ADVANCING RESILIENCE IN URBAN RESIDENTIAL CONSTRUCTION:

FORMALIZING HOUSING DESIGN AND DELIVERY IN THE DEVELOPING

WORLD

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by

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Abstract

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The residential construction industry in developing nations is often plagued by numerous constraining systems, including underdeveloped financial markets, ineffective governing bodies, and unregulated material and labor markets, which restrict safe and disaster-resilient housing to the wealthy minority. The majority are left in non-engineered, informally constructed homes, which, in countries with high exposure to hydro-meteorological and/or seismic hazards, can prove deadly. The thesis presented herein utilizes an integrated approach to increase the resilience of the informal residential construction industry in high-risk developing nations.

Through collaborative research and proposed intervention in multiple stages of the housing delivery process, this thesis will develop practical, evidence-based designs, frameworks, processes, tools, and recommendations that seek to advance the resilience of urban residential construction by providing a pathway to formalizing housing design and delivery in the developing world. The advantages and disadvantages of a variety of relevant housing typologies are discussed, and a comparative material cost analysis is used to establish the masonry-infilled special moment frame as the most cost-effective seismically-detailed typology. An exhaustive parametric analysis and evaluation framework is then utilized to select structural designs best-fit for the Haitian case study scenario. The methodology and results of a nonlinear static analysis, which assessed the performance of the selected designs when exposed to the seismic hazards characteristic of the case study scenario, is also presented. Lastly, this thesis proposes an integrated implementation framework to increase the market-driven uptake of the selected designs. It is the intention of the author that the housing design and delivery process presented in this thesis be applied, evaluated, and iterated by any organization seeking to create a lasting, positive impact on the sustainable development of housing in developing nations with significant exposure to natural hazards.

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CHAPTER 1:

INTRODUCTION

This chapter will introduce the main concepts to be investigated in this thesis, demonstrate the need for the studies detailed in the following chapters, and outline the goals of the thesis presented herein. First, the defining elements and causes of informal residential construction are discussed. Next, the community of Léogâne, Haiti is presented as the target case study scenario for the investigations conducted in this thesis. A brief summary of foundational work which this thesis will build upon is then provided. Lastly, this chapter will define the research objectives and organization of the following chapters.

1.1 Informal Residential Construction

It is estimated that 1.6 billion people worldwide lack adequate shelter (McKinsey 2014). The risk to human well-being posed by this massive deficit is only further exacerbated by climate change and trends in human migration. As anthropogenic warming and sea-level rise lead to stronger and more frequent tropical storms (Knutson et al. 2019), coastal and low-lying settlements are particularly vulnerable to flooding and wind hazards. Coastal populations are also especially susceptible to seismic hazards, as the majority of major fault lines lie along coastal boundaries (Christopherson et al. 2015).

Despite these risks, humans are increasingly migrating towards coasts (Neumann et al. 2015) and densely-populated urban centers (IOM 2015). This rapid urbanization, particularly in developing nations without strong, regulated housing markets, leads to the widespread construction of substandard housing units, which have again and again proven deadly for those who, out of necessity, take residence in them (Rossetto and Peiris 2009; Eberhard et al. 2010; Rai et al. 2016; Kijewski-Correa et al. 2018). Thus, there is a demonstrated global need for advancements in resilient urban housing, particularly in developing nations exposed to extreme natural hazards.

Unfortunately, the residential construction industry in such regions often faces significant technical, economic, and political challenges that hinder resilient housing development. Table 1-1 lists some common examples of these constraints.

TABLE 1-1: CONSTRAINTS ON RESIDENTIAL CONSTRUCTION INDUSTRY IN DEVELOPING REGIONS

Economic	**Technical**	**Political**
• Informal economy • Low and inconsistent income • Insufficient personal savings • Lack of formal financial services • Lack or reliable credit tracking or income verification	• Low-quality construction materials • Non-engineered designs • Incremental construction • Informally-trained laborers	• Insufficient or non-existent building codes • Ineffective or non-existent permitting and inspection procedures • Government corruption • Ineffective or non-existent land tenure systems

Combinations of these factors have led to two prevalent attributes that distinguish the residential construction industry in developing urban areas from the industry in developed nations such as the United States:

1. An informal blend of Design-Build and Master Builder methods of project delivery
2. Non-engineered, incrementally-constructed (and largely masonry) permanent homes

Design-Build (DB), as traditionally defined in the United States, is a "project delivery method in which the owner provides requirements for the specified project and awards a contract to one company who will both design and build the project" (Hale et al. 2009). This method has its roots in the traditional Master Builder construction process (described below), which was how nearly all structures were built up until the 20th century (Taylor 2000; Yates and Battersby 2003). This contrasts with the currently more common method of Design-Bid-Build, in which the owner first solicits design services which later form the basis of the requirements for the contract with a separate construction company (Hale et al. 2009). Although DB is also common in the United States, particularly for single-family residential construction, and was spurred by a push for more efficient and cost-effective project delivery, the informal DB method in residential construction in developing areas was borne out of necessity in these highly constrained markets and lacks the regulation and formality of its US counterpart.

Design-Build companies in the residential construction industry in developing areas are often led by a Master Builder. This individual generally serves as a surveyor, architect, engineer, project manager, procurer, foreman, and inspector. Although increased project complexity has outstretched the capabilities of a single individual in developed nations (Yates and Battersby 2003), the perceived simplicity of designs and lack of general regulation has not yet pressured a change in the residential construction industry in developing nations. Without a strong institutional infrastructure regulating and enforcing design reviews, building codes, third-party inspections, site safety, professional accreditation, or laborer training, Master Builders constrained by limited resources and capacity have few regulations and requirements; thus, they rely heavily on experience. With the exception of occasionally securing a construction permit, there is often zero third-party involvement in the process. Given the freedom experienced by professionals in the informal residential construction industry, design decisions are often driven by cost-effectiveness and convenience rather than structural integrity and resilience. Although a symptom of its economic and political context, informal residential construction often directly contributes to the problem by constructing substandard homes that would not be allowed in a more regulated environment.

The second distinguishing attribute of the informal residential construction industry is the prevalence of masonry typologies. Masonry is often the cheapest and/or most plentiful material in the local market for the construction of permanent homes, can be assembled incrementally with little formal training, and requires minimal equipment. For these reasons and others, including cultural preferences toward permanence and modern materials, security (Mix et al. 2011), and, in many instances, a lack of lumber due to deforestation (Williams 2011), masonry has become the primary building material of informal urban residential construction in many developing areas (Macabuag and

Bhattacharya 2009). Although not permitted in high-seismic regions in the United States (ASCE 2016), both unreinforced masonry (URM) and confined masonry are common residential typologies in developing nations with significant seismic hazards. In fact, confined masonry is promoted by numerous international organizations (CMN 2011; USAID 2014; Chourasia 2017; SDC 2018) as well as foreign building codes (Alcocer et al. 2003; AIS 2010). Although post-earthquake reconnaissance research shows that well-executed confined masonry can perform well in seismic events (Salinas and Lazares 2008; Astroza et al. 2012), when combined with the lack of quality control and constrained project budgets often found in informal residential construction, the line between confined masonry and URM is blurred and can prove disastrous (Mix et al. 2011). This dangerous element of informal residential construction in the developing world demonstrates the need for cost-effective and adaptable, yet formally engineered, structural solutions.

As stated above, the use of non-engineered and non-codified designs, informally constructed without significant quality control or oversight, creates vulnerable homes. This technical issue is further exacerbated by other context-driven economic factors. Weak financial institutions, inflation, and frail legal systems have inhibited the maturation of mortgage markets in developing nations (Sanders 2005), vastly limiting the availability of mortgage financing that could reduce the reliance on incremental construction and thereby the bias toward masonry typologies. Furthermore, more than half of the developing world's labor force operates in the informal economy (Kus 2010), which often leads to low and inconsistent income and no formal credit systems. Even if mortgages were available in developing nations, a lack of sufficient systems to verify income, credit history, and land tenure would restrict them to the wealthy minority. Thus, most families must build incrementally, buying materials and building as their income allows. The family remains exposed not just throughout this process, which often takes 10 or more years, but after, as the high variability in materials and workmanship render an incrementally-constructed home highly vulnerable to natural hazards (Mix et al. 2011).

Lastly, there remains a crucial knowledge gap, as most home buyers do not possess the expertise needed to properly mitigate risk when making design decisions for their new home. Research regarding homeowner risk awareness and reduction via structural mitigation has only recently emerged for developing nations (Richman et al. 2018). In developed nations like the United States, strict building codes are in place in the residential construction industry to ensure life safety of occupants. Thus, the average homeowner does not need to maintain any understanding of resilient structural design principles to ensure the safety of their family. However, in informal construction projects, clients have a significant say in the design that their contractor builds, and may even procure materials. As a result, the builder may defer to the homeowner against his or her better judgement and experience. For example, homeowners in Caribbean communities may select a concrete slab roof for its performance in high-wind hazards without properly understanding the seismic risk of such an element. Thus, it is imperative that clients of informal residential construction are presented with the risks of typologies, roof systems, and other design decisions. An unbiased performance assessment, when presented alongside other factors such as cost, aesthetics, and security, can empower homeowners to make risk-informed decisions that are truly in the best interests of their family.

1.2 The Haitian Case Study Scenario

Considering all of the aforementioned factors, the Republic of Haiti presents the optimal case study for research seeking to formalize residential construction. Located on the western half of the island of Hispaniola, Haiti has both significant seismic and hurricane risk. In 2010, a 7.0 Mw earthquake killed an estimated 230,000 people, injured 300,000, and displaced an additional 1.2 million (Margesson and Taft-Morales 2010). In 2018, Hurricane Matthew made landfall as a Category 4 storm and destroyed tens of thousands of homes (Kijewski-Correa et al. 2018). In addition to its multi-hazard risk, Haiti also faces countless political and economic challenges, ranking 168th (out of 189 nations) on the Human Development Index (UNDP 2018) and 182nd (out of 190 nations) on the World Bank's Ease of Doing Business Index (World Bank 2018a). In particular, Léogâne, located near the epicenter of the 2010 earthquake, presents a stage ripe for research investigations in post-disaster rebuilding and proactive risk reduction. In 2010, 93% of buildings in Léogâne were collapsed or damaged (Eberhard et al. 2010). Despite the recent 10-year anniversary of the 2010 Haiti earthquake, survey data from Léogâne states that, as of 2017, 61% of people whose homes were completely destroyed in the earthquake have not yet started rebuilding (Kijewski-Correa et al. 2019). Based on its expressed extreme need and the existing capacity and relationships between Notre Dame and this community, Léogâne, Haiti is selected as the high-risk developing area that will serve as the case study for this thesis.

1.3 Foundational Work

After reconnaissance trips and extensive research in Léogâne, the author's advisors and former graduate students at the University of Notre Dame founded Engineering2Empower (E2E) and presented an alternative building model for Haiti (Kijewski-Correa et al. 2012; Mix 2013; E2E 2016; Fink et al. 2017). Rather than relying on confined masonry shear walls as the primary lateral system, they utilized a codified special reinforced concrete moment frame. The frame was then clad with an innovative concrete paneling system, rather than the typical practice of infilling the frame with concrete masonry units (CMUs). Following validation through technical analyses (Jensen 2016) and the construction of a prototype home on the University of Notre Dame campus, several homes were built in Haiti in 2015 and 2016, establishing the constructability of this new system.

Although cladding with panels rather than CMU reduces the potential for lateral load transfer during a seismic event, the panels required a significantly higher finishing cost. Likewise, a robust comparative economic analysis with other structural typologies common in the developing world, namely confined masonry, was never performed. Furthermore, the initial structural design was relatively conservative and the possibility of further cost reduction was not explored. Lastly, as the prior efforts were centered on proof of concept, other aspects necessary to achieve scale and sustainable implementation, such as financing options and construction quality control frameworks, had not yet been pursued — deficits the author aims to address in this thesis.

1.4 Research Objectives

The following chapters utilize an integrated approach to reduce risk in the informal residential construction industry in high-risk developing nations. Through collaborative research and proposed intervention in multiple stages of the Housing Market Value Chain (see Figure 1-1), this thesis will develop practical, evidence-based designs, frameworks, processes, and recommendations that seek to formalize the housing delivery process in the case study scenario, through the following objectives:

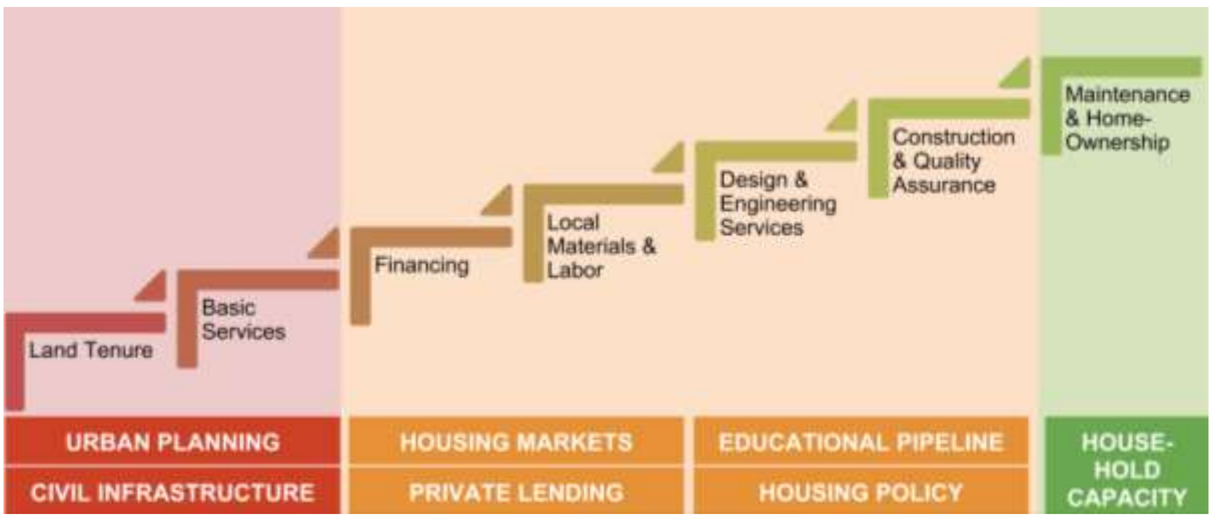


Figure 1-1: Housing Market Value Chain (Image Source: Kijewski-Correa 2012)

Objective 1: Inventory the common structural typologies available in the Léogâne case study context and compare the material cost of each to determine the most cost-effective typology for single-family homes.

In order to make cost-effective recommendations with regards to structural typology, one must comparatively assess the options available. This process will begin with a discussion of the common structural typologies available in the case study scenario and the advantages and disadvantages of each. A variety of structures, with a range of structural systems and superstructure elements, will be designed to the same standard architectural plan so that material quantity and cost estimates can be directly compared. The product of this objective will be a comprehensive comparison of construction material costs for common structural typologies in Léogâne. From this analysis, the preferred typology for the Haitian case study scenario, in terms of cost-effectiveness and seismic resilience, will be selected. This typology will then be further analyzed in the second objective.

Objective 2: Develop a procedure and the associated tools for designing, parametrically analyzing, evaluating, and ultimately selecting the best-fit structural design given a unique set of assessment criteria, and utilize this algorithm to define the best-fit structural designs for the case study scenario.

Once the completion of the first objective defines the most cost-effective structural typology for the case study scenario, this typology will undergo an exhaustive parametric analysis to determine the best structural design for the case study scenario. Again utilizing a standard architectural plan, hundreds of combinations of cross-sectional dimensions and reinforcement configurations will be designed, analyzed, and evaluated using a three-part scoring framework. A three-dimensional Pareto optimization will then be administered to define a set of optimal designs, and a categorical weighting process will be applied to select the final designs. The final products of this objective will be the selected designs themselves, as well as the design, analysis, and scoring procedures and tools used, which are generalizable and can be adapted for various applications. The seismic performance of the designs selected herein will then be assessed under the third objective.

Objective 3: Determine the expected performance level of the selected structures when subject to the characteristic seismic events of the Léogâne case study scenario.

After selecting the best-fit designs for the case study scenario, the expected performance level of the structure will be assessed via nonlinear static analysis. First, the structures will be modeled via two-dimensional lumped plasticity frames developed in SAP2000, utilizing the equivalent strut assumption to model masonry walls. Nonlinear hinges will be added to both the frame elements and the equivalent struts. The expected performance level of the frames will then be assessed due to the Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE) events via a nonlinear static analysis, also known as a pushover analysis, in SAP2000. The final product of this objective will be the expected performance levels of each of the frames in the DBE and MCE seismic events.

Objective 4: Propose an integrated implementation framework to mitigate and navigate the constraints of the Haitian housing sector and improve the sustainable delivery of resilient housing.

The structure designed and assessed via the previous objectives will remain an engineering concept, rather than be widely used by those in need of resilient housing in the developing world, without an integrated approach to implementing such a design. Thus, the goal of this objective is to analyze the factors which are likely to restrict the market-based implementation of the previously presented design and offer potential conceptual solutions and procedures to increase the feasibility and sustainability of implementation. First, the technical, economic, and political constraints of the Léogâne case study scenario will be presented and analyzed. Then, the housing delivery process will be discussed in the context of the seven-step Housing Market Value Chain (see Figure 1-1). Lastly, by engaging local stakeholders in Léogâne, potential implementation concepts and procedures will be proposed for each component of the Housing Market Value Chain. Combined, these proposals will form the final product of this objective: an integrated housing delivery framework which the author intends to be applied to create a lasting, positive impact on the sustainable development of housing in Haiti and other developing nations.

1.5 Thesis Outline

This introduction has defined informal residential construction in urban, high-risk developing regions, demonstrated the need for evidence-based research and development in this sector, and introduced Léogâne, Haiti as a case study scenario for further analysis. The following chapters will discuss the methodology and findings of investigations aimed at designing, selecting, evaluating, and implementing a structure specifically for the Haitian case study scenario. Chapter 2 introduces the common structural typologies of single-family homes in Léogâne and comparatively assesses the construction material cost of each to define the most cost-effective resilient typology. Chapter 3 then presents an exhaustive parametric analysis of the typology recommended in Chapter 2, which is used in conjunction with a Léogâne-specific scoring framework to define a pair of structural designs best-fit for the case study scenario. Chapter 4 describes the methodology and results of nonlinear static pushover analyses, which evaluate the seismic performance of the designs selected in Chapter 3. Recognizing that a structural design alone cannot effect sustainable change, Chapter 5 presents a detailed analysis of the contextual factors likely to hinder a market-driven uptake of the best-fit designs and proposes an integrated housing delivery framework. Lastly, Chapter 6 summarizes the contributions to the four research objectives and discusses directions for future work.

CHAPTER 2:

COMPARATIVE ASSESSMENT OF RELEVANT TYPOLOGIES

This chapter first provides an overview of the predominant structural typologies available in the case study scenario. Brief descriptions, advantages, and disadvantages are presented for unreinforced masonry, reinforced masonry, confined masonry, and masonry-infilled reinforced concrete frames. This is followed by a comparative assessment of material costs of the relevant typologies, including a detailed presentation of the selected architectural design, the nine combinations of structural system, foundation, cladding, and roof types considered, and the design and cost estimation process for each. The chapter concludes with a discussion of the results, limitations, and a quantification of the “cost of safety” for aspiring homeowners in the Haitian case study scenario.

2.1 Overview of Existing Typologies

The variety of economic, political, technical, environmental, and social constraints outlined in the previous chapter result in a masonry-dominated construction industry. In theory, these masonry structures can be defined as one of the following four typologies: unreinforced masonry (URM), reinforced masonry, confined masonry, and masonry-infilled reinforced concrete frame. These different typologies are distinguished by their columns and wall reinforcement (see Table 2-1). Columns can be sized and detailed to act as full axial, shear, and moment resisting elements (e.g., full columns in masonry-infilled frames) or to act as boundary elements for the masonry walls (e.g., tie columns in confined masonry). Likewise, masonry walls can be left completely unreinforced (e.g., cladding in masonry-infilled frames) or detailed with vertical reinforcement and grouting to increase stiffness and ductility (e.g., masonry shear wall in reinforced masonry structure). The following sections will briefly describe the defining characteristics, advantages, and disadvantages of the four masonry typologies mentioned above in the context of the Haitian case study scenario. For more detailed information regarding masonry construction practices, structural behavior, and failure mechanisms, refer to the referenced literature and Fink (2016).

TABLE 2-1: PRIMARY LOAD RESISTING SYSTEM CHARACTERISTICS FOR DIFFERENT MASONRY TYPOLOGIES

Typology	**Load-Bearing Walls**		**Column**		
	Unreinforced	Reinforced	None	Tie	Full
Unreinforced Masonry	●		●		
Reinforced Masonry		●	●		
Confied Masonry	●	●		●	
Infilled Frame					●

2.1.1 Unreinforced and Reinforced Masonry

Unreinforced masonry is one of the most prevalent building typologies in the developing world due to its low cost and simplicity. As seen in Figure 2-1, masonry blocks are stacked with a thin layer of mortar between each unit. The material of the masonry blocks is highly dependent on the region and are usually constructed of concrete (concrete masonry unit, CMU), clay (brick), stone, or earth (adobe). In the case study scenario, CMU makes up the vast majority of the masonry blocks used in construction. Furthermore, it has also been observed that it is common to fill the cells of the unreinforced CMU walls with concrete, a process known as grouting.

Figure 2-1: Unreinforced masonry residential structure in Quito, Ecuador (Image source: Fink 2016)

Unreinforced masonry can be used for any small to medium custom build with minimal, if any, required design detailing and can be constructed by unskilled to moderately skilled laborers using hand tools, eliminating the need for expensive equipment or professional services. The cost is further reduced by the lack of reinforcing steel. However, this low cost has significant tradeoffs, as masonry blocks perform poorly in tension (Taly 2001). Thus, unreinforced masonry structures have very little resistance to lateral loads. As a result, the American Society of Civil Engineers (ASCE 2016) does not allow ordinary plain masonry shear walls beyond Seismic Design Category B. For comparison, a single-family home in Léogâne, Haiti would require a structure to be designed for Seismic Design Category E.

Reinforced masonry externally appears similar to unreinforced masonry, but is different due to the presence of reinforcement (see Figure 2-2) and grouting. Horizontal reinforcement is used to strengthen bed joints between rows of masonry blocks, while vertical reinforcement provides tensile strength, significantly increasing the flexural capacity of the structure (Shing et al. 1990). Spaces within CMU blocks that contain reinforcement are then filled with grout to bond the reinforcement to the blocks. Like unreinforced masonry, reinforced masonry can be constructed with minimal professional equipment and services. However, proper steel detailing for high seismicity requires advanced structural engineering knowledge and careful quality control. For applications beyond Seismic Design Category C, masonry walls must be detailed as special reinforced masonry shear walls according to ASCE standards (ASCE 2016).

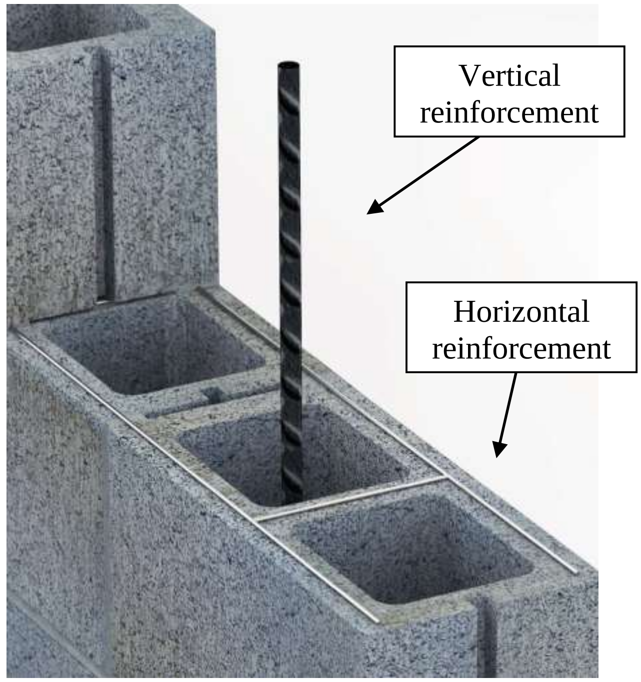


Figure 2-2: Horizontal and vertical steel reinforcement in a reinforced masonry wall (Image credit: John Maniatis)

Despite its poor performance in seismic events, unreinforced masonry is included in this study to define the baseline for calculating the “cost of safety.” On the other hand, reinforced masonry, which can be properly designed for seismic demands, is not included in this study. This is due to reinforced masonry’s critical reliance on the compressive strength of CMU blocks, which has been deemed insufficient to resist lateral loads in the case study scenario (Marshall et al. 2011; Mix et al. 2011).

2.1.2 Confined Masonry

Confined masonry is a hybrid typology that uses both load-bearing masonry and reinforced concrete frame elements. Masonry walls, generally unreinforced, are confined by small reinforced concrete elements, referred to as tie columns and tie beams. Although the gravity load is transferred through the load-bearing masonry wall, the confining elements are critical to resisting lateral loads and enable a strut-and-tie system. When lateral loads are applied, a diagonal compression strut forms in the masonry wall and the tie elements confine the masonry wall to prevent separation of masonry units (see Figure 2-5). To maximize their confining effects, engineers recommend that tie elements are placed on all sides of each wall, as well as bordering all windows and doors (CMN 2011). Furthermore, it is suggested that tie columns be "toothed" (see Figure 2-3) to ensure a strong bond with the masonry wall.

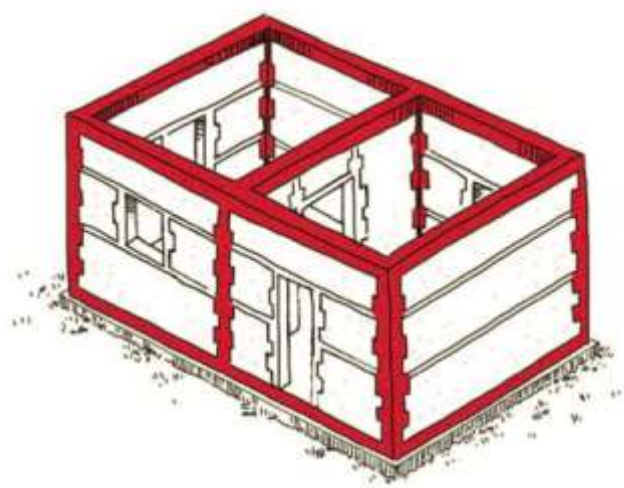


Figure 2-3: Confined masonry structure with proper tie columns, grade beam, and ring beam in red (Image source: SDC 2018)

Confined masonry is widely endorsed as the recommended building typology in developing regions prone to seismic activity. Researchers have found that well-executed confined masonry buildings have performed well in earthquakes (Salinas and Lazares 2008; Astroza et al. 2012) and the typology is recognized by several international building codes (Alcocer et al. 2003; AIS 2010). Furthermore, international organizations

(CMN 2011; Build Change 2011b; USAID 2014; Chourasia 2017; SDC 2018) have standardized and promoted confined masonry. Despite this, confined masonry is not a recognized lateral load resisting system in United States building codes (ASCE 2016). The following sections explore the advantages and disadvantages of confined masonry construction in the Haitian case study scenario.

2.1.2.1 Advantages of Confined Masonry

First and foremost, the growing body of literature on confined masonry construction indicate that confined masonry structures can withstand earthquake forces. A number of shake-table tests (Toranzo et al. 2009; Terán-Gilmore et al. 2009; Chourasia et al. 2016) and analytical studies (Riahi et al. 2009; Ruiz-García and Negrete 2009; Nguyen 2014) have been performed to increase the overall understanding of confined masonry behavior and the accuracy of numerical models. Similarly, numerous post-earthquake reconnaissance studies indicate that confined masonry structures have performed well after major events such as the 2010 Mw 8.8 Maule earthquake in Chile (Astroza et al. 2012) and the 2007 Mw 7.9 Pisco earthquake in Peru (Salinas and Lazares 2008). Such research has enabled the emergence of simplified confined masonry design guidelines (CMN 2011). Therefore, it is safe to conclude that confined masonry structures, when built correctly, can withstand strong ground shaking.

Confined masonry structures also have several important constructability advantages. First, they can be constructed incrementally. Because the walls are load-bearing, they are constructed first. Then, the walls act as key components of the formwork when concrete is poured for the tie beams and tie columns. This defining factor of confined masonry allows the home to be built slowly as funds for construction become available, contrary to an infilled frame (discussed in the following section), which requires that the frame be poured prior to the construction of the masonry infill walls. Using walls as formwork for tie columns and tie beams also cuts construction costs, as reduced amounts of shoring and wooden formwork are needed. Furthermore, this process, along with the reduced size of the tie elements, substantially reduces the volume of concrete that must be poured at once, a critical factor in rural and underdeveloped regions where concrete is often mixed by hand on site. Lastly, confined masonry may be viewed as a preexisting typology in the Haitian case study scenario, indicating that the local industry's contractors, supply chains, and labor markets are already prepared for confined masonry construction. Current and pre-quake construction practices resemble confined masonry construction (Mix et al. 2011), though with critical details at times lacking. This likely explains why it was a popular recommendation after the 2010 earthquake to formally promote the introduction of this specific structural typology (MTPTC 2010; MTPTC 2012; Build Change 2011a).

2.1.2.2 Disadvantages of Confined Masonry

Many of the abovementioned characteristics and advantages of confined masonry also present numerous disadvantages. The key role of the masonry walls in the lateral load resisting system raises concern, as the strength of CMU blocks in the case study scenario is often extremely low (Marshall et al. 2011; Mix et al. 2011; Build Change 2011a). Likewise, while building incrementally is a necessity for families without significant personal savings or access to housing finance, it is exceptionally difficult to maintain consistent quality control practices over a build that could last ten or more years. This is exacerbated by the large number of cold joints that are introduced to the home throughout the long construction process. Thus, the wide variety in materials and workmanship render an incrementally-constructed home highly vulnerable to natural hazards (Mix et al. 2011).

Another major disadvantage is the need for constant, overarching quality control. In order for the strut-and-tie lateral load resisting system to behave as designed, every individual component must be properly designed and constructed. The number, placement, size, and detailing of tie elements is critical to the performance of the structure and should follow recognized building codes (Alcocer et al. 2003; AIS 2010) and design guidelines (CMN 2011; USAID 2014; Chourasia 2017; SDC 2018).

Although the historical presence of confined masonry in the case study scenario indicates that the local industry (mainly, supply chains and labor markets) is able to build confined masonry homes, it also presents a problematic preexisting knowledge bias. After the 2010 Haiti earthquake, structural engineers noted that many collapsed buildings in the region appeared to partially follow confined masonry principles (Mix et al. 2011). Further study during reconstruction efforts revealed that many, including masons that had received training in proper confined masonry construction, were rebuilding in similar, insufficient ways (Mix et al. 2011). Furthermore, even studies that report positive performance of confined masonry acknowledge the vulnerability of "partially confined" masonry structures during earthquakes (Astroza et al. 2012). For example, unreinforced masonry walls were often bounded by tie columns, but those tie columns were often too few, too small, insufficiently reinforced, or not "toothed." Or, even if the wall itself was properly confined on its edges, an unconfined doorway or window could significantly weaken the wall, leading to premature collapse. Although international organizations have attempted to mitigate this risk through mason training (Build Change 2014) and construction guidelines (Build Change 2011b), these preexisting misconceptions and behaviors present a challenge for promoting proper confined masonry construction practices.

2.1.3 Masonry-infilled Reinforced Concrete Frame

The other commonly used earthquake-resistant typology which this study explores is the masonry-infilled reinforced concrete frame. At first glance, masonry-infilled reinforced concrete frames appear similar to confined masonry, but there are several key distinctions. First and foremost, the frame is both the main gravity and lateral load resisting systems, while the masonry infill's main purpose is to serve as an inexpensive and easily constructible cladding element. While the infill does contribute to the stiffness of the frame by forming a diagonal compression strut (see Section 3.1.3.4.3) when lateral loads are applied, the concrete frame is designed independently of the masonry infill and is poured prior to the construction of the walls (see Figures 2-4 and 2-5). Infilled frames are common in high-seismicity regions in developed nations and are heavily codified (ASCE 2016; CEN 2003). The following sections highlight some key advantages and disadvantages of masonry-infilled reinforced concrete frames in the case study scenario.

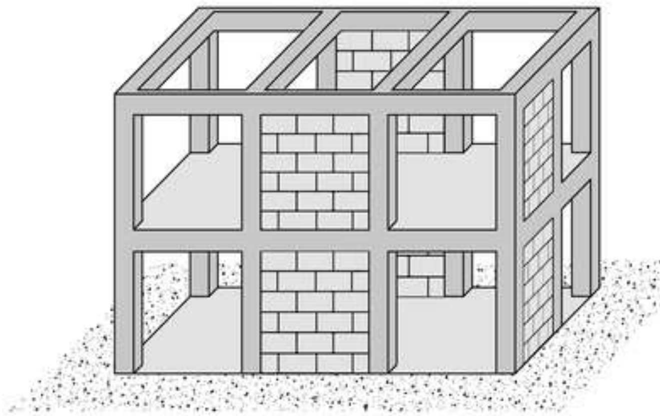


Figure 2-4: Masonry-infilled reinforced concrete frame (Image source: Openquake)

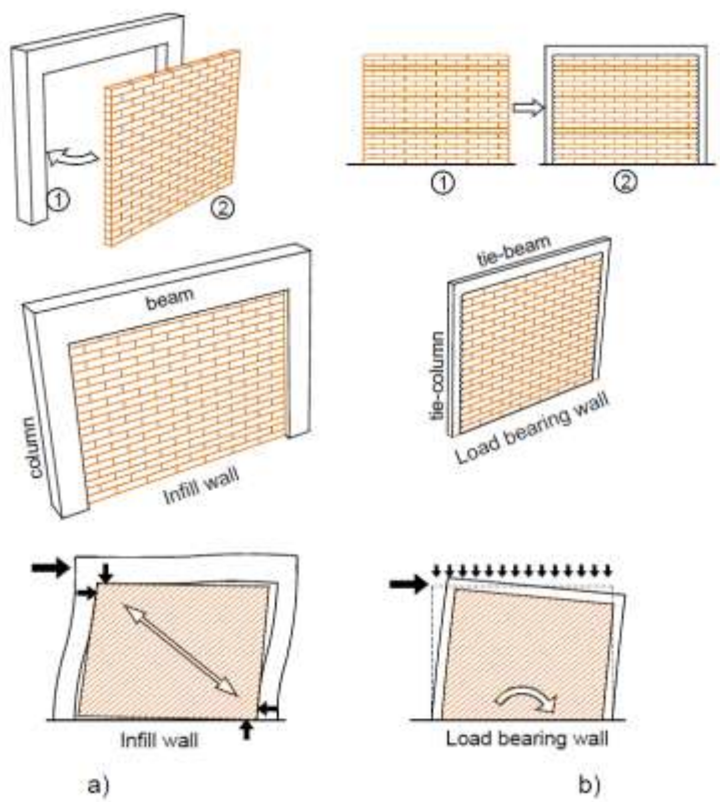


Figure 2-5: A comparison of reinforced concrete frames with masonry infills (a) and confined masonry (b): construction sequence (top), size of confining elements (middle), and seismic response (bottom) (Image source: CMN 2011)

2.1.3.1 Advantages of Masonry-infilled Reinforced Concrete Frame

The key advantages of a masonry-infilled reinforced concrete frame are seismic resiliency, a minimal reliance on masonry strength, and a concentrated period during construction where quality control is especially critical.

First and foremost, masonry-infilled reinforced concrete frames can resist strong earthquake forces. When detailed as a special (ductile) moment frame, this typology can be implemented without height limits in all Seismic Design Categories (ASCE 2016). In other words, building codes indicate that the reinforced concrete special moment frame is the safest concrete-based typology for high seismic regions.

Another key advantage is the lack of reliance on masonry block strength. Because the masonry is merely a cladding element, infilled frames are well suited for developing regions where CMU quality is low. Although stronger CMU blocks do increase the stiffness of the structure, the frame is designed such that the CMU infill is accounted for in its seismic mass, but not in the lateral load resisting system. In fact, the weaker block can be seen as an advantage, because it decreases the magnitude of the load transfer to the top and base of the column when the masonry compression strut fails during strong earthquake shaking. This phenomenon is explained in greater detail in Section 3.1.3.4.3.

Lastly, the critical quality control period during construction of a masonry-infilled reinforced concrete frame is significantly shorter than that of confined masonry. The two main critical components that need strong quality control in a masonry-infilled reinforced concrete frame are the steel rebar cages and the concrete mix. Because the rebar cages for the entire frame are assembled and connected prior to pouring concrete, the entire frame “skeleton” can be inspected at once. Likewise, the concrete frame should be poured in one day. While logistically challenging in a setting where concrete is mixed on site, this heavily concentrates the quality control processes needed to ensure sufficient concrete strength. Furthermore, frames minimize the need for future quality control during modification or additions. For example, windows, doors, and entire walls can be removed or added without significantly influencing the load resisting systems of the structure. This concentrated quality control period is especially advantageous in developing regions where structural engineering professionals and reliable third-party inspections are scarce.

2.1.3.2 Disadvantages of Masonry-infilled Reinforced Concrete Frame

Several defining elements of masonry-infilled reinforced concrete frames can present challenges in the case study scenario. First, much like confined masonry, if the column is undersized or not properly reinforced, load transfer from the wall could result in shear failure of the column. The other key disadvantages of masonry-infilled reinforced concrete frames are constructability issues. For example, while the foundation, frame, walls, and roof can be constructed at different times, masonry-infilled reinforced concrete frames cannot be constructed as incrementally as confined masonry. They also have higher equipment and labor costs, as they require formwork and shoring. While the quality control schedule is concentrated for frame construction, inspecting and verifying the entire frame rebar “skeleton” at once could prove intimidating to an unfamiliar practitioner. Lastly, as stated above, large concrete pours, although possible, are logistically difficult in underdeveloped areas.

2.1.3.3 Alternative Cladding: Concrete Panels

The use of concrete panels as an alternative to masonry infill is also included in this study. This alternative design option, shown in Figure 2-6, was developed in the past decade and is detailed fully in Mix (2013), Jensen (2016), and Fink et al. (2017), including conceptualization, experimental testing, and finite element modeling. The thin concrete panels are reinforced by mesh and supplemented by vertical ribs. Similar to masonry infill, these panels contribute to the lateral stiffness but significantly reduce the seismic mass of the structure (Jensen 2016). This design was influenced by the desire to minimize the risk of load transfer from masonry struts to columns, which was heavily observed after the 2010 Haiti earthquake (Mix et al. 2011). For a more detailed description of the design, analysis, and testing of these panels, see Mix (2013), Jensen (2016), and Fink et al. (2017).

Figure 2-6: Reinforced concrete special moment frame clad with
thin concrete panels (Image Source: Jensen 2016)

2.1.4 Spectrum of Masonry Typologies

The typologies described above (with the exception of frames cladded with concrete panels, of which only a few have been constructed) represent the vast majority of the building stock in residential construction in urban developing areas (Macabuag and Bhattacharya 2009). However, the lack of quality control, constrained budgets, and non-engineered designs often present in informal residential construction blur the lines between such typologies, resulting in a continuous spectrum of masonry typologies (see Figure 2-7) defined by variable amounts and sizes of confining elements.

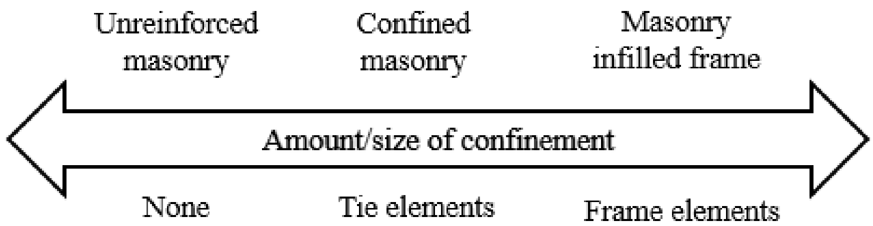


Figure 2-7: Spectrum of masonry typologies

Unreinforced masonry, which offers no tensile resistance and thus is not permitted above Seismic Design Category B (ASCE 2016), represents the lower end of this spectrum. At the other end of the spectrum are infilled frames, which, when designed as specially reinforced, can be implemented without height limits in all Seismic Design Categories (ASCE 2016). Confined masonry, which is defined by complex wall-frame interactions, falls between these two extremes. However, most informally constructed homes in the case study scenario not only fall somewhere between these two extremes, but also fall somewhere between the three typologies (Mix et al. 2011). For example, a confined masonry structure without sufficient (in number, placement, size, or reinforcement) tie columns will behave somewhere between an unreinforced masonry structure and a confined masonry structure. Contrarily, increasing the strength and ductility of the tie columns (by increasing dimensions and amount of reinforcement) could result in behavior more consistent with masonry-infilled frames.

Likewise, the presence of grouting and reinforcement (reinforced masonry) increases the stiffness of masonry walls. This further complicates the interaction between walls and columns by increasing the seismic mass and attracting more force to the walls, which is later transferred to the columns when the induced compression strut in the wall fails. Designing and modeling the interactions between masonry walls and tie elements is very complex (NIST 2014; Basha et al. 2020; Nguyen 2014) and is beyond the scope of this thesis. As described by Mix et al. (2011), such elements are often not sufficiently detailed, which proved deadly in the 2010 Haiti earthquake. This demonstrates the need for a single standardized and robust design solution to be defined and effectively communicated in the case study scenario.

2.1.5 Need for Further Analysis

Clearly, the fluid implementation of the spectrum of masonry typologies encourages the selection of a single, best-fit design solution. However, confined masonry and infilled frames each demonstrate unique advantages and disadvantages in the case study scenario. Furthermore, these characteristics can vary over time as a region's economy and construction industry develop. For example, the introduction of financing options, new construction technologies, or improved quality control methods could influence the selection of the recommended design. These dynamic factors are nearly impossible to quantify or predict. However, there is one factor that can accurately be calculated and compared: the relative material cost of each typology. Thus, a thorough economic analysis of the construction material cost of all relevant typologies is necessary and is presented in the following section.

2.2 Comparative Cost Analysis of Construction Materials

In order to determine the most cost-effective structural typology in the Haitian case study scenario, the material cost of structural typologies and elements prevalent in the case study scenario were estimated and compared. First, a standard architectural plan was selected. Next, nine different homes were designed to international standards and guidelines using a variety of structural systems, foundations, cladding types, and roof elements. The material cost of each was then estimated using pricing data sourced from the Haitian case study scenario. Lastly, the material costs were compared and the most cost-effective typology was determined.

2.2.1 Standard Architectural Plan

Through a years-long collaborative design process in Léogâne, E2E previously presented two-, three-, and four-room models (Mix 2013). A recent survey of 554 households in Léogâne found that the mean household size is five persons (Kijewski-Correa et al. 2019). Thus, the three-room model was selected for this case study because it is well suited for the average family in Haiti. This middle range model features three rooms measuring 4 m by 4 m and a front porch measuring 2 m by 4 m, thus totaling 56 m^2 (603 ft^2) of livable space. For this comparative assessment, a bathroom was also added to reflect the most realistic home desired by a Haitian family. Figure 2-8 displays this general floorplan. The height of the walls and columns was taken as 2.5 m (8 ft 2 in).

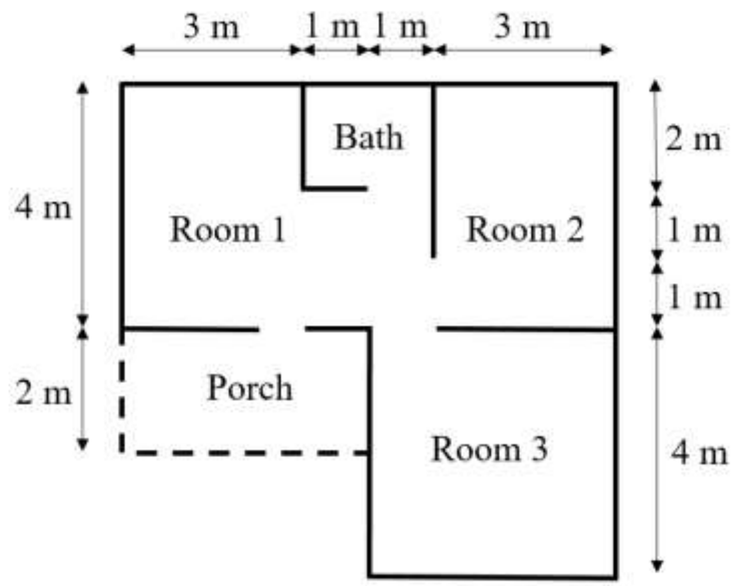


Figure 2-8: Standard architectural plan used in comparative assessment

2.2.2 Material Properties

Material properties for concrete and steel used in design calculations were sourced from US and international codes based on the properties of commonly available materials in Haiti. The design compressive strength (f'_c) for concrete was assumed to be 3,000 psi (20.7 MPa) (E2E 2016), which is slightly higher than Build Change's conservatively suggested strength of 2,500 psi for the case study scenario (2011a). However, Build Change also acknowledges that the "mix proportions specified may provide higher actual strength" (2011a). Thus, with an appropriate amount of quality control oversight (see Chapter 5), it is reasonable to assume that a compressive strength of 3,000 psi can be achieved in the case study scenario. Normal weight concrete was assumed (λ=1), with a density of 154 lb/ft^3 (24 kN/m^3). The modulus of elasticity was calculated via ACI-318 (2014a) as 3,122 ksi (21,525 MPa). All reinforcing steel was taken to be grade 60 (which is widely available in Haiti), with a yield strength of 60 ksi (413 MPa) and modulus of elasticity of 29,000 ksi (19,995 MPa). Tables 2-2 and 2-3 restate these material properties.

TABLE 2-2: MATERIAL PROPERTIES OF CONCRETE

Property	**Value**	**Units**
Design compressive strength (f'_c)	3,000 (20.7)	psi (MPa)
Density	154 (24)	lb/ft^3 (kN/m^3)
Modulus of elasticity	3,122 (21,525)	ksi (MPa)

TABLE 2-3: MATERIAL PROPERTIES OF STEEL

Property	**Value**	**Units**
Yield strength	60 (413)	ksi (MPa)
Modulus of elasticity	29,000 (19,995)	ksi (MPa)

Properties for masonry blocks and walls were sourced from Build Change's *Calculation Report for Confined Masonry Housing in Haiti* (2011a). Because of the wide range of CMU quality available in Haiti (Mix et al. 2011; Marshall et al. 2011), Build Change presents a low, medium, and high value for CMU compressive strength (f'_b), masonry compressive strength (f'_m), and modulus of elasticity of masonry. The lowest of these were conservatively assumed. Respectively, these selected properties are 700 psi

(4.8 MPa), 560 psi (3.86 MPa), and 392 ksi (2,700 MPa). CMU blocks in Haiti are typically 40 cm long and 20 cm tall, with widths of 10, 15, or 20 cm. The seismic mass of the wall was calculated based on the density of unreinforced masonry constructed from 15 cm CMU units, which Build Change (2011a) states is 47 lb/ft^2 (2.25 kN/m^2). The mortar was assumed to be Type M with a compressive strength of 2,500 psi (17 MPa). Table 2-4 restates these material properties.

TABLE 2-4: MATERIAL PROPERTIES OF CMU MASONRY

Property	**Value**	**Units**
Compressive strength of CMU block (f'_b)	700 (4.8)	psi (MPa)
Compressive strength of masonry (f'_m)	560 (3.86)	psi (MPa)
Modulus of elasticity of masonry (E_m)	392 (2,700)	ksi (MPa)
Density of infill wall	47 (2.25)	lb/ft^2 (kN/m^2)
Mortar Type M compressive strength (f'_j)	2,500 (17)	psi (MPa)

2.2.3 Unit Costs

Unit pricing for the necessary construction materials was obtained from local vendors to ensure accuracy throughout the design and cost estimating process. In March 2019, E2E staff engineer Gede Jean Benoit surveyed five vendors throughout Léogâne, Haiti and noted the prices of rebar, gravel, sand, cement, and masonry blocks. The unit price of concrete was calculated using a 3:2:1 volumetric ratio for gravel, sand, and cement, respectively. The unit price of mortar was calculated using a 5:1 sand to cement volumetric ratio. Lastly, the unit price of stucco finishing was calculated using a 4:1 sand to cement volumetric ratio. Table 2-5 presents these unit costs.

The abovementioned unit prices are based on a March 2019 exchange rate of US$1.00 per 82.3 Haitian Gourde (HTG) (Oanda 2019). It is important to note that this exchange rate has been highly volatile over the past five years (increasing to US$1.00 per 99.1 HTG by February 2020) and is subject to change in the future (Oanda 2020). Although price fluctuations are inevitable and the final construction material costs for each home presented in the next section are likely to change, the purpose of this study is to compare the material costs of various designs. Thus, it is reasonable to assume that such fluctuations will not significantly affect the conclusions of this comparative analysis.

Pricing for other materials used to construct the concrete panels and CGI roofing were taken from previous E2E estimates completed in 2017. These unit costs are also included in Table 2-5. When calculating concrete, mortar, and stucco material quantity estimates, the volumes presented in Tables 2-6 through 2-16 were increased by 10% from the calculated volumes of the elements to simulate realistic material use conditions (i.e., some material is unavoidably wasted during construction).

TABLE 2-5: UNIT COSTS OF CONSTRUCTION MATERIALS IN LÉOGÂNE, HAITI

Material	Units	Unit Cost (USD)	Year Price Sourced
Concrete	m3	$98.75	2019
Mortar	m3	$111.50	2019
Stucco	m3	$123.55	2019
Cement	bag	$6.69	2019
Sand	m3	$10.60	2019
Gravel	m3	$14.22	2019
Water	gal	$0.24	2019
#2 Rebar	bar	$1.32	2019
#3 Rebar	bar	$4.25	2019
#4 Rebar	bar	$7.29	2019
10cm block	block	$0.34	2019
15cm block	block	$0.41	2019
20cm block	block	$0.67	2019
Wire mesh	sheet	$8.00	2017
PVC 1"	ft	$0.15	2017
Anchor Bolts (1/2" x 5 1/2")	unit	$0.50	2017
Large Trusses	unit	$68.91	2017
Small Truss	unit	$37.50	2017
Purlins (HSS 1" x 2" X 1/8")	bar	$10.00	2017
Angle L top brace (3/4" x 3/4" x 1/16")	bar	$8.00	2017
Roof sheeting	ft	$3.00	2017
Nails	box	$60.00	2017
Wood 1" x 2" x 16' (Eaves)	unit	$6.00	2017
Plywood	unit	$40.00	2017

2.2.4 Design of Structures and Components

In total, nine different structures were designed with a variety of structural typology, roof, foundation, and cladding combinations. This section summarizes the prerequisites the typologies or components were required to meet for inclusion in this analysis, outlines the design procedure of each structure and component, and presents the material cost estimate for each structure and component.

2.2.4.1 Prerequisites for Consideration

In order to promote a locally sustainable solution, the structures were limited to concrete and masonry typologies, as these are the primary building materials available in the case study scenario as discussed earlier. Cultural preferences, security concerns (Mix et al. 2011), and widespread deforestation (Williams 2011) all contribute to the popularity of masonry and concrete in urban Haiti. This restriction ensures that the materials and skills needed to build the proposed solution already exist in the case study scenario. These criteria led to the three main structural typologies, two cladding types, four foundations, and two roof types presented in the following sections.

2.2.4.2 Main Structural Typology

Three typologies were considered in this study and are described below in the following order: unreinforced masonry, confined masonry, and reinforced concrete frame.

2.2.4.2.1 Unreinforced Masonry

Unreinforced masonry was included in this study to define the baseline from which the "cost of safety" can be determined. This structure was not structurally designed or analyzed and is not expected to withstand significant lateral loads. The wall area of the standard architectural design was calculated, and the number of blocks needed was estimated by assuming the use of 15 cm (width) x 20 cm (height) x 40 cm (length) blocks. As described in Section 2.1.1, the cells in the CMU of the unreinforced masonry wall were assumed to be filled with concrete to be consistent with the current construction practices in the Haitian case study scenario. A 2 cm stucco finish was included on both the interior and exterior walls. Table 2-6 displays the material cost estimate for the URM structure.

TABLE 2-6: MAIN STRUCTURE MATERIAL ESTIMATE – UNREINFORCED MASONRY

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Walls	Block (15x20x40)	1250	block	$0.41	$512.50	$2,056.30
	Concrete fill	5.01	m^3	$98.75	$464.24	
	Mortar	4.54	m^3	$111.50	$505.94	
	Stucco	4.40	m^3	$123.55	$543.62	
Unreinforced masonry total material estimate:						**$2,056.30**

2.2.4.2.2 Confined Masonry

Next, a confined masonry home was designed using the standard architectural layout presented in Figure 2-8 according to the Confined Masonry Network's *Seismic Design Guide for Low-Rise Confined Masonry Buildings* (2011). Similar to unreinforced masonry, 15 cm (width) x 20 cm (height) x 40 cm (length) blocks, which are standard in Haiti and suggested by the Confined Masonry Network (2011), were assumed. The number of blocks required was reduced from the unreinforced masonry estimate to account for the space filled by the tie columns. Likewise, the cells in the CMU of the unreinforced masonry wall were assumed to be filled with concrete to be consistent with the current construction practices in the Haitian case study scenario. Tie columns measuring the same width as the masonry walls (15 cm x 15 cm) were added at a maximum spacing of four meters. These tie columns were reinforced with four #3 longitudinal bars with stirrups (#2) spaced every 10 cm. To properly confine the top of the walls and increase diaphragm action, a ring beam (15 cm x 30 cm) reinforced with four #3 longitudinal bars and #2 stirrups spaced every 10 cm was also included. Lastly, in order to maintain consistency with the standard architectural plan, two reinforced concrete columns (25 cm x 25 cm) were added to support the roof over the porch. Figure 2-9 illustrates the layout of these element.

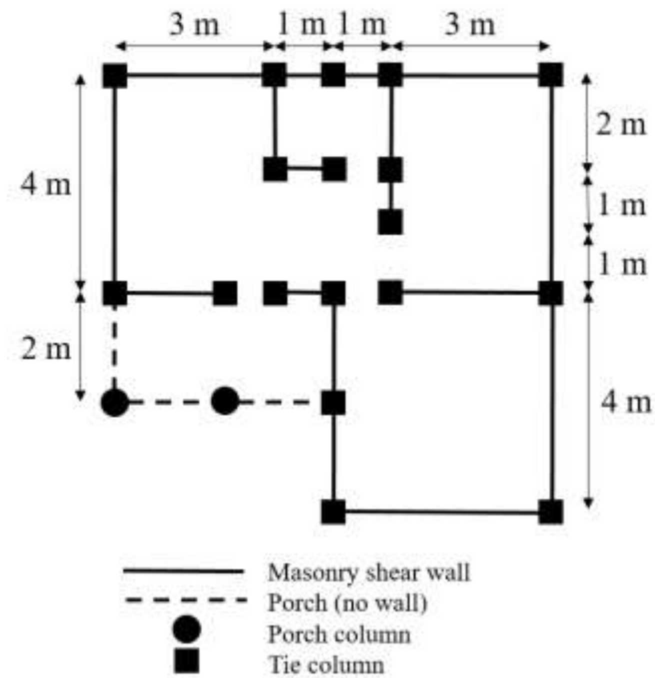


Figure 2-9: Confined masonry wall and tie column layout

This confined masonry home was then checked according to the Simplified Method for Wall Density Calculation in Low-Rise Buildings in the Confined Masonry Network's *Seismic Design Guide for Low-Rise Confined Masonry Buildings* (2011). Appendix A of the aforementioned guide (CMN 2011) details this process with two examples. In summary, the wall density in both the x- and y-axis must surpass a minimum density. Wall density, $d_{x,y}$, is defined as:

$$d_{x,y} = \frac{A_{W_{x,y}}}{A_P} \tag{2.1}$$

where A_W is equal to the cross-sectional area of all walls in a single direction and A_P is the area of the enclosed building floor plan (48m^2). It is important to note that A_W includes both interior and exterior walls. The thickness of the walls used to define A_W was taken as 15 cm, the width of the masonry blocks, conservatively excluding the assumed 2 cm stucco finish on both sides of each wall. Table 2-7 presents the calculated cross-sectional area, A_W, and the wall density, d, in both the x- and y-axis.

TABLE 2-7: CROSS-SECTIONAL WALL AREA AND DENSITY

	X-Axis	**Y-Axis**
Cross-sectional wall area, A_W (m^2)	2.85	3.15
Wall density, $d_{x,y}$ (%)	5.94	6.56

The Confined Masonry Network (2011) also recommends minimums for wall density. These minimums, which apply to both the x- and y-axis, are determined by the following equation:

$$d \geq \frac{F_S\, c\, w\, n}{v} \tag{2.2}$$

where F_S is equal to the factor of safety (F_S = 1.6), c is equal to the seismic coefficient, w is equal to the weight per unit area of the structure, n is equal to the number of stories (n = 1), and v is equal to the masonry shear strength.

The seismic coefficient, c, was calculated by the following equation:

$$c = \frac{I\ K_T\ S}{R}\ a_0 \tag{2.3}$$

where I is defined as the building importance factor (I = 1.0 for residential buildings), K_T is the dynamic amplification factor (K_T = 2.5 for structures with fundamental periods less than 0.4 seconds), S is equal to the soil amplification factor (conservatively assumed to be 1.4 for soft clay conditions), R is equal to the response reduction factor (R = 3 for hollow masonry units), and a_o is equal to the peak ground acceleration [a_o = 0.6 g for Léogâne, Haiti (Build Change 2011a)].

The weight per unit area of the structure, w, was calculated by summing the mass of the walls and roof (488 kN) and dividing by the floor area (48 m^2) of the structure. The roof was assumed to be a 20 cm concrete slab, which is typical in the Haitian case study scenario. The weight per unit area was calculated to be 10.17 kPa.

The masonry shear strength, v, was calculated using the following equation:

$$v = 0.5v_m + 0.3\sigma\ \leq 1.5v_m \tag{2.4}$$

where σ is equal to the average compressive stress and v_m is equal to the basic masonry shear strength (without considering axial load). The average compressive stress, σ, was calculated by summing the weight of the walls and roof (488kN) and dividing by the assumed wall area (6 m^2). The basic masonry shear strength, v_m, was calculated using the following equation, taken from Build Change (2011a) for the estimation of masonry shear strength when diagonal compression test results are not available:

$$v_m = 0.25\sqrt{0.55f'm} \tag{2.5}$$

where f'm (3.86 MPa) is the compressive strength of the masonry prism. The basic masonry shear strength was calculated to be 0.36 MPa. Thus, the adjusted masonry shear strength, calculated via Equation 2.4, was calculated to be 0.204 MPa.

Subsequently inputting these values into Equations 2.3 and 2.2 results in a recommended minimum wall density of 5.6%, which is less than the calculated densities for d_x (5.94%) and d_y (6.56%) presented in Table 2-7. Thus, the design presented in Figure 2-9 is viable. The material cost estimate of the home described above is detailed in Table 2-8.

TABLE 2-8: MAIN STRUCTURE MATERIAL ESTIMATE – CONFINED MASONRY

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Tie columns	Concrete	1.1	m^3	$98.75	$108.62	$290.98
	#2 Rebar (20’)	48	bar	$1.32	$63.36	
	#3 Rebar (30’)	28	bar	$4.25	$119.00	
Walls	Block (15x20x40)	1166	block	$0.41	$478.06	$1,917.95
	Concrete fill	4.67	m^3	$98.75	$461.03	
	Mortar	4.23	m^3	$111.50	$471.94	
	Stucco	4.10	m^3	$123.55	$506.92	
Ring beam	Concrete	1.65	m^3	$98.75	$162.94	$375.44
	#3 Rebar (30’)	50	bar	$4.25	$212.50	
Porch Columns	Concrete	0.34	m^3	$98.75	$33.67	$118.08
	#3 Rebar (30’)	13	bar	$4.25	$55.25	
	#4 Rebar (30’)	4	bar	$7.29	$29.16	
Confined masonry total material estimate:						**$2,702.46**

2.2.4.2.3 Reinforced Concrete Frame

The reinforced concrete frame used in this study was previously designed and analyzed as a special moment frame by E2E (Mix 2013; E2E 2016; Jensen 2016; Fink et al. 2017). The columns (25 cm x 25 cm) were reinforced with four #4 and four #3 longitudinal bars. The beams (25 cm x 30 cm) were reinforced with three #3 longitudinal bars at both the top and bottom. Both beams and columns were tied with #3 lateral ties with variable spacing based on special moment frame minimums. Figure 2-10 shows the location of beams and columns in this frame, and Table 2-9 displays the corresponding material and cost estimates. For more information on this design, see the *Engineering2Empower Model Home Peer Review Report* (2016). It is important to note that unlike the previous unreinforced masonry and confined masonry sections, the reinforced concrete frame material estimate does not include cladding. Cladding estimates are calculated in a later section.

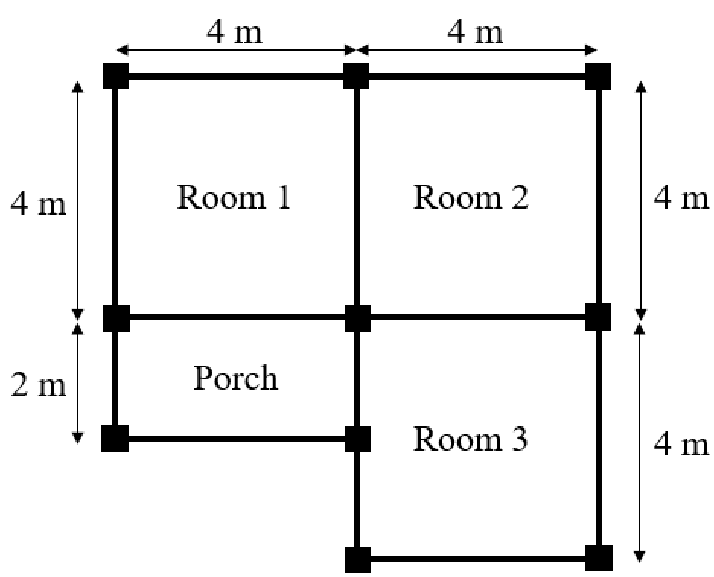


Figure 2-10: Beam and column layout of the reinforced concrete frame

TABLE 2-9: MAIN STRUCTURE MATERIAL ESTIMATE – REINFORCED CONCRETE FRAME

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Columns	Concrete	1.76	m^3	$98.75	$173.80	$558.19
	#3 Rebar (30')	63	bar	$4.25	$267.75	
	#4 Rebar (30')	16	bar	$7.29	$116.64	
Ring beam	Concrete	3.96	m^3	$98.75	$391.05	$782.05
	#3 Rebar (30')	92	bar	$4.25	$391.00	
Infilled frame total material estimate:						**$1,340.24**

2.2.4.3 Foundation

Considering the aforementioned prerequisites, four different concrete and masonry foundations were designed and estimated. These are described below in the following order: slab on grade, strip footing, raft, and footing and beam.

2.2.4.3.1 Slab on Grade

The simplest foundation considered was a slab on grade. Similar to unreinforced masonry, this foundation was included in this study to serve as the baseline from which the "cost of safety" can be evaluated. No design calculations were completed for the concrete slab design, it was simply assumed to be unreinforced and 10 cm thick, as suggested by the Confined Masonry Network (2011).

TABLE 2-10: FOUNDATION MATERIAL ESTIMATE – SLAB ON GRADE

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Floor Slab	Concrete	6.16	m^3	$98.75	$608.30	$608.30
Slab on grade total material estimate:						**$608.30**

2.2.4.3.2 Strip Footing

The strip footing used in this study was previously designed by Build Change (2011b). Figure 2-11 illustrates the cross-section utilized, while Figure 2-12 details the plan view. The footing features a grade beam (also referred to as a plinth beam) reinforced with four longitudinal #3 bars and a #2 lateral tie every 10 cm. Between the columns and below the grade beam lies a 60 cm unreinforced masonry wall resting on a 50 cm by 30 cm unreinforced concrete footing. Table 2-11 itemizes the material cost estimate.

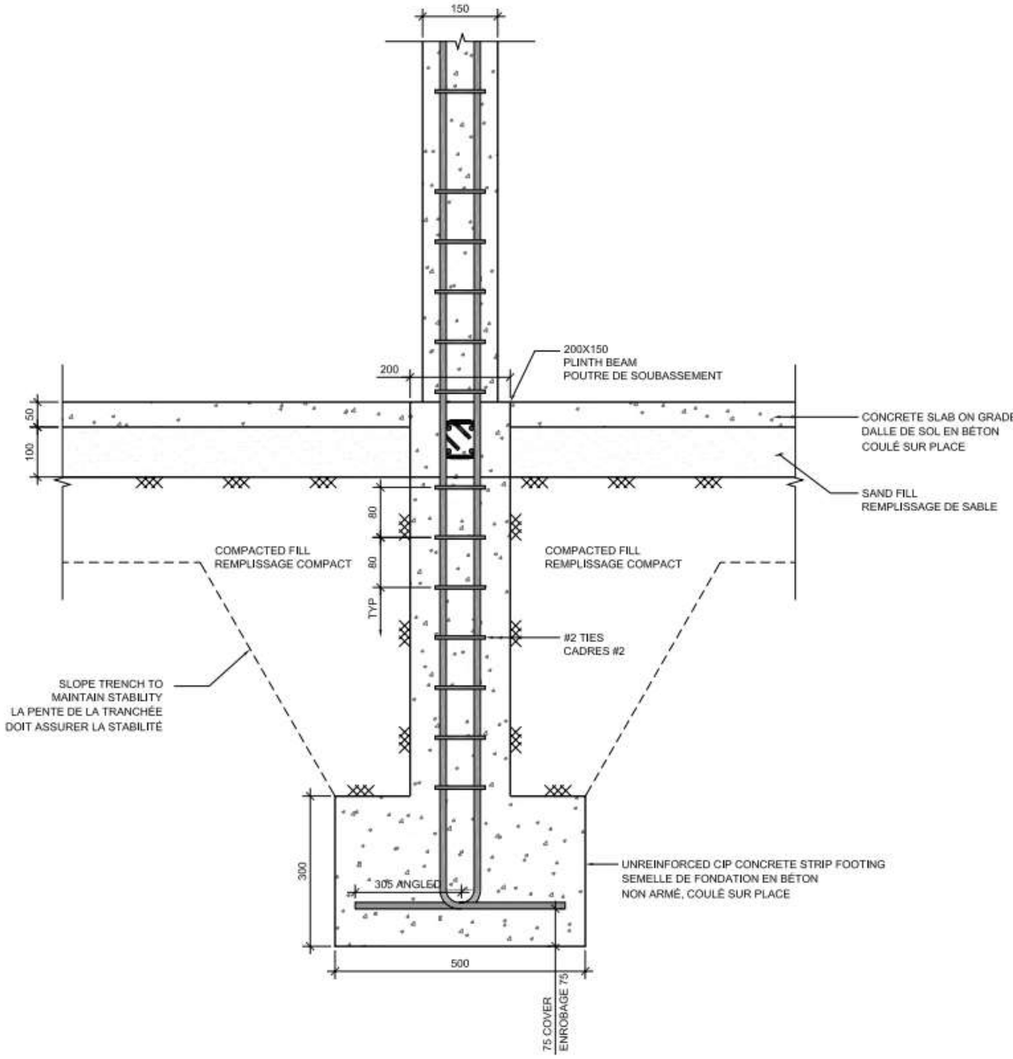


Figure 2-11: Cross-section of strip footing at interior column
(Image source: Build Change 2011b)

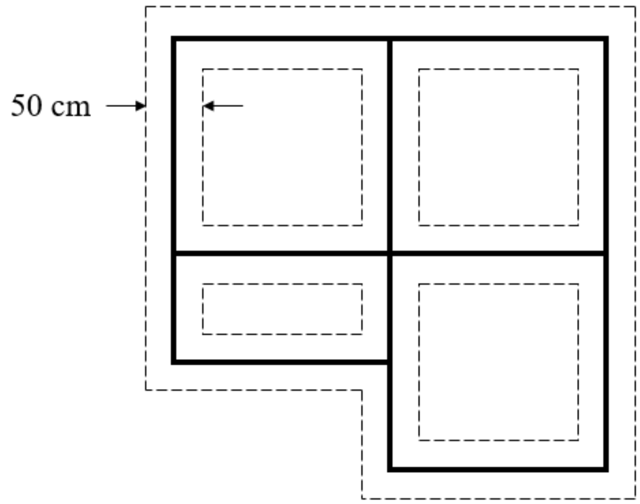


Figure 2-12: Strip footing plan view

TABLE 2-11: FOUNDATION MATERIAL ESTIMATE – STRIP FOOTING

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Floor Slab	Concrete	5.6	m^3	$98.75	$553.00	$553.00
Strip Footings	Concrete	6.9	m^3	$98.75	$681.37	$1,188.57
	Block (20x20x40)	345	block	$0.67	$231.15	
	Concrete fill	1.38	m^3	$98.75	$136.41	
	Mortar	1.25	m^3	$111.50	$139.64	
Plinth Beam	Concrete	2.3	m^3	$98.75	$227.12	$443.87
	#3 Rebar (30’)	51	bar	$4.25	$216.75	
Strip footing total material estimate:						**$2,185.45**

2.2.4.3.3 Raft

The raft foundation (also known as “beam and slab raft” or “mat” foundation) was designed according to Varghese’s *Design of Reinforced Concrete Foundations* (2009). This foundation consists of a 20 cm reinforced slab with downstanding (below the slab in the ground) beams underneath major loadbearing walls and connecting column bases (see Figure 2-13). In addition, a 10 cm cantilevered apron slab extends 50 cm beyond the exterior downstanding beams to further reduce bearing pressure under load bearing elements (see Figure 2-14). The raft slab was reinforced with #3 rebar spaced every 15cm at the top and bottom. Each downturned beam is 15 cm wide and 30 cm deep and reinforced with a #4 bar in each corner.

Temperature and shrinkage reinforcement was not included in order to be consistent with the unreinforced slabs presented in the aforementioned slab on grade, strip footing, and footing and beam foundations. Likewise, it is important to note that the guidelines and examples followed for this design process were geared towards large, multi-story construction projects. Thus, further optimization is suggested for this application. For more information, see Example 12.1 in Varghese’s *Design of Reinforced Concrete Foundations* (2009). Table 2-12 itemizes the material cost estimate for the raft foundation.

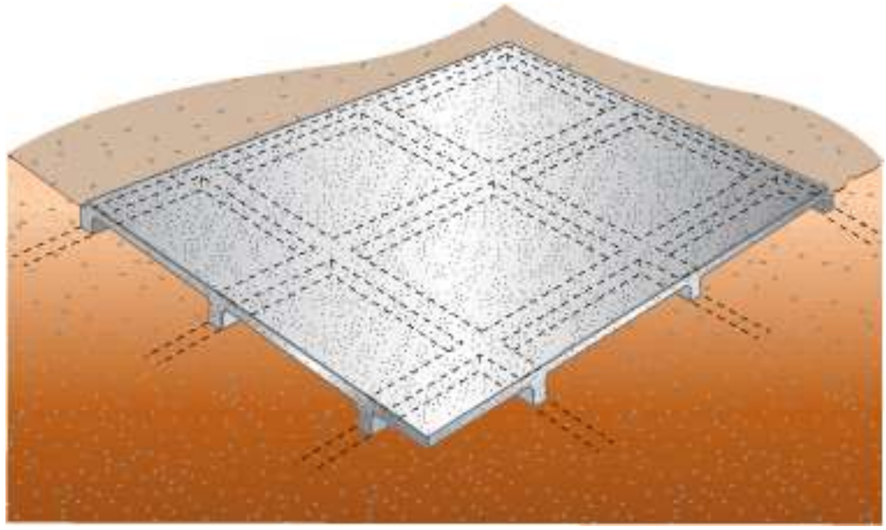


Figure 2-13: Raft slab with downstanding beams (Image credit: Build Right)

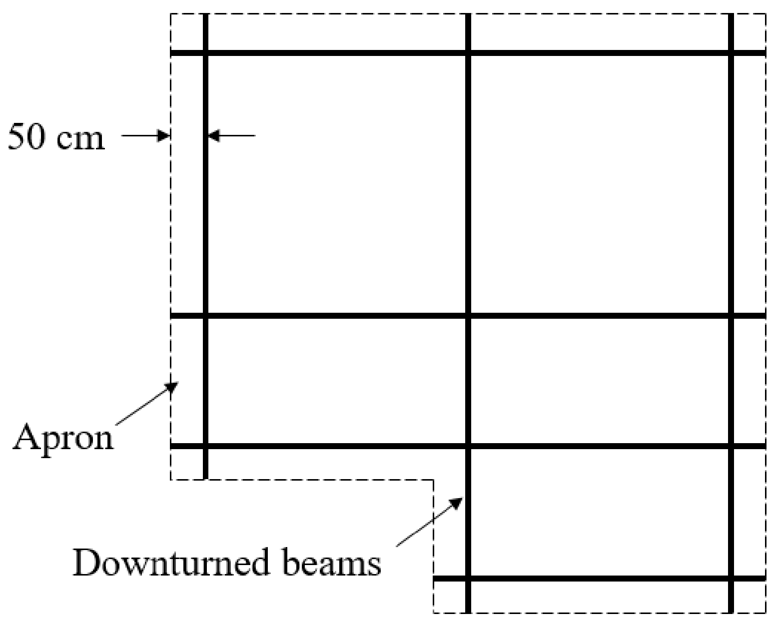


Figure 2-14: Plan view of raft foundation

TABLE 2-12 FOUNDATION MATERIAL ESTIMATE – RAFT

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Raft slab	Concrete	14.19	m^3	$98.75	$1,401.26	$1,898.51
	#3 Rebar (30’)	117	bar	$4.25	$497.25	
Subraft beams	Concrete	2.86	m^3	$98.75	$282.42	$631.04
	#3 Rebar (30’)	34	bar	$4.25	$144.50	
	#4 Rebar (30’)	28	bar	$7.29	$204.12	
Raft total material estimate:						**$2,529.55**

2.2.4.3.4 Footing and Beam

The footing and beam foundation used in this study was previously designed by Engineering2Empower (2016). The grade beams run along each framing line in the x- and y-axis and distribute lateral loads across the structure. Similarly, a footing is placed under each column to distribute gravity load to the soil. Figure 2-15 shows this layout, and Figure 2-16 displays a rendering of a comparable foundation for a slightly larger home. Each grade beam is 25 cm wide and 30 cm deep and detailed as shown in Figure 2-17. The square footings are each 60 cm wide and 20 cm deep and reinforced as shown in Figure 2-17. While the detail in Figure 2-17 includes the base of the column, the material cost estimate presented in Table 2-13 only includes the concrete and rebar needed for the footings and grade beams. For more information on this foundation, see the *Engineering2Empower Model Home Peer Review Report* (2016).

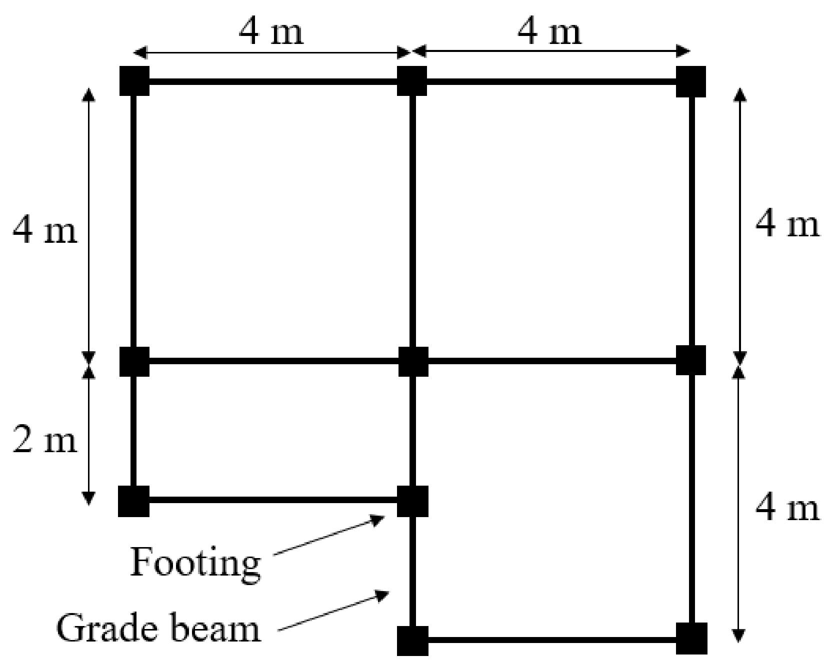


Figure 2-15: Layout of footing and beam foundation for case study three-room home

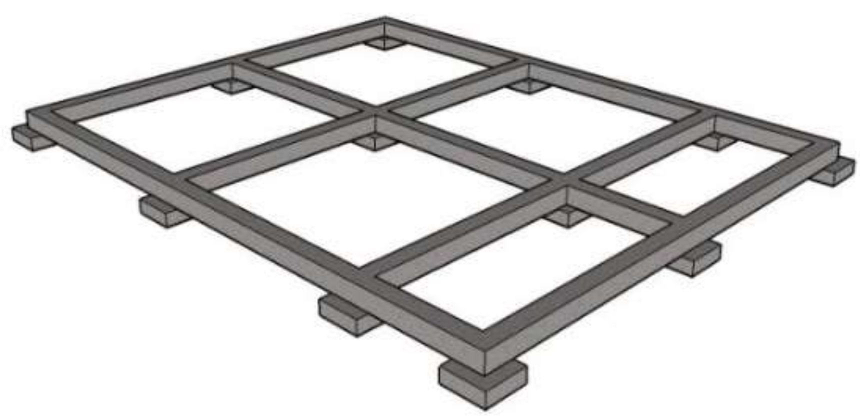


Figure 2-16: Footing and beam foundation of a similar four-room house (Image source: E2E 2016)

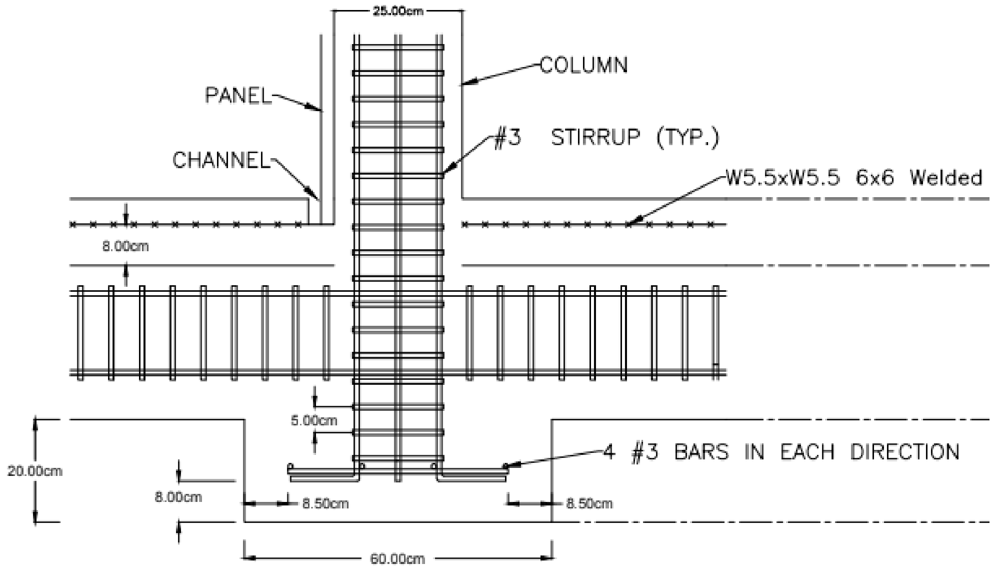


Figure 2-17: Footing and grade beam cross-section and detailing
(Image credit: E2E)

TABLE 2-13: FOUNDATION MATERIAL ESTIMATE – FOOTING AND BEAM

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Footings	Concrete	0.79	m^3	$98.75	$78.21	$99.46
	#3 Rebar (30’)	5	bar	$4.25	$21.25	
Grade beams	Concrete	3.96	m^3	$98.75	$391.05	$820.30
	#3 Rebar (30’)	101	bar	$4.25	$429.25	
Floor slab	Concrete	6.16	m^3	$98.75	$608.30	$608.30
Footing and beam total material estimate:						**$1,528.06**

2.2.4.4 Cladding

Two cladding types were considered to enclose the reinforced concrete special moment frame presented previously: masonry and concrete panels. These are respectively described in the subsequent sections.

2.2.4.4.1 Masonry

The first cladding type considered was a CMU masonry infill. The number of blocks required was reduced from the unreinforced masonry estimate to account for the space filled by the columns. To be consistent with the most common existing practices in Haiti, 15 cm width CMU blocks were used in this study. However, it should be noted that 10 cm wide blocks could be used to minimize the weight and cost of the infill wall, as the thinner blocks not only cost less, but also require less mortar. A #3 vertical bar was added every 50 to 67 cm to mitigate out of plane failure. Lastly, a 2 cm stucco finish was again included on both the interior and exterior walls. Table 2-14 presents the material cost estimate for the CMU masonry walls.

TABLE 2-14: CLADDING MATERIAL ESTIMATE – CMU MASONRY INFILL

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Walls	Block (15x20x40)	1166	block	$0.41	$478.06	$1,355.96
	Mortar	2.79	m^3	$111.50	$311.48	
	#3 Rebar (30’)	14	bar	$4.25	$59.50	
	Stucco	4.10	m^3	$123.55	$506.92	
Infilled frame total material estimate:						**$1,355.96**

2.2.4.4.2 Concrete Panels

The concrete panels used in this study were previously designed by E2E. Introduced in Section 2.1.3.3, these panels (see Figure 2-18) are fully described in Jensen (2016). The vertical ribs are reinforced with a #2 bar to increase out of plane stiffness, and a steel mesh provides ductility to the panel itself (see Figure 2-19). These panels are then bolted to the structure, and a mesh lath backing is placed across the ribs and finished with stucco to provide a smooth interior wall. Table 2-15 presents the material cost estimate to clad the case study architectural design with concrete panels, including finishing costs.

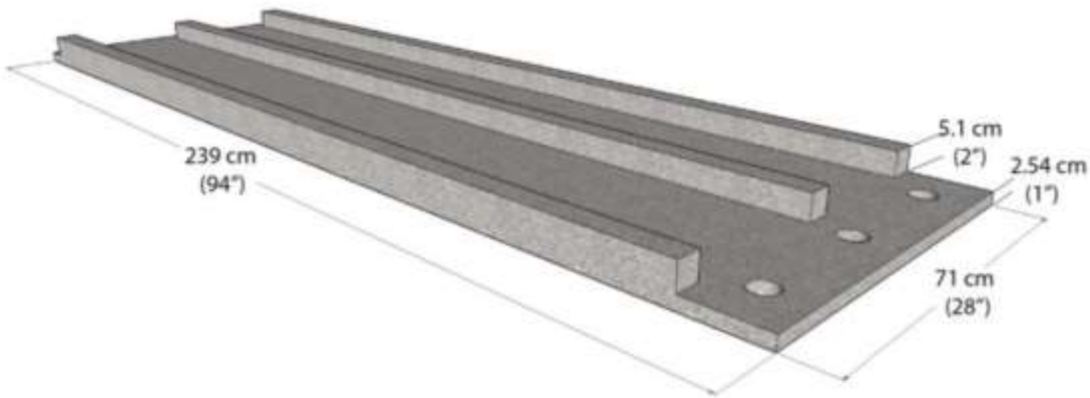


Figure 2-18: Dimensions of a ribbed concrete panel (Image source: Jensen 2016)

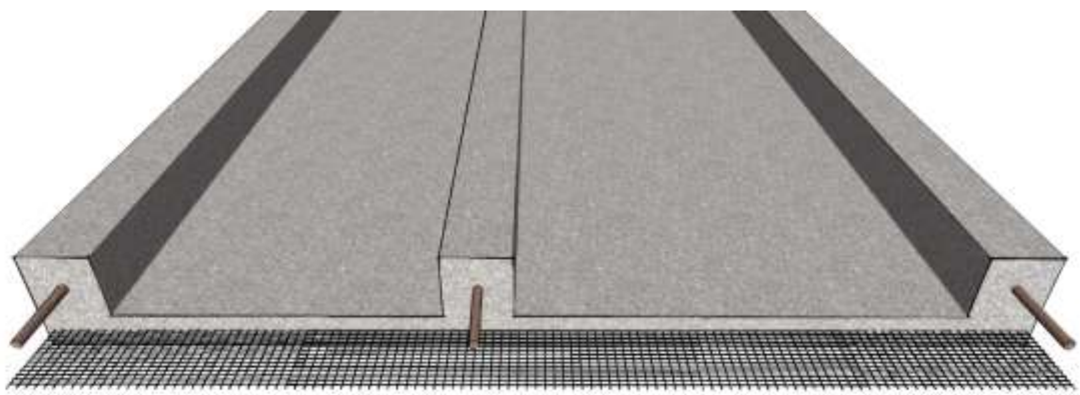


Figure 2-19: Cross-section of a ribbed concrete panel (Image source: Jensen 2016)

TABLE 2-15: CLADDING MATERIAL ESTIMATE – CONCRETE PANELS

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Panel walls	Concrete	2.67	m^3	$98.75	$263.66	$719.68
	Wire mesh	42	sheet	$8.00	$336.00	
	#2 Rebar (20')	42	bar	$1.32	$55.44	
	PVC 1"	10.5	ft	$0.15	$1.58	
	Anchor Bolts (1/2" x 5 1/2")	126	unit	$0.50	$63.00	
Wall finishing	Studded Walls	6.48	lin m.	$107.03	$693.55	$1,625.63
	Stucco	3.74	m^3	$123.55	$462.08	
	Mesh Lath Backing	47	sheet	$10.00	$470.00	
Paneled frame total material estimate:						**$2,345.31**

2.2.4.5 Roof

Two different roof types were designed for the standard architectural plan based on the prevalent roof types in the Haitian case study scenario. They are discussed in the subsequent sections in the following order: concrete slab and corrugated galvanized iron (CGI).

2.2.4.5.1 Concrete Slab

The concrete slab roof was approximately designed according to the Confined Masonry Network’s *Construction Guide for Low-Rise Confined Masonry Buildings* (2015). The thickness was taken as 20 cm, and the slab was reinforced on the top and bottom with #4 bars in the x-axis spaced every 15 cm and #3 bars in the y-axis spaced every 20 cm. Table 2-16 itemizes the material cost estimate for this concrete slab roof.

TABLE 2-16: ROOF MATERIAL ESTIMATE – CONCRETE SLAB

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Slab	Concrete	12.98	m^3	$98.75	$1,281.77	$2,173.42
	#3 Rebar (30’)	64	bar	$4.25	$272.00	
	#4 Rebar (30’)	85	bar	$7.29	$619.65	
					Slab total material estimate:	**$2,173.42**

2.2.4.5.2 Corrugated Galvanized Iron

The corrugated galvanized iron (CGI) roof used in this study was previously designed by E2E. The design and cost estimate were not revisited and can be found in the *Engineering2Empower Model Home Peer Review Report* (2016). This roof consists of CGI sheeting nailed to HSS cold formed steel purlins and prefabricated trusses attached to the beams with concrete wedge anchors, as shown in Figure 2-20. Table 2-17 details the material cost estimate of the CGI roof.

Figure 2-20: Interior view of the CGI roof (Image credit: E2E)

TABLE 2-17: ROOF MATERIAL ESTIMATE – CORRUGATED GALVANIZED IRON

Assembly	Item	Amount	Units	Unit Cost	Cost	Subtotals
Sheeting	CGI sheeting	268	ft	$3.00	$804.00	$918.00
	Nails	1	box	$60.00	$60.00	
	Wood (1” x 2” x 16’)	9	unit	$6.00	$54.00	
Framing	Large truss	2	unit	$68.91	$137.82	$522.83
	Small truss	2	unit	$37.50	$75.01	
	Purlins (HSS 1” x 2” x ⅛”)	27	bar	$10.00	$270.00	
	Angle L top brace (¾” x ¾” x ⅙”	5	bar	$8.00	$40.00	
Plywood cover	Eaves	6	unit	$40.00	$240.00	$480.00
	Gables	6	unit	$40.00	$240.00	
Metal roof total material estimate:						**$1,920.83**

2.2.4.6 Design Combinations

After designing the individual components and estimating the cost of construction materials for each, the material cost of nine different structures was estimated by considering various combinations of typology, foundation, cladding, and roof elements. Although 48 possible combinations theoretically exist, only nine were considered. The reasons for this simplification are outlined in the following paragraphs.

Unreinforced masonry was included to define the baseline from which the “cost of safety” can be measured. Thus, more expensive, formally detailed foundations (strip footings, raft, and footing and beam) were not considered with URM. Likewise, only the CGI roof was considered, as it is the least expensive option.

Restrictions on foundation types were also considered for the confined masonry and infilled frame typologies. The walls of confined masonry structures are load bearing, thus a continuous foundation is necessary. Only strip footings and a raft foundation fulfill this requirement. On the other hand, the infill walls of an infilled frame are not loadbearing, so this continuous support is unnecessary. Therefore, the footing and beam foundation, which is the least expensive formally detailed foundation type presented (see Table 2-19), was the only foundation considered for the infilled frame typology. Slab on grade foundations do not sufficiently tie together structural elements and were thus not considered with confined masonry and infilled frame typologies.

Lastly, because unreinforced masonry and confined masonry utilize masonry walls as part of the structural systems, additional cladding was not considered for either of these typologies. Table 2-18 lists the nine viable combinations considered.

TABLE 2-18: VIABLE COMBINATIONS OF TYPOLOGY, FOUNDATION, CLADDING, AND ROOF ELEMENTS

No.	Typology	Foundation	Cladding	Roof
1	URM	Slab on grade	-	CGI
2	CM	Strip footings	-	CGI
3	CM	Strip footings	-	Slab
4	CM	Raft	-	CGI
5	CM	Raft	-	Slab
6	RCF	Footing and beam	Concrete panels	CGI
7	RCF	Footing and beam	Concrete panels	Slab
8	RCF	Footing and beam	Infilled masonry	CGI
9	RCF	Footing and beam	Infilled masonry	Slab

2.3 Analysis of Results

Tables 2-19, 2-20, and 2-21 present the side-by-side comparisons of the typologies and elements discussed in the previous section.

TABLE 2-19: FOUNDATION MATERIAL COST ESTIMATES

Foundation Type	Material Cost
Slab on grade	$608.30
Strip footings	$2,185.45
Raft	$2,529.55
Footing and beam	$1,528.06

As expected, an unreinforced concrete slab on grade is the least expensive of the foundations considered. The raft and strip footings are both options to achieve the continuous foundation required by confined masonry construction, but the cost comparison indicates that a strip footing is the most cost effective option.

TABLE 2-20: TYPOLOGY AND CLADDING MATERIAL COST ESTIMATES

Typology/Cladding	**Material Cost**
Unreinforced masonry	$2,056.30
Confined masonry	$2,702.46
CMU infilled frame	$2,696.20
Paneled frame	$3,685.54

The typology and cladding estimates were combined so that confined masonry and URM (which inherently include cladding costs) can be effectively compared to the infilled frame. Notable conclusions from Table 2-20 include the relative similarity between the cost of confined masonry and infilled frame structures as well as the high relative cost of the paneled frame, mostly due to interior finishing costs (see Table 2-15).

TABLE 2-21: ROOF MATERIAL COST ESTIMATES

Roof Type	**Material Cost**
Concrete slab	$2,173.42
CGI	$1,920.83

Table 2-21 shows that the cost of a concrete slab roof is relatively similar to that of a CGI roof.

Table 2-22 presents the side-by-side comparison of the estimated cost of construction materials for the nine viable combinations considered in this study. It is important to note that the estimates for structures No. 3 and No. 5 are not purely additive from Tables 2-19, 2-20, and 2-21. When constructing confined masonry with a concrete slab roof, the ring beam and slab are poured simultaneously. Thus, the overlap in the estimated volume of concrete for the ring beam and slab was removed. Although it is possible that the volume of slab concrete will also be slightly reduced when building a reinforced concrete frame with a slab roof, the potential reduction will depend on construction techniques. Because the beams in the frame are always poured prior to the roof slab and the reduction is uncertain, this potential reduction was conservatively ignored.

TABLE 2-22: MATERIAL COST ESTIMATES FOR ALL STRUCTURES

No.	Typ.	Foundation	Cladding	Roof	Material Cost
1	URM	Slab on grade	-	CGI	$4,585
2	CM	Strip footings	-	CGI	$6,809
3	CM	Strip footings	-	Slab	$6,898
4	CM	Raft	-	CGI	$7,153
5	CM	Raft	-	Slab	$7,242
6	RCF	Footing and beam	Concrete panels	CGI	$7,134
7	RCF	Footing and beam	Concrete panels	Slab	$7,387
8	RCF	Footing and beam	Infilled masonry	CGI	$6,145
9	RCF	Footing and beam	Infilled masonry	Slab	$6,398

The above results indicate that, of the structures designed for seismic loads (structures No. 2 through No. 9), a masonry-infilled reinforced concrete special moment frame with a footing and beam foundation and CGI roof (structure No. 8) has the lowest estimated construction material cost. This frame is $664 (9.8%) less expensive than structure No. 2, the least expensive of the confined masonry structures considered. While the costs for the structures and cladding are quite similar (see Table 2-20), the need for a continuous foundation greatly increases the cost of confined masonry.

2.3.1 Conclusions and Limitations

First, it is important to note that only the cost of construction materials was estimated in this analysis. To more accurately compare typologies and define the "cost of safety," a more thorough investigation into associated costs for each considered design would be required, as different typologies require differing amounts of equipment, labor, formwork, and other overhead costs. These factors could disproportionately increase the actual cost of construction of each typology and element, significantly changing the results of this analysis.

When compared to the vulnerable URM structure with a slab on grade foundation and a CGI roof (structure No. 2), the selected frame (structure No. 8) is $1,560 (32%) more expensive. This indicates that the "cost of safety" for Haitian family in the process of constructing a home is approximately $1,560. Furthermore, because many Haitians are not purely building URM and are in fact building a combination of URM and confined masonry, many are spending money on tie columns and ring beams. Thus, it is likely that the estimated $1,560 is the maximum "cost of safety" that an aspiring homeowner in Haiti faces for the type of building (three-room) considered here. Depending on the degree to which families are spending on confined masonry elements and the effectiveness of their implementation, it is possible that the "cost of safety" could even drop below zero, indicating that families are in fact paying more for a non-resilient home than they could be for a codified, seismically-detailed structure. Regardless, it is clear from this analysis that the construction of safe housing is not restricted by cost alone.

The results presented in this chapter raise several important conclusions. First and foremost, although confined masonry is heavily promoted by the international engineering community for developing nations, the estimated construction material cost of confined masonry is actually 10.8% higher than a masonry-infilled reinforced concrete special moment frame. However, despite the increased cost, confined masonry remains the standard typology promoted by the international engineering community for developing nations. This is likely due to the market constraints of the informal residential construction industry. As mentioned in Section 2.1.2, confined masonry can be constructed incrementally, which is necessary in markets with limited access to housing finance. Unfortunately, incremental construction often reduces the quality and safety of the final product. Similarly, because the lateral force-resisting elements in a frame are concentrated in beams and columns, they require a higher standard of quality control to ensure adequate concrete strength and ductile steel detailing. Lastly, the incremental nature of confined masonry construction does not require the large concrete pour needed to construct a frame, which can be difficult in constrained construction industries where concrete is mixed by hand on site. While these factors could overpower the 10.8% material cost difference, the results indicate that the special moment frame, which is embraced by national building standards in the most developed and technologically advanced nations in the world, is at best less expensive than, and at worst comparable in cost to, confined masonry.

These conclusions motivate further analysis into the market viability and optimization of reinforced concrete frames. The analysis also demonstrates the benefits of a carefully executed comparative assessment in evaluating the costs and benefits of different typologies. The following chapters include a parametric analysis and evaluation to define the best-fit reinforced concrete frame in the case study scenario, a performance-based analysis to predict behavior during seismic events, and an exploration of potential solutions to critical market barriers, such as housing finance and quality control procedures, for frame construction.

CHAPTER 3:

PARAMETRIC ANALYSIS AND SELECTION

This chapter presents the process for designing, evaluating, scoring, and selecting two best-fit masonry-infilled reinforced concrete special moment frames, one with a CGI roof and another with a concrete slab roof, for the Haitian case study scenario. It first explains the assumptions, procedures, and results of an extensive parametric analysis used to design and analyze 576 different infilled frames. The chapter then details the selection process of the best-fit designs, in which scores were assigned to each structure based on the design's resiliency, constructability, and cost. Pareto optimization and a subsequent categorical weighting system were then utilized to select the best-fit designs. The chapter concludes with a discussion of the applications and limitations of the presented processes.

3.1 Parametric Analysis

After the comparative material cost analysis of relevant typologies determined that an infilled reinforced concrete special moment frame ("infilled frame") was the most cost-effective solution, a parametric study was undertaken to identify viable infilled frame structural designs for the Haitian case study scenario. This process is represented graphically in Figure 3-1. Throughout the analysis, material properties, floorplan dimensions, and external loads remained fixed while cross-sectional dimensions and steel detailing were varied. Each design was analyzed using an automated Rapid Design and Analysis Tool (RDAT) and accepted or rejected based on a variety of code-based parameters. In total, 576 different structures were designed and analyzed. Of these, 234 were accepted as viable.

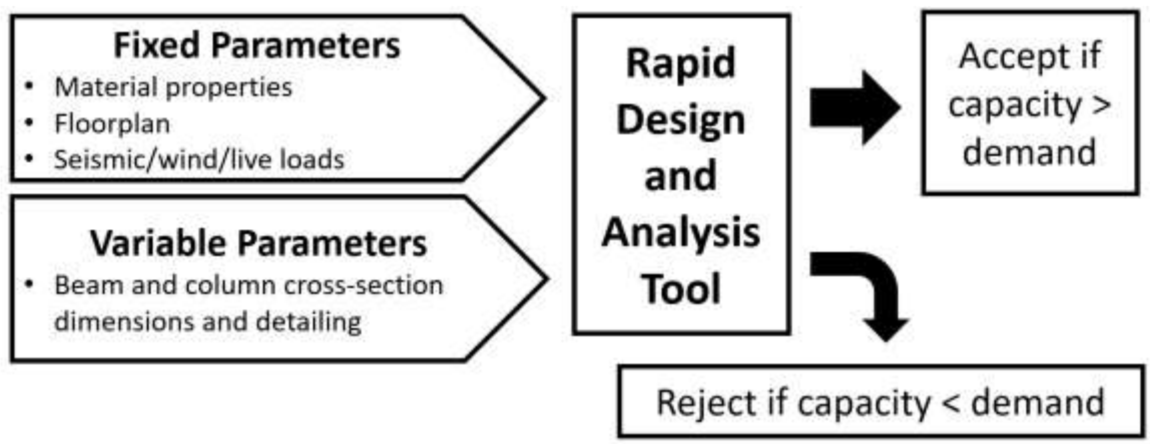


Figure 3-1: Workflow for parametric analysis

3.1.1 Standards Utilized

The design and analysis procedures were completed in accordance with accepted national and international standards. The American Society of Civil Engineers' (ASCE) *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, known as ASCE 7, was used to determine live, roof live, wind, and seismic loading (ASCE 2016). The design was carried out in accordance with the American Concrete Institute's (ACI) *Building Code Requirements for Structural Concrete*, known as ACI 318, including *Design Aid SP-17* (ACI 2014a; ACI 2014b). ACI provisions are generally highly conservative for single-story dwellings, since they were developed specifically with multi-story buildings in mind (E2E 2016; Fink 2017). Thus, some code provisions from the European Standard were also considered, as Eurocode explicitly addresses single-story frames (CEN 2003). Lastly, FEMA 306 was utilized for the analysis of in-plane compression struts formed in masonry infill walls (ATC 1998).

3.1.2 Parameters

In order to analyze and compare a large number of infilled frames, certain parameters were varied while others remained fixed. Throughout the analysis, the beam and column cross-sectional dimensions and steel detailing were varied, while the element lengths, material properties, and loading assumptions remained fixed. While the underlying assumptions regarding loading remained fixed, the dead loads and seismic weight (and therefore lateral earthquake loads) were dependent on the size of the members and thus varied with each design. The loading is further detailed in Section 3.1.3.1. The subsequent sections describe the fixed and variable parameters, respectively.

3.1.2.1 Fixed Parameters

Parameters that do not impact the strength of structural members or that correspond to material properties were assigned nominal values throughout the parametric analysis. First, a standardized architectural plan was utilized for each design, ensuring that the general geometric layout was consistent across all 576 considered structures. Likewise, material properties also remained constant throughout the entire analysis. The standardized architectural plan and material properties are described in the following sections.

3.1.2.1.1 Standard Architectural Plan

The standard architectural plan was modified from the three-room plan utilized throughout the comparative cost analysis detailed in Chapter 2. Instead, E2E's four-room model (Figure 3-2) was selected as the standard architectural plan for the parametric analysis (2016). This plan features four rooms, each measuring 4 m by 4 m, and a front porch measuring 2 m by 8 m, thus totaling 80 m^2 (861 ft^2) of livable space. The height of the walls and columns was taken as 2.5 m (8 ft 2 in).

This model was selected because its symmetry across both axes allows a single frame from both the x- and y-axis to be analyzed independently. This significantly reduced the complexity of the portal frame analysis, which is detailed in Section 3.1.3.2.

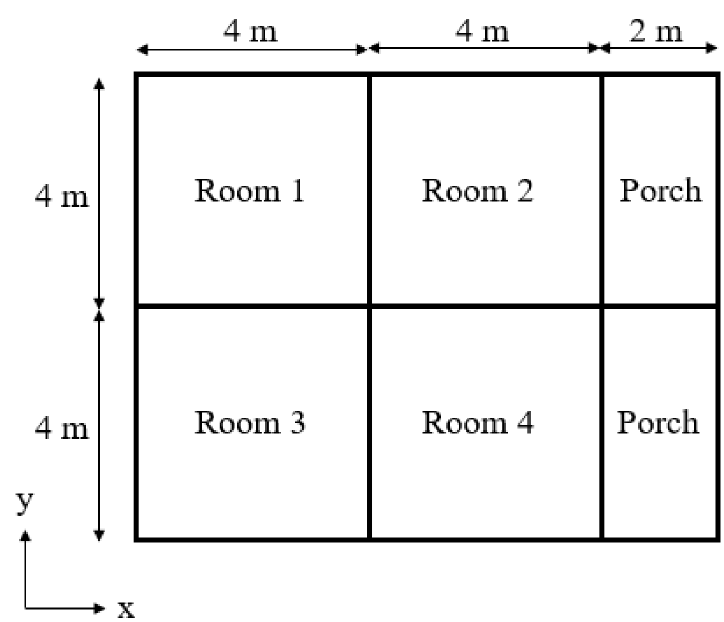


Figure 3-2: Standard architectural plan used in parametric analysis

3.1.2.1.2 Material Properties

The material properties for concrete and steel used in design calculations were sourced from US and international codes based on the properties of commonly available materials in Haiti. These properties are consistent with properties used in the comparative assessment in Chapter 2 and can be found in Tables 2-2 and 2-3.

Likewise, masonry properties were again sourced from Build Change's *Calculation Report for Confined Masonry Housing* in Haiti (Build Change 2011a) and are also described in Chapter 2. Table 2-4 displays these properties. To be consistent with the most common existing practices in Haiti, 15 cm width CMU blocks were again used in this study. The equivalent solid thickness of these blocks was assumed to be 5.4 cm (Build Change 2011a).

The weights of roof materials were sourced from the *Engineering2Empower Model Home Peer Review Report* (2016) and were not recalculated from their base components in this study. Table 3-1 lists these weights.

TABLE 3-1: WEIGHTS OF ROOF MATERIALS

Material	**Weight**	**Units**
Roof truss	3.08	lb/ft
Purlins	2.26	lb/ft
CGI sheeting	0.459	lb/ft^2

3.1.2.2 Design Parameters

Cross-sectional dimensions and steel detailing were varied throughout the analysis, and both CGI and concrete slab roofs were considered. The varied cross-sectional dimensions were column width, beam depth, and beam width. Note that column depth was always equal to column width and thus not independently varied, as only square columns were considered in the study. Furthermore, beam depth and beam width were varied in pre-defined pairs to eliminate inefficient sections in which the beam is as wide or wider than it is deep. Table 3-2 displays the cross-sectional dimensions considered in this study.

TABLE 3-2: DESIGN PARAMETERS: COLUMN AND BEAM DIMENSIONS

Parameter	**Values (cm)**
Column width	25 30 35
Beam dimensions (width x depth)	20 x 25 20 x 30 20 x 35 25 x 30 25 x 35 30 x 35

In a similar fashion, different combinations of #3 and #4 longitudinal reinforcing bars were considered in both columns and beams. These combinations are displayed in Tables 3-3 and 3-4, respectively.

TABLE 3-3: DESIGN PARAMETERS: COLUMN LONGITUDINAL STEEL COMBINATIONS

Combination No.	Number of #3 bars	Number of #4 bars
C1	0	4
C2	4	4
C3	0	8
C4	4	8

TABLE 3-4: DESIGN PARAMETERS: BEAM LONGITUDINAL STEEL COMBINATIONS

Combination No.	Number of #3 bars	Number of #4 bars
B1	0	2
B2	0	3
B3	2	0
B4	3	0

Lastly, both CGI and slab roofs were considered in this study because of the comparable price and the high demand for each in the case study scenario. Although the results in Table 2-21 indicate that the concrete slab is slightly more expensive than the CGI roof, concrete slabs perform better in high wind events (e.g., tropical storms and hurricanes) and are thus popular in Haiti. The CGI roof included in this analysis was previously designed by E2E (2016) and was not revisited in this study. The concrete slab selected was 13 cm thick, the minimum thickness mandated for a two-way slab by ACI 318 (2014a). The reinforcement was approximately designed via Confined Masonry Network's *Construction Guide for Low-Rise Confined Masonry Buildings* (2015), with #4 bars spaced at 15 cm in the x-axis and 20 cm in the y-axis at both the top and bottom. ACI (2014a) deflection requirements were not considered.

In summary, the variable parameters and number of variations of each considered in this study are as follows: column width (3), beam depth and width (6), column longitudinal steel (4), beam longitudinal steel (4), and roof type (2). Thus, 576 different structures were designed and analyzed in this parametric study.

3.1.3 Rapid Design and Analysis Tool

All design calculations were automated in a Rapid Design and Analysis Tool (RDAT) developed in Microsoft Excel. This tool calculated the design loads on the structure, determined force and moment demands through an approximate portal frame analysis, assessed load combinations, and evaluated the capacity of members compared to the demands. First, an RDAT was developed for structures with a CGI roof. This tool was later modified to accommodate a concrete slab. The following sections describe each step of the RDAT and discuss the differences between the CGI and concrete slab RDATs. All calculations subsequently described can be found directly in the RDAT sheets themselves (Burlotos 2020a; Burlotos 2020b), linked in the bibliography.

3.1.3.1 Design Loads

ASCE 7-16 was used to determine live, seismic, and wind loads (ASCE 2016). Dead loads were calculated using the aforementioned material weights. An uninhabitable attic without storage (10 psf) was assumed when calculating the live roof loads for the CGI roof. For the slab roof, it was conservatively assumed that it could be occupied, so roof live loads were taken as 40 psf. Occupancy live and dead loads on the ground floor were ignored because the structure only has a single story with a slab on grade floor. Roof loads along each beam line, both dead and live, were calculated based on tributary area. The roof trusses, which transfer dead and live loads from the CGI roof to the frame, are positioned on the beams in the y-axis, thus no roof loads were applied on beams in the x-axis. For the slab roof, the loads were distributed assuming a two-way slab for the 4 m x 4 m rooms and a one-way slab for the porch (see Figure 3-3).

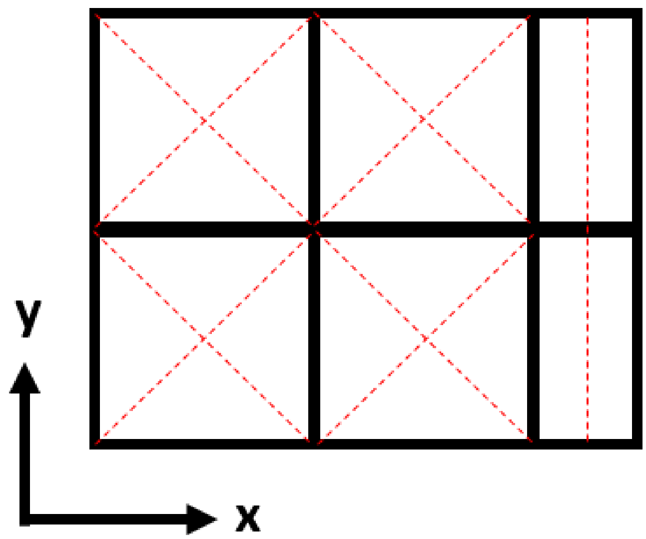


Figure 3-3: Tributary areas of beams supporting concrete slab roof

Seismic demands were calculated via the equivalent lateral force procedure as permitted by ASCE 7-16 Table 12.6-1 (ASCE 2016). Short period spectral acceleration, S_s, and one-second period spectral acceleration, S_1, were obtained from United States Geological Survey's Worldwide Seismic "DesignMaps" Web Application (USGS 2015). Site class was conservatively assumed to be soft soil (site class D). The structure was assigned to Seismic Design Category E based on its Risk Category (II) and its S_1 acceleration (0.79 g). As required in Seismic Design Category E, the structure was detailed as a special moment frame in compliance with Chapter 18 of ACI 318-14 (ACI 2014a). Thus, the response modification factor was taken as 8. While utilizing a lower value would have been more conservative, the selection procedure and performance assessment respectively outlined in Section 3.2 and Chapter 4 account for and validate this assumption. Table 3-5 displays the tabulated calculations for the base shear coefficient, as well as appropriate references.

TABLE 3-5: BASE SHEAR COEFFICIENT CALCULATIONS

Design Characteristic		**Value**		**Source**
Response Modification Factor	R	8.0		ASCE 7-16 Table 12.2-1
Seismic Importance Factor	I_e	1.00		ASCE 7-16 Table 1.5-2
Short Period Spectral Acceleration	S_s	1.89	g	USGS 2015
One-second Period Spectral Acceleration	S_1	0.79	g	USGS 2015
Shear Wave Velocity	V_{s30}	350	m/s	Frankel et al. 2010
Site Class		D		ASCE 7-16 Table 20.3-1
Short Period Site Coefficient	F_a	1.0		ASCE 7-16 Table 11.4-1
Short Period MCE_R Spectral Response Acceleration	S_{ms}	1.89	g	ASCE 7-16 Eqn 11.4-1
Short Period Design Earthquake Spectral Response Acceleration	S_{ds}	1.26	g	ASCE 7-16 Eqn 11.4-3
Base Shear Coefficient	C_s	0.1575		ASCE 7-16 Eqn 12.8-2

Next, the seismic weight of each structure was calculated based on the previously defined material weights. It was assumed that half of the force generated by the columns and infill walls under lateral acceleration would be distributed to the ground, so a contribution factor of 0.5 was applied to their weights. Beams and roof components were given contribution factors of 1.0. A contribution factor of 0.3 was assigned to the live load on the slab roof, accounting for 30% of the design live load being present at the time of a seismic event. This 30% consideration was neglected for the CGI roof due to the unlikelihood of it being occupied due to its pitched shape. The base shear force was then determined by multiplying the total seismic mass by the base shear coefficient. Tables 3-6 and 3-7 display these calculations for the CGI and slab roof, respectively. The calculations shown are for the final designs presented in Section 3.2. The slight differences in the column and infill wall weights are due to minor geometrical differences resulting from a deeper beam being used for the slab roof (see Section 3.2).

TABLE 3-6: SEISMIC WEIGHT AND BASE SHEAR CALCULATIONS – CGI ROOF

Component	**Component Weight**		**Contribution Factor**	**Seismic Weight**	
Beams	74.40	kN	1.0	74.40	kN
Columns	58.32	kN	0.5	29.16	kN
Trusses	1.44	kN	1.0	1.44	kN
Purlins	7.92	kN	1.0	7.92	kN
CGI Sheeting	2.08	kN	1.0	2.08	kN
Infill Walls	222.75	kN	0.5	111.38	kN
			Total Seismic Weight	**226.38**	**kN**
			Base Shear	**35.65**	**kN**

TABLE 3-7: SEISMIC WEIGHT AND BASE SHEAR CALCULATIONS – CONCRETE SLAB ROOF

Component	**Component Weight**		**Contribution Factor**	**Seismic Weight**	
Beams	89.28	kN	1.0	89.28	kN
Columns	57.02	kN	0.5	28.51	kN
Slab (Dead)	249.60	kN	1.0	249.60	kN
Slab (30% Live)	76.80	kN	0.3	23.04	kN
Infill Walls	217.80	kN	0.5	108.90	kN
			Total Seismic Weight	**499.33**	**kN**
			Base Shear	**78.64**	**kN**

Wind loads were calculated via the Envelope Procedure of Chapters 26 and 28 of ASCE 7-16 (ASCE 2016). The design wind speed for Léogâne, Haiti was taken as 150 mph and is based on a 700-year return mean recurrence interval (Gibbs 2008). Similar to the seismic weight contribution of the CMU infill and the columns, only 50% of the total wind load was applied, as point loads at the beam and column intersections, to the frame. Wind loads calculated for the gabled CGI roof were also conservatively applied to the structure with the concrete slab roof. The maximum total wind load applied in the x- and y-axis was 16.14 kN and 20.18 kN, respectively.

3.1.3.2 Structural Analysis

The structure then was approximately analyzed using the portal frame approach. The aforementioned lateral loads were applied to the structure and distributed to individual frames, which were subsequently broken down into portals. Solutions for each portal frame were then obtained using results from Beton Kalender (1984). These portal demands were then reassembled into their respective frames, which were subsequently globally reassembled with various reduction factors to form the entire structure. This process, described in detail in the following paragraphs, is presented graphically in Figures 3-4 and 3-5.

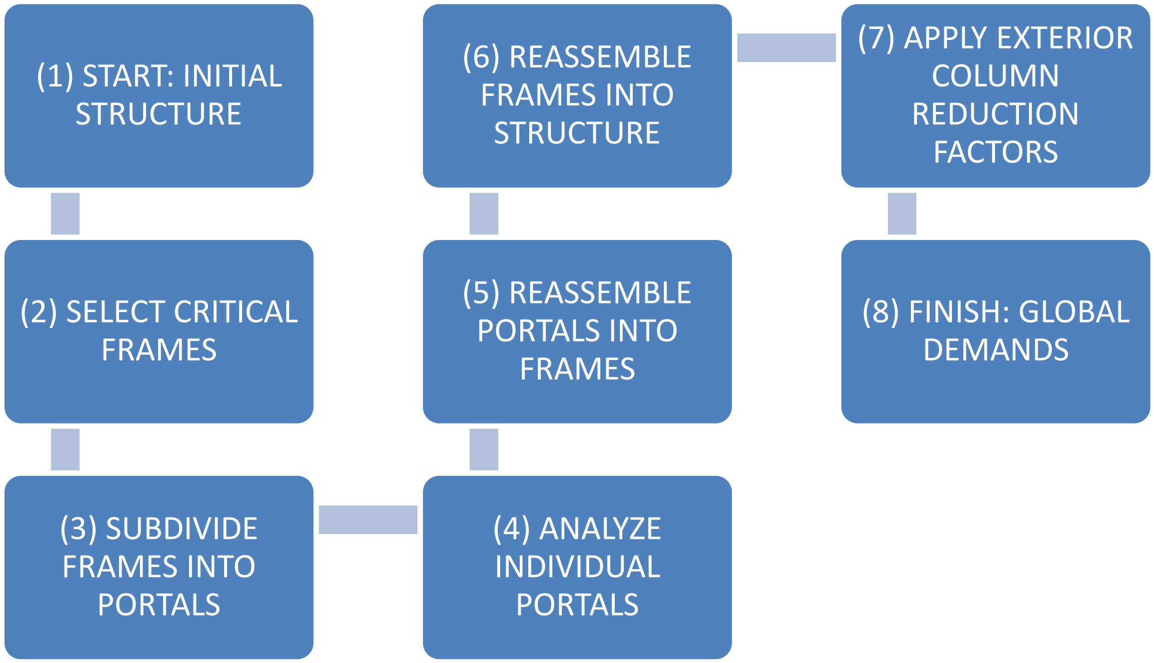


Figure 3-4: Steps of the approximate analysis process

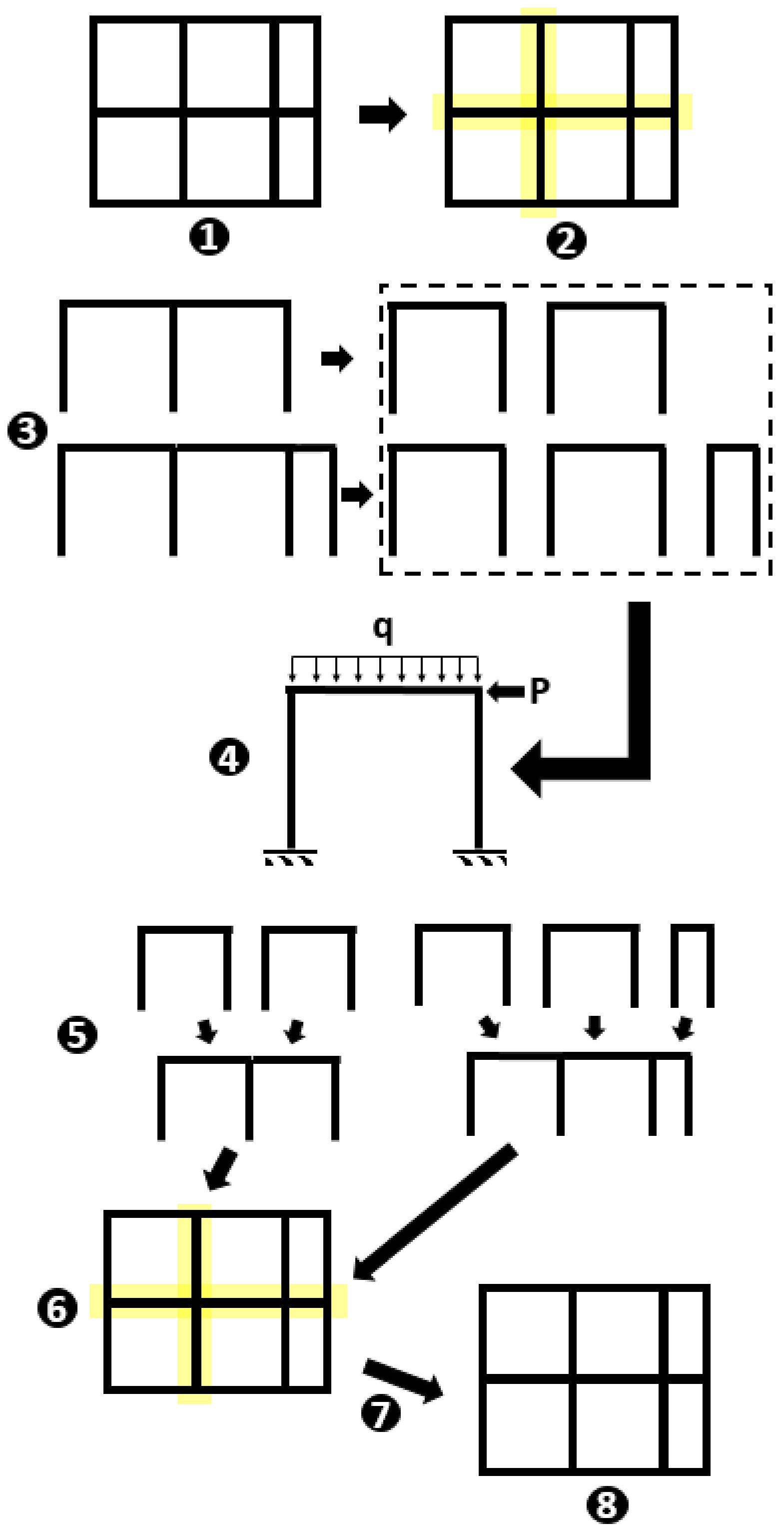


Figure 3-5: Schematic of disassembly and reassembly of structure using portal frames

First, a grid was defined and the columns and beams of the structure were labeled to facilitate the subdivision and reassembly process. The columns were labeled A through L (see Figure 3-6). Beam lines 2 and 6, which have the greatest tributary area, were selected as the critical beams and labeled M through Q. Only these two critical frames (see Figure 3-7) were analyzed, and the calculated frame demands were later assembled to determine the global demands on the structure.

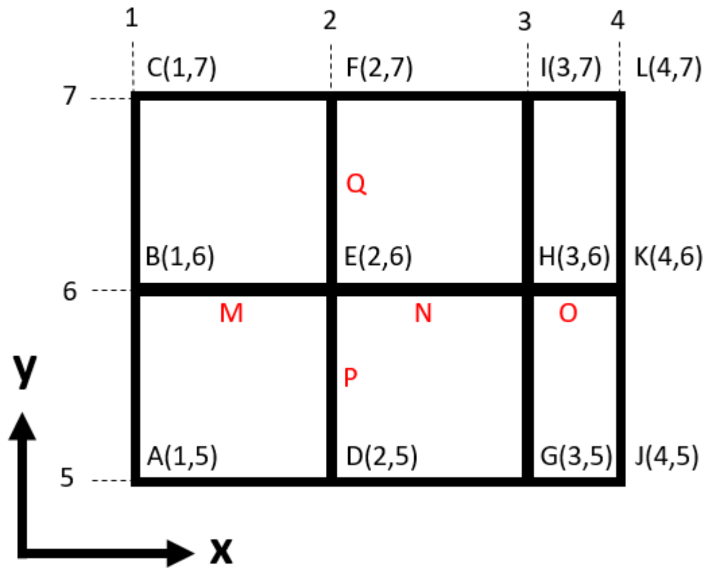


Figure 3-6: Column and critical beam labels

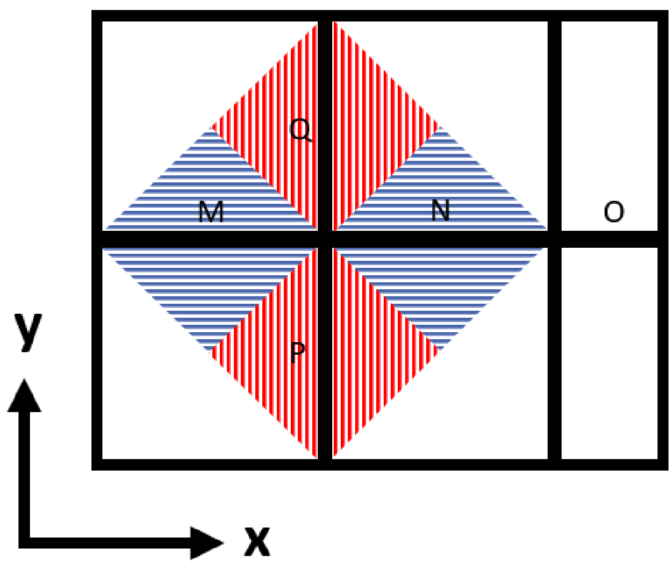


Figure 3-7: Critical beam lines with assocated tributary area

The two critical frames were then disassembled into two or three portals for analysis, as shown in Figure 3-8. The y-axis frame was subdivided into two portals (top), while the x-axis frame was subdivided into three portals (bottom). These portals were subsequently analyzed as individual components.

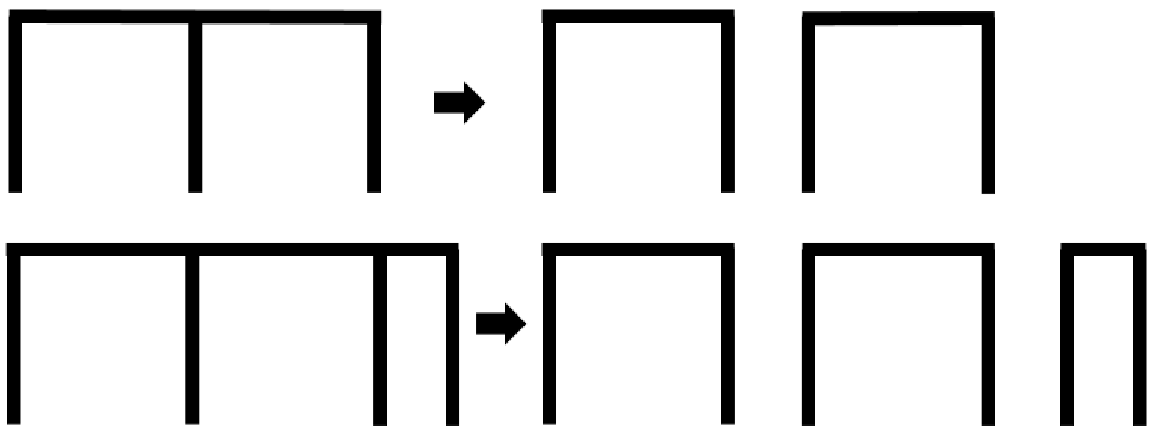


Figure 3-8: Disassembly of frames into portals

Dead and live loads were then applied to the individual portals as vertical distributed loads based on tributary area, while wind and seismic loads were applied as lateral point loads at the tops of the columns.

The seismic and wind loads previously determined were calculated in terms of the entire structure. Thus, for the portal analysis, these loads were reduced and applied to each frame and portal separately through the use of contribution factors. Each frame and portal were assigned contribution factors which directly correspond to the portion of the total lateral load each frame or portal was expected to take. The frame contribution factors also differed depending on the roof type, as the CGI roof is not assumed to be stiff enough to warrant the diaphragm assumption. For example, with a CGI roof, the critical frame in the x-axis was expected to attract 50% of the lateral load, as it accounts for 50% of the total tributary area of x-axis beams. Subsequently, the portal contribution factors were applied based on the relative length of the individual portal. So, the first portal in the critical frame in the x-axis was assigned 40% of the lateral load applied to that frame, as it accounts for 40% of the total length of the frame. The portal and frame contribution factors can then be multiplied to determine the portion of the total lateral load that is applied to the individual portal. In the example given, this would mean that 20% of the total lateral load was applied to the first portal of the x-axis critical frame. The presence of a slab roof, and therefore the diaphragm assumption, did not influence the portal contribution factors. Tables 3-8 and 3-9 display the contribution factors and their products for the x- and y-axis, respectively.

TABLE 3-8: PORTAL AND FRAME CONTRIBUTION FACTORS IN X-AXIS

		Portal		
		A	**B**	**C**
Frame		0.4	0.4	0.2
CGI (without diaphragm assumption)	0.5	0.2	0.2	0.1
Slab (with diaphragm assumption)	0.33	0.132	0.132	0.066

TABLE 3-9: PORTAL AND FRAME CONTRIBUTION FACTORS IN Y-AXIS

		Portal	
		A	**B**
Frame		0.5	0.5
CGI (without diaphragm assumption)	0.4	0.2	0.2
Slab (with diaphragm assumption)	0.25	0.125	0.125

Once the load demands for each portal were determined, the portals were individually analyzed according to equations provided in Beton Kalendar (1984), represented in the following figures and equations. The sign convention established is shown in Figure 3-9. Equation 3.1 defines the portal constant, *k*. Equations 3.2 – 3.8 were used to calculate the internal forces and moments in the columns due to an applied vertical distributed load (see Figure 3-10), such as dead and live loads. Equations 3.9 – 3.13 were used to calculate the internal forces and moments in the columns due to an applied lateral point load (see Figure 3-11), such as wind and earthquake loads.

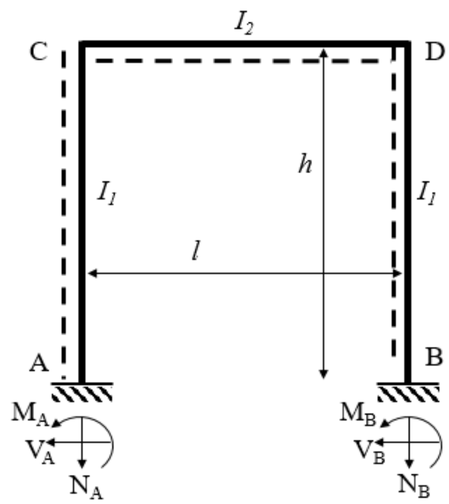


Figure 3-9: Sign convention and parameters of a portal
[reproduced from Beton Kalendar (1984)]

The portal constant, k, was determined by the following equation:

$$k = \frac{I_2}{I_1} \cdot \frac{h}{l} \tag{3.1}$$

where I_1 and I_2 are equal to the moments of inertia of the column and beam, respectively, h is equal to the height of the portal, and l is equal to the length of the portal.

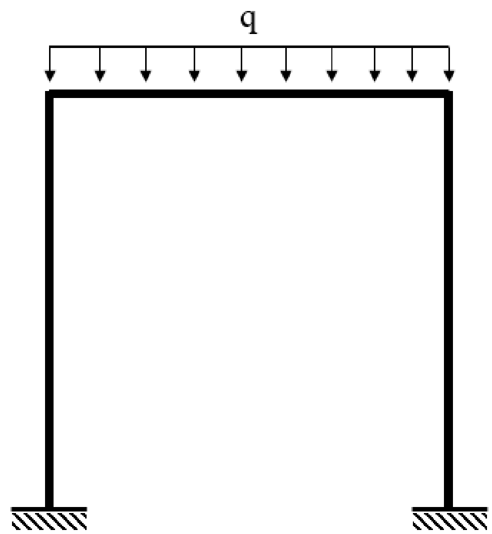


Figure 3-10: Portal with distributed vertical load, q

The dead and live loads were applied as vertical distributed loads on each individual portal, as shown above in Figure 3-10. The shear force, *V*; axial force, *N*; and bending moment, *M* of the columns due to the vertical distributed load were calculated using the following equations:

$$V_A = \frac{-ql^2}{4h(k+2)} \tag{3.2}$$

$$V_B = \frac{ql^2}{4h(k+2)} \tag{3.3}$$

$$N_A = N_B = \frac{-ql}{2} \tag{3.4}$$

$$M_A = \frac{-ql^2}{12(k+2)} \tag{3.5}$$

$$M_B = \frac{ql^2}{12(k+2)} \tag{3.6}$$

$$M_C = \frac{ql^2}{6(k+2)} \tag{3.7}$$

$$M_D = \frac{-ql^2}{6(k+2)} \tag{3.8}$$

where q is equal to the magnitude of the vertical distributed load and all other variables have been previously identified.

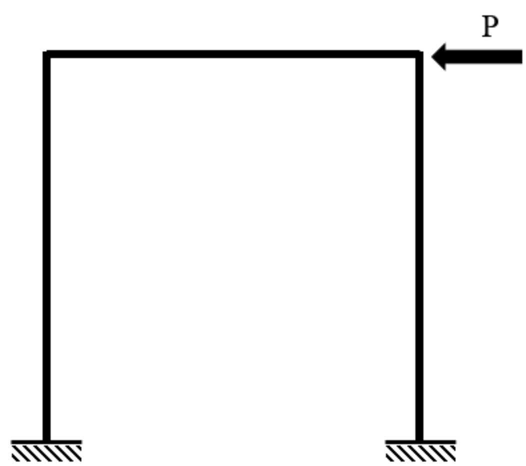


Figure 3-11: Portal with lateral point load, P

The wind and earthquake loads were applied as lateral point loads, as shown above in Figure 3-11. The shear force, V; axial force, N; and bending moment, M of the columns due to the lateral point load were calculated using the following equations:

$$V_A = V_B = \frac{-P}{2} \tag{3.9}$$

$$N_A = \frac{-3Phk}{l(6k+1)} \tag{3.10}$$

$$N_B = \frac{3Phk}{l(6k+1)} \tag{3.11}$$

$$M_A = M_B = \frac{-Ph}{2} \cdot \frac{3k+1}{6k+1} \tag{3.12}$$

$$M_C = M_D = \frac{Ph}{2} \cdot \frac{3k}{6k+1} \tag{3.13}$$

where P is equal to the magnitude of the lateral point load and all other variables have been previously identified.

Axial forces in the beam were ignored. Beam end moments were calculated by summing the moments at each joint. Likewise, the shear force in each beam was calculated by the following equation:

$$V_{beam} = \frac{M_\beta - M_\alpha}{l} + \frac{ql}{2} \tag{3.14}$$

where M_α is equal to the moment at the left end of the beam, M_β is equal to the moment at the right end of the beam, and all other variables have been previously identified.

The portals were then reassembled into frames as shown in Figures 3-12 and 3-13. Column moments, axial forces, and shear forces from individual portals were summed at overlapping points. For example, in the x-axis frame in Figure 3-12, the moment at point 6 is the sum of the moments calculated at point D in the first frame and point C in the middle frame.

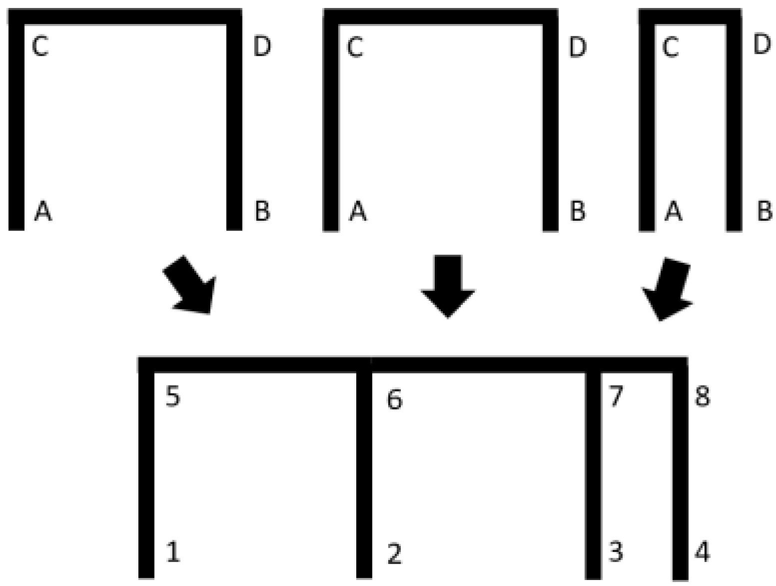


Figure 3-12: Reassembly of portals into x-axis frame

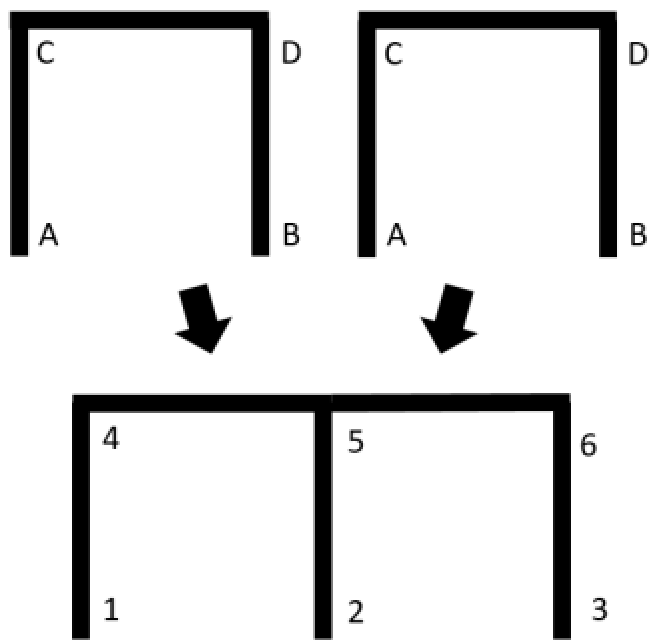


Figure 3-13: Reassembly of portals into y-axis frame

Lastly, the frame loads were assembled globally to define loads across the entire structure. The column axial demands calculated along these two critical frames were combined with each other to define the unique axial load at each of the structure's twelve columns. In the dead load case, the self-weight of the column was also included. Shear forces and moments in columns and beams were also assembled globally; however, as shear force and moment were only calculated in the in-plane direction for both the x-axis and y-axis critical frames, these were not summed together.

In the case with the slab roof, the exterior demands were multiplied by various approximate load reduction factors to account for the decreased tributary area, and therefore loads, on the edge (B, D, F, G, I, and K) and corner (A, C, J, and L) columns. For example, the moment and shear force demands due to live loads (as well as axial force due to live loads in corner columns) were reduced by 50% in corner and edge columns because the tributary area for both the x- and y-axis critical frames contributing to that demand is 50% smaller. However, the axial force due to live load in edge columns was only reduced by 25% (corresponding to a multiplicative reduction factor of 0.75) because only one of the two frames contributing to that axial load has a reduced tributary area at that point. This same methodology was applied to the dead load demands, but they are reduced slightly less due to the consistent presence of column and beam self-weight. Table 3-10 presents these reduction factors.

TABLE 3-10: EXTERIOR COLUMN LOAD REDUCTION FACTORS

		Corner	Edge
Dead	Moment and shear force	0.6	0.6
	Axial force	0.65	0.85
Live	Moment and shear force	0.5	0.5
	Axial force	0.5	0.75

These reductions were only applied to columns because of the increased complexity associated with selecting design demands from load combinations (e.g., potential overturning, biaxial combination). In other words, reduction factors were not applied to the exterior beams because it is clear that the interior beam will govern the design due to its large tributary area. Likewise, the reduction factors were not applied to the CGI roof because the roof loads are significantly smaller and the effect of the reduction factors was deemed insignificant due to the relatively large self-weight of the columns and beams.

3.1.3.3 Load Combinations

The demands were then combined using load combinations specified in ACI 318-14 Equations 5.3.1a – 5.3.1g (ACI 2014a). These seven combinations were simplified based on the loading assumptions discussed in Section 3.1.3.1. Table 3-11 presents both the original and simplified combinations.

TABLE 3-11: ACI 318 BASIC LOAD COMBINATIONS

No.	Full Equation (ACI 2014a)	Simplified Equation (R=S=L=0)
C1	U = 1.4D	U = 1.4D
C2	U = 1.2D + 1.6L + 0.5(L_r or S or R)	U = 1.2D + 0.5L_r
C3	U = 1.2D + 1.6(L_r or S or R) + 1.0(L or 0.5W)	U = 1.2D + 1.6L_r + 0.5W
C4	U = 1.2D + 1.0W + 1.0L + 0.5(L_r or S or R)	U = 1.2D + 1.0W + 0.5L_r
C5	U = 1.2D + 1.0E + 1.0L + 0.2S	U = 1.2D + 1.0E
C6	U = 0.9D + 1.0W	U = 0.9D + 1.0W
C7	U = 0.9D + 1.0E	U = 0.9D + 1.0E

These seven basic load combinations were further differentiated based on the direction of earthquake and wind loading. Lateral earthquake loads were considered in the $E_{h,1}$ and $E_{h,2}$ directions, which were defined in accordance with ACI 318 Section 12.5.4 (ACI 2014a) using the following equations:

$$E_{h,1} = E_x + 0.3\,E_y \qquad (3.15)$$

$$E_{h,2} = 0.3\,E_x + E_y \qquad (3.16)$$

where E_x and E_y represent the demand due to the application of the earthquake loads in the x- and y-axis, respectively.

Likewise, the vertical component of the earthquake force, E_v, was also included. This was calculated using ASCE 7-16’s Equation 12.4-4a (ASCE 2016), defined here as Equation 3.17:

$$E_v = 0.2\,S_{ds}\,D \qquad (3.17)$$

where S_{ds} is equal to the short period design earthquake spectral response acceleration and D is equal to the demand due to the dead load.

Wind loads were applied in the x- (W_x) and y-axis (W_y), as well as along the diagonal (W_c). W_c was defined by Case 3 in Figure 27.3-8 of ASCE 7-16 (ASCE 2016), represented in the following equation:

$$W_c = 0.75\ W_x + 0.75\ W_y \tag{3.18}$$

All of the aforementioned lateral loads were considered in both the positive and negative direction, resulting in a total of 36 load combinations to be considered when calculating design demands. Of these, combination #15 governed in all cases. Table 3-12 lists these combinations in full.

TABLE 3-12: ACI 318 COMPLETE LOAD COMBINATIONS

C1	$U_1 = 1.4\ D$
C2	$U_2 = 1.2\ D + 0.5\ L_r$
C3	$U_3 = 1.2\ D + 1.6\ L_r + 0.5\ W_x$
	$U_4 = 1.2\ D + 1.6\ L_r - 0.5\ W_x$
	$U_5 = 1.2\ D + 1.6\ L_r + 0.5\ W_y$
	$U_6 = 1.2\ D + 1.6\ L_r - 0.5\ W_y$
	$U_7 = 1.2\ D + 1.6\ L_r + 0.5\ W_c$
	$U_8 = 1.2\ D + 1.6\ L_r - 0.5\ W_c$
C4	$U_9 = 1.2\ D + 0.5\ L_r + 1.0\ W_x$
	$U_{10} = 1.2\ D + 0.5\ L_r - 1.0\ W_x$
	$U_{11} = 1.2\ D + 0.5\ L_r + 1.0\ W_y$
	$U_{12} = 1.2\ D + 0.5\ L_r - 1.0\ W_y$
	$U_{13} = 1.2\ D + 0.5\ L_r + 1.0\ W_c$
	$U_{14} = 1.2\ D + 0.5\ L_r - 1.0\ W_c$
C5	$U_{15} = 1.2\ D + E_{h1} + E_v$
	$U_{16} = 1.2\ D + E_{h1} - E_v$
	$U_{17} = 1.2\ D - E_{h1} + E_v$
	$U_{18} = 1.2\ D - E_{h1} - E_v$
	$U_{19} = 1.2\ D + E_{h2} + E_v$
	$U_{20} = 1.2\ D + E_{h2} - E_v$
	$U_{21} = 1.2\ D - E_{h2} + E_v$
	$U_{22} = 1.2\ D - E_{h2} - E_v$
C6	$U_{23} = 0.9\ D + 1.0\ W_x$
	$U_{24} = 0.9\ D - 1.0\ W_x$
	$U_{25} = 0.9\ D + 1.0\ W_y$
	$U_{26} = 0.9\ D - 1.0\ W_y$
	$U_{27} = 0.9\ D + 1.0\ W_c$
	$U_{28} = 0.9\ D - 1.0\ W_c$
C7	$U_{29} = 0.9\ D + E_{h1} + E_v$
	$U_{30} = 0.9\ D + E_{h1} - E_v$
	$U_{31} = 0.9\ D - E_{h1} + E_v$
	$U_{32} = 0.9\ D - E_{h1} - E_v$
	$U_{33} = 0.9\ D + E_{h2} + E_v$
	$U_{34} = 0.9\ D + E_{h2} - E_v$
	$U_{35} = 0.9\ D - E_{h2} + E_v$
	$U_{36} = 0.9\ D - E_{h2} - E_v$

3.1.3.4 Frame Design and Analysis

After determining loads, approximately analyzing the demands in the frame, and evaluating load combinations to define the design demands for the specified input parameters, the RDAT evaluated the strength of the frame using standardized processes presented by the American Concrete Institute (ACI 2014a; ACI 2014b) and FEMA (ATC 1998). The following sections present the strength analysis process for beams, columns, and masonry walls.

3.1.3.4.1 Beams

The beam analysis procedure followed Chapters 9, 18, 21, and 22 of ACI 318 (ACI 2014a). First, the bending moment demand was calculated by taking the maximum of the beam end moment demand (calculated in Section 3.1.3.2) and the moment at the center of the beam due to gravity loads alone. The latter was calculated assuming a fixed-fixed beam. The minimum required longitudinal steel area was then calculated using ACI 318 Equation 9.6.1.2 (ACI 2014a). The moment capacity of the beam, specific to the cross-sectional dimensions and longitudinal steel arrangement specified at the current iteration of the parametric analysis, was calculated using ACI 318 Section 9.5.1.1 (ACI 2014a). Following Eurocode recommendations capacity design was not performed for beam bending moment demand (CEN 2003).

The shear force demand was calculated via capacity design. The design shear strength based on capacity design assumptions, V_e, was calculated via Figure R18.6.5 (ACI 2014a) using the following equation:

$$V_e = \frac{M_{pr,1} + M_{pr,2}}{l_n} \pm \frac{w_u l_n}{2} \tag{3.19}$$

where $M_{pr,1}$ and $M_{pr,2}$ are equal to the probable moment strength at both ends of the beam, l_n is equal to the length of the beam, and w_u is equal to the factored distributed load. The greater of the above calculated V_e and the maximum of the beam shear demands calculated in Section 3.1.3.2 was taken as the design shear demand. The beam shear capacity was then evaluated via ACI 318 Section 9.5.1.1 and minimum lateral tie spacing was calculated via ACI 318 Table 9.6.3.3 (ACI 2014a).

3.1.3.4.2 Columns

The column analysis procedure followed Chapters 18, 20, 21, and 22, as well as Design Aid SP-17, of ACI 318 (ACI 2014a; ACI 2014b). The bending moment demands in both the x- and y-axis and the axial demand were previously calculated in Section 3.1.3.2. Biaxial analysis was completed via the Load Contour Method, as described in Design Aid SP-17, and Interaction Diagram R3-60.6 (see Figure 3-14), which assumes a steel-to-steel depth ratio, γ, of 0.6. (ACI 2014b). First, the dimensionless nominal axial load, K_n, was calculated using the following equation, adapted from ACI (2014b):

$$K_n = \frac{P_n}{\Phi f_c' A_g} \tag{3.20}$$

where P_n is equal to the axial load, f'_c is equal to the concrete strength, A_g is equal to the gross area of the column section, and Φ is equal to the capacity reduction factor [Φ = 0.65 for compression according to Table 21.2.2 (ACI 2014a)].

The RDAT then utilizes an iterative algorithm to select a corresponding reinforcement ratio, ρ_g, and dimensionless nominal bending moment, $R_{n,max}$, from the interaction diagram (Figure 3-14). The algorithm selects the lowest possible ρ_g for which the following condition is met:

$$\left(\frac{M_{nx}}{\Phi M_{nox}}\right)^{a} + \left(\frac{M_{ny}}{\Phi M_{noy}}\right)^{a} \leq 1.0 \tag{3.21}$$

where M_{nx} and M_{ny} are equal to the design moment demand in the x- and y-axis, respectively, the exponential constant, α, is equal to 1.6 (ACI 2014b), and ΦM_{nox} and ΦM_{noy} are equal to the reduced bending moment capacity in the x- and y-direction, respectively (ACI 2014b). Because all proposed column designs are square (see Section 3.1.2.2), ΦM_{nox} is equal to ΦM_{noy} and is defined as:

$$\Phi M_{nox,y} = \Phi R_n \, f'c \, A_g h \tag{3.22}$$

where Φ is equal to the capacity reduction factor [taken as 0.9 for tension-controlled bending according to Table 21.2.2 (ACI 2014a)], h is equal to the width of the column, and all other variables have been previously defined. The algorithm considered reinforcement ratios up to 0.03, although the minimum of 0.01 was viable in both the CGI and slab roof structures.

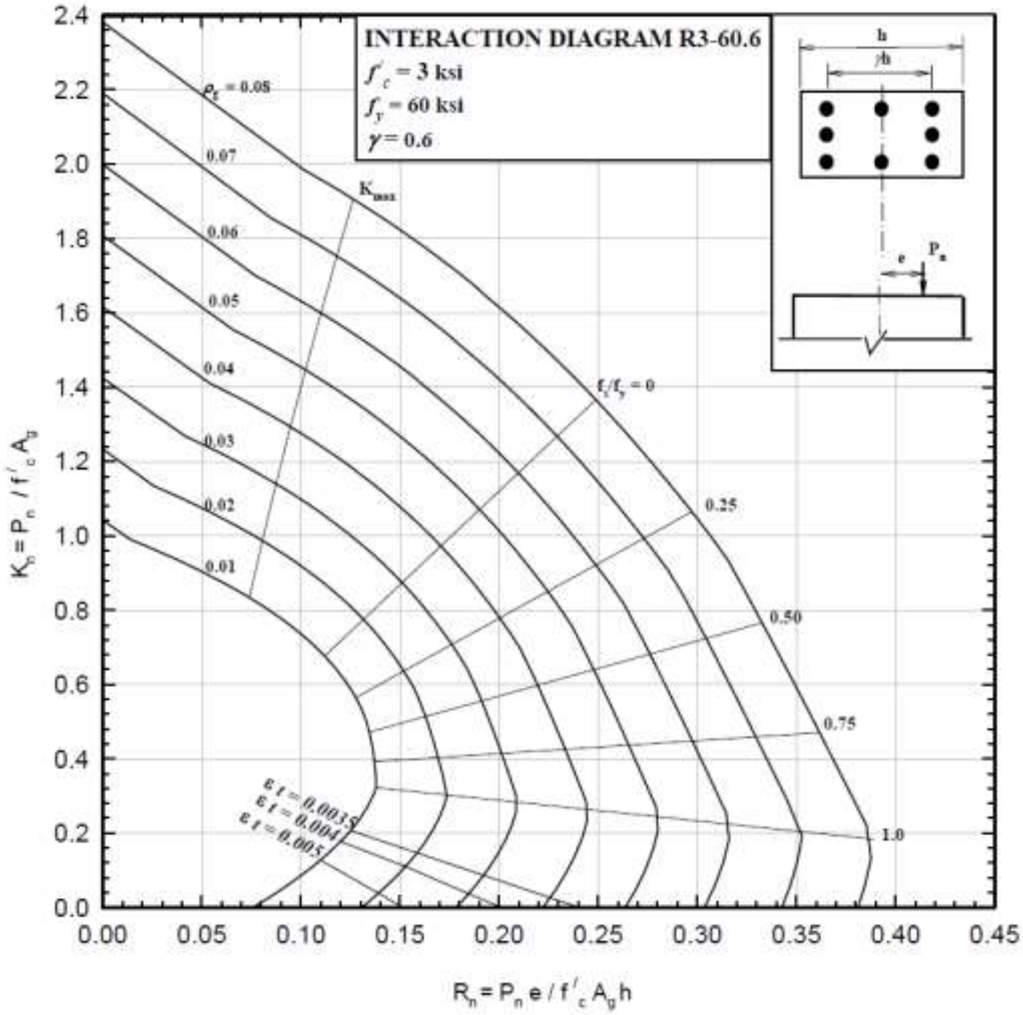


Figure 3-14: Interaction diagram utilized for column design (Image source: ACI 2014b)

Similar to the beam, the shear force demand was calculated by taking the maximum of the column shear demand based on approximate analysis and the design shear strength based on capacity design assumptions (Equation 3.19). The column shear capacity was then evaluated via ACI 318 Section 9.5.1.1 and minimum lateral tie spacing was calculated via ACI Section 18.7.5.3 (ACI 2014a).

3.1.3.4.3 Walls

Lastly, the in-plane strength of the unreinforced masonry walls was analyzed via an Equivalent Strut Analysis procedure outlined in Chapter 8 of FEMA 306 (ATC 1998). Upon application of lateral loads, it was assumed that the masonry walls form a compression strut, increasing the lateral stiffness of the frame (see Figure 3-15). Although the frame was previously designed to resist lateral forces without this increased stiffness, it is important to verify that the column can resist the additional shear force that could be applied by the wall. To calculate this potential shear load, the in-plane strength of the wall was determined by evaluating the strength of the compressive strut. This capacity (i.e., the lateral force at which the wall will fail) was then added to the shear demand of the column. Conservatively accounting for this additional shear load reduces the risk of instantaneous column shear failure upon collapse of the masonry infill wall, a common failure mode observed after the 2010 Haiti earthquake (Mix et al. 2011).

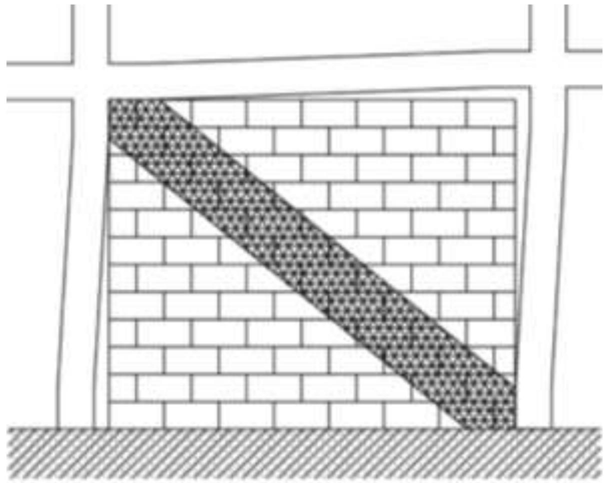


Figure 3-15: Visualization of masonry compression strut (Image credit: Structure Magazine)

The strength of the masonry compression strut, V_c, was calculated via Equation 8-10 (ATC 1998), restated below as Equation 3.23:

$$V_c = at_{inf} f'_{m90} \cos \theta \tag{3.23}$$

where α is equal to the width of the masonry strut, t_{inf} is equal to the equivalent thickness of the masonry wall, f'_{m90} is equal to the expected horizontal strength of masonry, and θ is equal to the angle of the diagonal strut.

The width of the masonry strut, α, was calculated using Equation 8-1 (ATC 1998), restated below as Equation 3.24:

$$a = 0.175(\lambda_1 h_{col})^{-0.4} r_{inf} \tag{3.24}$$

where h_{col} is equal to the column height, r_{inf} is equal to the diagonal length of the infill panel, and λ_1 was defined according to Equation 8-2 (ATC 1998), restated below as Equation 3.25:

$$\lambda_1 = \left[\frac{E_{me} t_{inf} \sin 2\theta}{4 E_{fe} I_{col} h_{inf}}\right]^{\frac{1}{4}} \tag{3.25}$$

where E_{me} is equal to the expected modulus of elasticity of the infill material in psi, E_{fe} is equal to the expected modulus of elasticity of the frame material in psi, I_{col} is equal to the moment of inertia of the column in in^4, h_{inf} is equal to the height of the infill panel in inches, and all other variables have been previously defined.

Diagonal tension failure of the panel, an alternate in-plane failure mode for masonry walls, was also checked via Equation 8-11 (ATC 1998) and found to be approximately 2.5x greater than the compression strut capacity. Thus, the compression strut failure mode governed. The strength of the compression strut, V_c, was multiplied by a factor of safety of 1.5 to account for potential variations in strength (Stavridis 2019) and was then applied as a shear force at the base of the column.

3.1.3.5 Minimum Requirements

To summarize, the RDAT was utilized to analyze 576 different structural designs with variable combinations of the parameters defined in Section 3.1.2. It was subsequently necessary to review the 576 designs and accept or reject them based on a variety of code-based criteria.

First, the reduced capacities of the beams and columns determined in Section 3.1.3.4 were compared to the demands calculated in Sections 3.1.3.2 and 3.1.3.3. If axial, moment, or shear capacity was less than the demand for any given member of a structure, that entire structure was rejected per ACI 318 Section 9.5.1.1 and 10.5.1.1 (ACI 2014a). For the columns, which were designed based on the biaxial Load Contour Method, it was verified that the uniaxial capacity was also greater than the maximum uniaxial moment demands.

Various checks were also completed regarding reinforcement. First, the spacing of longitudinal reinforcement was calculated and compared to ACI code minimums. If the existing spacing was less than the required minimums specified in ACI 318 Section 25.2.1 (ACI 2014a), the entire structure was rejected. Furthermore, beam sections were checked to ensure that they met maximum longitudinal reinforcement requirements per ACI 318 Section 9.3.3.1 (ACI 2014a). Likewise, column sections were checked to ensure that longitudinal and transverse reinforcement area fell between the minimum and maximum given by ACI 318 Section 10.6.1.1 and 10.6.2.1 (ACI 2014a). It was also verified that the beam was underreinforced by calculating the balanced steel area and comparing it to the provided longitudinal reinforcement area.

Lastly, reinforcement in the joints was checked to ensure that the design complied with special moment frame confinement guidelines. Maximum joint stirrup spacing was verified via ACI 318 Section 18.7.5.3 and minimum area of transverse steel was verified according to ACI 318 Section 18.7.5.4 (ACI 2014a). Designs that did not comply with special moment frame joint requirements were rejected.

The above restrictions were used by the RDAT to filter viable designs. ACI code restrictions regarding minimum member dimensions, such as column width, were ignored at this phase but later accounted for in Section 3.2.1.1. Of the 288 designs considered with the CGI roof, half (144) were accepted. Of the 288 designs considered with the slab roof, 90 were accepted. Thus, a total of 234 designs of the original 576 were included in the subsequent design selection process.

3.2 Design Selection

After the filtering process described in the previous section reduced the number of viable designs to 234, a more rigorous process was applied for selecting the final two designs. Each of the 234 designs accepted via the parametric analysis was evaluated and scored based on its resiliency, constructability, and cost. A three-dimensional Pareto Optimization was then utilized for both the CGI and slab roof structures to determine two sets of optimal designs. A weighting system was later applied to select the best-fit designs in the case study scenario from these optimal sets. The following sections describe these processes in detail and present the selected designs.

3.2.1 Evaluation and Scoring of Designs

Each of the 234 designs was assigned a score for its resiliency, constructability, and cost. These three categories were selected because of their importance to the sustainable success of the design in the Haitian case study scenario. First, resiliency is critical because of the high seismic risk and lack of regulation in the construction industry. Ensuring the structure is designed above the minimum requirements aims to mitigate the strength reductions introduced by potentially low quality construction materials or improper implementation. Second, constructability must be considered to account for the difference in construction technology in the case study scenario. For example, the volume of a concrete pour for a single-story structure becomes a restrictive factor when workers are mixing concrete by hand on site. Lastly, minimizing the cost is extremely critical due to the low financial capacity of aspiring homeowners and the scarcity of housing finance options in the Haitian case study scenario.

The resiliency and constructability scores were assigned from a total of 100 possible points, which were allocated based on a variety of factors explained in the subsequent sections. On the other hand, the cost "score" was simply the estimated cost of construction materials. The following sections detail the process, scoring criteria, and respective weights used to evaluate each design.

3.2.1.1 Resiliency

The resiliency score was defined to quantitatively compare the different structures' abilities to remain in use after the design event. To determine the resiliency score, factors of safety against four local failures and compliance with five code-based minimums for member cross-sectional dimensions were evaluated for each accepted design. The factors of safety were measured above the required minimum capacity-demand relationships specified by ACI 318 (ACI 2014a), meaning that a factor of safety of 1.0 indicates that the member's reduced capacity is equal to the calculated factored demand.

Factors of safety against local failure due to bending and shear stresses in both the beams and columns were evaluated by the following equation:

$$Factor\ of\ Safety = \frac{Capacity}{Demand} \tag{3.26}$$

where capacity includes the application of capacity reduction (Φ) factors and demand refers to the maximum factored demands calculated in Section 3.1.3.3. These factors of safety were then normalized on a 0 to 1 scale by dividing each by the maximum corresponding factor of safety of all structures accepted with the same roof type.

A variety of weights (listed in Table 3-13 as "Available Points") were assigned to the factors of safety. The factor of safety against column shear failure was given the highest weight, 40% of the total resiliency score, because this brittle failure mechanism was commonly observed after the 2010 Haiti earthquake and often resulted in the collapse of the entire structure (Mix et al. 2011). When calculating the column shear factor of safety, the additional load due to the formation and failure of a compression strut in the masonry wall (see Section 3.1.3.4.3) was included in the demand. Factors of safety for column bending, beam bending, and beam shear contributed significantly less to the overall resilience score, as such failure mechanisms are less likely to be catastrophic. The factors of safety for beam bending and shear were given weights of 10% each, while column bending was assigned a weight of 15%, as column failure is more likely than beam failure to result in structural collapse.

Code compliance accounted for the final 25% of the resilience score. Beam and column cross-sections were compared against ACI and Eurocode minimums (ACI 2014a; CEN 2003) and were awarded 5 percentage points for each code provision the structure met. Partial points were not awarded, meaning that a member dimension that was under the minimum received zero points, regardless of how close it was to the minimum. These criteria and corresponding point values are restated in Table 3-13.

TABLE 3-13: RESILIENCY SCORING CRITERIA

Criteria		Available Points
Code Compliance (ACI 2014a; CEN 2003)	Beam depth [ACI 318 18.6.2.1 (a)]	5
	Beam width [ACI 318 18.6.2.1 (b)]	5
	Column width [ACI 318 18.7.2.1 (a)]	5
	Beam width [CEN 8.2.5.3.1]	5
	Column width [CEN 5.5.1.2.2]	5
Factors of Safety	Beam bending	10
	Beam shear	10
	Column bending	15
	Column shear	40
	Total Possible Score	100

The minimum, maximum, median, and mean of each factor of safety, as well as the overall resilience scores, are listed in Tables 3-14 and 3-15 for the CGI roof and slab roof structures, respectively. These values are the original (unnormalized) factors of safety. Before calculating the resiliency score, each value was normalized with respect to the maximum factor of safety for the given criteria and roof type. Because the factors of safety were normalized with respect to each roof type, the resiliency scores in Table 3-14 cannot be directly compared with those of Table 3-15. However, because the factors of safety shown are unnormalized, these can be compared between tables. It also important to note that the factors of safety listed below are calculated above the code minimums, as capacity reduction (Φ) factors and factored loads were already included in the calculations of capacity and demand.

TABLE 3-14: RESILIENCE CRITERIA AND SCORE DISTRIBUTION SUMMARY – CGI ROOF

Criteria	Minimum	Median	Mean	Maximum
Beam bending factor of safety	1.48	3.09	3.23	5.98
Beam shear factor of safety	3.39	5.55	5.58	8.77
Column bending factor of safety	2.56	4.14	4.98	10.50
Column shear factor of safety	1.89	1.91	1.92	1.96
Resilience score	73.59	80.03	80.56	92.39

TABLE 3-15: RESILIENCE CRITERIA AND SCORE DISTRIBUTION SUMMARY – SLAB ROOF

Criteria	Minimum	Median	Mean	Maximum
Beam bending factor of safety	1.03	1.38	1.52	2.44
Beam shear factor of safety	2.84	3.79	3.67	4.60
Column bending factor of safety	1.64	1.98	2.93	5.89
Column shear factor of safety	1.83	1.84	1.85	1.90
Resilience score	75.34	79.86	83.10	93.42

For the CGI roof, all 144 accepted structures passed four of the five code minimum checks. The exception was ACI 318 Section 18.7.2.1(a), which states that all columns must be no smaller than 12 inches (30 cm) (ACI 2014a), of which 50% of the structures passed. The same was true for the 90 slab roof structures, except only 46.7% of the structures (42) passed ACI 318 Section 18.7.2.1(a) (ACI 2014a).

3.2.1.2 Constructability

The constructability score was defined to comparatively assess the difficulty of the construction process for each frame design. To determine the constructability score, the volume of the concrete frame pour and the spacing between longitudinal reinforcing bars was quantitatively assessed. Whether or not the beam and column were the same width also contributed to the score.

It is important to note that the constructability score applies to the primary reinforced concrete frame structure only, as both the CGI and concrete slab roofs each present unique constructability advantages and challenges. For example, the CGI roof requires significant amounts of metalwork and welding to construct the steel trusses, while the concrete slab roof requires shoring and a large concrete pour. Comparatively evaluating these substantially different construction challenges is beyond the scope of this thesis, thus roof type was not explicitly considered in the constructability score.

The volume of concrete needed for the frame pour was determined by summing the volume of all of the beams and columns in the structure. The volume was then normalized by dividing by the maximum concrete frame volume of all accepted structures with the same roof type. Furthermore, to be consistent with the spacing and beam/column dimension criteria described in the following paragraphs (for which a greater value is deemed “better”), the complement of the normalized volume was taken by subtracting the normalized volume from 1. Because concrete is generally mixed by hand on residential construction sites in Haiti and the frame must be poured in a single day, reducing the volume of the frame pour significantly decreases the difficulty of construction. Thus, the complement of the normalized pour volume was given a weight of 75%, constituting the majority of the constructability score.

The spacing between the longitudinal reinforcing bars also contributed to the constructability score. The columns and beams of the single-story home are relatively small and detailed for ductile performance, which leads to densely packed rebar cages. Furthermore, construction crews in the Haitian case study scenario are less likely to use vibrators while pouring concrete or plasticizers within the concrete mix. These factors make it difficult to pour concrete when small elements are densely reinforced, as is the case in these single-story special moment frames. Thus, the spacing between longitudinal bars in both the beam and column for each structure was measured, normalized, and assigned a weight of 10% each. It is important to note that in addition to being part of the scoring process, all reinforcement was previously designed and checked with ACI 318 requirements (ACI 2014a) in Section 3.1.3.5.

The last portion of the constructability score was attributed to the relative width of the beams and columns. If the beams and columns are the same width, the formwork for the frame is easier to construct. So, 5 points were given if the width of the beams and columns matched. Table 3-16 restates these criteria and weights.

TABLE 3-16 CONSTRUCTABILITY SCORING CRITERIA

Criteria	Available Points
Volume of frame concrete pour	75
Longitudinal rebar spacing in column	10
Longitudinal rebar spacing in beam	10
Beam and column width match	5
Total Possible Score	100

The minimum, maximum, median, and mean of the frame volume, longitudinal rebar spacing, and the overall constructability scores are listed in Tables 3-17 and 3-18 for the CGI roof and slab roof structures, respectively. The volumes and spacing dimensions presented are the original (unnormalized) values.

TABLE 3-17: CONSTRUCTABILITY CRITERIA AND SCORE DISTRIBUTION SUMMARY – CGI ROOF

Criteria	Minimum	Median	Mean	Maximum
Volume of frame concrete pour (m^3)	4.79	6.66	6.76	9.67
Long. rebar spacing in column (in)	1.45	2.33	2.37	3.28
Long. rebar spacing in beam (in)	1.38	3.25	4.22	7.50
Constructability score	12.91	36.53	35.45	49.73

TABLE 3-18: CONSTRUCTABILITY CRITERIA AND SCORE DISTRIBUTION SUMMARY – SLAB ROOF

Criteria	Minimum	Median	Mean	Maximum
Volume of frame concrete pour (m^3)	4.79	6.99	6.95	9.67
Long. rebar spacing in column (in)	1.45	2.30	2.35	3.28
Long. rebar spacing in beam (in)	1.38	2.56	3.08	7.25
Constructability score	13.07	35.45	33.83	46.96

The constructability scores are noticeably lower than the resiliency scores. This is because the complement of the normalized volume was taken, which means the maximum value (complement of normalized volume) that can be multiplied by the 75% weight was 0.5, as the minimum frame volume shown in Table 3-17 is half of the maximum frame volume.

For the CGI roof, 22% (32) of the 144 accepted structures were awarded the 5 points for having the same beam and column width. For the slab roof, 27% (24) of the 90 accepted structures were awarded the 5 points.

3.2.1.3 Cost

Thirdly, the cost of construction materials for each of the 234 accepted structures was calculated. The pricing assumptions and exchange rates used were previously detailed in Section 2.2.3 and unit costs were listed in Table 2-5. Similar to the comparative cost analysis presented in Chapter 2, this estimate only includes the cost of construction materials. Labor, equipment, tools, formwork, overhead, and other associated costs were not considered. The minimum, maximum, median, and mean of the construction material costs for both roof types are listed below in Table 3-19.

TABLE 3-19: COST DISTRIBUTION SUMMARY (IN US DOLLARS)

Roof Type	Minimum	Median	Mean	Maximum
CGI	$6,754	$7,212	$7,225	$7,848
Concrete slab	$7,172	$7,559	$7,558	$8,110

3.2.2 Pareto Optimization

A set of optimal designs was then selected from the list of accepted designs using a Pareto Optimization. Pareto Optimization is a multi-objective optimization procedure which analyzes a set of data (of two or more dimensions) and identifies the points at which one objective cannot be improved without harming another objective. This identified set of dominant designs is known as the Pareto Front (Cao 2020). In this analysis, a three-dimensional Pareto Optimization was completed based on each design's resiliency, constructability, and cost.

First, the complements of the resiliency and constructability scores were taken by subtracting each score from 100. This inversion converts these two variables to objectives for which Pareto Optimization can then search for optimal minimum values. As cost is already an objective for which minimization is the goal, a complementary inversion is not necessary. Then, a MATLAB function (Cao 2020; MATLAB 2017) was used to identify the Pareto Fronts, or sets of optimal minimal values, for the set of accepted CGI and slab roof structures. For the CGI roof, 8 of the 144 accepted designs were identified in the Pareto Front. For the slab roof, 20 of the 90 accepted designs were identified in the Pareto Front.

The best-fit design for the case study scenario was then selected from these Pareto Fronts using a categorical weighting system described in the subsequent section. The scores of all accepted designs, the Pareto Fronts, and the best-fit designs are plotted in Figures 3-16 and 3-17 for CGI and slab roof structures, respectively.

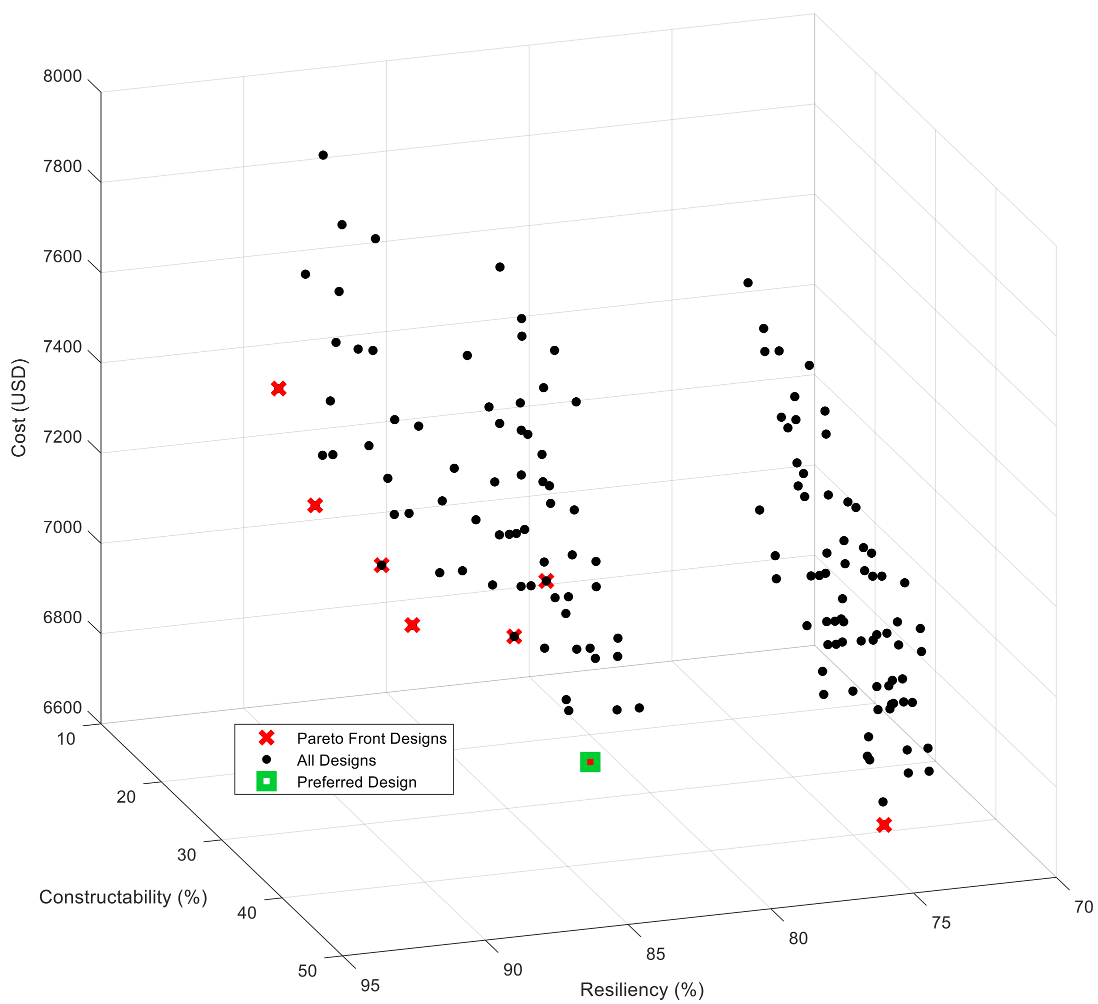


Figure 3-16: Cost, constructability, and resiliency scores of 144 accepted structures with CGI roofs

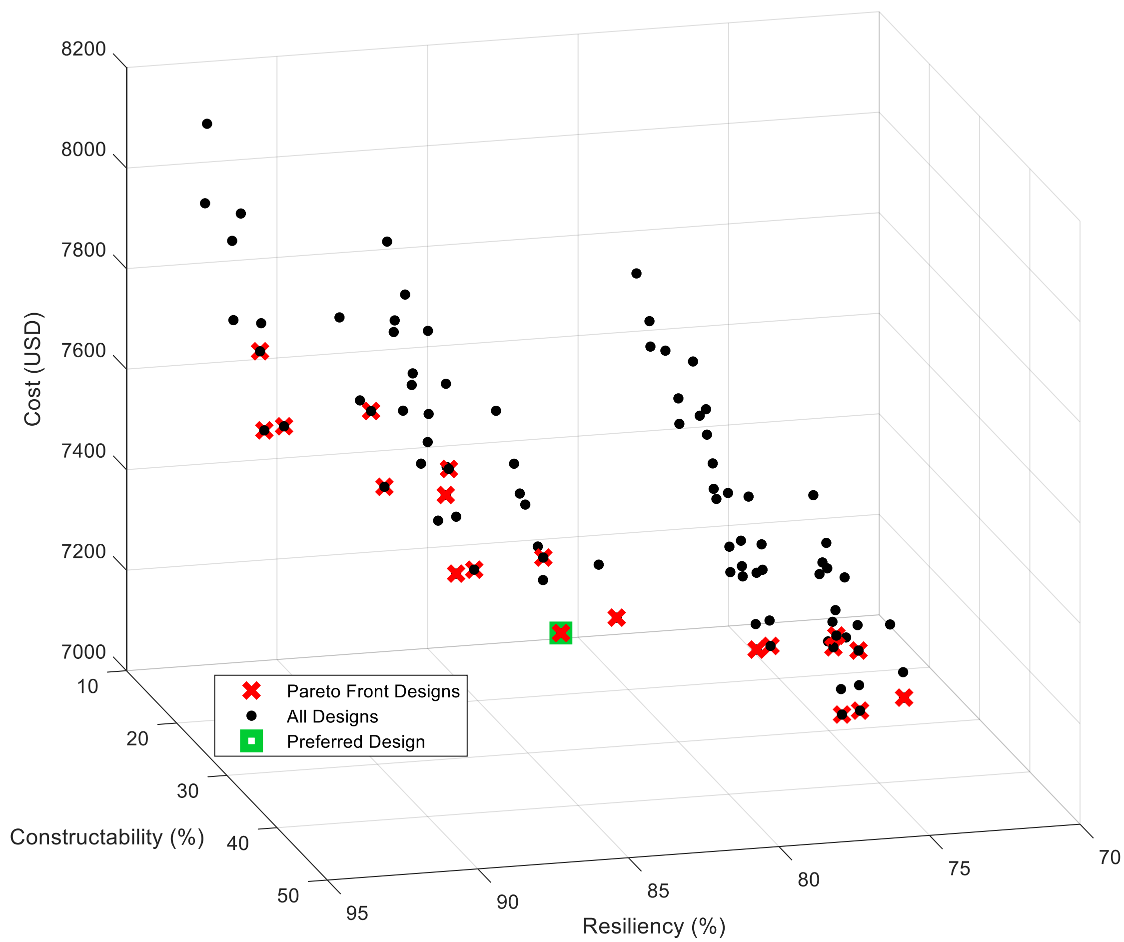


Figure 3-17: Cost, constructability, and resiliency scores of 90 accepted structures with slab roofs

3.2.3 Categorical Weighting and Selection

The designs identified in the Pareto Front in the previous section are all Pareto dominant (optimal), meaning that one of the three objectives cannot be further minimized without increasing one of the other two. Thus, it was necessary to apply a categorical weighting system to each Pareto Front to identify the best-fit design for the Haitian case study scenario.

First, each of the scores was normalized using a standard normalization procedure for multi-objective functions (see Equation 3.27). Weights were then applied to each of the three normalized scores to identify the best-fit design for the Haitian case study scenario (defined as the design with the lowest sum of weighted squared scores). The normalized cost and resiliency score were each given a weight of 0.4, while the normalized constructability score was assigned a weight of 0.2. Cost and resiliency were defined as more critical than constructability for a variety of reasons. First, it has already been confirmed through the construction of prototypes that a comparable four-room concrete frame can be mixed and poured by hand in one day in Léogâne. Second, the longitudinal rebar spacing which contributed to the constructability score already adhered to ACI 318 code requirements (ACI 2014a). These two observations indicate that the constructability score is less critical to the structure's overall fit in the Haitian case study scenario. Likewise, the heavily constrained resources of the average aspiring homeowner in Haiti, in conjunction with the high seismic risk associated with Seismic Design Category E, indicate that the cost and resiliency of the design are very critical. Lastly, it is important to note that all of the designs to which this weighting system was applied already met the minimum requirements specified in Section 3.1.3.5, thus all selection procedures presented herein are choosing among designs already identified as viable in the Haitian case study scenario. Table 3-20 restates these categorical weights.

TABLE 3-20: CATEGORICAL WEIGHTS

Score Category	**Weight**
Resiliency	0.4
Constructability	0.2
Cost	0.4

In summary, each design's cost, resiliency, and constructability scores were normalized with respect to their respective Pareto Fronts and multiplied by the weights specified above to determine each structure's Sum of Weighted Squared Scores (*SWSS*). This normalization and weighting procedure is shown in the following equation:

$$SWSS = \sum_{j=1}^{3} w_j \left[\frac{S_{ij} - \min(S_j)}{\max(S_j) - \min(S_j)} \right]^2 \tag{3.27}$$

where w_j is equal to the category weight, S is equal to the normalized cost, normalized complementary resiliency score, or normalized complementary constructability score of a specific design in the Pareto Front, i indicates the design number within the Pareto Front, and j indicates the category (cost, resiliency, or constructability) being normalized and weighted. The structure with the lowest *SWSS* was identified as the best-fit design solution for the Haitian case study scenario. The MATLAB scripts and functions utilized for the parametric analysis, Pareto Optimization, and categorical weighting process for both roof types are included in Appendix A.1, A.2, and A.3.

3.2.4 Selected Designs

The designs in both the CGI and slab roof structures' Pareto Fronts with the lowest Sum of Weighted Squared Scores (*SWSS*) were selected as the best-fit designs in the case study scenario. Tables 3-21 and 3-22 show the evaluation criteria of the selected designs in comparison with the distribution summaries previously presented in Tables 3-14, 3-15, 3-17, 3-18, and 3-19.

TABLE 3-21: SELECTED DESIGN WITH SCORING AND CRITERIA DISTRIBUTION SUMMARY – CGI ROOF

Criteria	Minimum	Median	Mean	Maximum	Selected
Beam bending factor of safety	1.48	3.09	3.23	5.98	1.51
Beam shear factor of safety	3.39	5.55	5.58	8.77	8.77
Column bending factor of safety	2.56	4.14	4.98	10.50	5.68
Column shear factor of safety	1.89	1.91	1.92	1.96	1.96
Volume of frame concrete pour (m^3)	4.79	6.66	6.76	9.67	5.53
Longitudinal rebar spacing in column (in)	1.45	2.33	2.37	3.28	3.28
Longitudinal rebar spacing in beam (in)	1.38	3.25	4.22	7.50	3.50
Resilience score	73.59	80.03	80.56	92.39	85.64
Constructability score	12.91	36.53	35.45	49.73	46.78
Cost	$6,754	$7,212	$7,225	$7,848	$6,923

TABLE 3-22: SELECTED DESIGN WITH SCORING AND CRITERIA DISTRIBUTION SUMMARY – SLAB ROOF

Criteria	Minimum	Median	Mean	Maximum	Selected
Beam bending factor of safety	1.03	1.38	1.52	2.44	1.13
Beam shear factor of safety	2.84	3.79	3.67	4.60	3.73
Column bending factor of safety	1.64	1.98	2.93	5.89	3.25
Column shear factor of safety	1.83	1.84	1.85	1.90	1.89
Volume of frame concrete pour (m^3)	4.79	6.99	6.95	9.67	6.10
Longitudinal rebar spacing in column (in)	1.45	2.30	2.35	3.28	3.28
Longitudinal rebar spacing in beam (in)	1.38	2.56	3.08	7.25	3.25
Resilience score	75.34	79.86	83.10	93.42	85.94
Constructability score	13.07	35.45	33.83	46.96	42.20
Cost	$7,172	$7,559	$7,558	$8,110	$7,370

Most factors of safety, dimensions, and scores of the selected designs fall between the center of the distribution and the desired extreme (e.g., in terms of cost, the desired extreme is the minimum) of the considered ranges. However, there are a few exceptions. For example, the column shear factor of safety was heavily weighted (0.4 within resiliency x 0.4 category weight = 0.16 total weight) and thus the selected designs' column shear factor of safety coincides with (or falls very close to, in the case of the slab roof) the distributions' maximum. Likewise, longitudinal spacing in the column also coincided with the distributions' maximum. This is an example of the coordination of several different evaluation criteria. While the scoring and weighting system favors large spacing between longitudinal rebar to increase the constructability score, utilizing fewer and smaller bars not only increases the spacing between bars, but also lowers the overall cost of construction materials. Another example is the volume of the concrete pour. The scoring and weighting system favors the minimization of both the volume of concrete and the cost of construction materials, which both effectively minimize the cross-sectional dimensions of the frame. However, the volume of the frame and the cost of construction materials for the selected design lie closer to the center of the distribution than to the minimum. This is because the resiliency criteria, as well as the longitudinal rebar spacing criteria, favor a larger, more expensive structure. These various conflicting and coordinated relationships demonstrate the need for the multi-objective optimization and selection procedure presented herein.

Table 3-23 presents the variable cross-section parameters, evaluation criteria, and scores of the two selected designs side by side.

TABLE 3-23: INPUT PARAMETERS, EVALUATION, SCORING, AND WEIGHTING OF SELECTED DESIGNS

Roof type		CGI	Slab
Input Parameters			
Column width (cm)		30	30
No. of #4 bars in column		8	8
No. of #3 bars in column		0	0
Beam width (cm)		20	20
Beam depth (cm)		25	30
No. of #4 bars in beam		0	2
No. of #3 bars in beam		2	0
Resilience Analysis			
ACI Beam height		Pass	Pass
ACI Beam width		Pass	Pass
ACI Column width		Pass	Pass
Eurocode Beam width		Pass	Pass
Eurocode Column depth		Pass	Pass
Beam bending		1.51	1.13
Beam shear		8.77	3.73
Column bending		5.68	3.25
Column shear		1.96	1.89
Constructability Analysis			
Volume of frame pour		5.53	6.10
Long. rebar spacing - column		3.28	3.28
Long. rebar spacing - beam		3.50	3.25
Column/beam width match?		No	No
Weights	**Final Scores**		
0.4	Resiliency	85.64	85.94
0.2	Constructability	46.78	42.20
0.4	Cost (USD)	6,923	7,370
Inverse Scores			
Resiliency		14.36	14.06
Constructability		53.22	57.80
Weighted Squared Norm. Scores			
Resiliency		0.06762	0.06851
Constructability		0.00339	0.01150
Cost		0.01823	0.03896
SWSS		**0.08924**	**0.11897**

Although the cost, resiliency, and constructability scores utilize normalization, which does not cross over between roof types and thus cannot be compared, several conclusions can be drawn from Table 3-23. First, the column design for both the CGI and slab roof structures are identical. Second, both selected designs pass all of the member dimension code minimums considered in the resiliency analysis. Third, all four factors of safety evaluated are higher for the CGI roof structure, indicating that it is more resilient, despite the fact that the resiliency scores are incomparable. The frame with the CGI roof can also be considered to be slightly more easily constructed, as the frame volume required is approximately 10% less (due to shallower beams) and the longitudinal rebar spacing in the beam is slightly larger. Lastly, the material cost of the best-fit structure with the CGI roof is approximately 6% less than the best-fit slab roof structure. Therefore, if only considering these three factors, the preferred choice would be the CGI roof structure. However, the slab presents other advantages in terms of durability, waterproofing, and resiliency during high wind events, which aspiring homeowners in the Haitian case study scenario may find attractive. Similarly, the construction of each presents unique challenges (metalwork and welding versus shoring and a large concrete pour), and comparatively evaluating these processes is beyond the scope of this thesis. Thus, both designs are presented.

3.3 Conclusions, Applications, and Limitations

This chapter presented the design, evaluation, and selection of two best-fit masonry-infilled reinforced concrete frame structures in the Haitian case study scenario. A Rapid Design and Analysis Tool was utilized to complete a parametric analysis. These designs were then screened against a set of minimum requirements, evaluated, and scored in three areas: resiliency, constructability, and cost. A Pareto Optimization, followed by a categorical weighting system, selected the two best-fit structures. The resulting design parameters, evaluation criteria, and scores were then presented.

Section 2.3.1 of this thesis initially presented the “cost of safety,” defined as the material cost difference between the reference unreinforced masonry structure and the masonry-infilled reinforced concrete special moment frame with a CGI roof, as $1,560. When considering the best-fit frames presented herein and applying these cross-sections to the three-room standard architectural plan utilized in Chapter 2, the cost of the comparable masonry-infilled reinforced concerete special moment frame with a CGI roof reduces from $6,145 to $5,932. Thus, this parametric analysis and selection process reduced the estimated “cost of safety” by approximately $200. However, it is again worth noting that the material cost estimation procedure utilized in this chapter and in Chapter 2 did not consider labor, equipment, supplies, and other overhead costs. Thus, a complete construction cost analysis should be completed and incorporated into this scoring and selection procedure.

The procedures presented herein can be modified in a number of ways. Because all of the accepted structures were already designed to code minimums (with the exception of minimum member dimensions, which were considered in the resiliency score), the selection framework can be openly modified to select the preferred design in different implementation scenarios (ACI 2014a). If implementation efforts in the specified Haitian case study scenario render observations that indicate the categorical or individual scoring weights need adjusted, this can easily be done. For example, if frame construction reveals that code-minimum rebar spacing does not hinder the construction process, but that a high volume of the frame pour (or a differing width of the columns and beams) does complicate the construction process more than initially expected, the maximum scores for each can be reallocated to ensure that the constructability score best reflects the actual construction process. Likewise, if observations reveal that constructability as a whole is more important than the weights in Table 3-20 indicate, these weights can also be adjusted to more accurately reflect the needs of the aspiring Haitian homeowner. The categorical weights and individual scoring weights could also be adapted to fit other case study scenarios in other developing regions.

Similarly, the RDAT itself is extremely generalized and can be adapted to accommodate different frame dimensions, numbers of bays, loads (including seismic and wind conditions), material properties, roof types, cross-section designs, and material costs. The development of the RDAT constitutes a significant contribution of this study; it allowed for a comprehensive parametric analysis to define hundreds of code-compliant home designs. Coupled with the Pareto optimization and subsequent categorical weighting, this process supported the identification of the best-fit design for a specific case study scenario. The adaptability of these processes and tools, combined with the conclusion from Chapter 2 that a masonry-infilled reinforced concrete special moment frame is the most cost effective typology, indicate that the procedures presented herein could be adapted to identify the best-fit structural design in any earthquake-prone region in which concrete is the prevailing construction material.

Although the final cross-sections presented in Table 3-23 were designed for the four-room model (see Figure 3-2), it is assumed that the designs would also be viable for the three-room model presented in Chapter 2 (see Figure 2-8) or any similar floorplan. If the selected cross-sections are utilized in an architectural plan other than the presented four-room model, the shear, axial, and moment demands should be calculated (likely via finite element model) and compared with the capacities calculated in Section 3.1.3.4 to determine whether modifications need to be made.

Likewise, it is important to note that the calculation of shear, axial, and moment demands relied on a linear analysis dependent on the portal frame assumption. In order to more definitively identify the selected designs as best-fit in the Haitian case study scenario, more robust nonlinear finite element modeling should be utilized to verify the performance of the selected designs under different demand scenarios. Consequentially, the following chapter presents a performance assessment of the selected designs via nonlinear static analysis in SAP2000.

CHAPTER 4: PERFORMANCE ASSESSMENT

This chapter presents the parameters, methodology, and results of nonlinear static pushover analyses of the best-fit designs selected in the previous chapter. It first discusses the properties of the eight planar frames analyzed, including roof types, presence of infill, and loads. Then, the methodology for modeling the masonry infill walls as equivalent struts is presented, along with the introduction of nonlinearity to the planar frames via flexural (in the frame elements) and axial (in the struts) plastic hinges. It then explains the nonlinear static pushover analysis procedure and the process for calculating the target roof displacement expected due to both the Design Basis Earthquake and the Maximum Considered Earthquake hazards. The expected performance levels of the planar frames and plastic hinges due to each hazard is then presented. The chapter concludes with a discussion of the results and their implications.

4.1 Modeling Approach

The two structures designed and selected in the previous chapter were modeled in SAP2000 as a set of planar frames. Eight different planar frames, representing variable combinations of building axes, roof types, and infill levels, were modeled in SAP2000. Masonry-infilled walls were modeled as equivalent struts, and axial plastic hinges were included at the midspan of each strut to account for nonlinear behavior. Nonlinear flexural hinges were also included at the ends of each beam and column. Figure 4-1 shows the frame, equivalent struts, and nonlinear hinge locations for an infilled x-axis frame.

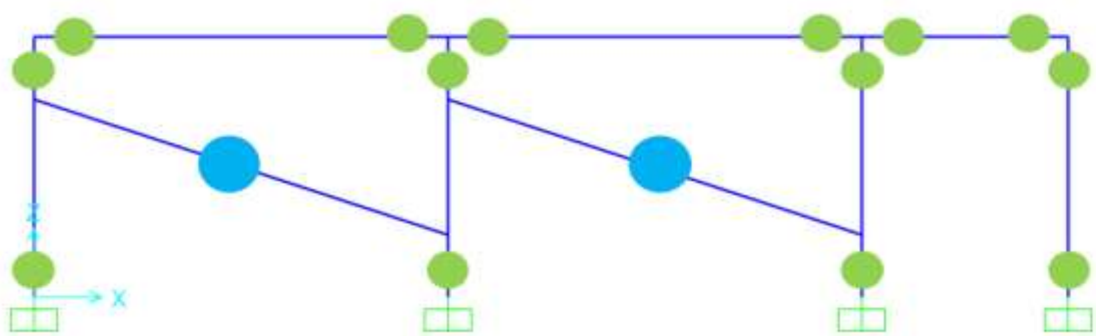


Figure 4-1: SAP2000 model of an x-axis infilled frame (Frames #4 and #8) with locations of nonlinear hinges shown with green (flexural) and blue (axial) circes

In conjunction with the use of planar frames, out-of-plane contributions to stiffness and strength were ignored in this analysis. While masonry infills can largely increase the in-plane stiffness and strength of a structure (Al-Chaar 2002), out-of-plane strength of masonry walls relies on arching action and masonry tensile stress. Due to the weak masonry blocks and informal construction practices, it is assumed that the walls would fail out-of-plane (Jensen 2016). Therefore, out-of-plane contributions were ignored and the nonlinear static procedure was applied to planar frames.

In all, eight planar frames were modeled. Frames in both the x- (three bays) and y-axis (two bays) were modeled from both the selected CGI and slab roof structures. Likewise, both infilled and empty frames were modeled to account for in-plane shaking after potential out-of-plane failure of the masonry walls. Furthermore, infilled and empty frames represent the two extremes of the equivalent strut assumption, which is further discussed in the next section. Table 4-1 describes the labeling of these eight frames and their characteristics.

TABLE 4-1: CHARACTERISTICS OF PLANAR FRAMES

Frame Number	**Frame Label**	**Roof**	**Axis**	**Wall**
1	SYE	Slab	Y	Empty
2	SYI	Slab	Y	Infilled
3	SXE	Slab	X	Empty
4	SXI	Slab	X	Infilled
5	CYE	CGI	Y	Empty
6	CYI	CGI	Y	Infilled
7	CXE	CGI	X	Empty
8	CXI	CGI	X	Infilled

The dimensions and cross-sectional designs of both frames were defined and selected in the previous chapter and can be found in Sections 3.1.2.1.1 and 3.2.4. The critical frame in each axis, previously defined in Section 3.1.3.2, was selected from each structure for analysis. An “equal” constraint was applied to the top joints in the four frames with the slab roof to model the diaphragm assumption. However, the CGI roof was not assumed to be stiff enough to warrant the diaphragm assumption.

Gravity loads were then applied to each frame as described in Section 3.1.3.1. Self-weights of the beams and columns were included in the models. Likewise, because the analysis considered planar frames, point loads were added at each beam-column intersection to account for the weight of the beams (and their tributaries) perpendicular to the modeled frame. Loads from the roof slab were applied as triangular distributed loads along the beams. As noted in Section 3.1.3.1, the trusses that support the CGI roof are supported by the y-axis beams only. Thus, no roof loads were included on the x-axis beams with the CGI roof (Frames #7 and #8). The distributed dead load on the strut was calculated by dividing the weight of half of the masonry wall by the length of the strut. However, the self-weight of the strut itself was neglected in the model, as it is not a physical component of the frame. In addition to the dead load, 30% of the roof live load was conservatively included in the analysis.

4.1.1 Equivalent Strut Methodology

The use of equivalent struts to model the strength and stiffness contributions of masonry infills is widely accepted as a good modeling practice (Panagiotakos and Fardis 1996; ATC 1998; Uva et al. 2012; Jensen 2016; ASCE 2017; Basha et al. 2020). The Equivalent Strut Analysis procedure outlined in Chapter 8 of FEMA 306 (ATC 1998), used in the RDAT in the previous chapter, was adapted for this purpose. The equivalent strut width, α, was previously defined in Equation 3.24. Calculations for the equivalent strut width, taken as 20.55 inches for all walls, can be found in the previously mentioned RDAT (see Section 3.1.3).

This strut, assumed to be pinned at both ends, was attached to the columns as shown in Figure 4-1. Rather than be placed at the extreme top and bottom ends of the column, an offset distance, l_{ceff}, of 23.54 inches was defined by FEMA 356 Equation 7-16 (FEMA 2000), restated below as Equation 4-1:

$$l_{ceff} = \frac{a}{\cos\theta_c} \tag{4.1}$$

where $\tan\theta_c$ is defined as:

$$\tan\theta_c = \frac{h_{inf} - \frac{a}{\cos\theta_c}}{L_{inf}} \tag{4.2}$$

with h_{inf} and L_{inf} being equal to the height and length of the infill wall, respectively. FEMA 356 Section 7.5.2.3.1 (FEMA 2000) requires that the columns adjacent to an infill strut can withstand the application of the horizontal component of the expected infill strut force, which was included in the design and analysis in the previous chapter (see Section 3.1.3.4.3). Likewise, the column shear strength is also required to be greater than the shear force resulting from the development of expected column flexural strengths at the top and bottom of a column with the reduced height calculated above (FEMA 2000), which was also verified in the attached RDAT.

Previous studies also include various reduction factors which are applied to the equivalent strut width to account for window and door openings, existing damage, material quality, and limited connectivity between wall panels and columns (Al-Chaar 2002; Jensen 2016; Basha 2020). However, the accurate use of such reduction factors requires detailed knowledge about the masonry walls being analyzed, including the number, size, and location of windows and doors, the quality of materials and craftsmanship, and any existing damage. Likewise, homes in the Haitian case study scenario generally have minimal amounts of small windows for security purposes. Furthermore, these windows are generally reinforced with security bars, giving the window an unknown, but presumably quite high, degree of stiffness. Because these criteria will vary significantly, this analysis, like in the previous chapter, does not include the use of any strut width reduction factors. Instead, this study considers the two extreme cases: (1) infilled frame with the full strut width calculated in Equation 3.24 and (2) a corresponding empty frame without a strut. As shown in Figure 4-2, as strut width increases, both initial and post-yield stiffness increases. Similarly, reducing strut width increases the deformation capacity of the structure. Thus, the analysis of a full, unreduced strut and an empty frame captures the entire range of stiffness and ductility of the various struts considered in Figure 4-2.

It is also important to note that the nonlinear static analysis does not account for the transfer of shear forces into column after failure of the masonry wall, but manual calculations in the previous chapter were completed to check that the column could resist the shear transfer.

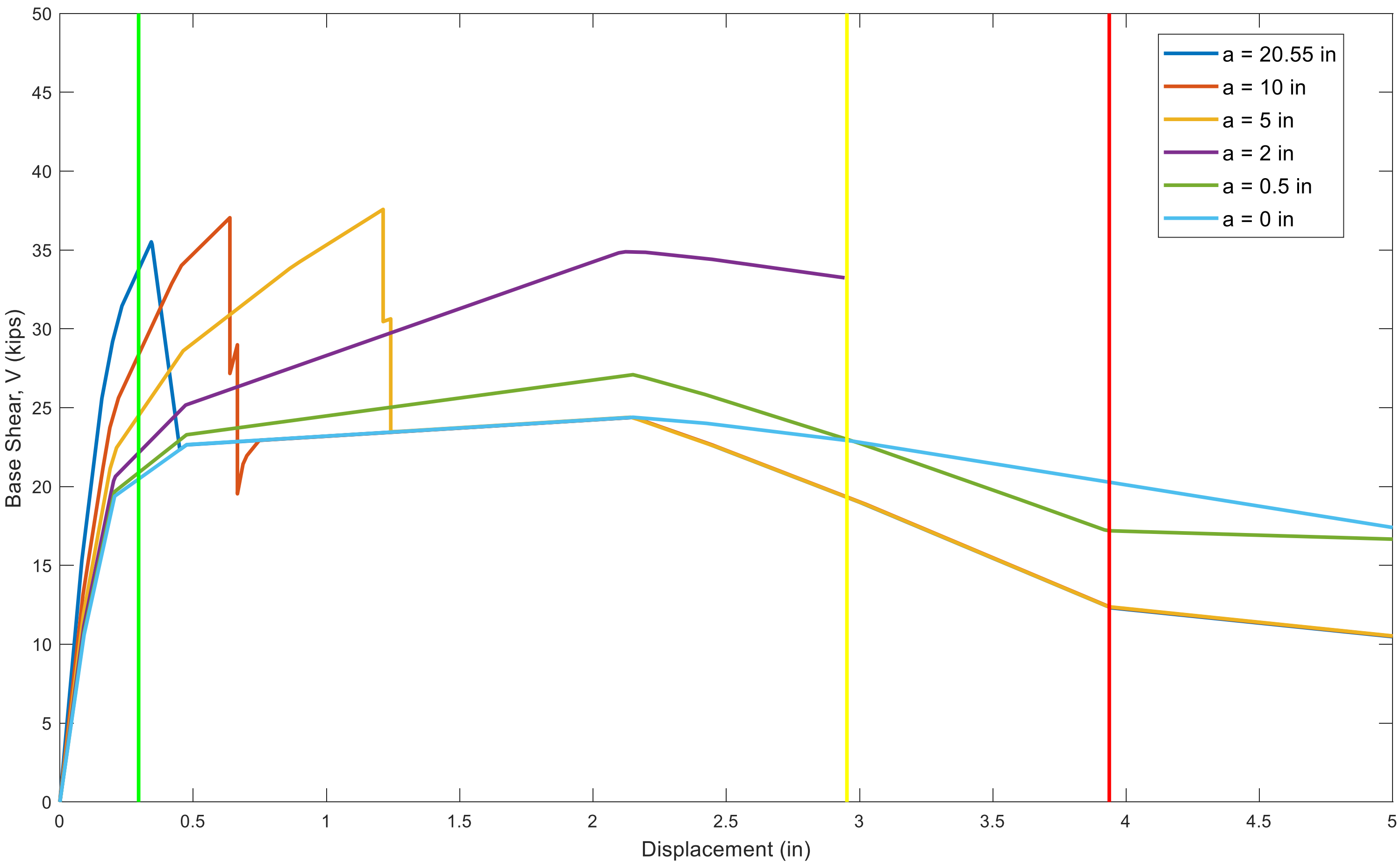


Figure 4-2: Pushover curves of Frame 2-SYI with varying infill widths, *a*. The green, yellow, and red lines mark Immediate Occupancy, Life Safety, and Collapse Prevention, respectively (see Section 4.1.2).

4.1.2 Nonlinear Hinge Methodology

The introduction of nonlinear hinges to the models follows standard approaches defined by FEMA 356 (FEMA 2000) and ASCE 41-17 (ASCE 2017). Details are similar to Jensen (2016), which examined pushover analyses for a similar type of structure in the same geographical region. Nonlinear behavior was modeled through the use of flexural and axial plastic hinges assigned to frame and strut elements according to backbone curves recommended by FEMA 356 (FEMA 2000) and Panagiotakos and Fardis (1996), respectively.

Plastic hinges followed the general backbone curve presented in Figure 4-3, which is composed of four regions: linear elastic range (A-B), positive post-yield range (B-C), negative post-yield range (C-D), and residual strength range (D-E). Likewise, three performance levels are considered in these analyses: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). All three of these are defined within the positive post-yield range for flexural hinges (see Figures 4-4, 4-5, and 4-6), while Life Safety and Collapse Prevention fall on the negative post-yield portion of the axial hinge force-displacement curve (see Figure 4-8). These performance levels will later be used to assess the performance of each frame under specified seismic demands.

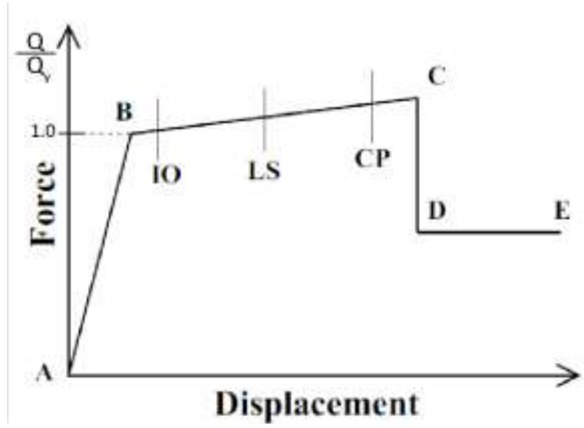


Figure 4-3: Generalized backbone curve adopted for nonlinear plastic hinges with targeted performance levels (Image credit: Computers and Structures, Inc.)

Nonlinear behavior was accounted for in the beams and columns using flexural plastic hinges, defined by a characteristic moment-curvature relationship. Backbone curves were generated for each element automatically in SAP2000 using ASCE 41-17 Tables 10-7 and 10-8 (ASCE 2017) based on the member's steel reinforcement, cross-sectional geometry, and material properties. Figure 4-4 shows the backbone curve for the flexural hinge placed at the top and bottom of all columns. Because the beam cross-sections vary based on roof type (see Section 3.2.4), the resulting backbone curves also vary. Thus, Figures 4-5 and 4-6 show the backbone curves for the flexural hinges for the beams with the slab and CGI roof, respectively.

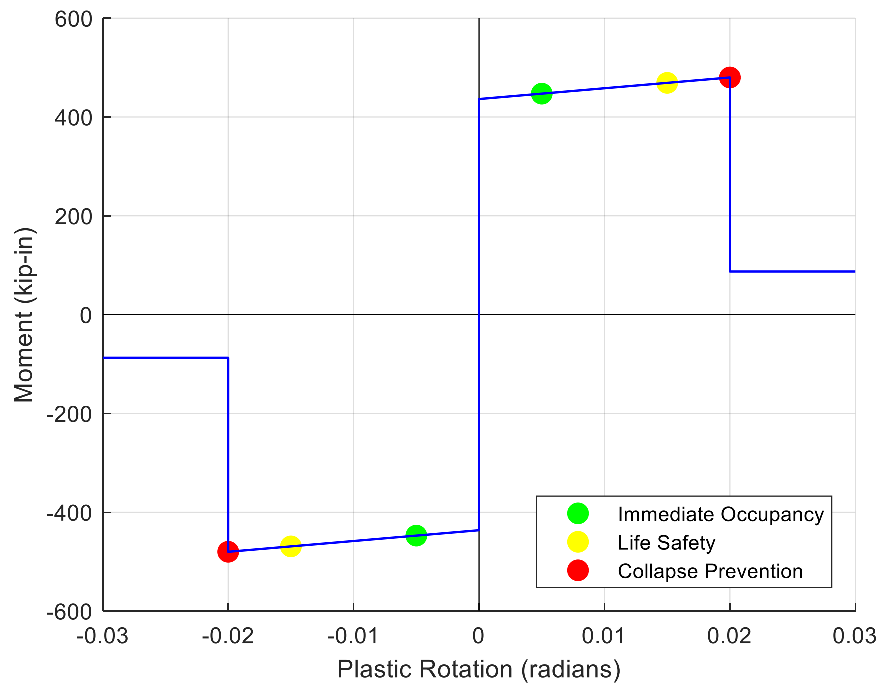


Figure 4-4: Backbone curve of flexural hinge placed at top and bottom of all columns in all models

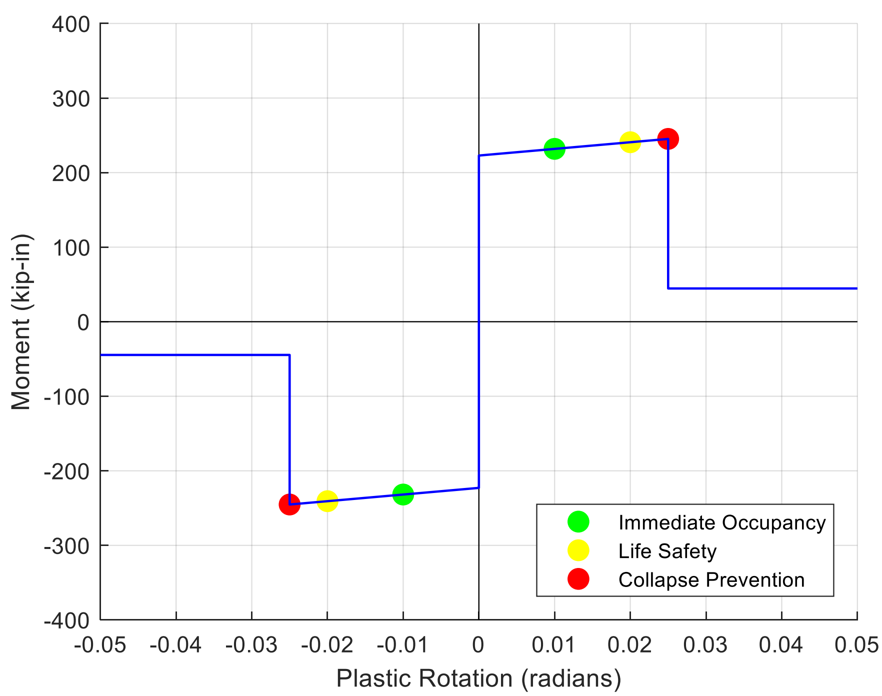


Figure 4-5: Backbone curve of flexural hinge placed at both ends of all beams in frames with a slab roof (Frames #1 through #4)

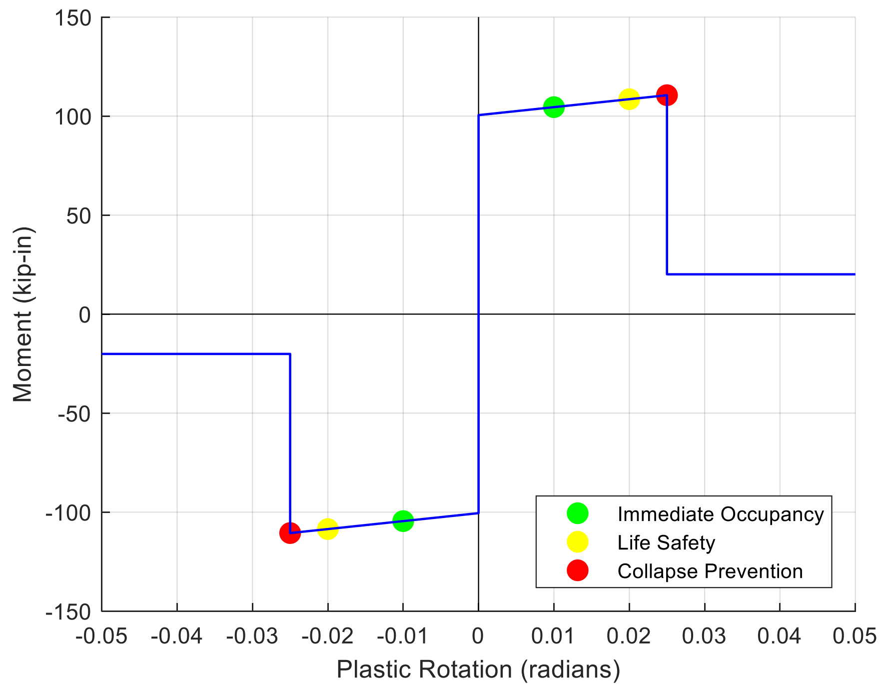


Figure 4-6: Backbone curve of flexural hinge placed at both ends of all beams in frames with a CGI roof (Frames #5 through #8)

Nonlinear behavior was accounted for in the equivalent struts through axial plastic hinges placed at midspan. These hinges were defined by a force-displacement relationship validated by experimental cyclic tests (Panagiotakos and Fardis 1996). The Panagiotakos and Fardis (1996) model was selected because it exclusively focuses on the diagonal tension strength of the panel, unlike another commonly used model (Bertoldi et al. 1993), which takes into account multiple failure mechanisms (Uva et al. 2012). Thus, the Panagiotakos and Fardis (1996) model can potentially overestimate the strength of the panel, which is consistent with this study's adoption of the two extremes (unreduced strut and empty frame) mentioned in the previous section. This backbone curve is shown in Figure 4-7 and is made up of four segments: the initial shear behavior of the uncracked panel (with stiffness K_1), the formation of the equivalent strut in the panel (with stiffness

K_2), the softening response of the panel (with negative stiffness K_3), and the final, or residual, resistance of the panel. In this study, however, it is assumed that the residual stiffness is zero and thus the backbone curve only consists of three segments.

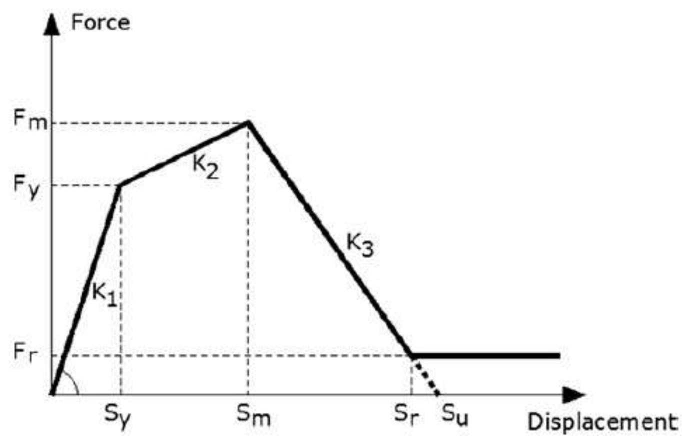


Figure 4-7: The force-displacement relationship proposed by Panagiotakos and Fardis (1996) (Image source: Uva et al. 2012)

The parameters that define the force-displacement relationship shown in Figure 4-7 can be defined by a series of equations presented by Uva et al. (2012). The initial stiffness, K_1, was defined as:

$$K_1 = \frac{G_W t_W L_W}{H_W} \tag{4.3}$$

where t_W, L_W, and H_W are equal to the thickness, length, and height, respectively, of the masonry panel and G_W is equal to the shear modulus of the masonry, which was defined as:

$$G_W = 0.4\, E_m \tag{4.4}$$

based on TMS 402-11 Section 1.8.2.2.2 (TMS 2011), where E_m is equal to the modulus of elasticity of the masonry panel. The yield force corresponding to the first cracking of the panel, F_y, was defined as:

$$F_y = f_{tp} t_W L_W \tag{4.5}$$

where f_{tp} is equal to the tensile strength of the panel. Because diagonal compression test results were not available, TMS 402-11 Table 2.2.3.2 (TMS 2011) was used to estimate this value. Mortar Type M was assumed (Build Change 2011a). The corresponding displacement at yielding, S_y, was calculated via the following equation:

$$S_y = \frac{f_y}{K_1} \tag{4.6}$$

where all variables have been previously defined. The axial stiffness of the equivalent strut, K_2, was defined as:

$$K_2 = \frac{E_m a t_W}{d} \tag{4.7}$$

where d is equal to the diagonal length of the panel and all other variables have been previously defined. The maximum force, F_m, was assumed to be $1.3F_y$ (Uva et al. 2012), and the corresponding displacement at maximum force was calculated as:

$$S_m = S_y + \frac{F_m - F_y}{K_2} \tag{4.8}$$

The residual force, F_r, was assumed to be zero and the ultimate displacement, S_u, was assumed to be $5S_m$ (Dolšek and Fajfar 2005; Dolšek and Fajfar 2008). Table 4-2 presents the corresponding values for these parameters.

TABLE 4-2: AXIAL PLASTIC HINGE BACKBONE CURVE PARAMETERS

Parameter		**Value**	**Units**
Shear modulus of masonry panel	G_W	156.8	ksi
Elastic modulus of masonry	E_m	392	ksi
Thickness of masonry panel	t_W	2.13	inches
Height of masonry panel	H_W	98.43	inches
Length of masonry panel	L_W	157.28	inches
Initial stiffness	K_1	534.35	kips/inch
Tensile strength of masonry panel	f_{tp}	33	psi
Yield force of masonry panel	F_y	11.07	kips
Yielding displacement	S_y	0.0207	inches
Axial stiffness of equivalent strut	K_2	103.36	kips/inch
Width of equivalent strut	a	20.55	inches
Diagonal length of masonry panel	d	166	inches
Maximum force	F_m	14.39	kips
Displacement at maximum force	S_m	0.0528	inches
Residual force	F_r	0	kips
Ultimate displacement	S_u	0.2641	inches

The plastic hinge described above was placed at the midspan of all struts in the SAP2000 models. The backbone curve for this plastic hinge is shown in Figure 4-8.

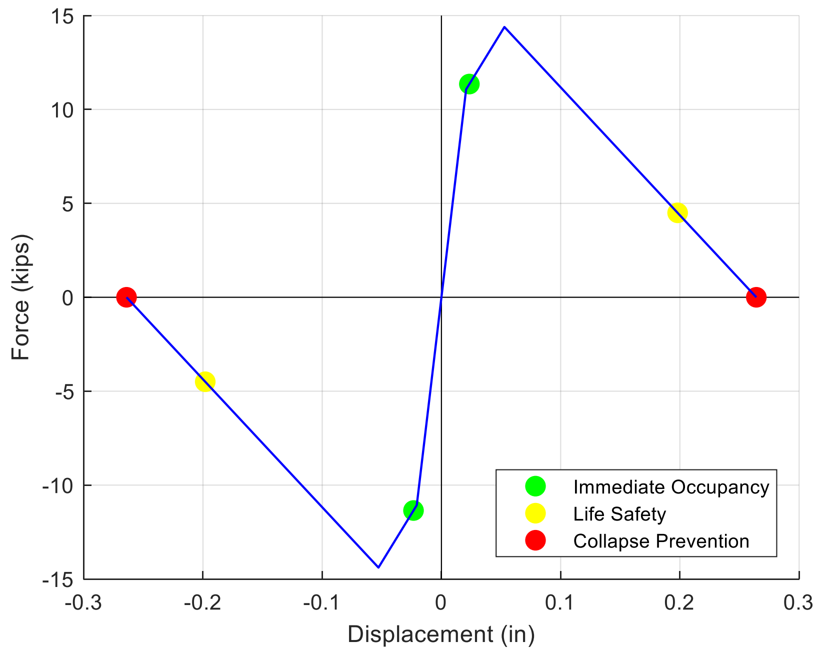


Figure 4-8: Backbone curve of axial plastic hinge placed at midspan of all equivalent struts in all models

To help with numerical convergence, SAP2000 automatically limits strength degradation, indicated by the negative post-yield slope of the backbone curve, to 10% (CSI 2015). Thus, the author utilized SAP2000's "hinge overwrite" function to manually decrease the size of the frame element and thus increase the steepness of the negative post-yield portion of the axial hinge backbone.

Acceptance criteria for the three performance levels were defined both globally (for the entire frame) and locally (for specific structural elements) according to Chapters 10 and 11 of ASCE 41-17 (ASCE 2017). Acceptance criteria for the global pushover curve were calculated based on ASCE 41-17 Table 10-17 (ASCE 2017). Local acceptance criteria for the equivalent struts' axial plastic hinge were calculated based on ASCE 41-17 Table 11-13 (ASCE 2017) and are noted in Figure 4-8. This procedure was adapted slightly to fit with the Panagiotakos and Fardis (1996) model, with assumptions and deviations as follows:

1) It was assumed that the column shear strength to masonry panel shear strength ratio, β, was greater than 0.7 due to the aforementioned low quality of masonry construction in the Haitian case study scenario.

2) Displacement at which residual strength is reached, Δ_{res}, was set equal to the ultimate displacement, S_u, defined by Panagiotakos and Fardis (1996).

Lastly, the acceptance criteria for the flexural hinges in the beams and columns were taken directly from ASCE 41-17 Tables 6-7 and 6-8, respectively, via SAP2000 (ASCE 2017) and are noted in Figures 4-4, 4-5, and 4-6.

4.1.3 Materials

The materials used in this analysis are consistent with those previously described in Sections 2.2.2 and 3.1.2.1.2. The concrete for the structural frame was modeled isotropically via the Mander et al. (1988) model. Table 4-3 lists the concrete material parameters, and Figure 4-9 shows the corresponding stress-strain relationship.

TABLE 4-3: CONCRETE MODELING PARAMETERS

Parameter		Value	Units
Modulus of elasticity	E	3122	ksi
Poisson ratio	v	0.2	-
Design compressive strength	f'_c	3	ksi
Shear modulus	G	1301	ksi

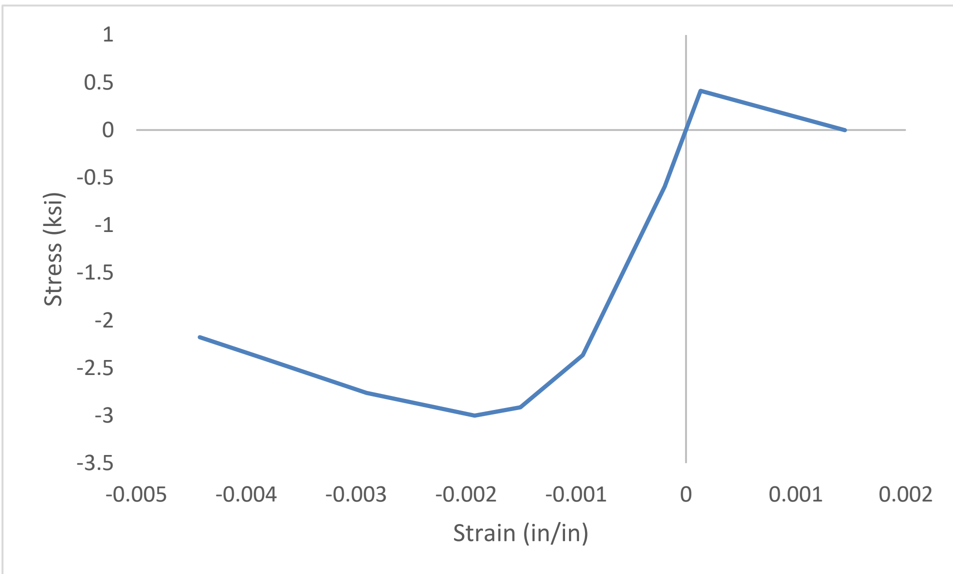


Figure 4-9: Stress-strain relationship for 3 ksi concrete

The material comprising the equivalent strut was also modeled isotropically via the Mander et al. (1988) model, with design compressive strength (f'_c) corresponding to the compressive strength of the masonry panel (f'_m). Table 4-4 lists the strut material parameters, and Figure 4-10 displays the corresponding stress-strain relationship.

TABLE 4-4: MASONRY STRUT MODELING PARAMETERS

Parameter		Value	Units
Modulus of elasticity	E	392	ksi
Poisson ratio	v	0.2	-
Design compressive strength	f'_c	560	psi
Shear modulus	G	163.3	ksi

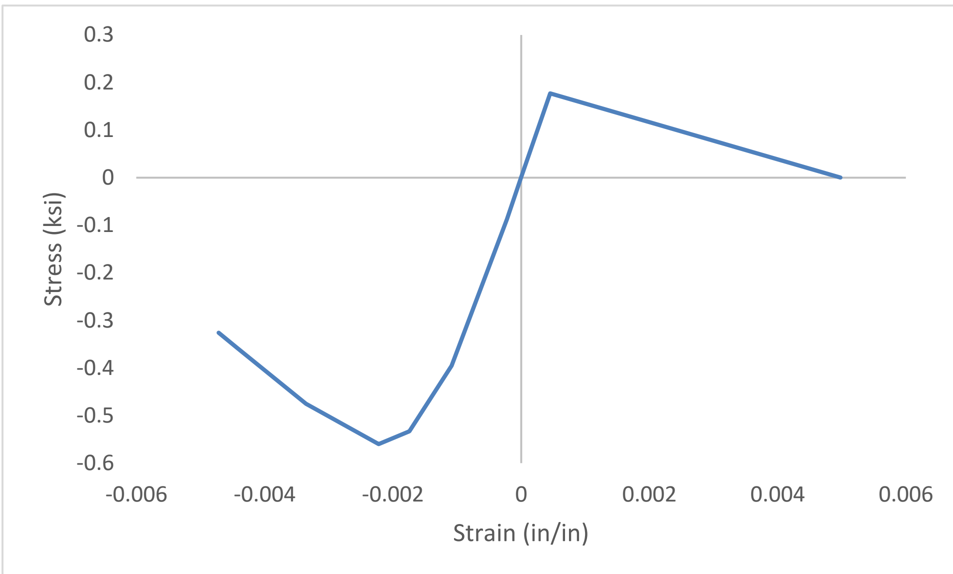


Figure 4-10: Stress-strain relationship for equivalent strut

Steel reinforcement was taken as grade 60 and was modeled with uniaxial symmetry. Table 4-5 shows the steel material parameters specified in SAP2000, and Figure 4-11 displays the corresponding stress-strain relationship.

TABLE 4-5: STEEL MODELING PARAMETERS

Parameter		Value	Units
Modulus of elasticity	E	29000	ksi
Poisson ratio	v	0.3	-
Minimum yield stress	F_y	60	ksi
Minimum ultimate tensile stress	F_u	90	ksi
Shear modulus	G	11154	ksi

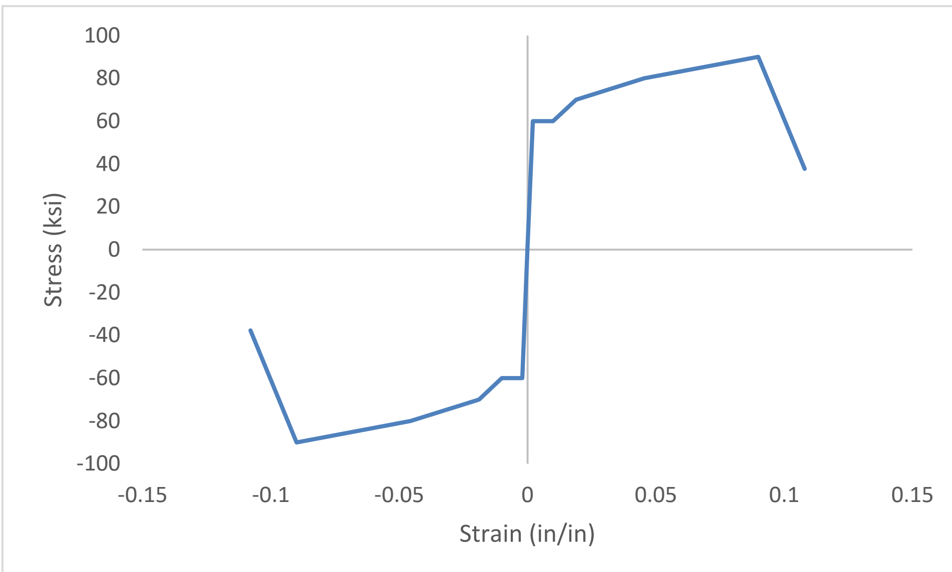


Figure 4-11: Stress-strain relationship for grade 60 steel

4.2 Nonlinear Static Analysis Methodology

After the planar frame models were assembled with the previously described equivalent struts, nonlinear hinges, and materials, a nonlinear static analysis, also known as a pushover analysis, was performed according to FEMA 356 Section 3.3.3 (FEMA 2000). This procedure was selected due to its applicability with low-rise regular buildings in which the response is dominated by the fundamental mode (NIST 2010). Furthermore, the incremental procedure of the nonlinear static analysis is particularly useful for analyzing yielding mechanisms (NIST 2010).

First, the gravity load was applied to the frame as described in Section 4.1. Then, a lateral load point load, applied at the top of the leftmost column of the frame, was monotonically increased. This load application was displacement controlled and continued until a specified control node along the roof (the top of the leftmost column) translated to a specified final displacement. The resulting load-displacement curve can be utilized to determine the seismic demands and corresponding performance levels (Immediate Occupancy, Life Safety, and Collapse Prevention) due to specific earthquake parameters. By comparing the calculated target displacement (expected roof displacement during a specific seismic event) with the acceptance criteria for various performance levels, one can determine the expected performance level after a specific seismic event.

A five-inch final displacement was used for the analysis, as presented in Section 4.3. However, one-inch pushover curves were utilized for the bilinear idealization, as the increased density of points at the lower displacements increases the accuracy of the numerical procedure and all target displacements calculated were less than one inch.

The seismic demand was determined for each frame via FEMA 356 Section 3.3.3.3.2 (FEMA 2000). A target displacement, δ_t, was calculated by Equation 4.9, which incorporates the nonlinear load-deformation relationship from the pushover curve as well as the seismic hazard:

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g \tag{4.9}$$

where:

C_0 = Modification factor to relate spectral displacement of an equivalent SDOF system to the roof displacement of the building MDOF system

C_1 = Modification factor to relate expected minimum inelastic displacements to displacements calculated for linear elastic response

C_2 = Modification factor to represent the effect of pinched hysteretic shape, stiffness degradation, and strength degradation on maximum displacement response

C_3 = Modification factor to represent increased displacements due to dynamic P-Δ effects

S_a = Response spectrum acceleration, at the effective fundamental period and damping ratio of the building in the direction under consideration (g)

T_e = Effective fundamental period of the building in the direction under consideration (seconds)

g = Acceleration of gravity

This equation was used to calculate a target displacement for each of the eight frames defined in Section 4.1 for both the Design Basis Earthquake (DBE) hazard, with a return period of 475 years, and the Maximum Considered Earthquake (MCE) hazard, with a return period of 2475 years. The DBE spectral accelerations were defined according to ASCE 7-16 Section 11.4.5 (ASCE 2016) by multiplying the MCE spectral accelerations by 2/3. Tables 4-6 and 4-7 present these tabulated. In all cases, 5% damping was assumed, meaning that damping coefficients B_s and B_1 are both equal to 1.0 according to FEMA 356 Table 1-6 (FEMA 2000). Likewise, site coefficients F_a and F_v

were set to 1.0 and 1.5, respectively, according to FEMA 356 Tables 1-4 and 1-5 (FEMA 2000). The effective mass factor, C_m, was set to 1.0 according to FEMA 356 Table 3-1 (FEMA 2000). Lastly, coefficient C_3 was set to 1.0 in all cases (meaning that post-yield stiffness was always assumed to be positive, despite the fact that post-yield stiffness coefficient, α, is in fact negative in three cases) based on the assumption that P-Δ effects would be negligible for a single-story structure.

TABLE 4-6: TARGET DISPLACEMENT CALCULATIONS FOR DESIGN BASIS EARTHQUAKE

Frame Number and Label	**1SYE**	**2SYI**	**3SXE**	**4SXI**	**5CYE**	**6CYI**	**7CXE**	**8CXI**	**Source**
C_0	1	1	1	1	1	1	1	1	FEMA 356 Table 3-2
Elastic Fundamental Period, T_i (sec)	0.172	0.139	0.158	0.135	0.099	0.081	0.092	0.069	SAP2000 Models
Elastic Lateral Stiffness, K_i	116.8	185.5	174.2	246	93.35	154.4	133.8	255.2	FEMA 356 Fig 3-1
Effective Lateral Stiffness, K_e	111.0	169.9	174.2	246.5	93.0	152.5	131.0	255.1	FEMA 356 Fig 3-1
Post-yield Slope Coefficient, α	0.070	-0.145	0.088	0.163	0.697	0.852	2.372	1.001	FEMA 356 Fig 3-1
Effective Fundamental Period, T_e (sec)	0.177	0.145	0.158	0.135	0.099	0.081	0.093	0.069	FEMA 356 Eqn 3-14
Short Period Spectral Acceleration, S_S	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	USGS 2015
1s Period Spectral Acceleration, S_1	0.527	0.527	0.527	0.527	0.527	0.527	0.527	0.527	USGS 2015
Design Short Period Sp. Resp. Acc., S_{XS}	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	FEMA 356 Eqn 1-4
Design 1s Period Sp. Resp. Acc., S_{X1}	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	FEMA 356 Eqn 1-5
Characteristic Period, T_s (sec)	0.627	0.627	0.627	0.627	0.627	0.627	0.627	0.627	FEMA 356 Eqn 1-11
T_0(sec)	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	FEMA 356 Eqn 1-12
Response Spectrum Acceleration, S_a	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	FEMA 356 Eqn 1-8,9,10
Yield strength, V_y (kips)	19.33	34.79	26.55	35.26	9.48	13.67	21.99	13.12	FEMA 356 3.3.3.2.4
Elastic Strength Demand Ratio, R	7.319	4.066	5.327	4.011	6.764	4.691	2.916	4.886	FEMA 356 Eqn 3-16
C_1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	FEMA 356 3.3.3.3.2
C_2	1	1	1	1	1	1	1	1	FEMA 356 Table 3-3
C_3	1	1	1	1	1	1	1	1	FEMA 356 Eqn 3-17
Target Displacement, δ_t (in)	**0.577**	**0.390**	**0.462**	**0.336**	**0.182**	**0.122**	**0.160**	**0.088**	FEMA 356 Eqn 3-15

TABLE 4-7: TARGET DISPLACEMENT CALCULATIONS FOR MAXIMUM CONSIDERED EARTHQUAKE

Frame ID	1SYE	2SYI	3SXE	4SXI	5CYE	6CYI	7CXE	8CXI	Source
C_0	1	1	1	1	1	1	1	1	FEMA 356 Table 3-2
Elastic Fundamental Period, T_i (sec)	0.172	0.139	0.158	0.135	0.099	0.081	0.092	0.069	SAP2000 Models
Elastic Lateral Stiffness, K_i	116.8	185.5	174.2	246	93.35	154.4	133.8	255.2	FEMA 356 Fig 3-1
Effective Lateral Stiffness, K_e	107.8	170.4	174.2	241.9	93.1	152.8	132.9	255.1	FEMA 356 Fig 3-1
Post-yield Slope Coefficient, α	0.028	-0.196	0.039	-0.191	0.340	0.703	0.484	0.912	FEMA 356 Fig 3-1
Effective Fundamental Period, T_e (sec)	0.179	0.145	0.158	0.136	0.099	0.081	0.092	0.069	FEMA 356 Eqn 3-14
Short Period Spectral Acceleration, S_S	1.89	1.89	1.89	1.89	1.89	1.89	1.89	1.89	USGS 2015
1s Period Spectral Acceleration, S_1	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	USGS 2015
Design Short Period Sp. Resp. Acc., S_{XS}	1.89	1.89	1.89	1.89	1.89	1.89	1.89	1.89	FEMA 356 Eqn 1-4
Design 1s Period Sp. Resp. Acc., S_{X1}	1.185	1.185	1.185	1.185	1.185	1.185	1.185	1.185	FEMA 356 Eqn 1-5
Characteristic Period, T_s (sec)	0.627	0.627	0.627	0.627	0.627	0.627	0.627	0.627	FEMA 356 Eqn 1-11
T_0(sec)	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	FEMA 356 Eqn 1-12
Response Spectrum Acceleration, S_a	1.89	1.89	1.89	1.89	1.89	1.89	1.89	1.89	FEMA 356 Eqn 1-8,9,10
Yield strength, V_y (kips)	20.90	33.50	28.40	46.91	13.47	16.38	16.45	24.43	FEMA 356 3.3.3.2.4
Elastic Strength Demand Ratio, R	10.150	6.333	7.471	4.523	7.141	5.870	5.846	3.937	FEMA 356 Eqn 3-16
C_1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	FEMA 356 3.3.3.3.2
C_2	1	1	1	1	1	1	1	1	FEMA 356 Table 3-3
C_3	1	1	1	1	1	1	1	1	FEMA 356 Eqn 3-17
Target Displacement, δ_t (in)	**0.892**	**0.583**	**0.693**	**0.514**	**0.272**	**0.183**	**0.237**	**0.131**	FEMA 356 Eqn 3-15

In order to calculate the post-yield stiffness, the pushover curves were idealized according to FEMA 356 Section 3.3.3.2.4 (FEMA 2000), as shown in Figure 4-12. The pushover curves, idealized to the MCE target displacement, are shown in Figure 4-13 for each of the eight frames analyzed. The idealized yield strengths (V_y), elastic lateral stiffness (K_i), effective stiffness (K_e), post-yield slope coefficients (α), and target displacements (δ_t) for both the DBE and MCE hazards can be found in Tables 4-6 and 4-7. The MATLAB functions used to obtain the idealizations can be found in Appendix A.4 and A.5.

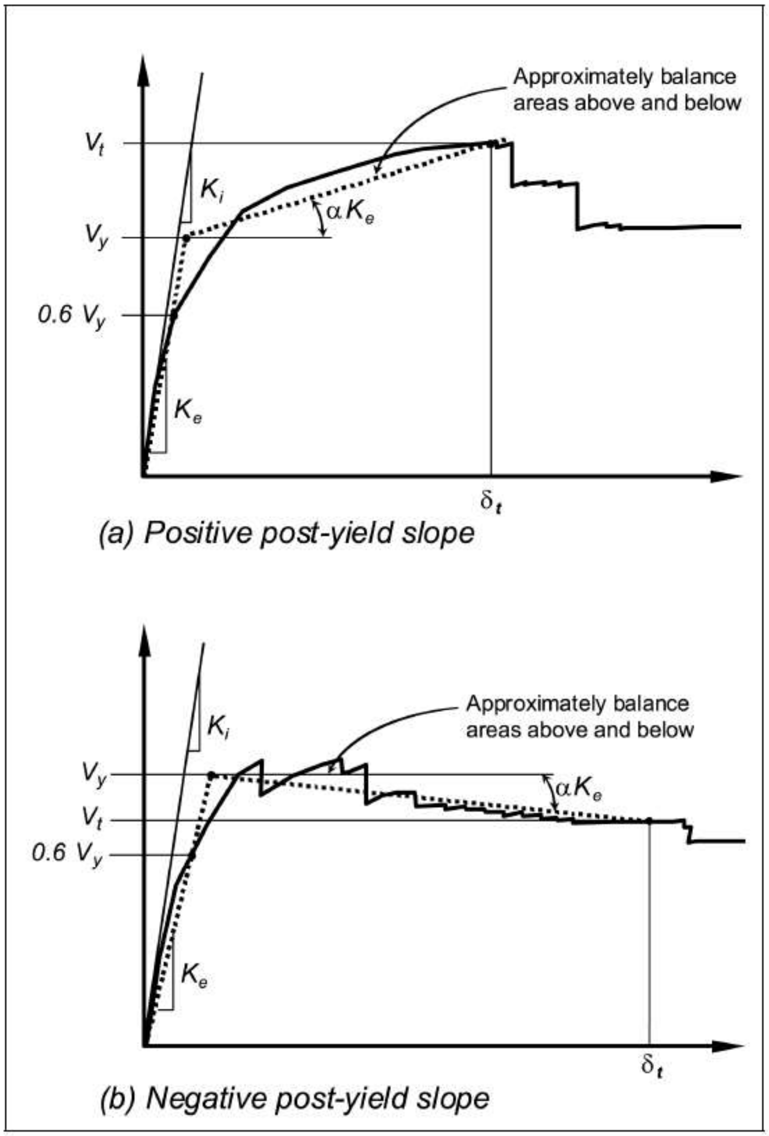


Figure 4-12: Idealized force-displacement curves (Image Source: FEMA 2000)

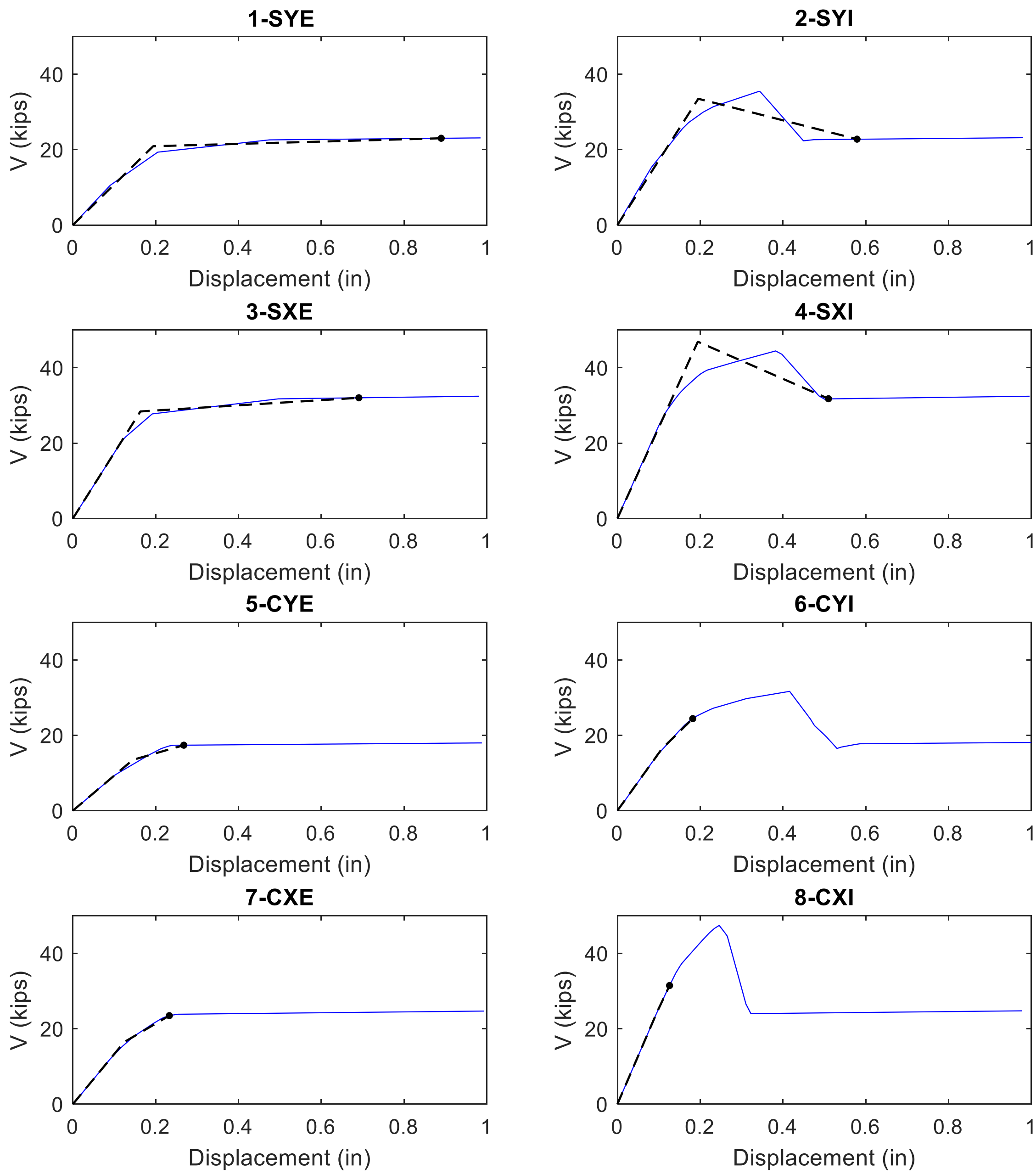


Figure 4-13: Bilinear idealization of pushover curves to MCE hazard target displacement (plot range 0-1 inch)

4.3 Nonlinear Static Analysis Results

The nonlinear static analysis described in the previous section was performed for all eight frames. The lateral load was applied monotonically until the designated control node reached the DBE and MCE target displacements specified in Tables 4-6 and 4-7. The performance states of the frames and their various plastic hinges were determined by comparing the displacements and rotations to ASCE and FEMA guidelines defined in the previous section.

Each frame and hinge was assigned one of the following performance states: Immediate Occupancy (IO), Life Safety (LS), Collapse Prevention (CP), or Failure (F). Immediate Occupancy is defined as the "post-earthquake damage state in which a structure remains safe to occupy and essentially retains its pre-earthquake strength and stiffness" (ASCE 2017). Life Safety is defined as the "post-earthquake damage state in which a structure has damaged components but retains a margin of safety against the onset of partial or total collapse" (ASCE 2017). Collapse Prevention is defined as the "post-earthquake damage state in which a structure has damaged components and continues to support gravity loads but retains no margin of safety against collapse" (ASCE 2017). Lastly, Failure is used to categorize any structure or element which has surpassed the Collapse Prevention threshold and has no remaining stiffness. The results of the nonlinear static analysis are presented below for both the frames and plastic hinges.

4.3.1 Frame Results

The performance state of each frame due to both the DBE and MCE hazards is presented in Table 4-8. In the frames with the concrete slab roof, Life Safety is maintained after both the DBE and MCE events. Likewise, the frames with the CGI roof all maintain Immediate Occupancy status after both events.

TABLE 4-8: PERFORMANCE STATES OF FRAMES FOR DESIGN BASIS EARTHQUAKE (DBE) AND MAXIMUM CONSIDERED EARTHQUAKE (MCE) HAZARDS

Frame	**DBE**	**MCE**
1-SYE	LS	LS
2-SYI	LS	LS
3-SXE	LS	LS
4-SXI	LS	LS
5-CYE	IO	IO
6-CYI	IO	IO
7-CXE	IO	IO
8-CXI	IO	IO

These performance states were determined from the global load-displacement (pushover) curves for each frame, presented in Figures 4-14 and 4-15. Although the performance states were assessed at the specified target displacements, the pushover analysis was completed to a control node displacement of 5 inches so that stiffness degradation and frame ductility could be qualitatively observed. These pushover curves are plotted in Figure 4-14. However, because all target displacements and the most significant stiffness degradation occurs prior to reaching a control node displacement of one inch, a close-up of these segment of the curves is also presented in Figure 4-15.

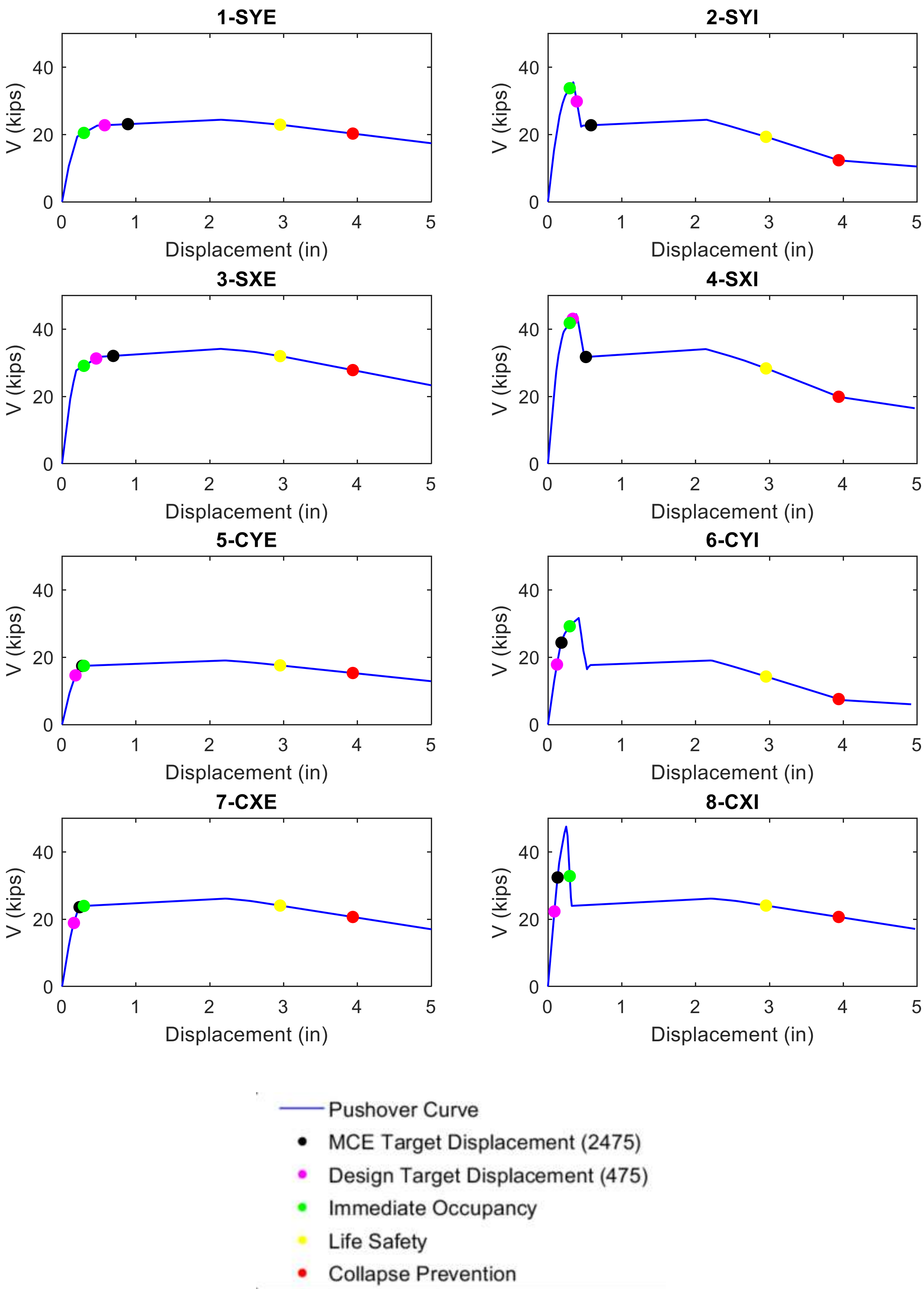


Figure 4-14: Nonlinear static pushover curves for all eight frames considered (plot range 0-5 inches)

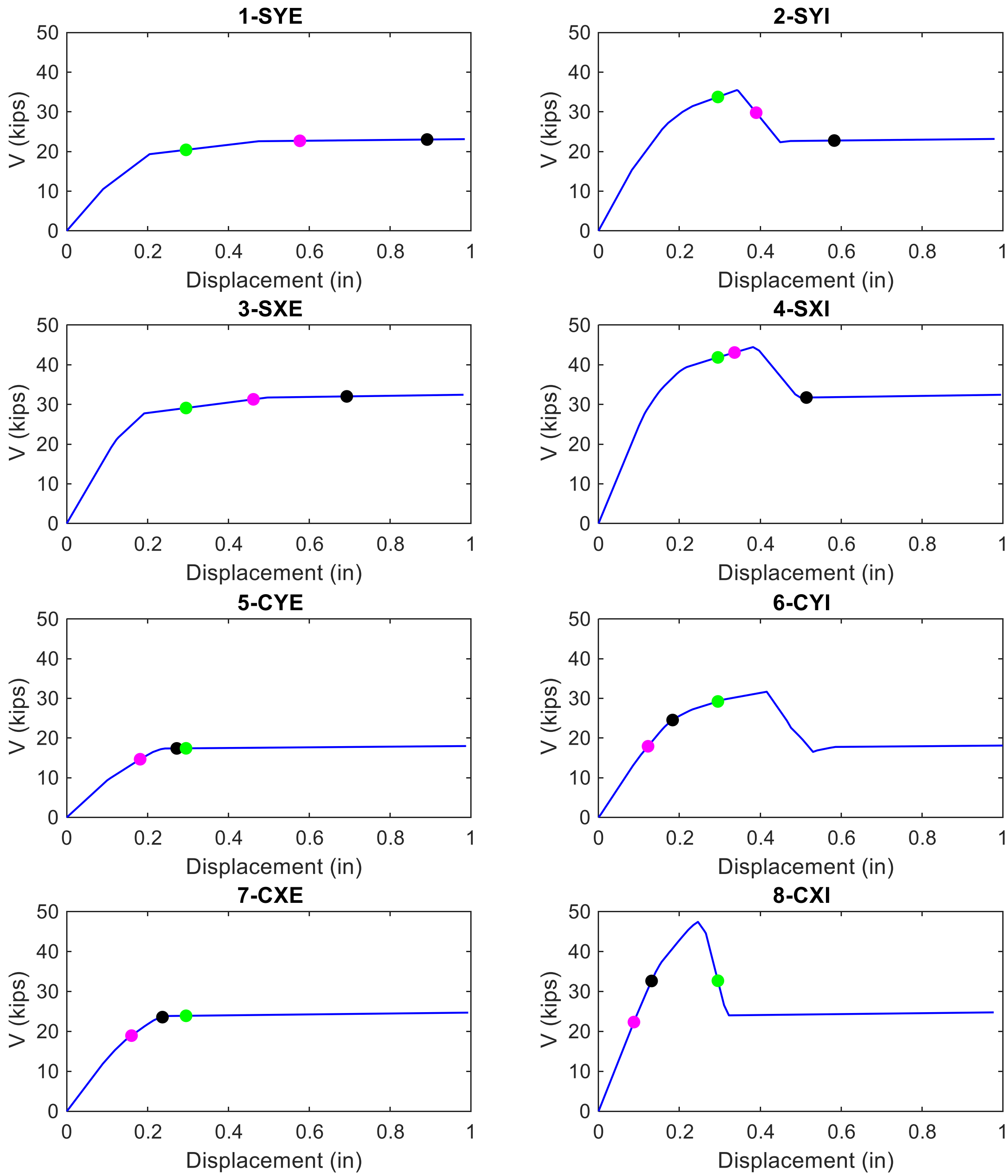


Figure 4-15: Nonlinear static pushover curves for all eight frames considered (plot range 0-1 inch)

Lastly, the ductility demand, μ_{demand}, for each frame was calculated via the following equation for both the DBE and MCE hazards:

$$\mu_{demand} = \frac{\delta_t}{\delta_y} \tag{4.10}$$

where δ_t is equal to the target displacement and δ_y is equal to the yield displacement, calculated by the following equation:

$$\delta_y = \frac{V_y}{K_e} \tag{4.11}$$

where V_y is equal to the yield strength and K_e is the effective stiffness. Both were calculated by the bilinear idealization function and presented in Tables 4-6 and 4-7.

These ductility demands are presented in Table 4-9. Because all eight of the frames were designated as special moment frames according to ACI-318 Chapter 18 (ACI 2014a), they were detailed to achieve a ductility capacity corresponding to a response modification factor, *R*, used at the design stage, of at least 8. Thus, when comparing the ductility demands to this response modification factor, it is apparent that all frames have sufficient ductility for both the DBE and MCE hazards.

TABLE 4-9: DUCTILITY DEMANDS FOR DESIGN BASIS EARTHQUAKE (DBE) AND MAXIMUM CONSIDERED EARTHQUAKE (MCE) HAZARDS

Frame	DBE	MCE
1-SYE	3.33	4.60
2-SYI	1.90	2.99
3-SXE	3.03	4.25
4-SXI	2.35	2.65
5-CYE	1.78	1.88
6-CYI	1.37	1.71
7-CXE	0.95	1.91
8-CXI	1.70	1.37

4.3.2 Plastic Hinge Results

The performance state of each plastic hinge in all eight frames was also determined for both the DBE and MCE hazards. First, the hinges were labeled as defined below in Figure 4-16. It is important to note that hinges S1, S2, C7, C8, B5, and B6 were not present in all frames.

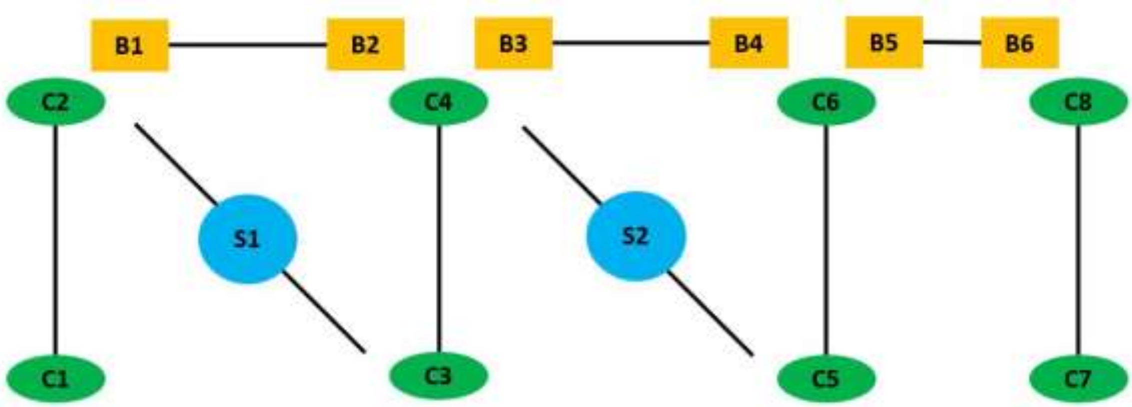


Figure 4-16: Plastic hinge mapping and labeling

Table 4-10 presents the performance states of the plastic hinges in all eight structures for the DBE hazard.

TABLE 4-10: PERFORMANCE STATES OF PLASTIC HINGES FOR DESIGN BASIS EARTHQUAKE HAZARD

Hinge	1-SYE	2-SYI	3-SXE	4-SXI	5-CYE	6-CYI	7-CXE	8-CXI
C1	IO	IO	IO	IO	IO	IO	IO	IO
C2	IO	IO	IO	IO	IO	IO	IO	IO
C3	IO	IO	IO	IO	IO	IO	IO	IO
C4	IO	IO	IO	IO	IO	IO	IO	IO
C5	IO	IO	IO	IO	IO	IO	IO	IO
C6	IO	IO	IO	IO	IO	IO	IO	IO
C7	-	-	IO	IO	-	-	IO	IO
C8	-	-	IO	IO	-	-	IO	IO
B1	IO	IO	IO	IO	IO	IO	IO	IO
B2	IO	IO	IO	IO	IO	IO	IO	IO
B3	IO	IO	IO	IO	IO	IO	IO	IO
B4	IO	IO	IO	IO	IO	IO	IO	IO
B5	-	-	IO	IO	-	-	IO	IO
B6	-	-	IO	IO	-	-	IO	IO
S1	-	LS	-	LS	-	IO	-	IO
S2	-	LS	-	LS	-	IO	-	IO

As shown in Table 4-10, all flexural hinges in all eight frames maintained Immediate Occupancy status after the DBE hazard. Likewise, the Life Safety status of the masonry panels in Frames #2 and #4 indicate that although the panel has not retained its strength and stiffness, a margin of safety against in-plane collapse remains.

Table 4-11 presents the performance states of the plastic hinges in all eight structures for the MCE hazard.

TABLE 4-11: PERFORMANCE STATES OF PLASTIC HINGES FOR MAXIMUM CONSIDERED EARTHQUAKE HAZARD

Hinge	1-SYE	2-SYI	3-SXE	4-SXI	5-CYE	6-CYI	7-CXE	8-CXI
C1	LS	IO	LS	IO	IO	IO	IO	IO
C2	IO	IO	IO	IO	IO	IO	IO	IO
C3	LS	IO	LS	IO	IO	IO	IO	IO
C4	IO	IO	IO	IO	IO	IO	IO	IO
C5	LS	IO	LS	IO	IO	IO	IO	IO
C6	IO	IO	IO	IO	IO	IO	IO	IO
C7	-	-	LS	IO	-	-	IO	IO
C8	-	-	IO	IO	-	-	IO	IO
B1	IO	IO	IO	IO	IO	IO	IO	IO
B2	IO	IO	IO	IO	IO	IO	IO	IO
B3	IO	IO	IO	IO	IO	IO	IO	IO
B4	IO	IO	IO	IO	IO	IO	IO	IO
B5	-	-	IO	IO	-	-	IO	IO
B6	-	-	IO	IO	-	-	IO	IO
S1	-	F	-	F	-	IO	-	IO
S2	-	F	-	F	-	IO	-	IO

Several key conclusions can be drawn from these results. First and foremost, all plastic hinges in frames with a CGI roof (#5 through #8) maintained Immediate Occupancy status after both the DBE and MCE hazards. Similarly, all flexural plastic hinges in Frames #2 and #4 (slab roof, infilled) maintained Immediate Occupancy status after both seismic hazards. However, the axial plastic hinge in the equivalent struts experienced displacements consistent with masonry panel failure. Lastly, in all remaining frames (#1 and #3), the flexural hinges at the bases of the columns surpassed Immediate Occupancy levels and were defined as achieving Life Safety requirements, indicating that although damages have occurred, there remains a margin of safety against partial or total collapse.

The performance levels of the individual hinges can also be discussed in comparison to the global performance levels defined for the frames in the previous section. While the performance level criteria for plastic hinges (deflections and rotations) and frames (drifts) are independent and thus not expected to correlate directly, twelve of the sixteen frames analyzed were assigned the same performance level as the "worst" performance level assigned to their constituent hinges. For example, in every frame that maintains Immediate Occupancy performance through both seismic hazards (Frames #5 through #8), all constituent hinges also maintain Immediate Occupancy performance. Similarly, Frames #1 and #3 meet Life Safety performance criteria after the MCE hazard, while Frames #2 and #4 meet Life Safety performance criteria after the DBE hazard, which is consistent with the performance state of the "worst" plastic hinge after the corresponding hazard. While the other four frames do not correlate directly with the performance levels of their constituent hinges, Figure 4-15 demonstrates that the target displacements are very close to the Immediate Occupancy threshold and therefore such minor inconsistencies are expected.

An example of the deformed shape of the frame and progression of nonlinear hinge development is presented in Figure 4-17 for Frame #3. As indicated by the color-coded key, although none have surpassed Immediate Occupancy levels due to the DBE hazard, numerous flexural hinges have yielded. As the analysis progresses to the larger target displacement for the MCE hazard, it is apparent that two more flexural hinges have yielded and the flexural hinges at the bases of the columns have progressed to the Life Safety performance state.

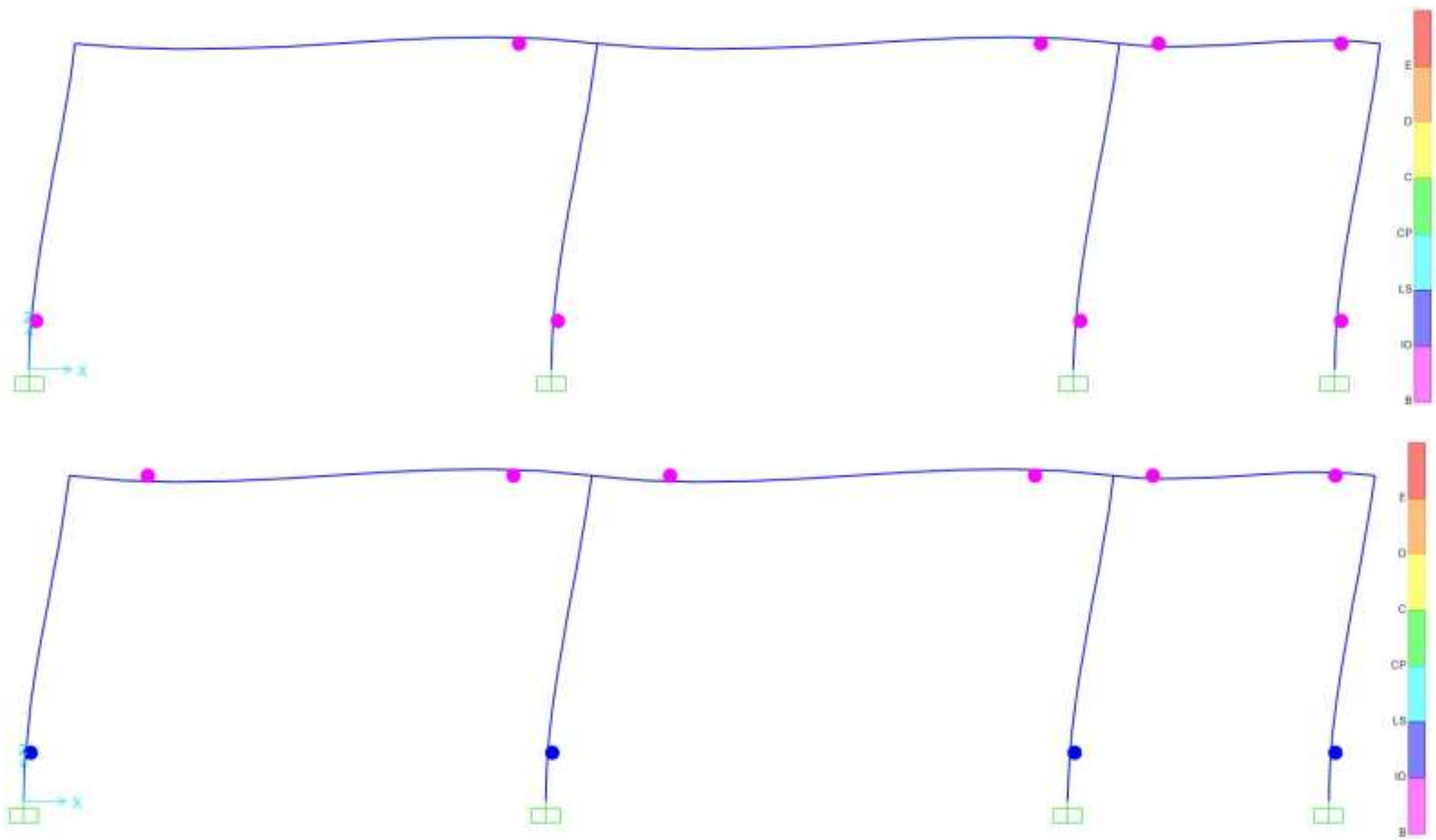


Figure 4-17: Deformed shape and hinge states of Frame 3-SXE due to Design Basis Earthquake (top) and Maximum Considered Earthquake (bottom)

4.4 Conclusion

The nonlinear static analyses discussed in this chapter reveal acceptable performance levels for both designs selected in the previous chapter. Both structures maintain Immediate Occupancy or Life Safety requirements in both the Design Basis Earthquake and Maximum Considered Earthquake hazards. Furthermore, although the masonry infill panels are expected to fail, all flexural plastic hinges are expected to also maintain Immediate Occupancy or Life Safety requirements. As shown in Figure 4-14, all target displacements are either just before or just after the Immediate Occupancy threshold, indicating that significant margins of safety remain against partial or total collapse. Likewise, Table 4-9 demonstrates that the ductility demands generated by the DBE and MCE hazards are conservatively below the ductility capacity assumed in the structure due to the special moment frame detailing. It is also worth noting that the structure with the CGI roof performed noticeably better than the structure with the slab roof, maintaining Immediate Occupancy performance criteria for even the MCE hazard. However, the analyses presented herein demonstrate that both the CGI and slab roof structures are highly unlikely to collapse during a seismic event.

In fact, these results could be considered by some to be excessively conservative, indicating the possibility that the structure has been overdesigned. Because the selection process utilized a multi-objective analysis, the selected designs were not governed by the code minimums (see Section 3.2.1.1 and 3.2.4). It is possible that bias in the scoring and categorical weighting system employed in Chapter 3 resulted in the selection of an excessively resilient design. Thus, it is also possible that the size of the elements (namely, the columns) or the amount of steel reinforcement could be further reduced to further lower the cost of the structure while still maintaining Life Safety performance criteria. However, as seen in Tables 3-22 and 3-23, the material costs of the selected designs are already near the minimum, with maximum potential savings (i.e., the difference between the cost of the selected design and the minimum considered cost) expected to be less than $200. So, it is reasonable to conclude that while the selected designs appear as excessively conservative, the minor cost savings resulting from a reduction in member size or reinforcement would not be worth the potential reduction in resiliency and loss of codification.

Likewise, although the performance assessment indicates strong margins of safety against collapse in the event of an earthquake, such results are dependent on a quality of construction materials consistent with those defined in Section 4.1.3. Similarly, in order for the frame to behave as desired, the design must be implemented with a high level of accuracy. For example, an appropriate amount of confining steel, an avoidance of cold joints, and proper masonry to frame connections are all critical to the proper seismic performance of the structure. As noted in Chapter 1, many of these critical construction materials and processes are dependent on financial factors, as low-income families without access to housing finance resort to low-quality incremental construction. Thus, the potential of the structures proposed herein, despite being designed and selected specifically for the case study scenario, cannot be fully realized without an accompanying framework for effectively integrating the various steps of the housing delivery process. The following chapter examines these issues and proposes integrated implementation mechanisms in the Haitian case study scenario.

CHAPTER 5: MARKET IMPLEMENTATION

This chapter addresses the implementation of the structure, designed and analyzed in the previous three chapters, in the Haitian case study scenario. The purpose of the chapter is to explore the issues that could hinder successful housing delivery and offer possible interventions at various points in the Housing Market Value Chain. It begins by redefining the Haitian housing deficit from an isolated engineering and construction problem to a complex by-product of technical, economic, and political factors. The market context of the Haitian case study scenario is presented in detail, accompanied by a discussion of various industry constraints that could restrict uptake of the best-fit design in the local market. Then, the Housing Market Value Chain is introduced, and its inherent interconnectedness discussed. Each of the seven points of the Housing Market Value Chain is discussed individually, and an integrated implementation framework is proposed, with a heavy focus on housing finance and construction quality assurance. The chapter concludes with a brief discussion of the common themes and the applications of the housing delivery framework presented herein.

5.1 Introduction: More Than Engineering

The Haitian Government estimates that the country requires the construction of 500,000 homes over the next 10 years (USAID 2020). This need is far beyond the capabilities of governments or private philanthropists, and major global organizations are shifting their focus toward long-term, market-based solutions. In May 2013, Oxfam stated in its *Housing Delivery and Housing Finance in Haiti* Report:

> Positive examples of permanent housing solutions are scant. Too much focus has been placed on the construction of physical structures rather than on setting up the sustainable delivery mechanisms that will stimulate the creation of sustainable communities and private investment in the sector (Huynh et al. 2013).

Recognizing this same problem, USAID is focusing on helping "financing institutions and housing developers play a greater role in housing construction" in Haiti (USAID 2020). Similarly, Habitat for Humanity's Home Ownership and Mortgage Expansion program works alongside financial institutions and housing developers with the goal of increasing access to long-term financing for low- and middle-income households in Haiti (Habitat 2016).

Clearly, in order to effectively and efficiently use their resources to promote safe housing in Haiti, organizations must focus not only on the construction of hazard-resilient structures, but also on the establishment of market-driven delivery mechanisms that can function within Haiti's complex, and too often unstable, political and economic environment. Recognizing this need, this chapter will propose a variety of integrated implementation mechanisms, ranging from conceptual ideas to detailed procedures, that, when paired with the resilient design presented in the previous chapters, have the potential to create a lasting, positive impact on the sustainable development of housing in Haiti. It should be stressed that though developed through an integrated research effort, these concepts and procedures have not been tested in the field, and thus require thoughtful application, evaluation, and iteration in the future.

Following the framework of Human-Centered Design, before one can offer potential solutions, one must thoroughly understand the problem. Consequentially, the following section builds upon the landscape introduced in Chapter 1 to thoroughly discuss the barriers present in the Haitian case study scenario.

5.2 Constraints of the Haitian Housing Market

Despite the recent 10-year anniversary of the 2010 Haiti earthquake, survey data from Léogâne states that, as of 2017, 61% of people whose homes were completely destroyed in the earthquake have not yet started rebuilding (Kijewski-Correa et al. 2019). Of those who have started rebuilding or repairing their homes, only 33% have completed the reconstruction of their walls, and only 26% have completed the reconstruction of their roofs (Kijewski-Correa et al. 2019). This slow process of reconstruction, akin to a systemic lack of resiliency, and the ineffectiveness of both the pre- and post-earthquake Haitian housing sectors can be attributed to a variety of technical, economic, and political factors.

While the historical origins of these constraints are well beyond the scope of this thesis, it is unfair to discuss Haiti's challenges without first acknowledging that the economic and political context of modern day Haiti is rooted in centuries of colonial oppression and slavery, followed by centuries of racist and predatory post-colonial foreign interference. It is important to understand this history, from the virtual extinction of the indigenous Taíno people by the Spanish, to the crippling debt that the young nation was forced to pay France for its independence—an estimated US$21 billion in today's dollars—for 122 years, to the multiple 20th century United States military occupations and operations, when considering the economic and political constraints of conducting business in modern day Haiti. For detailed accounts of Haitian history and foreign relations, the author suggests Paul Farmer's *The Uses of Haiti* (1994) or Laurent Dubois' *Haiti: The Aftershocks of History* (2013).

5.2.1 Technical Constraints

The frame presented in the previous chapters was designed in accordance with the technical constraints present in Léogâne's housing sector. First and foremost, concrete, both cast-in-place and locally produced concrete masonry units (CMU), was utilized as the primary building material. Concrete is highly valued among aspiring homeowners for cultural, environmental, and security reasons (Mix et al. 2011). Furthermore, because Haiti is a heavily deforested nation (Williams 2011), timber is expensive and therefore rarely used for construction in urban areas such as Léogâne. The design process also considered the use of unregulated construction materials, specifically the consistently low compressive strength of CMU blocks and poured concrete, as described by Mix et al. (2011), Marshall et al. (2011), and Build Change (2011a).

In combination with the poor quality of construction materials, houses in Haiti are generally constructed incrementally, by laborers without formal training, and without the consultation of structural engineers (Eberhard et al. 2010; Mix et al. 2011). Incremental construction not only leaves families exposed throughout the construction process, which often takes ten or more years, but also after, as the high variability in materials and workmanship render an incrementally-constructed home highly vulnerable to natural hazards (Mix et al. 2010). Similarly, laborers untrained in aseismic construction are unlikely to provide sufficient detailing needed to facilitate a ductile response during an earthquake. Lastly, without the consultation of a structural engineer during the design process, concrete homes, which have significant seismic mass, are likely to pose a risk to their occupants.

5.2.2 Economic Constraints

The contextual constraints begin at the microeconomic level of the household. As of 2018, 42.2% of the Haitian population lives on less than $3.20 USD per day, when adjusted for purchasing power parity (PPP) (ILO 2019). Zooming in on the case study community of Léogâne, a recent survey of 552 households found that 40% of households (of which the average size is five persons) earn less than 1000 HTG per week, while 32% of households earn between 1000 and 2500 HTG per week (Kijewski-Correa et al. 2019). Considering the February 2020 exchange rate of $1.00 USD to 99.1 HTG (Oanda 2020), this data indicates that 72% of households in Léogâne earn less than $25 USD per week (not adjusted for PPP).

The challenges associated with living off of this exceptionally low income are further exacerbated by the prevalence of the informal economy. In Léogâne, only 19% of 550 randomly-sampled survey participants reported working for a Haitian or foreign employer, while 50% responded that they own or operate their own business (Kijewski-Correa et al. 2019). Considering that an estimated 2/3 of Haiti's workforce is informally employed (Huynh et al. 2013), it is reasonable to assume that the majority of Léogâne's entrepreneurs operate in the informal sector. The inconsistent and fluctuating income associated with informal employment and entrepreneurship often makes long-term financial planning and saving difficult.

Constant exposure to environmental hazards, including earthquakes, hurricanes, and deforestation-driven landslides, further exacerbates the economic constraints by creating significant disruptions in the Haitian economy. In addition to killing or injuring people and destroying personal property, these events can also destroy sources of sustenance and revenue generation, such as crops and businesses. For example, Hurricane Matthew, which swept through Haiti's Tiburon Peninsula in 2016, snapped or uprooted countless fruit trees, which will take decades to regrow (Kijewski-Correa et al. 2018). Similarly, heavy rains, post-hurricane disease, and saltwater inundation due to the storm surge destroyed much of the region's subsistence crops (Kijewski-Correa et al. 2018). Intense economic interruptions such as these, which disproportionately affect the low-income population, further increase the difficulty of accumulating wealth. This low and fragile financial capacity, coupled with Haiti's underdeveloped housing finance market, limits the construction of safe homes to the wealthy minority.

Haiti's ratio of private sector credit to GDP, a measurement of the robustness of a country's financial sector, at only 12%, is among the lowest in the world (USAID 2011). Thus, it is no surprise that in a recent Léogâne survey, 78% of respondents reported never receiving a loan from a bank, cooperative, or credit union (Kijewski-Correa et al. 2019). While this lack of accessible formal financial services hinders Haitian economic development across all sectors, its impact on the housing sector is specifically devastating, as it is exceptionally difficult to obtain a mortgage in Léogâne. In addition to the previously described low household income and limited formal sector employment, Oxfam (Huynh et al. 2013) also attributes the low mortgage lending volume to the following factors:

1) Perceived high credit risk due to volatile political and economic conditions;

2) Lack of information to assess credit worthiness of borrowers;

3) Limited supply of affordable housing, which drives up property prices and results in housing that is too expensive for most consumers;

4) Reluctance to lend to those without solid collateral, which is rare in Haiti due to the country's complicated title and lien registration process.

Even if one possesses the financial capabilities and finds a bank willing to lend, the formal documentation required for mortgage financing is also restrictive, as banks usually require proof of multiple years of formal employment and land title, which the majority of Haitians cannot provide (Huynh et al. 2013). Clearly, macroeconomic factors further restrict housing finance in Haiti to a wealthy minority. Unfortunately, Haiti's political system does little to reduce this inequity.

5.2.3 Political Constraints

Article 22 of the 1987 Haitian Constitution "recognizes the right of every citizen to decent housing" (Haiti 1987). However, it is clear that the Government of Haiti has not maintained this ideal. Even before the 2010 earthquake, it was estimated that 86% of Haiti's urban population lived in informal settlements (Rencoret et al. 2010). Likewise, Oxfam's 2013 research report on *Housing Delivery and Housing Finance in Haiti* found that "urban management and planning mechanisms are unstructured, dysfunctional, or nonexistent" (Huynh et al. 2013). Government policy is critical to the housing sector, even in the world's wealthiest nations, where government agencies maintain public records of land ownership, legal systems settle disputes and enforce contracts, and public funds provide housing subsidies to low-income households. Unfortunately, in Haiti these systems are generally ineffective or nonexistent.

It takes an average of 301 days and five procedures to register property in Haiti, a process that will cost the owner 6% of the property value (World Bank 2012). Furthermore, private owners cannot purchase public lands because of an "antiquated legal hurdle that requires the authorization of a non-existent municipal assembly" (Huynh et al. 2013). Even when titles are issued and possessed, they are often disputed, and poor record keeping and ineffective legal procedures makes it difficult to settle such disputes. These constraints make it difficult for banks to trust land as collateral, reduce the supply and thus drive up the cost of buildable land, and prevent developers from investing.

A lack of enforcement for non-repayment also hinders the development of the mortgage industry. Legal proceedings for foreclosure are expensive and complex, making Haitian banks "extremely risk averse" (Huynh et al. 2013). In fact, housing institutions such as Habitat for Humanity and EPPLS (a public housing project administered by the Government of Haiti, see Section 5.4.3.1.3) have often failed to evict their borrowers who cannot pay rent and instead simply accept the financial loss (Huynh et al. 2013). Without proper protections for lenders who are not repaid and sufficient incentives for borrowers to repay, for-profit financial institutions are unlikely to accept the financial risks associated with lending to low-income households.

In addition to record-keeping and contract enforcement, governments often also play a critical role in assisting their low-income citizens through housing subsidies. It can be assumed from the financial assessment previously presented in this section that, if available, a significant portion of Haitians would qualify for such subsidies. However, Oxfam found that a comprehensive government-led subsidy program to assist low-income households in gaining access to housing finance in Haiti has never existed (Huynh et al. 2013), likely due to underfunded government ministries.

Even if executed perfectly, the systems (or lack thereof) described above would prove ineffective in providing the stability and structure needed for a prosperous housing industry. Unfortunately, the capacity of these systems are further reduced by an uncoordinated, and often corrupt, government. Oxfam's 2013 investigation found that many of the actions needed to implement Haiti's 2012 *Politique National du Logement* (National Housing Policy) were split among the responsibilities of a variety of government ministries, resulting in an uncoordinated and inefficient implementation (Huynh et al. 2013). Likewise, Transparency International identifies Haiti's Corruption Perceptions Index as a mere 18/100, which places it among the most corrupt nations in the world (tying with Libya and one point ahead of North Korea) with an overall rank of 168th among the 180 nations considered (Transparency International 2019).

When considering the above constraints, it becomes apparent why Haiti ranked 182nd (out of 190 nations) on the World Bank's 2018 Ease of Doing Business Index (World Bank 2018a). Such analysis also clearly demonstrates the complex interconnectivity of the private and public sectors. Even the nations with the most efficient and robust economies require intense government involvement in the housing system. Heavily cited above, Oxfam's 2013 report on *Housing Delivery and Housing Finance in Haiti* (Huynh et al. 2013) offers a full assessment of the interconnected roles of the private and public sectors in alleviating the Haitian housing deficit. This report also offers a detailed analysis of each the numerous public institutions involved in housing finance and delivery in Haiti and correspondingly suggests a high-level reconfiguration of their various approaches. While complex political and macroeconomic efforts are certainly required to harbor an efficient and widespread reduction in Haiti's housing deficit, such a political restructuring is beyond the scope of this thesis. Contrary to these "top-down" solutions, the implementation framework proposed in the following sections has been developed from a "ground-up" end-user perspective considering the current economic and political state of Haiti described above.

5.3 Engagement of Local Stakeholders

Participatory design can be summarized as stakeholder participation and citizen involvement in the conceptualization and design of engineering projects (Sheller et al. 2013). By involving the end users throughout the design process, one increases the chances that such efforts are aligned with local needs and capacities (Daniell et al. 2010). This importance of stakeholder participation in such work is widely recognized (Barreteau et al. 2010; Daniell et al. 2010). Therefore, E2E's Léogâne-based Innovation Clubs were continually engaged to support and co-develop the "ground-up" concepts and procedures presented in the following sections.

These teams of creative local leaders were formed in 2014, when E2E researchers sought to identify community members to engage in their design processes. By hosting open innovation challenges in each of Léogâne's six zones, E2E identified local innovators who demonstrated leadership, problem-solving skills, and creativity in one of three activities. These local innovators, forty-two men and women of various professions representing each of the six zones, were then trained and certified in the *Pwosesis pou Innovasyon* (Innovation Process) - a Creole-adapted form of Human-Centered Design based on IDEO's *Human-Centered Design Toolkit* (2009) and *The Field Guide to Human-Centered Design* (2015). These individuals subsequently engaged their neighbors to form six Innovation Clubs, each tied to a zone of the community. More details on the selection and training of the Clubs can be found in Burlotos et al. (2021).

These Innovation Clubs assisted with the development of the implementation framework proposed in the following sections through a variety of practices, ranging from collecting data via field surveys to actively co-designing specific processes. These focus groups, design sessions, and surveys were facilitated by E2E's current and former Léogâne-based staff members: Lamarre Presuma, Gede Jean Benoit, and Edson Jean. Given their respective backgrounds in law, civil engineering, and education, the expertise of the staff members themselves was also heavily utilized. By continuously leveraging their unique local perspective to develop viable and sustainable implementation practices, this professional team and the Innovation Clubs have acted as co-designers for many of the concepts and procedures proposed in the following sections.

5.4 The Housing Market Value Chain

As evident from Section 5.2, a country's housing sector can be both bolstered and constrained by the broader economic and political context of the country. The industry can be further affected by a variety of other components of what Oxfam refers to as the "housing ecosystem," defined as the "totality of markets, laws, resources, participants, and inventory that make up housing delivery and housing finance" (Huynh et al. 2013). Each country's housing ecosystem is unique and "rooted in geography, climate, history, culture, national government, legal structure (including original laws, if the country was colonized), economy, the macro-economy (including inflation and interest rates), taxation, and existing political and governmental systems" (Huynh et al. 2013). The output of the ecosystem is housing, and an ecosystem's ability to provide quality housing is dependent on the strength and cohesion of its components.

It is paramount that the various components of the system be considered in conjunction with each other, as a modification to an individual component or subsystem will influence the entire ecosystem. Similarly, one must consider every component, as one underdeveloped subsystem will limit the output of the entire housing ecosystem. The term "ecosystem" itself implies that each component directly and indirectly influences every other component in the system, and that the entire system evolves in relation to a change in a single subsystem. This distinction explains why the importation of a subsystem (e.g., training of construction workers) that works well in one ecosystem may not necessarily work well in the Haitian housing ecosystem. Figure 5-1 presents a generic system map of the various components and co-dependent relationships of a functional housing ecosystem.

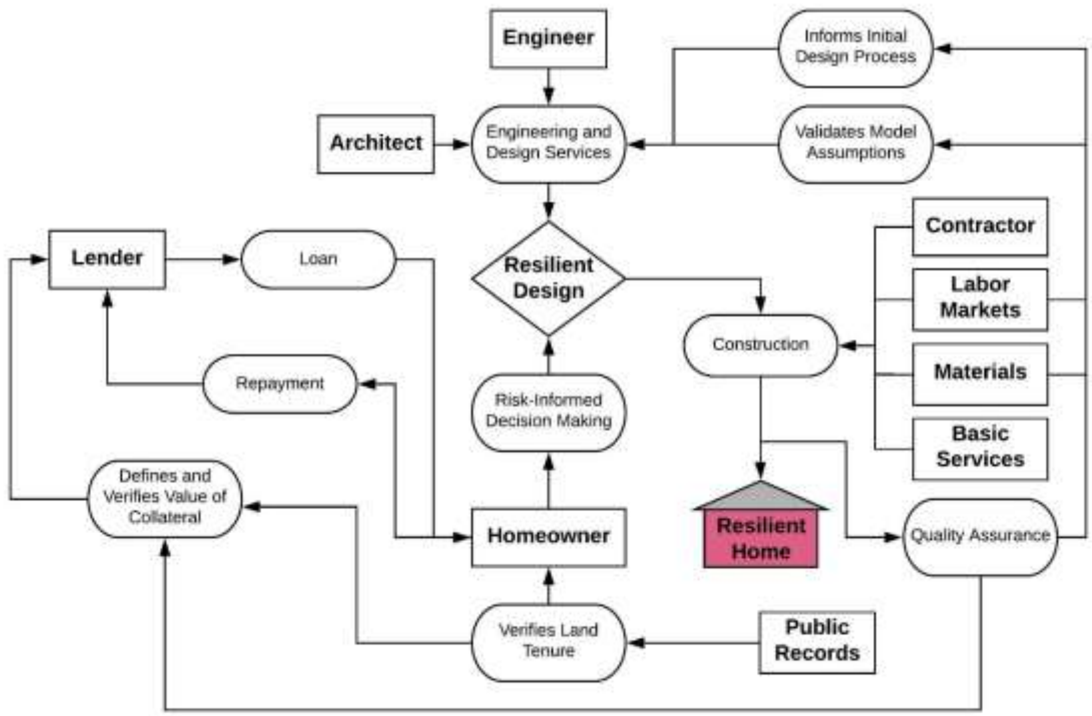


Figure 5-1: Generic system map of the housing ecosystem

This map is simplified, as it is not possible to capture the influence of government processes and regulations that are critical to every component of the ecosystem. Some analogous examples in the United States include but are certainly not limited to: professional licensing of engineers and architects, apprenticeships and technical schools for tradespersons, building codes, ASTM material regulations, third-party construction inspections (often administered at the municipal or county level), federal interest rate manipulation, bankruptcy policies, and the structured judicial process for settling civil disputes. It is also important to recognize the critical role the insurance industry plays in protecting investments and reducing risk for the lender and homeowner.

These various components can also be assembled into the Housing Market Value Chain, originally formulated by Kijewski-Correa (2012) and previously presented in Figure 1-1 but restated again in Figure 5-2. This simplified model organizes the complex system map in Figure 5-1 into a seven-point linear chain. Like the system map in Figure 5-1, this chain is generalizable to all housing ecosystems, with each point likely to appear substantially different in disparate nations and economies.

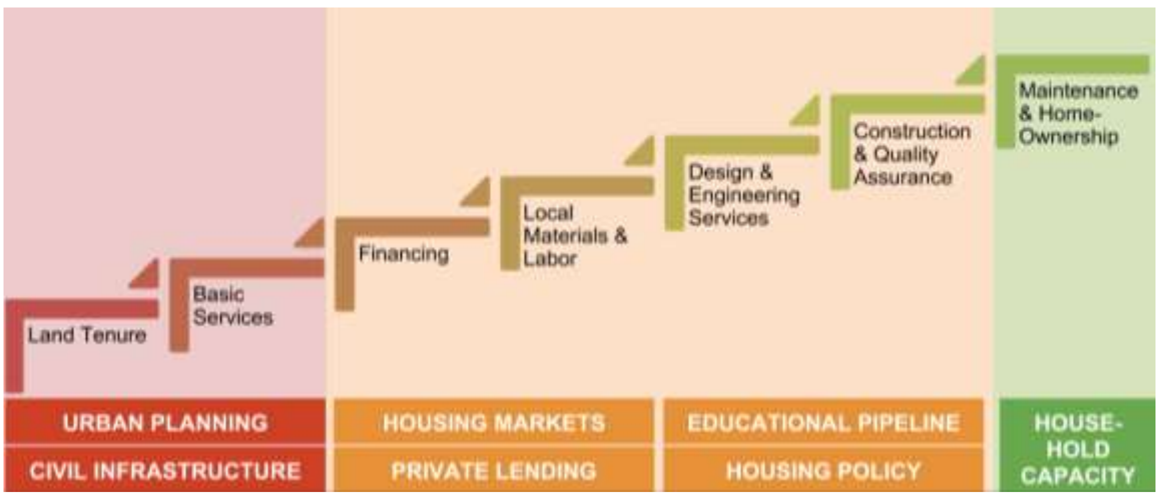


Figure 5-2: Housing Market Value Chain (Image Source: Kijewski-Correa 2012)

As shown in Figures 5-1 and 5-2, when not surrounded by other strong components of the housing ecosystem, such as land tenure, quality assurance, or financing, a resilient structural design cannot be effectively or sustainably implemented. The following sections will address each point of the Housing Market Value Chain individually and will offer a variety of proposals for the effective implementation of the best-fit design presented in the previous chapters. While they will be discussed individually, each proposed implementation concept was designed within the integrated context of the entire housing ecosystem.

Although all seven points of the value chain will be discussed to some degree, Financing, Construction & Quality Assurance, and Maintenance & Homeownership will be the central focus. It should be stressed again that though developed through an integrated research effort, these concepts and procedures have not been tested in the field, and thus, are not intended to be presented as complete plans. However, it is the intention of the author that the following sections form an implementation framework that can be applied, evaluated, and iterated by any organization seeking to create a lasting, positive impact on the sustainable development of housing in Haiti.

5.4.1 Land Tenure

The first step in the linear Housing Market Value Chain, and for aspiring homeowners looking to build, is documenting and proving land tenure. As noted in Section 5.2.3, this process is a major challenge in Haiti, taking nearly a year on average. Simply put, Haiti "lacks a comprehensive, functional system for recording land ownership" (USAID 2010a). The Haiti Property Law Working Group (2012) identifies some of the specific challenges of the legal system that make it so difficult, including unclear requirements, complex procedures that involve multiple government agencies (see Figure 5-3), high fees, and inheritance laws that give shared property rights to heirs.

Due to these ineffective government policies, which are further challenged by a historically rural society, the traditional *lakou* system, and rapid urbanization, few landowners possess a legal title or transaction receipt. Before the 2010 earthquake that devastated a significant portion of the Haiti's capital city of Port-au-Prince, only 38% of property owners in the metropolitan area possessed documentation of their tenure (Haiti Property Law Working Group 2012). Then, the earthquake destroyed 300,000 homes, left 1.5 million people homeless, and even badly damaged the office of the *Direction Generale des Impôts* (DGI), the office responsible for maintaining and updating registration records (USAID 2010a; Ritchie and Tierney 2011). Through its widespread devastation, the earthquake quickly exposed this weakness in the Housing Market Value Chain, and land tenure became a major obstacle to reconstruction.

Step of the procedure*	Institution or professional involved	Documents needed	Estimated Time
1. Preliminary sale agreement **1 STEP**	Notary	• Preliminary sale agreement or promise of sale	
2. Survey Survey of the property and writing of survey document by the surveyor. **6 STEPS**	• Surveyor • Court Clerk • District Attorney • Office of Land Registry (DGI)	• Prior survey • Property title • Seller's identity card • *Exploit ou sommation* • New survey • Copy of new survey • Copy of receipt from DGI	3 to 12 months
3. Preparation of the bill of sale Verification of title documents, compilation of documentation for the sale, writing of bill of sale, collection of fees and taxes by the notary **6 STEPS**	• Notary • Office of Land Registry (DGI) • Ministries, consulate, general assembly, etc. (depending on legal status of seller or buyer)	• Copy of new survey with the old property title in the margin and the DGI receipts • Mortgage situation of the property • Evidence of payment of taxes on built properties (CFPB) and bills for utilities (DINEPA and EDH) for the past five years, including the current year • Documentation proving the identity of the seller and the buyer and required permissions (4-6 docs.)	10 days to 5 months
4. Registration, transcription and payment of taxes Notary submits the deed of sale to the DGI for registration and trancription and pays the fees and taxes to the DGI **4 STEPS**	Office of Land Registry (DGI)	• Bill of sale with all of the above documents in the annex • Receipt of payment of taxes and fees from DGI	3 months to 1.5 years
Total: 17 steps	4 to 8 institutions and 2 professionals	14 to16 documents	6 months to 2.5 years

Figure 5-3: Summary of the steps of a "Sale by Genuine Deed" procedure, one of two methods of property transfer (Image Source: Haiti Property Law Working Group 2012)

Securing proof of land tenure is a critical step of the Housing Market Value Chain, as proper collateral is almost always required when seeking mortgage financing. Therefore, any individual or organization, whether government, business, or NGO, that seeks to reduce the housing deficit in Haiti must take the necessary steps to formally register the land used for all projects, and if applicable, legally transfer the title to the new homeowner. In all programs, clear procedures must be defined for applicants and participants to meet minimum standards to collateralize land during a prequalification process.

However, the specifics, and suggestions for reform, of this complex legal process are beyond the scope of this thesis. But given the scale of the issue and the consequences of the process' shortcomings, detailed studies and guidelines have been produced by experts and are publicly available for use by implementing organizations. Lopes (2016) analyzes Haiti's pre-earthquake land administration system and explains the related challenges that emerged after the 2010 earthquake. Furthermore, Haiti Property Law Working Group's *Haiti Land Transaction Manual* (2012) documents existing laws and practices related to legal property transfer and provides a step-by-step guide to legally selling and purchasing land in Haiti.

5.4.2 Basic Services

The next component of the Housing Market Value Chain is basic services, which includes water, sanitation, and energy systems. These components are critical to the health and quality of life of homeowners and tenants and must be considered when building homes in Haiti. Nationally, only 58% of Haitians have access to clean water (World Bank 2011). In Léogâne, residents used to obtain their water from a centralized water distribution system built with international aid money in the early 1980's, but it has been inoperable since the 2008 hurricane season (Galada et al. 2014). Without a centralized system, residents are forced to use a variety of decentralized water sources, many of which must be treated prior to consumption. Figure 5-4 compares the frequency of use of current sources with the reported preferences of sources, showing that the majority would prefer piped water to their property.

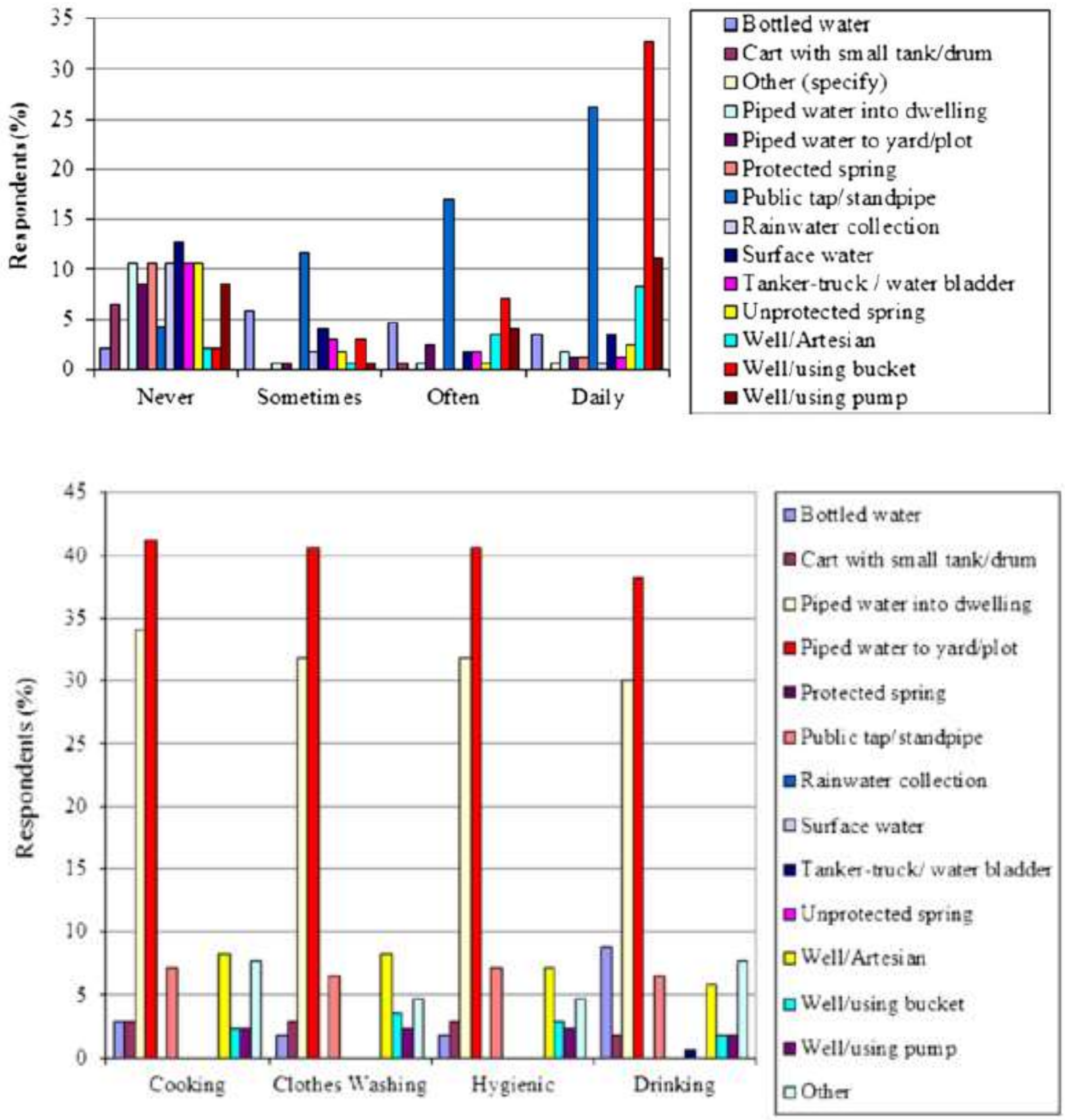


Figure 5-4: Frequency of water source use in Léogâne (top) and reported preferences for water sources (bottom) (Image Source: Galada et al. 2014)

Similarly, modern sanitation is also exceedingly rare, with only 19% of Haitians having access to improved sanitation facilities (World Bank 2011). Even in urban areas, wastewater collection systems are “practically nonexistent,” as stated by the Government of Haiti’s Ministry of Public Health and Population (MPHP) in its *National Plan for the Elimination of Cholera in Haiti* (2013). Septic tanks and outdoor pit latrines are the main systems used to contain wastewater, but the collected sludge is generally disposed of, untreated, into “ditches” or the “natural environment” (MPHP 2013). This can amount to serious public health problems, clearly evident by the post-earthquake outbreak of cholera.

Zooming in on the case study region of Léogâne, Pieslak (2017) provides an overview of the household sanitation options and preferences. Through a survey of 24 residents, Pieslak found unanimous preference for an indoor system (e.g., standard toilet) over an outdoor system (e.g., pit latrine) (2017). Similarly, focus groups revealed a strong anecdotal preference for flushing systems. Although Pieslak’s sample size is too small to draw scientific conclusions, it is clear that new homes built in Léogâne should, whenever possible, be outfitted with indoor sanitation facilities.

Unlike water and wastewater, there is a centralized electrical grid in Léogâne which nearly all homes connect to. However, it is often unreliable, and those who can afford it will supplement their energy system with a generator, solar panels, or both.

Considering the above context, and through collaboration with Haitian colleagues and a contractor in Léogâne, the author suggests the following range of options for both off-grid and on-grid integrated utilities be offered to aspiring homeowners. In terms of electricity, all homes should be connected to the grid, and a variety of generators and solar panels should be offered. For buyers who cannot at the moment afford a generator or solar panel but are interested in installing an additional system in the future, conduit should be laid to accommodate such an addition.

In terms of water, a similar three-tiered approach should be offered. At the basic level, no water system is required, which assumes that the resident will be acquiring their water, likely in buckets or jugs, from a public tap or nearby well. At the second tier, plumbing should be installed before finishing walls so that an on-site source can be added later when funds are available. The third tier includes a fully functioning on-site system, with internal plumbing, a well, solar pump, and treatment system (refer to Galada et al. (2014) and Gillespie et al. (2020) for treatment sources available in Léogâne). This can also be additionally supplemented with a rooftop rainwater collection system.

For sanitation, the basic level consists of an outdoor pit latrine. The second tier, similar to the water and electricity options, includes framing and plumbing for a fully functioning bathroom, but does not include fixtures or a septic tank. Additional second tier options include a low-cost, urine diverting dry toilet (WCEF 2015) or a composting toilet from a social business like SOIL (2020), although at the time of writing they are not available in Léogâne. The third tier includes a septic tank and fully functioning bathroom, with toilet, sink, and shower. Servicing contracts for septic tanks and latrines should also be discussed and, if possible, arranged, at the time of construction to ensure the timely and hygienic disposal of sludge.

These basic services fill an important role in protecting the quality of life and health of the home's residents and community and should be considered early in the conceptual design phase of the home. While the tiers proposed above are meant to serve as a starting point for developers, it is important to understand the needs and expectations of the aspiring homeowner. For example, if building a home on a traditional *lakou*, it is possible that these utilities and facilities will serve multiple families and should be selected and designed accordingly.

5.4.3 Financing

The next critical component of the Housing Market Value Chain is financing. An effective financing system allows the aspiring homeowner to acquire a loan to build (or purchase) a home and pay it back over an extended period of time. Being able to finance the construction of a home is exceptionally important in the Léogâne context, as the seismic and wind hazards, combined with the reliance on concrete as the primary building material, render incremental construction very dangerous. This section will discuss the design process of a community-based housing finance program proposed for Léogâne.

In order to design and propose a housing finance program suitable for the complex market conditions of Léogâne, the author and his team employed design thinking methodology. First, the context of the housing market was explored, as described in Section 5.2. Then, numerous case studies were analyzed, both from Haiti and from other developing contexts. The findings of this background research were organized into a list of constraints to define the barriers which the program must consider. These constraints, along with analogous solutions found in case studies, were used to map a corresponding solution space, which summarizes the guiding principles, criteria, and components of the proposed program. From there, the concept was passed to E2E’s Léogâne-based Innovation Clubs for further development. The following sections will describe the case studies analyzed (including a discussion of housing microfinance), present the constraints and corresponding solution space derived from the background and case study research, and propose an outline for a community housing fund model co-created with E2E's Innovation Clubs in Léogâne.

5.4.3.1 Background: Housing Finance in Haiti and Similar Contexts

The first step in the human-centered design process, as defined by IDEO (2015), is the inspiration phase. To develop a thorough understanding of the "problem" to be addressed and the surrounding market context, a variety of case studies were explored (in addition to the background research previously presented in Section 5.2). Case studies from similar contexts outside of Haiti were also considered in order to broaden the variety of projects considered. The first type of housing finance program discussed is the standard mortgage.

5.4.3.1.1 Mortgages

Mortgages are collateralized loans offered by for-profit banks which enable aspiring homeowners to build or purchase a home and pay it back over an extended period of time, typically between 15 and 30 years. This system is commonplace in developed economies across the globe, including in the United States. Unfortunately, weak financial institutions, inflation, and frail legal systems have inhibited the maturation of mortgage markets in developing nations like Haiti (Sanders 2005), vastly limiting the availability of mortgage financing. As of March 31, 2011, housing loans make up only 8.3% of Haiti's banking sector's loan portfolio (USAID 2011). In contrast, the loan portfolios of the top five largest banks in the United States consist of 28% mortgage loans, on average (Forbes 2018). USAID estimates that even SOGEBEL, the leading lender for housing in Haiti, provides less than 100 mortgage loans per year (2010b). Although rare, some of Haiti's largest banks do offer mortgages.

For example, Banque Nationale de Credit (BNC) offers *Kay P'am* (Haitian Creole for "my house"), which is a mortgage program available to those between the ages of 18 and 65 who can prove stable employment in the public or private sector for at least three years and possess a valid title for their land (BNC 2020). These fixed-interest loans, offered for a length of up to 30 years, can be applied for via an online form (written in French) on the BNC website (BNC 2020). Banque de l'Union Haïtienne (BUH) and Sogebank also offer loans for acquiring real estate. The repayment period is shorter than that offered by BNC (up to 20 years), and online applications are not offered, with both the BUH and Sogebank websites referring those interested to their nearest branch location (BUH 2020; Sogebank 2020). It is important to note that these programs are far beyond the reach of most Haitians due to the loan requirements, which include multiple forms of official personal documents, life insurance, proof of sufficient income, and valid land title. Moreover, their websites and applications are all written in French, which is only spoken by 42% of the Haitian population and read by even fewer (Wolff 2014).

Underdeveloped economic and political systems necessary to support mortgage markets, along with the low financial capacity of the majority of the population in developing economies like Haiti, result in high risks for institutions providing mortgage loans. Because of these high risks, many organizations have turned to housing microfinance.

5.4.3.1.2 Housing Microfinance

Housing microfinance has been adopted by both non-profit and for-profit institutions and consists of short term, relatively small, housing-focused loans which target low-income, yet economically active, households who have limited access to traditional forms of financing (Daphnis and Ferguson 2004). By offering loans with terms more affordable to these households than traditional mortgages, the lending also becomes less risky and more financially viable to the lending institution as well. The amount of a housing microfinance loan varies widely, as does the way in which the loan is used.

In global surveys of dozens of microfinance institutions (48 and 101, respectively) in 2015 and 2017, Habitat for Humanity's Terwilliger Center for Innovation in Shelter found that approximately 60% of housing microfinance loans are under US$2,000 (Habitat 2015a; Habitat 2017). Because of these relatively small loan values, only 14% were used toward full house construction and only 6% were used towards land purchase or tenure (Habitat 2015a). The majority (57%) were designated as home improvement loans (HIL) and used for basic home repair or improvement, such as tiling, plastering, or roofing, while another 23% were designated as small construction loans (SCL) and used for adding rooms or systems, such as latrines or solar panels (Habitat 2015a). Figures 5-5 and 5-6 display the distribution of these loan values and uses.

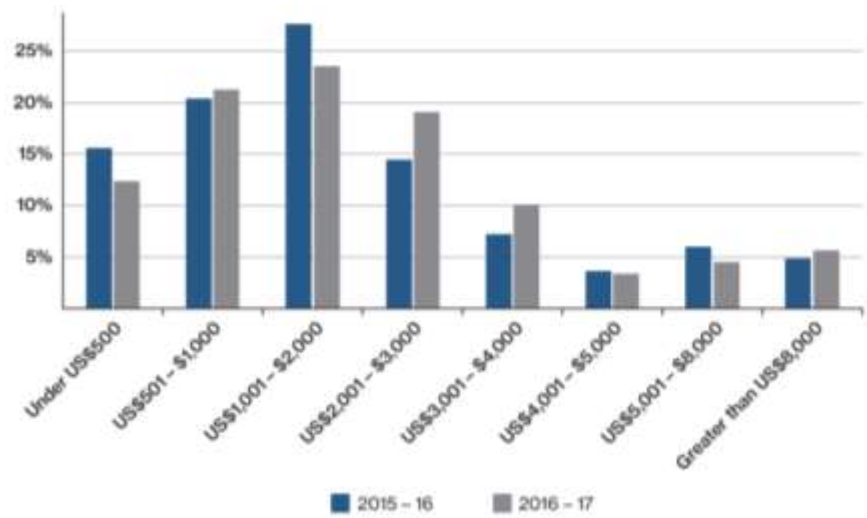


Figure 5-5: Average size of housing microfinance loans (Image Source: Habitat 2017)

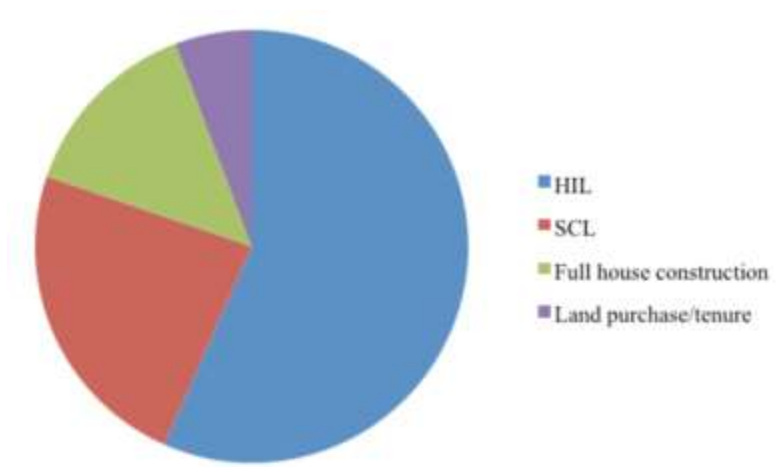


Figure 5-6: Average housing microfinance loan uses, where HIL is a home improvement loan and SCL is a small construction loan (Image Source: Habitat 2015a)

Although traditionally limited to financing entrepreneurial endeavors, microfinance for housing is widely available across the globe. One particularly successful program is Banco Solidario (BancoSol) in Bolivia. Initially started as an NGO in 1986, BancoSol became the world's first regulated microfinance bank in 1992 (BancoSol

2020). In its first 22 years, the bank dispersed US$4.6 billion to over two million micro-enterprise projects (Global Alliance 2018). They later introduced housing microloans, which accounted for a growing 7% of their total portfolio in 2004 (Daphnis and Ferguson 2004). In order to accommodate the significant number of entrepreneurial Bolivians, these housing loans have a unique set of qualifying criteria for both salaried clients and microentrepreneurs (Daphnis and Ferguson 2004).

Another example of housing microfinance is Guatemala's Génesis Empresarial, which offers loans to homeowners for major improvements and additions. This program, a collaboration between the Guatemalan government and the Swedish International Development Cooperation Agency, also includes construction assistance, offering basic design services, budget verification, guidance on procurement of materials and labor, assistance with permits and legal requirements, and construction oversight (Leion 2006). Leion (2006) offers an analysis of the program and its construction assistance component and concludes that "housing microfinance should not be provided without it," as construction assistance increases the quality of housing, and therefore the financial well-being and quality of life of the homeowners, as well as reduces corruption by ensuring proper use of loan funds. Additional housing support services extending beyond construction assistance, as well as a comprehensive guide for practitioners seeking to design and implement a program, can be found in Habitat for Humanity's *Housing Microfinance Product Development: A Handbook* (2015b).

Housing microfinance institutions such as BancoSol and Génesis Empresarial have the potential to improve the quality of housing for those with limited access to traditional financing. Such a loan could be incredibly useful for a family seeking to make repairs or install water, sanitation, security, or electrical systems to improve their quality of life. Likewise, with proper technical oversight, housing microfinance loans could be used to seismically retrofit vulnerable homes in earthquake-prone regions. Furthermore, non-microfinance programs looking to increase the accessibility or effectiveness of their mortgage loans could borrow analogous concepts from housing microfinance institutions, such as BancoSol's accommodation of non-salaried workers or Génesis Empresarial's construction assistance.

However, housing microfinance can also be incredibly dangerous due to its promotion of incremental construction. While potentially appropriate in aseismic settings of rural poverty where homes are constructed of light-weight materials, incrementally constructed concrete and masonry homes can, and too often do, prove deadly in the face of an earthquake. Instead, the housing financing programs discussed in the following section bridge the gap between mortgages and housing microfinance, borrowing elements of both systems to expand access to full construction financing.

5.4.3.1.3 Other Housing Finance Models

In addition to the previously mentioned standard mortgage programs offered by major banks and the housing microfinance programs offered by BancoSol and Génesis Empresarial, three other case studies were also analyzed which combine elements of both mortgage financing and housing microfinance. The first of these was the Evangelical Social Action Forum (ESAF) Small Finance Bank. Similar to BancoSol, this bank started as a microfinance NGO before transitioning to a business in 2015, currently employing 2500 people (ESAF 2019). Located in India, this bank's Micro Housing Loan bridges the gap between microfinance and mortgage financing, offering loans up to approximately US$27,000 with repayment periods up to 20 years (ESAF 2019). These loans can be used to fund up to 80% of the cost of the project and can be used for purchase of an existing home, construction of a new home, renovations, or extensions (ESAF 2019). ESAF requires the applicant to secure a co-applicant and a comprehensive set of documentation, including construction plan and estimate, copies of the title deed, permits, and proof of income (ESAF 2019).

The second unique program considered was Cordaid's housing initiative in the Foyer Sainte Marie community in Port-au-Prince. An NGO based in the Netherlands, Cordaid sought to act as an "enabler of housing production" rather than a "provider of free houses" by utilizing an integrated approach to improve the quality of housing in Foyer Sainte Marie (Cordaid 2013). Instead of constructing a large community of homes in an open area, often far from the city and therefore employment opportunities (as was done by other aid organizations in the new communities of Zorange and Morne a Cabrit), Cordaid invested heavily in a single existing community. Working with a local contractor, they constructed "durable earthquake-resistant housing with basic utilities" and coordinated long-term leases for the homeowners (Cordaid 2013). The project was subsidized by grant funds, but participants were required to make monthly payments, estimated at 30% of their monthly income, for up to 10 years (Cordaid 2013). The program participants were also organized into a savings cooperative and "supported towards achieving more self-reliance, independency, and ownership of homes" (Cordaid 2013). At the time of writing, this program is still progressing and thus data regarding project outcomes is not presently available.

The Government of Haiti also offers a subsidized public housing program, known as *Enterprise Publique de Promotion de Logements Sociaux* (EPPLS). Funded by the Haiti Reconstruction Fund (World Bank 2018b), these homes are offered on a lease-to-own basis, with the title transferred to the occupant after five years of consistent monthly lease payments (Haiti Press Network 2015). The EPPLS program has constructed several housing projects across the nation and also acquired others built by foreign donors (Inter-American Development Bank, Food for the Poor, the Venezuelan government, and USAID) following the 2010 earthquake, including Morne-a-Cabrit and Zorange near Port-au-Prince and the Caracol Industrial Park near Cap-Haitien (Huynh et al. 2013). Unfortunately, this program has been notably unsuccessful, with many of the projects constructed far from employment opportunities, many of the homes in disrepair, and 84% of residents not paying rent (Huynh et al. 2013).

Based on these case studies, there is no clear path to success in housing finance in Haiti. Thus, design thinking methodology was utilized to identify and map the constraints and possible solutions for the unique Léogâne context. The community-based housing finance program proposed for Léogâne in the following sections will combine the integrated approaches of Cordaid, EPPLS, and Génesis Empresarial (e.g., construction assistance) with elements of housing microfinance to increase accessibility of financial services without sacrificing the safety of a well-constructed, seismically-detailed home.

5.4.3.2 Formulation of Constraints and Solution Space

Insights generated through market research and the review of case studies were then used to formulate the list of constraints, from which the proposed solution was derived. The constraints define the obstacles and challenges of working in the Léogâne context, similar to the way the laws of physics and design parameters define a technical engineering problem. These constraints and the corresponding proposed methods for overcoming each, as well as specific details from case studies to support the proposals, are documented in Table 5-1. The industry equivalent in the United States housing sector is also included.

TABLE 5-1: LIST OF CONSTRAINTS AND CORRESPONDING PROPOSED SOLUTIONS

Constraints of Léogâne, Haiti	Proposed Solution	Example Analogous Solutions	US Industry Equivalent
Low personal savings	Financial education and savings groups	Cordaid placed residents in a savings cooperative which provided support and financial assistance (2013).	Personal financial counseling
Wide gap between high “cost of safety” and low financial capacity	Low interest, long-term loans	ESAF offers a fixed interest rate and loan repayment periods of up to 20 years (2019). Also see Cordaid (2013), BNC (2020), and BancoSol (2020).	Mortgage
	Subsidies	Cordaid secured initial funding through grants (2013), EPPLS is also subsidized by the government (Huynh et al. 2013).	HUD Voucher Program

TABLE 5-1: LIST OF CONSTRAINTS AND CORRESPONDING PROPOSED SOLUTIONS (CONTINUED)

Lack of personal financial history	Cosigners and community-based approval process	ESAF requires a co-applicant for each loan (2019).	Co-signer
	Clients must meet certain qualifications	EPPLS required clients to be of Haitian nationality, have a job, and have a clean judicial record (Haiti Press Network 2015). Also see BNC (2020), BancoSol (2020), and ESAF (2019).	Credit report, credit score
Political and environmental instability	Flexible loan payment plans	USAID suggests "flexible payment approaches" (2010b) for lower and mid-middle class families.	Grace period, refinancing, home equity line of credit
Variable income			
Low technical knowledge and capacity	Engineered design and quality control	Génesis Empresarial offers construction assistance, in addition to many other education programs, to its clients (Leion 2006).	Building codes and regulations
Minimal proof of land ownership	Alternative methods to prove land ownership	Habitat for Humanity accepted purchase agreements or utility bills as proof of ownership (2013).	Deed and title
Lack of mortgages and lending infrastructure	Rent-to-own payment plans	EPPLS had clients pay 1,500 HTG per month for five years (Haiti Press Network 2015). USAID also suggests "lease-purchase-based rentals" (2010b).	Mortgage
	Direct housing loans	Cordaid offered subsidized loans directly to their borrowers (2013).	

These constraints and their corresponding proposed program elements can also be further defined as the "solution space," which concisely summarizes the guiding principles and components of the proposed housing finance program. Figure 5-7 graphically presents the solution space. Specifically, the solution space defines the path which can be used to navigate the constraints. Again comparing to a technical engineering problem, the solution space defines the equations, tools, and procedures which can be effectively leveraged to "solve" the problem.

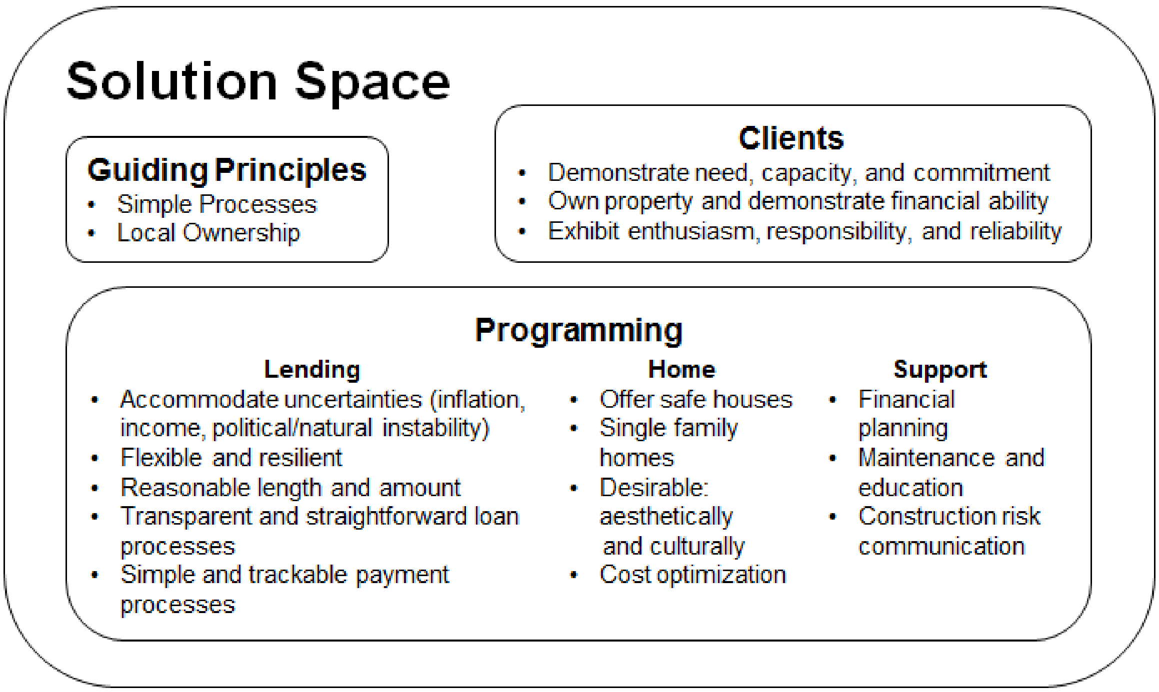


Figure 5-7: Solution Space governing the design of the proposed housing finance program

This solution space was then used to define a conceptual program, known as the Léogâne Community Building Fund.

5.4.3.3 The Léogâne Community Building Fund

In order to navigate the complex constraints of the public and private sectors, the author proposes a community-based housing fund. Initially seed funded by donors but managed locally, this fund would offer lease-to-own housing loans to those who meet a certain set of qualifications. As they pay back their loans, the fund replenishes and more housing loans can be offered to other community members. The defining element of the community building fund is the social incentive for repayment. In a country with widespread distrust and dislike of both banks and the government, compounded by weak enforcement policies, the community-based fund creates a social incentive to meet payments so that one's peers can benefit from new loans offered as the fund is replenished. This social incentive is not likely to manifest in a relationship with a large corporate bank or the Government of Haiti, as EPPLS' 84% non-repayment rate demonstrates. In order to develop this concept into a locally viable solution, the author turned to E2E's Léogâne-based Innovation Clubs (introduced in Section 5.3).

Club Director Lamarre Presuma selected six Innovation Club members from across different zones of Léogâne for this project. Table 5-2 lists these individuals. This team was then challenged with developing the community-based housing fund concept into a program outline. The team was presented with the concept and some of the expected key challenges, such as selecting families for the program, ensuring honesty from applicants, creating trust and transparency in all processes, and ensuring repayment. The team was also asked to consider the practices of other businesses in Léogâne and what would be required to garner respect and trust from local banks and NGOs, in the hopes of eventually collaborating and expanding.

TABLE 5-2: LIST OF INNOVATION CLUB TEAM MEMBERS AND THEIR ZONES

Name	Zone of Léogâne
Olinx Gustave	Belval
Marie Maude Fredling	Bino/Ça Ira
Fabienne Coiolan	Dufort
James Coimin	Rue Poudriere
Susane Dorval Thegenus	Corail/Barriere Rouge
Moise Bien Aime	Nan Jadin/Chatuley

After a month of team meetings and discussions with other members of the community, each of the six team members presented their plan. Then, the team spent another few weeks negotiating and combining ideas to form one plan, which they named *Kredi Lojman Kominote Léogâne* (KLKL), which translates as the Léogâne Community Housing Fund.

The target population is middle-income residents of Léogâne who already own land, either alone or shared with extended family, and currently rent homes or live with relatives. Many people in this category have been saving money to rebuild their homes destroyed in the 2010 earthquake. Furthermore, those who rent are used to making regular housing payments. In order to qualify for a housing loan from KLKL, applicants must meet the following qualifications:

1. At least 18 years' old;
2. Valid ID and two ID photos;
3. Proof of employment, through either an employment contract (verified by institution's director) OR registration of business ownership (verified with General Direction of Taxes);
4. Verification of sufficient income to cover family expenses and monthly housing payment;

5. Two local cosigners within the family who meet all of the above criteria OR one diaspora cosigner (preferred) who can meet and verify the local equivalent of the above criteria;

6. Two witnesses to also serve as character references;

7. Valid title to property in Léogâne, signed and verified by the notary's office (or proof of sufficient income to purchase land AND an initial agreement from landowner to sell);

8. Construction permit.

If initially approved, KLKL staff would visit the land and evaluate the site. They would also meet with the family to design their home (see Section 5.4.4.2) and coordinate the specifics of the loan. Prior to construction, they would also verify that a building permit has been obtained. Then, a specially-trained local contractor would construct the house for the family (see Section 5.4.4.3). It is also important to note that while many international housing projects, such as Food for the Poor's Ça Ira village near Léogâne, opt to build a large number of homes on one cleared plot of land, these communities disrupt cultural norms. In order to differentiate from charity programs and facilitate a sustainable, market-driven housing business, homes should be constructed on an aspiring homeowner's own family land or an individual plot which they select and purchase with the assistance of the housing loan.

The Innovation Club team suggests that payments be made on a monthly basis for 15 years, starting one month after the family moves into the home. A down payment is also suggested, varying between 10-20% of the total construction cost, depending on the family's financial situation. The family cannot sell the house prior to completing all of their payments without the written consent of KLKL. Late payments will be charged a penalty of 1% of the value of the payment. If a family fails to make payments for 6 months, KLKL will list the home for sale and the family will be forced to move out. When the final payment is made, the family will assume ownership of the home and the title will be transferred.

In order to both evaluate the program's results and increase transparency to encourage collaboration with local banks and organizations, the monthly payments will be carefully monitored and recorded. Each family will be assigned an account book to track their payments. Moreover, the fund itself will be deposited in a local bank, with KLKL staff collecting payments and making deposits each month. This monitoring and evaluation is critical in order to prove the concept, solicit more funding from grants and donors, or sell the debt to a local bank.

Another key element of the program is the utilization of Haiti's global diaspora network to promote sustainable economic development. Remittances from the Haitian diaspora make up an estimated 31.2% of Haiti's GDP (KNOMAD 2017). By tapping into diaspora networks and directing a small portion of this money into resilient homes, these remittances can help families in Léogâne build equity and improve their standard of living, while also supporting the local construction industry. These funds can not only subsidize homes for those who otherwise may not be able to afford them, but also provide a year-round stabilizing force for those with fluctuating incomes and those who experience emergencies and do not have sufficient financial resiliency (i.e., savings) to also make housing payments. This sustainable use of remittances should be marketed at the personal level in Léogâne, so aspiring homeowners can tap into their relatives abroad as cosigners or contributors, and in Haitian American communities for those who are interested in earmarking their remittances specifically for housing.

In conclusion, KLKL seeks to create a sustainable, market-driven delivery mechanism for hazard resistant houses in Haiti. Essentially, the proposed program seeks to harness the value of unused land as collateral to kick start the mortgage industry for Léogâne's middle class. This process can be summarized in KLKL's Theory of Change, shown below in Figure 5-8.

Figure 5-8: KLKL Theory of Change

Two provisional tools were also developed to support the KLKL project. The first is a draft applicant screening survey, which is included in English alongside the Haitian Creole translation in Appendix B. This survey was developed with assistance from the Innovation Club team mentioned above and an American anthropologist with substantial experience working in Léogâne (Richman 2019). The second is a Selection and Payment Calculator (Burlotos 2020c), linked in the bibliography. This multi-layered spreadsheet will allow KLKL staff and aspiring homeowners to design their home from a pre-set list of options for floorplans, finishes, fixtures, and basic services. It also rapidly calculates an estimated total cost for the structure as well as a corresponding monthly payment amount. This allows the design process to be performed iteratively, giving families autonomy in the design of their own home, the chance to consider a variety of options and combinations, and the immediate knowledge of what that will cost them each month so that they can decide what is best for their family. It is important to note that both of these tools are provisional and should be evaluated and updated accordingly (especially the unit prices and cost estimates) prior to any implementation.

5.4.4 Design and Construction

Once land tenure is verified, basic infrastructure services considered, and a source for financing identified, the buyer is ready to design and build his or her home. This process can be broken down into its three constituents, which correspondingly make up components four through six of the Housing Market Value Chain: Local Materials & Labor, Design & Engineering Services, and Construction & Quality Assurance. Like all components of the Housing Market Value Chain, these steps are interdependent. The design and engineering process requires a base knowledge of the locally available materials and their engineering properties (e.g., strengths and moduli of elasticity). Furthermore, an understanding of common local construction techniques and the skills and training of the workers who use them also informs the design. Likewise, the quality assurance process during and immediately after construction validates the assumptions of the engineer. These three components are discussed in the following sections.

5.4.4.1 Local Materials & Labor

As previously noted in Sections 2.2.2, 3.1.2.1.2, 4.1.3, and 5.2.1, the quality of construction materials, particularly concrete and concrete block, available in Léogâne is subpar. Similarly, there is also a deficit of laborers formally trained in aseismic construction. These deficiencies severely hinder the Housing Market Value Chain because even if all other components are effective, weak materials and failure to properly follow detailing requirements will render even a carefully engineered design vulnerable to seismic demands. And as noted by Mix et al. (2011), training of masons in earthquake-resistant construction is not necessarily effective, as other factors (such as cost, pre-existing habits, and a lack of thorough understanding of seismic design principles) prevent the skills learned through training from being applied in full. Specific proposals which promote resilient construction in the context of the local material and labor markets are integrated into those presented in Section 5.4.4.3 Construction & Quality Assurance.

5.4.4.2 Design & Engineering Services

The vast majority of residential construction in Haiti is non-engineered (Mix et al. 2011; Lang and Marshall 2011). Unfortunately, this absence of engineered designs had deadly consequences during the 2010 earthquake. Therefore, it is obvious that any housing initiative in the Léogâne case study scenario must utilize seismically-detailed structures. Chapters 2 through 4 of this thesis explored this issue and presented the design, analysis, selection, and performance-based assessment of a resilient structure fit for the case study scenario. The comparative cost analysis of typologies, coupled with the parametric analysis of reinforced concrete frames, works to ensure that construction capital is used as efficiently as possible while also maintaining a strong seismic safety standard. Similarly, the adoption of performance-based analysis procedures in this scenario will allow homeowners to make risk-informed decisions that navigate the inevitable tradeoffs between cost and risk.

While proper engineering is crucial to ensuring safety for the individual homeowners and their families, architectural services are another key component of a market-driven system. In order to develop a sustainable mechanism for housing delivery, one must offer a desirable product in which a consumer is willing to invest significant resources. The benchmark for such architectural considerations (e.g., size, layout, finishes) should be the homes that contractors are building and selling in Léogâne, not what aid organizations are providing for free or with heavy subsidies.

Whenever possible, it is important to involve the aspiring homeowner in the design process to acknowledge their dignity and foster a sense of ownership, valuable emotional capital which can be harnessed to motivate repayment. One method for facilitating this is through risk-informed, multi-criteria decision making, a strategy which gives buyers the autonomy to make their own design decisions. However, it is imperative that clients are thoroughly informed of the advantages and disadvantages of the options available to them. An unbiased performance assessment, when presented alongside other factors such as cost, aesthetics, and security, can empower homeowners to make risk-informed decisions that are truly in the best interests of their family.

Recognizing the importance of both architectural and engineering design and the organizational complexity required to provide custom services, the author proposes providing aspiring homeowners with a suite of semi-custom options based on the best-fit reinforced concrete frame presented in Section 3.2.4. In terms of size, both the four and three-room standard models presented in Sections 2.2.1 and 3.1.2.1.1 should be offered, as well as a smaller two-room model. Suites of various interior layouts should be provided for each model, along with tiered options for doors, windows, fixtures, and finishes. Selection of basic service options, as described in Section 5.4.2, should also be completed at this time. A corresponding KLKL Design and Cost Estimation Tool, as mentioned in Section 5.4.3.3, should be fully developed to allow the family to iteratively design their home and facilitate the risk-informed, multi-criteria decision making process. If an aspiring homeowner insists on a custom home outside of these options, they should be referred to a trusted local contractor for custom design services, and the resulting construction drawings should be professionally reviewed at the aspiring homeowner's expense. Once the design is set, the final cost estimate should be approved by the partnering contractor and the terms of the housing loan finalized. At this point, construction can begin.

5.4.4.3 Construction & Quality Assurance

Construction of the home should be completed by a trusted local partner with each step of the construction process carefully monitored for quality assurance. The differences between infilled frame construction, which may be new to many laborers, and confined masonry must be heavily stressed throughout the construction process. Although the main construction skills and processes required (e.g., mixing and pouring concrete, tying rebar cages, and laying masonry) will not be new to any experienced

Haitian construction laborer, some of the following details and practices, critical to the integrity of the frame structure, may be unfamiliar:

1. Increased standards for assessing quality of materials;
2. Relatively large cross-sectional dimensions of beams and columns;
3. Amount of longitudinal and confining steel in beams and columns;
4. Special moment frame steel detailing at beam-column connections;
5. Decreased water-cement ratio in concrete mix;
6. Pouring the concrete frame prior to building the CMU walls;
7. Extensive documentation and continuous quality assurance practices.

Thus, the implementing organization will likely need to provide guidance to actively promote such behavior change at all personnel levels, from laborers to site foremen to the leaders of the partner construction firm. Effective construction practices will not only ensure that the home is constructed as designed, but will also continually verify and document the process throughout. Such documentation is critical to validating engineering assumptions and verifying the collateral value of the home. However, this transition is not expected to be simple and will require a specific behavior change framework.

In order to develop such a framework, numerous analogous construction manuals were reviewed. These included manuals and guidelines specific to residential construction in Haiti, such as the Ministère des Travaux Publics, Transports, et Communications' *Guide de Bonnes Pratiques pour la Construction de Petits Bâtiments en Maçonnerie Chaînée en Haïti* (MTPTC 2010) and *Guide de Renforcement Parasismique et Paracyclonique des Bâtiments* (MTPTC 2012). Other documents reviewed were specific to confined masonry construction, which possesses similar fundamental construction procedures as infilled frame construction. These include Build Change's *Design and Construction Guidelines for Confined Masonry Housing* (2011b) and *Sekrè Konstriksyon Masonri Chene* (2014), as well as the Confined Masonry Network's *Construction Guide for Low-Rise Confined Masonry Buildings* (2015). Bridges to Prosperity's *Bridge Builder Manual* (2016) was also included in this review process, as it has been translated into three languages and used to build hundreds of pedestrian bridges in developing settings across the globe. Lastly, Chip Heath and Dan Heath's *Switch: How to Change Things when Change is Hard* (2010), although not a construction manual, was also reviewed for its detailed recommended strategies on promoting behavior change in the workplace.

Similar to the design thinking process defined in Section 5.4.3.2 and utilized to develop the solution space for the proposed housing finance structure, insights from the abovementioned resources were noted, compiled, and analyzed. These specific strategies, examples, and analogous solutions were grouped and organized into four themes, each of which were subdivided into three generalized recommendations. These guiding principles were then utilized to guide the development of a quality control manual specific to the frame structure presented in Section 3.2.4. The framework is presented in Table 5-3 with examples corresponding to each strategy.

TABLE 5-3: QUALITY ASSURANCE GUIDING PRINCIPLES

Theme	Strategy	Example
Make It Easy	Shrink daily tasks	Minimize number of required forms, reports, and photos
	Create a space for the process	Define a specific role and/or time of day to complete forms
	Simplify complex procedures	Provide simple, step-by-step instructions
Make It Clear	Utilize visuals	Utilize checklists, photographs, diagrams, and 3D models
	Define practical goals	Prepare realistic timelines and contingency plans
	Provide key instruction	Host workshops and tutorials on the most critical steps
Make It Haitian	Find what works	Consider quality control practices already in use in local analogous situations, such as hospitals or manufacturing
	Leverage social structure	Compare quality control to very honorable profession and give hats, shirts, or certificates to those with special training
	Inspire from within	Empower local leaders to foster a sense of identity within construction teams
Make It Real	Create family-builder connection	Harness emotion by introducing workers to family whose home they are building
	Envision success (and failure)	At relevant construction stages, share photographs of buildings that did and did not fail during the 2010 earthquake and explain why or why not
	Inspire and sustain responsibility	Foster a sense of pride among workers and create systems of accountability

A construction manual specific to the frame structure presented in Section 3.2.4 was then developed from these principles with the assistance of Léogâne-based E2E engineer Gede Jean Benoit. Draft versions of the Site Preparation, Concrete Mixing, Foundation, and Frame manual chapters are included in Appendix C in both English and Haitian Creole. It is important to note that these drafts have not yet been tested in the field, and thus require thoughtful application, evaluation, and iteration in the future.

Furthermore, additional manual chapters must be produced for other construction stages, such as masonry walls, roof, and finishes.

5.4.5 Maintenance & Homeownership

It is imperative that support for aspiring homeowners does not end with the completion of construction. If an aspiring homeowner fails to make loan repayments, they will lose their home. Or if they are unable to recognize damages and perform (or hire someone else to perform) routine maintenance on their home, their investment could depreciate or become unsafe. Thus, the last component of the Housing Market Value Chain, Maintenance & Homeownership, is as critical as any other component, and skills such as home maintenance and personal finance should continue to be developed throughout the repayment process. One mechanism for maintenance knowledge transfer is through a support agreement with the contractor. For example, following construction, the contractor could meet with the buyer once a month for a period of two years to advise the buyer on maintenance and repairs. Or, KLKL program participants could form a support group and meet monthly to discuss any home maintenance issues. In addition to maintenance skills, it is critical that the financial well-being of each participant also be supported.

5.4.5.1 Personal Financial Education

Unlike most households in the United States, the majority of Haitian families do not operate on monthly financial cycles. Sporadic and low income restricts many families in Léogâne from operating on a consistent monthly budget. Even regular expenditures, such as school fees and rent, are often paid on a yearly basis. Furthermore, an insufficient safety net of savings means unexpected costs can often become financial emergencies for families. For these reasons, among others, informal lending and borrowing among families, friends, and street lenders is widespread in Léogâne. Given the above details, it is clear that low- and middle-income families in Léogâne who are given housing loans face potential cultural and behavioral obstacles that could significantly hinder their ability to make monthly housing payments. Therefore, it is recommended that a personalized financial education program be administered to continuously support this shift and assist families in meeting their required KLKL repayments.

In the past decade, the effectiveness of financial education programming in developing nations has been evaluated in numerous randomized control trials (RCT). In general, these programs focused on different methods of teaching financial concepts and practical toolsets. Effectiveness was quantitatively assessed using entrance and exit exams. For example, Carpena et al (2011) concluded "pay for performance" monetary incentives did not improve financial literacy test scores and that prior cognitive restraints due to lack of education hinder the learning progress of complex financial concepts. This is further supported by Drexler et al. (2014) whose simplified "rule of thumb" training in the Dominican Republic proved to be more effective than formalized financial management training. Jamison et al. (2014) found that direct access to financial institutions was not a substitute for financial training in Uganda, concluding that in order to best improve financial well-being, education needed to be combined with direct access to financial institutions. This was reiterated by Cole et al. (2014), whose financial literacy course in South Africa had no effect on bank account ownership. Lastly, Carpena et al.

(2015) found that detailed goal-setting and personalized financial counseling sessions greatly improved the translation of knowledge to positive financial behaviors.

Unfortunately, the overall measured impact of these programs has generally not been extremely noteworthy. Many of the results found to be *statistically significant* are unfortunately insignificant as they focused solely on the success of the program in imparting knowledge and not on whether that knowledge was actually applied successfully in daily life. For example, a study surrounding a large-scale financial education program in Mexico City found statistically significant data that the program increased financial knowledge among attendees (Bruhn et al. 2014). However, this statistically significant increase in knowledge (which research later found to be short-lived) was a mere 9%. More concerning is the fact that the program, which has already reached over 300,000 people throughout Latin America, was found to have no statistically significant impact on borrowing behavior (Bruhn et al. 2014). A much smaller financial education program in South Africa found that budgeting and savings are the most retained and applied topics (Cole et al. 2014). Nevertheless, the percentage of those with savings of any form increased by only 12.9 percentage points, while frequent budgeting habits increased by only 6.1 percentage points (Cole et al. 2014). Essentially, these programs had little practical impact on the financial well-being of the majority of participants in the treatment group.

However, in a study in South Africa, viewers of a soap opera with specially-designed financial messages were found to significantly decrease informal borrowing habits (Berg and Zia 2013). When compared to the control group, those who had viewed the program were 69% more likely to borrow primarily from a formal bank (Berg and Zia

2013). Furthermore, in 2016, Mercy Corps delivered soap opera episodes with strong financial messages via automated cell phone calls to 20,000 Filipinos displaced by Typhoon Haiyan. Later, those who received the messages were found to be more than twice as likely to save money and use banking services (Goodier 2016). These studies show that contextualized messages that provoke emotion can be effective in changing financial behaviors. Other sources, including clinical psychology practices (Epp 2016), Alcoholics Anonymous (2016), and Financial Peace University (Ramsey 2003) further support the role of emotion in behavioral change, described in full in Appendix D. Thus, it becomes clear that access to financial institutions, accessible teaching in fundamental financial concepts, personalized counseling, and emotional triggers are all necessary to positively shift financial behaviors in resource-constrained settings.

Based upon 1) the lack of overall success in the financial literacy studies that simply took practical approaches to delivering knowledge and 2) the perhaps surprisingly effective nature of the contextualized programming that elicited emotional responses, the proposed financial education program (shown in Table 5-4) takes an extremely personalized and integrated approach, blending elements of classroom instruction with personalized financial counseling. They embrace the use of practical financial toolsets proven to be effective in other programs and emotionally and culturally contextualizes them to achieve an effect similar to the aforementioned soap opera programs. Table 5-4 provides a mapping between the conclusions drawn from the literature and the recommended program features.

TABLE 5-4: PROPOSED PROGRAM FEATURES AND CORRESPONDING

LITERATURE-BASED STRATEGIES

Literature-based Strategies	Proposed Program Features
Focus should be on main ideas, simplification of complex topics, and the "rule of thumb" education format (Cole et al. 2014; Drexler et al. 2014)	• Rely heavily on "rule of thumb" learning • End with catchy summary phrases and jingles
Numeracy skills are vital to financial literacy but are not effective when taught alone (Carpena et al. 2011; Jamison et al. 2014)	• Basic mathematics via budgeting worksheets • Utilize familiar denominations, presenting mathematics in a literal, monetary manner
Must consider the education level of participants (Cole et al. 2014; Carpena et al. 2011)	• Rely on simplified, activity-based learning rather than text or lecture-heavy delivery • Disregard complicated calculations (i.e., compound interest, present value)
Must be a sustainable balance between education, action, and empowerment (Carpena et al. 2015; Jamison et al. 2014)	• Utilize both passive and active classroom sessions for introduction to topics and brainstorming activities (Education) • Establish direct partnership with local bank and open savings accounts for participants (Action) • Weekly/monthly personal counseling requires full commitment and accountability of potential homeowner (Empowerment)
Direct access to financial products is vital and should be either offered on site or, better yet, involve individualized educational field trips to a bank, insurance office, notary office, etc. (Carpena et al. 2011; Jamison et al. 2014; Berry et al. 2018)	• Establish direct partnerships with local institutions • Provide detailed action plans for obtaining financial products or supporting processes (e.g., land tenure) • Use skits and mock scenarios

TABLE 5-4: PROPOSED PROGRAM FEATURES AND CORRESPONDING LITERATURE-BASED STRATEGIES (CONTINUED)

Personalized counseling and tutoring in the home are vital and should be provided monthly at a minimum (Carpena et al. 2015)	• Weekly/monthly in-home active management sessions monitor progress and maintain commitment • Designate *sipo* (peer support network) to increase accountability
Goal setting, both short-term and long-term, should be included (Carpena et al. 2015)	• Weekly/monthly counseling includes establishing short-term goals and identifying and breaking down long-term goals, as well as tracking progress
Teach children about financial literacy and social education (Berry et al. 2018)	• Counseling conducted in home in presence of extended family members, activities involving family members in natural roles • Stress importance to parents that their children, family, and friends will be mimicking their financial habits
Specific training for employees and entrepreneurs (Drexler et al. 2014)	• Course dedicated to enhancing employability and entrepreneurial skills • Teach general behaviors that increase value to employer, customers
Inspire participants to assess and apply personal emotional motivation for success (Berg and Zia 2013)	• Pose personal questions to provoke emotional commitment • Emphasize goal setting and effectively track successes and failures • Utilize family relationships in discussion
Establish a system for support, mentorship, and accountability (Brooks et al. 2018)	• Oversee establishment of a *sipo* (support) network for each participant • Create an environment of accountability within classroom/counseling sessions
"Rigorous self-evaluation" is vital to improvement and continued success of educational program (Miller et al. 2009)	• Must establish internal assessment process for determining success and adapt accordingly • Examine metrics from participants

5.5 Conclusion

This chapter explored the constraints in the Haitian case study scenario that could hinder the implementation of the best-fit structural design presented in the previous chapters. Then, the complex interconnectedness of the housing ecosystem was presented in the form of the seven-step Housing Market Value Chain. Each component was analyzed independently, and corresponding implementation procedures and concepts were presented for each. Although presented separately, these recommendations, as noted throughout the chapter, are interdependent and should not be implemented individually. Combined, these mechanisms form an integrated housing delivery framework that can be applied, evaluated, and iterated by any organization seeking to create a lasting, positive impact on the sustainable development of housing in Haiti.

The presented implementation procedures, concepts, and frameworks share several common themes. The first and foremost common theme is the application of human-centered design, which aims to keep the end users' needs and desires at the core of the design process (IDEO 2015). Similarly, each proposal was developed specifically for the Léogâne case study scenario, contextualized through thorough market research, case study analysis, and cultural considerations. Another consistent theme present in the proposed framework is the focus on decentralization and local ownership. For example, the KLKL program proposes that aspiring homeowners build on existing family land rather than constructing a central community of homes on an empty plot of land. Similarly, the proposed financing system involves loans distributed from a locally-managed community housing fund rather than a top-down, national system like EPPLS. This consistent focus on autonomy, the individual development of each participant, and the development of their community emphasizes the central goal of sustainably empowering the target population to improve their own housing situation and the local housing ecosystem. Lastly, as mentioned above and stated throughout this chapter, the entire housing ecosystem was considered while designing each individual component of the proposed framework. Although presented in a chronologically linear maner, the success of the individual components is codependent on the others. This unifying theme of integration is the most important element of the proposed framework, as intervention at any single step in the Housing Market Value Chain is extremely unlikely to contribute to sustainable advancements in resilient housing design and delivery.

It is important to again note that although developed through an integrated research effort, these concepts and procedures have not been tested in the field, and thus, are not intended to be presented as complete plans. Lastly, although developed specifically for the unique context of Léogâne, the guiding frameworks presented within this chapter (see Figures 5-7 and 5-8 and Tables 5-1, 5-3, and 5-4) are generalizable and can be adapted to other similar contexts. Given the extreme technical, economic, and political constraints on the Haitian housing industry, if successful in Léogâne, the proposed frameworks could likely be adapted and implemented to increase the resiliency of residential construction in many other nations across the developing world.

CHAPTER 6: CONTRIBUTIONS AND FUTURE WORK

6.1 Contributions

The residential construction industry in the developing world is often constrained by technical, economic, and political factors which steer the sector toward informal and unregulated design and construction practices. Unfortunately, these deficient systems leave countless families with inadequate housing, which in turn renders them vulnerable to natural hazards. This thesis presented four individual investigations, which together seek to advance the resilience of urban residential construction by providing a pathway to formalizing housing design and delivery in the developing world. The community of Léogâne, Haiti was selected as the case study scenario for investigation due to its significant housing deficit following the 2010 Haiti earthquake and its exposure to both seismic and hydro-meteorological hazards.

The introductory chapter defined informal residential construction in urban, high-risk developing regions, demonstrated the need for evidence-based research and development in this sector, and introduced Léogâne, Haiti as a case study scenario for further analysis. The comparative assessment of relevant typologies in Chapter 2 demonstrated that a masonry-infilled reinforced concrete frame is the most cost-effective disaster-resilient design solution. The parametric analysis and evaluation presented in

Chapter 3 isolated the frame structure that is best-fit for the case study scenario. Then, a performance-based nonlinear static analysis verified the safety of the selected design when exposed to the seismic hazards characteristic of the case study scenario. Lastly, an integrated housing delivery framework was proposed to facilitate the advancements needed in Léogâne's housing ecosystem to promote the market-driven uptake of the best-fit frame. Together, the results of these investigations have the potential to increase the efficiency, reach, and resiliency of urban residential construction in the case study scenario and other similar developing settings.

Through these developments, the following four research objectives were realized:

Objective 1: Inventory the common structural typologies available in the Léogâne case study context and compare the material cost of each to determine the most cost-effective typology for single-family homes;

Objective 2: Develop a procedure and the associated tools for designing, parametrically analyzing, evaluating, and ultimately selecting the best-fit structural design given a unique set of assessment criteria, and utilize this algorithm to define the best-fit structural designs for the case study scenario;

Objective 3: Determine the expected performance level of the selected structures when subject to the characteristic seismic events of the Léogâne case study scenario;

Objective 4: Propose an integrated implementation framework to mitigate and navigate the constraints of the Haitian housing sector and improve the sustainable delivery of resilient housing.

The following sections will further summarize this thesis' contributions to each of these defined objectives.

6.1.1 Contributions to Objective 1

Chapter 2 of this thesis compared the common typologies used as disaster-resilient housing in the case study scenario. The defining elements, advantages, and disadvantages of each were discussed, and the need for a detailed comparative cost assessment was established. From there, nine structures, consisting of combinations of a variety of typologies, foundations, cladding, and roof types, were designed to a uniform architectural plan using industry-standard guidelines. The material quantities of each were estimated and Léogâne-specific pricing data was used to calculate the expected material cost of each structure. Ultimately, this chapter produced tables comparing the material cost of nine complete structures, three structural systems, four foundation types, two roof types, and two cladding types available in Haiti. This comparative material cost analysis clearly defined a masonry-infilled reinforced concrete special moment frame with a footing and beam foundation as the most cost-effective seismic design solution. Lastly, the "cost of safety," defined as the difference in material cost between the reference URM structure and the masonry-infilled reinforced concrete special moment frame, was calculated to demonstrate that the "cost of safety" alone does not restrict the construction of safe housing.

6.1.2 Contributions to Objective 2

After the first objective established masonry-infilled reinforced concrete special moment frames as the most cost-effective typology in the case study scenario, further analysis was needed to design the frame best-fit for the case study scenario. Chapter 3 of this thesis presented the methodology and results of a parametric design, analysis, and scoring procedure to determine the cross-sectional dimensions and steel detailing of the structure best-fit for the case study scenario. In order to directly compare designs, the same standard architectural plan, material properties, and loading assumptions were used in each design. Two Rapid Design and Analysis Tools (RDAT) were developed to, structurally analyze and evaluate 576 different frames for their constructability, resiliency, and cost. A Pareto Optimization and associated categorical weighting process then identified the two designs (one for each roof type) best-fit for the case study scenario. Ultimately, this chapter produced several key contributions to the second research objective. First, a procedure and the associated tools (RDATs and MATLAB codes) for parametrically analyzing masonry-infilled reinforced concrete special moment frames were produced. These tools were intentionally designed to be modifiable, and thus they can be easily adapted to a wide variety of applications with differing frame configurations, design loading assumptions, and material properties. Second, a scoring, weighting, and selection framework was developed to choose a best-fit structure based on several competing objectives. This procedure can also be easily adapted for any case study scenario by adjusting the scoring criteria and weights. Lastly, this chapter used these tools and procedures to define two structures best-fit for the Léogâne case study scenario.

6.1.3 Contributions to Objective 3

The fourth chapter of this thesis presented the methodology and results of a performance-based nonlinear static analysis. The two structures identified by the previous objective were modeled as two-dimensional lumped plasticity frames in SAP2000, utilizing the equivalent strut assumption to model masonry walls. Nonlinear hinges were added to both the frame elements and the equivalent struts. The expected performance levels of the frames were then assessed via pushover analysis due to the Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE) characteristic of the Léogâne case study scenario. Ultimately, this chapter produced pushover curves and corresponding tables of performance levels for the two best-fit structures due to the seismic hazard in the case study scenario. This investigation concluded that although the masonry walls are expected to fail in the MCE event, a performance level consistent with life safety requirements would be maintained for the frame after both the DBE and MCE events.

6.1.4 Contributions to Objective 4

Chapters 2, 3, and 4 presented a rigorous, multi-step investigation to design and evaluate two preferred designs best-fit for the case study scenario. However, the engineering and design process is only one component of the incredibly complex housing ecosystem. In order for the best-fit designs to be sustainably implemented in the case study scenario, the other elements of the housing ecosystem must also be considered. Chapter 5 of this thesis proposed an integrated housing delivery framework in order to address the deficiencies throughout the Housing Market Value Chain that could hinder the market-driven uptake of the best-fit designs. First, an analysis of the technical, economic, and political constraints that restrict the housing sector in the Léogâne case study scenario was presented. The broader concepts of the housing ecosystem and Housing Market Value Chain were also introduced. Then, each component was discussed in the context of Léogâne and interventions to improve housing delivery were developed via human-centered design methodologies and proposed for each component. Ultimately, this chapter offered an integrated framework for formalizing housing delivery in the case study scenario. Although developed specifically for Léogâne, this framework can also easily be adapted and contextualized to fit other developing world settings.

6.2 Future Work

This thesis utilized evidence-based investigations to present designs, procedures, and frameworks that have significant potential to formalize the design and delivery of housing in the developing world. However, future work is required to further progress and validate the conclusions presented in this thesis.

6.2.1 Further Design, Analysis, and Validation

There are several ways in which the design and analysis procedures presented in this thesis can be improved. First, the design and selection phase presented in Chapter 3 was completed independently of the performance-based assessment procedure presented in Chapter 4. Integrating these two processes and redesigning the criteria and weights that constitute the resiliency score to be based solely on the results of the performance-based analysis would more realistically assess the resiliency of each design. Second, another advanced modeling procedure, such as nonlinear dynamic analysis, could be used in conjunction with the nonlinear static analysis procedure presented in this thesis.

Similarly, full-scale shake-table experimentation could be pursued to validate these models. These improvements could more accurately select a design best-fit for the case study scenario by further lowering the cost of the structure. For example, an integrated design, performance-based analysis, and selection procedure supported by experimental results could eliminate the need to consider building code requirements in the resiliency analysis, possibly resulting in the selection of (and validating the use of) designs with smaller column and beam cross-sections and less reinforcing steel, resulting in a reduction in cost. Lastly, a similar investigation into the design and potential size and cost reduction of the footing and beam foundation and roof designs could also be undertaken to further reduce the cost of the structure.

6.2.2 Implementation and Iteration

As mentioned throughout Chapter 5 of this thesis, though developed through an integrated research process, the proposed housing delivery framework has not yet been tested in the field. Thus, the obvious next step is to apply, evaluate, and iterate the various components of the entire framework in the case study scenario. In order to evaluate the effectiveness of the proposed framework, the KLKL program should be piloted with several well-qualified aspiring homeowners in Léogâne. In addition to the community-based lending structure, other components of the proposed housing delivery framework should be continuously evaluated and iterated to best accommodate the needs and challenges of the project.

Some specific examples include the method of verifying land tenure, the options available to the buyer during the home design process, and the issue of post-construction home maintenance. Similarly, the presented quality assurance framework should be used to fully develop the construction and quality assurance manual specific to the best-fit designs. Throughout the construction of multiple homes, this manual and the associated construction processes should be continuously evaluated and refined. Next, special attention should be paid to the scoring and weighting process utilized in Chapter 3 to select the designs. If necessary, the maximum scores and relative weights should be adjusted to best reflect the challenges faced on the ground, especially with regards to constructability. If needed, the selection of the best-fit designs should then be revisited.

6.2.3 Additional Cost Analysis

Lastly, as material cost is just one dimension of a construction project, a complete construction cost analysis is needed to more accurately compare the typologies presented in Chapter 2 and the designs parametrically analyzed in Chapter 3. During the construction phase of the aforementioned KLKL pilot program, detailed financial records should be kept to evaluate the accuracy of the cost estimates produced in Chapters 2 and 3 of this thesis and adjust them as needed, including various labor and overhead costs, e.g., tools, formwork, and supplies. While project cost estimates often include an expected labor cost as a percentage of the material cost, different structural typologies will require different equipment, supplies, timelines, skills, and numbers of workers. Thus, a full-project cost analysis is required to accurately compare different designs.

6.3 Closing Remarks

It is the goal of the author that the designs, procedures, and frameworks presented in this thesis be applied, evaluated, and iterated in order to increase the sustainability and resilience of housing design and delivery in Haiti. Furthermore, these concepts have implications extending beyond the Haitian case study scenario, carrying with them the potential to improve informal residential construction throughout the developing world. Based on the investigations presented in this thesis, government, NGO, and private organizations seeking to improve the seismic resilience of new home construction in regions where CMU is the primary building material should shift their focus from confined masonry to masonry-infilled reinforced concrete special moment frames. Furthermore, in order to effectively spur housing markets, equal emphasis must be placed on the sustainable development of the surrounding components of the housing ecosystem. While not small endeavors, human-centered, integrated approaches to housing design and delivery, like the one presented in this thesis, are urgently needed in order to alleviate the global housing deficit and guarantee access to safe housing for all.

APPENDIX A: MATLAB SCRIPTS AND FUNCTIONS

A.1 Parametric Analysis and Selection Script – CGI Roof

```
% TITLE: Parametric Analysis of Masonry-infilled Reinforced Concrete
Special
% Moment Frames - CGI ROOF

% AUTHOR: Christianos Burlotos
% DATE: November 2019
%
% DESCRIPTION: This script parametrically designs and analyzes masonry
% infilled reinforced concrete special moment frames (with CGI roof)
using
% the RDAT excel tool. It scores each design, runs a pareto
optimization,
% weights the results, and presents the results visually.
%
%% Input Parameters

w_col_list = [25 30 35];
n_w_col = length(w_col_list);

st_col_list = [0 4 0 4 ; 4 4 8 8 ];
n_st_col = length(st_col_list);

dim_beam_list = [20 20 20 25 25 30 ; 25 30 35 30 35 35];
n_dim_beam = length(dim_beam_list);

st_beam_list = [0 0 2 3 ; 2 3 0 0 ];
n_st_beam = length(st_beam_list);

num_input_pars = 7;
num_outputs = 16;
%% Parametric Analysis

% Initialize arrays and counter
des_num = 1;
k_des = n_w_col*n_st_col*n_dim_beam*n_st_beam;
input_pars = zeros(num_input_pars,k_des);
des_results = zeros(num_outputs,k_des);

% Loop over all parameter ranges
for i = 1:n_w_col                %loop over all column widths
    for j = 1:n_st_col           %loop over all column steel
configurations
        for k = 1:n_dim_beam     %loop over all beam dimensions
            for l = 1:n_st_beam    %loop over all beam steel
configurations

            % Define parameters from lists
            w_col = w_col_list(i);
```

```
            st_col = st_col_list(:,j);
            no_3_col = st_col(1);
            no_4_col = st_col(2);

            dim_beam = dim_beam_list(:,k);
            w_beam = dim_beam(1);
            d_beam = dim_beam(2);

            st_beam = st_beam_list(:,l);
            no_3_beam = st_beam(1);
            no_4_beam = st_beam(2);

            % Assemble parameters into one array
            input_pars(:,des_num) = [w_col ; no_4_col ; no_3_col ;
w_beam ;...
                d_beam ; no_4_beam ; no_3_beam];

            % Write parameters in Rapid Design Tool
            xlswrite('RDT_Light_Roof.xlsx',
input_pars(:,des_num),'Input', 'D4:D10')

            % Pull outputs from Rapid Design Tool and store
            des_results(:,des_num) =
xlsread('RDT_Light_Roof.xlsx','Output','C5:C20');

            % Reset Design Number for next iteration
            des_num = des_num + 1;

            end
        end
    end
end

all_data_out = [input_pars ; des_results]; %all values
para_data = all_data_out; %all values (to be trimmed)

%% Eliminate failures

aux_index=find(para_data(8,:).*para_data(9,:)==0);
para_data(:,aux_index)=[];
save('para_data_light.mat','para_data')

%% SCORING

% Resilience score weights

tot100 = 100; %total possible score

wt_ACI_bm_ht = 5;
wt_ACI_bm_w = 5;
wt_ACI_col_w = 5; %original = 5
wt_EU_bm_w = 5;
wt_EU_col_w = 5;
```

```
wt_FS_bm_ben = 10;
wt_FS_bm_sh = 10;
wt_FS_col_ben = 15; %original = 15
wt_FS_col_sh = 40; %original = 40

res_wt = [wt_ACI_bm_ht ; wt_ACI_bm_w ; wt_ACI_col_w ; wt_EU_bm_w ; ...
    wt_EU_col_w ; wt_FS_bm_ben ; wt_FS_bm_sh ; wt_FS_col_ben ; ...
    wt_FS_col_sh];

% Constructability score weights
wt_vol_pour = 75;
wt_rebar_col = 10;
wt_rebar_bm = 10;
wt_colbm_match = 5;

cons_wt = [wt_vol_pour ; wt_rebar_col ; wt_rebar_bm ; wt_colbm_match];

% Score calculations

% Define data for scoring
res_data = para_data(10:18, :);
cons_data = para_data(20:23,:);

% Normalize resilience data
res_max = max(res_data(6:9,:),[],2);
for i=1:4
    j=i+5;
    res_data(j,:) = res_data(j,:)./res_max(i);
end

% Normalize constructability data
cons_max = max(cons_data(1:3,:),[],2);
for i=1:3
    cons_data(i,:) = cons_data(i,:)./cons_max(i);
end
cons_data(1,:) = 1 - cons_data(1,:);

% Score resiliency
res_scores = sum(res_data .* res_wt);

% Score constructability
cons_scores = sum(cons_data .* cons_wt);

% Cost (does not need scored or normalized)
cost = para_data(19,:);

scores = [res_scores ; cons_scores ; cost];
%% Data Visualization

plot3(res_scores,cons_scores,cost, '.')
grid on
xlabel('Resiliency')
ylabel('Constructability')
```

```
zlabel('Cost')

%% Pareto Optimization

% Flip scores so best is minimization
hundreds = 100*ones(1,size(para_data,2));
res_prto_in = hundreds - res_scores;
cons_prto_in = hundreds - cons_scores;

% Set Pareto input data
prto_in = [res_prto_in ; cons_prto_in ; cost]';

% Find Pareto front
[front, membership] = paretoset(prto_in);

% Plot Pareto front
% plot3(front(:,1),front(:,2),front(:,3), '.')
% grid on
% xlabel('Resiliency')
% ylabel('Constructability')
% zlabel('Cost')

% Plot Pareto front alongside all data
hundreds_p = 100*ones(1,size(front,1))';
res_prto_plot = hundreds_p - front(:,1);
cons_prto_plot = hundreds_p - front(:,2);

figure(2)

plot3(res_prto_plot,cons_prto_plot,front(:,3),'mx',res_scores,cons_scor
es,cost, 'k.',85.64,46.78,6922.94,'bs');
legend('Pareto Front Designs', 'All Designs','Optimal Design')
grid on
xlabel('Resiliency')
ylabel('Constructability')
zlabel('Cost (USD)')

% Data Manipulation for output of pareto front information

ind_f = find(membership);
para_data_f = para_data(: , ind_f);
scores_f = scores(: , ind_f);

out_f = [;para_data_f ; scores_f];

% Weighted Analysis of Pareto Front

max_res = max(front(:,1));
min_res = min(front(:,1));
max_cons = max(front(:,2));
min_cons = min(front(:,2));
max_cost = max(front(:,3));
min_cost = min(front(:,3));
```

```
res_wt = .4;
cons_wt = .2;
cost_wt = .4;

sum_score = zeros(size(front,1),1);
for i=1:length(sum_score)
    f_res = ((front(i,1) - min_res)/(max_res-min_res))^2;
    f_cons = ((front(i,2) - min_cons)/(max_cons-min_cons))^2;
    f_cost = ((front(i,3) - min_cost)/(max_cost-min_cost))^2;
    sum_score(i) = res_wt*f_res+cons_wt*f_cons+cost_wt*f_cost;
end
```

A.2 Parametric Analysis and Selection Script – Slab Roof

```
% TITLE: Parametric Analysis of Masonry-infilled Reinforced Concrete 
Special
% Moment Frames - SLAB ROOF

% AUTHOR: Christianos Burlotos
% DATE: November 2019
%
% DESCRIPTION: This script parametrically designs and analyzes masonry
% infilled reinforced concrete special moment frames (with SLAB roof) 
using
% the RDAT excel tool. It scores each design, runs a pareto 
optimization,
% weights the results, and presents the results visually.
%
%% Input Parameters

w_col_list = [25 30 35];
n_w_col = length(w_col_list);

st_col_list = [0 4 0 4 ; 4 4 8 8 ];
n_st_col = length(st_col_list);

dim_beam_list = [20 20 20 25 25 30 ; 25 30 35 30 35 35];
n_dim_beam = length(dim_beam_list);

st_beam_list = [0 0 2 3 ; 2 3 0 0 ];
n_st_beam = length(st_beam_list);

t_slab_list = [13]; %%% 13cm is code minimum for the span (assumes 2-
way slab)
n_t_slab = length(t_slab_list);

num_input_pars = 8;
num_outputs = 16;
%% Parametric Analysis

% Initialize arrays and counter
des_num = 1;
k_des = n_w_col*n_st_col*n_dim_beam*n_st_beam*n_t_slab;
input_pars = zeros(num_input_pars,k_des);
des_results = zeros(num_outputs,k_des);

% Loop over all parameter ranges
for i = 1:n_w_col                       %loop over all column widths
    for j = 1:n_st_col                  %loop over all column steel 
configurations
        for k = 1:n_dim_beam            %loop over all beam dimensions
            for l = 1:n_st_beam         %loop over all beam steel 
configurations
```

```
                    for m = 1:n_t_slab    %loop over all slab thicknesses

                        % Define parameters from lists
                        w_col = w_col_list(i);

                        st_col = st_col_list(:,j);
                        no_3_col = st_col(1);
                        no_4_col = st_col(2);

                        dim_beam = dim_beam_list(:,k);
                        w_beam = dim_beam(1);
                        d_beam = dim_beam(2);

                        st_beam = st_beam_list(:,l);
                        no_3_beam = st_beam(1);
                        no_4_beam = st_beam(2);

                        t_slab = t_slab_list(m);

                        % Assemble parameters into one array
                        input_pars(:,des_num) = [w_col ; no_4_col ;
no_3_col ; w_beam ;...
                            d_beam ; no_4_beam ; no_3_beam ; t_slab];

                        % Write parameters in Rapid Design Tool
                        xlswrite('RDT_Slab_Roof.xlsx',
input_pars(:,des_num),'Input', 'D4:D11')

                        % Pull outputs from Rapid Design Tool and store
                        des_results(:,des_num) =
xlsread('RDT_Slab_Roof.xlsx','Output','C5:C20');

                        % Reset Design Number for next iteration
                        des_num = des_num + 1;

                    end
                end
            end
        end
end

all_data_out = [input_pars ; des_results]; %all values
para_data = all_data_out; %all values (to be trimmed)

%% Eliminate failures

aux_index=find(para_data(9,:).*para_data(10,:)==0);
para_data(:,aux_index)=[];
save('para_data_slab_13min.mat','para_data')
%% SCORING

% Resilience score weights
```

```
tot100 = 100; %total possible score

wt_ACI_bm_ht = 5;
wt_ACI_bm_w = 5;
wt_ACI_col_w = 5; %orig = 5
wt_EU_bm_w = 5;
wt_EU_col_w = 5;
wt_FS_bm_ben = 10;
wt_FS_bm_sh = 10;
wt_FS_col_ben = 15; %orig = 15
wt_FS_col_sh = 40; %orig = 40

res_wt = [wt_ACI_bm_ht ; wt_ACI_bm_w ; wt_ACI_col_w ; wt_EU_bm_w ; ...
    wt_EU_col_w ; wt_FS_bm_ben ; wt_FS_bm_sh ; wt_FS_col_ben ; ...
    wt_FS_col_sh];

% Constructability score weights
wt_vol_pour = 75;
wt_rebar_col = 10;
wt_rebar_bm = 10;
wt_colbm_match = 5;

cons_wt = [wt_vol_pour ; wt_rebar_col ; wt_rebar_bm ; wt_colbm_match];

% Score calculations

% Define data for scoring
res_data = para_data(11:19, :);
cons_data = para_data(21:24,:);

% Normalize resilience data
res_max = max(res_data(6:9,:),[],2);
for i=1:4
    j=i+5;
    res_data(j,:) = res_data(j,:)./res_max(i);
end

% Normalize constructability data
cons_max = max(cons_data(1:3,:),[],2);
for i=1:3
    cons_data(i,:) = cons_data(i,:)./cons_max(i);
end
cons_data(1,:) = 1 - cons_data(1,:);

% Score resiliency
res_scores = sum(res_data .* res_wt);

% Score constructability
cons_scores = sum(cons_data .* cons_wt);

% Cost (does not need scored or normalized)
cost = para_data(20,:);
```

```
scores = [res_scores ; cons_scores ; cost];
%% Data Visualization

plot3(res_scores,cons_scores,cost, '.')
grid on
xlabel('Resiliency')
ylabel('Constructability')
zlabel('Cost')

%% Pareto Optimization

% Flip scores so best is minimization
hundreds = 100*ones(1,size(para_data,2));
res_prto_in = hundreds - res_scores;
cons_prto_in = hundreds - cons_scores;

% Set Pareto input data
prto_in = [res_prto_in ; cons_prto_in ; cost]';

% Find Pareto front
[front, membership] = paretoset(prto_in);

% Plot Pareto front
plot3(front(:,1),front(:,2),front(:,3), '.')
grid on
xlabel('Resiliency')
ylabel('Constructability')
zlabel('Cost')

% Plot Pareto front alongside all data
hundreds_p = 100*ones(1,size(front,1))';
res_prto_plot = hundreds_p - front(:,1);
cons_prto_plot = hundreds_p - front(:,2);

figure(2)
plot3(res_prto_plot,
cons_prto_plot,front(:,3),'rx',res_scores,cons_scores,cost,
'k.',85.94,42.2,7370.03,'gs','MarkerSize', 20);
grid on
xlabel('Resiliency (%)')
ylabel('Constructability (%)')
zlabel('Cost (USD)')
legend('Pareto Front Designs', 'All Designs' , 'Preferred Design')

% Data Manipulation for output of pareto front information

ind_f = find(membership);
para_data_f = para_data(: , ind_f);
scores_f = scores(: , ind_f);

out_f = [;para_data_f ; scores_f];

% Weighted Analysis of Pareto Front
```

```
max_res = max(front(:,1));
min_res = min(front(:,1));
max_cons = max(front(:,2));
min_cons = min(front(:,2));
max_cost = max(front(:,3));
min_cost = min(front(:,3));

res_wt = .4;
cons_wt = .2;
cost_wt = .4;

sum_score = zeros(size(front,1),1);
for i=1:length(sum_score)
    f_res = ((front(i,1) - min_res)/(max_res-min_res))^2;
    f_cons = ((front(i,2) - min_cons)/(max_cons-min_cons))^2;
    f_cost = ((front(i,3) - min_cost)/(max_cost-min_cost))^2;
    sum_score(i) = res_wt*f_res+cons_wt*f_cons+cost_wt*f_cost;

end
```

A.3 Pareto Optimization Function

```
function [Front, membership]=paretoset(X)

% PARETOSET  To get the Pareto set from a given set of points.
% synopsis:           membership =paretoset (objectiveMatrix)
% where:
%   objectiveMatrix: [number of points X number of objectives] array
%   membership:      [number of points X 1] logical vector to indicate
if ith
%                    point belongs to the Pareto set (true) or not
(false).
%
% by Yi Cao, Cranfield University, 02 June 2007
% Revised by Yi Cao on 17 October 2007
% Version 3, 21 October 2007, new sorting scheme to improve speed.
% Bugfix, 25 July 2008, devided by zero error is fixed.
%
% Examples: see paretoset_examples
%

m=size(X,1);
Xmin=min(X);
X1=X-Xmin(ones(m,1),:);     %make sure X1>=0;
Xmean=mean(X1);
%sort X1 so that dominated points can be removed quickly
[x,checklist]=sort(max(X1./(Xmean(ones(m,1),:)+max(Xmean)),[],2));
Y=X(checklist,:);
membership=false(m,1);
while numel(checklist)>1
    k=checklist(1);
    [membership(k),checklist,Y]=paretosub(Y,checklist);
end
membership(checklist)=true;
Front=X(membership,:);

function [ispareto,nondominated,X]=paretosub(X,checklist)

Z=X-X(ones(size(X,1),1),:);
nondominated=any(Z<0,2);                     %retain nondominated points
from the check list
ispareto=all(any(Z(nondominated,:)>0,2));   %check if current point
belongs to pareto set
X=X(nondominated,:);
nondominated=checklist(nondominated);
```

A.4 Bilinear Idealization of Pushover Curves Script

```
% TITLE: Bilinear Idealization of Pushover Curves

% AUTHOR: Christianos Burlotos
% DATE: February 2020
%
% DESCRIPTION: This script bilinearizes pushover results for 8 frames
and
% plots the initial curves with their bilinear approximations in
% accordance with FEMA 356

%% INPUT from excel file
% filename = 'pushover_results.xlsx';
% sheetname = 'Pushover 1 in';
%
% % trim to 201 for 1"
% % trim to 205 for 5"
% push_1 = xlsread(filename,sheetname,'A4:B201');
% push_2 = xlsread(filename,sheetname,'D4:E201');
% push_3 = xlsread(filename,sheetname,'G4:H201');
% push_4 = xlsread(filename,sheetname,'J4:K201');
% push_5 = xlsread(filename,sheetname,'M4:N201');
% push_6 = xlsread(filename,sheetname,'P4:Q201');
% push_7 = xlsread(filename,sheetname,'S4:T201');
% push_8 = xlsread(filename,sheetname,'V4:W201');
%
% % combine pushover curves into one array
% pushdata(:,:,1) = push_1;
% pushdata(:,:,2) = push_2;
% pushdata(:,:,3) = push_3;
% pushdata(:,:,4) = push_4;
% pushdata(:,:,5) = push_5;
% pushdata(:,:,6) = push_6;
% pushdata(:,:,7) = push_7;
% pushdata(:,:,8) = push_8;
%
% save('pushdata_1in.mat','pushdata')
%% Input target displacements
clc
clear all

dt_list_2500 = [.89171; .58327 ; .69289 ; .51427 ; .27223 ; .18323 ;
.23689 ; .13123];
dt_list_500 = [.57690 ; .38998 ; 0.46192 ; 0.33644 ; 0.18168 ; 0.12240
; 0.16031 ; .08751];

% change depending on what file you are loading
load('pushdata_1in.mat')

dt_list = dt_list_2500;
xmax = 1; %max displacement (x-axis) in plots
```

```
%% Bilinear fit to FEMA 356 Guidelines
ns = 8; %number of structures
Ke = zeros(1,ns);
dy = zeros(1,ns);
Vt = zeros(1,ns);
dt = zeros(1,ns);
a = zeros(1,ns);
Ki = zeros(1,ns);
Vy = zeros(1,ns);

for i =1:ns
    pushcurve = pushdata(:,:,i);

    %%%%%% STEP 1: Trim pushover curve to target displacement %%%%%%

    for j=1:size(pushcurve,1)
        if pushcurve(j,1) > dt_list(i)
            pushcurve(j,:) = 0;
        end
    end

    aux_index=find(pushcurve(:,1)==0);
    pushcurve(aux_index,:)=[];

    % Define Vt and dt based on trimmed curve
    dt(i) = pushcurve(length(pushcurve),1);
    Vt(i) = pushcurve(length(pushcurve),2);

    %%%%%% STEP 2: Define bilinear curve such that:         %%%%%%
    %             a) Same area above and below
    %             b) Initial stiffness crosses curve at .6dy

    % Find initial stiffness, Ki
    if i<=7
    Ki(i) = (pushcurve(5,2) - pushcurve(1,2)) / (pushcurve(5,1) -
pushcurve(1,1));
    else
        Ki(i) = (pushdata(5,2,i) - pushdata(1,2,i)) / (pushdata(5,1,i)
- pushdata(1,1,i));
    end

    % Initialize Ke and dy
    init = [0.25;.32];

    % Run minimization

    [xopt,fopt(i),flag,exit,~,hessian] = fmincon(@(x)
bilin_fit_F356_CON(pushcurve,Vt(i),dt(i),Ki(i),x),init,[],[],[],[],[0.1
0.05],[5 1.2*max(pushcurve(:,2))/Ki(i)],@(x)
NONLCON(pushcurve,Ki(i),x));
```

```
    %[xopt] = patternsearch(@(x)
bilin_fit_F356(pushcurve,Vt(i),dt(i),Ki(i),x),init);
    % Define bilinear curves
    Ke(i) = xopt(1)*Ki(i);
    dy(i) = xopt(2);
    a(i) = (Vt(i) - Ke(i)*dy(i))/(Ke(i)*(dt(i)-dy(i)));

    d_vec = 0:.001:dt(i);
    bilin = zeros(1, length(d_vec));

    for k=1:length(d_vec)
        if d_vec(k) <= dy(i)
            bilin(k) = Ke(i)*d_vec(k);
        else
            bilin(k) = Ke(i)*dy(i)+a(i)*Ke(i)*(d_vec(k)-dy(i));
        end
    end

    Vy(i) = Ke(i)*dy(i);

    % Plotting
    %xmax = 1; %max displacement (x-axis) in plots
    ymax = 50; %max base shear (y-axis) in plots
    hp = 98.42; %height of panel

%     io_x = .003*hp;
%     ls_x = .03*hp;
%     cp_x = .04*hp;
%
%     io_y = interp1(pushdata(:,1,i),pushdata(:,2,i), io_x);
%     ls_y = interp1(pushdata(:,1,i),pushdata(:,2,i), ls_x);
%     cp_y = interp1(pushdata(:,1,i),pushdata(:,2,i), cp_x);

    figure(1)
    subplot(4,2,i)

    plot(pushdata(:,1,i),pushdata(:,2,i),'b')
    hold on
    plot(d_vec, bilin,'--k', 'LineWidth', 1)

    title('change title to structure name')
    axis([0 xmax 0 ymax])
    xlabel('Displacement (in)')
    ylabel('V (kips)')
    plot(d_vec(k), bilin(k),'k.','MarkerSize',10)
%     plot(io_x, io_y,'g')
%     plot(ls_x, ls_y,'y')
%     plot(cp_x, cp_y,'r')
end
```

A.5 Bilinear Minimization Functions

```
function [diff] = bilin_fit_F356_CON(pushover, Vt, dt, K,x)

Ke = x(1,:)*K;
dy = x(2,:);
a = (Vt - Ke*dy)/(Ke*(dt-dy));

%Calculate area difference
disp_vec = pushover(:,1);

for m=1:length(disp_vec)
    if disp_vec(m) < dy
        f2(m) = Ke*disp_vec(m);
    else
        f2(m) = Ke*dy+a*Ke*(disp_vec(m)-dy);
    end
end

diff = log((sum(pushover(:,2) - f2')).^2);

end
```

```
function [c,ceq] = NONLCON(pushover,K,x)

Ke = x(1,:)*K;
dy = x(2,:);

% Calculate difference at .6Vy (where the lines are supposed to cross)
sec_pt_1 = .6*Ke*dy;

%p = polyfit(pushover(:,1), pushover(:,2),2);
sec_pt_2=interp1(pushover(:,1), pushover(:,2),.6*dy);

%sec_pt_2 = polyval(p,.6*dy);

ceq = sec_pt_1 - sec_pt_2;
c=[];

end
```

APPENDIX B: DRAFT APPLICANT SCREENING SURVEY

Part 1: Introduction	Pati 1: Entwodiksyon
Hi, I'm ______. I work for ______. We are thinking about developing a new housing program. We want to know if it is possible for our idea to be successful in Léogâne. The Program: We want to help people in Léogâne build houses. We do not give away houses, but we want to help people build houses quickly. Many Haitians build slowly for many years, but we want to build houses quickly. Instead of paying all of the money for the house before building the house and building the house little by little, we want to help people build houses quickly with borrowed money and then the people pay slowly for some years. The borrowed money is fair with low interest rates. They pay almost the same amount of money, but in little payments over many years. We are speaking with you because we think you could be interested in our program, but we are not promising anything. Again, we are asking these questions to see if this program is possible. Can I ask you some questions about you, your land, your family, and building a house? Yes No [IF NO, END SURVEY]	Li pou moun la: Bonjou/bonswa. Mwen se ______. Mwen travay pou ________. N'ap panse sou devlopman yon nouvo pwogram lojman. Nou vle konnen si li se posib pou lide nou an reyisi nan Leyogan. Pwogram lan: Nou vle ede moun nan Léogâne bati kay. Nou pa bay kay yo, men nou vle ede moun bati kay yo byen rapid. Anpil Ayisyen bati dousman pou anpil ane, men nou vle bati kay yo byen rapid. Olye pou peye tout lajan an pou kay la anvan li bati ak bati kay la moso pa moso, nou vle ede moun bati rapidman avek lajan prete, epi moun yo peye ti kras pa ti kras pou kèk ane. Lajan prete a li jis avek pousantaj enterè yo ki ba. Yo peye prèske menm kantite lajan an, men nan ti peman pou plizye ane. N'ap pale ak ou paske nou panse ou ka enterese nan pwogram nou an, men nou p'ap pwomèt ou anyen. Ankò, nou ap poze kesyon sa yo pou wè si pwogram sa a kapab posib. Èske mwen ka poze ou kèk kesyon sou ou, tè ou, fanmi ou, ak bati yon kay? Wi Non
What is your name?	Koman ou rele?
Do you want to build a new house for yourself and your family? Yes No	Èske ou vle bati yon kay pou ou ak fanmi ou? Wi Non

	[**PA LI]** Pa gen repons
Have you been saving money to build a house? Yes No	Èske ou ap sere lajan pou ou bati yon kay? Wi Non [**PA LI]** Pa gen repons
Do you own land to build your house on? Yes No	Èske ou genyen tè kote ou ka bati kay ou? Wi Non [**PA LI]** Pa gen repons

Part 2: Open-Ended Conversation	**Pati 2: Yon Ti Pale**
Read to the person: Now, let's talk about why you have not started building your new home yet. (No response)	Li pou moun la: Kounye a, ann pale poukisa ou poko komanse bati yon kay. (Pa gen repons)
What is the biggest problem with building a new home?	Ki pi gwo pwoblem ki genyen pou w bati yon nouvo kay?
What would make the process of building a new home easier for you?	Kisa ki ta fè pwosesis bati yon nouvo kay pi fasil pou ou?
What are the three most important features you would like to see in a new home?	Ki twa pi gwo karakteristik enpotan ou vle wè nan yon nuovo kay?

Part 3: Sample Qualification Form	**Pati 3: Echantiyon Fòm Kalifikasyon**
To build a house with our program, people have to qualify. To qualify, people have to fill out the Qualification Form. If you want to be considered for the program, you need to fill out the Qualification Form.	Li pou moun la: Pou bati yon kay nan pwogram nou an, moun yo dwe kalifye. Pou kalifye, moun yo dwe ranpli Fòm Kalifikasyon lan. Si ou vle konsidere pou pwogram lan, ou dwe ranpli Fòm Kalifikasyon an.

To see if this program is possible in Léogâne, we are asking people who we think could be interested in our program to fill out the Qualification Form now. Filling out the Qualification form now does not guarantee that we start the program or guarantee you a house, but your information will help us decide what we can do to help in Léogâne. Do you agree to answer the following questions from the Qualification Form? Yes No [IF NO, END SURVEY]	Pou wè si pwogram lan se posib nan Leyogan, nou ap mande moun ke nou panse ki kab enterese nan pwogram nou pou ranpli Fòm Kalifikasyon an kounye a. Ranpli Fòm Kalifikasyon lan kounye a pa garanti ke nou kòmanse pwogram lan oswa garanti ou yon kay, men enfòmasyon ou pral ede nou deside sa nou kap fè pou ede nan Leyogan. Èske ou dakò pou ou reponn kesyon nan fòm lan? Wi Non
Personal Information	Enfomasyon Pèsonèl
I am glad you are interested in our program. It is very important that you provide honest information in the Qualification Form. Do you agree to provide the most honest and accurate answers to these questions? Yes No	Mwen kontan ke ou enterese ak pwogram nou an. Se trè enpòtan ke ou bay ènfomasyon onèt nan Fòm Kalifikasyon an. Èske ou dakò pou bay repons ki pi onèt ak egzat pou kesyon sa yo? Wi Non
Please sign to confirm your response. [SIGNATURE]	Tanpri siyen pou konfime repons ou. [SIYATI]
QUESTION FOR SURVEYOR: What is the gender of this person? 0 Male 1 Female	KESYON POU ANKETÈ: Èske moun sa a se yon fi oswa gason? 0 Gason 1 Fi
In what year were you born? Enter 0 for “Don’t Know”	Nan ki ane ou te fèt? Mete 0 pou “Pa konnen”

What is the highest level of school you completed? I never attended school 1 I completed some Primary/Fundamental 2 I completed Primary/Fundamental (Year 6) 3 I completed Secondary/Katrieme (Year 9) 4 I completed Reto (Year 12) 5 I completed Philo (Year 13) 6 I completed Professional school 7 I completed university	Nan ki klas ou rive lekòl? 0 Mwen pat janm ale lekòl 1 Mwen te fè kèk ane nan primè 2 Mwen fè primè (6 zyèm ane) 3 Mwen fè katriyèm (9 vyèm ane) 4 Mwen fè reto (12 zyèm ane) 5 Mwen fè filo (13 zyèm ane) 6 Mwen fini ak lekòl pwofesyonèl 7 Mwen fini ak inivèsite **[PA LI]** Pa gen repons
House Preferences	Preferans Kay
Read to the person: In this section, I will ask you questions about the house you want to build. Please remember that we are not promising to start a program or build you this house. If you qualify and are selected, you will need to pay for this house. (No response)	Li pou moun la: Nan seksyon sa a, mwen pral mande ou kesyon pou kay la ou vle bati. Tanpri sonje ke nou p'ap pwomèt pou kòmanse yon pwogram oswa pou bati kay sa a pou ou. Si ou kalifye epi chwazi, ou pral gen pouw peye pou kay sa a. (Pa gen repons)
Do you have a husband/wife that would live in the house with you? Yes No	Èske ou gen mari/madanm ki vle viv nan kay la avek ou? Wi Non **[PA LI]** Pa gen repons
How many other people would live in the house with you? [IF 0, SKIP NEXT QUESTION]	Konbyen lot moun ki ta vle viv nan kay la ak ou?
How many of these are children under the age of 18 years?	Konbyen ladan yo ki poko gen 18 an?
Do you want an indoor or outdoor toilet?	Èske ou vle yon twalèt anndan oswa deyò?

	Anndan;0 Deyò;1 [PA LI] Pa gen repons;99
Do you want an indoor or outdoor kitchen?	Èske ou vle yon kizin anndan oswa deyò? Anndan;0 Deyò;1 [PA LI] Pa gen repons;99
Please tell us how many other rooms you would like in your house and then tell us how you're going to use each room. For example, two rooms: one room for living area and one bedroom for myself and my partner.	Tanpri di nou, konbyen lòt chanm ou vle genyen nan kay ou epi di nou koman ou pral itilize chak chanm. Pa egzanp, 2 chanm: yon chanm pou salon an ak yon chanm a kouche pou mwen ak mari/madanm mwen.
We build houses that are beautiful, safe, and strong. Which is most important to you? 0 That my house is beautiful 1 That my house is safe from theft 2 That my house is strong against earthquakes and hurricanes	Nou bati kay ki bèl, ki an sekirite, ak ki dyanm. Kisa ki pi enpòtan pou ou? 0 Kay mwen an bèl 1 Kay mwen an sekirite pou vole 2 Kay mwen an dyanm pou tranbleman te ak siklon [PA LI] Pa gen repons;99
What makes a house beautiful?	Kisa ki fè yon kay bèl?
Financial Information	Enfòmasyon Finansye
Financial Capacity	Kapasite Finansye
Read this to the person: In this section, I will ask you questions about your finances.	Li pou moun la: Nan seksyon sa a, mwen pral mande kesyon sou finanse ou.
How do you earn a living? 1 I have my own business 2 I work for a Haitian employer 3 I work for a foreign employer 4 I cannot find a way to earn a living	Kisa ou fè pou ou chache lavi? 1 Mwen fè komès 2 Mwen travay pou yon Ayisyen 3 Mwen travay pou yon blan 4 Mwen pa jwenn anyen pou m fè pou m chache lavi

5 I no longer earn a living due to sickness or age 6 I care for children, adults or relatives who are sick 7 Other [IF 4-7, SKIP NEXT QUESTION]	5 Mwen pa fè anyen ankò pou chache lavi m paske m malad osnon m granmoun 6 Mwen pa fè anyen ankò paske m'ap okipe pitit, granmoun, oswa fanmi ki malad yo 7 Lòt [PA LI] Pa gen repons;99
If you have your own business or work for an employer (Haitian or foreign), please describe the business and your role in it.	Si ou genyen pwop biznis oswa travay pou yon moun (Ayisyen oswa Etranje), tanpri eksplike biznis la ak kisa ou fè ladan l.
How many years have you earned your living this way?	Konbyen ane ou genyen depi wap chache lavi jan sa a?
How much money do you make in a month?	Konbyen kòb ou fè nan yon mwa?
Currency: Gourdes Haitian Dollars	Kòb: Goud Dola Ayisyen
"House Money" is all the money for the house and house things, such as fixing things or bills. In addition to yourself, do other people give money to expenses in the house? Yes No [IF "NO" SKIP NEXT 2 QUESTIONS]	"Lajan Kay" se tout kòb pou kay la ak bagay kay, tankou ranje bagay oswa bòdwo. Anplis de ou menm, èske lòt moun bay lajan pou depanse nan kay? Wi Non [PA LI] Pa gen repons;99
"House Money" is all the money for the house and house things, such as fixing things or bills. In addition to yourself, how many other people contribute to your house money?	"Lajan Kay" se tout kòb pou kay la ak bagay kay, tankou ranje bagay oswa bòdwo. Anplis de ou menm, konbyen lòt moun ki bay lajan kay?
Person 1 - How is this person related to you? 0 Brother/Sister 1 Son/Daughter 2 Husband/Wife 3 Mother/Father 4 Mother-in-Law/Father-in-Law 5 Cousin 6 Friend	Moun 1 - Kisa moun nan ye pou ou? 0 Frè m / Sè m 1 Pitit gason m / Pitit fi m 2 Mari m / Madanm m 3 Manman m / Papa m 4 Belme m / Bope m 5 Kouzen m / Kouzin m

7 Other Person 1 - How much money do they give to the house each month? (In Gourdes)	6 Zanmi m 7 Lòt Moun 1 - Konbyen lajan kay li bay chak mwa? (nan Goud)
Do you have any family members or friends living abroad? Yes No [IF “NO” SKIP NEXT 4 QUESTIONS]	Èske ou genyen fanmi oswa zanmi k’ap viv lòtbò? Wi Non [PA LI] Pa gen repons;99
Do they send you money? Yes No [IF “NO” SKIP NEXT 3 QUESTIONS]	Èske yo voye lajan pou ou? Wi Non [PA LI] Pa gen repons;99
How often do they send money to you?	Chak kile yo voye lajan pou ou?
When they send you money, how much do they send?	Lè yo voye lajan pou ou, konbyen yo voye?
Currency: Gourdes Haitian Dollars	Kòb : Goud Dola Ayisyen
Do you currently have any debts? Yes No [IF “NO” SKIP NEXT 2 QUESTIONS]	Èske ou genyen dèt ou dwe? Wi Non [PA LI] Pa gen repons;99
In total, how much debt do you have?	Konbyen kob ou dwe an total?
Currency: Gourdes Haitian Dollars	Kòb : Goud Dola Ayisyen
Do you pay rent for your home? Yes No [IF “NO” SKIP NEXT 2 QUESTIONS]	Èske ou peye lwaye pou kay ou a? Wi Non [PA LI] Pa gen repons;99

How much money do you pay to rent your house each year?	Konbyen kòb ou peye pou kay ou a chak ane?
Currency: Gourdes Haitian Dollars	Kòb : Goud Dola Ayisyen
Do you use a sol? Yes No [IF "NO" SKIP NEXT 6 QUESTIONS]	Èske ou nan sol? Wi Non [PA LI] Pa gen repons;99
How much do you pay?	Konbyen ou peye?
Currency: Gourdes Haitian Dollars	Kòb : Goud Dola Ayisyen
How often do you pay that?	Chak kile ou peye?
How much do you get when it is distributed to you?	Konbyen kòb yo ba ou lè yo ba ou men pa ou la?
Currency: Gourdes Haitian Dollars	Kòb : Goud Dola Ayisyen
How many times per year do you get that amount?	Konbyen fwa pa ane ou resevwa kantite sa a?
Do you have a bank savings account? Yes No [IF "NO" SKIP NEXT 2]	Èske ou gen yon kane bank? Wi Non [PA LI] Pa gen repons;99
How much money do you have in all of your bank savings accounts?	Konbyen kòb ou genyen sou tout kane bank ou yo?
Currency: Gourdes Haitian Dollars	Kòb: Goud Dola Ayisyen
Do you have money saved that is not in a bank savings account or a sol? Yes No [IF "NO" SKIP NEXT 3 QUESTIONS]	Èske ou gen kòb sere ki pa sou kane bank ou byen ki pa nan sol? Wi Non [PA LI] Pa gen repons;99
Where or how do you save that money?	Ki kote ak koman ou sere kòb sa a?

How much money you have saved this way?	Konbyen kòb ou sere nan fason sa a?
Currency: Gourdes Haitian Dollars	Kòb: Goud Dola ayisyen
Of the money you have saved now, how much will you pay to build a house?	Nan kòb ou sere kounye a, konbyen ou pral peye pou bati yon kay?
Currency: Gourdes Haitian Dollars	Kòb: Goud Dola Ayisyen
Lending History	*Istwa Lajan Prete*
Read this to the person: In this section, I will ask you questions about lending money.	Li pou moun la: Nan seksyon sa a, mwen pral mande kesyon sou prete lajan.
Have you ever taken a loan from a friend or family member? Yes No	Èske ou te prete lajan prete nan men zanmi oswa fanmi? Wi Non
Have you ever taken a loan from an eskont? Yes No [IF "NO" TO THIS QUESTION AND PREVIOUS QUESTION, SKIP NEXT 3 QUESTIONS]	Èske ou te prete lajan prete nan men eskont? Wi Non
When you borrow money, how much do you usually borrow?	Lè ou prete lajan nan men moun, konbyen ou prete dabitid?
When you borrow money, what do you usually use the money for?	Lè ou prete lajan nan men moun, kisa ou pase lajan an, dabitid?
What is the largest loan you have received from someone (family, eskont, friend, or other?	Ki pi gwo lajan prete ou te pran nan men moun (fanmi, eskont, zanmi, oswa lòt)?
Currency: Gourdes Haitian Dollars	Kòb: Goud Dola Ayisyen
How long did it take you to pay the loan?	Konbyen tan sa te pran ou pou ou te fin peye lajan ou te prete a?
Do you own a car?	Èske ou genyen yon machinn?

Yes No [IF “NO” SKIP NEXT 4 QUESTIONS]	Wi Non
Did you purchase it with a loan or pay for it in cash? Loan Cash [IF “LOAN” SKIP NEXT QUESTION. IF “CASH” ANSWER THE NEXT QUESTION BUT SKIP THE FOLLOWING TWO QUESTIONS]	Èske ou te achte li ak lajan prete ou byen lajan likid? Lajan prete Lajan likid
How long did it take you to save that amount of money?	Konbyen tan li te pran ou pou ou te sere kantite kòb sa a?
Who provided the loan?	Kiyès ki te prete ou lajan sa a?
How long did it take you to pay the loan?	Konbyen tan li te pran ou pou ou te peye lajan sa ke ou te prete a?
Do you own a moto? Yes No [IF “NO” SKIP NEXT 4 QUESTIONS]	Èske ou genyen yon moto? Wi Non
Did you purchase it with a loan or pay for it in cash? Loan Cash [IF “LOAN” SKIP NEXT QUESTION. IF “CASH” ANSWER THE NEXT QUESTION BUT SKIP THE FOLLOWING TWO QUESTIONS]	Èske ou te achte li ak lajan prete ou byen lajan likid? Lajan prete Lajan likid
How long did it take you to save that amount of money?	Konbyen tan ou te pran pou ou sere kantite kòb sa?
Who provided the loan?	Ki moun kite prete ou lajan sa?

How long did you take to repay the loan?	Konbyen tan ou te pran pou ou te remet lajan ou te prete a?
Have you ever received a loan from a bank, cooperative, or credit union? Yes No [IF "NO" SKIP NEXT 3 QUESTIONS]	Èske ou toujou prete lajan nan bank, koperativ, oswa inyon kredi? Wi Non
What is the largest loan you have received from a bank, cooperative, or credit union?	Ki pi gwo lajan ou te prete nan bank, koperativ, oswa inyon kredi?
Currency: Gourdes Haitian Dollars	Kòb: Goud Dola Ayisyen
How long did you take to repay the loan?	Konbyen tan ou te pran pou ou te remet lajan ou te prete a?
Do you currently use a credit card?	Èske ou itilize yon kat kredi?
If you could, would you borrow money from a bank to build a house? Yes No	Si sa ta posib, eske ou ta mande prete lajan nan yon bank pou ou bati yon kay? Wi Non
Why or why not?	Poukisa? Ou poukisa non?
If you could, would you borrow money from the government to build a house? Yes No	Si sa ta posib, eske ou ta mande prete lajan nan men gouvenman an pou ou bati yon kay? Wi Non
Why or why not?	Poukisa? Ou poukisa non?
If you could, would you borrow money from a foreign institution to build a house? Yes No	Si se ta posib, eske ou ta mande prete lajan nan yon enstitisyon etranje pou ou bati yon kay? Wi Non
Why or why not?	Poukisa? Ou poukisa non?

If you could, would you borrow money from a foreign NGO to build a house? Yes No	Si se ta posib, eske ou ta mande prete lajan nan yon oganizasyon etranje pou ou bati yon kay? Wi Non
Why or why not?	Poukisa? Ou poukisa non?
If a person borrows money, he/she must pay it all back in a period of time. We call this the “Payment Period.” What is the longest payment period (in years) that you would agree to if you borrowed money to build a house?	Si yon moun prete lajan, li dwe peye tout nan yon peryòd de tan. Nou rele sa “peryòd peman an.” Konbyen ane kòm “peryòd peman an” ki pi long ke ou ta dako si ou te prete lajan pou ou bati yon kay?
When you take out a loan, the amount you pay each month depends on the length of the loan. For the payment period you just selected, what is the largest monthly payment your household would agree to?	Lè ou prete lajan, valè a ou peye chak mwa depann de peryòd peman an. Pou peryòd peman an ou fèk chwazi a, ki pi gwo lajan ou kapab peye pa mwa?
Currency: Gourdes Haitian Dollars	Kòb: Goud Dola Ayisyen
Do you worry that you would not be able to pay this monthly payment for that number of years? Please tell us any concerns.	Èske ou enkyete paske ou pa ta kapab peye peman pa mwa sa pou tout kantite ane saa yo? Tanpri di nou pwoblem yo.
Imagine there was a month when you do not have enough money to make your loan payment. What would you do to resolve the problem?	Sipoze ou gen yon mwa ou pa genyen ase lajan pou ou peye peman an. Kisa ou ta fè pou rezoud pwoblèm nan?
Do you have someone who would be willing to co-sign your loan? A cosigner is someone who agrees to pay if you can’t. They can live abroad or in Haiti. [IF NO SKIP NEXT QUESTION]	Èske ou gen yon moun ki vle siyen pou ou akò lajan prete a (Ko-Siyen). Ko-Siyen an, se yon moun ki ap dako peye lajan prete an pou ou si ou pa kapab peye li. Yo kapab viv an Ayiti oswa lòtbò.
Why do you think they would be a good choice for cosigner?	Poukisa ou panse yo se bon yon chwa pou Ko-Siyen?

Land Information	*Enfomasyon sou Tè*
Read this to the person: In this section, I will ask you questions about your land.	Li pou moun la: Nan seksyon sa a, mwen pral mande kesyon sou tè ou.
Do you own or rent the land you are going to use to build a house?	Èske ou posede oswa lwe tè a ou pral itilize pou bati yon kay?
Is this your land or your family's land?	Èske tè sa a se tè ou oswa tè lafanmi?
Are you the owner of this land?	Se ou menm ki mèt/mètrès tè sa a?
How did you become the owner of this land?	Ki jan ou vin mèt/mètrès tè sa a?
Do you have the paper to this land? Yes No	Èske ou gen papye tè sa a? Wi Non
Are there any things with the land's papers that could prevent you from building here? Yes No [IF NO SKIP NEXT 2 QUESTIONS]	Eske genyen yon bagay ak papye tè a ki ka anpeche ou bati la? Wi Non
Why? On what basis?	Poukisa? Ki jan
Is there any debris or foundation from a destroyed house that must be cleared for the land to be used for new construction? Yes No [IF NO SKIP NEXT QUESTION]	Èske gen debri oswa fondasyon yon kay ki te kraze ki dwe pwopte anvan pouw kapab bati yon nuovo kay la? Wi Non
If yes, explain.	Si wi, tanpri esplike.
Is the land bigger than what you will need to build this house? Yes No [IF NO SKIP NEXT QUESTION]	Èske tè sa a pi gwo ke sa ou bezwen pou bati kay sa a? Wi Non

What do you plan to do with the remaining land?	Kisa ou konte fè ak res tè a?
Besides the land you plan to use for building a new house, do you own other land or property? Yes No [IF NO SKIP NEXT 2 QUESTIONS]	Anplis tè ou konte itilize pou bati yon nouvo kay, èske ou posede lòt tè oswa pwopriyete? Wi Non
If yes, please explain.	Si wi, tanpri eksplike.
Would you be willing to use this land or property to guarantee your loan for your new house? "Guarantee" means that if you cannot pay, the person who lent you money can take your land. Yes No	Èske ou vle itilize tè sa oswa pwopriyete sa pou garanti lajan prete ou a pou nouvo kay ou a? "Garanti" vle di ke si ou pa kapab peye, moun ki prete ou lajan an kapab pran tè ou a. Wi Non
Is this (here) the land you will use for your new house? Yes No [IF YES, SKIP NEXT QUESTION] [IF NO, SKIP THE THREE FOLLOWING QUESTIONS]	Èske se isit la tè ou pral itilize pou bati nouvo kay ou a? Wi Non
Make arrangements to visit the land where they want to build a new house to take photos.	Fè aranjman pou vizite tè a kote yo vle bati yon nuovo kay pou ou pran foto yo.
Take picture of land from the street.	Pran foto tè a soti depi nan lari a.
Takee a picture of all buildings on the land.	Pran foto tout konstriksyon sou tè a.
Stand in the middle of the land and take a video of the land while turning in a full circle (less than 15 seconds)	Kanpe nan mitan tè a e pran video tè a pandan ou ap tounen fe yon sèk (mwens ke 15 segonn)

Part 4: Statement of Interest	**Pati 4: Deklarasyon Enterè**
This is the last section. I will summarize the steps of our program that we want to develop. 1. Person applies to join program 2. If they are selected, we help the person design a beautiful, safe, and secure home 3. The person pays some money before construction (10-20% of the cost of the house) 4. The lender gives money to our partner builder to build the house 5. The person pays back the loan over a number of years. 6. When the person finishes paying back the loan, they fully own the house.	Se dènye seksyon an. Mwen pral rezime pwosesis la nan pwogram lan ke nou vle devlope. 1. Yon moun aplike pou rejwenn pwogram nan. 2. Si li chwazi, nou ede li pou desine yon kay ki bèl, ki sekirite, ak ki dyanm. 3. Moun nan peye kèk lajan anvan konstriksyon (dis a ven pousan pri kay la) 4. Moun kap ba ou prè a bay patne nou lajan an, epi patnè nou bati kay la pou ou. 5. Moun nan remet lajan li te prete a pou yon kantite ane 6. Lè moun nan fin remet lajan li te prete a, moun nan totalman posede kay la.
If we can start this program in Léogâne, would you be interested in joining our program? Yes No [IF “NO” END SURVEY AFTER THE NEXT QUESTION]	Si nou kap kòmanse pwogram sa nan Leyogan, eske ou tap enterese rejwenn pwogram nou? Wi Non
Why?	Poukisa?
If we were ready to start tomorrow, how much money would you be able to pay as a deposit to join the program and build a house?	Si ou ta prè, konbyen kòb ou tap kapab depoze pou antre nan pwogram nan ak bati yon kay?
Currency: Gourdes Haitian Dollars	Kòb: Goud Dola Ayisyen
If you are interested, please sign here to indicate you are interested in continuing to work with our program.	Si ou enterese, tanpri siyen la pouw di ke ou enterese pou kontinye travay avek pwogram nou an.

[SIGNATURE]	
Please confirm the spelling of your family (last) name:	Tanpri konfime otograf jan ou siyen:
Please confirm the spelling of your given (first) name:	Tanpri konfime otograf jan ou rele:
Please confirm the phone number we should use to reach you in the future:	Tanpri konfime nimewo telefòn nou kapab itilize pou nou jwenn ou a lavni:
(The surveyor should leave a business card or a card with their telephone number)	(Ankete dwe kite yon kat biznis oswa yon kat ak nimewo telefòn li)
Thank you very much!	Mèsi anpil!

APPENDIX C: DRAFT CONSTRUCTION AND QUALITY CONTROL MANUALS

C.1 Site Preparation (English)

Prepare Site

Remove all vegetation and debris before construction.

Level the surface of the land so that it is flat.

- Build the house on a slope of no more than 35%.

Make sure there is good drainage.

Position of Site

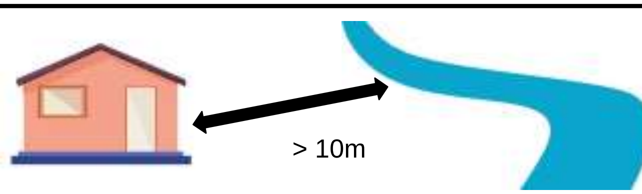
Ensure the house is being built in the proper location according to the design.

STOP: Check with chief engineer.

Guidelines:

-> Place houses at least 1.5 m away from other houses.

-> Build houses at least 10 m away from rivers.



Quality Control

Preparation of Site:
➔ Is all vegetation and debris removed from the site? Yes ☐ No ☐ ➔ Is the land flat (with a slope no more than 35 percent)? Yes ☐ No ☐ ➔ Does the site have good drainage? Yes ☐ No ☐ Every box must be checked yes to continue.

Position of Site:
➔ Does the chief engineer approve of the site location? Yes ☐ No ☐ ➔ Is the distance to the closest house greater than 1.5 m? Yes ☐ No ☐ ➔ Is the distance to the closest river greater than 10 m? Yes ☐ No ☐ Every box must be checked yes to continue.

Materials Storage

Store all materials inside.

If materials cannot be stored inside, make sure they are wrapped in a tarp so they are protected from water.

Materials Storage

Store the cement on an elevated surface (ex: wood palettes).

Store all wood on a flat surface.

Quality Control ☑

Material Storage:

		Yes	No
➔	Are all materials protected from water?	☐	☐
➔	Is the cement stored on an elevated surface?	☐	☐
➔	Is the wood stored on a flat surface?	☐	☐

Every box must be checked yes to continue.

Excavations and Backfill: General

Before excavating, measure the proper dimensions according to the design and mark them with stakes.

STOP: Check with chief engineer.

After excavating, double check that the dimensions are correct.

STOP: Check with chief engineer.

Ensure excavations are level and clean.

Quality Control

Excavations and Backfill:

Quality Control Check:	Yes	No
➔ Are excavations level and clean?	☐	☐
Confirm with chief engineer:		
➔ Is the site properly measured according to the design?	☐	☐
➔ Are the dimensions correct?	☐	☐

Every box must be checked yes to continue.

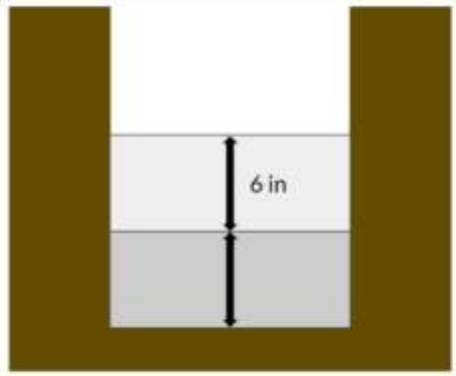
Excavations and Backfill: Trenches

Excavate trenches according to the design. STOP: Check with chief engineer.

Ensure excavations are level and clean.

Backfill using gravel with a maximum size of 0.75in (2cm)

- Backfill in 6in (15cm) lifts
- Compact after every lift



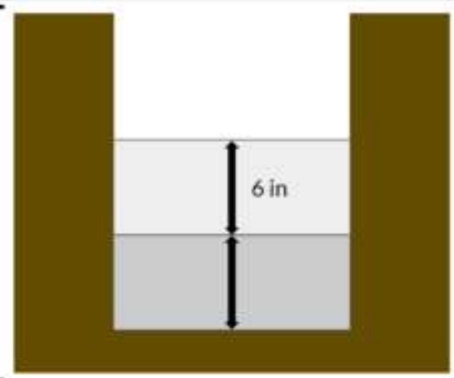
Excavations and Backfill: Footings

Excavate footings according to the design. STOP: Check with chief engineer.

Ensure excavations are level and clean.

Backfill using gravel with a maximum size of 0.75in (2cm)

- Backfill in 6in (15cm) lifts
- Compact after every lift



Quality Control ☑

Excavations and Backfill:

Quality Control Check:	Yes	No
➔ Are excavations level and clean?	☐	☐
➔ Is the gravel 0.75 in or smaller?	☐	☐
Confirm with chief engineer:	☐	☐
➔ Are trenches excavated according to the design?	☐	☐
➔ Are footings excavated according to the design?		

Every box must be checked yes to continue.

C.2 Site Preparation (Haitian Creole)

Prepare Sit

Deplase tout vejetasyon ak debri anvan konstriksyon.

Plati tè a pou fè li nivo.

- Bati kay la nan pant pi piti pase 35%.

Asire drenaj se bon.

Pozisyon Sit

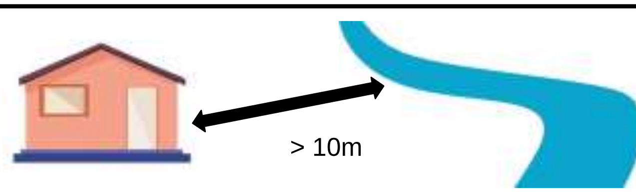
Enjinyè chèf dwe tcheke travayè yo ap bati kay la nan bon kote selon plan an.

RETE: Tcheke ak enjinyè chèf.

Lòt Kondisyon:

-> Bati kay omwen 1.5 m lwen lòt kay yo.

-> Bati kay omwen 10 m lwen rivye yo.



Kontwòl Kalite

Preparasyon Sit:

➔ Tout vejetasyon ak debri se deplace?

Wi ☐ Non ☐

➔ Tè se nivo (pant pi piti pase 35%)?

Wi ☐ Non ☐

➔ Drenaj se bon?

Wi ☐ Non ☐

➔ Chak bwat dwe tcheke "wi" pou kontinye.

Posisyon Sit:

➔ Enjenyè apwove pozisyon sou sit la?

Wi ☐ Non ☐

➔ Distans nan lòt kay yo omwen 1.5 m?

Wi ☐ Non ☐

➔ Distans nan rivye yo omwen 10 m?

Wi ☐ Non ☐

➔ Chak bwat dwe tcheke "wi" pou kontinye.

Depo Materyèl

Sere tout materyèl andedan.

Si materyèl pa kapab sere andedan, asire li vlope nan yon prela pou pwoteje yo nan dlo.

Depo Materyèl

Sere sak siman nan sifas wo (egzamp: bwa palettes).

Sere tout bwa sou yon sifas nivo.

Kontwòl Kalite ☑

Depo Materyèl:

	Wi	Non
➔ Materyèl pwoteje nan dlo?	☐	☐
➔ Siman sere nan sifas wo?	☐	☐
➔ Bwa sere sou yon sifas nivo?	☐	☐

Chak bwat dwe tcheke “wi” pou kontinye.

Ègzumasyon ak Ranpli Ankò: Jeneral

Anvan ègzumasyon, mezire dimansyon kòrèk selon plan an epi make yo ak baton yo.

RETE: Tcheke ak enjinyè chèf.

Apre ègzumasyon, tcheke ak enjinyè chèf sa dimansyon la se kòrèk.

RETE: Tcheke ak enjinyè chèf.

Asire ègzumasyon se nivo ak pwòp.

Kontwòl Kalite

Ègzumasyon ak Ranpli Ankò:

Kontwòl Kalite Tcheke:	Wi	Non
➔ Ègzumasyon se nivo ak pwòp?	☐	☐
Tcheke ak enjinyè chèf:		
➔ Sit la mezire kòrèk selon plan an?	☐	☐
➔ Dimansyon se kòrèk?	☐	☐

Chak bwat dwe tcheke “wi” pou kontinye.

Ègzumasyon ak Ranpli Ankò: Fòs

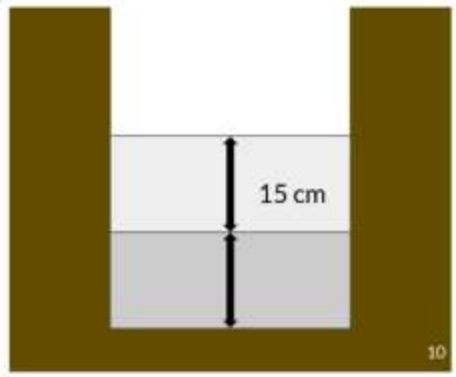
Fouye fòs (twou long) selon plan an.

RETE: Tcheke ak enjinyè chèf.

Asire ègzumasyon se nivo ak pwòp.

Ranpli ankò ak gravye ak gwosè maksimòm 2 cm.

- Ranpli ankò 15 cm chak fwa.
- Kondanse apre chak fwa.



Ègzumasyon ak Ranpli Ankò: Fondasyon pye

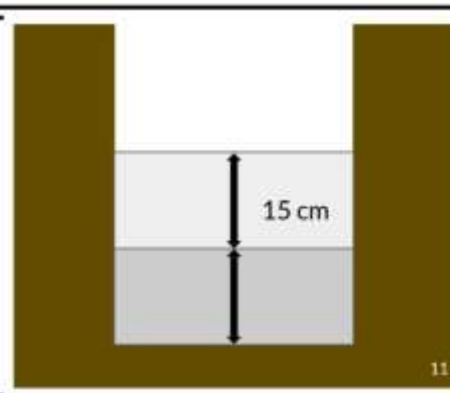
Fouye fondasyon pye (twou karE)selon plan an.

RETE: Tcheke ak enjinyè chèf.

Asire ègzumasyon se nivo ak pwòp.

Ranpli ankò ak gravye ak gwosè maksimòm 2 cm.

- Ranpli ankò 15 cm chak fwa.
- Kondanse apre chak fwa.



Kontwòl Kalite ☑

Ègzumasyon ak Ranpli Ankò:

Kontwòl Kalite Tcheke:

	Wi	Non
➔ Ègzumasyon se nivo ak pwòp?	☐	☐
➔ Gravye se pi piti pase 2 cm?	☐	☐

Tcheke ak enjinyè chèf:

	Wi	Non
➔ Fòs te fouye selon plan an?	☐	☐
➔ Fondasyon pye te fouye selon plan an?	☐	☐

Chak bwat dwe tcheke "wi" pou kontinye.

Step 1: GATHER TOOLS

Purchase:

- ➔ Shovels

- ➔ Buckets

- ➔ Concrete mixer

Step 2a: PURCHASE MATERIALS

Cement
- ➔ Should be dry, no older than 60 days, and from a reliable source
- ➔ Store cement bags raised off the ground

Sand
- ➔ Should be clean and free of debris (sticks, leaves, trash, etc.)
- ➔ Should be coarse, not round or shiny
- ➔ Should be free of silt and clay particles
- ➔ Test: Take a handful of sand in your hand and toss it. If your hand is clean, the sand is most likely good for construction usage. If your hand is dirty with remaining dirt ot or particles, the sand should not be used for construction.

Cement:

< 60 days

Sand:

Step 2a: PURCHASE MATERIALS

Quality Control Checks:

	Yes	No
→ Is cement dry?	☐	☐
→ Is cement less than 60 days old?	☐	☐
→ Is sand clean?	☐	☐
→ Does the sand have any debris in it?	☐	☐
→ Does the sand have any silt or clay particles in it?	☐	☐
→ Is the aggregate shiny or round?	☐	☐

→ Test: Take a handful of sand in your hand and toss it. If your hand is clean, the sand is most likely good for construction usage. If your hand is dirty with remaining dirt ot or particles, the sand should not be used for construction.

→ Every box must be checked yes to continue.

Step 2b: PURCHASE MATERIALS

Gravel

- → Should be clean and free of debris (sticks, leaves, trash, etc.)
- → Pieces should be no larger than 2 cm in diameter
- → Should have an overall round shape but a jagged surface

Water

- → Should be clean and transparent
- → Must not be sea water

Gravel:

Water:

Step 2b: PURCHASE MATERIALS

Quality Control Checks:

	Yes	No
➔ Is the gravel clean?	☐	☐
➔ Does the gravel have any debris in it?	☐	☐
➔ Are any of the pieces of gravel larger than 5 cm?	☐	☐
➔ Does the gravel have an overall round shape, but a jagged surface?	☐	☐
➔ Is the water transparent?	☐	☐
➔ Are there any particles in the water?	☐	☐

➔ Every box must be checked yes to continue.

Step 3: PREPARE MATERIALS

➔ Use a 1:2:3 ratio (by volume)
→ 1 cement : 2 sand : 3 gravel

0.25 m^3 cement
+
0.5 m^3 sand
+
0.75 m^3 gravel
=
1 m^3 concrete

➔ Minimum volume of water required to achieve minimum workability (can surround rebar and fill corners)

- Suggested ratio:
  → 0.6 water : 1 cement
  → 6 water : 10 cement

(60% full)

water

Step 3: PREPARE MATERIALS

Collected Data:	Quality Control Checks:
➔ Number of buckets of cement: _________ ➔ Number of buckets of sand: _________ ➔ Number of buckets of gravel: _________	➔ Is the ratio of cement to sand to gravel 1:2:3? Yes ☐ No ☐ Every box must be checked yes to continue.

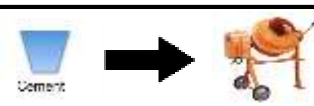
Step 4: MIX MATERIALS

▯ Add half of the water to the concrete mixer

½ x 

▯ Add all of the sand and gravel

▯ Add all of the cement and allow it to mix through completely



▯ Slowly add water until minimum workability is achieved

STOP: Check if the workability is good with the chief engineer. If not, add water.

½ x 

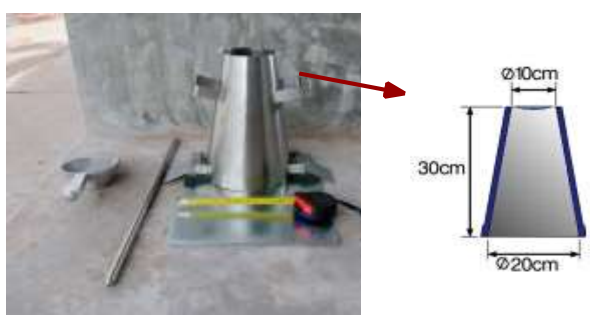
Step 4: MIX MATERIALS

Collected Data:	Quality Control Checks:
➔ Amount of cement used: _________ ➔ Amount of sand used: _________ ➔ Amount of gravel used: _________ ➔ Amount of water used: _________	➔ Is the concrete workable? Will it be able to surround the rebar and fill the corners? Yes ☐ No ☐ ➔ Does the concrete pass the slump test? Only check this two times a day. Yes ☐ No ☐ Every box must be checked yes to continue.

Step 5a: SLUMP TEST *Tools*

Collect tools:

- ➔ Slump cone: 20 cm base diameter x 10 cm top diameter x 30 cm tall
- ➔ Slump board (smooth flat surface)
- ➔ Concrete scoop
- ➔ Tamping rod (rod to poke with): at least 1.6 cm diameter x 30-40 cm length
- ➔ Tape measure

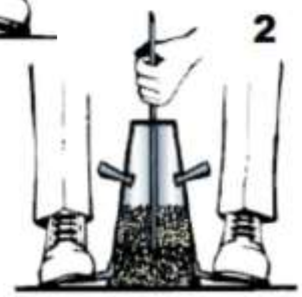


Step 5b: SLUMP TEST *Procedures*

<u>Prepare</u>: Wet the inside of the slump cone, the slump board, the concrete scoop, and the tamping rod. They should feel wet when touched.

Place the slump cone on the slump board and stand on the fins at the base of the slump cone to keep it steady.

1. Fill the cone ⅓ full will concrete. Use the tamping rod to poke the concrete with an up and down motion 25 times. Make sure to poke through the entire layer of concrete.
2. Fill the cone with another ⅓ of concrete. Use the tamping rod to poke the concrete 25 more times. Make sure to poke through only this layer of concrete.



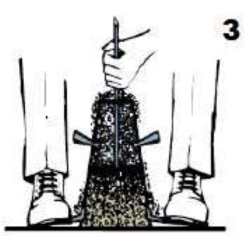
Step 5b: SLUMP TEST *Procedures*

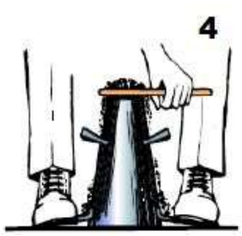
3. Fill the cone with the last ⅓ of concrete. Use the tamping rod to poke the concrete 25 more times. Make sure to poke through only this layer of concrete.

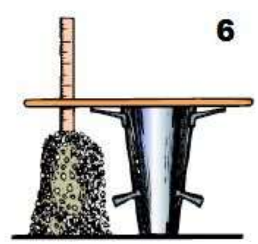
4. Use the tamping rod to smooth the top of the cone and remove any excess concrete.

5. Slowly pull the cone upwards to remove it. This should take about 5 seconds to do.

6. Turn the cone over (small side down), place next to the concrete, and measure the distance between the top of the cone and the center of the top of the concrete. This value is how much the concrete “slumped.”

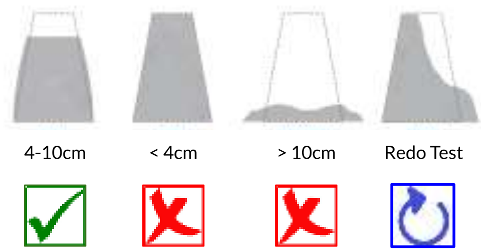


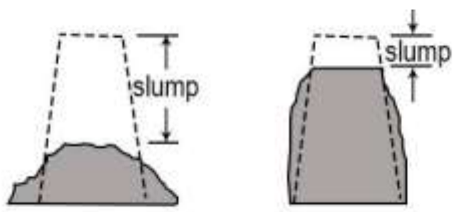




Step 5c: SLUMP TEST *Results*

- ➔ Slump tests for concrete should be 7.5-10 cm
- ➔ Slump tests must meet a minimum of 2.5 cm
- ➔ Slump tests must be no more than 12.5 cm
  - ○ If this limit is exceeded, concrete must be disposed of or used in a non-critical component





<u>Slump</u>

4 - 10cm	Great!
< 4cm	Bad!
> 10cm	Bad!

Step 5c: SLUMP TEST *Results*

Collected Data:

- ➔ Height of slump cone: _______
- ➔ Height of fallen concrete: _______
- ➔ How much did the concrete slump? _______
  - ◆ slump = height of slump cone - height of fallen concrete

Quality Control Checks:

- ➔ Is the slump greater than 4 cm?

  Yes ☐ No ☐
- ➔ Is the slump less than 10 cm?

  Yes ☐ No ☐

Every box must be checked yes to continue.

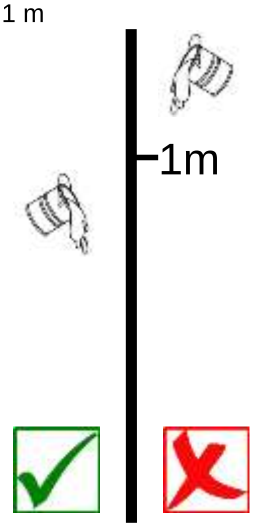
Step 6a: PLACING CONCRETE

- ➔ Place concrete within an hour of mixing to prevent hardening

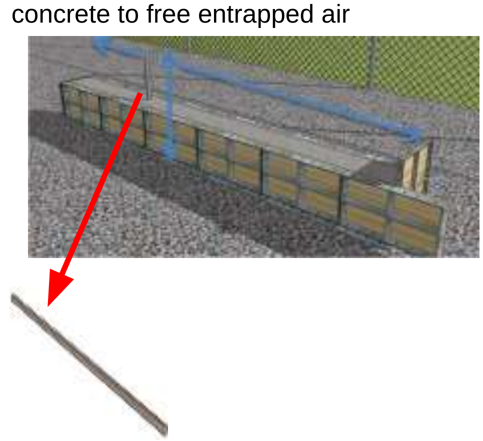
- ➔ Wet surfaces before placing concrete to prevent absorption of cement paste

Step 6b: PLACING CONCRETE

- Do not drop concrete from a height over 1 m



- Tamp (poke around with a rod) the concrete to free entrapped air



Diameter > 1.6cm

Step 6: PLACING CONCRETE

Collected Data:

- ➔ Amount of time between mixing concrete and placing concrete: __________ minutes

Quality Control Checks:

- ➔ Was the concrete placed within an hour of mixing?

  Yes ☐ No ☐
- ➔ Were the surfaces of materials contacting the concrete wetted before placing?

  Yes ☐ No ☐
- ➔ Was the concrete poured from less than 1 m high?

  Yes ☐ No ☐
- ➔ Are there any air bubbles left in the cement?

  Yes ☐ No ☐

Every box must be checked yes to continue.

Step 7: CURING CONCRETE

- ➔ Concrete will crack if it dries too quickly, so it's important to keep the concrete hydrated (wet)
  - ◆ Cover the concrete with wet burlap sacks or wet empty cement bags
  - ◆ Add water to the surface of the concrete every day

Step 7: CURING CONCRETE

Collected Data:	Quality Control Checks:
➔ Day 1: Has water been added to the surface of the cement? Yes ☐ No ☐ ➔ Day 2: Has water been added to the surface of the cement? Yes ☐ No ☐ ➔ Day 3: Has water been added to the surface of the cement? Yes ☐ No ☐ ➔ Day 4: Has water been added to the surface of the cement? Yes ☐ No ☐	➔ Is the cement covered in wet burlap sacks or empty, wet concrete bags? Yes ☐ No ☐ Every boox must be checked yes to continue.

Etap 1: RASANBLE ZOUTI

➔ Pèl

➔ Bokit

➔ Mixer konkrè

Etap 2a: ACHTE MATERYÈL

Siman

➔ Li dwe sèk, mwens pase 60 jou, ak soti nan yon sous serye.

➔ Sere sak siman leve soti nan tè a.

Sab

➔ Li dwe pwòp ak san debri (fè, bwa, fatra).

➔ Li dwe koryas, pa won ak klere.

➔ Li dwe pwòp ak san ajil oswa limon.

➔ Tès: Pran yon men sab lave ak men. Lè ou jete sab lave a ou ap wè men ou rete pwòp. Si men ou pa se pwòp, sab la pa se lave.

Siman:

< 60 jou

Sab:

Etap 2a: ACHTE MATERYÈL

Chèk kontwòl kalite:

	Wi	Non
➔ Siman se sèk?	☐	☐
➔ Siman se mwens pase 60 jou?	☐	☐

➔ Tès: Pran yon men sab lave ak men. Lè ou jete sab lave a ou ap wè men ou rete pwòp. Si men ou pa se pwòp, sab la pa se lave.

	Wi	Non
➔ Sab se pwòp?	☐	☐
➔ Sab se san debri?	☐	☐
➔ Sab se pwòp ak san ajil oswa limon?	☐	☐
➔ Gravye se koryas?	☐	☐

➔ Chak bwat dwe tcheke “wi” pou kontinye.

Etap 2b: ACHTE MATERYÈL

Gravye

- ➔ Li dwe pwòp ak san debri (fè, bwa, fatra).
- ➔ Li dwe pi piti pase 2 santimèt.
- ➔ Li dwe wonn men file.

Dlo

- ➔ Li dwe pwòp ak klè.
- ➔ Li pa dwe dlo lanmè.

Gravye:

Dlo:

Etap 2b: ACHTE MATERYÈL

Chèk kontwòl kalite:

	Wi	Non
➔ Gravye se pwòp ak san debri?	☐	☐
➔ Gravye se pi piti pase 2 santimèt?	☐	☐
➔ Gravye se wonn men file?	☐	☐
➔ Dlo se klè?	☐	☐
➔ Patikil yo se nan dlo?	☐	☐

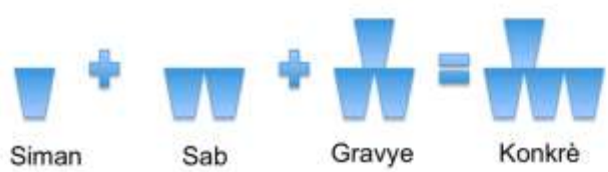
➔ EChak bwat dwe tcheke “wi” pou kontinye.

Etap 3: PREPARE MATERYÈL

➔ Itilize yon 1:2:3 rapò pa volim
→ 1 siman : 2 sab : 3 gravye

$0.25\ m^3$ siman
+
$0.5\ m^3$ sab
+
$0.75\ m^3$ gravye
=
$1\ m^3$ konkrè

➔ Minimòm volim dlo egzije pou reyalize minimòm konsistans (ka antoure rebar ak ranpli kwen)
- 0.6 rapò sijere
  → 0.6 dlo: 1 siman (pa volim)



Etap 3: PREPARE MATERYÈL

Kolekte Done yo:	Chèk Kontwòl Kalite:
➔ Kantite bokit siman: ________ ➔ Kantite bokit sab: ________ ➔ Kantite bokit gravye: ________	➔ Rapò pou siman:sab:gravye se 1:2:3? Wi ☐ Non ☐ ➔ Chak bwat dwe tcheke "wi" pou kontinye.

Etap 4: MELANJE MATERYÈL

☐ Mete mwatye dlo a mixer a konkrè

½ X 

☐ Mete tout sab ak gravye a mixer a konkrè

sab gravye

☐ Mete tout siman a mixer a konkrè epi melanje li nèt

siman

☐ Dousman, ajoute dlo plis jiskaske konsistans minimòm reyalize

RETE: Tcheke si konsistans konkrè se bon ak enjinyè chèf. Si pa, ajoute dlo.

½ x 

Etap 4: MELANJE MATERYÈL

Kolekte Done yo:

➔ Kantite siman te itilize: __________

➔ Kantite sab te itilize: __________

➔ Kantite gravye te itilize: __________

➔ Kantite dlo te itilize: __________

Chèk Kontwòl Kalite:

➔ Konsistans se bon? Li ka antoure rebar ak ranpli kwen?

Wi ☐ Non ☐

➔ Konkrè pase "Tès Tonbe" ? Sèlman tcheke sa de fwa nan chak jou.

Wi ☐ Non ☐

Chak bwat dwe tcheke "wi" pou kontinye.

Etap 5a: "Tès Tonbe" *Zouti*

Rasanble Zouti:

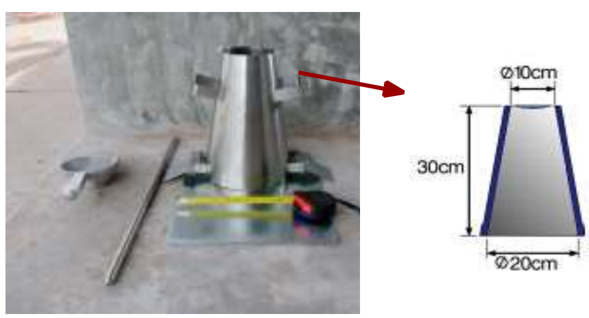
➔ "Kòn tonbe": 20 cm dyamèt baz x 10 cm dyamèt tèt x 30 cm wotè

➔ Baton pike: apeprè 1.6 cm dyamèt x apeprè 30-40 cm longè

➔ Tablo tonbe (sifas lis ak plat)

➔ Kiyè konkrè

➔ Mezi tep

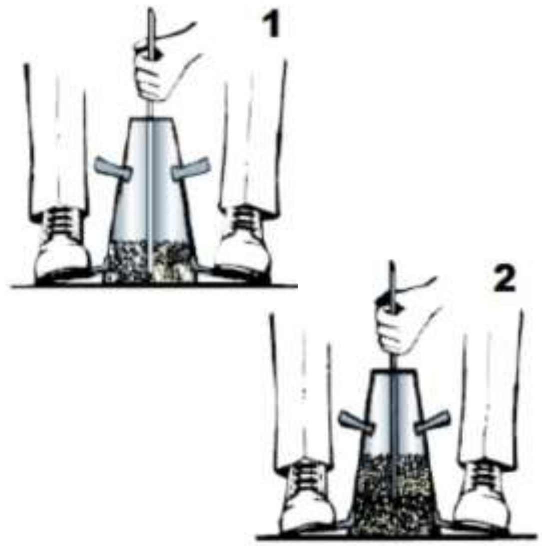


Etap 5b: “Tès Tonbe” *Pwosedi*

<u>Prepare</u>: Mouye anndan kòn tonbe a, tablo tonbe a, kiyè konkrè a, ak baton pike. Yo dwe santi mouye lè manyen yo.

Mete kòn tonbe a nan tablo tonbe a epi kanpe sou najwar yo nan baz la nan kòn tonbe a kenbe li fiks.

1. Ranpli kòn lan ⅓ plen ak konkrè. Pike konkrè (tout wout la anba) ak baton pike a monte e desann 25 fwa.
2. Ankò, ranpli kòn lan ⅓ plen ak konkrè. Pike konkrè (tout wout la anba) ak baton pike a monte e desann 25 fwa, men sèlman pike nan kouch ki pi resan an.



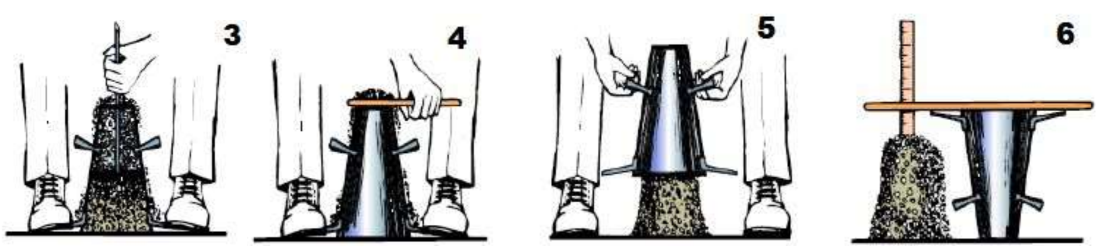
Etap 5b: “Tès Tonbe” *Pwosedi*

3. Ankò, ranpli kòn lan ⅓ plen ak konkrè. Pike konkrè (tout wout la anba) ak baton pike a monte e desann 25 fwa, men sèlman pike nan kouch ki pi resan an.

4. Aplati tèt kòn lan ak baton pike epi retire konkrè depase.

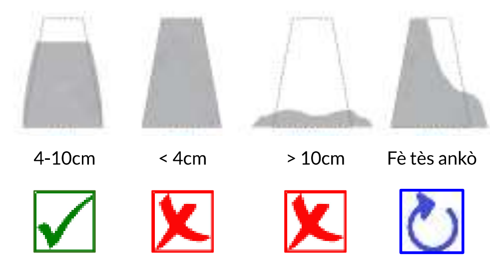
5. Dousman, rale kòn lan epi retire li. Sa dwe pran apeprè 5 segonn.

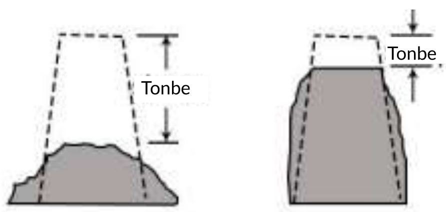
6. Vire kòn tonbe a (ti bò desann), mete li akote konkrè a, epi mezire distans ki genyen ant tèt kòn lan sant tèt konkrè. Distans sa se konbyen konkrè a “Tonbe.”



Etap 5c: “Tès Tonbe” *Rezilta*

- ➔ Rezilta “Tès Tonbe” pou konkrè dwe ant 4-10 cm.
- ➔ Si limit sa se depase, konkrè a dwe dispoze oubyen itilize nan eleman ki pa kritik.





<u>Tonbe</u>

4 - 10cm	**Bon!**
< 4cm	**Move!**
> 10cm	**Move!**

Etap 5c: “Tès Tonbe” *Rezilta*

Kolekte Done yo:

- ➔ Kombyen santimèt konkrè tonbe? ________

Chèk Kontwòl Kalite:

- ➔ “Tonbe” se plis pase 4 cm?

  Wi ☐ Non ☐

- ➔ “Tonbe” se mwens pase 10 cm?

  Wi ☐ Non ☐

Chak bwat dwe tcheke “wi” pou kontinye.

Etap 6a: METE KONKRÈ

➔ Mete konkrè nan yon èdtan pou anpeche redi.

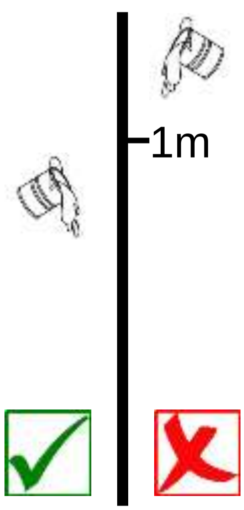
➔ Mouye sifas tout andann mete konkrè pou anpeche absòpsyon nan siman lakòl.

< 1 èdtan

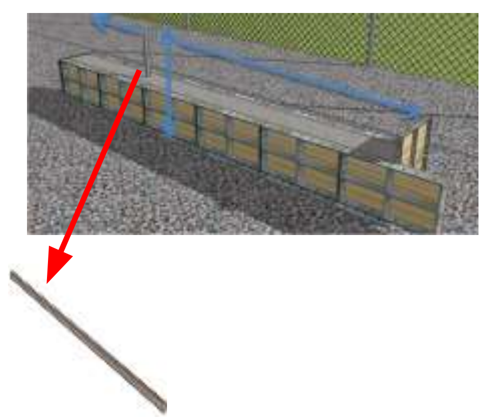
anvan

Etap 6b: METE KONKRÈ

- Pa lage konkrè nan wotè plis pase 1 m.



- Pike (pike ak "baton pike") konkre pou libere lè kwense.



Dyamèt > 1.6cm

Etap 6: METE KONKRÈ

Kolekte Done yo:

- ➔ Kantite tan ant melanje ak mete konkrè:
  __________ minit yo

Chèk Kontwòl Kalite:

- ➔ Konkrè a se te mete nan yon èdtan apre melanje?

  Wi ☐ Non ☐
- ➔ Sifas ki manyen konkrè la te mouye anvan mete konkrè?

  Wi ☐ Non ☐
- ➔ Konkrè te lage nan wotè mwen pase 1 m?

  Wi ☐ Non ☐
- ➔ Konkrè se san bul lè?

  Wi ☐ Non ☐

Chak bwat dwe tcheke "wi" pou kontinye.

Etap 7: SECHE KONKRÈ

- ➔ Konkrè ap krak si li seche twò rapidman, konsa se enpòtan pou kenbe konkrè a mouye.
  - ◆ Kouvri konkrè a ak sak twal mouye oubyen sak siman vid mouye.
  - ◆ Mete dlo sou sifas konkrè a chak jou pandan sèt jou.

Etap 7: SECHE KONKRÈ

Kolekte Done yo:	Chèk Kontwòl Kalite:
➔ Yon moun te ajoute dlo sou sifas konkrè a?	➔ Konkrè a kouvri ak sak twal mouye oubyen sak siman vid mouye?
➔ Jou 1: Wi ☐ Non ☐	Wi ☐ Non ☐
➔ Jou 2: Wi ☐ Non ☐	
➔ Jou 3: Wi ☐ Non ☐	
➔ Jou 4: Wi ☐ Non ☐	➔ Chak bwat dwe tcheke "wi" pou kontinye.
➔ Jou 5: Wi ☐ Non ☐	
➔ Jou 6: Wi ☐ Non ☐	
➔ Jou 7 Wi ☐ Non ☐	

C.5 Foundation (English)

Quality Control ☑

Preparation of Site:

→ Is the excavation level across the bottom?

Yes ☐ No ☐

→ Is the excavation free of debris (sticks, roots, etc.)?

Yes ☐ No ☐

→ Is the excavation free of standing water?

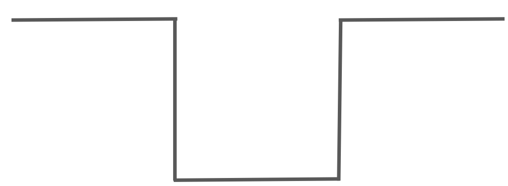
Yes ☐ No ☐

Every box must be checked yes to continue.

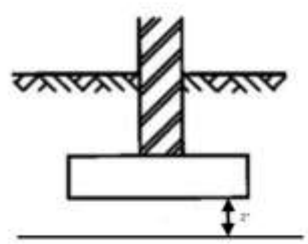
FOUNDATION: Footings

Ensure the excavations are completed according to the plans.

STOP: Check with chief engineer.



Set the footing reinforcement in place with a 2" clear cover on bottom. Ensure that the footings are placed 2 inches from the bottom of the excavation.



Quality Control ☑

Before pouring concrete for footings:

→ Is the aggregate evenly distributed in each lift?

Yes ☐ No ☐

→ Is the clear cover level across each surface along the bottom?

Yes ☐ No ☐

Every box must be checked yes to continue.

FOUNDATION: Footings

Tie in the column cage according to plan.

STOP: Check with chief engineer.

Pour footings according to Concrete Mixing Manual.

FOUNDATION: Footing

= 3 days

After three days…

STOP: Check with chief engineer to ensure concrete has cured properly.

If the concrete has cured properly, remove formwork.

Quality Control ☑

Before pouring concrete for grade beams:

→ Is the aggregate evenly distributed in each lift?

Yes ☐ No ☐

→ Is the clear cover level across each surface along the bottom?

Yes ☐ No ☐

Every box must be checked yes to continue.

FOUNDATION: Grade Beams

Form the grade beams according to plans.

Place and tie the grade beam cages.

STOP: Check with chief engineer.

Pour grade beams according to Concrete Mixing Manual...

FOUNDATION: Grade Beams

= 3 days

After three days...

STOP: Check with chief engineer to ensure concrete has cured properly.

If the concrete has cured properly, remove formwork.

Quality Control ☑

Foundation:

➔ Are columns bars plumb?

Yes ☐ No ☐

➔ Are all column bars secured in the footing?

Yes ☐ No ☐

➔ Are the tops of the grade beams level?

Yes ☐ No ☐

Every box must be checked yes to continue.

C.6 Foundation (Haitian Creole)

Kontwòl Kalite ☑

Preparasyon Sit:

→ Ègzumasyon se nivo?

Wi ☐ ☐ Non

→ Ègzumasyon se gratis nan debri (baton, rasin, etc.)?

Wi ☐ ☐ Non

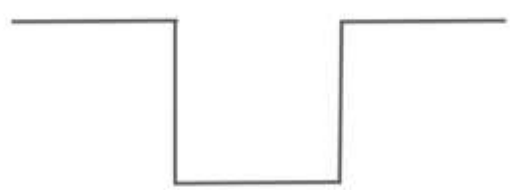
→ Ègzumasyon se sèk?

Wi ☐ ☐ Non

Chak bwat dwe tcheke "wi" pou kontinye.

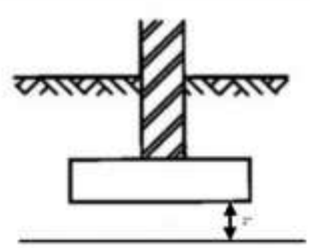
FONDASYON: Pye

Asire ègzumasyon se konplè selon plan an.



RETE: Tcheke ak enjinyè chèf.

Mete ranfòsman an ak yon 2" kouvèti klè sou anba. Asire ke fondasyon pye yo mete 2" anwo anba fon ègzumasyon an.



Kontwòl Kalite ☑

Anvan vide konkrè pou fondasyon pye:

→ Gravye se distribye egalman nan chak kouch?

Wi ☐ ☐ Non

→ Kouvèti klè se nivo sou tout sifas ansanm anba a?

Wi ☐ ☐ Non

Chak bwat dwe tcheke "wi" pou kontinye.

FONDASYON: Pye

Mare kaj ranfòsman kolòn la selon plan an.

RETE: Tcheke ak enjinyè chèf.

Vide konkrè pou fondasyon pye selon Manyèl Melanje Konkrè.

FONDASYON: Pye

= 3 jou

Apre twa jou...

RETE: Tcheke ak enjinyè chèf pou asire konkrè a seche kòrèkteman.

Si konkrè a seche kòrèkteman, retire kofraj.

Kontwòl Kalite

Anvan vide konkrè pou fondasyon travès tè:

→ Gravye se distribye egalman nan chak kouch?

Wi ☐ ☐ Non

→ Kouvèti klè se nivo sou tout sifas ansanm anba a?

Wi ☐ ☐ Non

Chak bwat dwe tcheke "wi" pou kontinye.

FONDASYON: Travès Tè

Fòme travès tè selon plan an.

Mete ak mare kaj ranfòsman travès tè yo.

RETE: Tcheke ak enjinyè chèf.

Vide konkrè pou fondasyon travès tè selon Manyèl Melanje Konkrè...

FONDASYON: Travès Tè

= 3 jou

Apre twa jou...

RETE: Tcheke ak enjinyè chèf pou asire konkrè a seche kòrèkteman.

Si konkrè a seche kòrèkteman, retire kofraj.

Kontwòl Kalite

Fondasyon:

- Ba kolòn yo vètikal?

  Wi ☐ ☐ Non
- Tout ba kolòn yo mete byen fèm nan fondasyon?

  Wi ☐ ☐ Non
- Tèt tout travès tè yo se nivo?

  Wi ☐ ☐ Non

Chak bwat dwe tcheke "wi" pou kontinye.

C.7 Frame (English)

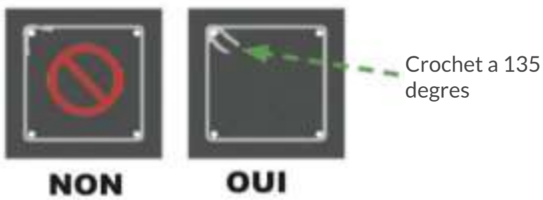
FRAME: Reinforcing Steel

Pre-bend rebar stirrups according to design.

a) Start with one bar with length specified by plans:

____

b) Bend reinforcement bar:

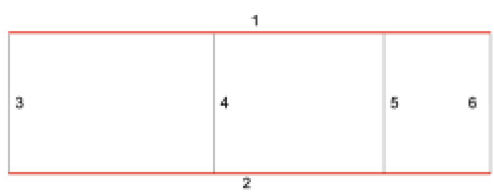


Before continuing, ensure that the stirrups are bent like the following:

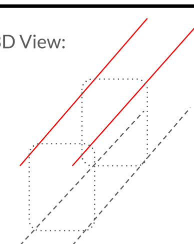
FRAME: Reinforcing Steel

1: Place top two longitudinal beam bars on the “long beams.”

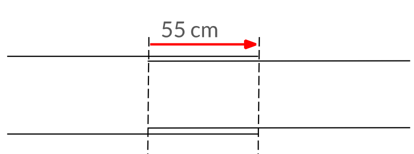
Plan View:

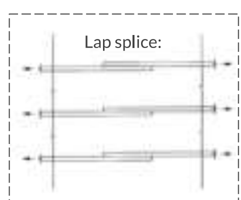


3D View:

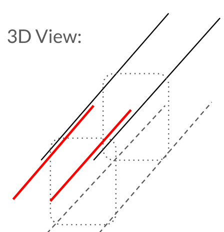


2: Add splices to top two longitudinal bars according to design (55 centimeter lap splice).



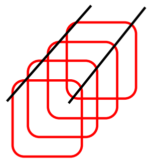


3D View:

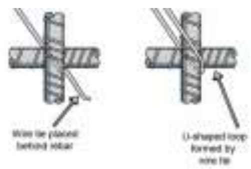


FRAME: Reinforcing Steel

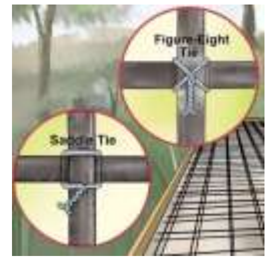
3a: Slide all corresponding beam stirrups onto top long beam bars.



3b: Tie stirrups in place.



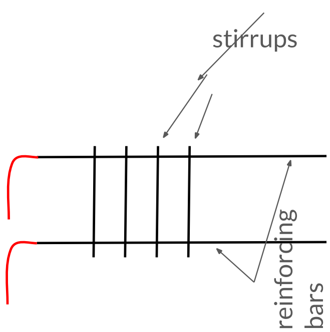
How to tie rebar:



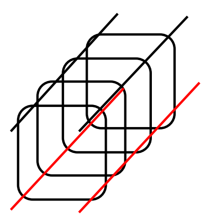
FRAME: Reinforcing Steel

4: Bend top longitudinal bars down into columns.

TOP VIEW

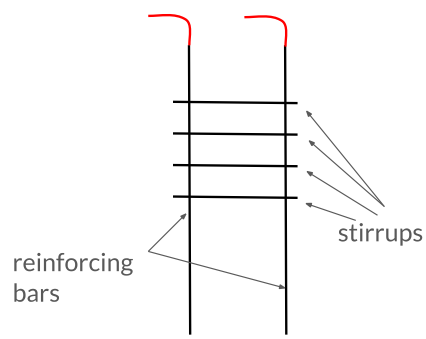


5: Slide bottom two longitudinal beam rebar through bottom of stirrups.



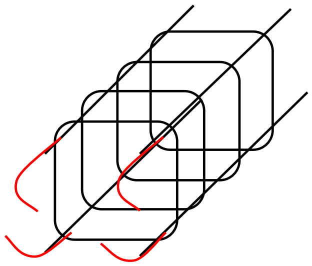
6: Bend bottom longitudinal bars up or down into columns.

BOTTOM VIEW



FRAME: Reinforcing Steel

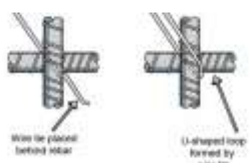
3D VIEW:



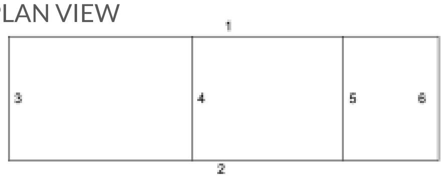
How to ensure quality connections:

FRAME: Reinforcing Steel

7: Tie bottom bars onto stirrups for the long beams.



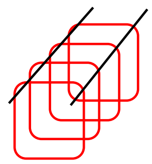
PLAN VIEW



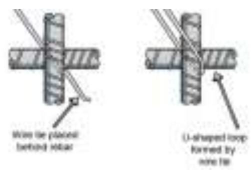
8: Insert top two longitudinal bars for the first "short beam."

FRAME: Reinforcing Steel

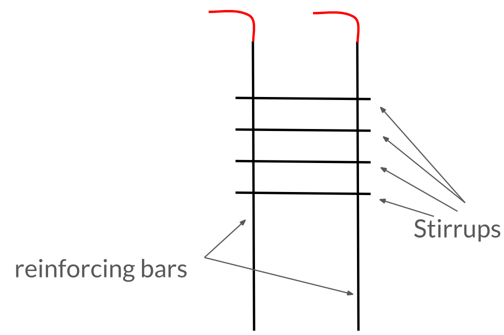
9a: Slide all corresponding beam stirrups onto top short beam bars.



9b: Tie stirrups in place.

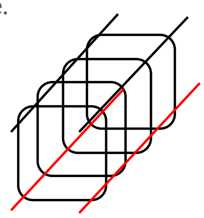


10: Bend top rebar for the “short beam” into columns.

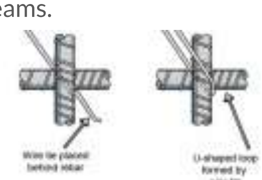


FRAME: Reinforcing Steel

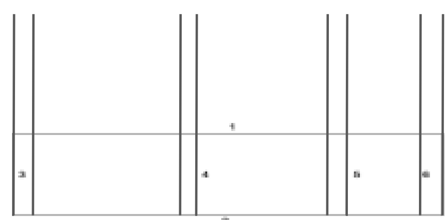
11: Slide bottom steel bars for the short beam in place.



12: Tie bottom bars onto stirrups for the short beams.

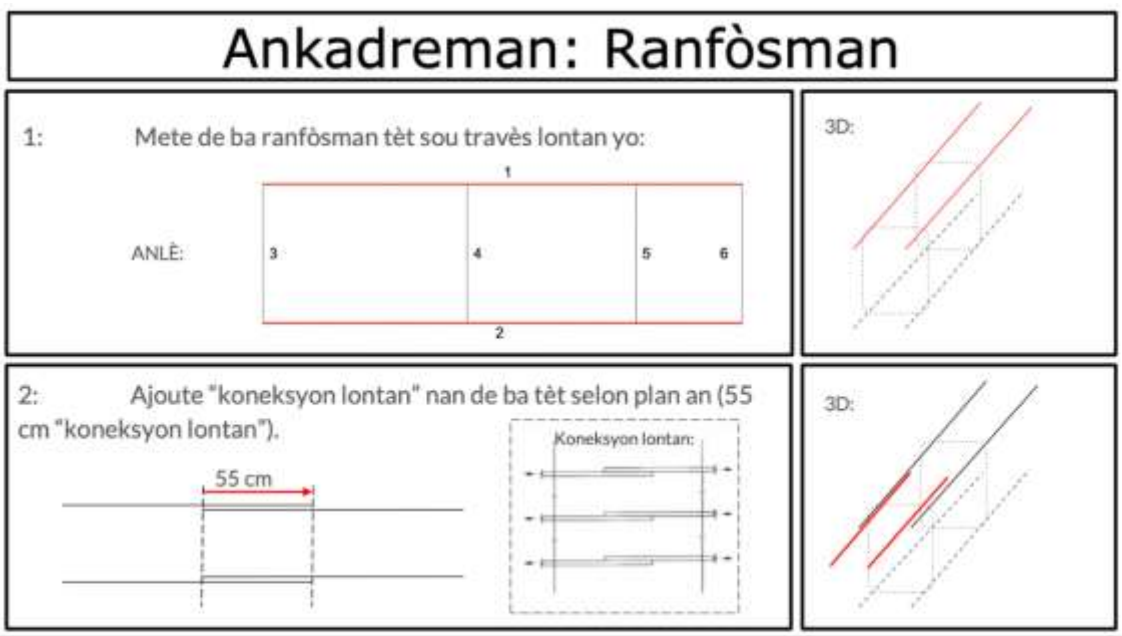


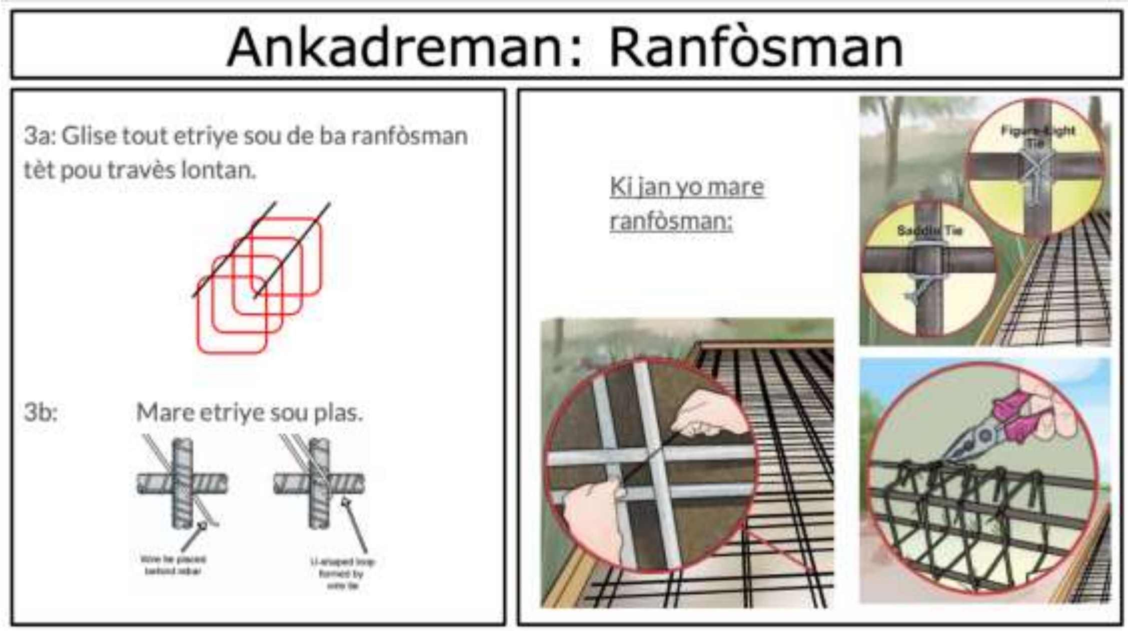
Repeat steps 9 –12 for beam lines 4, 5, and 6.

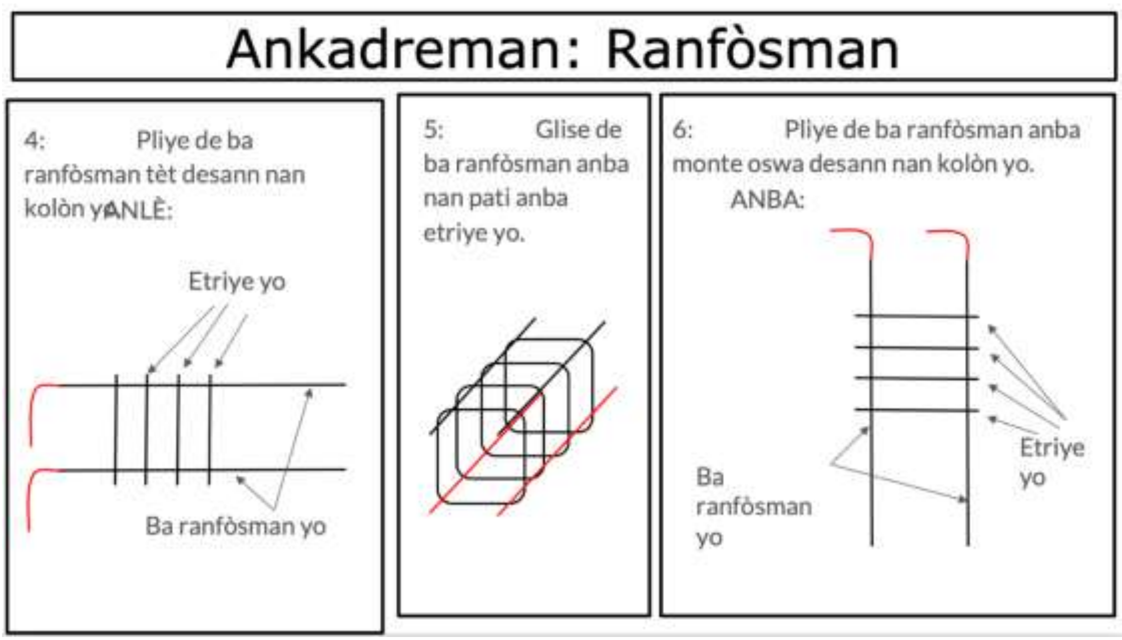


FINAL PRODUCT:

C.8 Frame (Haitian Creole)

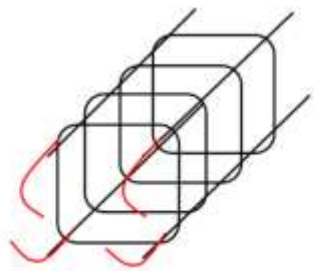



Ankadreman: Ranfòsman
3a: Glise tout etriye sou de ba ranfòsman tèt pou travès lontan.
3b: Mare etriye sou plas.
Ki jan yo mare ranfòsman:
Saddle Tie


Ankadreman: Ranfòsman
4: Pliye de ba ranfòsman tèt desann nan kolòn yo ANLÈ:
Etriye yo
Ba ranfòsman yo
5: Glise de ba ranfòsman anba nan pati anba etriye yo.
6: Pliye de ba ranfòsman anba monte oswa desann nan kolòn yo.
ANBA:
Etriye yo
Ba ranfòsman yo

Ankadreman: Ranfòsman

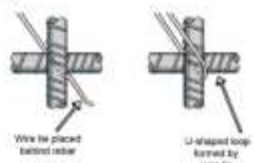
3D:



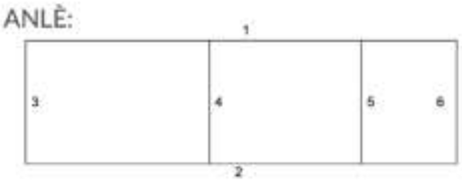
Ki jan asire koneksyon kalite:

Ankadreman: Ranfòsman

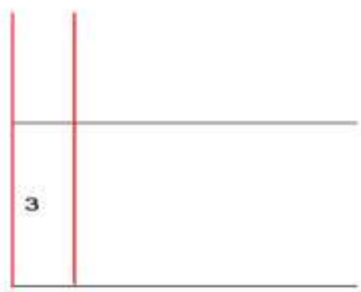
7: Mare ba ranfòsman anba sou etriye yo.

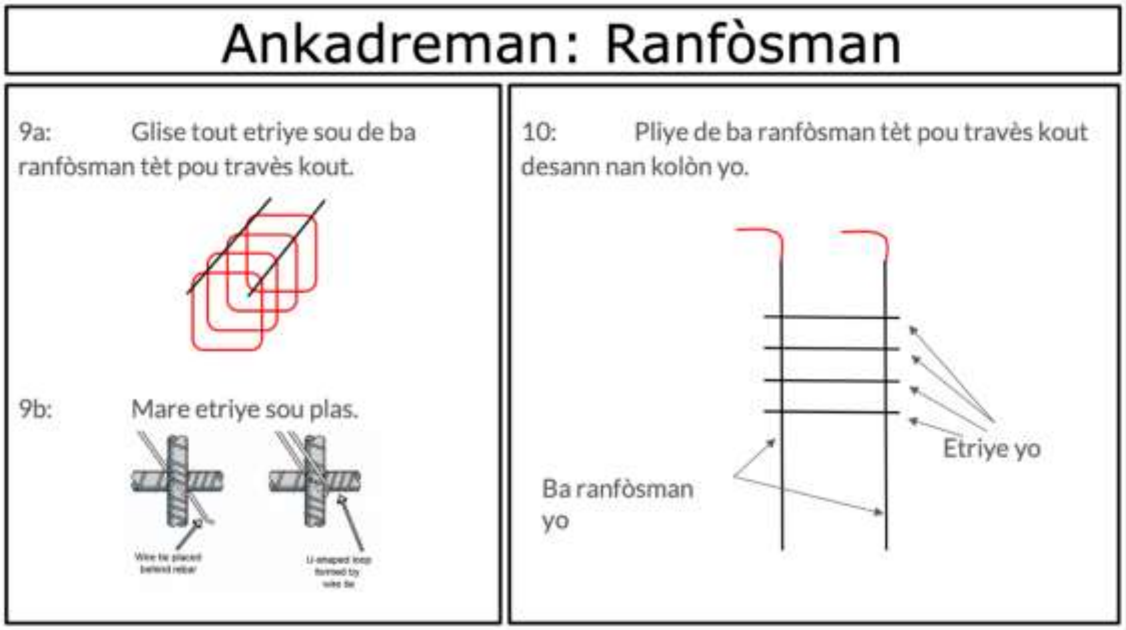


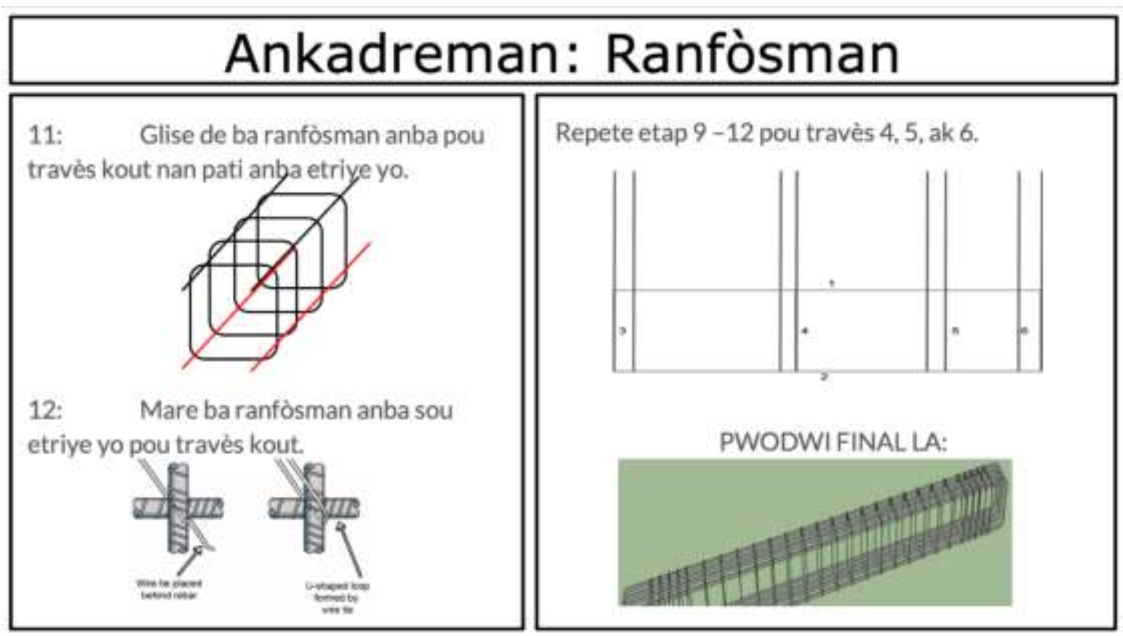
ANLÈ:



8: Ensere de ba ranfòsman tèt pou premye travès kout.




Ankadreman: Ranfòsman
9a: Glise tout etriye sou de ba ranfòsman tèt pou travès kout.
9b: Mare etriye sou plas.
10: Pliye de ba ranfòsman tèt pou travès kout desann nan kolòn yo.
Etriye yo
Ba ranfòsman yo


Ankadreman: Ranfòsman
11: Glise de ba ranfòsman anba pou travès kout nan pati anba etriye yo.
12: Mare ba ranfòsman anba sou etriye yo pou travès kout.
Repete etap 9 –12 pou travès 4, 5, ak 6.
PWODWI FINAL LA:

APPENDIX D: CONCEPT NOTE - HARNESSING EMOTIONAL MOTIVATION TO ADVANCE INTEGRAL HUMAN DEVELOPMENT IN FINANCIAL LITERACY EDUCATION

D.1 Introduction

In a survey administered by a San Francisco-based advertising firm in early 2014, 78% of respondents stated that they were looking forward to Super Bowl commercials more than the actual game (USA Today 2014). These ads are flashy, sexy, and generally leave the viewer with a lasting impression, subconscious or conscious, of the product or service being promoted. Each year, companies invest millions of dollars into their advertising departments for the purpose of promoting their products or services to the general population. In order to increase sales, they need to either increase current customers' consumption rates or attract new customers. Both of these tasks are achieved by promoting behavioral change in the consumer population. Companies attempt to change consumers' behavior daily by utilizing advertisements that provoke emotion. Nearly every television commercial, and most other forms of advertising, has an emotional goal. They want the viewer to associate feelings like patriotism, humor, guilt, sexiness, masculinity, or femininity with their product. And it works, as in 2016 many corporations dished out a record-breaking 5 million dollars for a single 30-second advertisement during the Super Bowl (Groden 2015). What if governments, NGOs, and other development agencies utilized this method of harnessing emotion to shift beneficiaries towards behaviors supportive of a stated development goal? And specific to this concept note, could this be a more effective approach in areas like financial literacy, where traditional programming has yielded limited success?

Financial literacy holds a vital role in the development of human societies. Understanding how to effectively manage money and navigate modern complex monetary systems empowers individuals to increase both their economic and holistic well-being. Financially empowering both consumers and business owners would intuitively spark grassroots economic development, as individuals who have increased financial knowledge—and can effectively translate that knowledge into action through behavioral change—will better manage their financial resources and increase their ability to address household needs. However, financial decisions are virtually always multidimensional. Other influences tend to overpower financial interest, including family obligations, societal influences, scarcity, addictions, and cognitive impulses. Due to these complex decision-making scenarios, financial knowledge alone is often not enough to promote changes in financial behaviors, especially in resource-scarce environments. Based on the success and universality of techniques used in the advertisement and marketing industries, emotion coupled with knowledge can be a powerful driver of behavioral change. Is it possible that, by harnessing emotional motivation in financial literacy education, financial empowerment and thus grassroots economic growth can be achieved as a manifestation of Integral Human Development?

Integral Human Development (IHD) is a term popularized by Catholic Relief Services to achieve a "state of personal well-being in the context of just and peaceful relationships and a thriving environment" (Heinrich et al. 2008). In order to achieve this well-being, one must approach the "holistic development of the human person, covering all aspects of life: social, economic, political, cultural, personal, and spiritual" (Caritas 2016). IHD also includes the "process by which a person achieves this well-being and common good… [which is] a long-term dynamic process based on human dignity and right relations" (Heinrich et al. 2008). In summary, IHD is both a process and a goal in which all aspects of a person's life are developed at once. Although originally based on

Catholic Social teaching, the ideas that IHD present are not limited to Catholic programs (Grassl 2013). The goals of IHD represent holistic individual development and focus on raising all facets of an individual's life gradually, rather than focusing on one area at a time. Obviously, this integral procedure could have substantial outcomes in the context of financial literacy education, as personal finances are closely linked to other aspects of life, including safety, health, family, social status, and personal dignity. By utilizing the methods of IHD, financial literacy education programs could be greatly improved to effectively promote both human dignity and bottom-up economic development.

The effectiveness of financial literacy programming has generally been assessed using randomized control trials (RCT). These trials have unfortunately revealed that even the most comparatively successful programs have made minor impacts on overall financial well-being in developing settings. Existing programs have almost exclusively focused on imparting financial concepts and practical toolsets and paid little attention to the psychological and emotional dimensions needed to embrace these tools and shift long-ingrained behaviors in resource-scarce settings. I hypothesize that financial literacy programs that incorporate these added dimensions to advance the concept of integral human development will have an increased likelihood of improving financial knowledge, behaviors, and well-being.

D.2 Literature Review

In recent years, a variety of RCT assessments have been administered in various developing regions around the globe. This existing literature has focused mainly on teaching financial concepts and practical toolsets to financially vulnerable individuals to explore a variety of research questions. Success has generally been measured by comparing financial literacy program entrance and exit exams and in some cases administering surveys regarding financial behaviors. These RCT's have quantified the effectiveness of program content and design in imparting financial knowledge and toolsets to communities. For example, Bruhn et al. (2014) noted that monetary incentives for program attendance have a slight impact, and low interest in a free financial literacy program in Mexico City was mainly due to the thought that "the benefits of attendance are not high enough." Carpena et al. (2011) concluded "pay for performance" monetary incentives did not improve financial literacy test scores and that prior cognitive restraints due to lack of education hinder the learning progress of complex financial concepts. This is further supported by Drexler et al. (2010) whose simplified "rule of thumb" training proved to be more effective than a standard financial accounting approach. Jamison et al. (2014) found that direct bank account access was not a substitute for financial training, concluding that in order to best improve financial well-being, education needed to be combined with direct access to financial institutions. This was reiterated by Cole et al. (2014), whose financial literacy course had no effect on bank account ownership. Lastly, Carpena et al. (2015) found that detailed goal-setting and personalized financial counseling sessions greatly improved the translation of knowledge to positive financial behaviors. All of the aforementioned studies focused only on the technical knowledge and toolsets associated with financial literacy. None of the programs directly addressed the emotional and personal factors that are imbedded in the financial decision-making process.

Despite statistically significant variations between treatment and control groups, the overall measured impact of these programs has generally not been extremely noteworthy. Many of the results found to be *statistically significant* are unfortunately insignificant as they focused solely on the success of the program in imparting knowledge and not on whether that knowledge was actually applied successfully in daily life. For example, a study surrounding a large-scale financial education program in Mexico City found statistically significant data that the program increased financial knowledge among attendees (Bruhn et al. 2014). However, this statistically significant increase in knowledge (which research later found to be short-lived) was a mere 9%. More concerning is the fact that the program, which has already reached over 300,000 people throughout Latin America, was found to have no statistically significant impact on borrowing behavior (Bruhn et al. 2014). A much smaller financial education program in South Africa found that budgeting and savings are the most retained and applied topics (Cole et al. 2014). Nevertheless, the percentage of those with savings of any form increased by only 12.9 percentage points, while frequent budgeting habits increased by only 6.1 percentage points (Cole et al. 2014). Essentially, even when treatment programs were statistically effective compared to the control groups, they had little benefit to the financial well-being of the majority of participants in the treatment group in practice. This begs the question as to how the effectiveness of such programs could be enhanced and invites a further exploration into methods that will overcome the challenges identified in the literature.

I propose that the effectiveness of these programs in shifting behavior around financial decision-making can be enhanced by a more holistic approach to program design that considers participant emotional triggers. One may ask why this has not been explored previously. This could be in part due to the fact that the logical starting point for any new program is content and basic delivery, so the infancy of these programs could explain why the approaches lacked these deeper dimensions. Or it could be due to the fact that the use of emotional triggers requires deeper cultural understanding and thus limits the transferability of findings and is more challenging to quantify.

The previous literature used RCTs to measure the impact of imparting different practical skills or concepts associated with financial literacy. Impact can be readily quantified by gauging knowledge retention, testing performance, and behavioral translation of knowledge. For instance, does paying for performance improve knowledge retention? Does setting concrete goals improve behavioral performance? Does a "rule of thumb" treatment work better than a detailed financial accounting education? Such technical aspects of program design are reasonably measured through RCTs and allow defendable inferences from the collected data. This is because practical toolsets are much easier to evenly teach and consistently deliver than emotional concepts, which are highly personalized and subject to influences that vary person to person. Financial concepts are in the end concepts that would be imparted to all participants in the same manner. If the goal is simply to measure retention, this is easier to assess and less subject to external, intervening variables. However, measuring behavioral changes and suggesting with some confidence that these were the result not of the knowledge imparted but the more holistic style of delivery with a heavy reliance on emotional triggers is inherently more challenging. Participants may not be consistently "dosed" as emotional response is highly personal and thus highly variable across the population and consistently tracking behaviors is much more difficult and easily affected by outside influences. For example, if a program incorporates personalized financial counseling sessions and the RCT seeks simply to encourage application of knowledge gained in the program in daily life, the counselor's may focus simply on mentoring the participant on the technical facets, maintaining objectivity and not invoking personal emotional motivation to maintain consistency in the intervention across the population. This may explain why prior programs focused on retention of knowledge and practical toolsets – their impacts were easier to measure and variables easier to control in RCTs, regardless of whether they had impact on the financial well-being of the participant in the long run. Interestingly, a recent study has utilized emotional motivation and integral human development concepts to promote behavioral change in financial decision making to reveal promising results (Berg and Zia 2013).

D.3 South African Soap Opera

In 2013, the World Bank sponsored a financial literacy RCT in Johannesburg and Pretoria, the two largest cities in the South African province of Gauteng (Berg and Zia 2013). Unlike previous financial literacy studies, this project did not involve any training, counseling, or classroom activities. The 1,031 participants were merely asked to watch one of two South African soap operas popular among the low and middle-income populations: *Scandal!* or *Muvhango*. The designers of the study worked closely with the National Debt Mediation Association, financial and marketing experts, and the producers of *Scandal!* to design a storyline that was aired over the course of two months. Throughout the two month period, one of the main characters in *Scandal!* excessively borrows via hire-purchase schemes, gambles, and falls into significant debt. Eventually, the character seeks assistance to recover and manage her debt responsibly. The 26 episodes that featured financial literacy messages focused on five key topics: getting into debt via financial mismanagement, the effects that debt and financial mismanagement have on family life, acknowledging the existence of a mismanagement problem and its causal chain, practical steps for escaping debt, and sound financial management. Viewers of *Muvhango*, a comparably popular soap opera without a financial crisis in the storyline, acted as the control group (Berg and Zia 2013).

Despite the fact that no formal financial education classes were held, the treatment group showed significant changes in financial knowledge and behaviors (Berg and Zia 2013). Face-to-face follow-up interviews showed that participants in the treatment group scored significantly higher when questioned about financial literacy topics addressed in the show. Furthermore, the most significant and noteworthy result of Berg and Zia's RCT is evident in the behavioral changes in borrowing. Overall borrowing propensity did not change. This was expected, as the storyline did not deject borrowing but only discouraged irresponsible borrowing. However, when compared to the control group, the treatment group was 69% more likely to borrow primarily from a formal bank. The shift to formal borrowing is also evident in a 4.5-month increase in average loan length among the treatment group. Berg and Zia (2013) state that shorter-term loans are generally associated with informal borrowing, thus the data indicates a reduction of informal borrowing in the treatment group. Lastly, viewers of the *Scandal!* were more likely to borrow for the purpose of investment, including business development, vehicles, or home improvement.

These results lend credibility to the hypothesis that emotional motivation is effective in changing financial behaviors. Rather than directly educating individuals in a classroom setting, the critical financial saga that the viewers of *Scandal!* witnessed gave them direct context and examples of the importance of financial literacy. It is likely that the relevance of the situations in the television program and the impact to characters they cared deeply about triggered an emotional response, thus providing motivation for behavioral change. Furthermore, this is not the only successful application of this concept. Mercy Corps recently delivered soap opera episodes via cell phone to 20,000 Filipinos displaced by Typhon Haiyan (Goodier 2016). These episodes were sent in the form of text or automated calls and featured strong financial literacy messages. They followed the episodes with a variety of survey questions to assess comprehension and used the information to design the subsequent episodes. The data showed that the automated calls were extremely effective, as the receivers were found to be more than twice as likely to save money and use banking services (Goodier 2016). By imparting knowledge in a contextualized, scenario-based manner and associating emotional motivational factors to that knowledge, these studies were able to promote financial literacy education in the context of IHD. This idea of facilitated yet highly individual improvement is further exemplified in the clinical psychological practice of "Motivational Interviewing" (Epp 2016).

D.4 Psychological Factors

Arlen Epp, a licensed clinical social worker at the University of Notre Dame's University Counseling Center, has over 25 years of experience in the field of cognitive behavioral therapy. Specializing in substance abuse, Epp noted that his work “almost always involves behavioral change” (2016). Therapy in itself is essentially a process of rewiring one’s brain. Epp stated that “doing something different requires a new set of neuropathways” and stressed the difficulty of changing a habitual behavior by comparing it to “blazing a trail through a dense forest” whereas reverting to the habitual behavior is as simple as driving down a “six lane expressway.” Due to this difficulty, the individual must rely heavily on his or her emotions to motivate this behavioral change. Without the “client claiming his or her own power and desire for this change,” change is virtually impossible (Epp 2016). Epp and other psychologists use Motivational Interviewing (MI) to provoke emotional motivation for change, help their client draft a “cognitive schema” to guide them, and use daily triggers to keep them on this track to successful behavioral change.

Motivational Interviewing is a counseling technique used by modern therapists to facilitate and provoke emotional motivation for behavioral change and “search for the client’s values” or emotional triggers (Epp 2016). Throughout the interview, the therapist asks open-ended questions while carefully listening for “change talk” (Epp 2016). The MI process can be broken down into four steps: pre-contemplation, contemplation, planning, and action (Epp 2016). In a clinical setting, the client always comes in with something in mind that they want to change, thus the pre-contemplation stage is generally already complete (Epp 2016). In order to move from the pre-contemplation stage to the contemplation stage, the client must experience an event, which generally occurs prior to the MI, that triggers thoughts about change (Epp 2016). During the contemplation stage, the client considers the idea of change with “ambivalence and ambiguity” (Epp 2016).

The therapist takes note of any “change talk” and guides the conversation in that direction, helping the client find his or her own reasons for change (Epp 2016). At this point, Epp finds it helpful for the client to make lists of negative consequences of leaving the behavior unchanged and contrast it with a list of benefits if the change is successful. This provides the client with both best and worst case scenarios and further motivates the client to change. Another technique in the contemplation stage is to find other successful examples of behavioral change in the client’s life and apply it to the current situation, affirming his or her abilities to change (Epp 2016). In the planning step, the client sets a small, realistic goal and establishes a plan to accomplish this goal (Epp 2016). Lastly, the client puts the plan into action, while readjusting for relapses (Epp 2016).

While the MI process is used to mainly provoke emotion, Epp and other therapists utilize follow-up processes to fully harness the emotion and translate it to behavioral change. The main way which he accomplishes this is by helping his clients write a “cognitive schema” (Epp 2016). He believes that “it is more effective for them to learn the new way of thinking more quickly if they create a script.” First Epp asks his clients to write down a “script” of the way they currently think about the behavior in question, resulting in a list of “values, interpretations, and beliefs” that have defined the initial behavior. This script is referred to as a cognitive schema (Epp 2016). Then he asks them to write a new cognitive schema that outlines the way of thinking that would be required to make the necessary behavioral change. Epp also utilizes thoughtfully placed “cue cards” or triggers to “raise their consciousness” and constantly remind the client of this cognitive schema, thus furthering the commitment to the goal. This new script allows the override of the initial cognitive schema, thus harnessing the initial emotional motivation to promote the formation of new neuropathways associated with the new behavior (Epp 2016).

In summary, the MI technique effectively discerns emotional motivations for change; the drafting of a cognitive schema assists in the harnessing of those emotions by helping the client prepare a mental guide; and the cue cards constantly keep the client on track. These three methods have immediate and direct purposes in the IHD approach to financial literacy education. The complexity of financial decisions requires immense discipline. In order to achieve financial well-being, one must not simply be educated on financial matters. One must effectively adapt both behaviors and internal mindset to apply newly acquired financial skills. In context of financial literacy, the MI could discern specific reasons a person wants to increase his or her financial well-being. A cognitive schema might include ways to change one's mindset from being focused on short-term gratification to understanding the benefits of and then applying long-term planning, a vital transformation to financial improvement. Cue cards would be effective reminders to assist the individual as they attempt to change their lending, borrowing, working, and/or spending behaviors and could include implementation programs such as using separate labeled envelopes for each budgeting category or placing photographs of cues, e.g., one's children if the motivation is to provide for their future, on such envelopes. By building up the mental, emotional, and financial states of the individual, these psychological techniques adhere to the concept of Integral Human Development and could have tremendous impacts on financial literacy education.

D.5 Domestic Examples

Many existing programs for behavioral change have utilized a similar process to promote behavioral change, including Financial Peace University and Alcoholics Anonymous. Financial Peace University (FPU) is a national program founded by Dave Ramsey, an investor and responsible financial management activist, in order to help Americans escape debt and become financially stable (Ramsey 2003). Although Ramsey's program is "biblically based," the 9-week course generally sponsored by churches can be extremely effective regardless of religious background (Ramsey 2003). Ramsey's program involves detailed step-by-step goals and procedures to overcome debt, establish savings, and build wealth (Ramsey 2003). While the translatability of these processes to developing nations is debatable due to unstable and sometimes nonexistent government and financial systems, I will focus on the beginning of the FPU process, which involves detailed self-reflection and emotional provocation. These conceptual topics and tools, although translatable to a variety of behavioral change challenges, are directly designed for financial empowerment.

In his 2003 publication of *The Total Money Makeover Workbook*, Ramsey begins by familiarizing the reader with his or her own personal financial situation and inciting emotion. His approach is summarized by the following statement: "Before you are truly willing to embark on a Total Money Makeover, you need to face up to how you FEEL about your current financial situation. That will tell you how motivated you are to do something about changing your financial situation" (Ramsey 2003). Similar to the event described between the pre-contemplation and contemplation steps of motivational interviewing, his goal in the beginning of his workbook is to make the reader completely realize the necessity for change. Ramsey then uses various activities with strongly worded titles such as the following: “How Do You Feel About Money?” (pg. 2), “Whose Fault Is It?” (pg. 7), “The Person in Your Mirror” (pg. 10), “The Willingness to Change” (pg. 12), “Let’s Get Real” (pg. 19), and “What Would Happen If…” (pg. 23). These exercises, as evident from the titles alone, connect the reader’s financial situation with his or her emotional and mental state, creating an essential link to effectively accomplish the goal of financial freedom (Ramsey 2003). The system also strongly utilizes personal accountability through emotional provocation for change. This establishes feelings of guilt, pride, and desire that help the reader adhere to the physical debt-removal steps, which can demand considerable personal sacrifice, and achieve financial freedom. Although no scholarly research has verified the effectiveness of FPU in comparison to other programs, its emotional testimonials from thousands of American families successfully completing the program are noteworthy. More than just knowledge, the activities in his workbook and his application of the snowball effect in debt recovery center on motivation, generating momentum through small victories, and reiterating emotional triggers to promote sustained financial behavioral change to reinforce the conclusion drawn by Berg and Zia (2013).

Alcoholics Anonymous (AA) is another example of a behavioral change program that harnesses emotions. Fundamental to AA is the famous program known as “The Twelve Steps of Alcoholics Anonymous” (AA 1981). Like FPU, the twelve steps of AA make theological references, but the content is not dependent upon the theological basis and thus can be applied secularly. This program is a deeply personal process used to motivate change and “if practiced as a way of life, can expel the obsession to drink and enable the sufferer to become happily and usefully whole" (AA 2016). This promotion of overall happiness and well-being to address the source of addiction, rather than simply approaching the symptom of alcoholism, is a modern example of IHD. This is exemplified in the first of the twelve steps, in which the person admits to being "powerless over alcohol" (AA 1981). Step four requires that the individual make a "searching and fearless moral inventory" of his or her self, which incites deep emotional motivation to overcome the addiction (AA 1981). Steps eight and nine establish a sense of accountability within, asking the individual to draft a "list of all persons [he or she] had harmed" and to make "direct amends to such people" (AA 1981). By establishing such accountability, AA is making an effort to establish internal motivations to assist the recovering addict in avoidance of alcohol. Furthermore, AA's twelve-step program has proven to be effective, with approximately one half (49.5%) of all participants abstaining from alcohol after one year (Gray 2012). Other areas of exploration for similar programming could include other drug rehabilitation programs (particularly nicotine, as the concept of many seemingly small decisions adding up to massive negative impact parallels the complexity of financial behaviors), Weight Watchers, and the industrialized marketing industry.

D.6 Conclusion

The ideas discussed in this concept note are not necessarily limited to financial literacy and could possibly be expanded to include many development education programs, such as health or sanitation. In order to further support the claims made in this concept note, a systematic RCT would need to be undertaken, noting the aforementioned challenges with controlling factors influencing emotion-based programming. To do so, I would propose an RCT that analyzes the effectiveness of a financial literacy education program in which one treatment group receives a core technical curriculum and financial toolset couched within additional activities and exercises that will tie these tools to emotional triggers to encourage their sustained application toward a stated financial goal. A second group would receive only the core technical curriculum and financial tool set. A control group would receive neither. If the RCT affirms the hypothesis in a particular setting, the approach would need to be systematized for translation to other settings and other development challenges. Again, one must caution that because emotional triggers are highly personal and their appropriateness would vary culturally, effective program design and translation would be more challenging. However, the benefits to global development educational programs may be well worth the added effort.

Financial literacy and subsequent financial empowerment among vulnerable populations in developing nations are vital factors in stimulating grassroots economic development. Empowered consumers and business owners have the ability to develop economies from the bottom up, leading to improved qualities of life on time scales that may be more reasonable than top down economic development in these settings. In order to empower individuals, they must be financially educated in ways that are directly applicable to their everyday life. The literature offers a variety of best practices for knowledge delivery and retention. However, the literature’s widespread impact is minimal and fails to make the connection between emotions and financial decisions, which cannot be ignored due to the complexity of variables that are considered when making financial decisions. This was affirmed by a study by Berg and Zia (2013) and further supported by Mercy Corps (Goodier 2016), which both concluded that emotional connections and motivations promote financial behavioral change. Furthermore, Epp (2016) described clinical psychological methods that rely heavily on emotional harnessing to invoke behavioral change. Dave Ramsey (2003) and his Financial Peace University join the principles of financial knowledge transfer and emotional harnessing in a highly effective domestic program for financial behavioral change. Meanwhile Alcoholics Anonymous delivers a well-known example supporting the success of holistically assisted behavioral change targeted at the root cause rather than the symptoms. Thus, I conclude that financial literacy education based on Integral Human Development concepts that harness emotional motivation is a promising approach to increase the likelihood of improved financial knowledge, behaviors, and overall well-being.

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