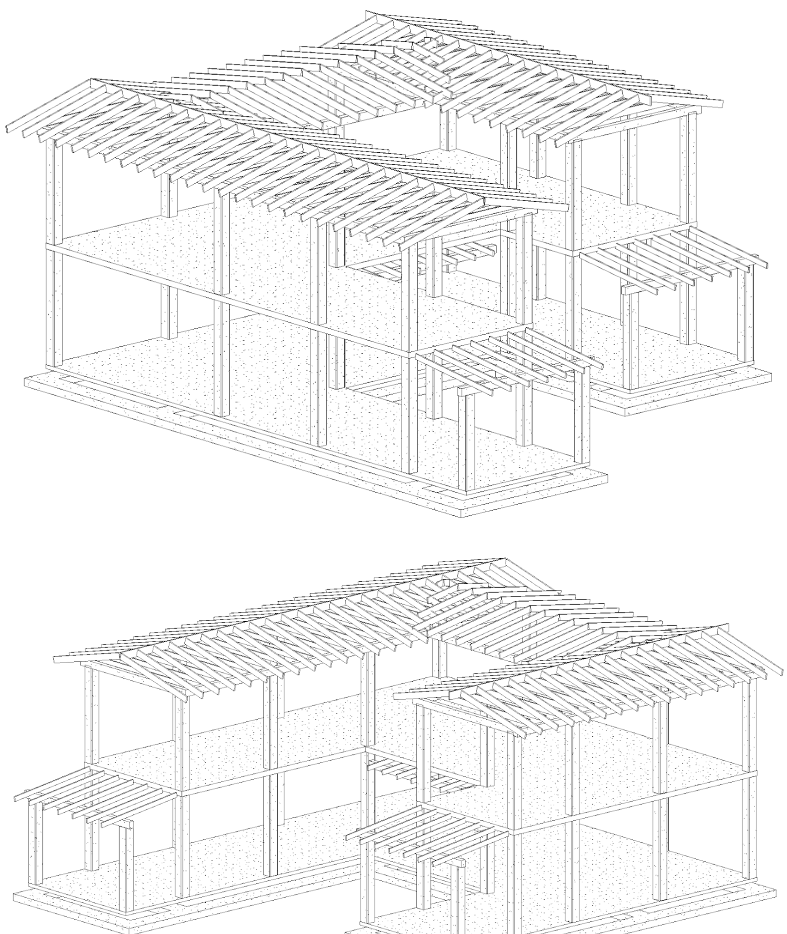


Figure 42. Isometric views of the structural system

4.4 ***Cost Analysis***

In order to have a rough price estimate of our proposed design, a cost estimate was performed by the group.

To construct one structure (containing five individual units), the estimated cost would be $35,594.30 USD (GH₵498,320.21) which is $7,118.86 USD (GH₵99,664.04) per unit. This rough estimate only accounts for the basic construction material costs such as the EcoBricks, concrete, rebar, windows, doors, wood framing, and appliances. This estimate does not account for labor costs. The total price to create all four structures (containing 20 units total) would therefore be $142,377.20 USD (GH₵1,993,280.84). Table 11 shows a cost breakdown of each category per structure.

Table 11. Cost Analysis Per One Structure.

Category	Quantity Required	Price Per Unit	Total
EcoBlocks	13170	$0.50	$6,585.00 USD GH₵92,190.00*
Concrete	39.49 (cubic yards)	$125.00	$4,935.76 USD GH₵69,100.69*
Rebar	2038.5 (ft)	$16 (per 20ft)	$1,630.80 USD GH₵22,831.20*
Windows	42.36 (m^2)	$90.00 (per m^2)	$3,812.74 USD GH₵53,378.37*
Doors	5 exterior doors 11 interior doors	$318.00 $135.00	$3,075.00 USD GH₵43,050.00*
Roof Rafters	110 2x8's (16' long)	$23.00	$2,530.00 USD GH₵$35,420.00*
Appliances	30	$434.17	$13,025.00 USD GH₵182,350.00*
Total			$35,594.30 USD GH₵498,320.21*

*At the time of conversion $1.00 USD → ₵14.00 GH (From Refinitiv – December 8th, 2022)

This price is due to a number of design elements that were utilized in our design. The two dominant factors that had the greatest contribution to the cost-effectiveness of this project are the utilization of Nelplast EcoBlocks and the implementation of an efficient floor plan layout as mentioned above.

4.5 *Deliverables*

Our affordable housing design for teachers in Akyem Dwenase includes several supplemental deliverables in order to simplify future construction processes. In addition to this **final report**, our complete project will include a **construction document drawing set**, a **construction manual**, and a **3-D Revit model**. The construction document drawing set can be found in Appendix G and the construction manual can be found in Appendix H.

The construction document drawing set will provide all of the information necessary to construct one of the housing structures. The complete set will include floor plans, a site plan, elevations, sections, details of specific intersections, structural plans, lighting plans, electrical plans, plumbing plans, a roofing plan, and 3-D renderings.

To assist in understanding the construction process, we created a construction instruction manual. This manual is designed to make the construction process as understandable and seamless as possible. With complications including a language barrier, contrasting construction practices, and the fact that our team will not be there in person to assist with the housing construction, we felt it was important to include this additional form of information.

Our 3-D Revit model of our design will also be included in our submission. This will help to provide another interface in which developers can understand design details if needed.

Supporting calculations that determined our design decisions are included in this report (Appendix B-F). In producing and submitting these deliverables, our hope is to facilitate and accelerate the construction process as much as possible in order to reach the end goal of creating affordable housing units for teachers in Akyem Dwenase.

5 *Opportunities for Further Research and Development*

The design process that arrived at the final model by the design team utilized feedback and iteration to increase the probability of successful construction of this project. However, there are some areas in which the team either does not have adequate expertise or requires further research.

One area that the team does not have expertise in is septic systems. Locally, many residents of Akyem Dwenase utilize a septic tank below their homes that must be serviced every 2 years. It is assumed by the team that this system is provided by a company that is able to supplement its installation, and was therefore not in the scope of this project.

Akyem Dwenase provides its residents with the ability to access the town water line. The location of the closest access point and the procedure for adding residences to this line will require further coordination with town officials and was therefore not in the scope of this project.

Worcester Polytechnic Institute has multiple future projects that would be logical additions to our current housing unit design. Should these project ideas come to fruition, they should be considered to be used in conjunction with the proposed design. First of which is a micro-flush toilet system that would reduce the amount of water required by the toilets and could possibly eliminate the need for a septic tank. The micro-flush system utilizes vermiculture composting to produce organic, nutrient-rich compost that can be harvested and used in agriculture. Another future project will design a roofing system using coconut sheathing. As this is a highly sustainable material that is likely inexpensive to harvest, it would be an advantageous material replacement for corrugated aluminum roofing.

Nelplast Eco Ghana Ltd. is a growing company that has yet to perfect the EcoBlock construction system. The blocks themselves have evolved as Nelplast's work has expanded. The main issue with the system is the connection between EcoBlock column blocks and wall blocks. The current column block is only provided with the ability to connect to wall blocks if they are intersecting at a 180° angle. Therefore, a solid connection cannot be made between each wall from this system at a corner, t-intersection, or cross-intersectional wall detail. The primary cause for concern in this design concept is in relation to the structure's ability to properly withstand shear forces without additional reinforcements. Although Nelplast has yet to have an issue with this feature in their portfolio, it should be addressed in the future to expand the EcoBlocks' constructible versatility. If possible, the team would recommend that Nelplast invest in a new EcoBlock hollow column mold with connection points on all four sides of the block.

Lastly, our project could be enhanced if we visited our site. Our sizing estimate of the site came from Google Earth, which is not accurate enough for our purposes. Videos and pictures of the site were provided by our partners but could not provide sufficient scale or perspective of the site. Trees and other terrains also cannot be accurately estimated from Google Earth, which could affect the utilized area of the site. In addition to having a physical understanding of the space, speaking in person to our partners in Akyem Dwenase would be extremely beneficial to the communication of our project goals with them.

6 *Conclusion*

There is a lack of affordable housing in Southern Ghana, largely due to the cost of building materials in Ghana in conjunction with the recent housing crisis in Accra. Our design addresses this problem by utilizing EcoBlocks as an affordable building material and specifically provides a satisfactory home for teachers and nurses stationed in the town. The town of Akyem Dwenase has specifically identified the need for rentable housing for teachers and nurses, but this project develops housing units that could be replicable across all southern Ghanaian towns.

Design considerations for the area are fairly consistent across southern Ghana, but this information should be verified prior to construction. The results showcase our findings regarding the structural properties of the EcoBlocks, passive design considerations and strategies, and structural systems necessary to construct a safe building that meets the needs of its occupants. The included construction plans and documentation provide a means for procuring materials and constructing the building.

However, for this project to come to fruition additional considerations may have to be made. These considerations are outlined in the Opportunities for Further Research and Development section and include the use of a septic system, the connection to town water, and the development of new EcoBlock shapes to facilitate stronger wall connections. Our hope is that this MQP provides a basis for the construction of affordable housing in Akyem Dwenase, as well as data that can be used for the design of additional buildings that utilize EcoBlocks and similar construction materials.

Fulfilling the needs of the town required a thoughtful co-design process with stakeholders of the project. The process of drafting, requesting feedback, and incorporating suggestions was a beneficial process not only for our project but for the team as individuals. We grew to understand the general way of life in Akyem Dwanese, how the circumstance of teachers affects their priorities, and how we might align ourselves to accomplish a successful design. The main takeaway that stuck with the team was the deep sense of community in Akyem Dwenese, which is evident through the number of celebrations held in the town. On most Sundays, all town residents and their families gather on the main road to celebrate a wedding, birth, or engagement or observe a funeral. We were proud to contribute to their town and hope our work benefits the education of their children.

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Appendices

Appendix A: Interview Transcripts

Chief Osabarima

- The rain season in Ghana lasts from May through July typically.
- They would benefit from places for teachers and nurses to come to rent in the town.
- The apartment-style they need is simple: a living room, bedroom, and bathroom.
- There is a specific site they have picked out for the location of this housing
- His vision for the land has a small common space for everyone on the compound.
- In the villages all of the structures are very low.
- Need to house 20 teachers and 6 nurses. There are 5 at the secondary school, 4 at preschool, 8 in elementary, and 6 in Deness.
- Some bring husbands, and some are alone.
- They do not use a sewage system; they build a septic that is attached to the home - they have a two/three year period before they are replaced.
- The town has a community water supply system that connects to the electricity line.
- Aluminum roofs are common, which protect against the rainy season.
- Some homes have AC which is a luxury, and most homes have ceiling fans.
- Most homes have lots of windows because the town is between two mountains so the temperature can drop significantly at night.
- 4,300 people live in the town. Lots of people live outside, but their family is from there so for events they come home.
- Many generations live together, sisters, children, and grandparents. 7 people may live in the house together, with many people per bedroom.

Head Mistress

- Francisca's responsibility is to take care of the school & school environment, and she has been there for 1.5 years.
- She rents her home from the town with a private bathroom, which is considered to be a luxury.
- Teachers are typically stationed at the school for 2-5 years. District education services decide where teachers work, and they can request for a transfer (write a letter) to be swapped. Some teachers stay at a posting for 10+ years if they are doing a satisfactory job.
- Some live alone, while some live with their families, which will determine if they rent two or one rooms. There are 12 teachers total (6 at the lower school and 6 at the upper school).

- The number of teachers in the town is expected to increase as they increase their education system.
- They have mainly nuclear & extended-style homes. The extended style has a single room with a veranda, while the nuclear style has separate bathrooms and toilets.
- Housing conditions for teachers are generally bad (in a majority of houses).
- Some stay in the next town because of accommodations and drive in every day.
- Each teacher prefers a single room with a toilet and kitchen inside, while families want a double room, toilet, kitchen, and bath.
- Children have to carry water that they pay for from their houses to their schools.
- Teachers have water in their houses.
- The bill is often too high to connect to the town water supply, so people walk to the common pipe at the center of town where they get buckets of water.
- The location of the new teacher homes is adjacent to the school (5 or 6 meters).
- Some do not have kitchens so they cook on their veranda.
- The town does not have a big market. They have raw items, food commodities, plantains, cassava, and other items that are grown in town. They have to go two towns over to buy items like oil and rice in bulk.
- Common things to have in their kitchen are a fridge, microwave, and gas cooker.
- The headmistress clarified that currently, all teachers in town are single. There are 3 male teachers in secondary school, and 2 female teachers in secondary school.
- Single females and single males will not live together in one unit, but they can still be in the same building.
- "Common kitchen creates a whole lot of confusion" "Some people even prefer cooking in their own bedroom rather than in a common kitchen with other people" - People like privacy regarding the type of food they prepare. They prefer single rooms with a porch/veranda that they can use as the kitchen, even if a common kitchen is available. They fence in the porch with nets (screened porch) to divide the porch into 2 with one area used for cooking. Shelves are inside for cooking utensils. Many would still prefer having an indoor kitchen to an outdoor one if it isn't shared.
- She has one bedroom, one hall, and one porch in her own home
- Ghanaians want to separate work from home, and does not want to live with work colleagues. Ghanaians are very private.
- A courtyard between units is good, they don't want people to interfere in their private life but do enjoy sitting together for conversation when they choose.

- No teachers have cars besides the headmistress. The road is bad and driving is not ideal. A commercial car is like a rental car, and many teachers use this option to get to the next town to go to the market.
- A normal day in the headmistress's life:
    - Wake up
    - Take bath
    - Breakfast
    - School
    - Use sign-in book ("Time Book") and check that other teachers are there
        - She and other teachers have their own office
    - Goes to other classes to observe and ensure classes are being held
    - Have general assembly, pledge of allegiance, national anthem, and announcements
    - Has schedule dictating when each teacher has to go teach
        - She monitors the teachers according to this schedule, goes around and inspects classrooms
    - Teach from 7-10, then break for meal (30 minutes)
    - Begin learning again at 10:30, from 10:30-12:30
    - Break again at 12:30, have lunch
    - 1:00 move back to classroom
    - Teach 1:00-3:00
    - Have closing assembly, teachers sign out in Time Book
    - Has extra class for final-year students from 3-5, teachers rotate teaching this class
    - Headmistress leaves last, not long after 3
    - Goes back to house, has 1 hour rest, then makes supper
- The headmistress has a husband and children that live in a nearby town. She visits them on the weekends. Her family doesn't live with her in Akyem Dwenase because she was only posted to AD last year and she doesn't want to move her children from their current school.
- They own a house with plenty of room, but there is not enough room in Akyem Dwenase.
- She washes her clothes and prepares bulk meals on Saturdays. She prepares about 5 different things to supplement her meals throughout the week.
- The bigger market in the next town is open Tuesday, Thursday, and Friday. It is located in the same town as her family, so she buys in bulk while visiting.

Nelson Boateng

- Overview of the EcoBlock creation process: Collect plastics, shred, wash if needed, dry, mix sand and plastic, add color (red, brown, or green), heat to 180-220 degrees, place the paste in mold
- A block takes approximately 1-3 minutes to produce.
- There are only two types of bricks produced; wall and column blocks.
- They utilize a typical concrete foundation in their homes. One with concrete and mortar attaching to the first layer of blocks. The mortar sets for 14 days then only a hammer is required to continue.
- Building system wiring is installed by cutting into the blocks and then cementing it in. This is also used for plumbing systems.
- They are trying to develop a roofing system, but they do not have one yet.
- They do not currently have any issues with the process, possibly the only issue being that the process can be slow since it takes a significant amount of time to melt sand.
- The production and installation process can be about 10-12 months in total.
- The corner pieces interlock like lego bricks.
- Windows and doors are installed by leaving room for them within the block system, then being screwed into the blocks, which is a very secure connection.
- The interior is finished with drywall and plaster.
- Bricks are tested by the Ghana Standards Authority to ensure safety.
- Rebar and cement are used inside of column blocks, but there is no need for cement to be used in the rest of the structure. He estimated that about 2 boxes of cement go into the column blocks.
- He creates a horizontal beam in the structure from the second type of brick and cement.
- The bricks are Ghana Building Code compliant and certified to be lived in.

Appendix B: Footing Design Calculations

<u>Service Loads</u>

$Roof:\ L = 20\,psf,\ D = 10\,psf$

$Live:\ (20\,psf)(7\,ft\ tributary\ area\ width) = 140\,plf$

$Dead:\ (10\,psf)(7\,ft\ tributary\ area\ width) = 70\,plf$

$Floor:\ L = 40\,psf,\ D = 10\,psf$

$Live:\ (40\,psf)(7\,ft\ tributary\ area\ width) = 280\,plf$

$Dead:\ (10\,psf)(7\,ft\ tributary\ area\ width) = 70\,plf$

$Walls:\ L = 0\,psf,\ D = 35\,psf$

$Dead:\ (35\,psf)(10\,ft + 10\,ft\ height) = 700\,plf$

$Total\ Service\ Dead\ Load = 840\,plf$

$Total\ Service\ Live\ Load = 420\,plf$

$Total\ Service\ Load = 1260\,plf$

<u>Design Loads</u>

$LRFD\ load\ combination:\ 1.6L + 1.2D = 1.6(420\,plf) + 1.2(840\,plf) = 1680\,plf$

$Use\ unfactored\ loads\ in\ footing\ size\ determination.$

$Assume\ soil\ type\ to\ be\ clay.$

$q_a = soil\ bearing\ capacity = 1500\,psf\ (IBC\ 2021\ Table\ 1806.2)$

$q_e = effective\ bearing\ pressure = q_a - q_{soil} - q_{self}$

$q_e = 1500\,psf - (100\,pcf)(\frac{14\,in}{12\,in/ft}\ depth) - (150\,pcf)(\frac{8\,in}{12\,in/ft}\ height\ of\ concrete)$

$q_e = 1283.33\,psf$

$b_{required} = \frac{D+L}{q_e} = \frac{1260\,plf}{1283.33\,psf} = 0.98\,ft \rightarrow Use\ b = 2\,ft\ for\ constructability$

$Use\ factored\ loads\ to\ determine\ ultimate\ bearing\ capacity,\ q_u$

$q_u = \frac{1.6L+1.2D}{b} = \frac{1680\,plf}{2\,ft} = 840\,psf$

$Determine\ ultimate\ footing\ moment, M_u$

$M_u = \frac{1}{8}q_u(b - a)^2$

$a = 0.5\,ft, b = 2\,ft$

$M_u = \frac{1}{8}(840\ psf)(2 - 0.5\ ft)^2 = 236.25\ lb \cdot ft\ (per\ unit\ width)$

$Assume\ depth,\ d,\ to\ be\ 6"\ to\ determine\ ultimate\ shear\ strength,\ V_u$

$V_u = q_u\left(\frac{b-a}{2} - d\right) = (840\ psf)\left(\frac{2\ ft - 0.5\ ft}{2} - \frac{6\ in}{12\ in}\right) = 210\ lb$

$Concrete\ punching\ shear\ strength,\ V_c = \sqrt{f'c} \cdot bd = \sqrt{3,000\ psi} \cdot (12"\ unit\ width)(6"\ depth)$

$V_c = 3943.60\ lb$

$Check\ against\ shear\ capacity,\ \phi V_c$

$\phi = 0.75$

$\phi V_c = (0.75)(3943.60\ lb) = 2,957.70\ lb \geq V_u = 210\ lb \rightarrow acceptable$

$Use\ b = 2\ ft,\ d = 6",\ h = 8"$

$Determine\ reinforcement\ ratio,\ \rho$

$M_u = \phi\rho f_y bd^2\left(1 - 0.59\rho \cdot \frac{f_y}{f'_c}\right)$

$(236.25\ ft \cdot lb)(12") = (0.9)\rho(40,000\ psi)(12")(6")^2\left(1 - 0.59\rho \cdot \frac{40\ ksi}{3\ ksi}\right)$

$2835\ lb \cdot in = 15,552,000\rho(1 - 7.867\rho) \rightarrow \rho = 0.000206 \leq A_{s,min} = 0.0018A_g$

$Calculate\ required\ reinforcements\ along\ short\ side$

$A_{s,min} = 0.0018A_g = 0.0018hb = 0.0018(8")(12") = 0.1728\ in^2$

$Use\ \#4\ bars\ at\ 12\ O.C. \rightarrow A_s = 0.2\ in^2$

$\rho = \frac{A_s}{bd} = \frac{0.2\ in^2}{(12")(6")} = 0.00278$

$Check\ \phi V_c\ once\ again.$

$\phi V_c = \phi 8\rho^{1/3}\sqrt{f'_c} \cdot bd = (0.75)(8)(0.00278)^{1/3}\sqrt{3000\ psi} \cdot (12")(6") = 3,326.16\ lb$

$\phi V_c = 3,326.16\ lb \geq V_u = 474.38\ lb \rightarrow acceptable$

$Calculate\ required\ reinforcements\ along\ long\ side$

$A_{s,min} = 0.0018A_g = 0.0018hb = 0.0018(8")(24") = 0..3456\ in^2$

$Use\ 2\ \#4\ bars\ (2"\ cover\ on\ either\ side,\ one\ in\ the\ middle\ @\ 18")\ \rightarrow A_s = 0.4\ in^2$

Appendix C: Slab Design Calculations

$Assume\ 6"\ concrete\ slab\ with\ \#4\ reinforcements\ @\ 10"\ On\ Center$

Moment Calculation

$Live\ Load\ (L)\ =\ 40\ psf$

$Dead\ Load\ (D)\ =\ 10psf\ +\ 150psf\left(\frac{6'}{12"}\right) = 85\ psf$

$Factored\ Load,\ w\ =\ 1.6L\ +\ 1.2D\ =\ 1.6(40)\ +\ 1.2(85)\ =\ 166\ psf$

$Assume\ 1'\ unit\ width,\ 166\ psf(1')\ =\ 166\ plf$

$0.004\ \leq\ \rho\ \leq\ 0.008$

$\rho\ =\ 0.004$

$f_y =\ 60\ ksi$

$f'_c =\ 3\ ksi$

$\phi\ =\ 0.9\ (tension\ controlled)$

$d\ =\ h\ -\ 1\ =\ 6\ -\ 1\ =\ 5"$

$$M_n =\ \rho bd^2\left(1\ -\ 0.59\rho\frac{f_y}{f'_c}\right)\ =\ (0.004)(60)(12")(5")^2\left(1\ -\ 0.59(0.004)\left(\frac{60\ ksi}{3\ ksi}\right)\right) = 68.6\ k\cdot in$$

$$M_n =\ 68.6\ k\cdot in\ =\ 5,716.8\ \ lb\cdot ft$$

$$\phi M_n =\ 0.9M_n =\ .9(5,716.8\ \ lb\cdot ft)\ =\ 5,145.1\ lb\cdot ft$$

$$M_{max} = \frac{wL^2}{8} = \frac{(166plf)(14')^2}{8} =\ 4,067\ lb\cdot ft$$

$$\phi M_n \geq\ M_{max} \rightarrow\ 5,145.1\ lb\cdot ft \geq\ 4,067\ lb\cdot ft$$

Deflection Calculation

$E_s =\ 29\ \times\ 10^6\ psi$

$E_c =\ 57,000\sqrt{f'_c} =\ 57,000\sqrt{3,000\ psi} =\ 3.12\ \times\ 10^6\ psi$

$n\ = \frac{E_s}{E_c} = \frac{29\times10^6\ psi}{3.12\times10^6\ psi} =\ 9.29$

$w\ =\ 166\ psf \rightarrow 166\ plf$

$l\ =\ 14'$

$h\ =\ 6"$

$f_r =\ 7.5\sqrt{f'_c} =\ 7.5\sqrt{3,000\ psi} =\ 410.8\ psi$

$M_a = 5,145.1\ lb \cdot ft$

$l_{min} = \frac{l}{20} = \frac{14'(12")}{20} = 8.4"$
$l_{min} \geq h \rightarrow 8.4" \geq 6" \rightarrow deflection\ calculation\ needed$

$short\ term\ deflection = \Delta = \frac{5wL64}{384EI_e}$

$$I_e = \frac{I_{cr}}{1 - \left(\frac{\frac{2}{3}M_{cr}}{M_a}\right)^2\left(1 - \frac{I_{cr}}{I_g}\right)}$$

$I_g = \frac{bh^3}{12} = \frac{(12")(6")^3}{12} = 216\ in^2$

$y_t = \frac{h}{2} = \frac{6"}{2} = 3"$

$M_{cr} = \frac{f_r I_{ut}}{y_t} = \frac{f_r I_g}{y_t} = \frac{(410.8\ psi)(216\ in^2)}{3\ in} = 29,577.6\ in \cdot lb = 2,464\ ft \cdot lb$

$depth\ of\ neutral\ axis,\ c$
$\frac{b}{2}c^2 = nA_s(d - c) \rightarrow \frac{(12")}{2}c^2 = (9.29)(0.2in^2)(5" - c) \rightarrow c = 1.10"$

$I_{cr} = \frac{bc^3}{3} + nA_s(d - c)^2 = \frac{(12")(1.10")^3}{3} + (9.29)\left(0.2in^2\right)(5" - 1.10")^2 = 33.58\ in^4$

$M_L = \frac{w_L L^2}{8} = \frac{(40\ psf)(14')^2}{8} = 980.0\ lb \cdot ft$
$M_D = \frac{w_D L^2}{8} = \frac{(85\ psf)(14')^2}{8} = 2,082.5\ lb \cdot ft$

$M_{D+.6L} = 980.0 + .6(2,082.5) = 2670.5\ lb \cdot ft$

$$I_{e,D} = \frac{I_{cr}}{1 - \left(\frac{\frac{2}{3}M_{cr}}{M_D}\right)^2\left(1 - \frac{I_{cr}}{I_g}\right)} = \frac{33.58\ in^4}{1 - \left(\frac{\left(\frac{2}{3}\right)(2464.8\ ft \cdot lb)}{2,082.5\ ft \cdot lb}\right)^2\left(1 - \frac{33.58\ in^4}{216\ in^2}\right)} = 70.82\ in^4$$

$$I_{e,D+L} = \frac{I_{cr}}{1 - \left(\frac{\frac{2}{3}M_{cr}}{M_{D+L}}\right)^2\left(1 - \frac{I_{cr}}{I_g}\right)} = \frac{33.58\ in^4}{1 - \left(\frac{\left(\frac{2}{3}\right)(2464.8\ ft \cdot lb)}{3062.5\ ft \cdot lb}\right)^2\left(1 - \frac{33.58\ in^4}{216\ in^2}\right)} = 44.37\ in^4$$

$$I_{e,\,D+.6L} = \frac{I_{cr}}{1-\left(\frac{\frac{2}{3}M_{cr}}{M_{D+.6L}}\right)^2\left(1-\frac{I_{cr}}{I_g}\right)} = \frac{33.58\ in^4}{1-\left(\frac{\left(\frac{2}{3}\right)(2464.8\ ft\cdot lb)}{2670.5\ ft\cdot lb}\right)^2\left(1-\frac{33.58\ in^4}{216\ in^2}\right)} = 49.36\ in^4$$

short term deflection, Δ

$$\Delta = \frac{5wL64}{384EI_e} = \frac{5}{48}\cdot\frac{ML^2}{EI_e} = \frac{5}{48}\cdot\frac{((14')(12"))^2M}{(3.12\times10^6 psi)I} = 0.00904\frac{M}{I}\ in$$

initial live load deflection, $\Delta_L = \Delta_{D+L} - \Delta_D$

$$\Delta_L = \frac{0.00904(M_D+M_L)}{I_{e,\,D+L}} - \frac{0.00904(M_D)}{I_{e,\,D}} = \frac{0.00904(3062.5\ lb\cdot ft)}{44.37\ in^4} - \frac{0.00904(2{,}082.5\ lb\cdot ft)}{70.82\ in^4} = 0.36\ in$$

initial dead load deflection, Δ_D

$$\Delta_D = \frac{0.00904(M_D)}{I_{e,\,D}} = \frac{0.00904(2{,}082.5\ lb\cdot ft)}{70.82\ in^4} = 0.27\ in$$

initial 60% live load deflection, $\Delta_{6L} = \Delta_{D+.6L} - \Delta_D$

$$\Delta_{.6L} = \frac{0.00904(M_{D+.6L})}{I_{e,\,D+.6L}} - \frac{0.00904(M_D)}{I_{e,\,D}} = \frac{0.00904(2670.5\ lb\cdot ft)}{49.36\ in^4} - \frac{0.00904(2{,}082.5\ lb\cdot ft)}{70.82\ in^4} = 0.22\ in$$

Appendix D: Column Design Calculations

Column Interaction Diagram Matlab Code

Contents


```
clear
clc
```

Materials properties

```
fc = 3
fy = 40
```

Geometry

```
b = 4
h = 10
nrb = 4     % Number of bar rows
```

Areas of steel

```
As(1) = .2;%*pi*(9/8)^2/4;
As(2) = .2;%*pi*(9/8)^2/4;
As(3) = .2;%0*pi*(10/8)^2/4;
As(4) = .2;%0*pi*(10/8)^2/4;
%As(5) = 4*pi*(10/8)^2/4;
cover = 2;
bar_spacing = (h-2*cover)/(nrb-1);
for i = 1:nrb
    d(i) = cover + (i-1)*bar_spacing;
end

beta1 = 0.85-.05*(fc-4)/1
E = 29000    %ksi
eps_y = fy/E;

%%%%% TIE COLUMN
alpha_tie = 0.8;
phi_tie = 0.65;
phi_tension = 0.9;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

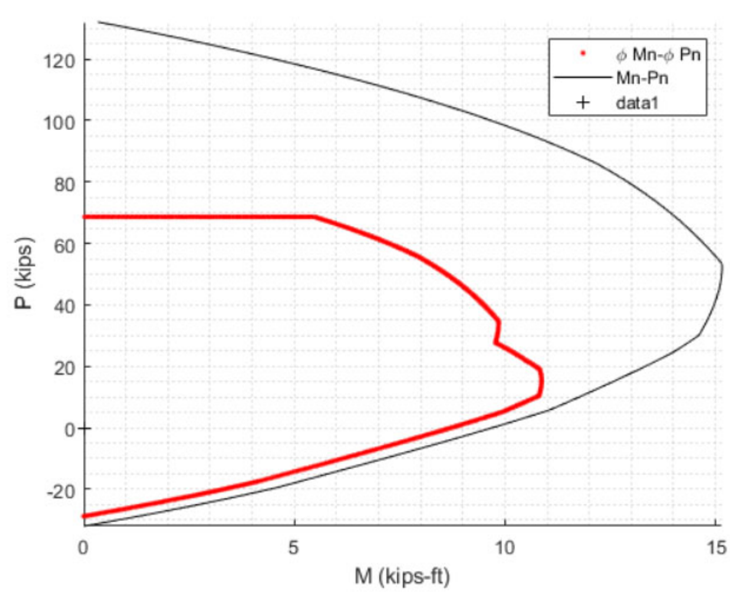
LOADING

```
Pu1 = 0
Mu1 = 0

j = 0
figure
hold
```

```
Ast = sum(As)
P0 = 0.85*fc*(b*h-Ast) + Ast*fy;
for c = .001:.01:25
    j = j +1;
    a = beta1*c;
    eps(1:nrb,j) = zeros(nrb,1);
    for i = 1:nrb
        eps(i,j) = (c-d(i))/c*0.003;

        fs(i,j) = E*eps(i,j);

        if abs(fs(i,j)) >= fy
            fs(i,j)=fy*sign(fs(i,j));
        end
    end
    if eps(nrb,j) <= -0.005
        phi=0.9;
    elseif eps(nrb,j) < -0.002 && eps(nrb,j) > -0.005
        phi=0.65+(abs(eps(nrb,j))-0.002)*83.3333;
    elseif eps(nrb,j)>= -0.002
        phi=0.65;
    end
    phi_j(j)=phi;

    %%%%%%%%%% Pn
    Fs = 0;
    for i = 1:nrb
        Fs = Fs + As(i)*fs(i,j);
    end


    Pn(j) = 0.85*fc*b*a+Fs;
    Pu(j) = phi_j(j)*Pn(j);


    if Pu(j) >= alpha_tie*phi_tie*P0
        Pu(j) = alpha_tie*phi_tie*P0;
    end


    %%%%%%%%%% Mn

    Ms = 0;
    for i = 1:nrb
        Ms = Ms + As(i)*fs(i,j)*(h/2-d(i));
    end

    Mn(j) = 0.85*fc*a*b*(h/2-a/2)+Ms;

    Mu(j) = phi_j(j)*Mn(j);

    %     if phi >=0.9
    %         plot(Mu(j)/12,Pu(j),'r.')
    %         plot(Mn(j)/12,Pn(j),'r.')
    %     elseif phi <= 0.65
    %         plot(Mu(j)/12,Pu(j),'b*')
    %         plot(Mn(j)/12,Pn(j),'b*')
    %     else
    %         plot(Mu(j)/12,Pu(j),'go')
    %         plot(Mn(j)/12,Pn(j),'go')
    %     end
```

```
    %     pause (.001);

end
axis([0 max(Mu/12) min(Pu) phi_tie*alpha_tie*P0])
grid minor
xlabel({'M (kips-ft)'})
ylabel({'P (kips)'})
plot (Mu/12,Pu,'r.')

axis([0 max(Mn/12) min(Pn) P0])
plot (Mn/12,Pn,'k-')
legend('\phi Mn-\phi Pn','Mn-Pn')

plot(Mu1/12,Pu1,'k+')

% figure
% for i = 1:j
%     k=0;
%     for theta =0:.01:2*pi
%         k= k+1;
%         x(i,k)=Mu(i)*cos(theta);
%         y(i,k)=Mu(i)*sin(theta);
%     end
%
% end
% for j = 1:k
% Pu_3D(:,j)=Pu;
% end

% contour3(x,y,Pu_3D,100)
% xlabel({'\phi M_x (kips-ft)'})
% ylabel({'\phi M_y (kips-ft)'})
% zlabel({'\phi P (kips)'})
```

```
fc =

     3


fy =

    40


b =

     4


h =

    10


nrb =

     4


beta1 =

    0.9000


E =

       29000


Pu1 =

     0


Mu1 =

     0


j =

     0

Current plot held

Ast =

    0.8000
```



Development Length

Development length equation:

$$l_d = \left(\frac{3}{40} \cdot \frac{f_y}{\lambda \sqrt{f'_c}} \cdot \frac{\Psi_t \Psi_e \Psi_s \Psi_g}{\left(\frac{C_b + K_{tr}}{d_b}\right)} \right) d_b$$

Simplified development length equation:

- Can be used as bars are smaller than #6 reinforcements, clear spacing of bars > bar diameter, clear cover > bar diameter, and ties follow code minimum of 8"

$$l_d = \left(\frac{f_y \Psi_t \Psi_e \Psi_g}{25\lambda \sqrt{f'_c}} \right) d_b = \left(\frac{(40\ ksi)\ (1)(1)(1)}{25(1)\ \sqrt{(3\ ksi)}} \right) (0.5") = 0.46" \rightarrow 0.5"$$

$\Psi_t = casting\ position\ factor = 1\ (12"\ concrete\ not\ present\ below\ horizontal\ reinforcement)$

$\Psi_e = epoxy\ coating\ factor = 1\ (uncoated)$

$\Psi_g = reinforcement\ grade\ factor = 1\ (assumed\ to\ be\ Grade\ 40)$

$\lambda = lightweight\ aggregate\ concrete\ factor = 1\ (normal\ weight)$

$d_b = bar\ diameter = 0.5"$

$f'_c = 3\ ksi$

$f_y = 40\ ksi$

Appendix E: Flexural Beam Design Calculations

Initial Reinforced Concrete Beam

$f'_c = 3\ ksi$

$f_y = 60\ ksi$

$\varepsilon_u = 0.003$

$\varepsilon_y = \frac{f_y}{E_s} = \frac{60\ ksi}{29{,}000\ ksi} = 0.00207$

$\rho_{max} = 0.85\beta_1 \cdot \frac{f'_c}{f_y} \cdot \frac{\varepsilon_u}{\varepsilon_u + \varepsilon_{t,min}}$

$\varepsilon_{t,min} = \varepsilon_y + \varepsilon_u = 0.003 + 0.00207 = 0.00507$

$\beta_1 = 0.85 - 0.5\left(\frac{f'_c - 4000}{1000}\right) = 0.85 - 0.5\left(\frac{3000-4000}{1000}\right) = 0.90$

$\rho_{max} = 0.85(0.90) \cdot \frac{3}{60} \cdot \frac{0.003}{0.003+0.00507} = 0.0142$

$\rho_{min} = \frac{1.6\sqrt{f'_c}}{f_y} = \frac{1.6\sqrt{3}}{60} = 0.00146$

$\rho = \frac{A_s}{bd}$

$\rho_{max} = \frac{A_{s,max}}{bd} \rightarrow 0.0142 = \frac{A_{s,max}}{(6)(13)} \rightarrow A_{s,max} = 1.1076\ in^2$

$\rho_{min} = \frac{A_{s,min}}{bd} \rightarrow 0.00146 = \frac{A_{s,min}}{(6)(13)} \rightarrow A_{s,min} = 0.1138\ in^2$

$Use\ 3\ \#4\ reinforcements \rightarrow A_s = 3(0.2) = 0.6\ in^2$

$Equally\ spaced\ with\ 2"\ vertical\ cover\ and\ 1.5"\ horizontal\ cover$

$M_n = A_s f_y\left(d - \frac{a}{2}\right)$

$When\ C = T,\ a = \frac{A_s f_y}{0.85 f'_c b} = \frac{(0.6\ in^2)(60\ ksi)}{0.85(3\ ksi)(6\ in)} = 2.35\ in$

$M_n = \left(0.6\ in^2\right)(60\ ksi)(13\ in - \frac{2.35\ in}{2}) = 425.7\ k \cdot in = 35{,}475\ lb \cdot ft$

$M_u = \phi M_n$

$\phi = ?$

$\varepsilon_t \geq 0.005 \rightarrow \phi = 0.9$

$\varepsilon_t \leq 0.005 \rightarrow \phi = 0.65$

$$\varepsilon_t = \varepsilon_u\left(\frac{d-c}{c}\right)$$

$$c = \frac{a}{\beta_1} = \frac{2.35\ in}{0.9} = 2.61\ in$$

$$\varepsilon_t = \varepsilon_u\left(\frac{d-c}{c}\right) = 0.003\left(\frac{13"-2.61"}{2.61"}\right) = 0.0142$$

$$\varepsilon_t = 0.0142 \geq 0.005 \rightarrow \phi = 0.9$$

$$M_u = \phi M_n = 0.9(35,475\ lb \cdot ft) = 31,927.5\ lb \cdot ft$$

$$\frac{c}{d} \leq 0.375 \rightarrow \frac{2.61\ in}{13\ in} = 0.201 \leq 0.375$$

Initial beam design is a 15" by 6" poured concrete with three #4 reinforcements equally spaced horizontally with 2" of cover.

Reinforced Concrete-Filled EcoBlock Beam

Assumed 15"x6" EcoBlock filled with concrete and three #8 reinforcements aligned vertically. Assumed a perfect bond and minimal clear cover.

$$f'_c = 2.6\ ksi$$

$$f_y = 60\ ksi$$

$$A_s = \left(0.79\ in^2\right)(3) = 2.37\ in^2$$

$$n = \frac{E_s}{E_c}\ \frac{29{,}000{,}000\ psi}{2{,}906{,}441\ psi} = 9.98 \rightarrow 10$$

$$E_s = 29,000,000\ psi$$

$$E_c = 57,000\sqrt{f'_c} = 57,000\sqrt{2,600} = 2,906,441\ psi$$

$$(n-1)A_s = (10-1)\left(2.37\ in^2\right) = 21.33\ in^2$$

$$\sigma = F_c = \frac{My}{I} = \frac{F}{A}$$

$y = h - y_t \rightarrow y_t = \frac{\Sigma Q}{\Sigma A} = \frac{(15)(6)(15/2)+(21.33\ in^2)(4.5)}{(15)(6)+21.33}$, 4.5”= reinforcement midpoint

$$y_t = 7\ in \rightarrow y = h - y_t = 15 - 7 = 8\ in$$

$$I_{ut} = \frac{1}{12}bh^3 + Ad^2 = \frac{1}{12}(6)(15)^3 + (6)(15)(.5)^2 + (21.33)(7-4.5)^2 = 1,843.3\ in^4$$

$\sigma = f'_c = \frac{My}{I} \rightarrow 2,600 = \frac{M(8")}{1,843.3\ in^4} \rightarrow M = 49,922.7\ lb \cdot ft$

M_{max} $controlled\ by\ 49,922.7\ lb \cdot ft$

Final Reinforced Concrete Beam

$f'_c = 3\ ksi$

$f_y = 60\ ksi$

$\varepsilon_u = 0.003$

$\varepsilon_y = \frac{f_y}{E_s} = \frac{60\ ksi}{29,000\ ksi} = 0.00207$

$\rho_{max} = 0.85\beta_1 \cdot \frac{f'_c}{f_y} \cdot \frac{\varepsilon_u}{\varepsilon_u + \varepsilon_{t,min}}$

$\varepsilon_{t,min} = \varepsilon_y + \varepsilon_u = 0.003 + 0.00207 = 0.00507$

$\beta_1 = 0.85 - 0.5\left(\frac{f'_c - 4000}{1000}\right) = 0.85 - 0.5\left(\frac{3000-4000}{1000}\right) = 0.90$

$\rho_{max} = 0.85(0.90) \cdot \frac{3}{60} \cdot \frac{0.003}{0.003+0.00507} = 0.0142$

$\rho_{min} = \frac{1.6\sqrt{f'_c}}{f_y} = \frac{1.6\sqrt{3}}{60} = 0.00146$

$\rho = \frac{A_s}{bd}$

$\rho_{max} = \frac{A_{s,max}}{bd} \rightarrow 0.0142 = \frac{A_{s,max}}{(6)(6)} \rightarrow A_{s,max} = 0.511\ in^2$

$\rho_{min} = \frac{A_{s,min}}{bd} \rightarrow 0.00146 = \frac{A_{s,min}}{(6)(6)} \rightarrow A_{s,min} = 0.0526\ in^2$

$Use\ 2\ \#4\ reinforcements \rightarrow A_s = 2(0.2) = 0.4\ in^2$

$Equally\ spaced\ with\ 2"\ clear\ cover$

$Maximum\ Carrying\ Load = f'_c\left(A_c + nA_s\right)$

$n = \frac{E_s}{E_c}\ \frac{29,000,000\ psi}{3,122,018.6\ psi} = 9.28 \rightarrow 9$

$E_s = 29,000,000\ psi$

$E_c = 57,000\sqrt{f'_c} = 57,000\sqrt{3,000} = 3,122,018.6\ psi$

$A_s = 0.4\ in^2$

$A_c = bd - A_s = (6)(6) - 0.4 = 45.6\ in^2$

$\%Steel = \frac{0.4\ in^2}{36\ in^2} = 0.0111 = 1.11\%$

$Max\ Carrying\ Load = f'_c\left(A_c + nA_s\right) = 3,000(45.6 + 9(0.4)) = 147,600\ lbs$

$Nominal\ Moment = M_n = A_s f_y\left(d - \frac{a}{2}\right)$

$When\ C = T,\ a = \frac{A_s f_y}{0.85 f'_c b} = \frac{(0.4\ in^2)(60\ ksi)}{0.85(3\ ksi)(6\ in)} = 1.57\ in$

$M_n = \left(0.4\ in^2\right)(60\ ksi)(8\ in - \frac{1.57\ in}{2}) = 173.2\ k \cdot in = 14,430\ lb \cdot ft$

$Ultimate\ Moment = M_u = \phi M_n$

$\phi = ?$

$\varepsilon_t \geq 0.005 \rightarrow \phi = 0.9$

$\varepsilon_t \leq 0.005 \rightarrow \phi = 0.65$

$\varepsilon_t = \varepsilon_u\left(\frac{d-c}{c}\right)$

$c = \frac{a}{\beta_1} = \frac{1.57\ in}{0.9} = 1.74\ in$

$\varepsilon_t = \varepsilon_u\left(\frac{d-c}{c}\right) = 0.003\left(\frac{6" - 1.74"}{1.74"}\right) = 0.0073$

$\varepsilon_t = 0.0073 \geq 0.005 \rightarrow \phi = 0.9$

$Ultimate\ Moment = M_u = \phi M_n = 0.9(14,430\ lb \cdot ft) = 12,987\ lb \cdot ft$

$Applied\ Moment = M_{applied} = \frac{wL^2}{8}$

$L = 16'$

$tributary\ width = \left(\frac{13.5'}{2}\right) = 6.75\ ft^2$

$LL = 20\ psf = 20(6.75') = 135\ plf$

$DL = (10\ psf)(6.75') + beam\ self\ weight = (10\ psf)(6.75') + 51.4\ plf = 118.9\ plf$

$Self = 150\ pcf\left(\frac{6}{12}' \cdot \frac{8}{12}' - \frac{0.6}{144}ft^2\right) + 490\ pcf\left(\frac{0.6}{144}ft^2\right) = 51.4\ plf$

$Load\ Combination,\ w = 1.2DL + 1.6LL = 1.2(118.9\ plf) + 1.6(135\ plf) = 358.7\ plf$

$M_{applied} = \frac{wL^2}{8} = \frac{(358.7\ plf)(16')^2}{8} = 11,477.8\ lb \cdot ft$

$$\frac{c}{d} \leq 0.375 \rightarrow \frac{1.96\ in}{8\ in} = 0.245 \leq 0.375$$

$Final\ beam\ design\ is\ a\ 6"\ by\ 8"\ poured\ concrete\ with\ two\ \#4\ reinforcement\ with\ 2"\ clear\ cover.$

Appendix F: Shear Beam Design Calculations

Add #3 stirrups and (2) #4 stirrup support bars to 6"x8" concrete beam

Determine required spacing of stirrups

$w = 358.7\ plf$

$L = 16'$

$V_{max} = \frac{wL}{2} = \frac{(358.7\ plf)(16')}{2} = 2869.6\ lb$

$V_u = V_{max} - wd = 2869.6\ lb - (358.7\ plf)(\frac{6"}{12"}) = 2690.25\ lb$

$\phi V_n = V_u \rightarrow V_n = \frac{V_u}{\phi} = \frac{2690.25\ lb}{0.75} = 3587\ lb$

$V_c = 2\lambda\sqrt{f_c'}b_w d = (2)(1)(\sqrt{3000})(6")(6") = 1971.8\ lb$

$V_n = V_c + V_s \rightarrow V_s = V_n - V_c = 3587\ lb - 1971.8\ lb = 1615.2\ lb$

$V_s = \frac{A_v f_v d}{s} \rightarrow s = \frac{A_v f_v d}{V_s} = \frac{(2*0.11\ in^2)(40{,}000\ psi)(6")}{1615.2\ lb} = 32.7"$

Check American Concrete Institute Provisions for S_{max}

$if\ V_s \leq 4\sqrt{f_c'}b_w d,\ then\ S_{max}\ is\ smallest\ of\ \left\{\frac{d}{2},\ 24,\ \frac{A_v f_v}{0.75\sqrt{f_c'}b_w} \leq \frac{A_v f_v}{50 b_w}\right\}$

$\frac{d}{2} = \frac{6"}{2} = 3" \rightarrow \frac{d}{2}\ governs$

Use #3 stirrups at 3" spacing

Appendix G: Roof Design Calculations

Member Properties

$width = b = 1.5\ in.$

$depth = d = 7.25\ in.$

$span = 6.75\ ft.$

$rafter\ spacing = 24"\ on\ center$

Service Loads

$Live\ Load = 20\ psf\ (IBC\ 2021\ Table\ 1607.1)$

$Dead\ Load = 10\ psf$

Design Loads

$Linear\ Live\ Load = (Live\ Load)(spacing) = (20\ psf)(\frac{24"}{12"}) = 40\ plf$

$Linear\ Dead\ Load = (Dead\ Load)(spacing) = (10\ psf)(\frac{24"}{12"}) = 20\ plf$

$LRFD\ load\ combination = 1.6L + 1.2D = (1.6)(40\ plf) + (1.2)(20\ plf) = 88\ plf$

$Maximum\ Bending\ Moment = M_{Max} = \frac{wL^2}{8} = \frac{(88\ plf)(6.75\ ft.)^2}{8} = 501.19\ ft \cdot lb$

Allowable Bending Stress

$Allowable\ Bending\ Stress = F_b' = F_b C_M C_t C_L C_F C_{fu} C_i C_r K_F \phi \lambda\ (AWC\ NDS\ 2018\ Table\ 4.3.1)$

$F_b = Nominal\ bending\ stress = 400\ psi\ (assumed)$

$C_M = Wet\ service\ factor = 1.0\ (assumed\ dry\ service\ conditions)$

$C_t = Temperature\ factor = 0.8\ (assumed\ 100\ °F \leq T \leq 125\ °F)$

$C_L = Beam\ stability\ factor = 0.98\ (calculated\ below)$

$C_F = Size\ factor = 1.2\ (AWC\ NDS\ Supplement\ 2018\ Table\ 4A\ Adjustment\ Factors)$

$C_{fu} = Flat\ use\ factor = 1.0\ (member\ to\ be\ positioned\ upright)$

$C_i = Incising\ factor = 1.0$

$C_r = Repetitive\ member\ factor = 1.15$

$K_F = Format\ conversion\ factor = 2.54$

$\phi = Resistance\ factor = 0.85$

$\lambda = Time\ effect\ factor = 0.8\ (AWC\ NDS\ 2018\ Appendix\ 9)$

$F_b' = (400\ psi)(1.0)(0.8)(0.98)(1.2)(1.0)(1.0)(1.15)(2.54)(0.85)(0.8) = 751.06\ psi$

C_L $Calculation$:

$l_u = unbraced\ length\ =\ 6.75\ ft.$

$\frac{l_u}{d} = \frac{(6.75\ ft.)(12\ in.)}{7.25\ in.} = 11.17$

$\frac{l_u}{d} \geq 7 \rightarrow l_e = 1.63l_u + 3d\ (AWC\ NDS\ 2018\ Table\ 3.3.3)$

$l_e = effective\ length\ =\ 1.63l_u + 3d = (1.63)(6.75\ ft.)(12\ in.) + (3)(7.25\ in.) = 153.78\ in.$

$R_B = slenderness\ ratio\ = \sqrt{\frac{l_e d}{b^2}} = \sqrt{\frac{(153.78\ in..)(7.25\ in.)}{(1.5\ in.)^2}} = 22.26\ (AWC\ NDS\ 2018\ Table\ 3.3.3.6)$

$E_{min}' = C_M C_t C_i C_T K_F \phi\ (AWC\ NDS\ 2018\ Table\ 4.3.1)$

$C_M = 1.0\ (assumed\ dry\ service\ conditions)$

$C_t = 0.8\ (assumed\ 100\ °F\ \leq\ T\ \leq\ 125\ °F)$

$C_i = 1.0\ (assumed\ no\ incisions)$

$C_T = 1 + \frac{K_M l_e}{K_T E} = 1 + \frac{(1200)(153.78\ in.)}{(0.59)(1{,}000{,}000\ psi)} = 1.31\ (AWC\ NDS\ 2018\ 4.4 \cdot 1)$

$K_F = 1.76$

$\phi = 0.85$

$E_{min}' = 581{,}316.84\ psi$

$F_{bE} = \frac{1.20E_{min}'}{R_B^{\ 2}} = \frac{(1.20)(581316.84\ psi)}{22.26^2} = 3{,}167.53\ psi$

$F_b{}^* = F_b C_M C_t C_i C_r K_F \phi \lambda = 762.73\ psi$

$C_L = \frac{1+(F_{bE}/F_b{}^*)}{1.9} - \sqrt{[\frac{1+(F_{bE}/F_b{}^*)}{1.9}]^2 - \frac{F_{bE}/F_b{}^*}{0.95}}\ (AWC\ NDS\ 2018\ 3.3.3.8)$

$C_L = 0.98$

<u>Member Design</u>

$Required\ section\ modulus\ =\ S_{xx,\ req'd} = \frac{M_{Max}}{F_b'}$

$S_{xx,\ req'd} = \frac{(501.19\ ft\cdot lb)(12\ in.)}{751.06\ psi} = 8.01\ in.^3$

$Use\ nominal\ 2x8,\ S_{xx} = 13.14\ in.^3 > 8.01\ in.^3$

$Use\ ceiling\ joists\ to\ eliminate\ need\ for\ structural\ ridge\ beam$

$Per\ IBC\ 2021\ Table\ 2308.7.1,\ nominal\ 2x6\ ceiling\ joists\ are\ adequate$

Appendix H: Construction Plans and Documentation

(see following documentation)

AFFORDABLE HOUSING UNIT UTILIZING NELPLAST ECOBLOCKS

INSTRUCTIONAL MANUAL

BY: Hannah Frieden, Kyle Mann,
Eda Raycraft, Jake Scalise, and Margot Schassler

ADVISORS: Professor Robert Krueger,
Professor Steven Van Dessel, and
Professor Nima Rahbar

NOT APPROVED FOR CONSTRUCTION

STUDENT PROJECT IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR OF SCIENCE

TABLE OF CONTENTS

FOREWORD

This instructional manual is an academic deliverable for a student project in partial fulfillment of the requirements for the degree of Bachelor of Science at Worcester Polytechnic Institute. This is not an approved document for construction.

This manual will utilize United States customary units for all measurements, mainly feet and inches. A single apostrophe (‘) denotes feet, while a double apostrophe (“) denotes inches.

This instructional manual aims to provide instructions for creating consistent and reliable housing units for teachers and nurses in the town of Akyem Dwenase utilizing the EcoBrick product produced by Nelplast Eco, Gh Ltd. The following documents are designed for, but are not limited to Akyem Dwenase and rural Ghanian townships.

This housing unit has 5 bedrooms, 5 bathrooms, 5 living room/kitchens, and 5 outdoor verandas.

Akyem Dwenase in southern Ghana has a tropical climate with temperatures averaging 76.2°F to 88°F year-round. There is little to no seismic activity in southern Ghana of concern to our design. These geographic characteristics informed design choices and are not applicable to all areas.

This building was designed not to be mechanically conditioned, therefore ventilated naturally.

Due to the lack of boring logs and soil testing, the soil conditions in Akyem Dwenase were assumed to be low-activity clay with high base saturation. The most conservative clay soil-bearing capacity of 1500 psf was assumed based on the 2021 International Building Code (IBC). This assumption guided the sizing of footings.

Concrete beams and columns were designed assuming the compressive strength of concrete is equal to 3,000 psi and the yield strength of steel reinforcement bar is equal to 40,000 psi. U.S. standard steel reinforcement bar sizes were used in the design.

REQUIRED MATERIALS

1. Excavation equipment
2. Concrete (approx. 40 cubic yards)
3. EcoBlocks (approximately 13,170 blocks)
4. #4 steel rebar (approximately 2,040 feet)
5. Windows (following specified sizes on construction documents)
6. Doors (following specified sizes on construction documents)
7. Wooden Roof Rafters (approximately 110 16-foot long 2x8's)
8. Corrugated Aluminum sheets
9. Electrical support equipment
10. Kitchen Fixture for 5 kitchens
11. Bathroom Fixtures for 5 bathrooms
12. Appropriately sized stair stringers (2 sets)
13. Lightweight wood to construct 2 sets of stairs, railings, and landings

NOTE: The quantity of materials specified is an estimate and will require further research.

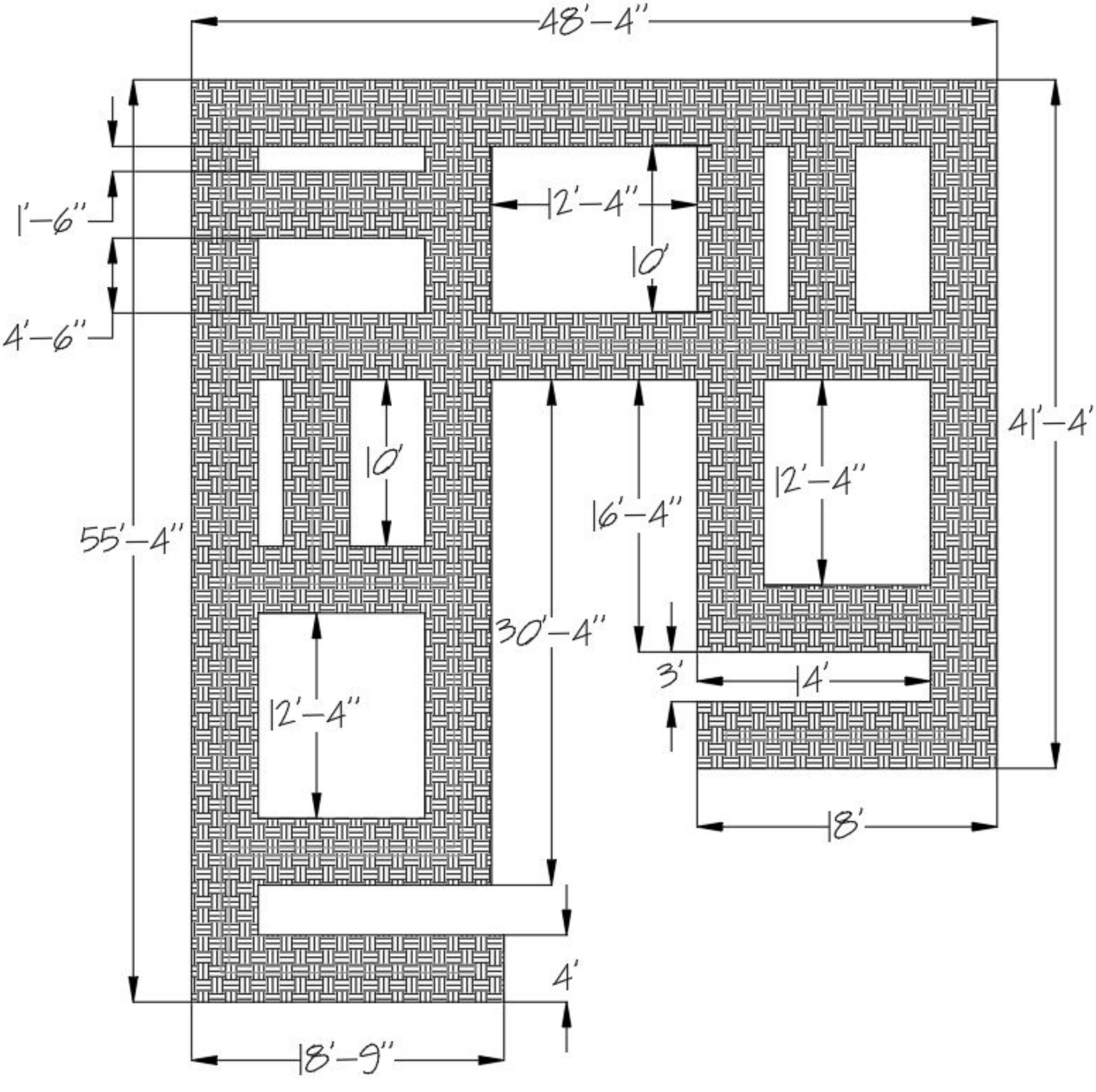
GRADING

The area identified as the site of construction must be graded prior to other construction activities. Grading involves removing trees, rocks, bushes, or anything else that might be on the site and creating a consistent slope away from the future structure. Grading ensures that any rainfall will be lead away from the structure's foundation. Then the foundation site must be leveled before excavation. Leveling involves ensuring that the ground surface is at a consistent level without significant differences in soil height or uneven surfaces. Grading and leveling require equipment capable of removing large amounts of soil and debris. Common tools such as shovels and metal rakes are helpful in achieving this goal.

Proposed site in Akyem Dwenase, Ghana

EXCAVATION

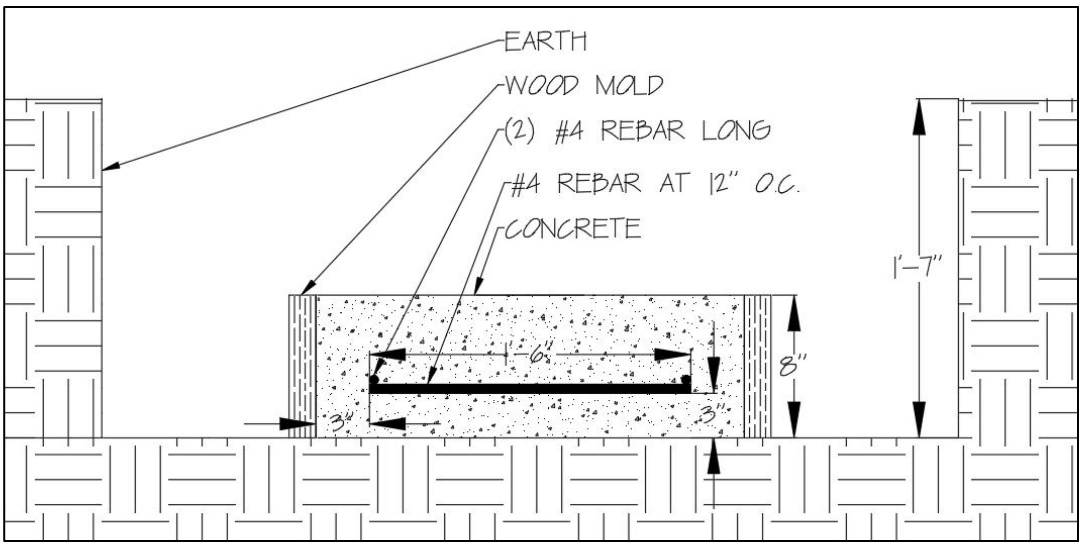
Soil must be removed to prepare for 2-foot wide poured concrete footings. A depth of 1’-7” deep should be dug in the areas denoted below:



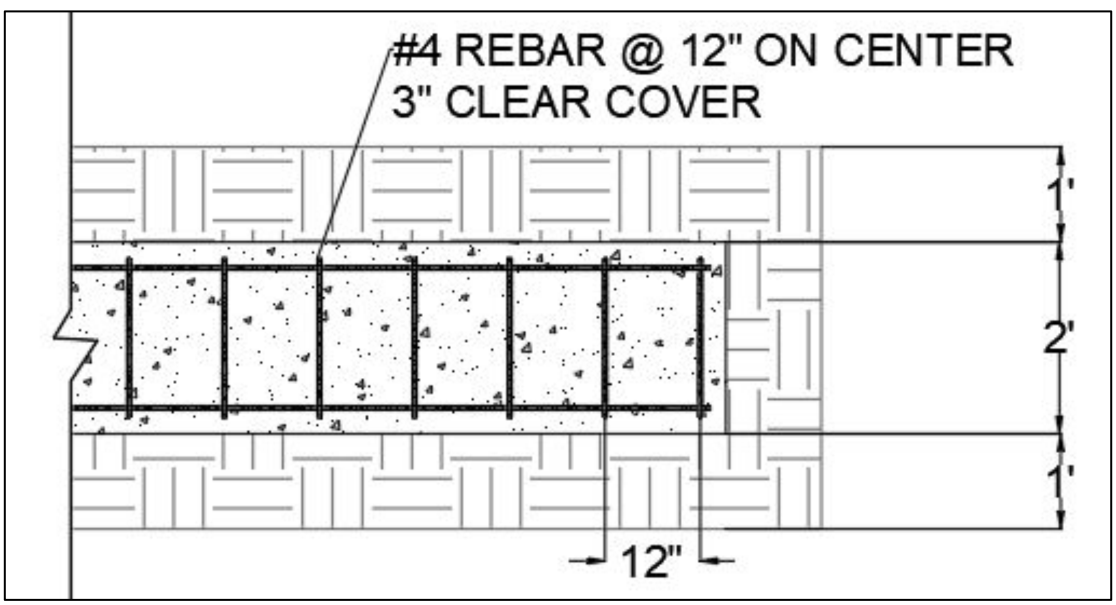
Shaded region denotes areas to be excavated to a depth of 2-feet

FOOTINGS AND FOUNDATION

A wooden mold should be constructed to hold rebar and concrete as it sets. #4 rebar will run both vertically and horizontally through the footing, 3-inches above the bottom of the mold (Figure 3). Running perpendicularly to each wall will be #4 rebar spaced 12-inches apart on center. Two #4 rebars will be running the length of the walls. These should be held in place in the wooden mold, then concrete poured in the mold to the depth of 8-inches (Figure 4).

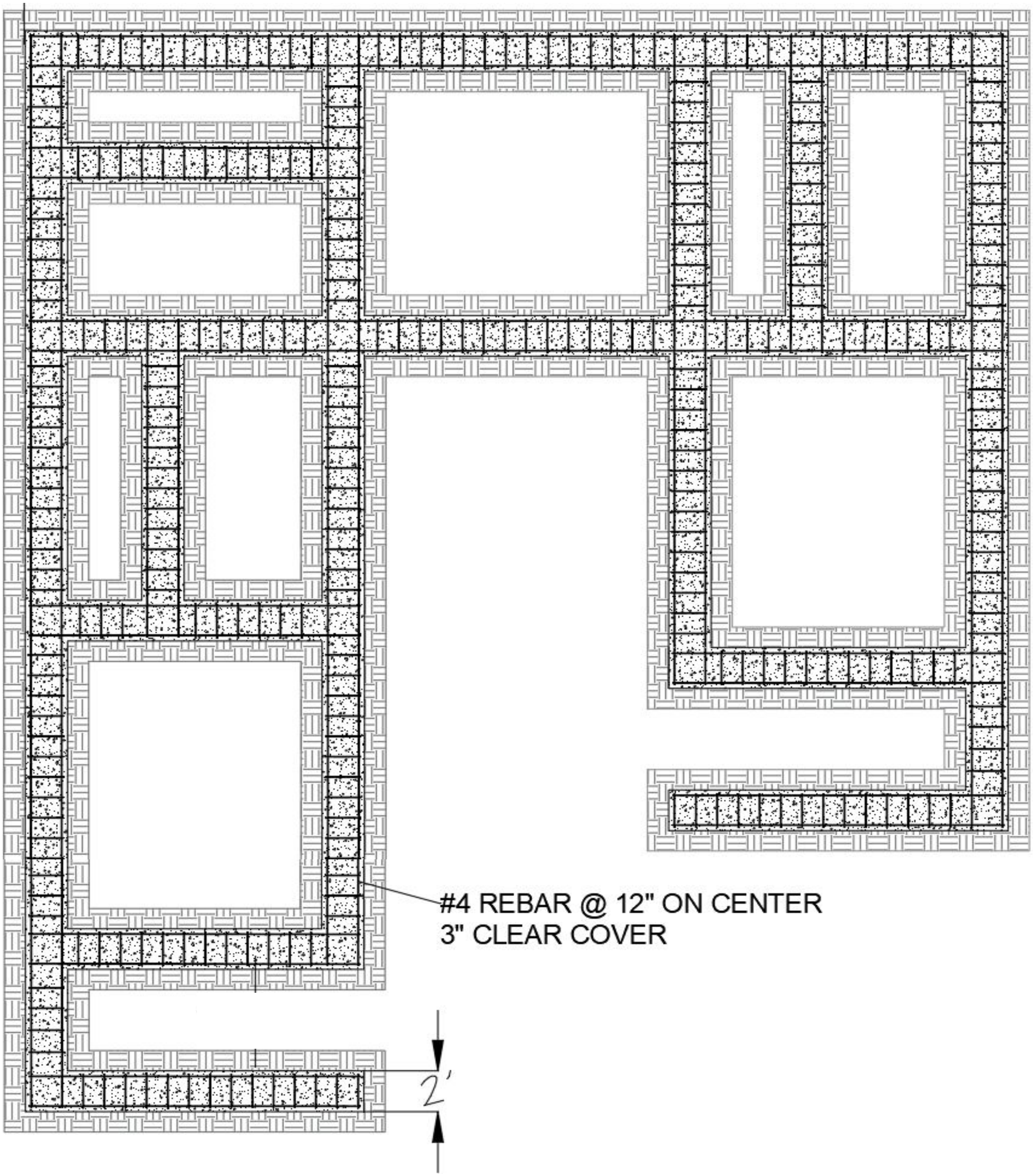


Section view of footings, wooden molds, and excavated earth



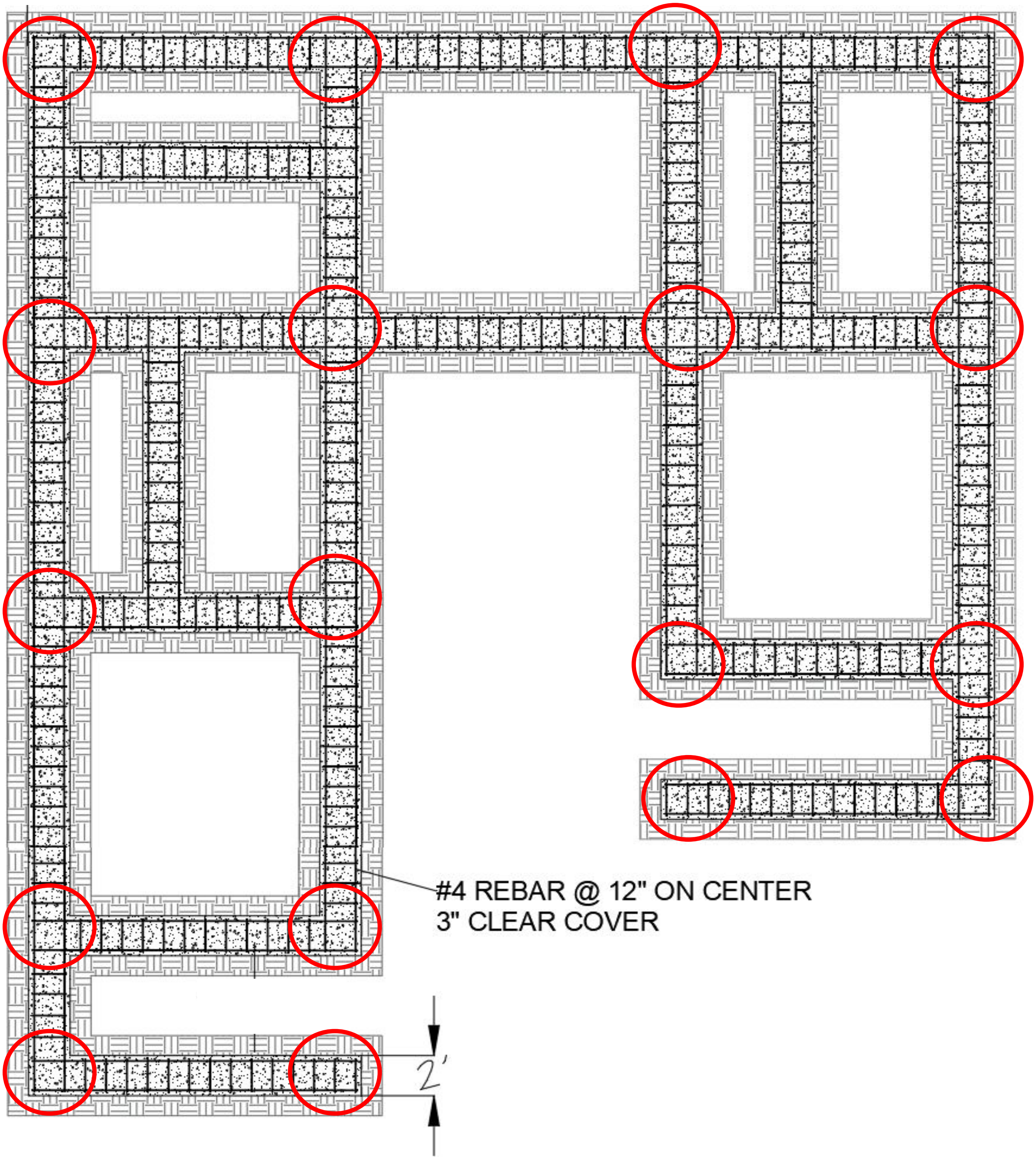
Layout of steel reinforcements located 3-inches above the Earth and 3-inches from the wooden mold

STEEL REINFORCEMENT LAYOUT



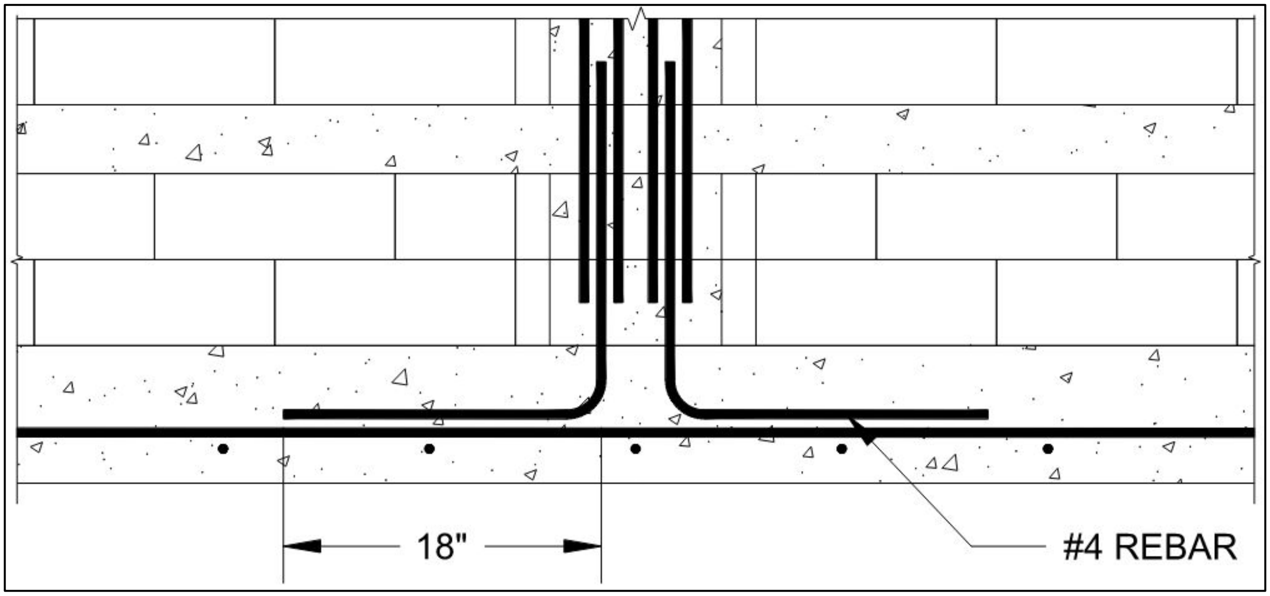
Layout of #4 steel reinforcements to install before concrete footings are poured.

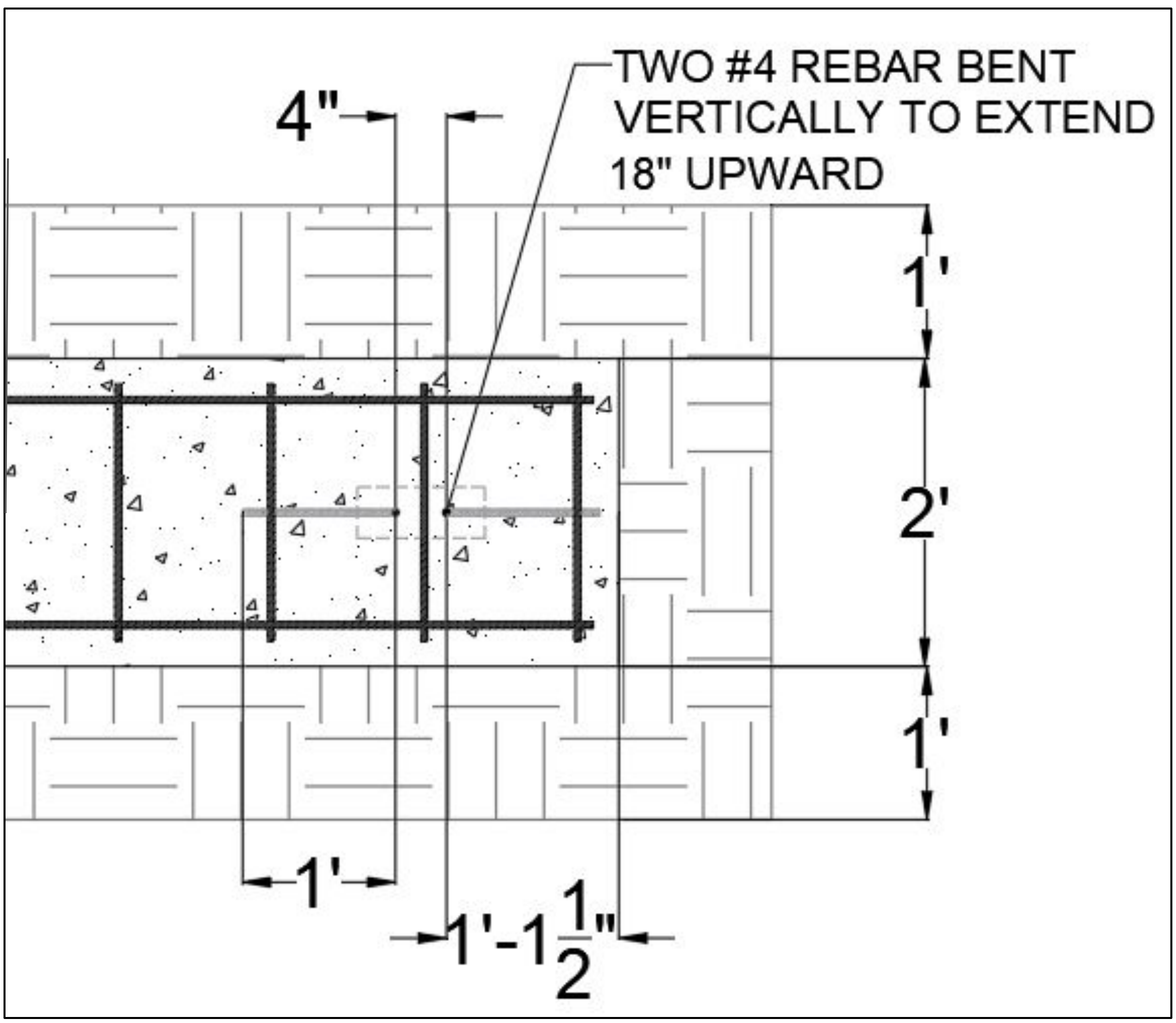
STEEL REINFORCEMENT LAYOUT CONTD.



Column locations where steel reinforcements tie-in from foundation to columns.

STEEL REINFORCEMENT LAYOUT AT COLUMNS





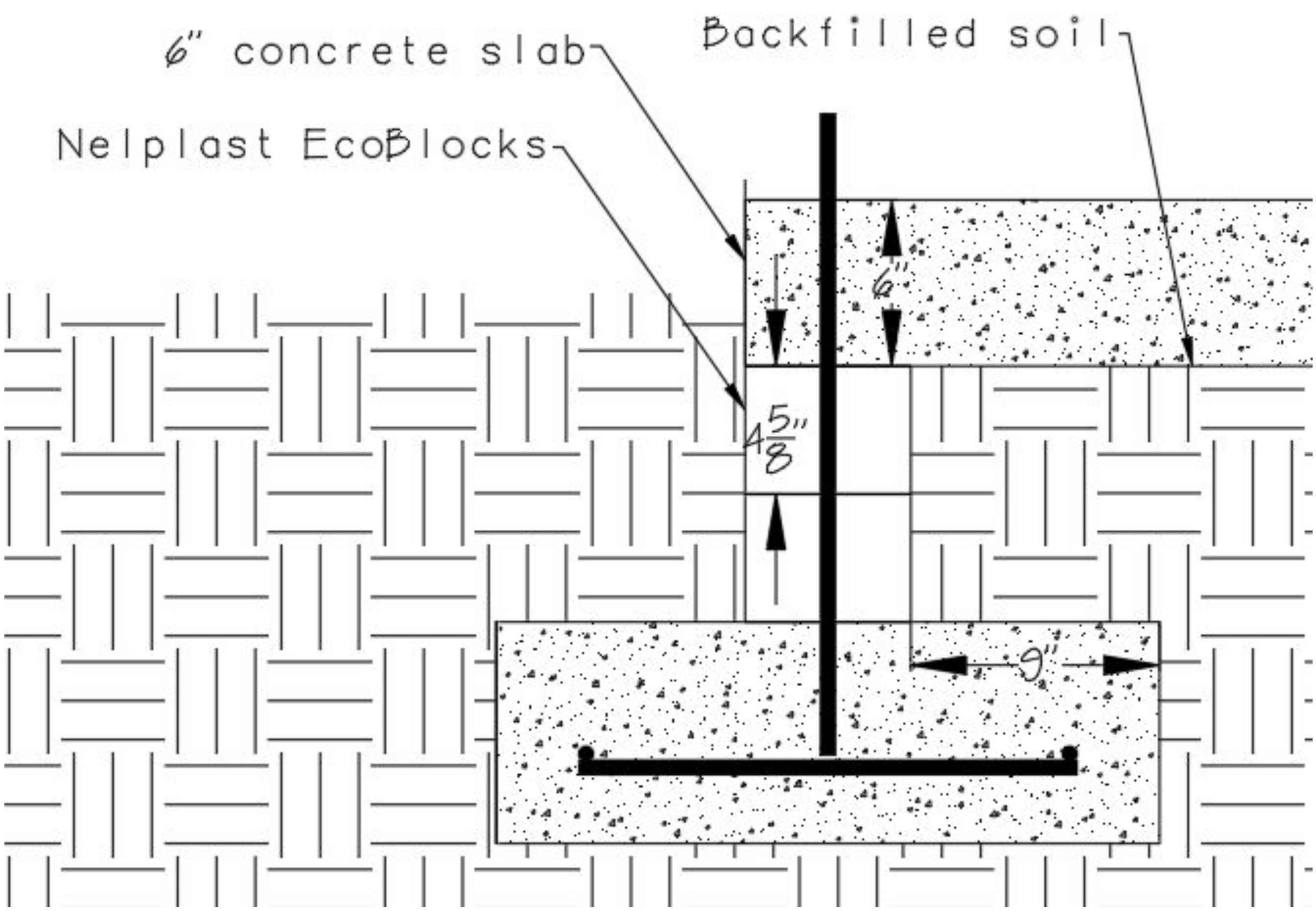
Layout of #4 steel reinforcements to install before concrete footings are poured at column locations.

FIRST FLOOR

FIRST FLOOR: FLOOR SLAB

Concrete footings should be untouched and allowed to cure per manufacturer's specifications. Then, mortar should be used to secure a row of EcoBlocks to the center of the footing. This mortar must also cure. While the mortar is setting, the wood molds should be removed from the footings. After 14 days, two more rows of EcoBlocks should be added. A 6-inch slab will rest on the EcoBlocks and packed earth as is shown in Figure 9. To accomplish this, the excavated area should be re-packed tightly, then a wood mold constructed to contain the 6" concrete slab as it cures.

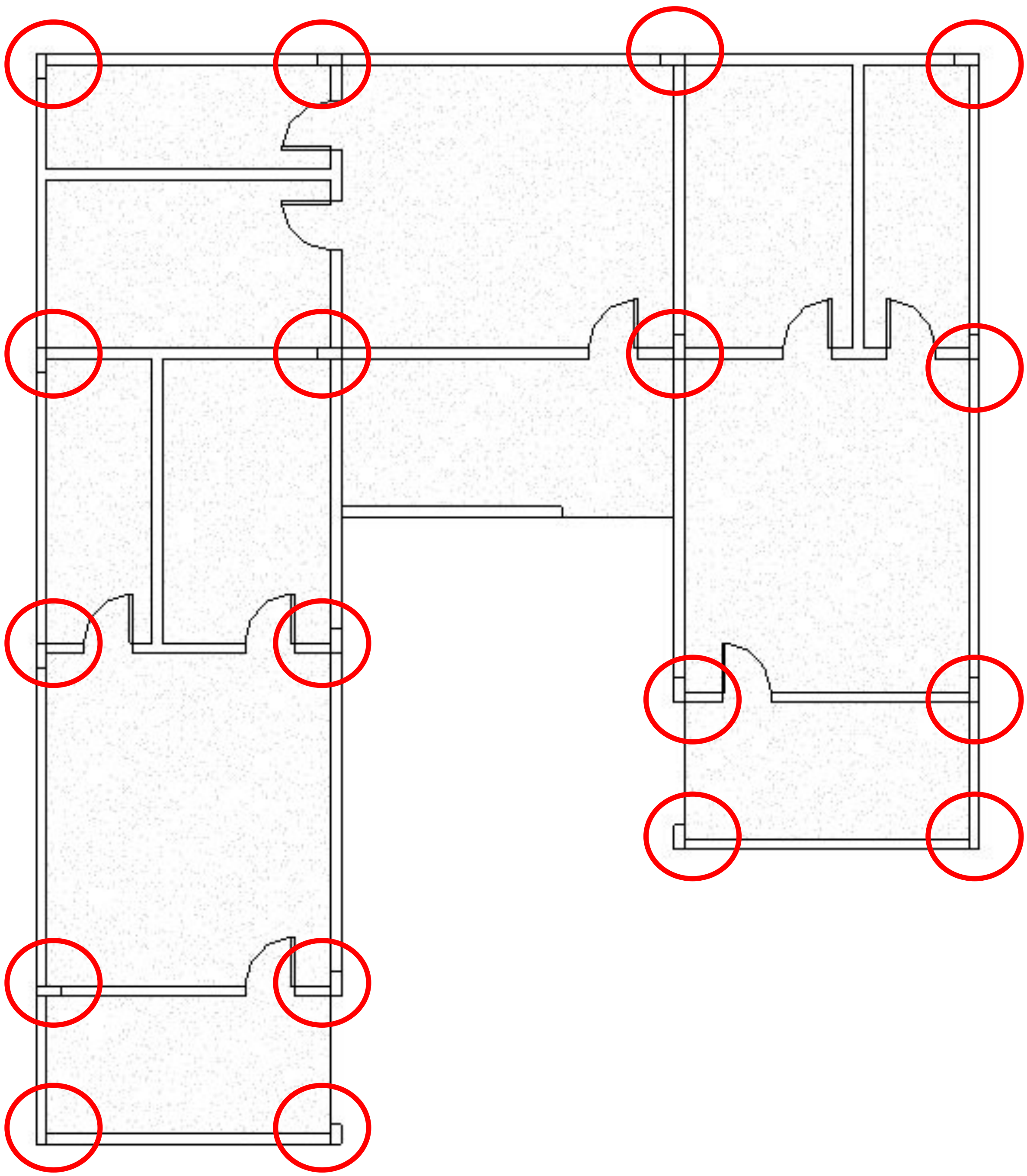
The following diagram shows a section view of the slab setup.



Section view of Footing to Slab Detail

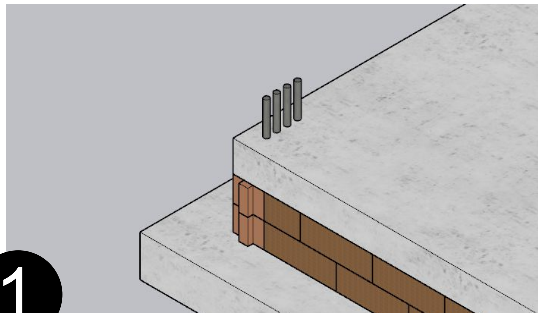
FIRST FLOOR: SUPERSTRUCTURE (COLUMNS)

Corner column blocks will be utilized in the following locations shown in Figure 10.



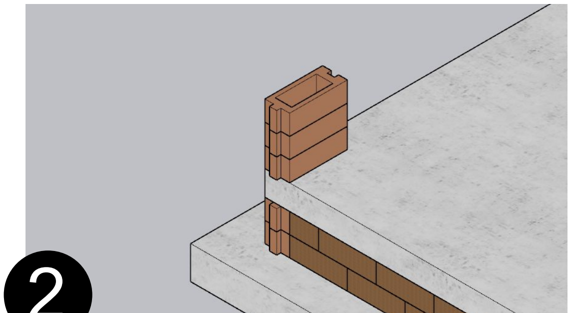
Column locations where steel reinforcements tie-in from foundation to columns.

FIRST FLOOR: SUPERSTRUCTURE (COLUMNS) CONTD.



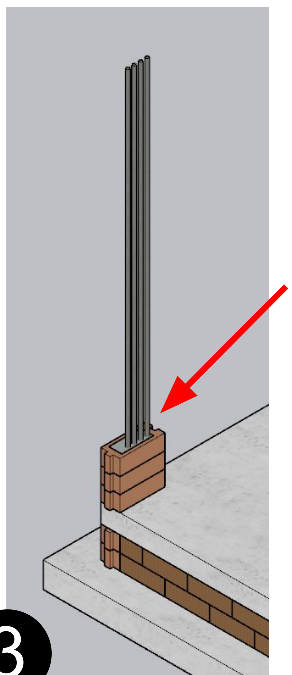
1

Locate the corner on the bottom left of the structure (based on the construction drawing set)



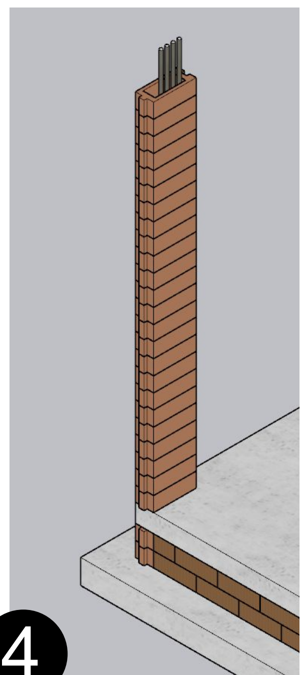
2

Stack three column blocks with the extruded end facing outwards



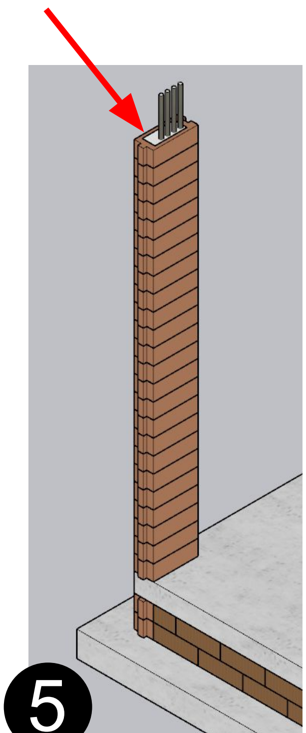
3

Place four 10’-9” pieces of #4 rebar inside of the center of the blocks (spaced 2 inches on center) and fill the remaining space with concrete



4

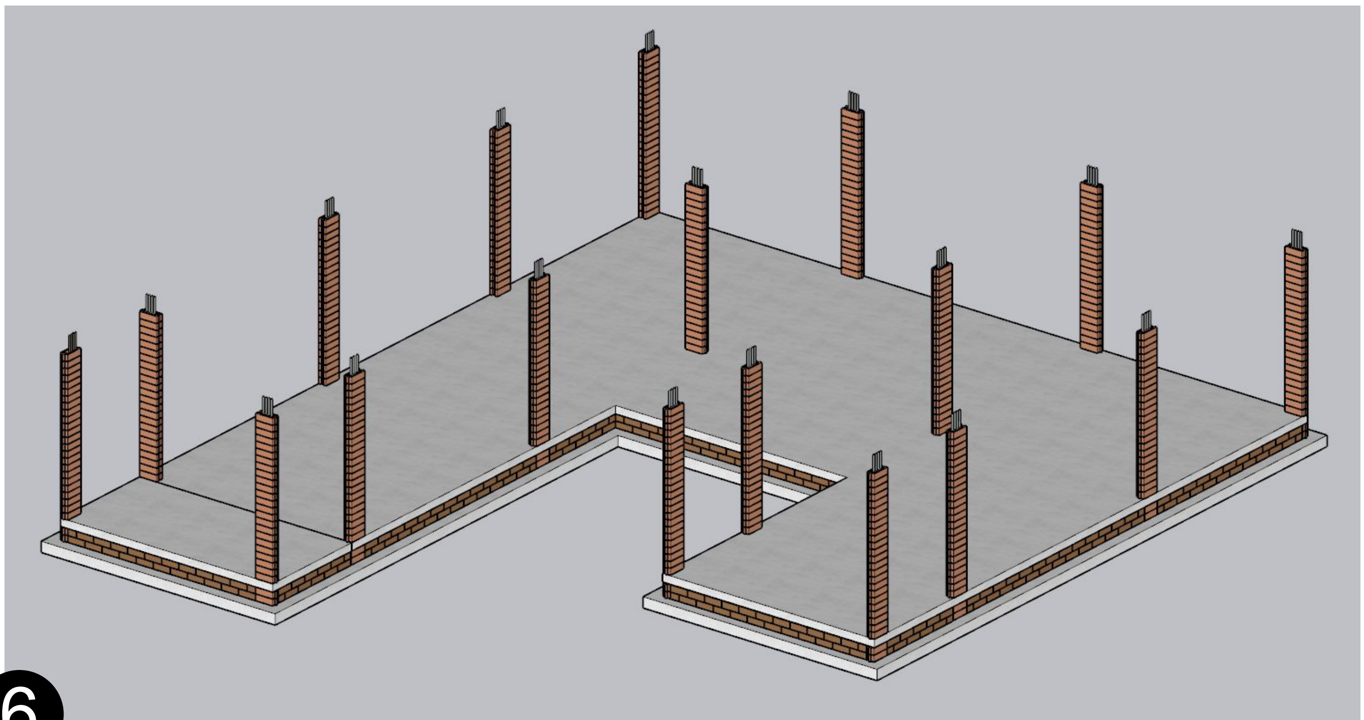
Once the concrete is set, continue stacking the rest of the 24 column blocks on top of one another



5

Fill the remaining space inside of the column blocks with concrete and let it cure per manufacturer's specifications

FIRST FLOOR: SUPERSTRUCTURE (COLUMNS) CONTD.

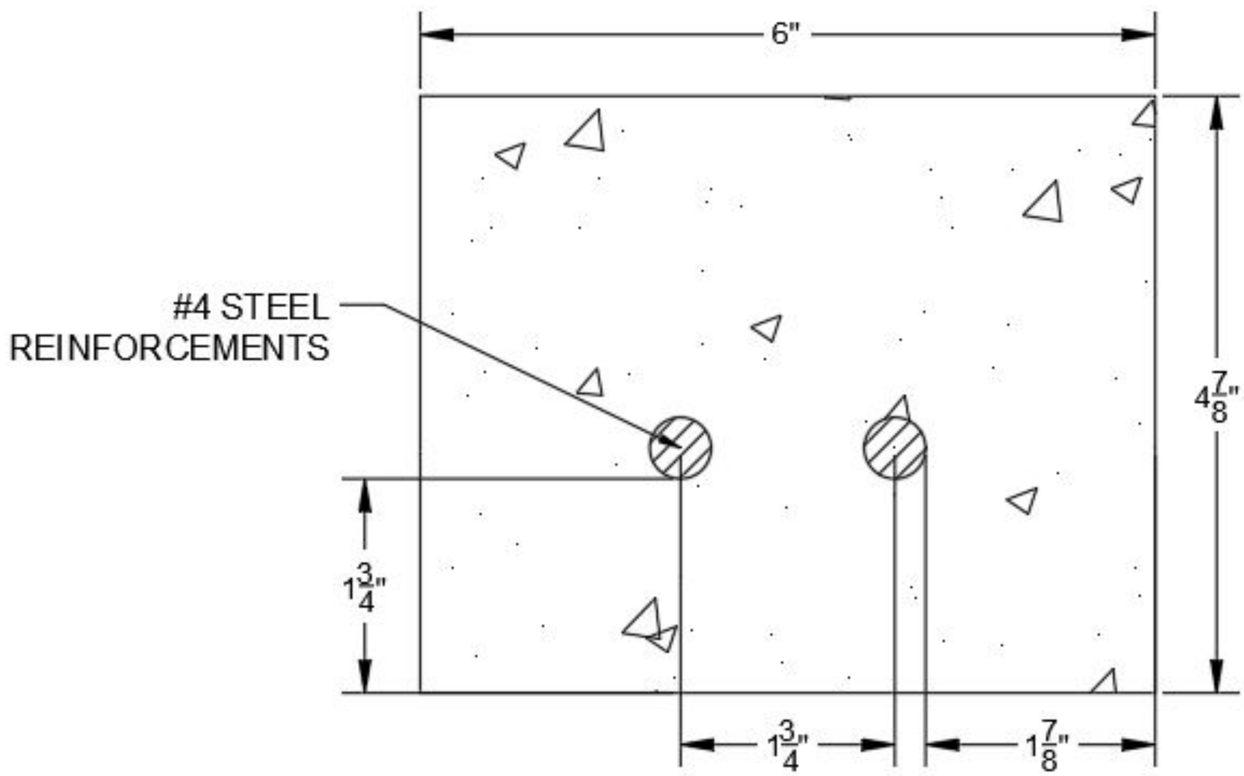


6

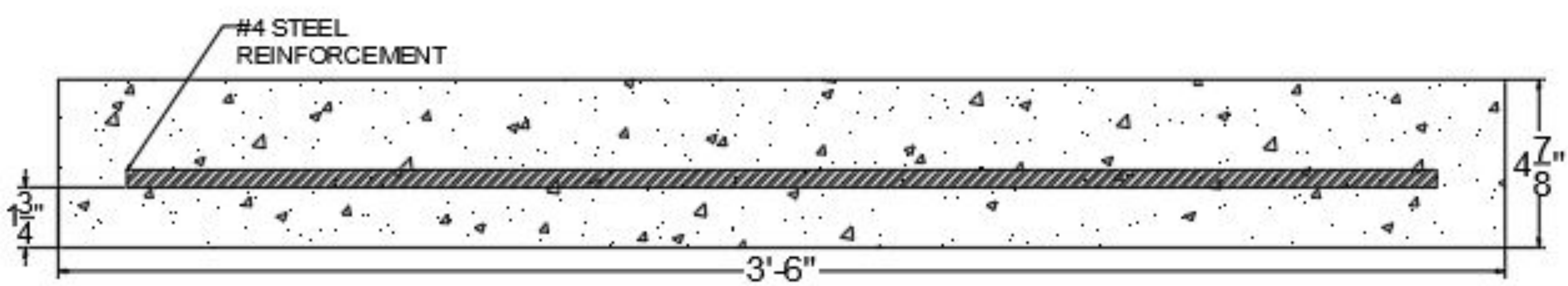
Repeat steps 1-5 for every column location (18 in total)

FIRST FLOOR: OVER-DOOR LINTELS

To make a lintel for doorways, create a rectangular wooden mold 3’ 6” long, 6” wide, and 4 ⅞” tall. Pour concrete into mold and install #4 steel reinforcements as shown in Figures 11 & 12. Allow reinforced concrete lintels to cure entirely before installing into the final structure. All top of windows are directly below a 6” steel reinforced concrete slab and do not require separate lintels.



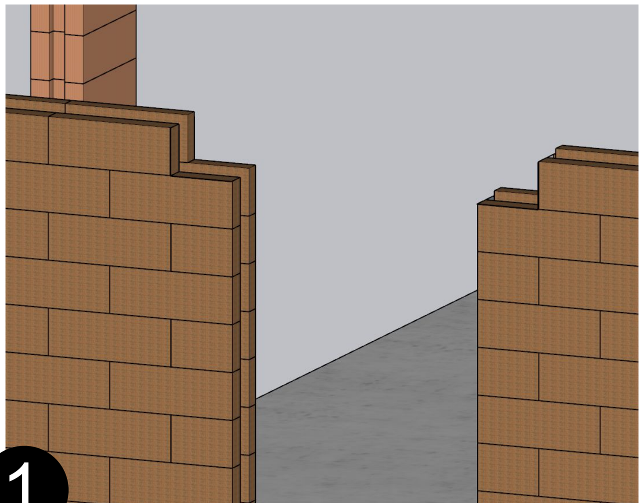
Transverse cross-section view of doorway lintel.



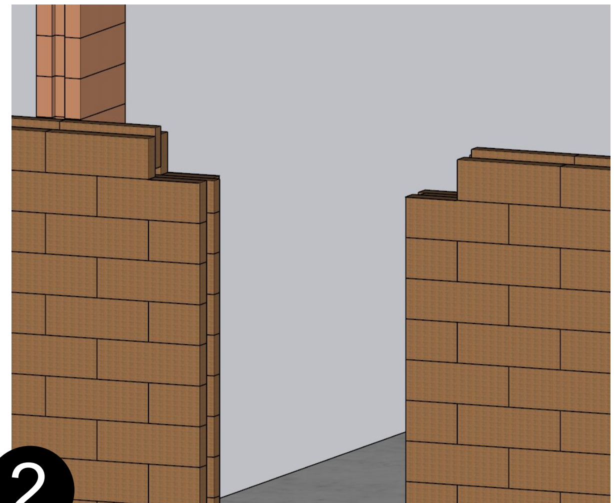
Longitudinal cross-section view of doorway lintel.

FIRST FLOOR: OVER-DOOR LINTELS CONTD.

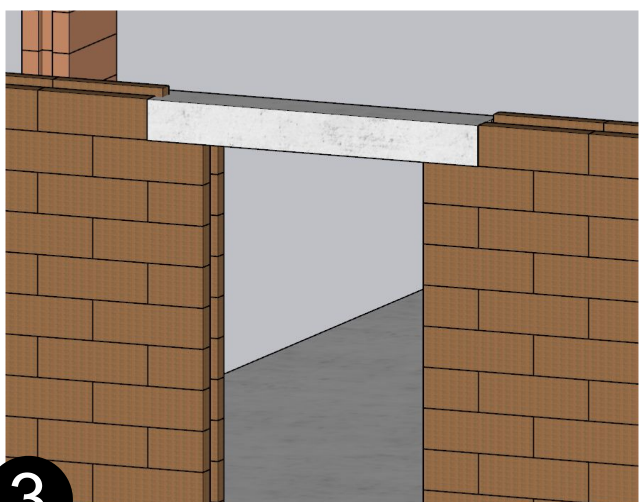
The following steps detail the installation of the precast reinforced concrete lintels above doorways:



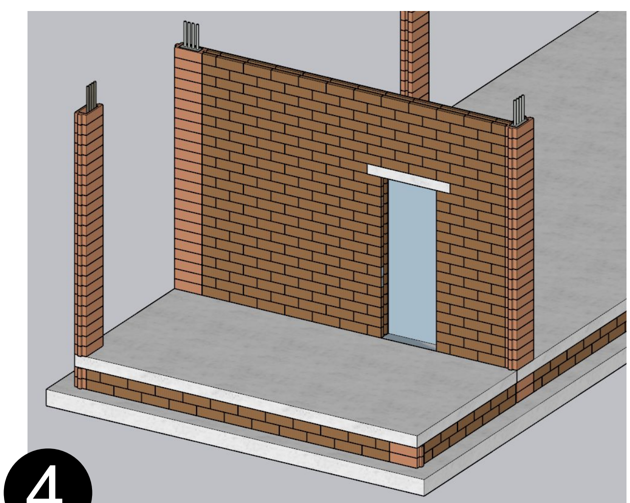
1 Build the EcoBlock wall with allocated space for a 28” by 80” door frame.



2 Remove notches in EcoBlock to make room for lintel.



3 Place precast reinforced concrete lintel above door frame.

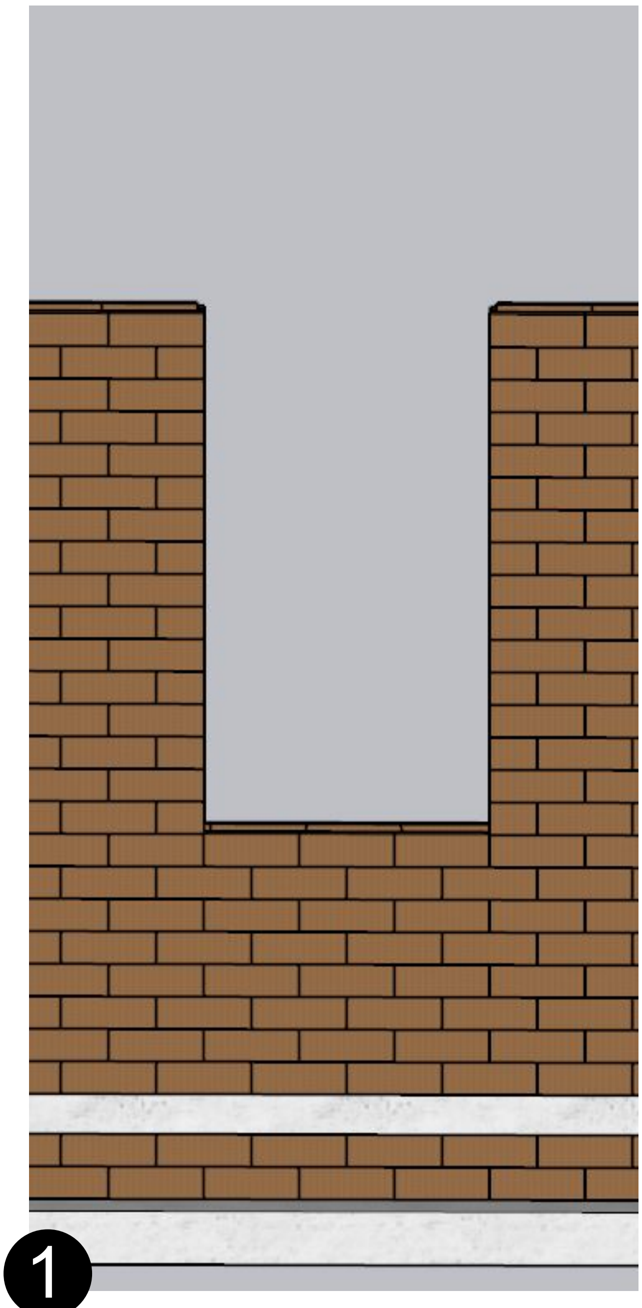


4 Finish the wall by stacking blocks above lintel.

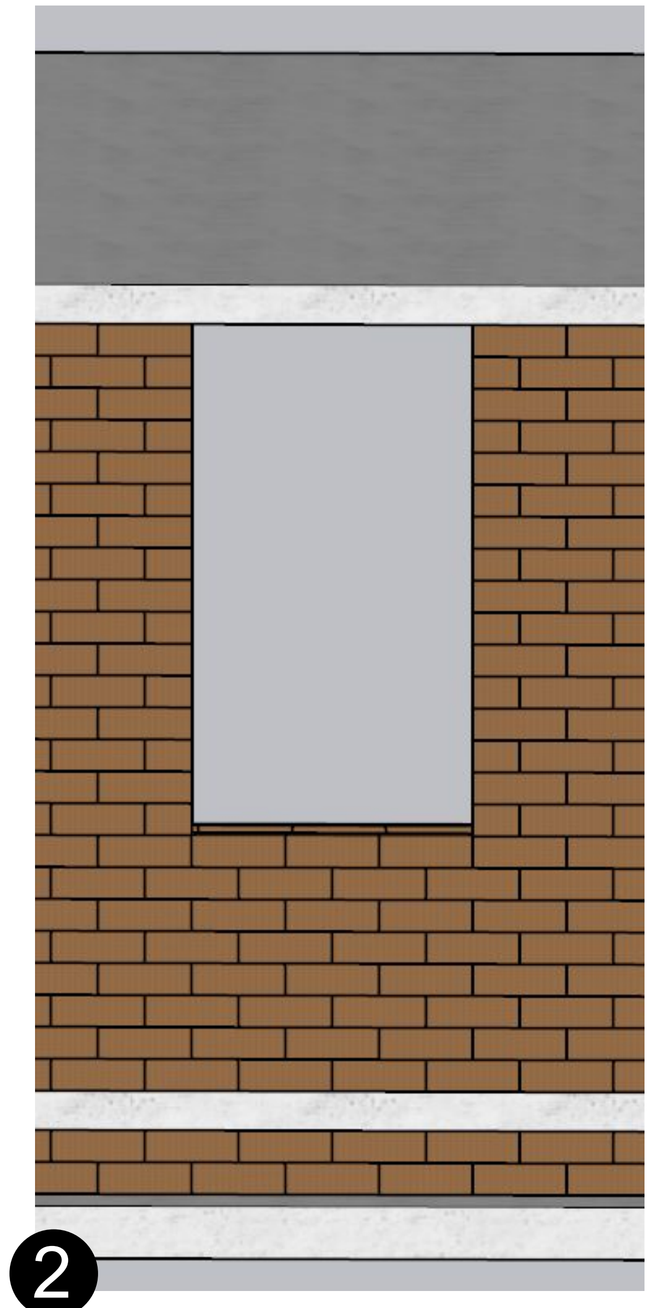
NOTE: Precast window lintels are not required. This is applicable to both the first and second floors.

FIRST FLOOR: OVER-WINDOW LINTELS

The following steps detail the top of window support:



Build the EcoBlock wall with allocated space for a 42” by 72” window frame.

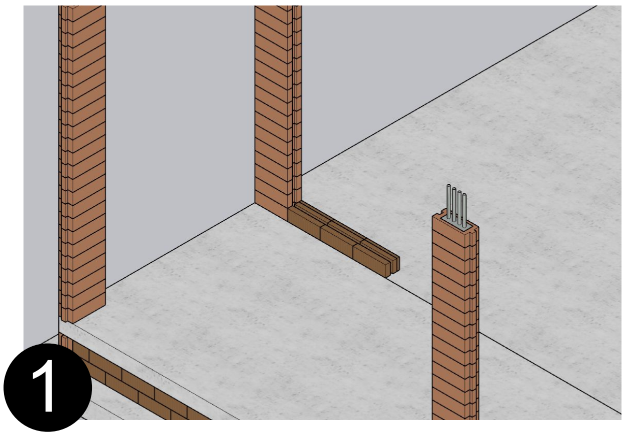


Frame and pour a 6” reinforced concrete slab..

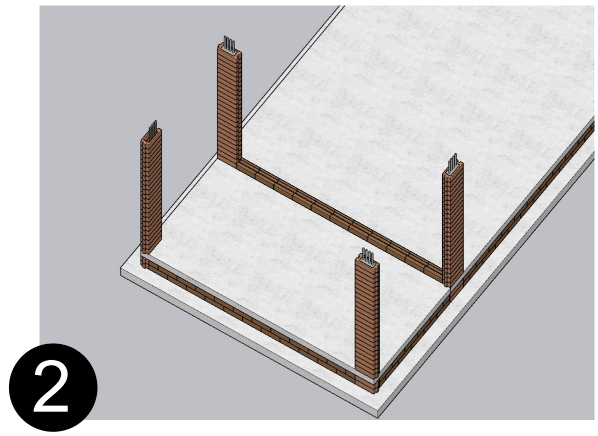
NOTE: Precast window lintels are not required. This is applicable to both the first and second floors.

FIRST FLOOR: ECOBLOCK MASONRY WALLS

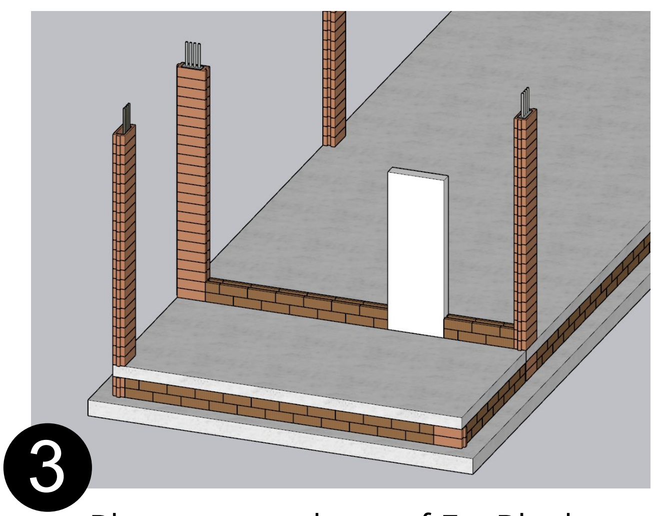
EcoBlocks are provided with notches and tabs that should be hammered together as tightly as possible. Blocks should connect with column block tabs whenever possible.



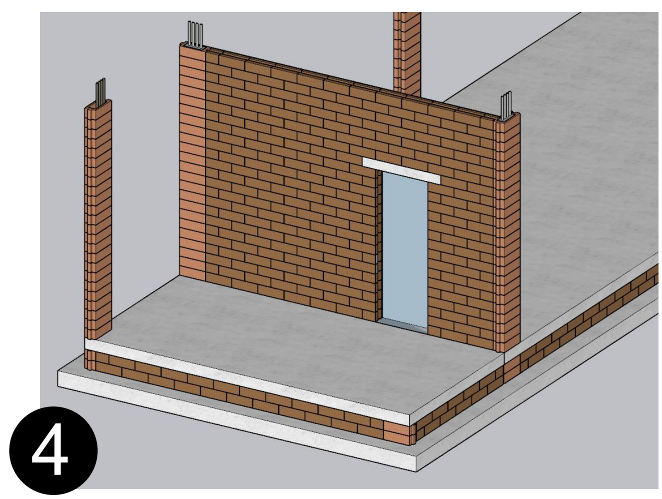
Locate the corner on the bottom left of the structure (based on the construction drawing set) and begin placing EcoBlocks against the column.



Continue to complete the row of blocks. See drawing set to know where spaces must be left to accommodate windows and doors.

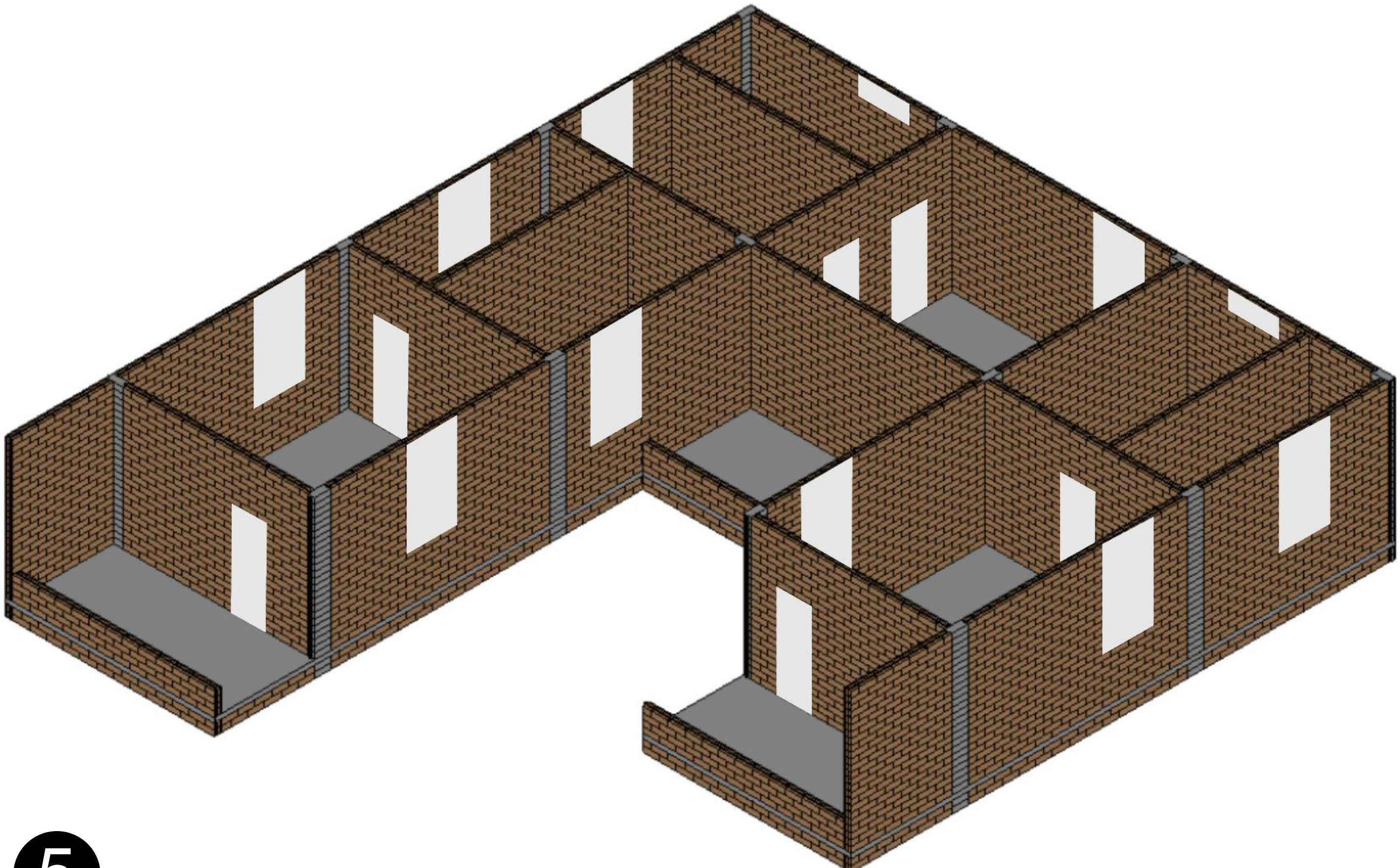


Place a second row of EcoBlocks on top of the first, offsetting the blocks by half of the block width.



Continue stacking EcoBlocks until the wall has reached the height of the column, incorporating the lintel detailed previously.

FIRST FLOOR: ECOBLOCK MASONRY WALLS CONTD.

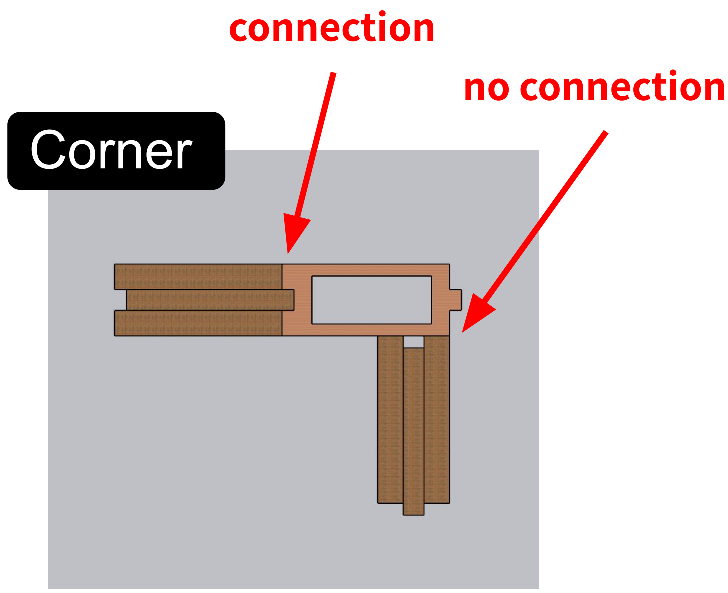


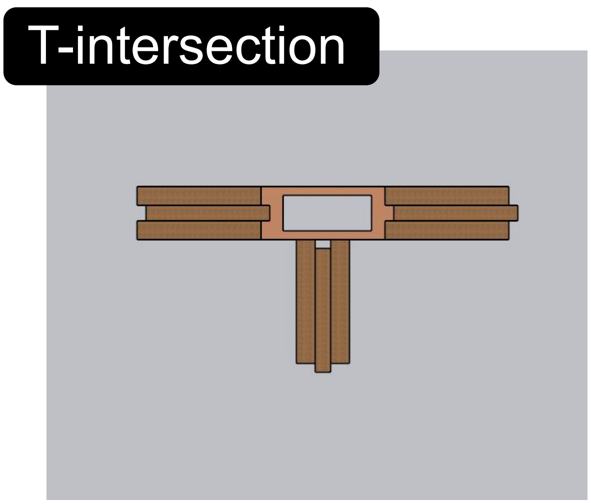
5

Repeat steps 1-4 for every wall location (27 in total) that are shown above. Accurate dimensions and spacing is shown in the drawing set. The half-wall provided on the porch is 3-feet tall.

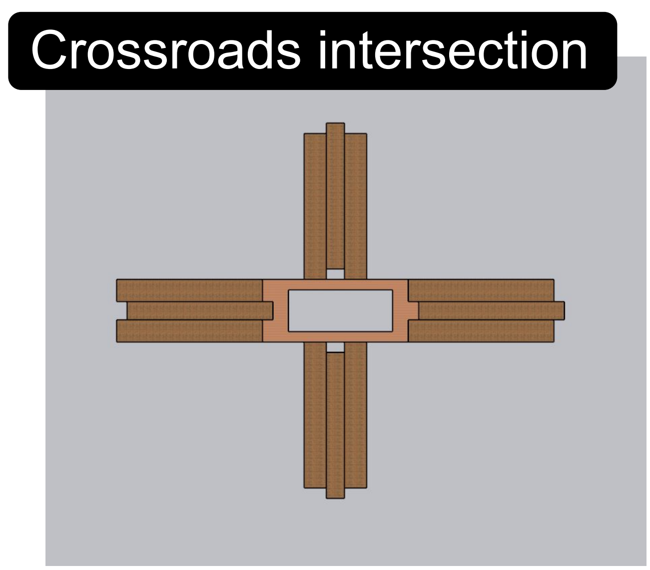
FIRST FLOOR: ECOBLOCK COLUMN & WALL JOINT CONNECTION

NOTE: Due to the shape of the Nelplast Column EcoBlocks, connections with the wall are only possible on two sides.





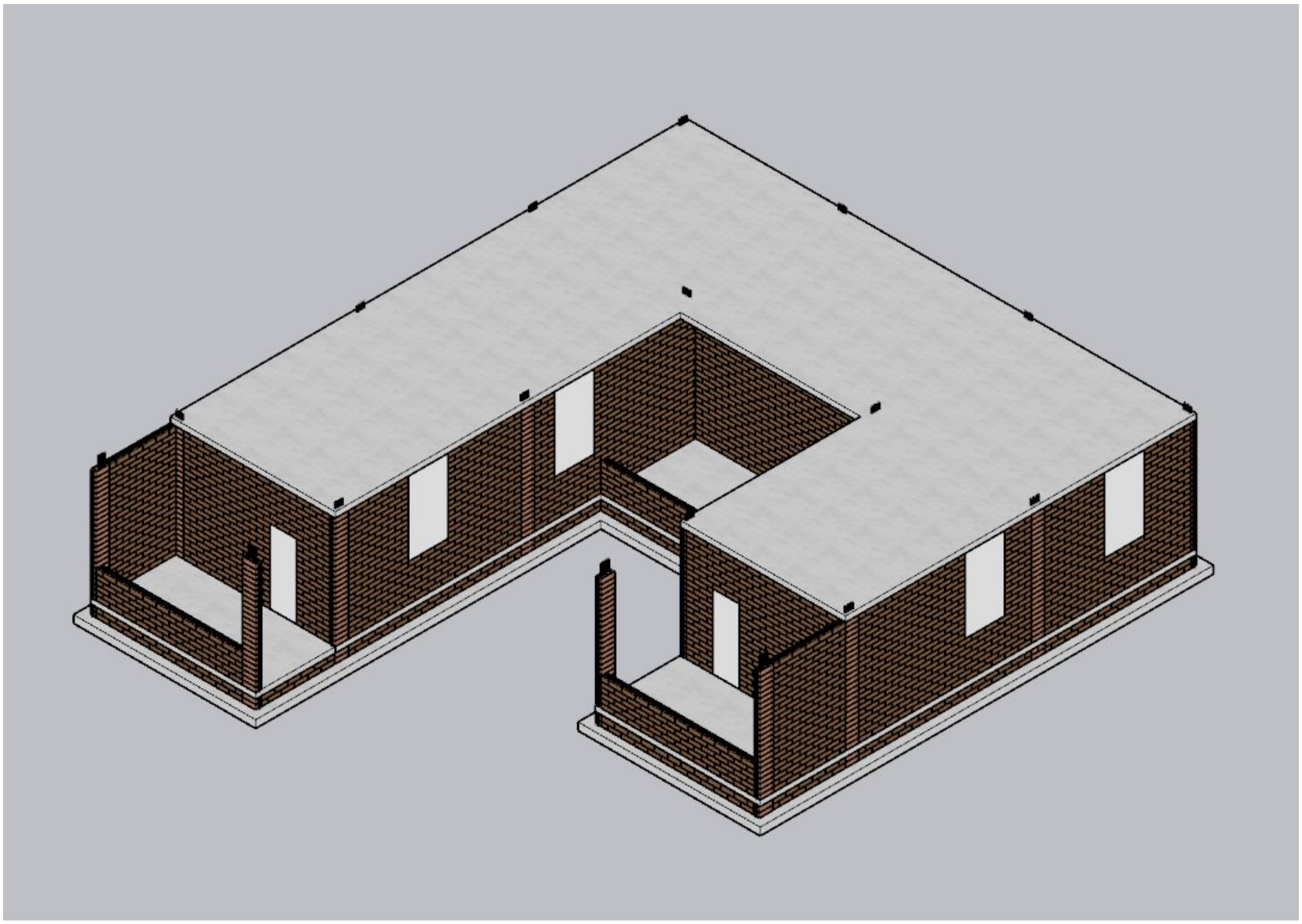
Therefore, some of the walls will interlock with the columns, while others will only align with them.



SECOND FLOOR

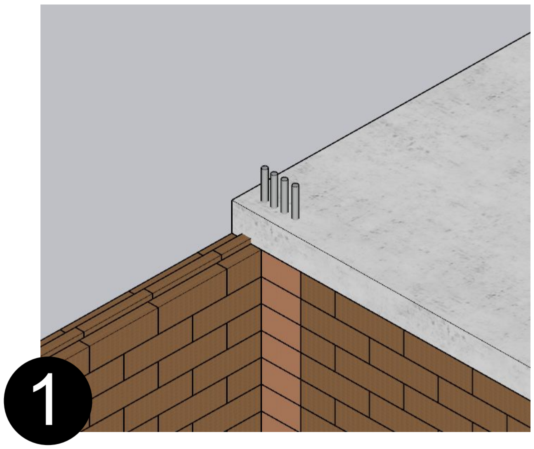
SECOND FLOOR: FLOOR SLAB

Figure X below indicates the floor plate of the second floor. This steel reinforced, one-way concrete slab is 6-inches thick and will need to be supported by wooden framing while it cures per manufacturer's specifications.

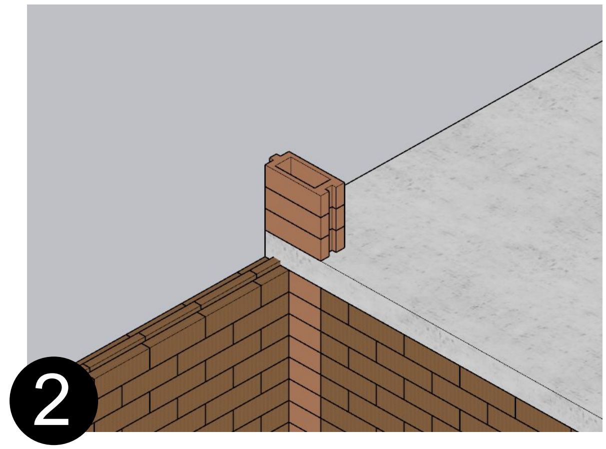


Second floor steel reinforced, one-way slab design.

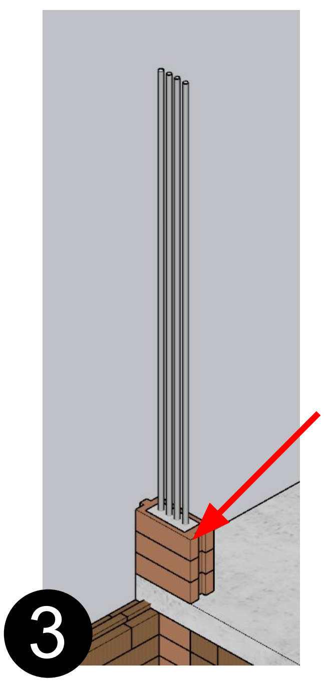
SECOND FLOOR: SUPERSTRUCTURE (COLUMNS)



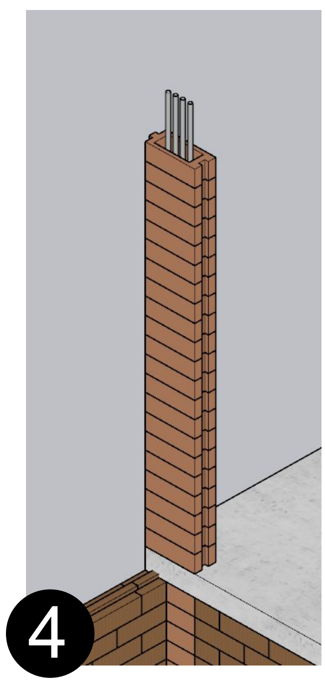
Locate the corner on the bottom left of the structure (based on the construction drawing set)



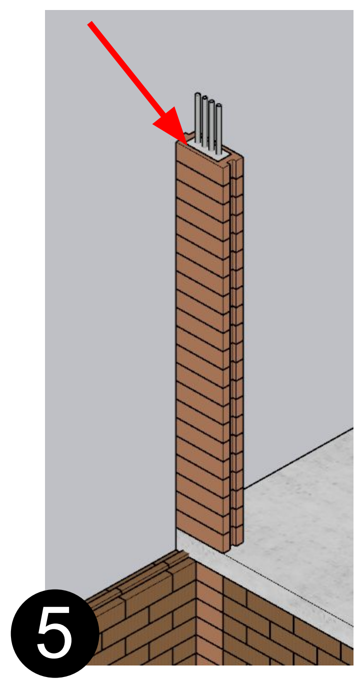
Stack three column blocks with the extruded end facing outwards



Place four 10’-9” pieces of #4 rebar inside of the center of the blocks (spaced 2 inches on center) and fill the remaining space with concrete

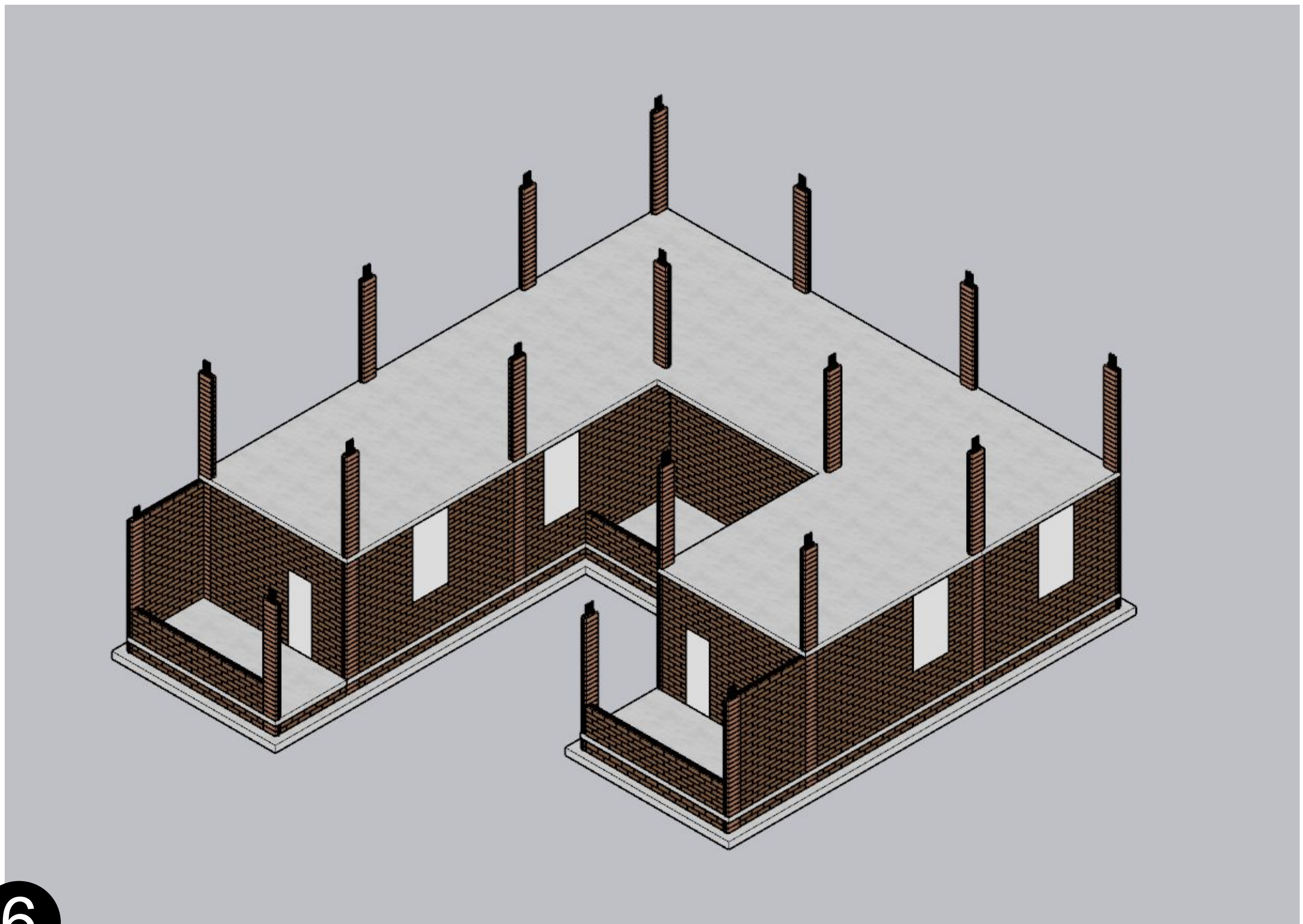


Once the concrete is set, continue stacking the rest of the 24 column blocks on top of one another



Fill the remaining space inside of the column blocks with concrete and let it cure per manufacturer's specifications

SECOND FLOOR: SUPERSTRUCTURE (COLUMNS) CONTD.

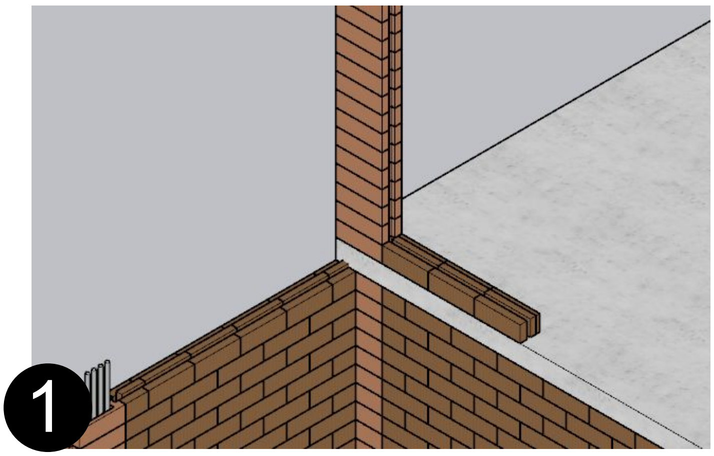


6

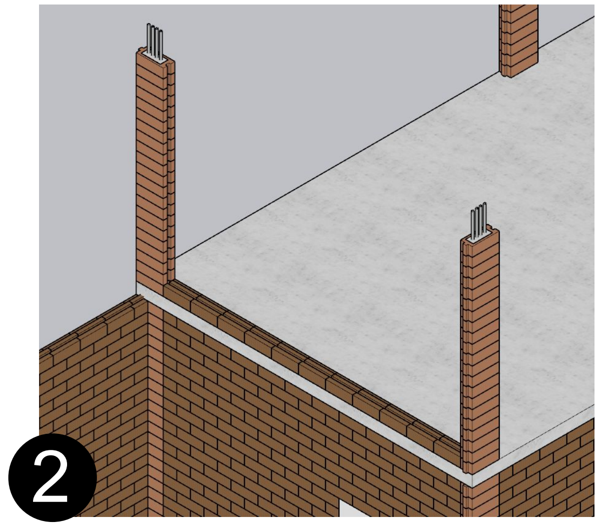
Repeat steps 1-5 for every column location (18 in total).

SECOND FLOOR: ECOBLOCK MASONRY WALLS

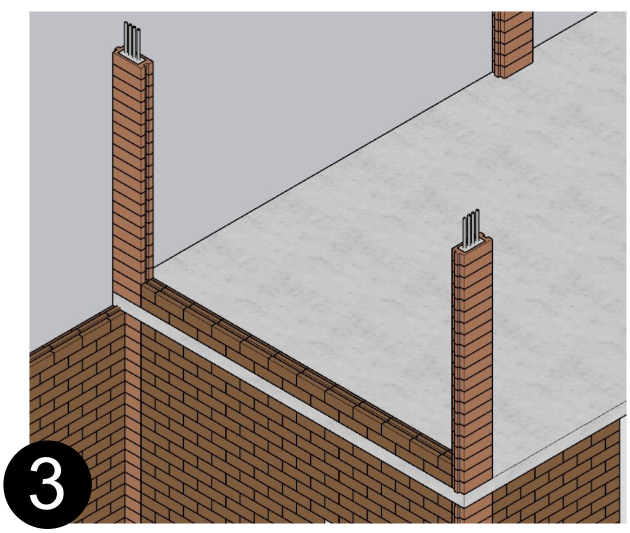
EcoBlocks are provided with notches and tabs that should be hammered together as tightly as possible. Blocks should connect with column block tabs whenever possible.



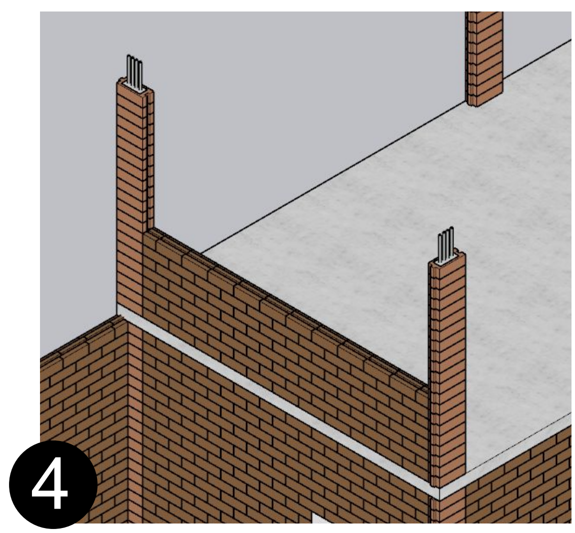
Locate the corner on the bottom left of the second floor slab(based on the construction drawing set) and begin placing EcoBlocks against the column.



Continue to complete the row of blocks. See drawing set to know where spaces must be left to accommodate windows and doors.

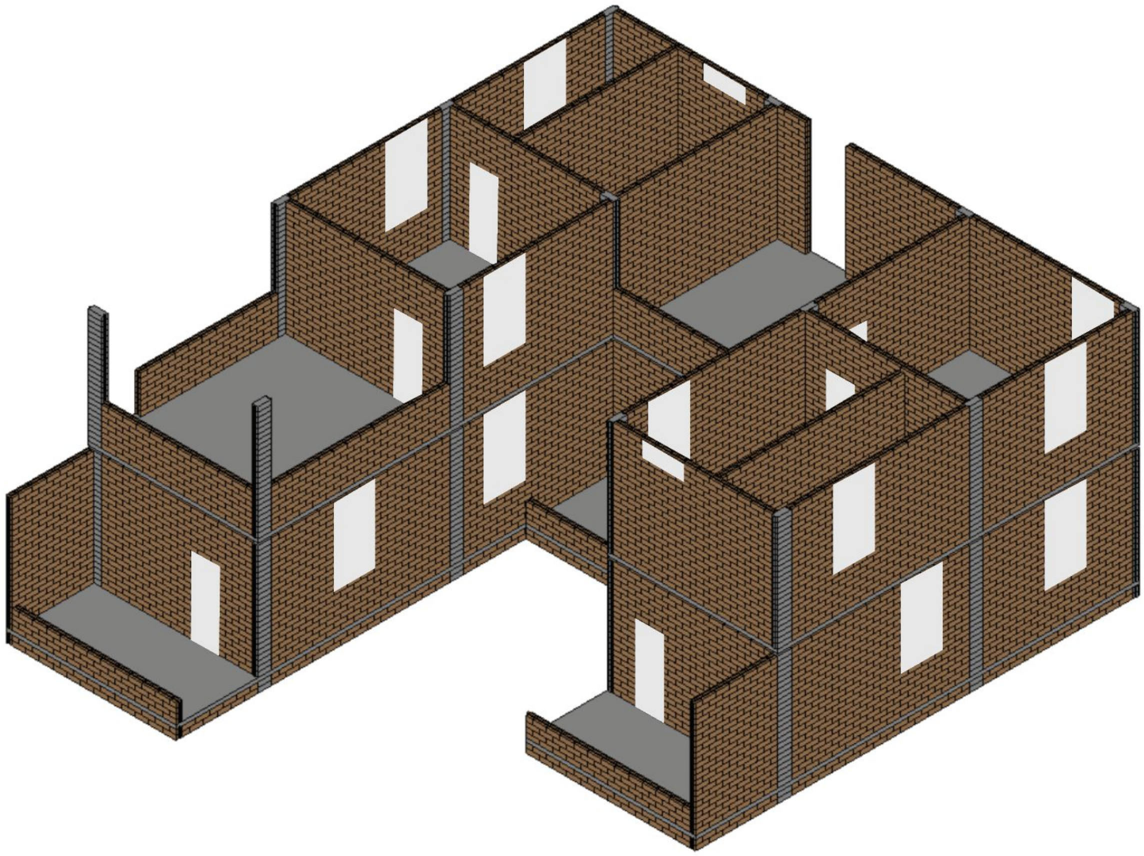


Place a second row of EcoBlocks on top of the first, offsetting the blocks by half of the block width.



Continue stacking EcoBlocks until the wall has reached the height of the column, incorporating the lintel detailed previously.

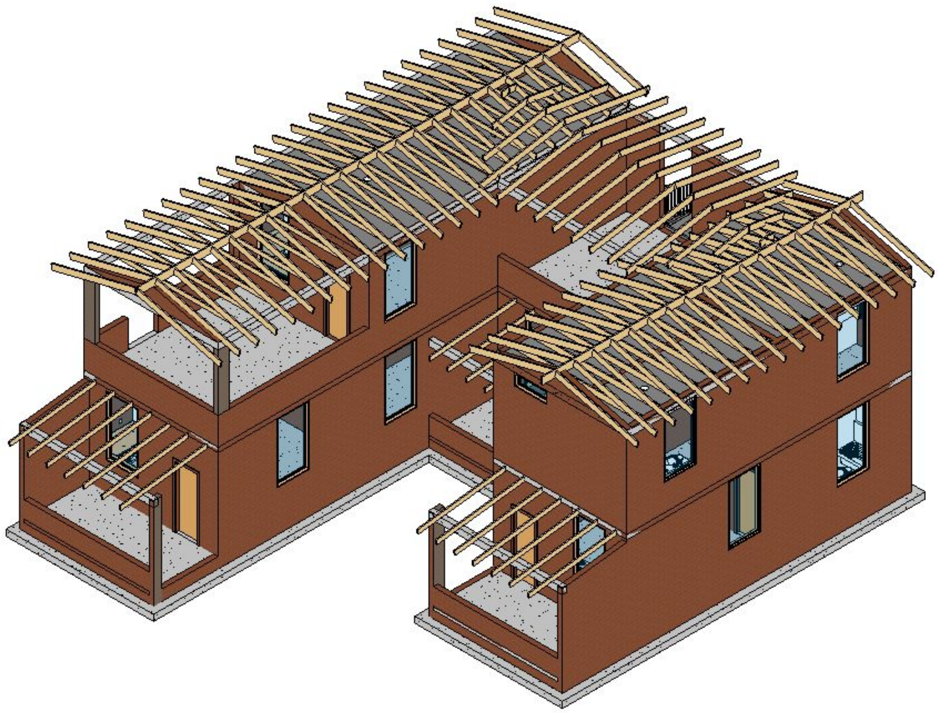
SECOND FLOOR: ECOBLOCK MASONRY WALLS CONTD.



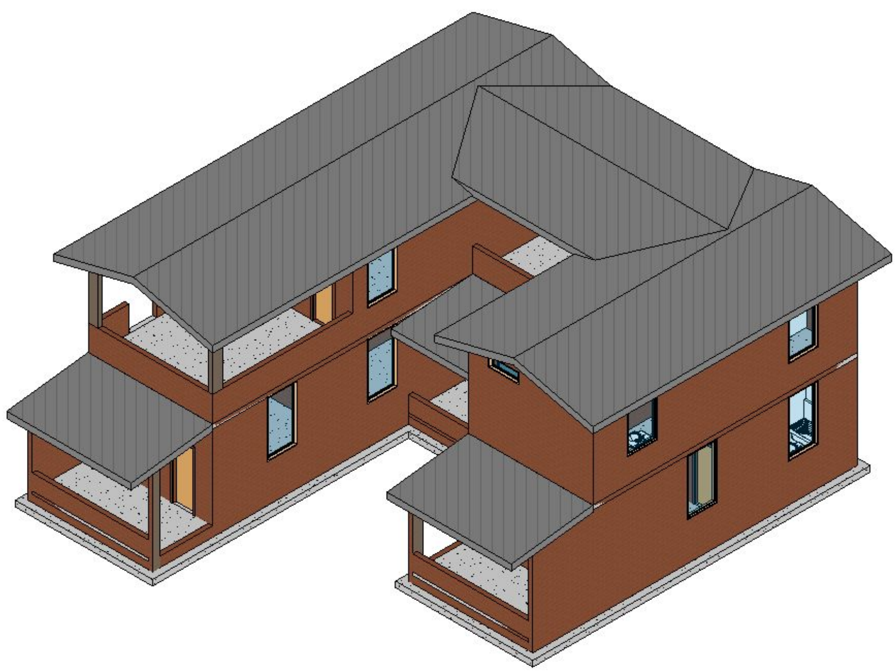
5

Repeat steps 1-4 for every wall location that are shown above. Accurate dimensions and spacing is shown in the drawing set. The half-wall provided on the porch is 3-feet tall.

ROOF STRUCTURE

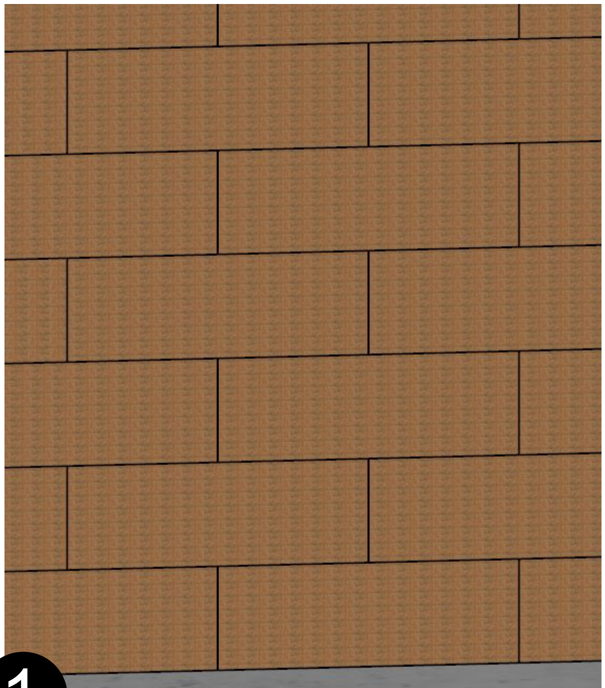


1 Frame a gable roofing system using 2” by 8” rafters at 24” on center, 2” by 6” ceiling joist, and 2” by 10” non-structural rafter.

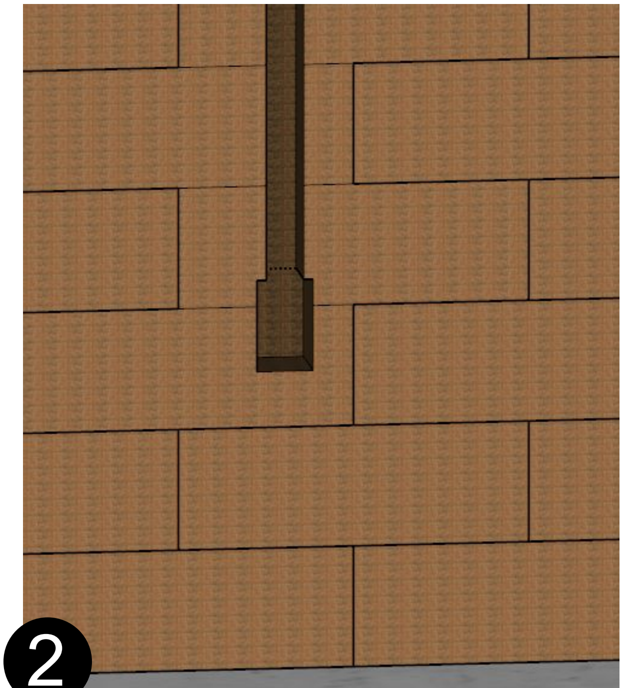


2 Place and secure corrugated metal panels to wood framing, ensuring 2’ of overhang.

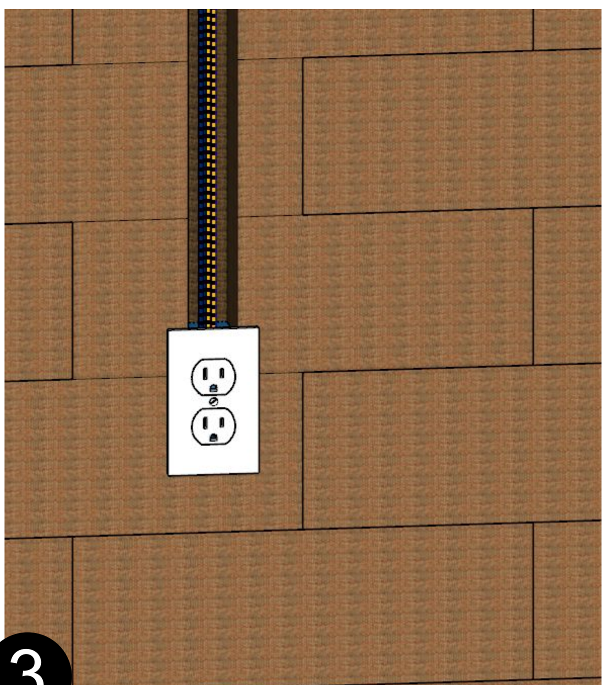
ELECTRICAL & PLUMBING



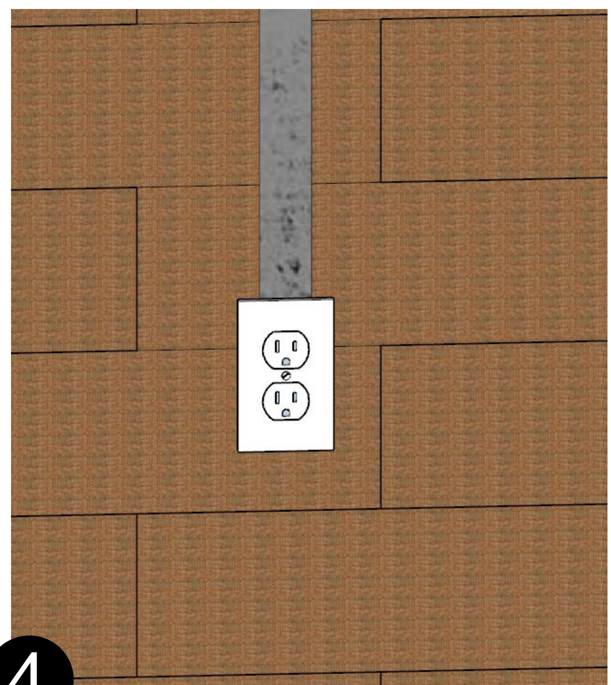
1 Identify locations for outlets and other electrical connections based on electrical plans.



2 Cut EcoBlock with handheld or circular saw to create space for electrical components.



3 Insert electrical wires into the wall.

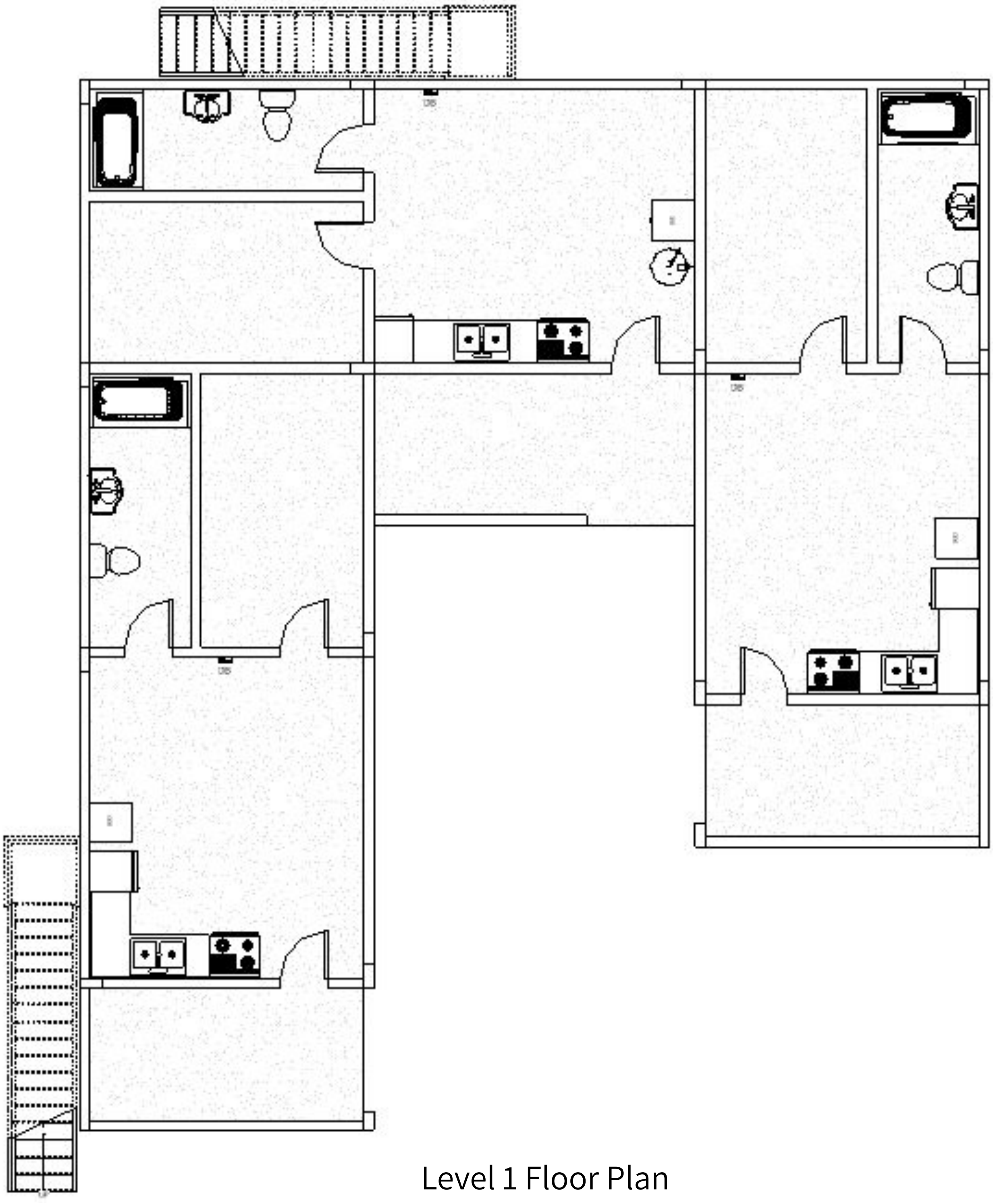


4 Fill in the wall with POP cement and smooth level with block wall.

NOTE: This technique is applicable to both electrical and plumbing systems. See attached plans for exact electrical and plumbing design.

INTERIOR FINISHES

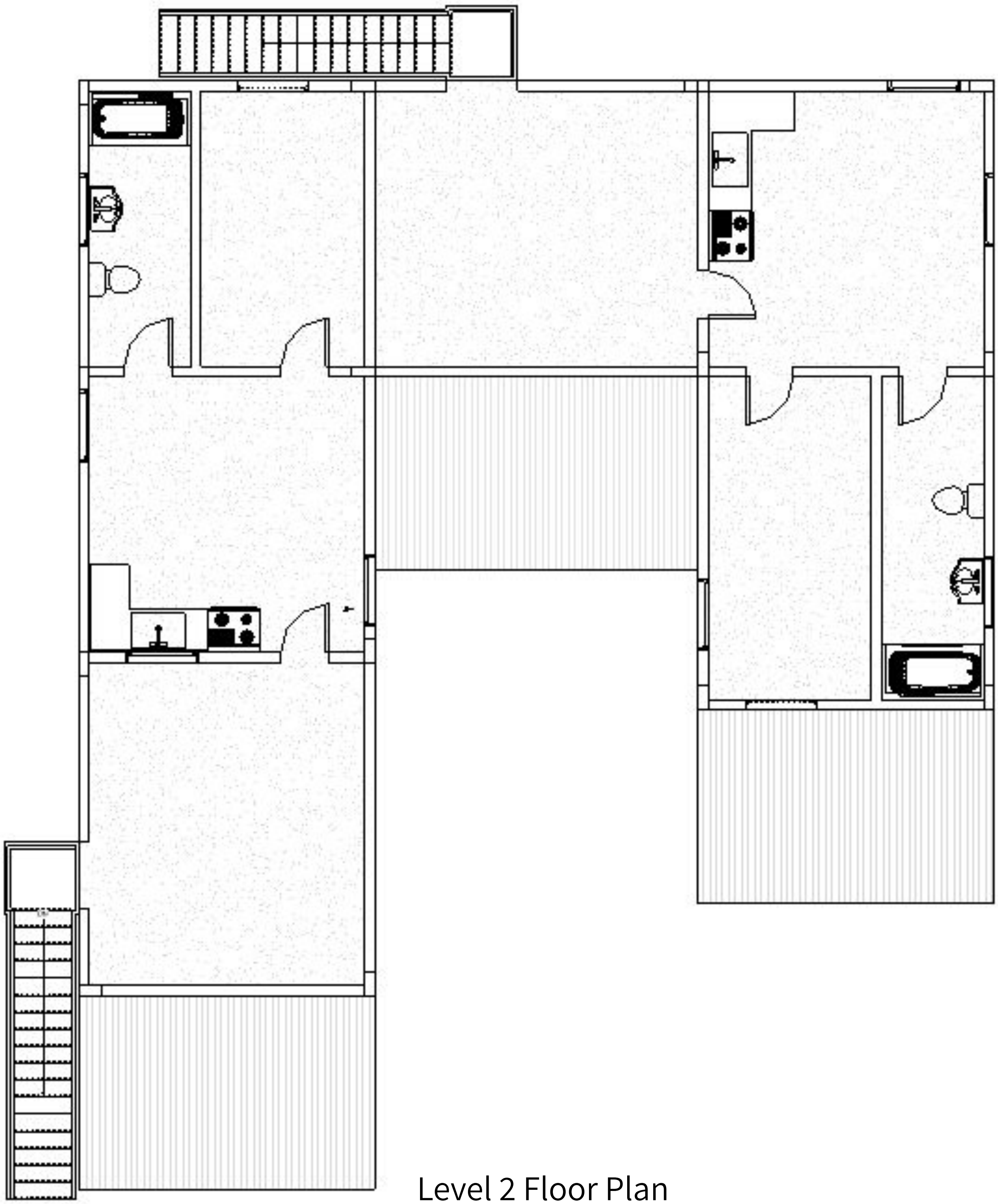
Locate the interior appliances and fixtures as they are located in the floor plans. For the kitchens, this includes a refrigerator, stove, sink, and counters/cabinets. For the bathrooms, this includes a shower/bathtub, sink, and toilet.



Level 1 Floor Plan

INTERIOR FINISHES

Locate the interior appliances and fixtures as they are located in the floor plans. For the kitchens, this includes a refrigerator, stove, sink, and counters/cabinets. For the bathrooms, this includes a shower/bathtub, sink, and toilet.



Level 2 Floor Plan

CONCLUSION

This manual acts as a guide to construct the proposed housing design. It should be noted that the images used to depict construction methods neglect to consider the realistic tendencies of the materials used.

Each of these steps are logical suggestions that would help to complete this project in the most efficient, cost-effective, and timely manner. However, logical alternate decisions can be made in the field.

Following these instructions will result in the creation of an affordable and sustainable housing structure, but there are several elements of building systems that fall outside of the scope of this manual. A septic system will be required to support the 5 toilets of these homes. It is assumed by the team that this system is provided by a company that is able to supplement its installation, and was therefore not in the scope of this project. Attachment to the town water line will also be required. The location of the closest access point and the procedure for adding residences to this line will require further coordination with town officials and was therefore not in the scope of this project.

Affordable Housing MQP

Akyem Dwenase, Ghana

LIST OF SHEETS	
SHEET NUMBER	SHEET NAME
A-001	Architectural (General)
A-101	Level 1 Floor Plan
A-102	Level 2 Floor Plan
A-103	Roof Plan
A-201	Elevations
A-301	Sections
A-401	Details
E-101	Electrical Level 1
E-102	Electrical Level 2
P-101	Plumbing Level 1
P-102	Plumbing Level 2
S-101	Foundation & Structural Plans
S-102	Structural Plans

WPI
100 Institute Road, Worcester, MA

PROJECT:
Affordable Housing MQP

Akyem Dwenase, Ghana

DATE: 11/16/22
PROJECT NO N/A

REVISION	DATE

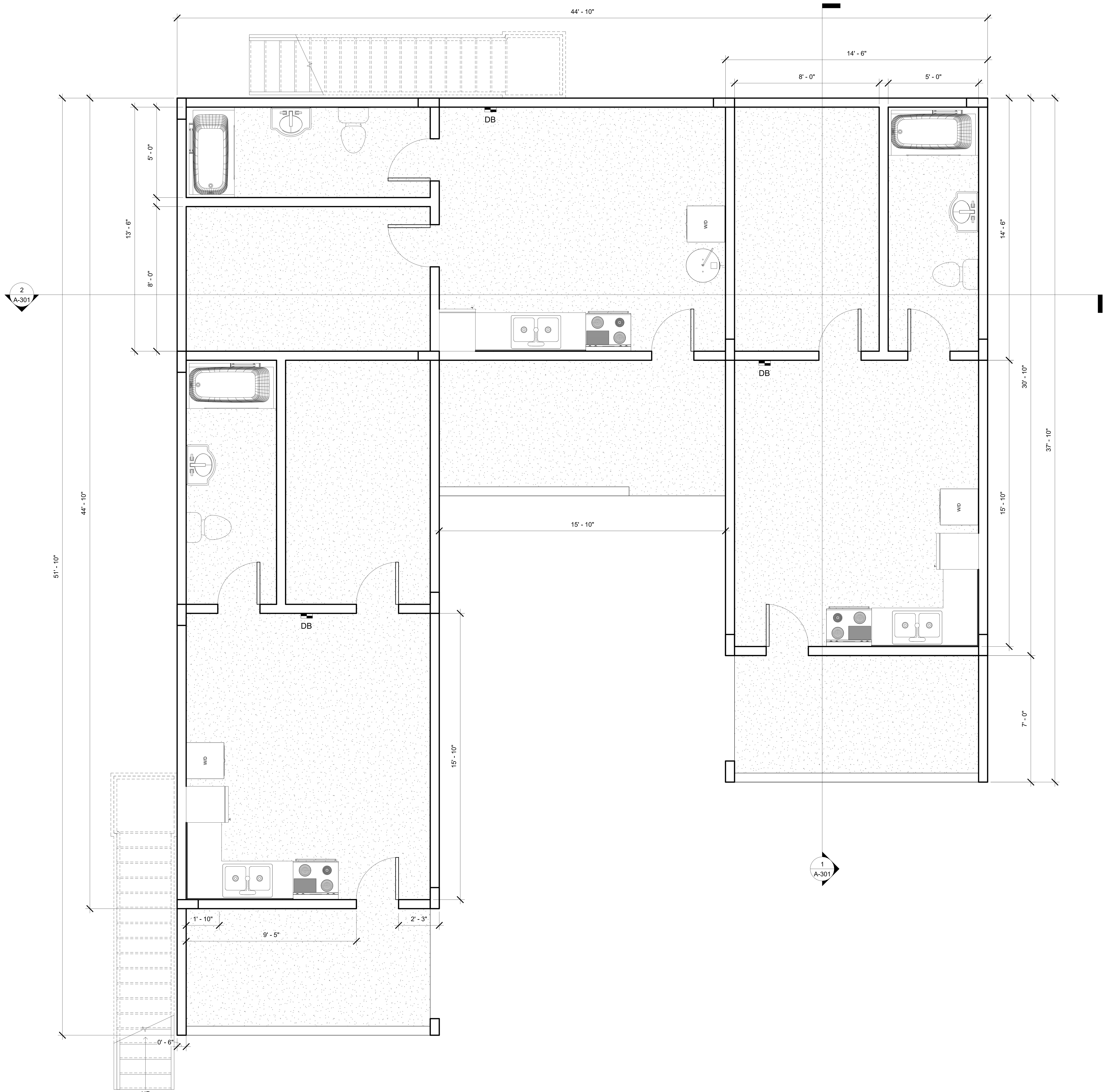
NOTES:

Architectural (General)

SCALE:

A-001

DRAWN BY: Author



1 Level 1
3/8" = 1'-0"

WPI

100 Institute Road, Worcester, MA

PROJECT:

Affordable Housing MQP

Akyem Dwenase, Ghana

DATE: 11/11/22
PROJECT NO N/A

REVISION DATE

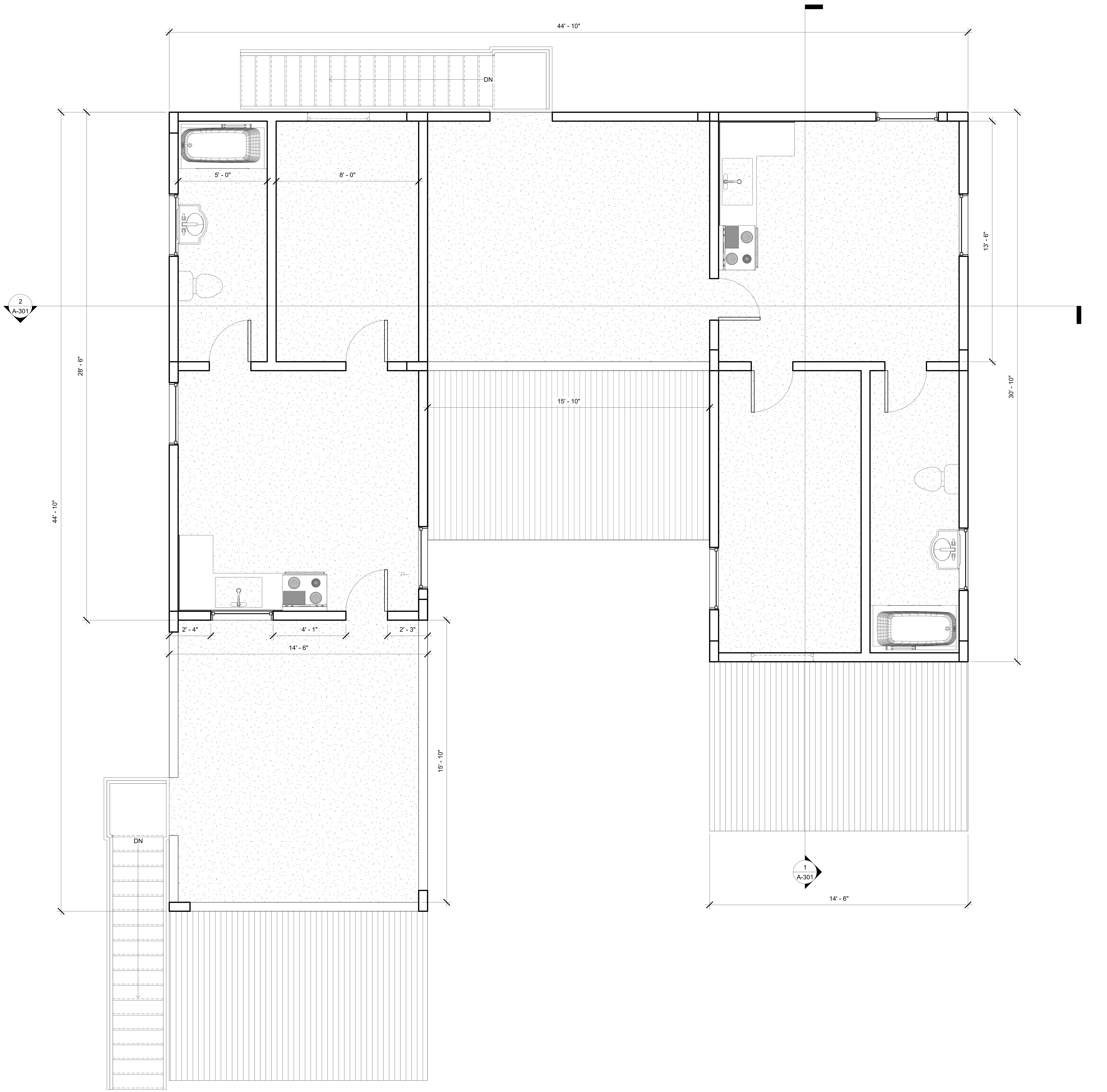
NOTES:

Level 1 Floor Plan

SCALE: 3/8" = 1'-0"

A-101

DRAWN BY: STUDENTS



1 Level 2
3/8" = 1'-0"

WPI
100 Institute Road, Worcester, MA

PROJECT:

Affordable Housing MQP

Akyem Dwenase, Ghana

DATE:	11/11/22
PROJECT NO	N/A
REVISION	DATE

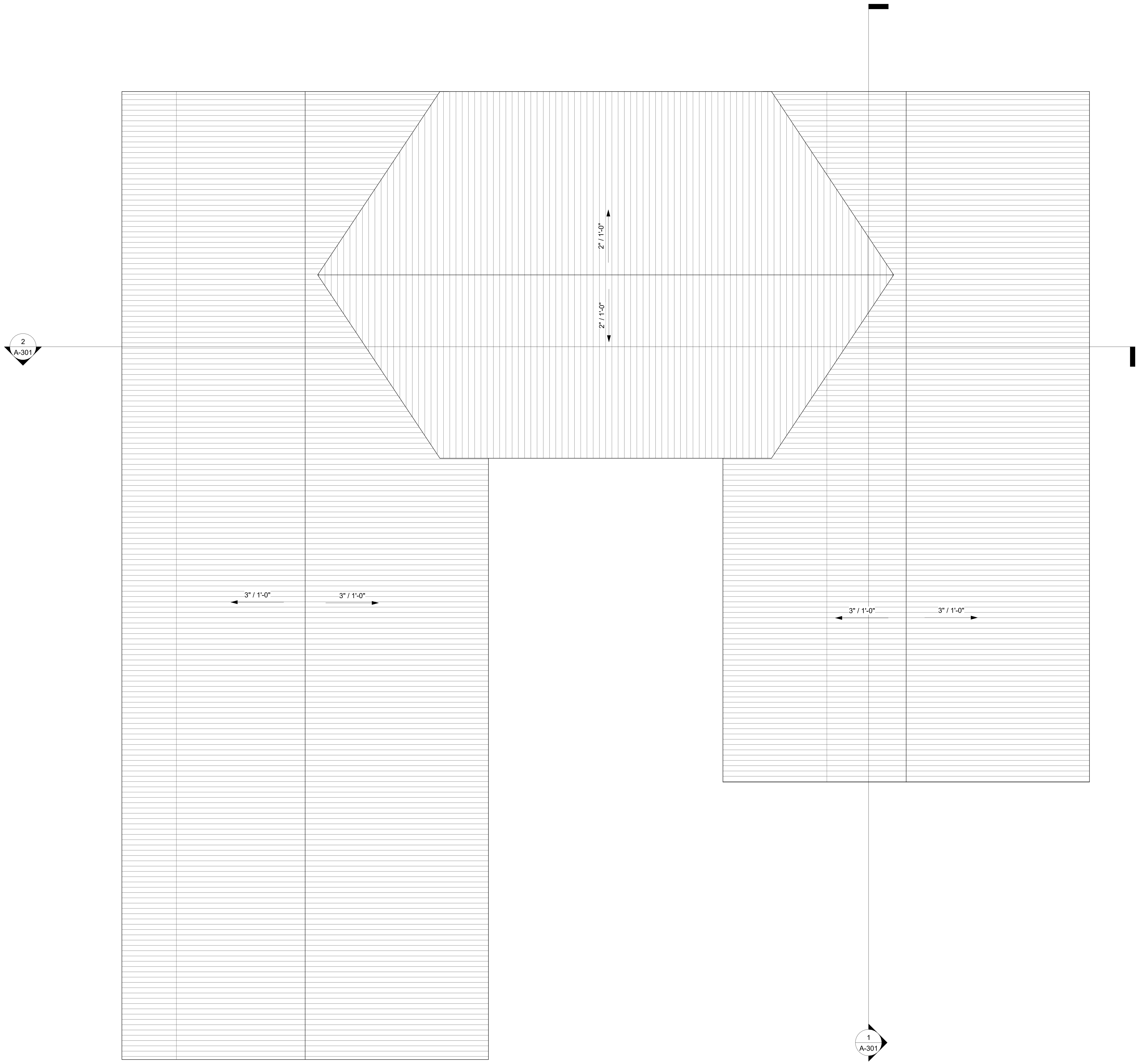
NOTES:

Level 2 Floor Plan

SCALE: 3/8" = 1'-0"

A-102

DRAWN BY: Author



1 Roof
3/8" = 1'-0"

WPI

100 Institute Road, Worcester, MA

PROJECT:

Affordable Housing MQP

Akyem Dwenase, Ghana

DATE:	12/09/22
PROJECT NO	N/A
REVISION	DATE

NOTES:

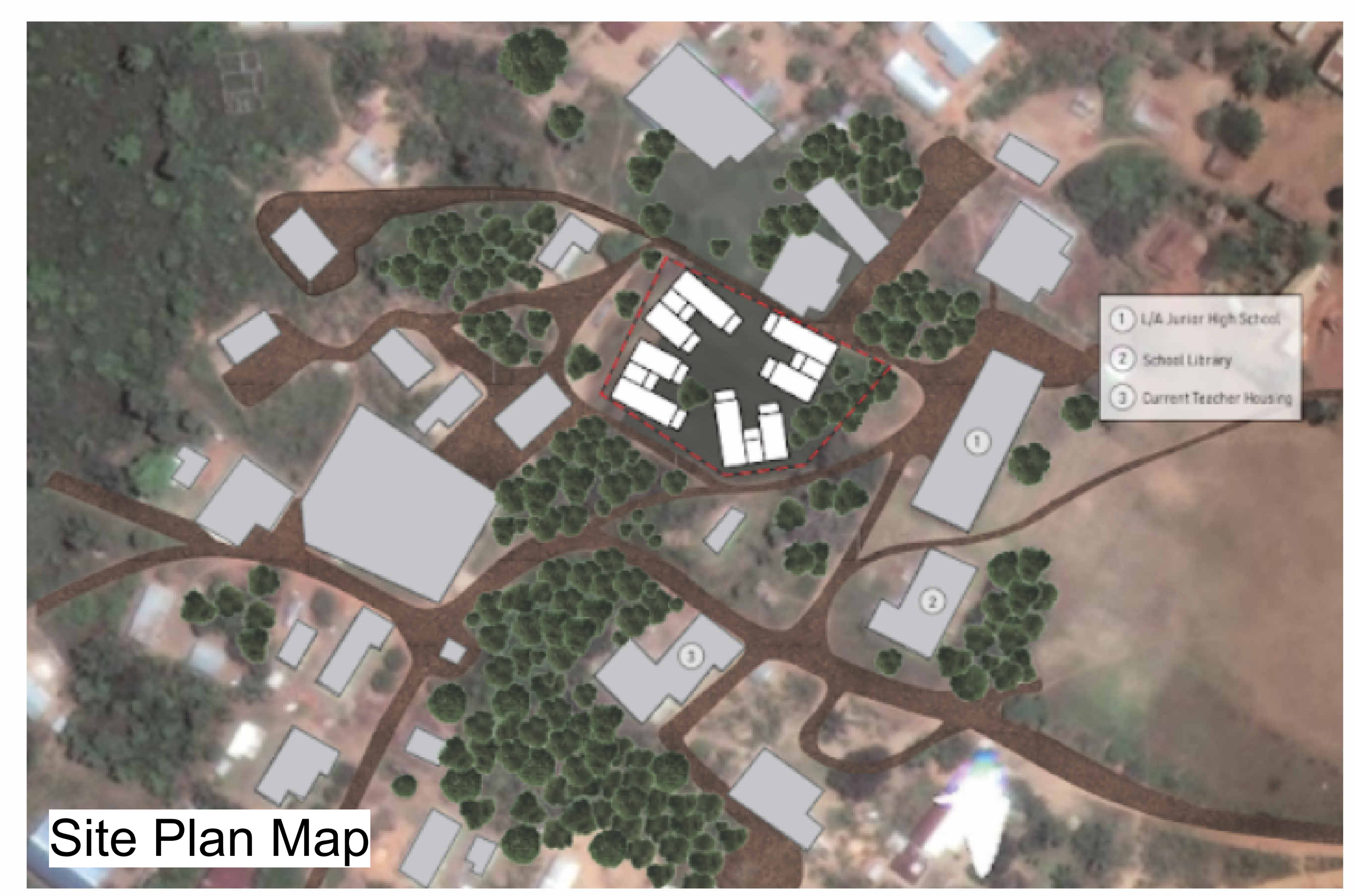
Roof Plan

SCALE: 3/8" = 1'-0"

A-103

DRAWN BY: Author

① Site Plan
1" = 60'-0"



100 Institute Road, Worcester, MA

PROJECT:
Affordable Housing MQP

Akyem Dwenase, Ghana

DATE:	12/13/22
PROJECT NO	N/A
REVISION	DATE

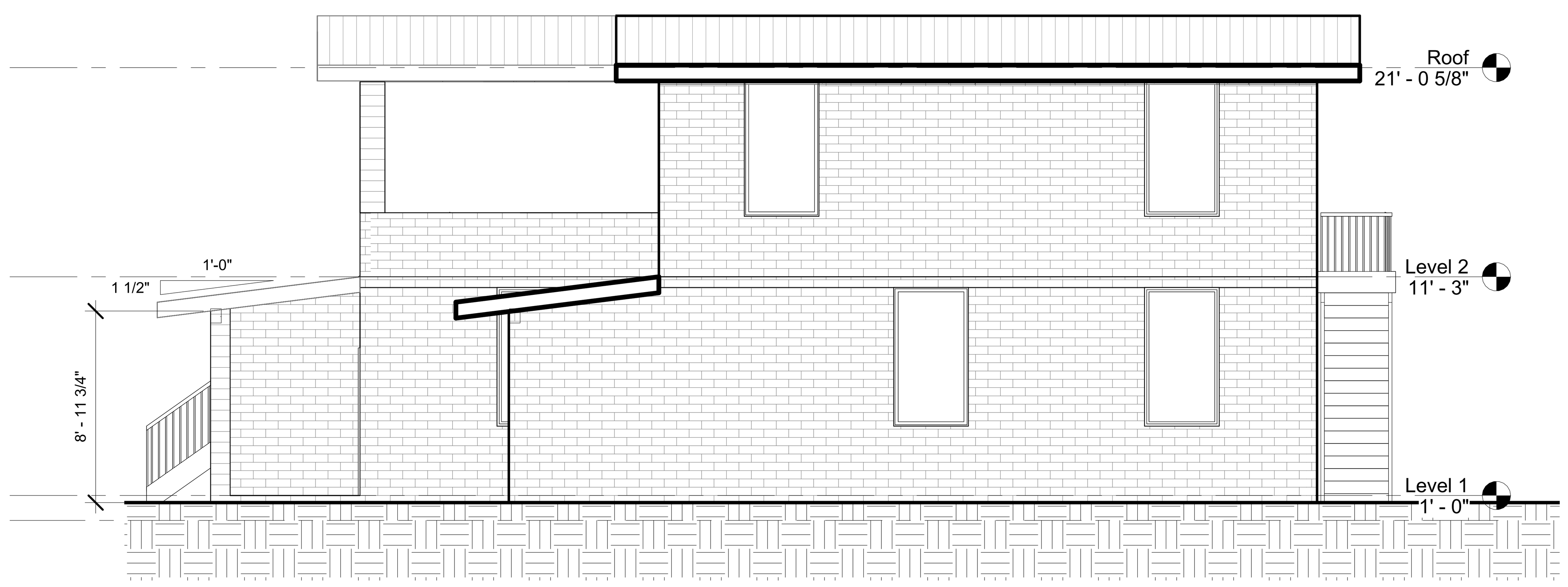
NOTES:

Site Plan

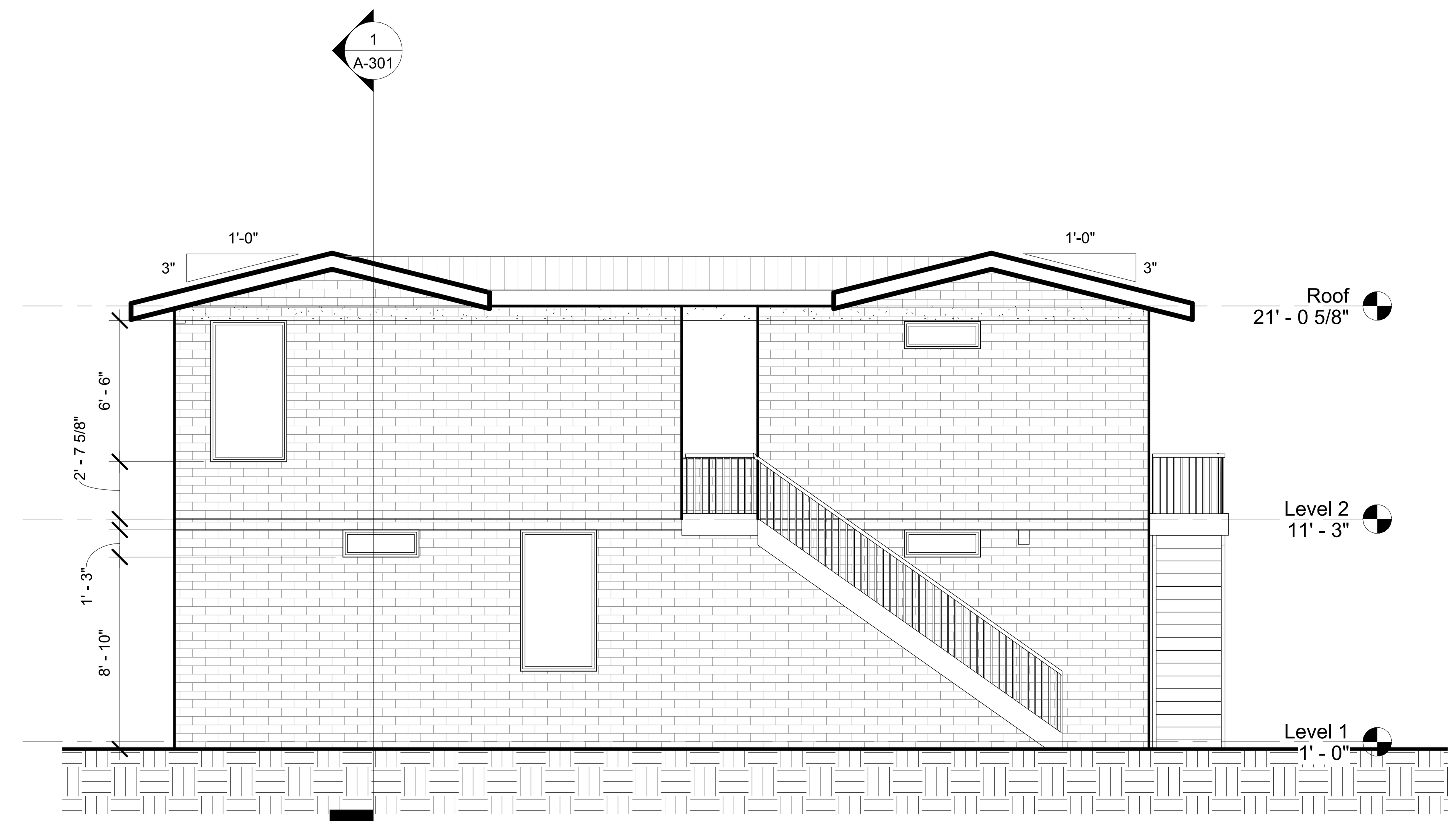
SCALE: 1" = 60'-0"

A-104

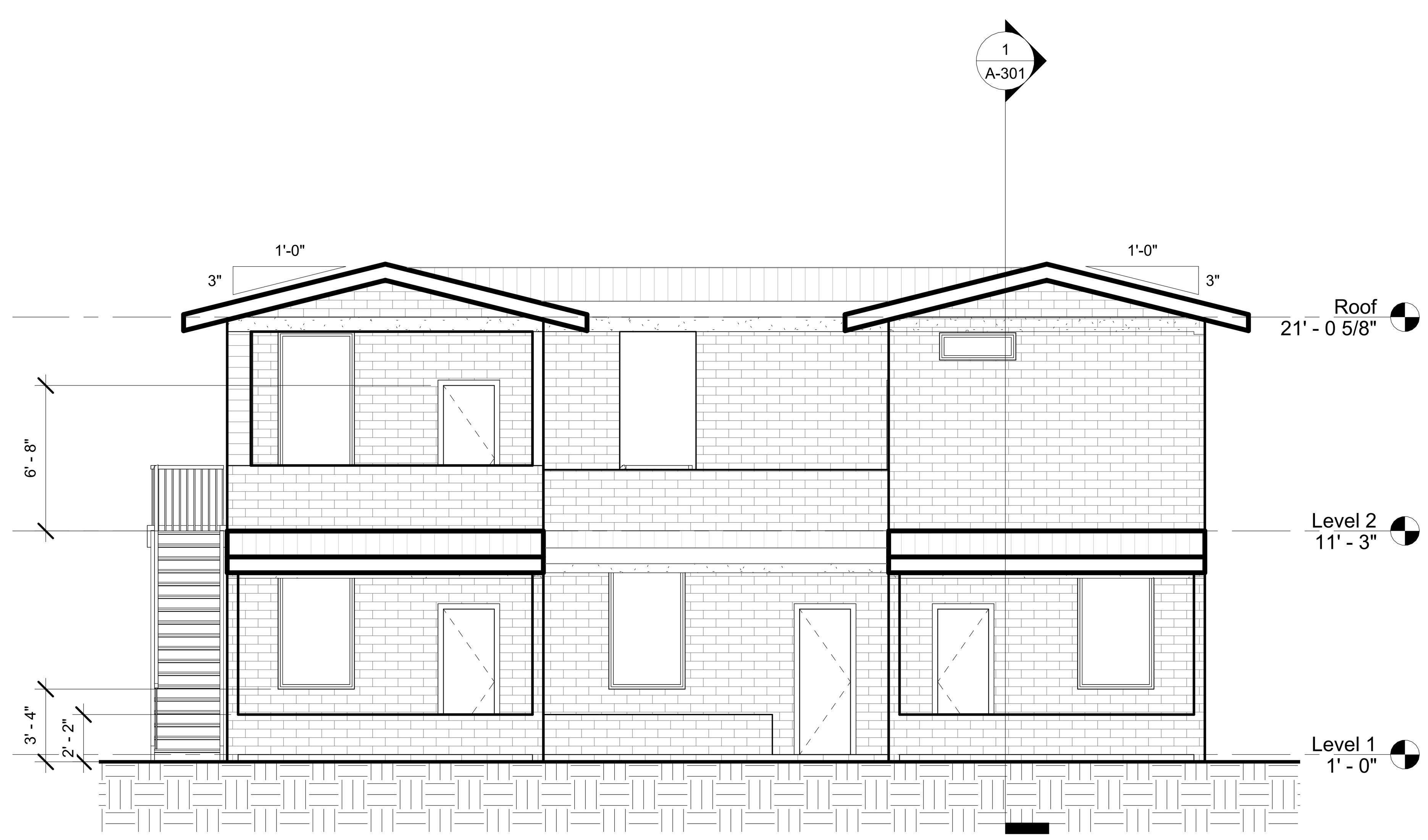
DRAWN BY: Author



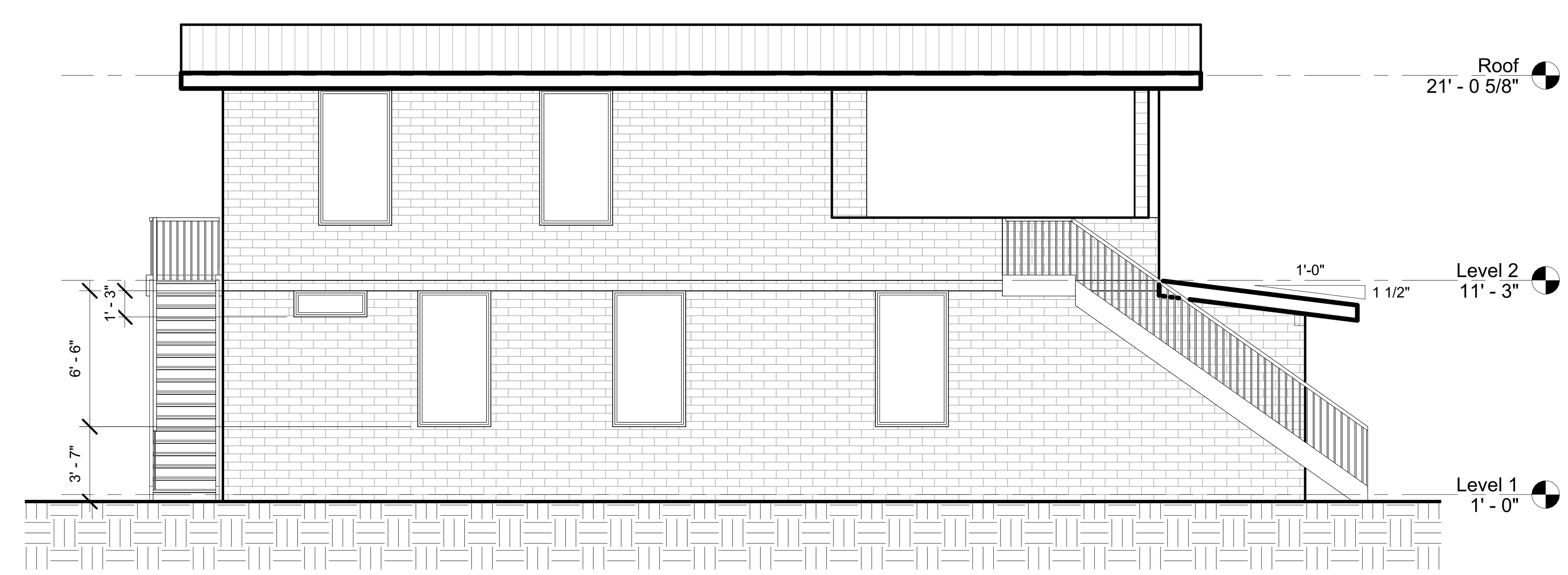
1 East
3/16" = 1'-0"



2 North
3/16" = 1'-0"



3 South
3/16" = 1'-0"



4 West
3/16" = 1'-0"

WPI

100 Institute Road, Worcester, MA

PROJECT:

Affordable Housing MQP

Akyem Dwenase, Ghana

DATE:	11/16/22
PROJECT NO	N/A
REVISION	DATE

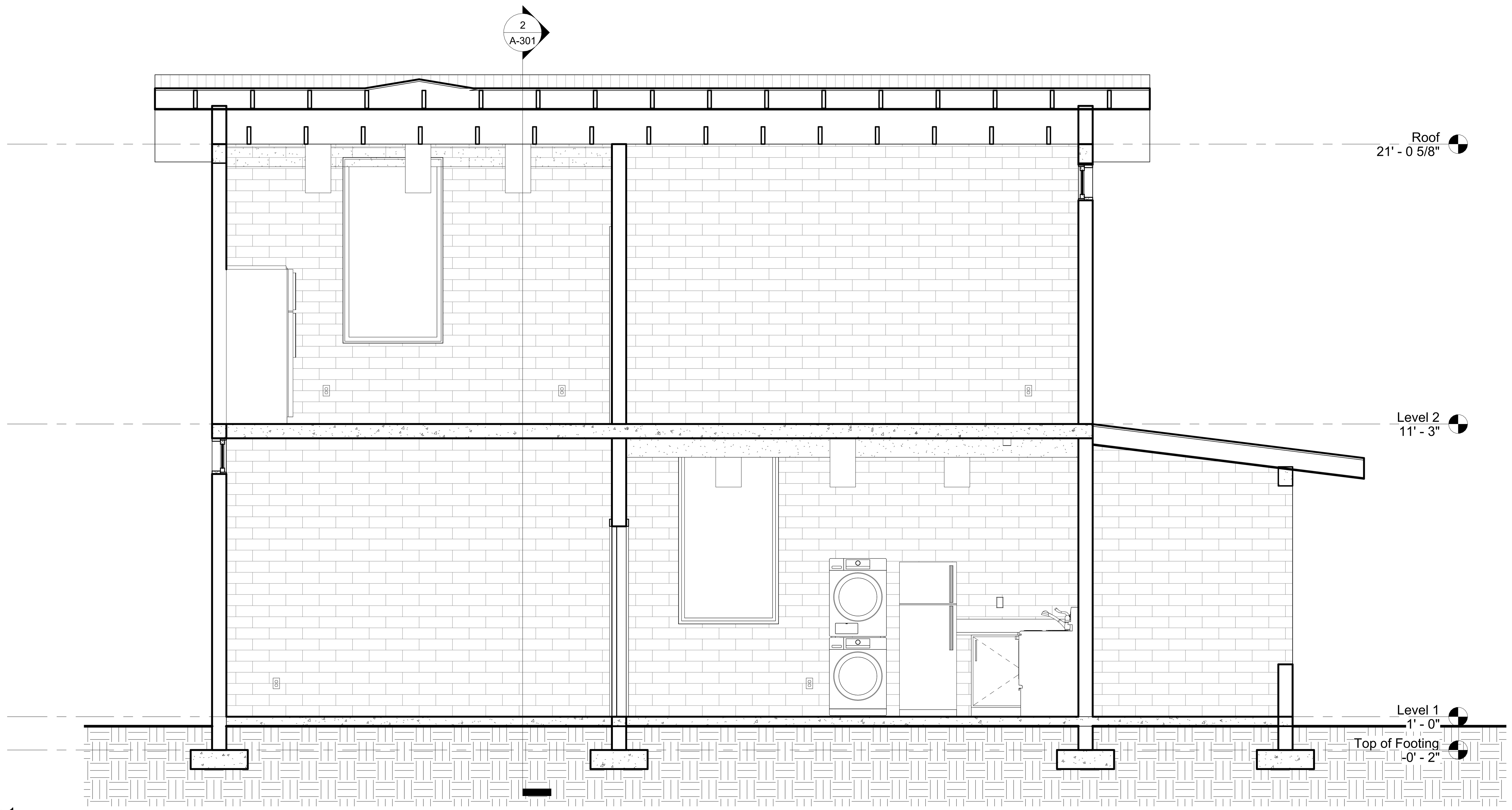
NOTES:

Elevations

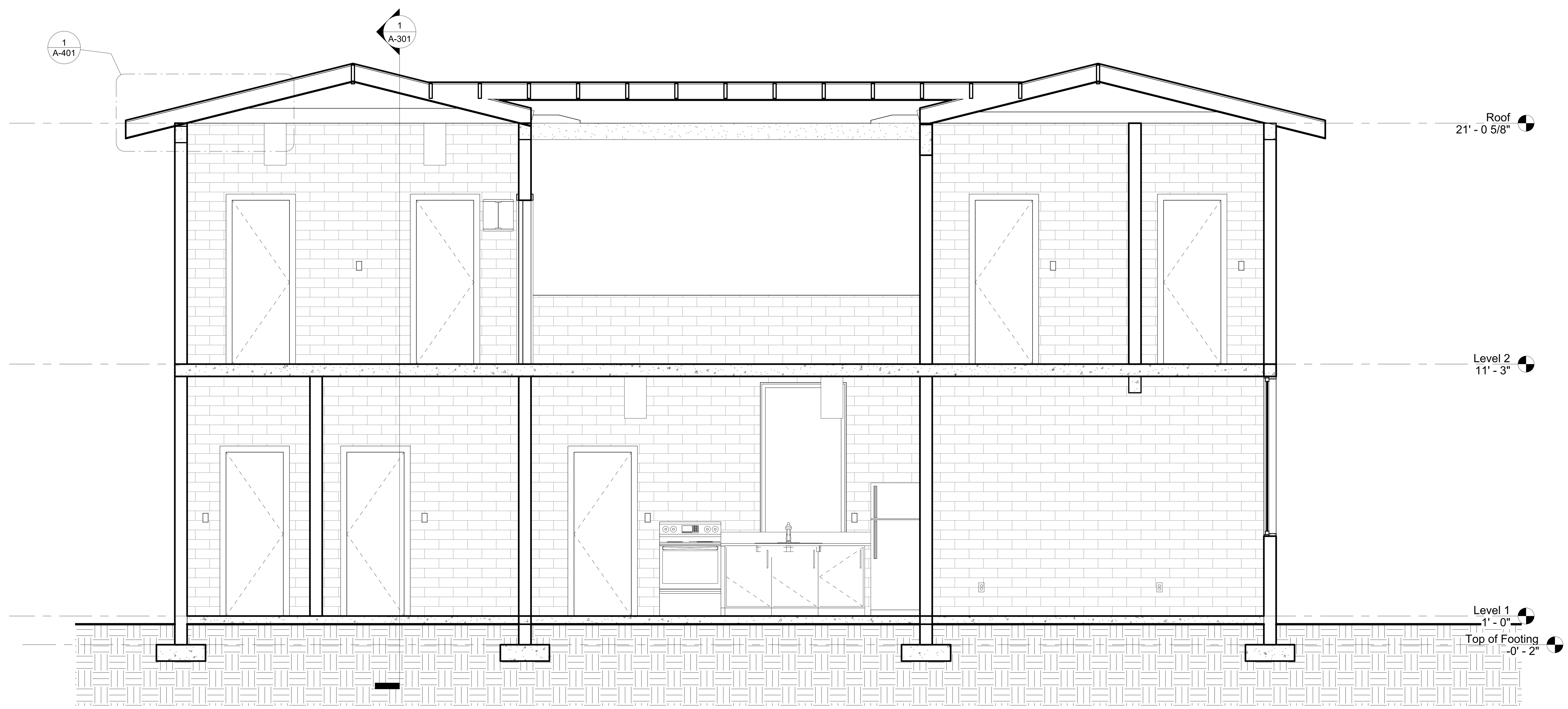
SCALE: 3/16" = 1'-0"

A-201

DRAWN BY: Author



1 Section 1
3/8" = 1'-0"



2 Section 2
3/8" = 1'-0"

WPI

100 Institute Road, Worcester, MA

PROJECT:

Affordable Housing MQP

Akyem Dwenase, Ghana

DATE: 11/16/22
PROJECT NO N/A

REVISION DATE

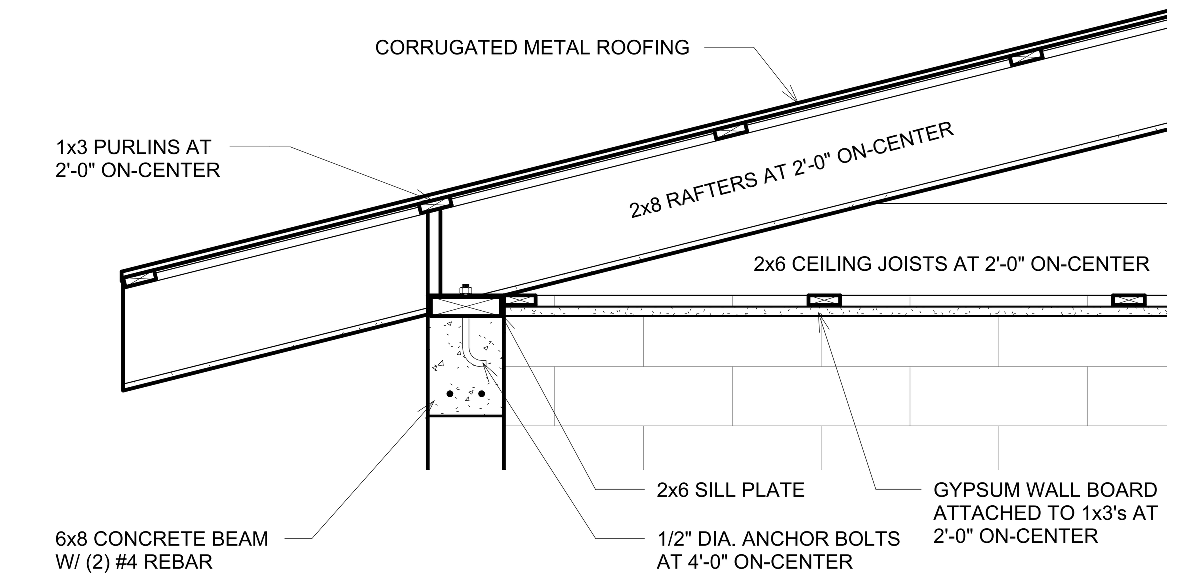
NOTES:

Sections

SCALE: 3/8" = 1'-0"

A-301

DRAWN BY: Author



1 Section 2 - Callout 1
1" = 1'-0"

WPI

100 Institute Road, Worcester, MA

PROJECT:

Affordable Housing MQP

Akyem Dwenase, Ghana

DATE: 11/16/22
PROJECT NO N/A

REVISION	DATE

NOTES:

Details

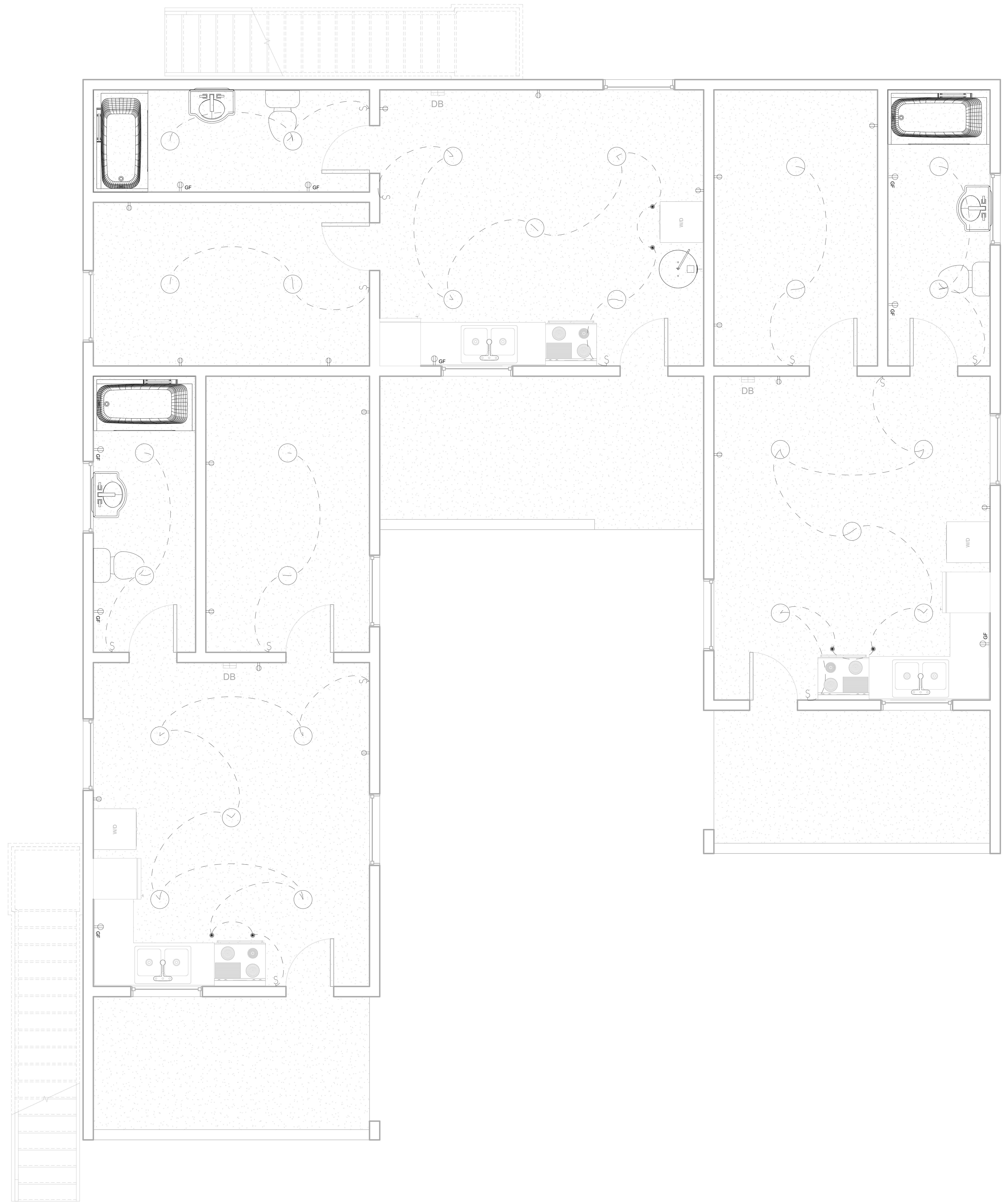
SCALE: 1" = 1'-0"

A-401

DRAWN BY: Author

ELECTRICAL SYMBOL LEGEND	
S	SINGLE SWITCH
	DUPLEX RECEPTACLE
GF	DUPLEX RECEPTACLE GROUND FAULT CIRCUIT INTERRUPTER
	ENDO LIGHTING ADJUSTABLE DOWNLIGHT
	COOPER LIGHTING LED 8" ROUND CYLINDERS
DB	DISTRIBUTION BOARD

Electrical Legend
3/8" = 1'-0"



1 Level 1 Electrical Plan
3/8" = 1'-0"

WPI

100 Institute Road, Worcester, MA

PROJECT:
Affordable Housing MQP

Akyem Dwenase, Ghana

DATE: 11/16/22
PROJECT NO N/A

REVISION DATE

NOTES:

Electrical Level 1

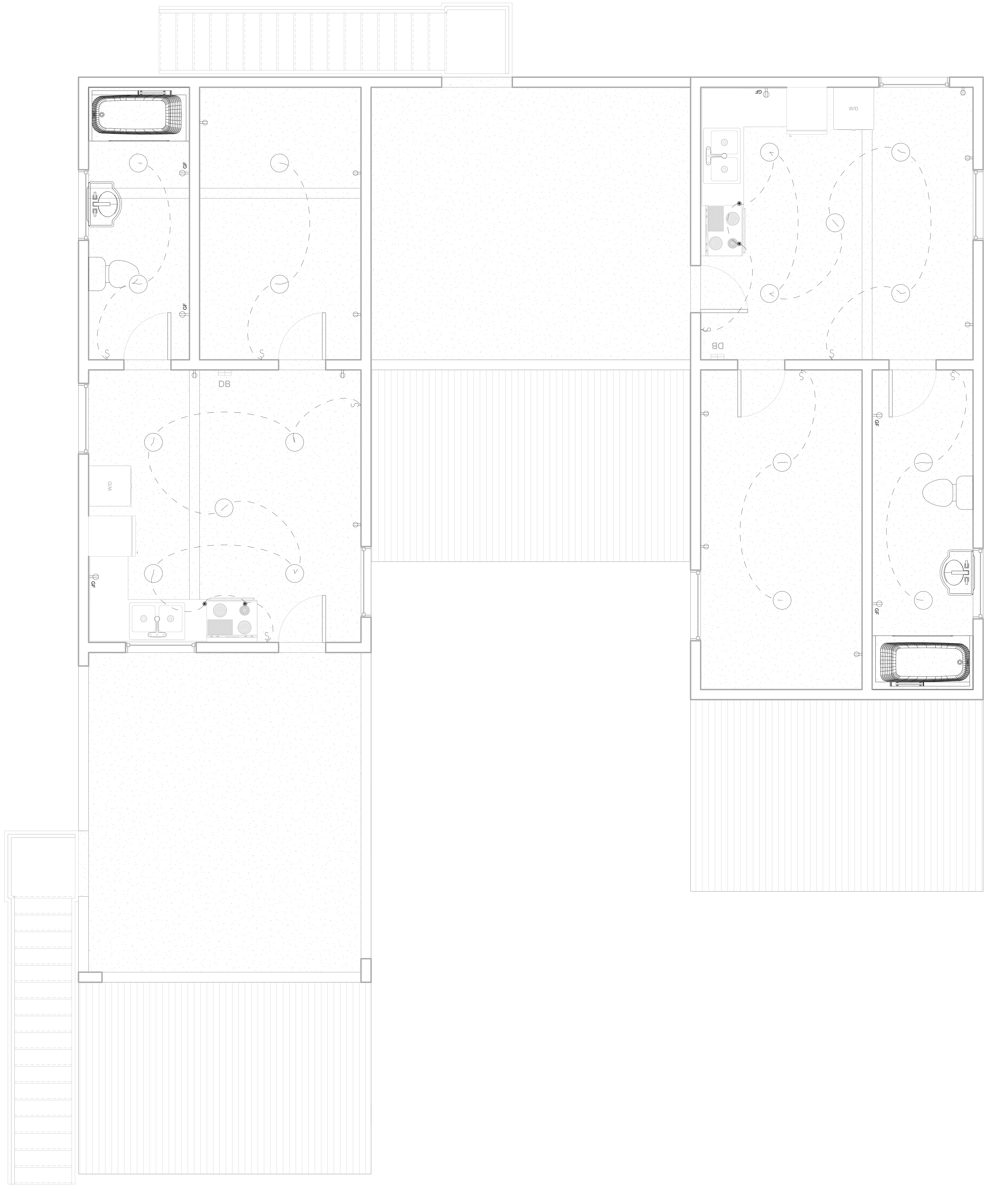
SCALE: 3/8" = 1'-0"

E-101

DRAWN BY: Author

ELECTRICAL SYMBOL LEGEND	
S	SINGLE SWITCH
	DUPLEX RECEPTACLE
GF	DUPLEX RECEPTACLE GROUND FAULT CIRCUIT INTERRUPTER
	ENDO LIGHTING ADJUSTABLE DOWNLIGHT
	COOPER LIGHTING LED 8" ROUND CYLINDERS
DB	DISTRIBUTION BOARD

Electrical Legend
3/8" = 1'-0"



1 Level 2 Electrical Plan
3/8" = 1'-0"

100 Institute Road, Worcester, MA

PROJECT:

Affordable Housing MQP

Akyem Dwenase, Ghana

DATE:	11/16/22
PROJECT NO	N/A
REVISION	DATE

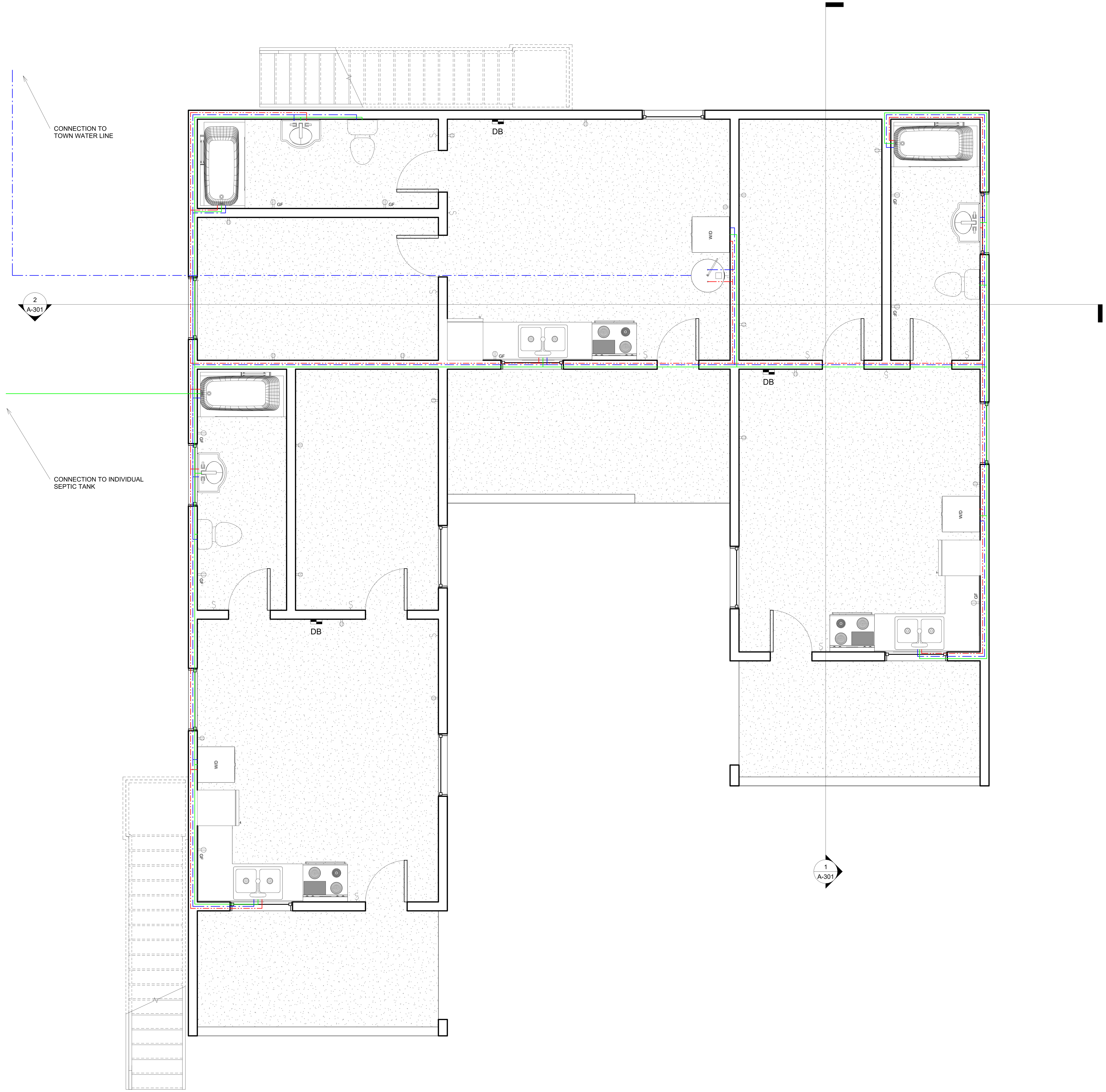
NOTES:

Electrical Level 2

SCALE: 3/8" = 1'-0"

E-102

DRAWN BY: Author



1 Level 1 Plumbing Plan
3/8" = 1'-0"

WPI
100 Institute Road, Worcester, MA

PROJECT:
Affordable Housing MQP

Akyem Dwenase, Ghana

DATE:	11/16/22
PROJECT NO	N/A
REVISION	DATE

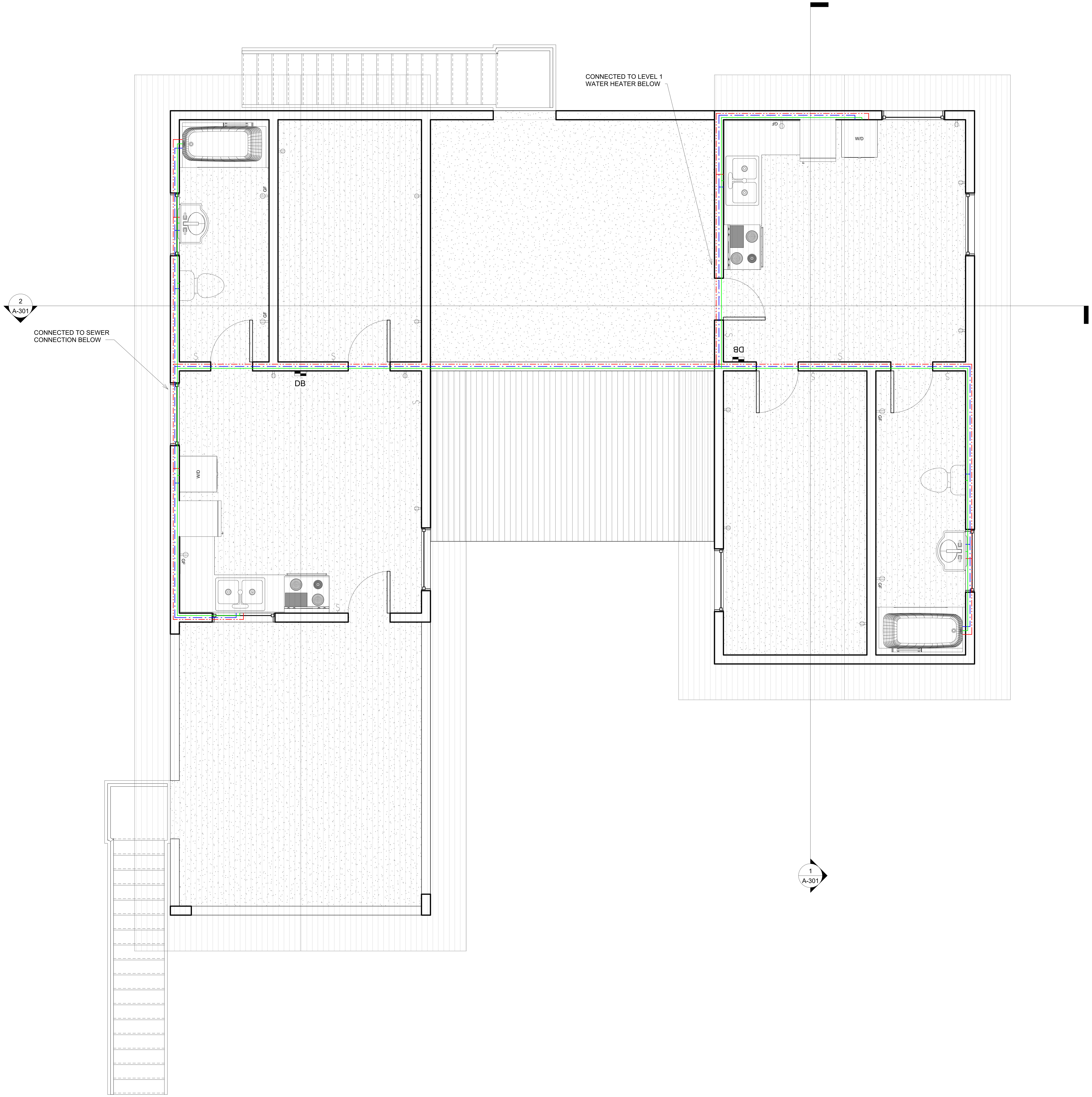
NOTES:

Plumbing Level 1

SCALE: 3/8" = 1'-0"

P-101

DRAWN BY: Author



1 Level 2 Plumbing Plan
3/8" = 1'-0"

WPI

100 Institute Road, Worcester, MA

PROJECT:

Affordable Housing MQP

Akyem Dwenase, Ghana

DATE: 11/16/22
PROJECT NO N/A

REVISION DATE

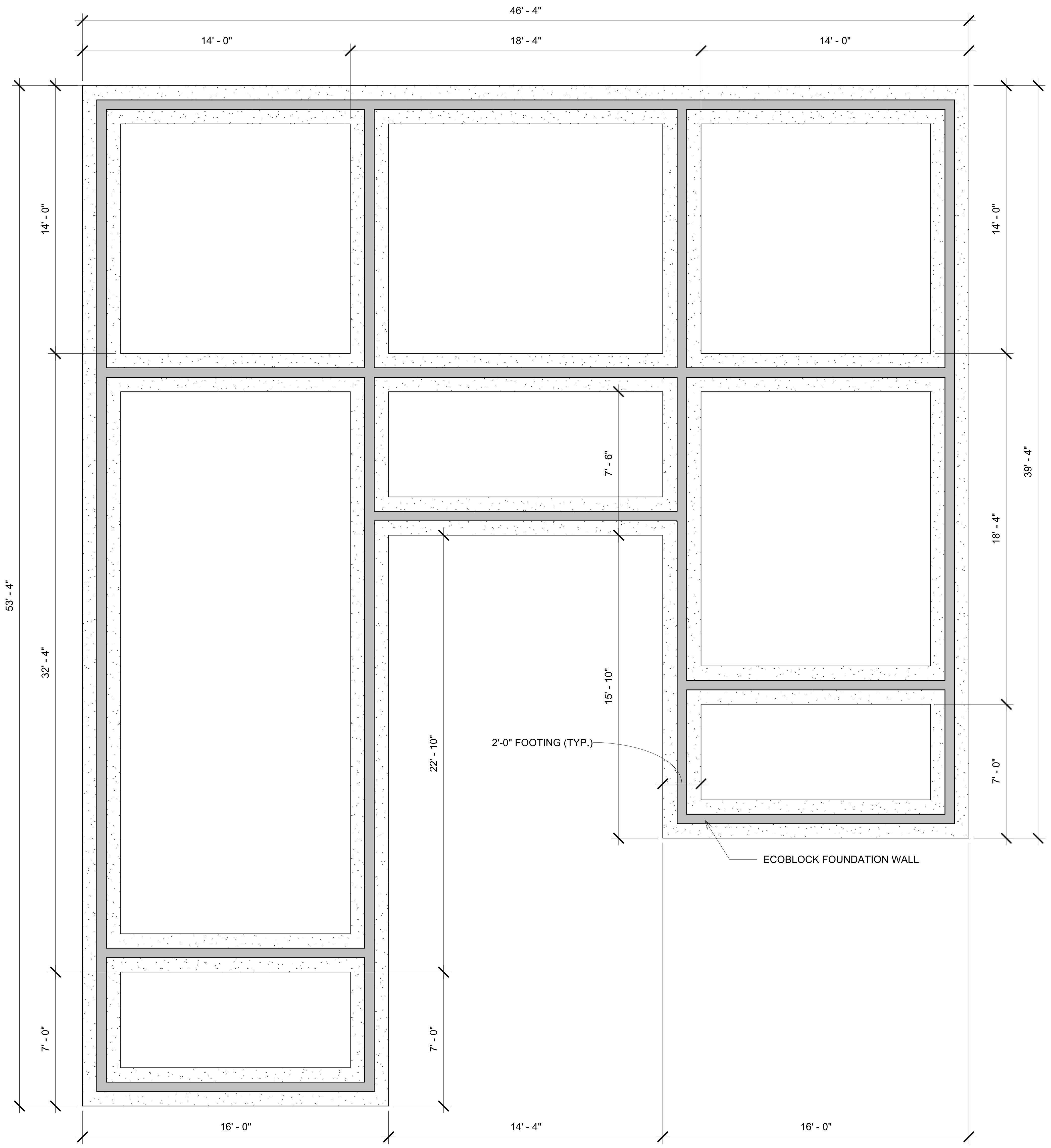
NOTES:

Plumbing Level 2

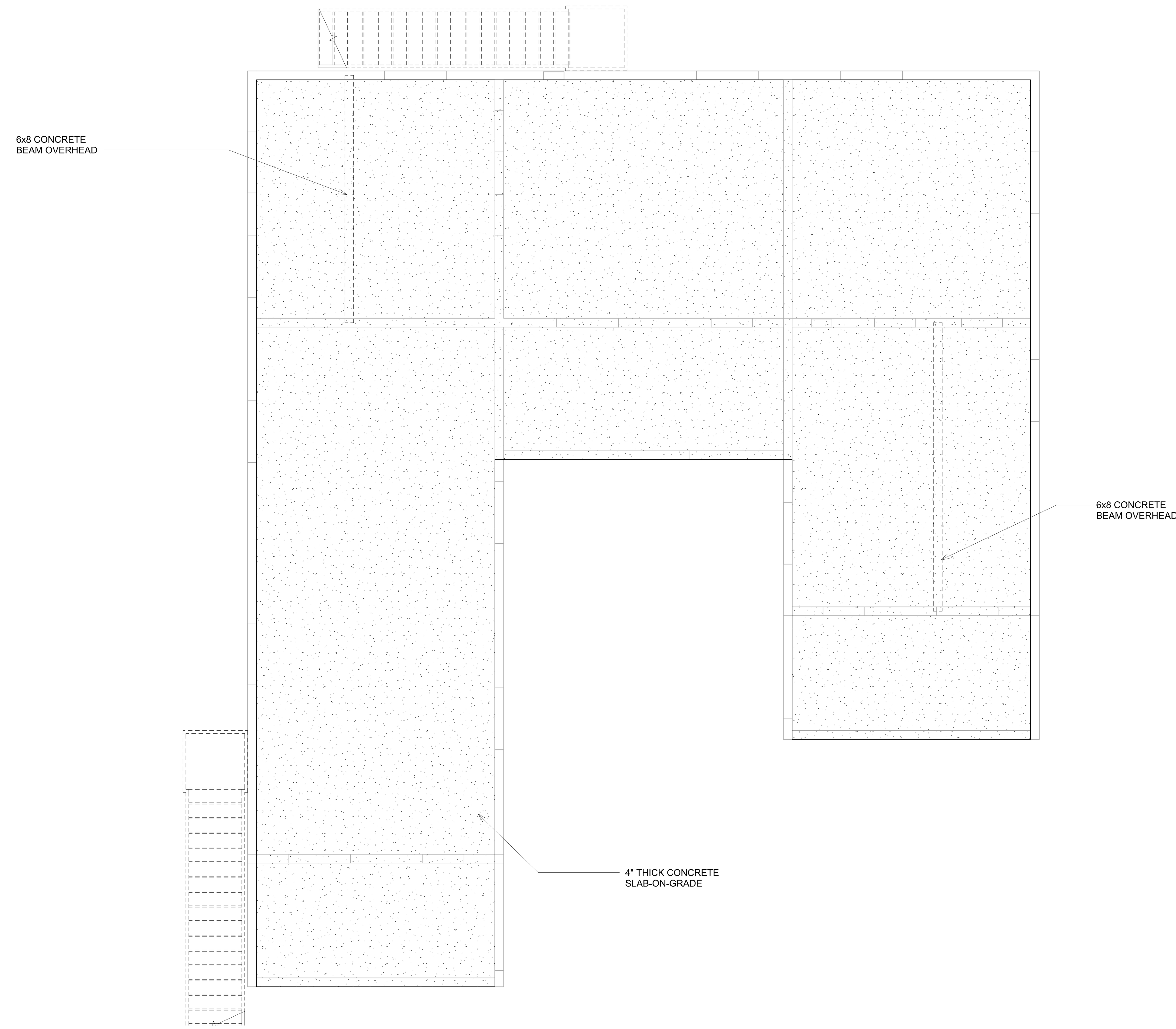
SCALE: 3/8" = 1'-0"

P-102

DRAWN BY: Author



1 Foundation Plan
1/4" = 1'-0"



2 Level 1 Structural Plan
1/4" = 1'-0"

WPI

100 Institute Road, Worcester, MA

PROJECT:

Affordable Housing MQP

Akyem Dwenase, Ghana

DATE:	11/16/22
PROJECT NO	N/A
REVISION	DATE

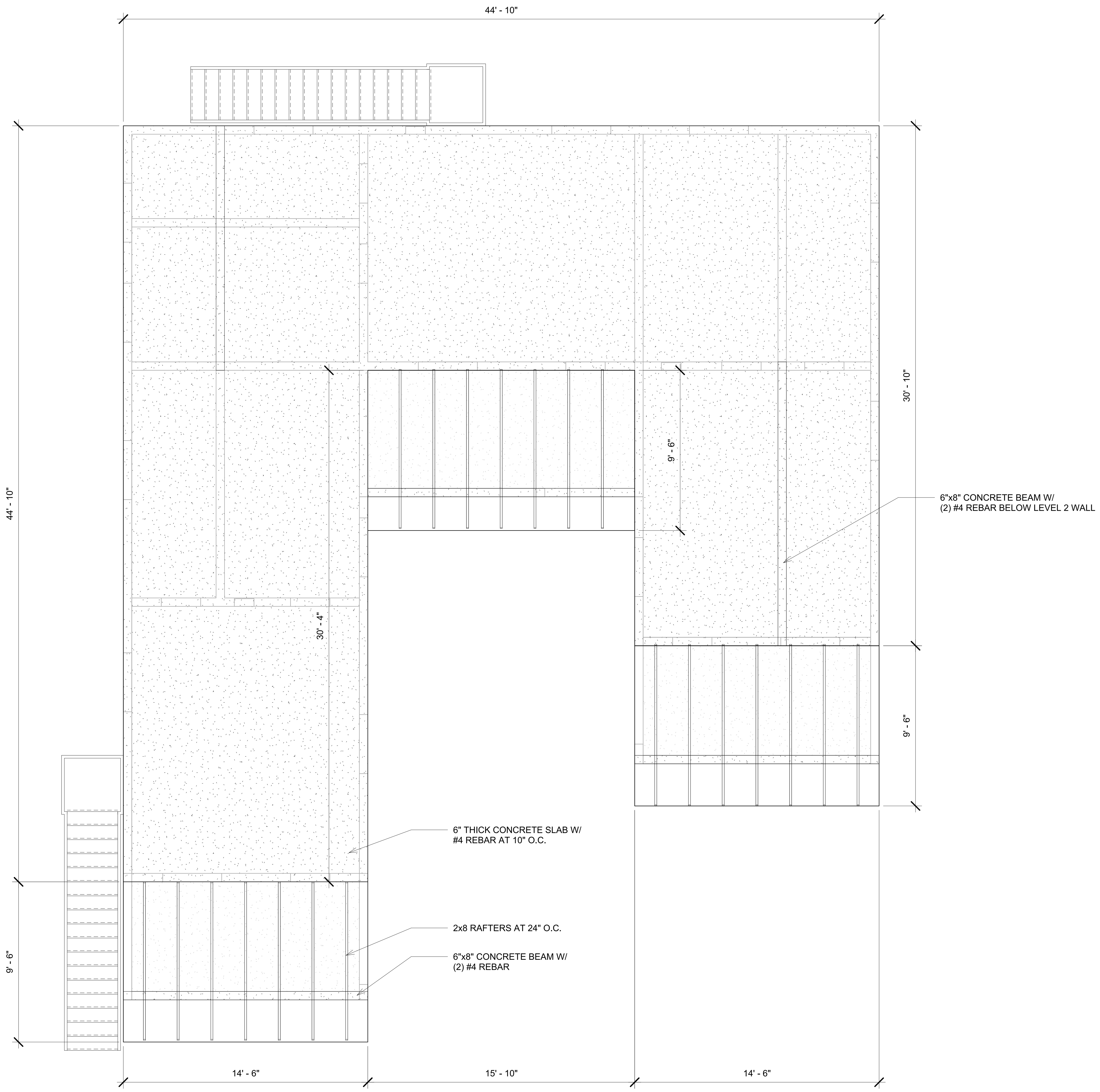
NOTES:

Foundation & Structural Plans

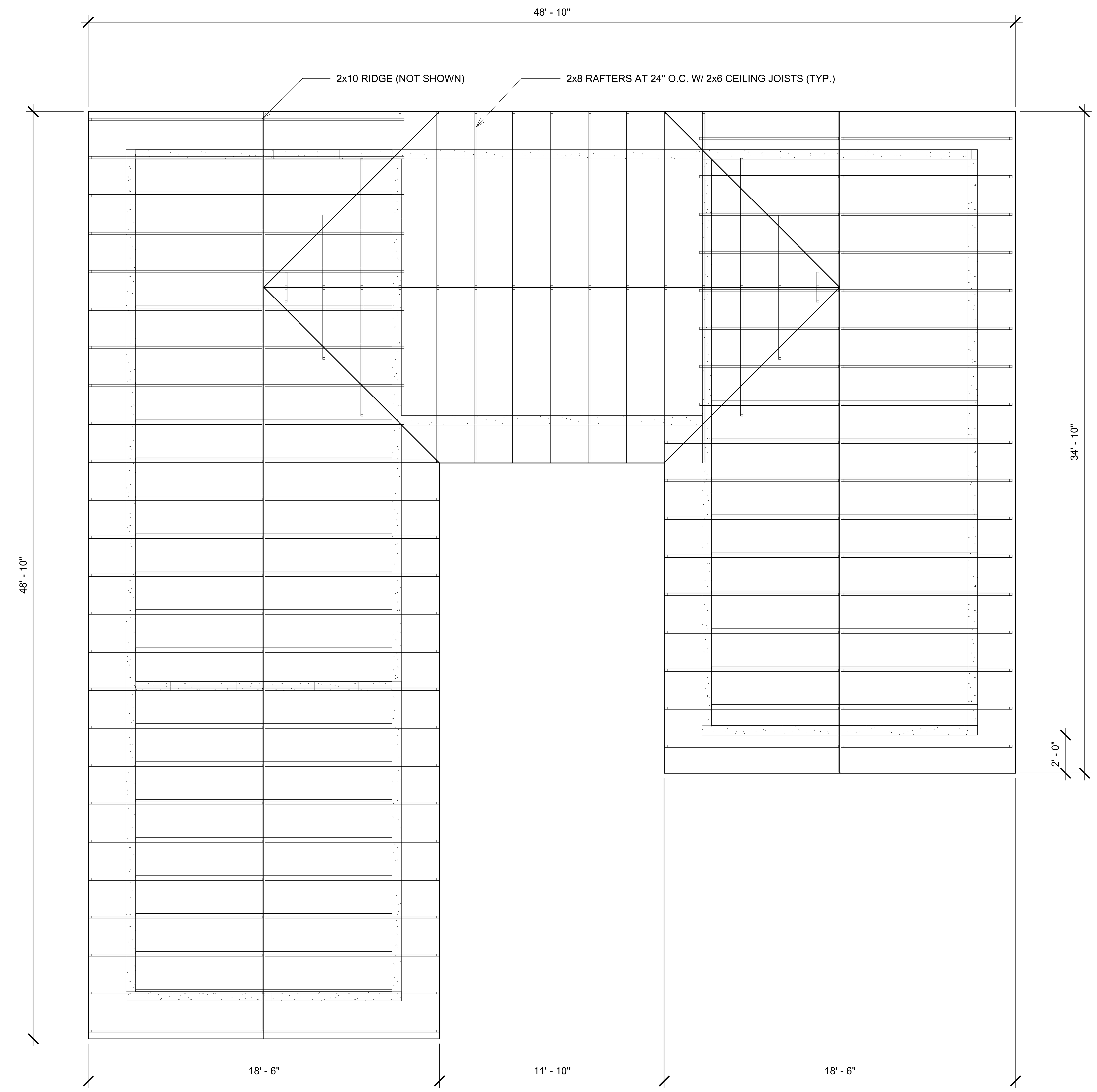
SCALE: 1/4" = 1'-0"

S-101

DRAWN BY: Author



1 Level 2 Structural Plan
1/4" = 1'-0"



2 Roof Framing Plan
1/4" = 1'-0"

100 Institute Road, Worcester, MA

PROJECT:
Affordable Housing MQP

Akyem Dwenase, Ghana

DATE:	12/02/22
PROJECT NO	N/A
REVISION	DATE

NOTES:

Structural Plans

SCALE: 1/4" = 1'-0"

S-102

DRAWN BY: Author