Seismic Resiliency Using Confined Masonry: Parametric Study using a Simplified Analysis Method

By

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Abstract

Earthquakes throughout the world can be devastating catastrophes, especially in developing nations. Confined masonry (CM) structures have proven to be a viable solution for seismic resiliency in the unique restraints and conditions of developing nations. CM provides benefits of increased shear capacity with smaller concrete frame members that provides economic benefit as well. However, the behavior of CM is highly non-linear during a seismic event and requires expertise to correctly model and analyze structures. A need for simplified guidelines are required for successful implementation of CM as a low cost solution for developing nations.

The study parameterizes a simplified procedure for the design of CM buildings that takes into account irregularities and torsional effects in order to provide a tool to aid in the development of simplified design guidelines for CM. Different building configurations are sampled in geometric and material studies to provide recommendations for the design guidelines. The design guidelines are developed for the context of the Kathmandu Valley in Nepal to aid in their reconstruction efforts following the 2015 Gorkha earthquake. The parameters can be easily changed according to the country location to develop similar guidelines. Then a prototypic study on school buildings will show the structural and economic benefit of CM structures.

Building shape typologies (L-, T-, and C-shaped plans) are explored in the geometric study. In the context of Nepal, only 3 story buildings have significant torsional effects. Design guidelines are recommended based on the building plan parameters. The material study aids in the understanding of the influence of wall thickness and brick strength. In the study, the increase in wall thickness and masonry compressive strength does decrease the utilization of the structure. However, there is a diminishing return and a limit on amount of improvement with the increase of both parameters. In an effort to contribute to the school sector as well, a prototypic study of approved school designs from Nepal is performed. While the approved school designs are for other material types (RC frame with brick infill, stone and mud, earthbag, etc.), the proposed architectural layout is maintained and analyzed as CM. Then the designs are compared with the same layout but a more economical design in CM. Saving in material quantities for the school building, the study shows that CM provides superior economic and structural benefits.

Thesis Supervisor: John Ochsendorf

Title: Class of 1942 Professor of Civil and Environmental Engineering and Architecture

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1 INTRODUCTION

1.1 Context and Problem Statement

Earthquakes around the world are catastrophic events and a huge danger for human life. However, the seismic risk is especially prevalent in developing countries due to the unique constraints and limited resources. While many initiatives have been undertaken to reduce human and economic losses around the world, developing countries remain at a much higher risk than developed countries. The population within 100 km of an active fault has increased at a much greater rate than that of developed countries (refer to Figure 1-1). Because of low resources, developing countries are at about a 2 to 3 times higher seismic risk than developed countries (Tucker, 2013).

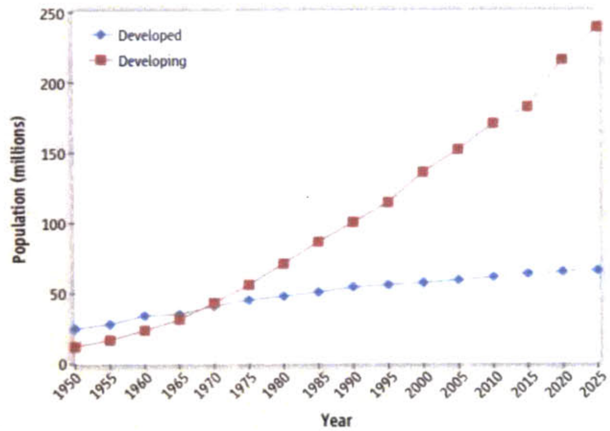

Figure 1-1: Urban Earthquake Risk (Tucker, 2013)

The April 2015 Gorkha earthquake in Nepal devastated 17 districts surrounding the Kathmandu Valley. Approximately 80% of the building stock collapsed or was damaged beyond repair in the affected districts (NSET, 2016; see Figure 1-2). Based on observations from the author's travels to Nepal in January 2016, there are several causes for the collapse of these buildings: poor construction materials, limited QA/QC during construction, corruption, etc. After performing a rudimentary needs assessment during travels to Kathmandu Valley and surrounding areas in January 2016, three main research areas have been identified:

Figure 1-2: Collapse School Building in Kavre, Nepal

quantitative retrofitting design methods, traditional building material/construction analysis methods, and seismic design of reinforced concrete (RC) frames with brick infills.

Figure 1-3: Collapse of Houses in Bugamati, Nepal

The current study focuses on the need for an improved and more economical engineered design of the RC frame with brick infill buildings, specifically for the housing and school sectors. The main problems in the current way RC frame buildings are designed in Nepal is that they are not designed or constructed properly, and engineers do not take into account brick infill as structural elements (see Figure 1-3). Engineers consider only frame action for lateral seismic resistance. However, once the frame is constructed and the brick infill is installed afterwards, the structure is much stiffer than expected, and the frame action may never develop in the way it was intended by design. As a result, the building can collapse due to a soft-story mechanism formed at the base level. Confined masonry (CM) construction is recommended as an alternative construction technology to replace current construction practices for RC frames.

1.2 Confined Masonry Construction

CM construction is similar to current practices of RC frame with brick infill. The main differences are that the foundation requires continuous footings throughout the entire length of the wall instead of spread footings underneath the columns. Furthermore, the brick walls are constructed first and then the RC tie columns and tie beams are cast around the wall to create a better bond between the concrete and masonry components. This allows for composite action for lateral resistance where the masonry behave as compressive struts and RC tie columns and tie beams behave like the tension or compression ties, such as in a strut-and-tie model. The composite action allows for increased strength and ductility during a seismic event in addition to reducing the sizes of the RC elements in CM (Brzev, 2008). An illustration of a CM building can be seen in Figure 1-4.

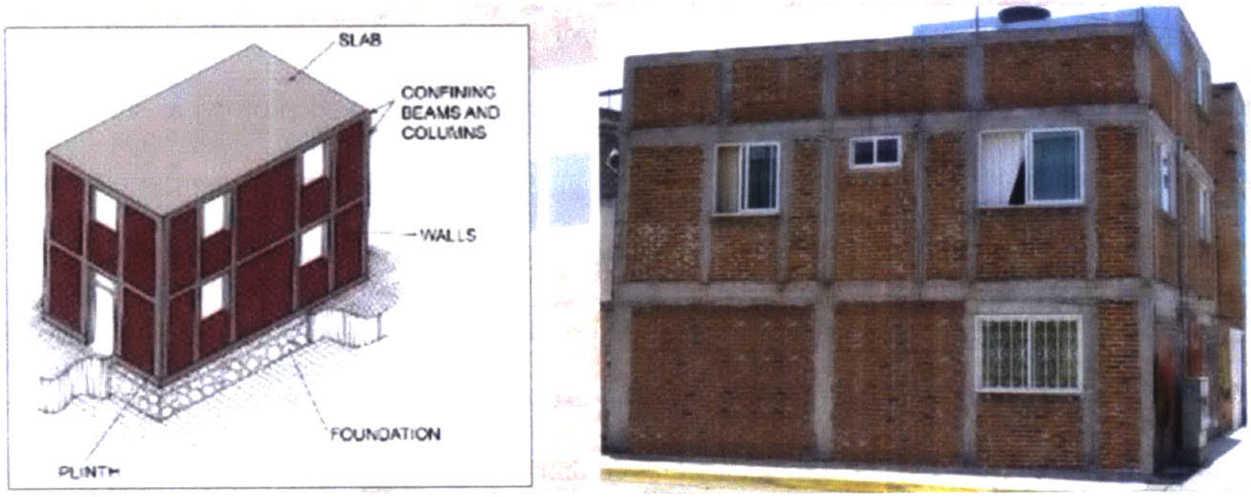

Figure 1-4: Key Components of a Confined Masonry Building (Meli et al., 2011)

CM buildings have performed extremely well throughout Latin America. Specifically in Chile, after CM construction was adopted in the 1930's after the 1928 Talca earthquake (M 8.0), most CM buildings performed well with a vast reduction of collapse even in the major 2010 Maule earthquake (M 8.8; Brzev, 2010). Therefore, it is recommended that a wider implementation of CM construction begins throughout seismic prone regions of Southeast Asia.

1.3 Thesis Outline

The current study explores the benefits of CM construction and surveys current methods for CM structural analysis and design. In an effort for an ease of implementation as a low-cost solution in developing countries, the study focuses on a conservative yet accurate Simplified Analysis Method. The SAM was adopted for Torsional Seismic Analysis by Porst (2015) and Brzev (2015). Based on the original method by Escobar (2008), the method can be used to analyze CM buildings with irregular building plans and wall layout. With this method, the thesis will address the following areas:

1. Application of a SAM for the development of building design guidelines
2. Exploration of material influence on seismic resistance of CM buildings
3. Cost savings associated with CM in comparison with alternative construction methods

The SAM will be parameterized to conduct a geometric, material, and prototypic study. The geometric study focuses on the seismic analysis of hundreds of different plan configurations of irregular building typologies. The design space will be explored with a direct application to the housing sector in developing countries where such irregular typologies are common. From the study, simplified design guidelines for the context of Nepal are proposed to aid in the reconstruction efforts in Nepal, but the guidelines could be easily modified for other locations with different seismic hazard parameters. A material study of buildings with a wide range of wall thicknesses and masonry compressive strengths will be conducted using a representative sample of building configurations from the geometric study. The study provides a better understanding of the influence of these parameters on building capacity to resist seismic loads. The exploration will be useful for implementation of the method at different locations since there is a wide variation of these parameters. Furthermore, a prototypic study of various approved school buildings in Nepal will be analyzed as CM to determine effects of openings in the walls (windows and doors). The approved school designs are to be reanalyzed and compared the same architectural layout but with reduced wall thickness. The comparison is to illustrate the advantages of the economic savings using CM but still remaining high performing.

2 LITERATURE REVIEW

2.1 Confined Masonry Introduction

Confined masonry (CM) provides many benefits in terms of lateral load capacity and material savings for good seismic performance over reinforced concrete (RC) frame with brick infill. Both systems look visually similar after construction but are structurally designed to behave inherently different during an earthquake (Okail, 2014).

The frame elements in the RC with brick infill construction are designed to carry applied gravity and lateral loads for the structure (floor loads, wind, earthquake, etc.). The foundation for RC frame buildings are spread footings underneath the columns. The frame is then cast first with the masonry infill panels built afterwards. The masonry panels serve a purely architectural purpose as partition walls and are usually not accounted for in the structural design of the building. The lateral resistance of a building during an earthquake is provided by moment frame action and plastic hinging within the frame. Although the masonry walls are not considered structurally, they act as the structural members during an earthquake. These infills are maybe much stiffer than the RC frame that surrounds them. Consequently, when the infill walls engage the structure becomes much stiffer than anticipated in the design process. The compression strut formed in the masonry infill walls may lead to development of high shear forces in the columns. These shear forces may cause the column to fail in shear rather than flexure as originally intended, causing premature collapse of the structure (Brzev, 2008).

The primary benefit of CM structures is that both the RC components and masonry walls contribute to the building's structural integrity (Mohyeddin, 2013). The foundation for CM building is a continuous footing throughout the length of the walls. Unlike RC frame construction, masonry walls are constructed first atop the foundation with the frame elements cast around the wall. The construction procedure allows for a bond to develop between the RC components and the masonry panel. The masonry wall acts as the primary element to resist gravity floor and roof loads of the structure since CM is a loadbearing wall system. The RC components and masonry act compositely during an earthquake. Similar to a tie-and-strut model, the frame components act as the tension tie and the masonry panels act as diagonal compressive struts, as demonstrated by experimental results (Crisafulli, 1997; Crisafulli et al., 2005). Since the composite action is taken into consideration during the design process, CM structures may behave better than typical RC frame buildings with brick infills while there are cost savings due to smaller size of RC components (Brzev, 2008).

Due to the composite action of the RC components and masonry wall, bond interaction between the two, and non-linear behavior of masonry, CM structures behave in a highly non-linear manner. Consequently, seismic design of CM structures require complicated analysis methods such as Finite Element Methods (FEM) to accurately model the structural response during an earthquake. Several studies described below have explored models using various FEM software packages. The studies then propose simplified tie-and-strut models calibrated to the FEM models and experimental results that are intended to be used for design and analysis of CM. Conservative simplified methods have been used to quickly design CM buildings without an intense computational effort required for FEM models, which is much more appropriate for the context of developing countries where the resources are limited.

2.2 Finite Element Method and Simplified Models for Confined Masonry

Due to the composite and highly non-linear behavior of CM walls, sophisticated analysis methods are used to predict the response during a seismic event. Typically, Finite Element Method (FEM) of CM walls that are calibrated to experimental data are proposed in order to predict the lateral capacity of CM structures. Various studies have been conducted to analyze the behavior of both CM masonry walls in comparison to RC frame with infills. Different FEM software such as ANSYS and Abaqus are used to construct the models and analyze the CM walls for lateral loads. The lateral load responses have been analyzed for in-plane loading (Okail, 2014; Torrisi, 2012; Abdel-Hafez, 2015; Mandara, 2003) while some studies took into account out-of-plane behavior as well (Mohyeddin, 2013). The FEM models were used to propose simplified models for practical design of CM buildings.

Different approaches to formulate the non-linear FEM models have been taken to model the RC components, brick infills, and the interaction between these two materials. The RC components are modelled as concrete truss elements with embedded reinforcing steel to represent a full bond between the concrete and rebar. For the brick infill, a general macro-level or smeared approach consists of the masonry panel modeled as a single element (Okail, 2014; Torrisi, 2012; Abdel-Hafez, 2015; Mandara, 2003), whereas a micro-level approach models each individual brick and the mortar joints (Mohyeddin, 2013). The studies are calibrated and compared with experimental results to validate the proposed method. Due to simplifications and assumptions in the formulation of the models, the general consensus is that the FEM models overestimate the stiffness of CM walls at the beginning of an earthquake, but still accurately represent the ultimate strength and ductility of the wall once separation between the RC frame and masonry infill occurs (Okail, 2014; Torrisi, 2012; Abdel-Hafez, 2015; Mohyeddin, 2013).

Parametric studies observe the influence of specific parameters on the strength, ductility, stiffness, and other characteristics of CM walls. Furthermore, some studies compared behaviors of CM walls, RC frame with brick infill, and bare RC frames (Mohyeddin, 2013; Abdel-Hafez, 2015; Torrisi, 2012). The most influencial parameters in regards to the strength and ductility of CM walls are compressive strength of the masonry and friction resistance between the RC frame and masonry from the bond that was able to develop from the construction method (Okail, 2014; Torrisi, 2012; Abdel-Hafez, 2015). Shear capacity and ductility were dramatically higher in CM walls and RC frame with infill brick walls compared to bare frames. Furthermore, CM walls performed better than RC frames with brick infills due to the bond between the frame and masonry (Torrisi, 2012; Abdel-Hafez, 2015).

While it is commonly accepted that CM walls behave better than alternative systems in a seismic event, siesmic analysis of such structures using FEM requires specialized expertise and computational effort. Therefore, simplified models have been developed using the results from experimental and analytical studies. Typical strut-and-tie models consider RC components acting as uniaxial ties and struts while the masonry walls act as compressive struts during an earthquake, other innovative models are proposed to more accurately represent the behavior of CM walls. From the micro-level modelling approach, a "dynamic-strut" model is proposed to account for the change in load path, which is not possible with a single diagonal compressive strut. When the lateral load increases and a separation occurs during an earthquake, the contact points change, while the number, locations, and widths of the compressive struts change (see Figure 2-1a; Mohyeddin, 2013). A macro-element model using the RC components as the tension ties and a total of six inclined compressive struts in, with three in each direction, is proposed to more accurately represent the increased contact area between the masonry and frame (see Figure 2-1b; Torrisi, 2012).

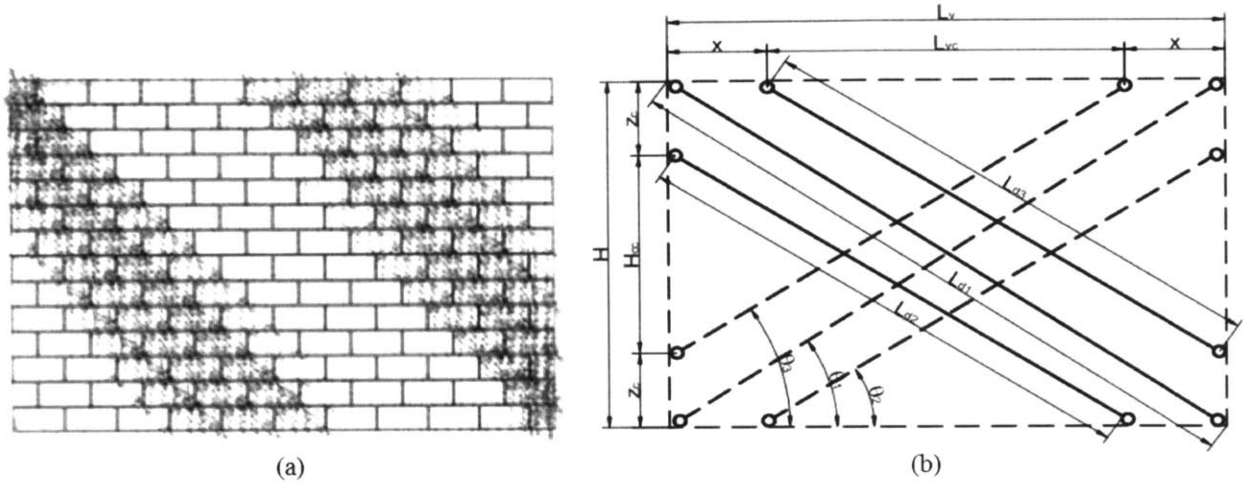

Figure 2-1: (a) Dynamic Strut Model (Mohyeddin, 2013), (b) Six Strut Model (Torrisi, 2012)

While significant research has been conducted using sophisticated FEM models that have been calibrated with experimental results, there are many limitations to the proposed simplified models. Many parameters influence the strength of the strut-and-tie models and have to be constructed on a "case-by-case" basis due to material properties, geometry of the structure, and many others (Mohyeddin, 2013). Therefore, a further conservative, simplified, yet accurate analysis method has been explored in the current study for implementation in developing countries.

2.3 Simplified Method for Torsional Seismic Analysis of Confined Masonry

In order to facilitate seismic design of CM structures, simplified analysis methods have been developed to provide conservative yet economical designs. These methods allow for simpler and significantly less computational intensive analysis of CM structures. The following methods described are the ones used in the current study in an effort to provide simple, useful, and accurate design guidelines for CM structures.

The Simplified Method for Seismic Analysis (SMSA) for CM gives a procedure that calculates the amount of required wall density in each orthogonal direction of a building to resist the given seismic base shear force (Brzev, 2015). The wall density in each orthogonal direction is the product of walls parallel to the seismic load divided by the building plan area. (Brzev, 2015; Porst, 2015) The sum of the wall lengths in each direction must be greater than the required value to provide enough shear capacity during an earthquake, as shown in Figure 2-2.

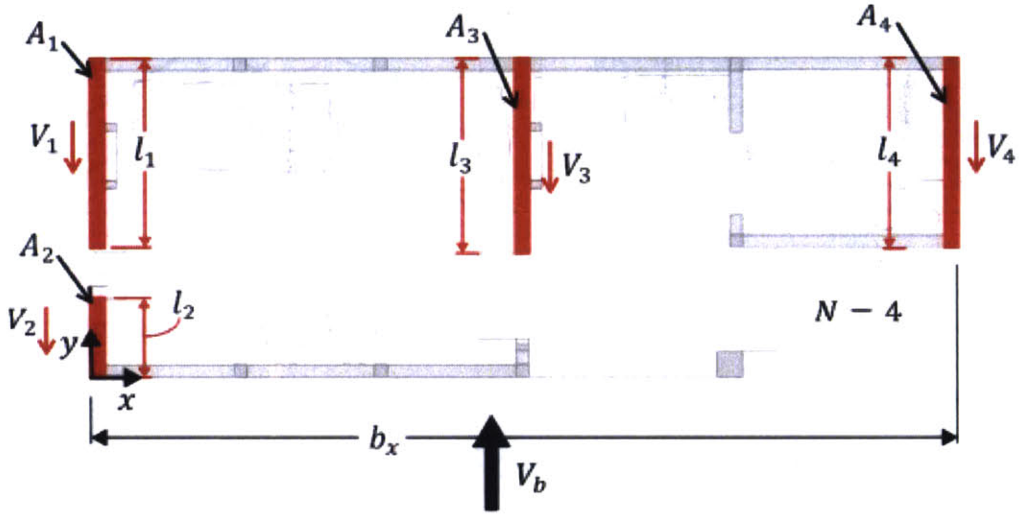

Figure 2-2: Wall Density for Simplified Method for Seismic Analysis (Porst, 2015; Brzev, 2015)

Various parameters contribute to the calculation of required wall length, such as the seismic zone, building type, thickness of masonry walls, shape of building plans, etc. In each orthogonal direction there must be sufficient wall length to ensure sufficient shear capacity to resist the design base shear (i.e. seismic design) during an earthquake.

However an irregular wall layout, irregular building plans, or openings in the wall such as windows and doors, may cause an eccentricity between the center of mass and center of resistance of the CM walls, and result in torsional effects, as shown in Figure 2-3.

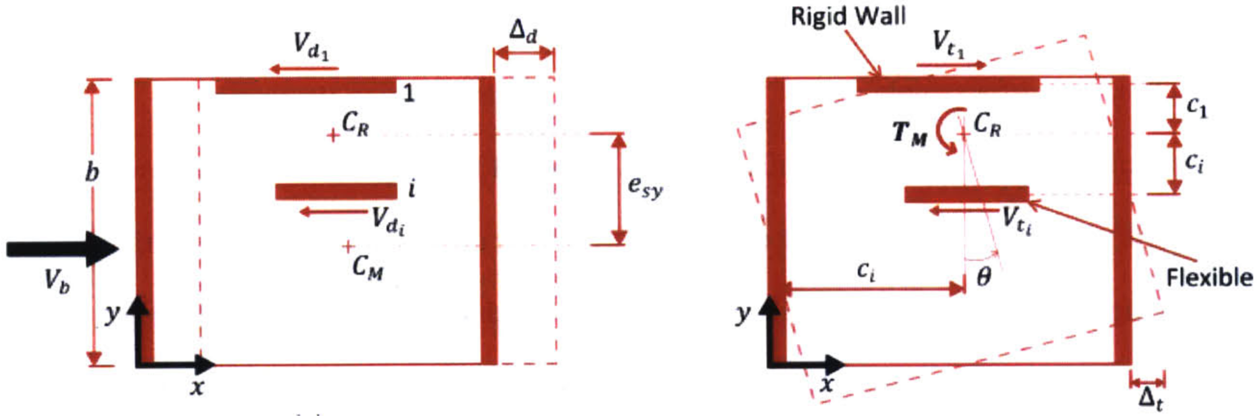

Figure 2-3: Torsional Seismic Effects (Porst 2015; Escobar 2008)

These torsional effects cause an amplification in shear forces within the CM walls. A simplified method takes this eccentricity into account to calculate an amplification factor for the design base shear forces, which the walls must resist (Guzmán and Escobar, 2010; Escobar, 2008; Escobar 2004).

These two methods are combined to provide a required wall density in both orthogonal directions of any irregular building plan that takes into account the torsional amplification (Porst, 2015). From a case study, Porst validated the method by comparing a design of a CM house using the proposed method with a more detailed analysis method (Naeim, 2000). He showed that the results of the simplified method were more conservative, as shown in Figure 2-4:

Table 2. Wall Density Comparison

	SMSA	Proposed Method	Conventional Analysis (% Difference)	Architectural Design (% Difference)
d_x	2.9	4.2	3.1 (-26%)	4.0 (-5%)
d_y	2.9	3.1	2.9 (-6%)	8.7* (181%)

*The wall density of the actual design for the y-direction is overdesigned due to the long dimension of the building, providing excess support.

Figure 2-4: House Case Study Comparison (Porst, 2015)

Herein, the proposed method will be referred to as the Simplified Method for Torsional Seismic Analysis of Irregular Buildings (SMTSA) for CM. Even though SMTSA for CM can be applied easily to various building configurations, material parameters, and seismic zones, there has not been an extensive parametric study conducted using this method. Porst (2015) began with a small parametric study of a sample size of 15 plans for 3 irregular building typologies (L-, T-, and C-shaped building plans). This study utilizes SMTSA for CM buildings to conduct a more extensive parametric study. A geometric study of buildings with irregular building plans, material study of a wide range of values, and prototypic study of approved school designs in the Kathmandu Valley, Nepal will be conducted to explore the design space and applications using SMTSA for CM.

2.4 Summary

This chapter introduced the structural and economic advantages of CM construction compared to the similar construction method of RC frame with brick infill. A brief review of current design and analysis methods for CM was performed. Due to its highly non-linear behavior, sophisticated and complicated FE models are developed and calibrated with experimental results for accurate prediction of the response of CM buildings during an earthquake. The FE models are used to propose simplified models for design and analysis. However, the primary limitation is the narrow scope of implementation and such models are typically used on a "case-by-case" basis (Mohyeddin, 2013). To address this limitation, the Simplified Method for Torsional Seismic Analysis (SMTSA) for CM is surveyed as a more appropriate method for vast implementation, especially in the context of developing countries. However, an extensive parametric study has not been conducted using this method, and this thesis explores the wider application of the SMTSA for CM by conducting geometric, material, and prototypic studies. The following chapter outlines the methodologies of the SMTSA for CM and the studies.

3 METHODOLOGY

This chapter will explain the methodology that implements the simplified analysis method introduced in Section 2.3. The analysis method will be used in the design space exploration for the geometric, material, and prototypic studies.

3.1 Simplified Analysis

The Simplified Method for Torsional Seismic Analysis (SMTSA) for CM buildings is used for the geometric, material, and prototypic studies. The seismic base shear forces for the CM are calculated for the context of the Kathmandu Valley in Nepal.

3.1.1 Simplified Method for Torsional Seismic Analysis

The following assumptions are taken:

- "The procedure applies only to buildings up to and including three stories tall.
- It is assumed that the plan aspect ratio is greater than or equal to 1:3 ($W : L \geq 1 : 3$).
- It is assumed that the structural walls are continuous throughout the building height.
- It is assumed that there are at least 2 lines of structural walls in each direction.
- Floors and roofs are assumed to act as rigid diaphragms (there is uniform inter-story displacement)." (Porst, 2015)

First, the seismic base shear force, V_b, for each orthogonal direction is determined based on the local building code's seismic design. The wall density in each orthogonal direction can be calculated from the following equation (Porst, 2015):

$$d = \sum_{i=1}^{N} \frac{l_i * t_i}{A} \qquad (3\text{-}1)$$

Where:

N = number of structural walls at the floor level

l_i = length of ith wall

t_i = thickness of ith wall

A = floor plan area for the first floor level

Then, the shear strength of the masonry wall, v_m, is determined based on the compressive strength of the masonry, f'_m, as follows (Porst, 2015).

$$v_m = 0.18 * \sqrt{f'_m} \tag{3-2}$$

The shear capacity of the structure, V_R, in each direction can be expressed as the sums of the shear capacities of individual walls. The shear capacity can be expressed using the required wall density, d, and floor plan area, A. A strength reduction factor, φ, is applied to the shear capacity of the building. This results in the following (Porst, 2015):

$$V_R = \varphi * v_m * d * A \tag{3-3}$$

The shear capacity of the structure must exceed the factored seismic base shear for the given seismicity as follows (Porst, 2015):

$$LF * V_b \leq V_R \tag{3-4}$$

Where:

LF = load factor

Combining equations (3-3) and (3-4) and rearranging terms, the required wall density can be calculated as follows (Porst, 2015):

$$d = \frac{LF * V_b}{\varphi * v_m * A} \tag{3-5}$$

An aspect ratio factor, f_{AR}, must be applied to the required wall density in the shorter direction as well (Porst, 2015):

$$f_{AR} = \begin{cases} 1.0 \ if \frac{W}{L} = 1 \\ 1.02 \ if \ 1 > \frac{W}{L} \geq \frac{2}{3} \\ 1.08 \ if \frac{2}{3} > \frac{W}{L} \geq \frac{1}{3} \end{cases} \tag{3-6}$$

Where:

W = the building's shorter overall dimension

L = the building's longer overall dimension

The torsional amplification factor must also be applied to the required wall density. First, the static eccentricity, e_s, must be found by finding the distance in each orthogonal direction between the center of mass, *COM*, and center of resistance, *COR*. The normalized eccentricity, e, is perpendicular to the applied load (Porst, 2015):

$$e = \frac{|e_S|}{b} \quad (3\text{-}7)$$

Where:

b = the overall building plan dimension perpendicular to the direction of load (W or L)

If shear-dominant behavior is assumed and the thickness of all masonry walls are constant, the radius of gyration in each direction of applied load, ρ_x, can be calculated as follows (Porst, 2015):

$$\rho_x = \frac{1}{b}\sqrt{\frac{\sum l_i * c_i^2}{\sum l_{xi}}} \quad (3\text{-}8)$$

Where:

c_i = the perpendicular distance of the wall i to the *COR* (refer to Figure 2-3)

l_{xi} = length of parallel wall i in the direction of loading

A ζ_i factor for each wall depends on the perpendicular distance of parallel walls to the *COR* and the building plan dimension, b, perpendicular to the direction of applied load (Porst, 2015):

$$\zeta_i = \frac{c_i}{b} \quad (3\text{-}9)$$

Accidental eccentricity is prescribed by the seismic codes in most countries. Factors β accounts for accidental eccentricity, while α and δ are multipliers for static eccentricity when the accidental eccentricity is positive and negative respectively. The factors are used in the determination of the design eccentricity, e_d, in the form of (Porst, 2015):

$$\begin{cases} e_d = \alpha e_s + \beta b \\ \quad or \\ e_d = \delta e_s - \beta b \end{cases} \tag{3-10}$$

These factors are used to calculate the torsional amplification factor, *FAT*. The method considers walls that are on the same side of the *COM* in regards to the *COR* as flexible (*f*) and rigid (*R*) otherwise as illustrated in the following figure (Porst, 2015):

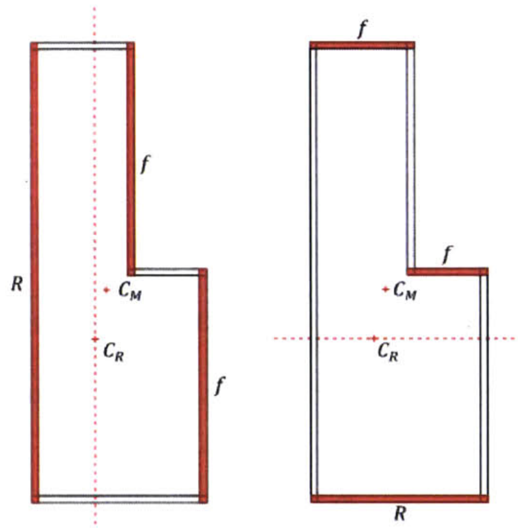

Figure 3-1: Flexible and Rigid Wall Illustration (Porst, 2015)

The *FAT* value for flexible (*FATf*) and rigid (*FATr*) walls are calculated from the following equations (Porst, 2015):

$$FATf_i = 1 + \frac{\zeta_i}{\rho^2}(\beta + \alpha e) \tag{3-11}$$

$$\begin{cases} FATr_i = 1 + \frac{\zeta_i}{\rho^2}(\beta - \delta e) \; if \; \delta e < \beta \\ FATr_i = 1 \; if \; \delta e \geq \beta \end{cases} \tag{3-12}$$

For each seismic force direction, that FAT factor will be assigned the maximum value of *FATf* or *FATr*. *FAT* will be used to determine the required wall density in the respective direction. The total required wall density, d_r, in the respective direction of seismic force is expressed as follows (Porst, 2015):

$$d_r = d * f_{AR} * FAT \tag{3-13}$$

Assuming constant masonry wall thickness throughout the floor plan, equation (3-13) can further be simplified in terms as required wall length, l_r, in each direction as follows (Porst, 2015):

$$l_r = \frac{A * d_r}{t} \tag{3-14}$$

The required wall length in each direction is the primary output from SMTSA for CM used in the present study.

3.1.2 Seismic Base Shear

The seismic forces are calculated using the Seismic Coefficient Method from the Nepal National Building Code NBC 105: 1994 (NBC 105 10.1). First the seismic weight, W_t, of the structure is calculated as the sum of the dead loads and seismic live loads (refer to Table 3-1) between the mid-heights of adjacent stories (NBC 105: 6).

Table 3-1: Seismic Live Load Determination (NBC 105: Table 6.1)

Design Live Load	Percentage of Design Live Load
Up to 3 kPa	25
Above 3 kPa and for vehicle garages	50
For Roofs	NIL

The natural period, T, of the structure is estimated from the following equation (NBC 105: 7.3):

$$T = \frac{0.09 * H}{\sqrt{D}} \tag{3-15}$$

Where:

H = overall building height

D = overall plan dimension of building perpendicular to direction of seismic load

The horizontal seismic force coefficient, C_d, is calculated from the following equation (NBC 105: 8.1.1):

$$C_d = CZIK \tag{3-16}$$

The basic seismic coefficient, C, is calculated based on the natural period of the structure using as follows (NBC 105: Figure 8.1):

$$\begin{cases} C = 0.08, T \leq 1.0 \\ C = \frac{0.08}{T}, 1.0 < T \leq 3.0 \end{cases} \quad (3\text{-}17)$$

The seismic zone factor, Z, is taken as 1.1, which is the most conservative value from Figure 8.2 in NBC 105. The importance factor, I, is taken as 1.0 and 1.5 for houses and schools respectively from Table 8.1 in NBC 105. The structural performance factor, K, is taken as 2.0 for frame with masonry infills from Table 8.2 in NBC 105. This is due to account for the similar responses both structural systems have during an earthquake (Torrisi, 2012).

Once the horizontal seismic force coefficient is calculated, the horizontal seismic base shear, V_b, is calculated from the following equation (NBC 105: 10.1.1):

$$V_b = C_d * W_t \quad (3\text{-}18)$$

The horizontal seismic force will be used in SMTSA for CM to determine the required wall density for irregular plan configurations for houses and school building prototypic case studies. The factors for eccentricity are taken as follows: $\beta = 0.1$, $\alpha = 1$, and $\delta = 1$ (NBC 105: 8.2.2).

3.2 Geometric Study

The SMTSA for CM described above in Section 3.1.1 will be used to analyze three irregular building typologies: L-, T-, and C- shaped building plans. The structural systems will consist of confined masonry walls, reinforced concrete floor slabs, and a concrete roof slab similar to that shown in Figure 1-4.

The SMTSA for CM is programed into a Matlab script to conduct the analysis of hundreds of randomized building configurations at a high rate. In order to analyze many different building configurations, geometric and material assumptions are made constant for the sample size. In order to generate enough samples for statistical significance, initially 1000 samples will be considered for each building typology. The assumptions taken into the context of the Kathmandu Valley case study and are as follows:

- Story height, $h = 2.75$ m
- Floor slab thickness, $t_f = 0.100$ m
- Masonry wall thickness, $t_m = 0.230$ m
- Reinforced concrete self weight, $\gamma_{rc} = 24.8$ kN/m^3
- Masonry self-weight, $\gamma_m = 18.85$ kN/m^3
- Masonry compressive strength, $f'_m = 4$ MPa (Guragain, 2012; Maharjan, 2016)
- Walls stack on every floor
- Load Factor, $LF = 1.5$
- Material reduction factor for masonry, $\varphi = 0.5$
- Only exterior walls engage the structure during a seismic event*

* *This assumption is taken to simplify calculations and to increase the eccentricity between the center of mass, COM, and center of resistance, COR.*

After the geometric, seismic, and material factors are defined, the configurations for the typical building plan shapes have to be set. In order to create varying configurations in the sample to explore the design space, the building plans are parametrized using 4, 5, and 6 variables respectively as shown in Figure 3-2.

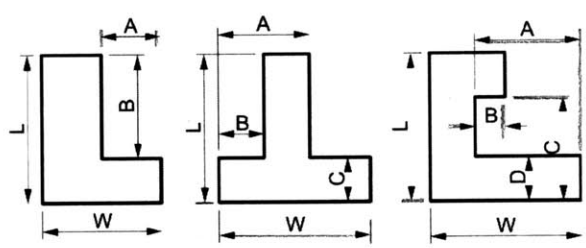

Figure 3-2: Building Plan Parameters

The parameters are generated randomly based on geometric constraints and bounds to assure realistic housing configurations and within reasonable bounds. For instance in an L-shaped building plan, a room that is only 1 meter wide and 100 meters long is unrealistic. Furthermore, the constraints assure that irregularity is maintained rather than having configurations that resemble a rectangular building plan. Figure 3-3 shows examples of undesirable configurations that are resolved by applying the constraints.

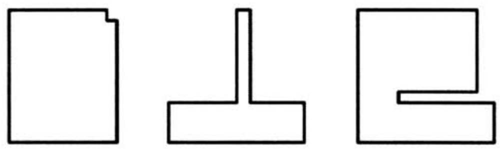

Figure 3-3: Unrealistic Building Plans

Certain sets of configurations that violate the constraints were discarded, which result in about a 1% reduction from the initial sample size. Variables for the geometric constraints of the three building typologies are illustrated in Figure 3-4.

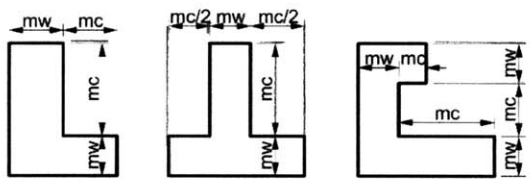

Figure 3-4: Geometric Constraints Illustration

The variables *mw* and *mc* denote minimum wing and cutout width respectively; these variables were set in an effort to avoid unrealistic building configurations during the generation of random parameters. The following constraints are assumed for the current study:

- Bounds for overall dimensions of buildings, 6 m $\leq W$ & $L \leq$ 30 m
- Minimum aspect ratio, $W / L \geq 1/3$*
- Minimum wing width, mw = 6 m
- Minimum cutout width, mc = 3 m

* *For L-shaped building plans, L is always longer than W. For T- and C-shaped building plans, W and L are taken as the shorter and longer of the overall building dimensions respectively.*

Each building configuration is then analyzed using SMTSA for CM for 1-, 2-, and 3-story structures. Once the required wall length, l_r, in each direction is calculated for the entire sample size of 1-3 stories, an utilization ratio, U_i, is calculated as follows:

$$U_i = \frac{l_r}{\alpha_i * l_{ai}} \quad (3\text{-}19)$$

Where:

α_i = factor to increase allowable wall length to include both interior and exterior walls = 1.50*

l_a = available total wall length parallel to direction of loading at the perimeter of the structure (see Figure 3-5)

* *α_i is calibrated from the five school building designs used in the prototypic study. It is calculated as the ratio of total wall length to the perimeter wall length (including openings). The school designs are taken for the value since typically schools have more open area to have more area for classrooms. Therefore, the wall density for school buildings are less than other building types. The value was calculated as 1.81, but reduced to 1.50 for a further safety factor.*

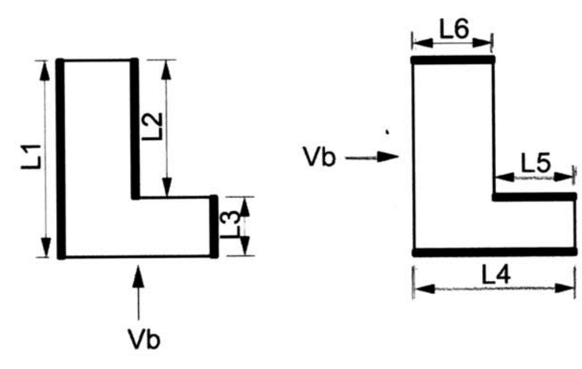

Figure 3-5: Wall Length Utilization Illustration (Left – Vertical Load Direction; Right – Horizontal Load Direction)

Visualization of the results will be used to search for significant relationships in the design space regarding the different sets of parameters. The data is visualized using different techniques for the exploration of the design space. The following flow of analysis and visualization is used for each building typology and height range of 1-3 stories:

1. Scatter plots of the utilization values in the horizontal and vertical loading direction are used first to assess the influence of the increased seismic demand in taller buildings.
2. Histograms illustrate the density distribution of utilization values for each story and loading direction.
3. Parallel coordinate graphs illustrate the relationships between the parameters that characterize the building plan. The graphs are separated depending on the primary length (the greatest overall length), where L-, T-, and C-Shaped building plans can have $L > W$, while only T- and C- shaped building plans have configurations where $W > L$. The samples that fail the utilization ($U_i > 1$, i.e. collapse) are superimposed in black to the sample size to determine the ranges of parameters that cause collapse.
4. The samples in the region of primary lengths that fail the utilization check are separated and analyzed in further detail. The samples in the region of primary lengths that always pass are not of concern. As long as the geometric constraints for building plan configuration described above are followed, the building will not collapse as long as it is constructed properly. The ranges are separated in equal intervals. Parallel coordinates of each interval is studied independently to find ranges of the secondary parameters that pass the utilization check to help develop design guidelines. This will be illustrated further in the following chapter.

5. Design guidelines are developed based on values of the primary length for each of the secondary paramters.

3.3 Material Study

In addition to considering the influence of geometric parameters on the capacity of a structure to resist seismic loads, a parametric study is conducted to examine the effect of the most important parameters: wall thickness and masonry compressive strength.

Nine representative samples for each building typology are chosen considering the best to worst preforming building plans based on the sum of utilization ratios in each loading direction:

$$U = U_h + U_v \qquad (3\text{-}20)$$

For each of these nine samples, the building height was set to be 3-stories. Then wall thicknesses and masonry compressive strengths were varied. The parametric study will enable a more general understanding of the influence of material parameters that vary over a wide range depending on the site. For example, the average compressive strength used in the study for the context of Kathmandu Valley, Nepal (4 MPa; Guragain, 2012; Maharjan, 2016) is much higher than the average compressive strength found in Gujarat, India (1 MPa; Porst, 2015).

The wall thickness will vary from a half brick thickness (0.115 m) with increments of half brick thick up to seven bricks thick (1.61 m). Although a seven brick thick wall is impractical in industry, the wide range will allow a better understanding of the wall thickness' influence on the structure's capacity. In order to sample a wide range of brick strengths found in different developing countries, the compressive strength for each sample building configuration will vary from 1 MPa to 10 MPa in 1 MPa intervals.

Scatter plots of the max utilization value of the horizontal and vertical loading direction will be used to observe the influence of material parameters. Upper and lower bounds corresponding to the least and most optimal building plan configurations respectively are fitted to the utilization data points.

3.4 Prototypic Study

In order to address the school sector, a prototypic study is performed by applying SMTSA for CM on five approved school building designs by the Department of Education (DoE) in Nepal. While the schools are of various material types (earth-bag, stone and mud, reinforced concrete frame with brick infill, etc.), the prototypic study will focus on the architectural features of the school (overall dimensions, locations of doors and windows, wall thickness, etc.) and analyze these schools as CM structures. School buildings in Nepal typically have rectangular plans and are symmetrical, with the building height ranging from 1 to 2 stories. Therefore, the prototypic study will focus on the irregularities caused by the door and window openings in the walls of the school designs that affect the required wall lengths in each direction.

Next, the designs will be compared when a reduced wall thickness is used to optimize cost effectiveness. The wall will be reduced to half a brick thick (0.115 m). Even though a building with a half brick thick wall may be impractical in reality due to gravity load capacity contraints and thermal comfort, the small thickness will illustrate the minimum building capacity for a CM school.

The following assumptions are made for the case studies:

- The material and seismic parameters are the same as the irregular building configuration study, unless otherwise noted
- Eccentricity only occurs in the y-direction, as school buildings are symmetrical along the y-axis
- Concrete roof slab*

- Masonry wall thickness is a half brick thick for comparison, $t_w = 0.115$ m
- Importance factor, $I = 1.5$ (NBC 105: Table 8.1)

* *Even though corrugated steel roofs are typically used in school buildings, a concrete roof slab is assumed as it is heavier per square meter and provide rigid diaphragm behavior. A corrugated metal roof can exhibit rigid diaphragm behavior as well with the design of a robust tie beam at the roof level to avoid out-of-plane failure and reduce the seismic weight of the school.*

The five school designs were obtained from the following organizations: National Society of Earthquake Technology (NSET), Edge of 7 (Eo7), Kids of Kathmandu (KoK), ABARI, and the Asian Development Bank (ADB). The architectural layout of each of the school designs can be found in the Appendix 7.1. The analysis is performed using the parameters shown in Figure 3-6:

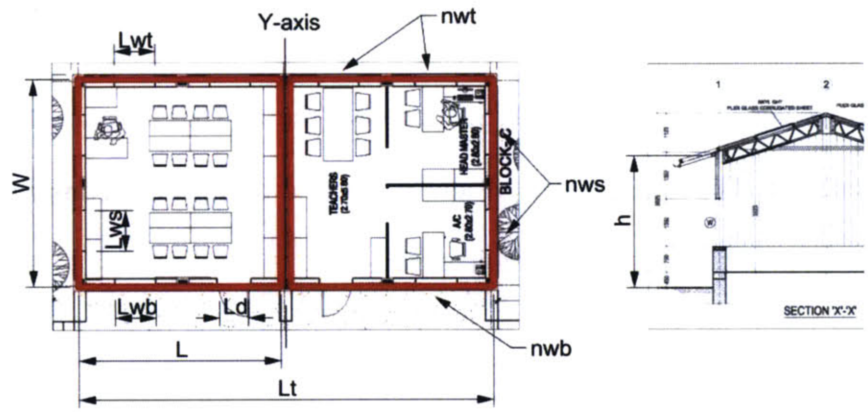

Figure 3-6: Parameters for the Prototypic School Case Study (School Design Shown by ADB)

The school designs will be simplified as being constructed out of classroom modules, outlined in red as shown in Figure 3-6. The remaining parameters used for the simplified analysis are listed in Table 3-2.

Table 3-2: Prototypic School Case Study Parameters

Parameters	Variables	School Designs				
		NSET	Edge of 7	Kids of Kathmandu	ABARI	ADB
No. of Modules	*nm*	4	2	2	2	2
No of Stories	*n*	1	1	1	1	1
Story height	*h*	2.8	2.3	2.7	2.5	3.5
Module Length	*L*	5.0	6.8	4.6	7.4	6.2
Module Width	*W*	7.6	6.4	5.9	6.8	6.4
No. of Side Windows	*nsw*	3	0	0	0	2
No. of Bot. Windows	*nbw*	0	1	2	1	1
No. of Top Windows	*ntw*	2	2	1	2	2
Length of Side Windows	*Lsw*	1.2	-	-	-	-
Length of Bot. Windows	*Lbw*	-	1	0.6	1.2	1.2
Length of Top Windows	*Ltw*	1.5	1	2	1.2	1.2
Door Length	*Ld*	1.8	1	0.76	1.2	1
Floor Slab Thickness	*tf*	-	-	-	-	-
Ext. Wall Thickness	*tew*	0.35	0.45	0.30	0.40	0.35
Int. Wall Thickness	*tiw*	0.35	0.45	0.30	0.40	0.35

After the analysis is performed using SMTSA for CM, the utilization ratios for each loading direction are calculated. The original design and prototypic designs are compared to illustrate material savings while maintaining structural integrity.

3.5 Summary

This chapter outlined the Simplified Method for Torsional Seismic Analysis (SMTSA) for confined masonry and seismic base shear calculations for the context of Nepal, which is used for the geometric, material, and prototypic studies. The geometric study methodology outlines the process of generating various building configurations, geometric parameters, and visualization of the results for the development of design guidelines. The material study methodology outlines the selection of a representative sample size from the geometric study and visualization of the results where wall thickness and masonry compressive strength are varied. The prototypic study methodology summarizes the parameters used from the five school designs and the comparison between the original and prototypic designs to illustrate potential material savings while maintaining structural safety. These methodologies are crucial for understanding the results presented in the following chapter.

4 RESULTS AND DISCUSSION

This chapter reports and illustrates the results of the geometric, material, and prototypic studies outlined above.

4.1 Geometric Study

For each building typology (L-, T-, and C-shape building plans), utilization ratios for the horizontal and vertical loading direction (U_h and U_v) are calculated and used for visualization of results.

4.1.1 Solution Space

For an initial general observation, scatter plots of the utilization ratios for each typology for 1-3 story building heights are plotted to assess the influence of building height on seismic safety (see Figure 4-1 to Figure 4-3). The y-axis shows the utilization ratios for the vertical loading direction (U_y), and x-axis shows the utilization ratios for the horizontal loading direction (U_x). The boundary of passing values (U_i = 1) is plotted to distinguish between the data points of building configurations that pass (i.e. are safe) and fail (i.e. collapse).

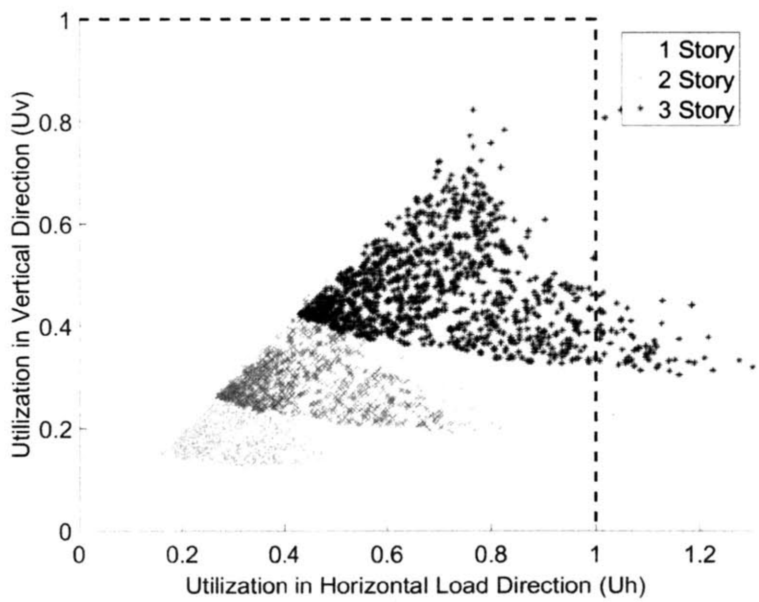

Figure 4-1: L-Shape Utilization Scatter Plot

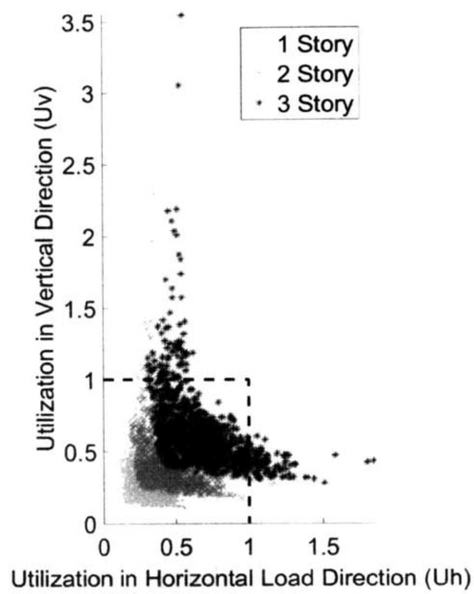

Figure 4-2: T-Shape Utilization Scatter Plot

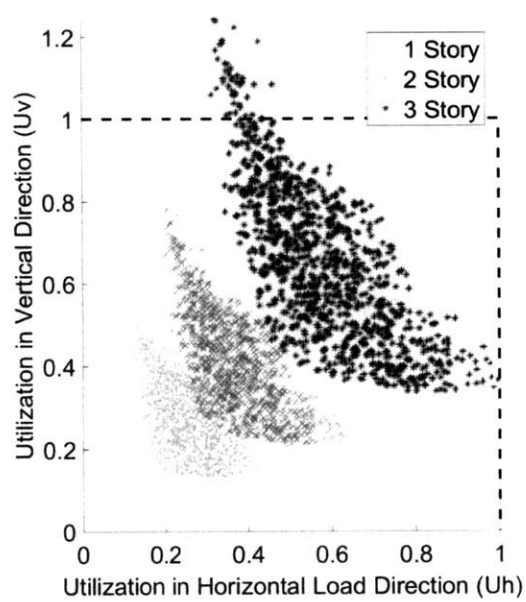

Figure 4-3: C-Shape Utilization Scatter Plot

In general, all of the 1-story building samples pass the utilization check. Also, very few 2-story T-shaped configurations collapse. However, a significant fraction of 3-story configurations for each building type collapse.

4.1.2 Solution Density and Distribution

Histograms are then plotted for a more detailed visualization of the utilization ratio densities. Utilization ratios for each building type are presented for each loading direction and number of stories (see Figure 4-4 to Figure 4-6). Values that fail (i.e. collapse with $U_i > 1$) are shown in dark gray.

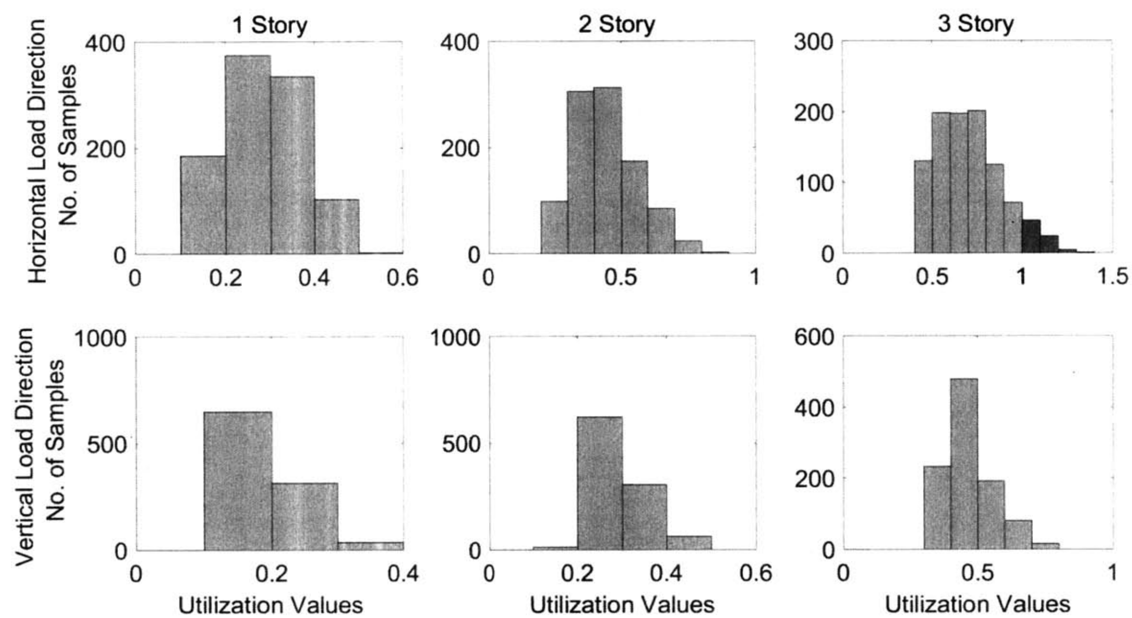

Figure 4-4: L-Shape Utilization Density Distribution of Building Configurations

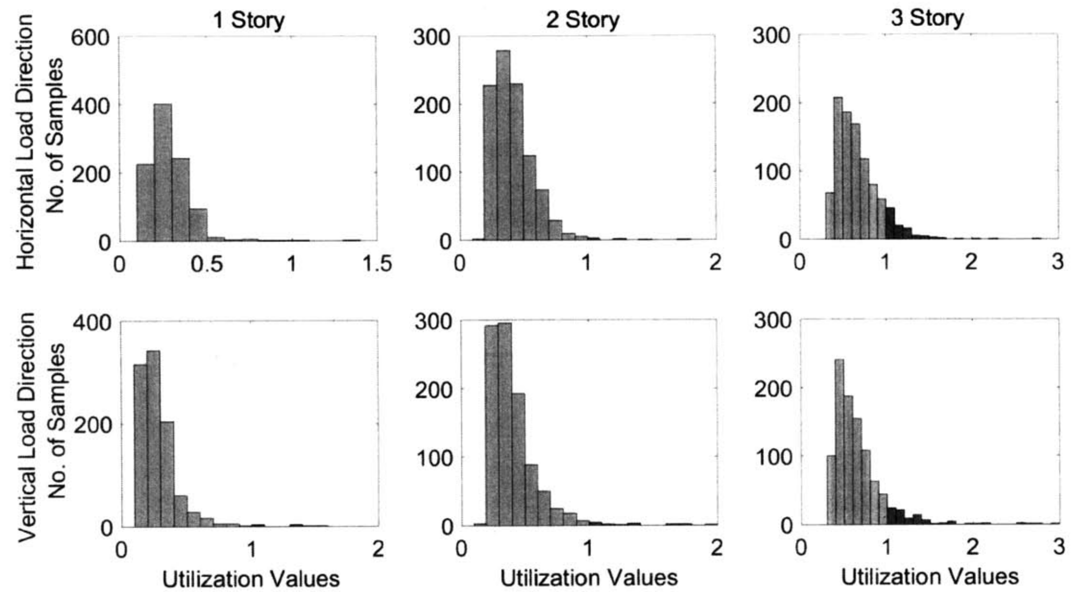

Figure 4-5: T-Shape Utilization Density Distribution of Building Configurations

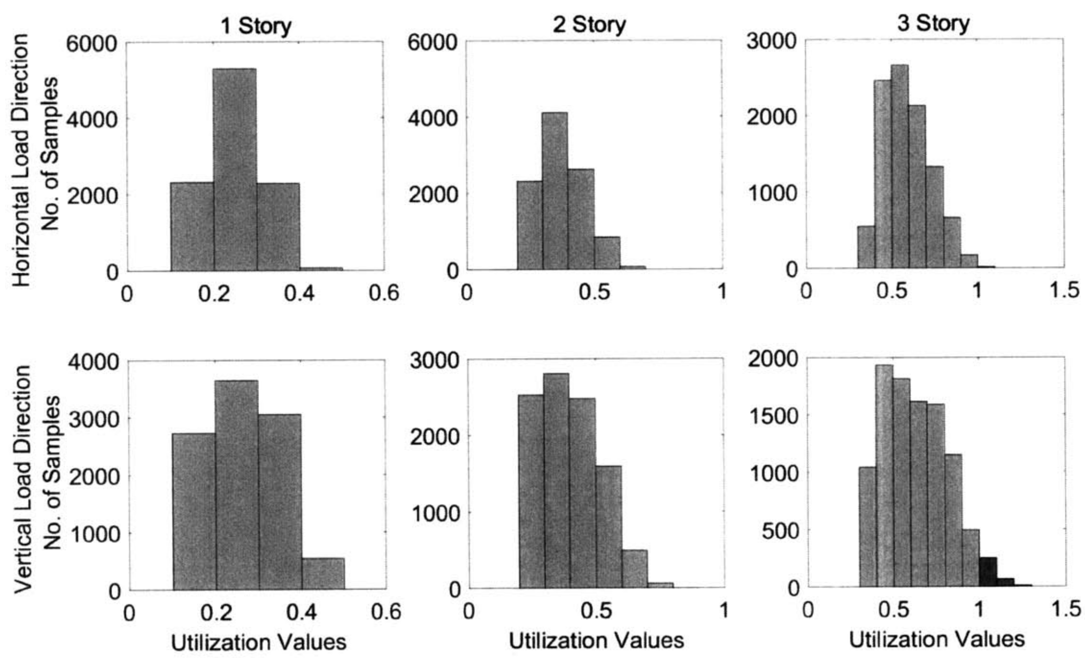

Figure 4-6: C-Shape Utilization Density Distribution of Building Configurations

As seen before, collapse is likely to happen when the building is 3-stories high. Few of the 1- and 2-story T-shaped building configurations are likely to collapse as well. For L-shaped buildings, all of the collapse happens in the horizontal loading direction. This intuitively makes sense since the primary length is always *L*. Therefore, the total length of horizontal walls (see Figure 3-5: Wall Length Utilization Illustration (Left – Vertical Load Direction; Right – Horizontal Load Direction)Figure 3-5: right) are usually always less than the vertical walls (see Figure 3-5: left). For T-shaped configurations, both loading directions have a significant amount of samples with utilization ratios that fail. C-shaped buildings only fail in the vertical loading direction. This is probably also due to the cutout dimensions that describe a C-shaped plan, where the total length of walls in the horizontal direction is more than the vertical walls.

4.1.3 Influence of Geometric Parameters

Parallel coordinate plots illustrate the combination of geometric parameters that describe the building plans for each of the building typologies shown in Figure 3-2. For example, Figure 4-7 illustrates an example of a single combination of parameters that describes an L-shaped building plan.

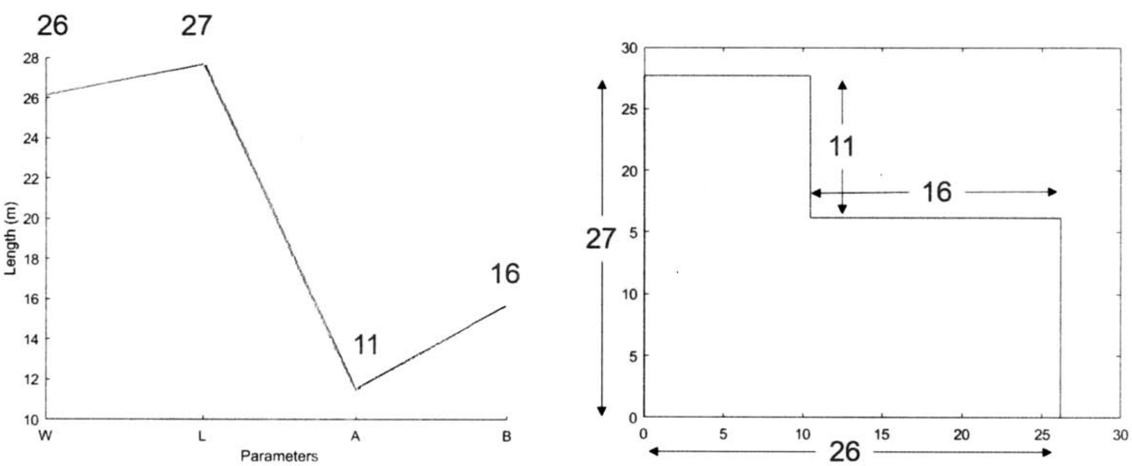

Figure 4-7. Geometric Parameter Description of L-Shaped Building Plan Illustrated as a Parallel Coordinate Graph

The samples are separated based on their primary lengths (overall plan dimension that is longer, *L* or *W*) to better understand influences of the geometric parameters. L-shape building plans only have *L* as the primary length (*L* > *W*), whereas T- and C- shaped building plans can have either *L* graph in gray and configurations that collapse are superimposed in black to visualize the contrast (see Figure 4-8 to Figure 4-12).

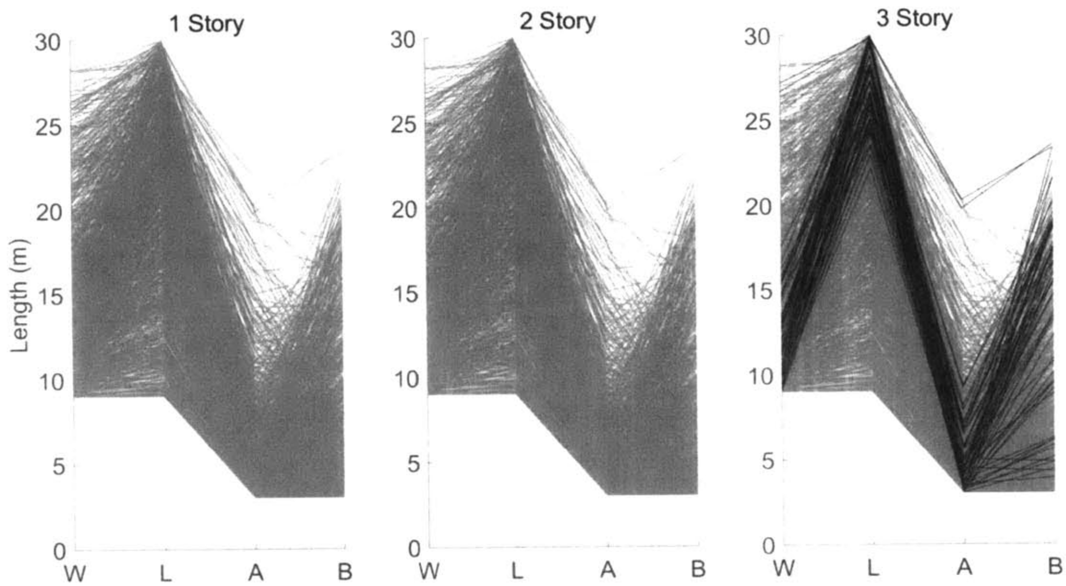

Figure 4-8: L-Shape Parameter Distribution (Grey – All Combinations; Black – Failing Combinations)

Note that 1- and 2- story L-shaped building plan configurations always. For 3-stories, L-shaped building plans have a range of L values that do not have any failing samples. In other words from Figure 4-8, for lengths of L up to approximately 22 meters, any configurations of W, A, and B will have sufficient shear resistance in an event of an earthquake in Nepal as long as the geometric constraints outlined in Section 3.2 are followed.

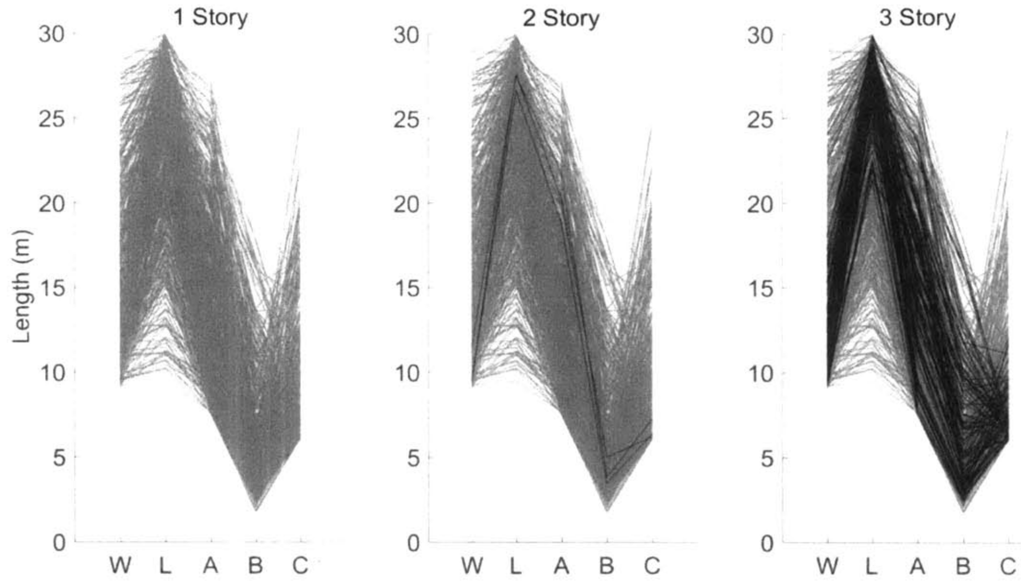

Figure 4-9: T-Shape (L > W) Parameter Distribution (Grey – All Combinations; Black – Failing Combinations)

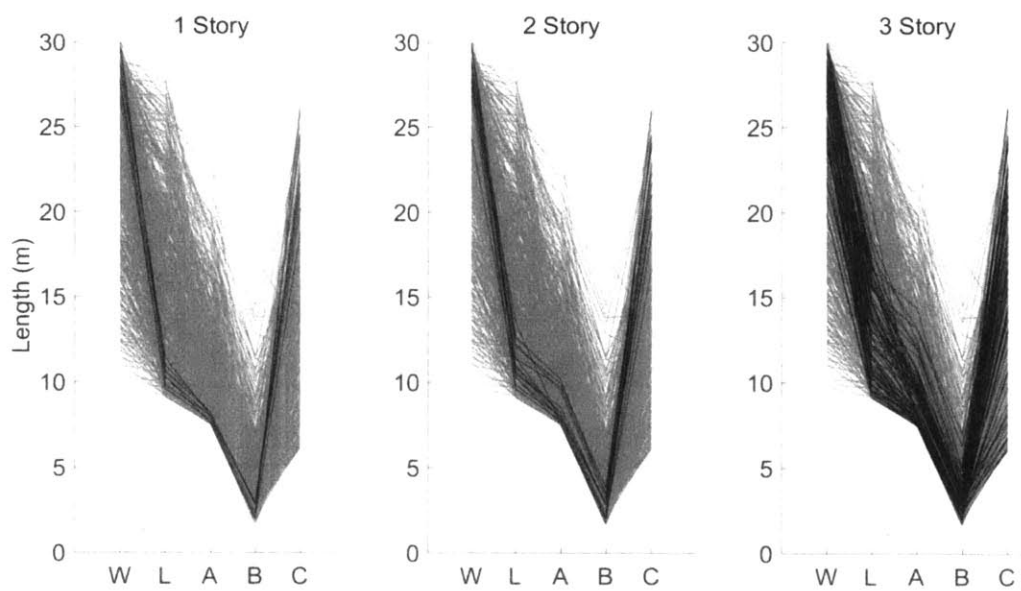

Figure 4-10: T-Shape (W > L) Parameter Distribution (Grey – All Combinations; Black – Failing Combinations)

Very few samples experienced collapse for 1- and 2-storty buildings with T-shaped plans (refer to Figure 4-9 and Figure 4-10). A significant amount of samples collapsed for 3-story structures. Similar to L-shaped buildings, there is a range of the primary lengths (*L* or *W*) that always pass, which allows for any configuration of the secondary geometric parameters (*W* or *L*, *A*, *B*, and *C*)

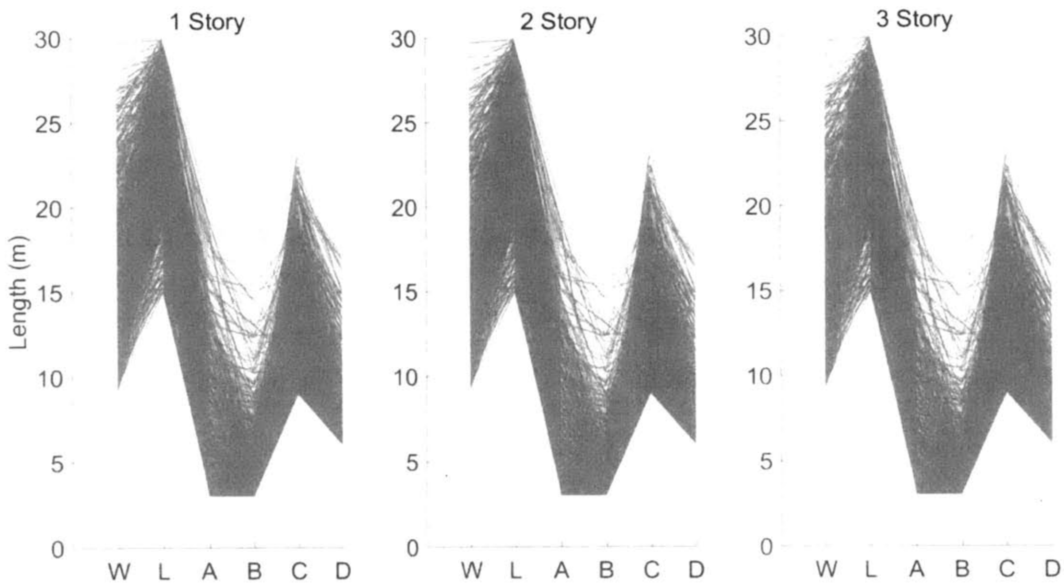

Figure 4-11: C-Shape (L > W) Parameter Distribution (Grey – All Combinations; Black – Failing Combinations)

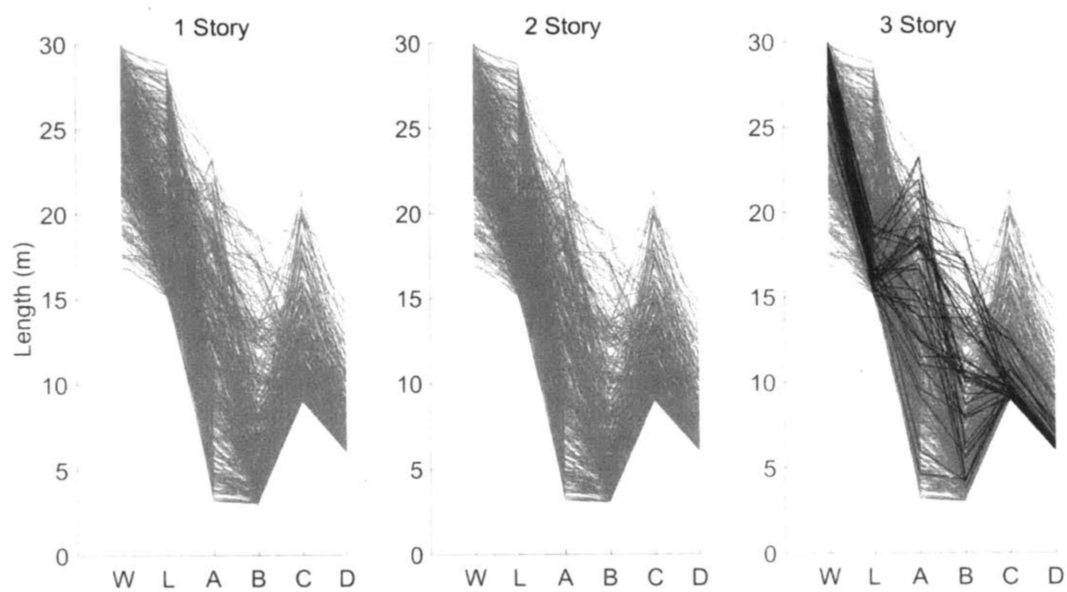

Figure 4-12: C-Shape (W > L) Parameter Distribution (Grey – All Combinations; Black – Failing Combinations)

C-shaped building plans have failing sample configurations only for 3-story buildings with *W* as the primary length. Again, there is a range of *W* values that will always will have sufficient shear capacity as long as the geometric constraints are satisfied.

4.1.4 Proposed Design Guidelines

For the development of the design guidelines, the focus is on the 3-story building types that have a significant amount of failing samples: L-shaped, T-shaped with both L and W as primary lengths, and C-shaped with W as the primary length. The range of primary lengths that have overlapping passing and failing configurations are the focus of the design guidelines. Anything out of that range of primary lengths can have any combination of the remaining geometric parameters as long as they satisfy the geometric constraints outlined in Section 3.2.

The range of primary lengths that have passing and failing configurations overlap are separated in different interval lengths of 0.5 meters from the minimum value that fails to the upper bound of 30 meters. From each interval, there is a range of the secondary length (L or W) that always passes. For example, in the case of 3-story L-shaped buildings, there is a maximum value of the secondary length, $W \sim 12.5$ meters, for the given interval of the primary length, $L = 23.9 - 24.4$ meters, that causes collapse (see Figure 4-13). Therefore, the range above the maximum failing value of the secondary length ($W = 12.5 - 22.5$ meters) is the allowable range for the length of the secondary parameter within the interval of the primary length, L.

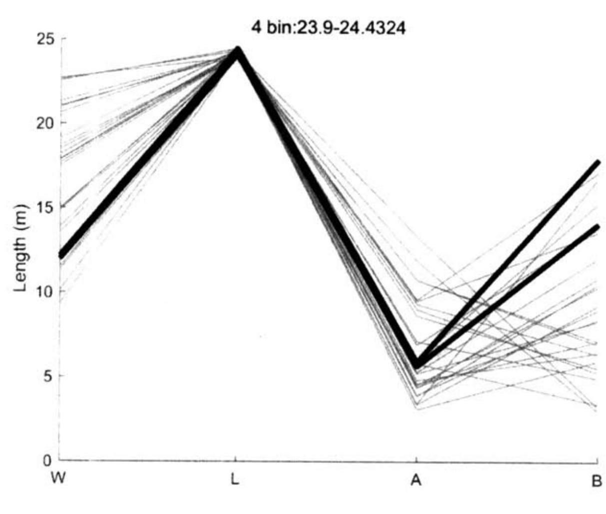

Figure 4-13: Design Guideline Formulation Illustration

The range of lengths for configurations of the remaining geometric parameters are extracted to provide an allowable range for the respective interval of the primary length. Design guidelines based on the primary lengths for each building category are developed and plotted graphically to appropriately choose the remaining geometric parameters which provide sufficient building capacity. Figure 4-14 to Figure 4-17 illustrate the proposed design guidelines for the building categories described above in the context of Nepal. The top line is the maximum bound for allowable values of the secondary parameters, while the bottom line is the lower bound.

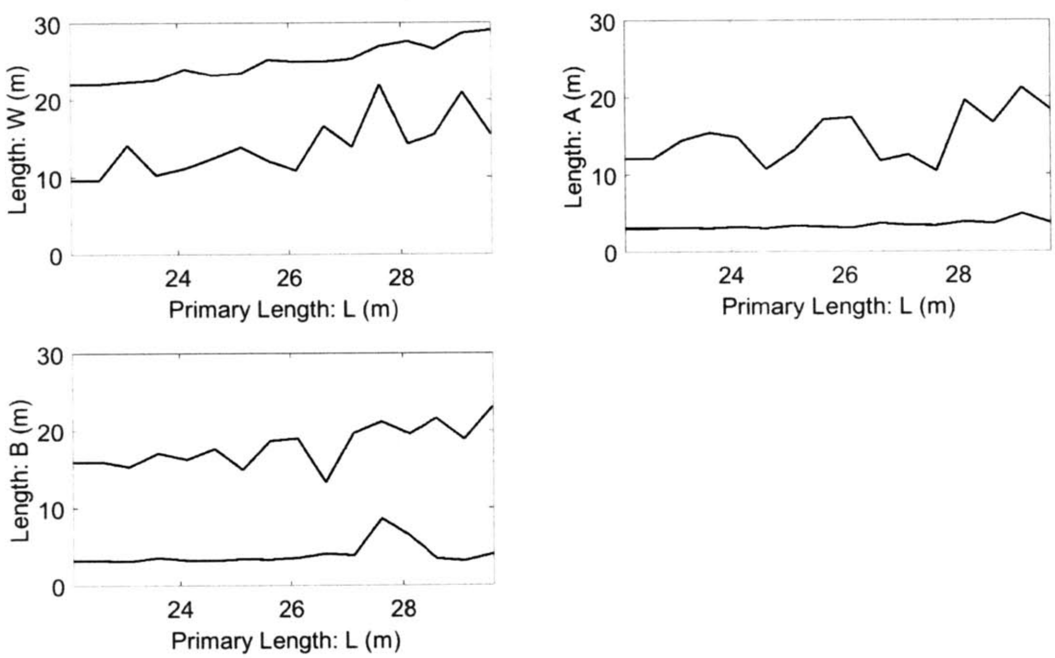

Figure 4-14: L-Shape Design Guideline, Primary Length: L

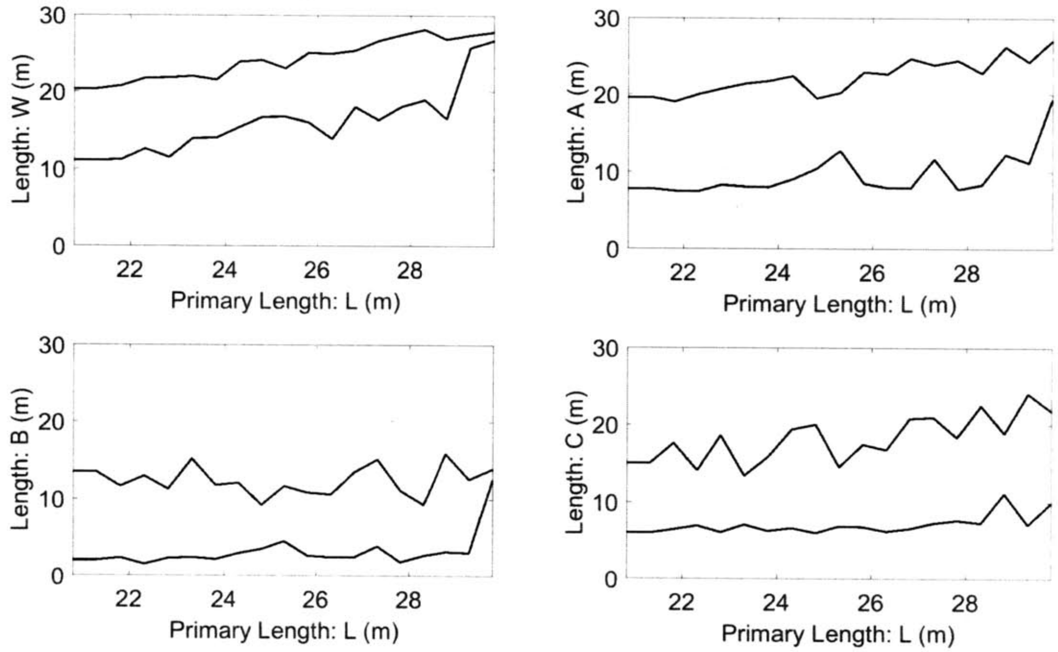

Figure 4-15: T-Shape Design Guideline, Primary Length: *L*

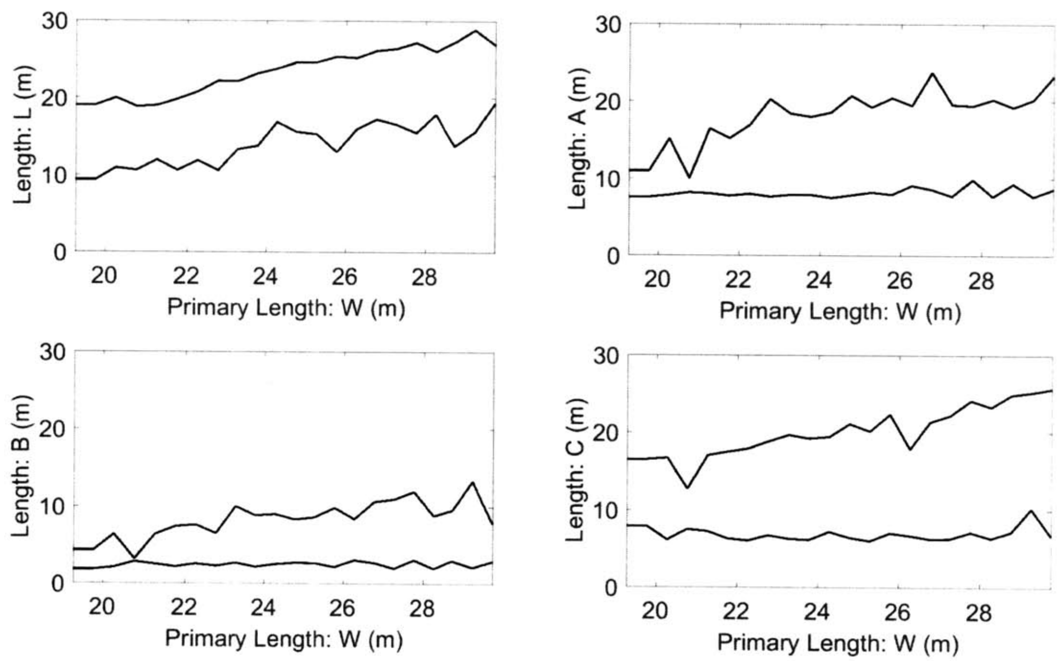

Figure 4-16: T-Shape Design Guideline, Primary Length: *W*

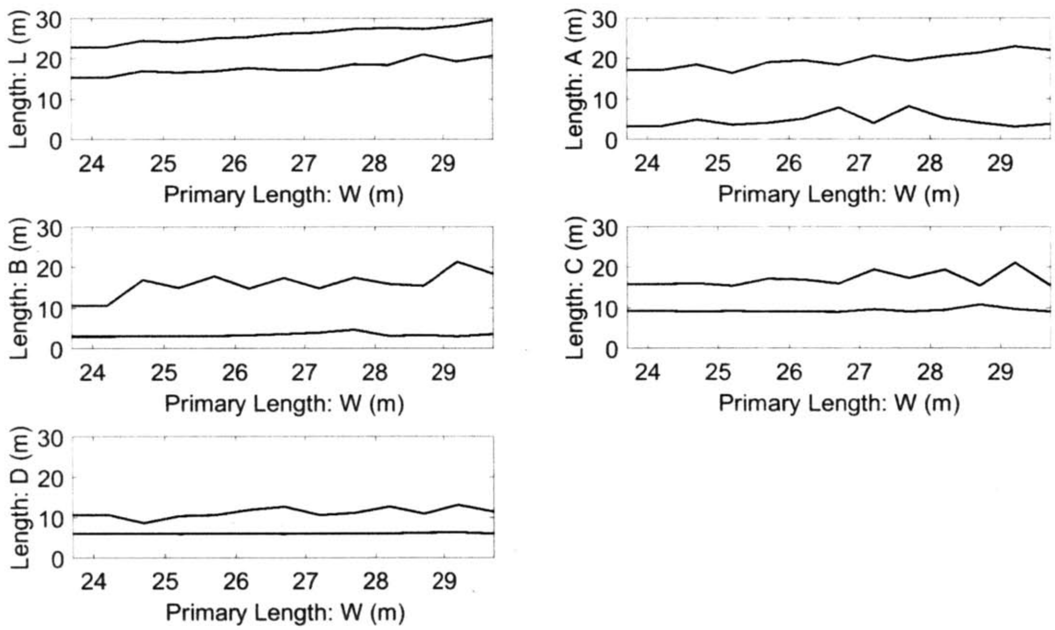

Figure 4-17: C-Shape Design Guideline, Primary Length: *W*

4.2 Material Study

The results of the seismic analysis for the representative sample size chosen from the geometric study is illustrated below.

4.2.1 Sample Configurations

The nine representative configurations for each building typology are illustrated in Figure 4-18 to Figure 4-20 from best to worst performing building plans. Each building configuration is analyzed as a 3-story building. For each building plan, the maximum utilization ratio (either for the horizontal or vertical loading direction) is listed underneath each plan shape for a reference.

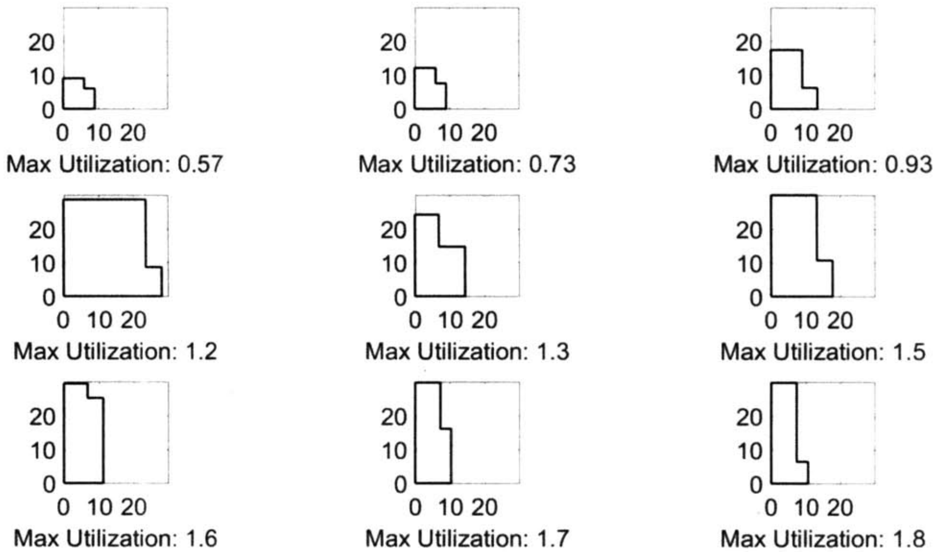

Figure 4-18: L-Shape Sample Representative Configurations for Material Study

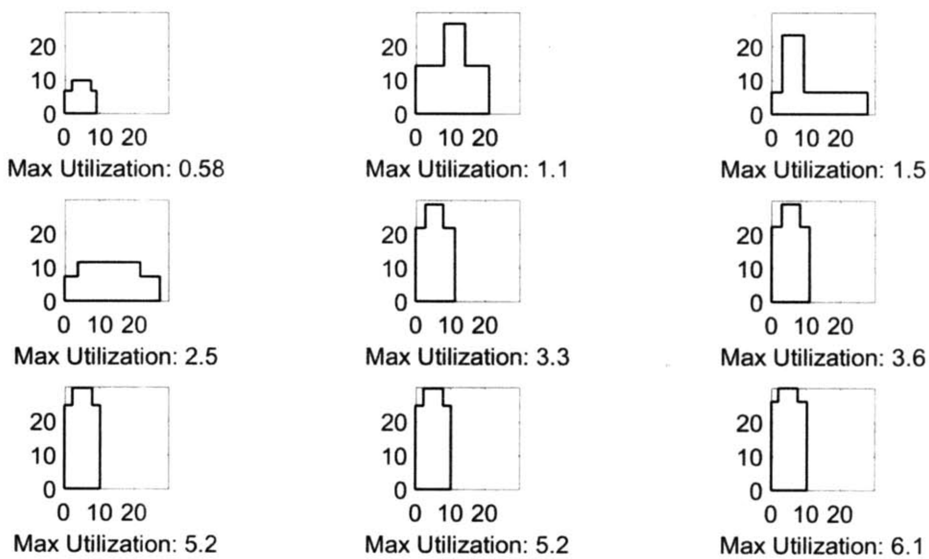

Figure 4-19: T-Shape Sample Representative Configurations for Material Study

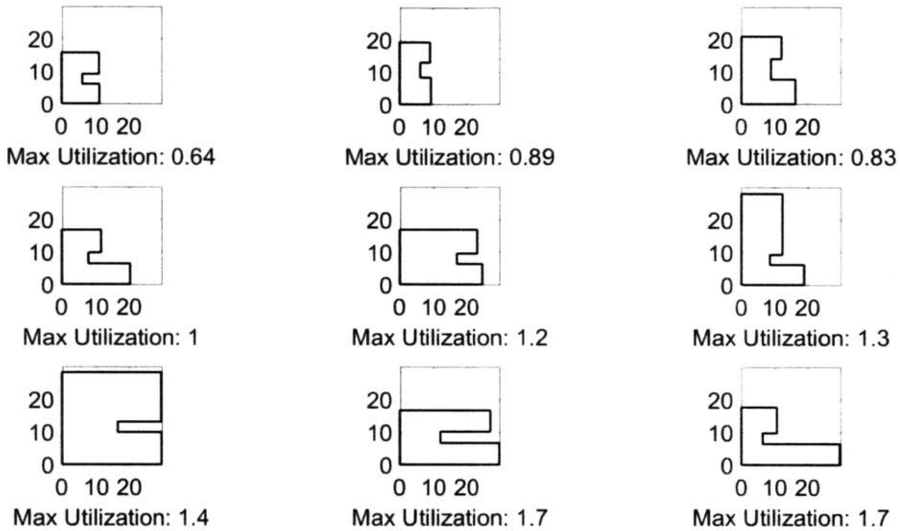

Figure 4-20: C-Shape Sample Representative Configurations for Material Study

From the graphical representation, the shapes for each typology that are most compact perform superior to plan shapes that are elongated.

4.2.2 Wall Thickness

With the geometric parameters now set constant, the wall thickness is increased from 0.115 meters (half-brick thick) to 1.61 meters (seven bricks thick) in increments of half bricks. Utilization ratios for each configuration are calculated using SMTSA for CM for each wall thickness. The data is then plotted in scatter plots for visualization (see Figure 4-21 to Figure 4-23).

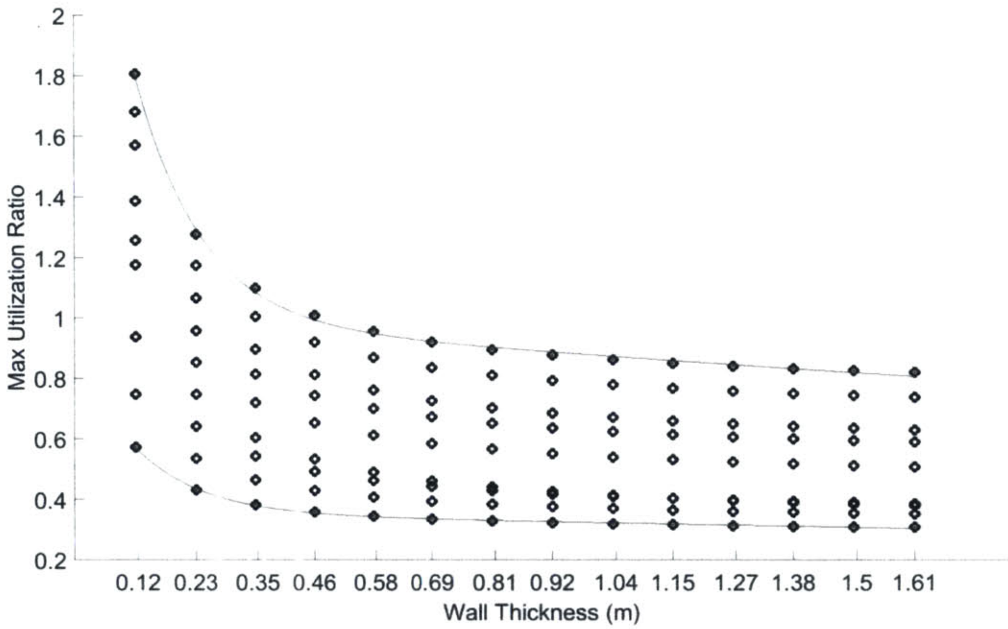

Figure 4-21: L-Shape Maximum Utilization vs Wall Thickness

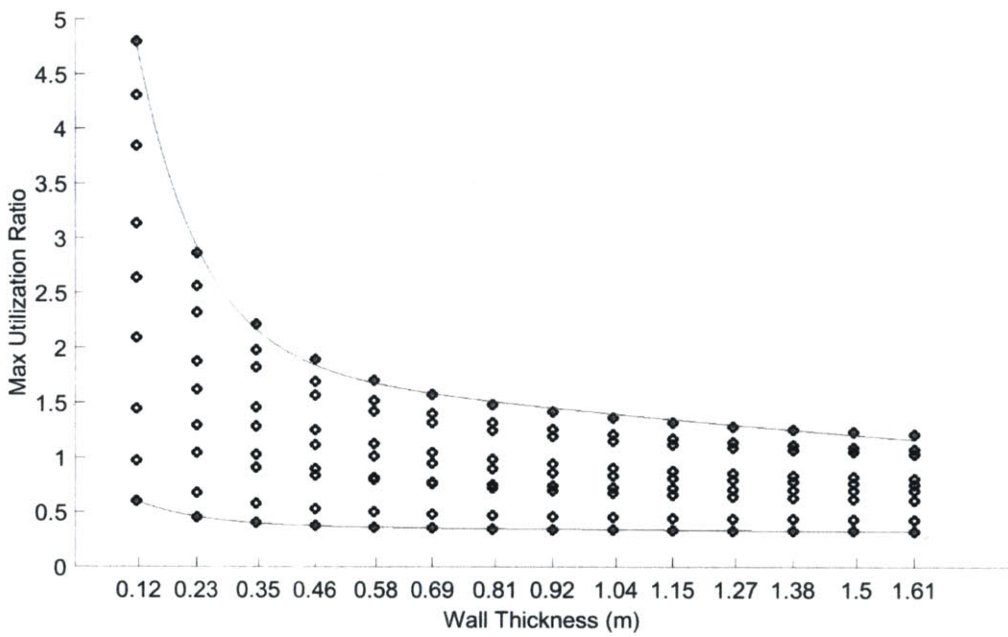

Figure 4-22: T-Shape Maximum Utilization vs Wall Thickness

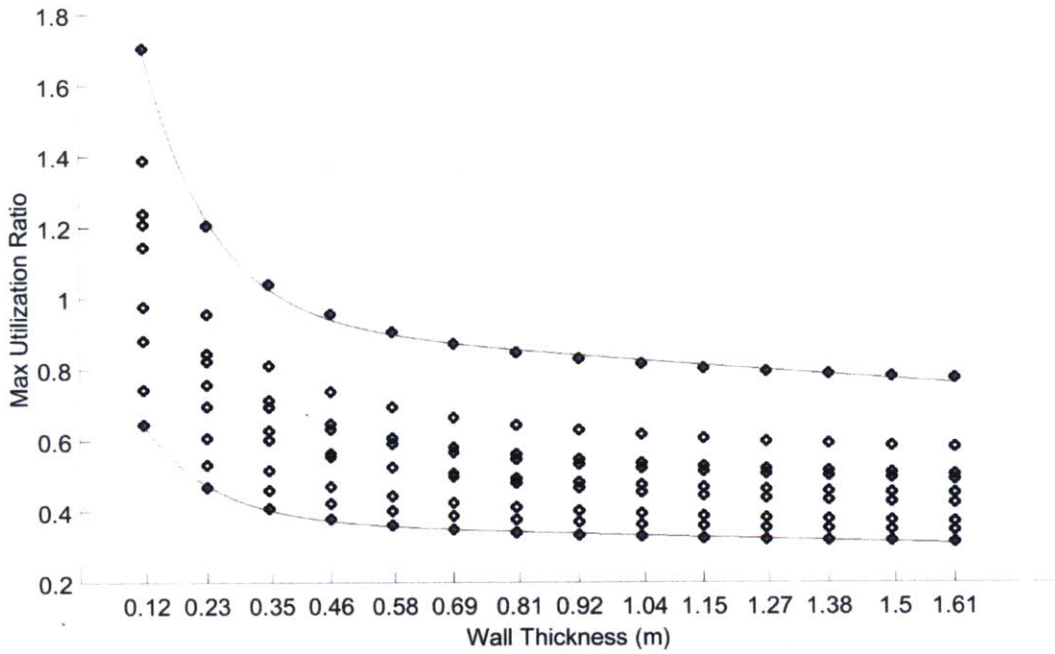

Figure 4-23: C-Shape Maximum Utilization vs Wall Thickness

Data bounds were fitted using a two-term exponential fitting function in Matlab. The top line is the upper bound for the utilization ratio of the worst building configuration as the wall thickness increases, while the bottom line is the lower bound for the best building configuration. For each building typology, there is a "diminishing return" for an increase of wall thickness. In other words, there is a huge improvement of utilization ratios when wall thickness is increased from 0.115 meter (one brick thick) to 0.230 meters (two bricks thick), while there is a much less significant improvement from 0.460 meters to 0.69 meters (three bricks thick). Furthermore, the percentage of increase is higher for the worst than the best configurations. This explains that optimization of the geometric layout of the building will allow for a higher performance without necessarily having to increase the wall thickness. Finally, there is a sort of asymptote on the building's utilization ratio as the wall thickness keeps increasing. This trend is due to the fact that a thicker wall contributes more to the seismic weight of the structure, which in turn increases the seismic base shear of the building. Therefore, there is a lowest possible value for the utilization ratio for a certain building configuration.

4.2.3 Compressive Strength

As in the wall thickness variation, the masonry compressive strengths is varied for each of the representative building configurations and each building typology. The compressive strengths are varied from 1 to 10 MPa in increments of 1 MPa. These values are chosen to simulate the same building in different countries. For example, Porst (2015) tested brick strengths in Gujarat, India, which showed low masonry strengths of around 1 MPa. However, in Nepal bricks have higher strengths in the range from 7-10 MPa (Guragain, 2012; Maharjan, 2016). The data for each compressive strength is plotted on the following scatter plots similar to the wall thickness study (see Figure 4-24 to Figure 4-26).

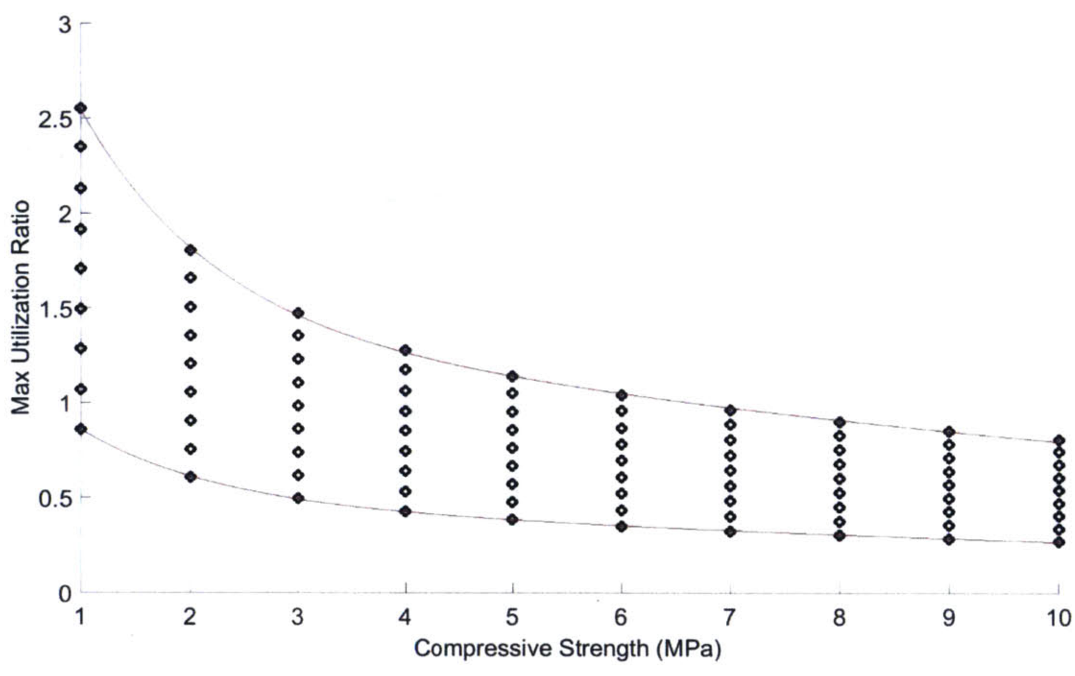

Figure 4-24: L-Shape Maximum Utilization vs Masonry Compressive Strength

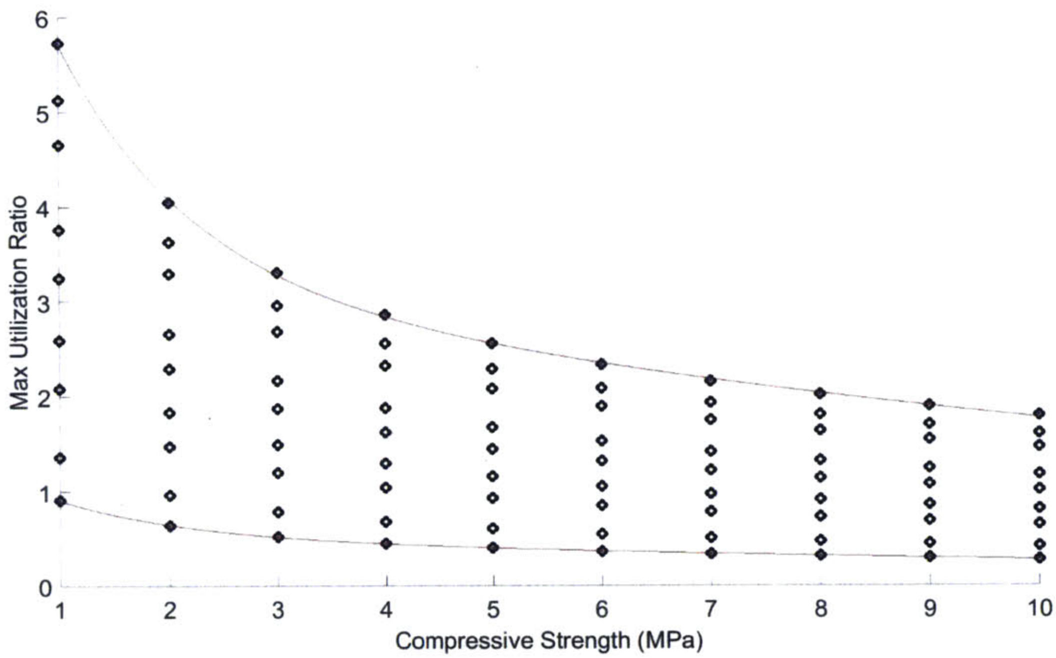

Figure 4-25: T-Shape Maximum Utilization vs Masonry Compressive Strength

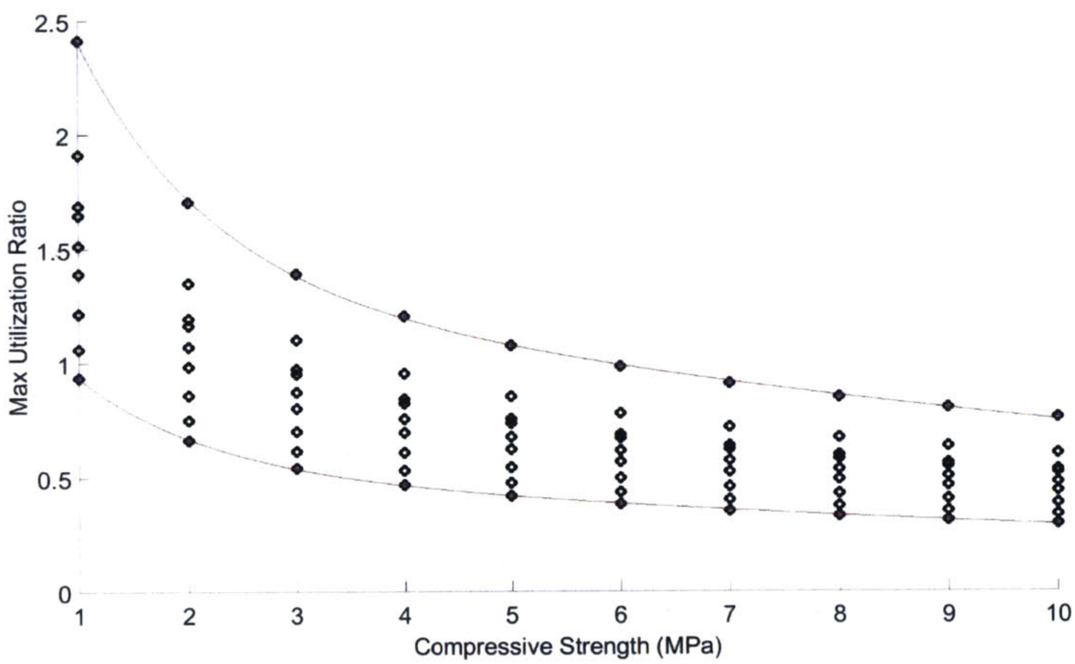

Figure 4-26: C-Shape Maximum Utilization vs Masonry Compressive Strength

Patters for the wall thickness variation are similar as the masonry compressive strength increases. There remains the "diminishing return" and a lower bound for the maximum utilization ratio with increasing strength. Also, the amount of improvement is less in less optimal building configurations for the same amount of increase in masonry compressive strength. This trend further places importance on building configuration.

4.3 Prototypic Study

Five school designs approved by the Nepal Department of Education are analyzed using the SMTSA for CM to calculate the utilization ratios in both loading directions. While school buildings in Nepal are typically rectangular-shaped and symmetrical, eccentricities of the building exist because of the exterior door and window openings. The results of both original school designs (light crosses) and prototypic school designs (dark circles) with a reduced wall thickness of 0.115 meters are illustrated below. The utilization ratios of both loading directions are visualized using the scatter plot in Figure 4-27.

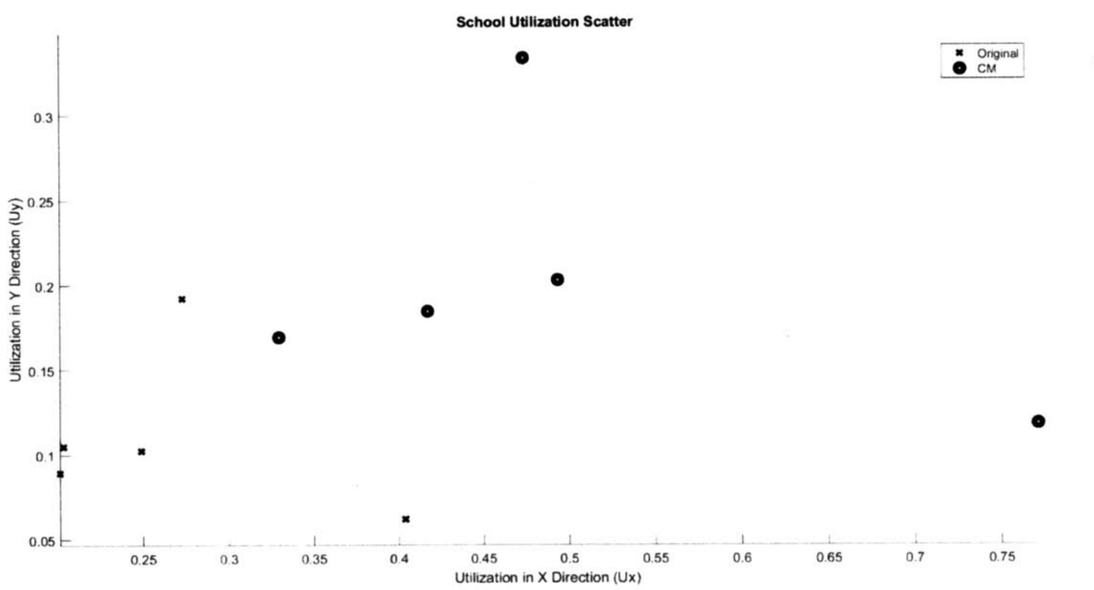

Figure 4-27: Prototypic School Comparison

As expected, the prototypic school designs all have higher utilization ratios in both directions (refer to Section 4.2.2). However, the least performing prototypic design has a maximum utilization of under 80% of its shear capacity. For the building with the thinnest walls (0.3 meters thick) for Kids of Kathmandu's school design, the prototypic design saves 50% of material in the wall alone while remaining to perform satisfactory. Since school designs with only half brick wide walls are impractical, the schools would be built with at least one brick thick (0.230 meters). Even so there is still a 23% material savings. Therefore, CM construction with thinner walls would provide better economic and structural performance than the current school designs.

4.4 Summary

This chapter reports the results from the geometric, material, and prototypic case studies. The geometric study provides an understanding of the geometric influences on the shear capacity of irregular building plans. Furthermore, simple guidelines are provided for 3-story structures of each building typology for the context of Nepal. Depending on the location where seismic and material parameters change, the method can be used by changing the respective parameters to generate such guidelines. The material study shows the influence of wall thickness and masonry compressive strengths on the shear capacity of the structure. By varying both parameters, a "diminishing return" is observed for increasing the values of both wall thickness and masonry compressive strengths. Taking wall thickness as an example, the increase is much more significant from 0.155 – 0.230 meters than 0.460 – 0.690 meters. There is a sort of asymptote as well (minimum bound for utilization value given a set building configuration). Finally the prototypic study shows that CM construction is a viable low-cost solution that offers economic and structural benefits.

5 SUMMARY AND CONCLUSIONS

5.1 Summary

Confined masonry (CM) is a viable low-cost solution in the context of developing countries which are at a much higher seismic risk than developed countries. The reinforced concrete frames with masonry infills in CM construction act compositely to provide the lateral resistance in a building during an earthquake. Due to the composite action, CM behaves non-linearly and requires complex models for a "case-by-case" basis (Mohyeddin, 2013) to predict the behavior during a seismic event. However, simplified analysis methods that take into account building irregularities have been developed as a conservative and accurate alternative to the complex models for ease of implementation in a variety of situations.

The Simplified Method for Torsional Seismic Analysis (SMTSA) for CM (Porst, 2015; Brzev S., 2015; Guzmán and Escobar, 2010; Escobar, 2004; Escobar, 2008) is used to perform an extensive parametric study. This method is used in the thesis to understand the influence of geometric and material parameters for the shear capacity of CM structures. For the geometric, material, and prototypic studies, the following contributions have been made:

- Geometric – Building typologies of L-, T-, and C- shaped buildings are parameterized into geometric parameters that describe the building plan. Hundreds of parameter configurations are analyzed using SMTSA for CM to explore the influence of these parameters on the structure's shear capacity. Simple design guidelines based on the primary length of 3-story buildings for each irregular building typology are recommended for the context of Nepal. Because of the simplicity and ease of implementation of SMTSA for CM, the guidelines presented in this thesis can be used to adjust the relevant parameters for other countries.

- Material – A representative sample of building configurations from the geometric study, from the best to worst performing ones, are used to observe the influence of wall thickness and masonry compressive strength on the structure's shear capacity. The wide range of these two parameters addresses possible variation of these parameters in different countries. As expected, there is an improvement of structural performance when both parameters are increased, but there is a "diminishing return" when the parameters increase beyond certain values. Furthermore, there is a lower bound for utilization ratio for a certain building configuration. In other words, an infinite increase in either parameter converges to the minimum utilization ratio for a unique building shape. Lastly, the geometric influence affects the extent of improvement resulting from increasing the wall thickness and/or masonry compressive strength. In other words, an increase in either parameter increases improvement significantly for a poorly configured building plan much more than a properly configured building plan. Therefore, a designer must take into account the influence of geometric parameters for a CM structure, instead of solely increasing wall thickness and/or masonry compressive strength during design. An optimization of the building plan significantly plays an important role to keep material costs low.
- Prototypic – Five school designs approved by the Nepal Department of Education are analyzed with SMTSA for CM based on the architectural layouts. Then each design is analyzed with a half a brick thick wall (0.115 meters). While this reduces the shear capacity of the school buildings, the prototypic designs still performed satisfactory with the maximum utilization of less than 80% for the worst case. The reduced wall thickness saves at least 50% of material costs using half-brick thick wall and 23% for a one brick thick wall (0.230 meters). Therefore, schools constructed using CM technology have both economic

and structural advantages over alternative technologies such as RC frames with brick infills.

5.2 Future Work

Potential future work that could be done to build off the parametric studies done in this thesis are as follows:

- Exploration of other material parameters
- Further geometric exploration in addition to the ranges of parameters such as aspect ratios, etc.
- Prototypic studies on other types of buildings with irregularity in the building plans
- Development of proposed design guidelines for contexts in other countries and varying seismic regions
- Development of simple and quantitative design guidelines

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7 APPENDICES

7.1 School Designs

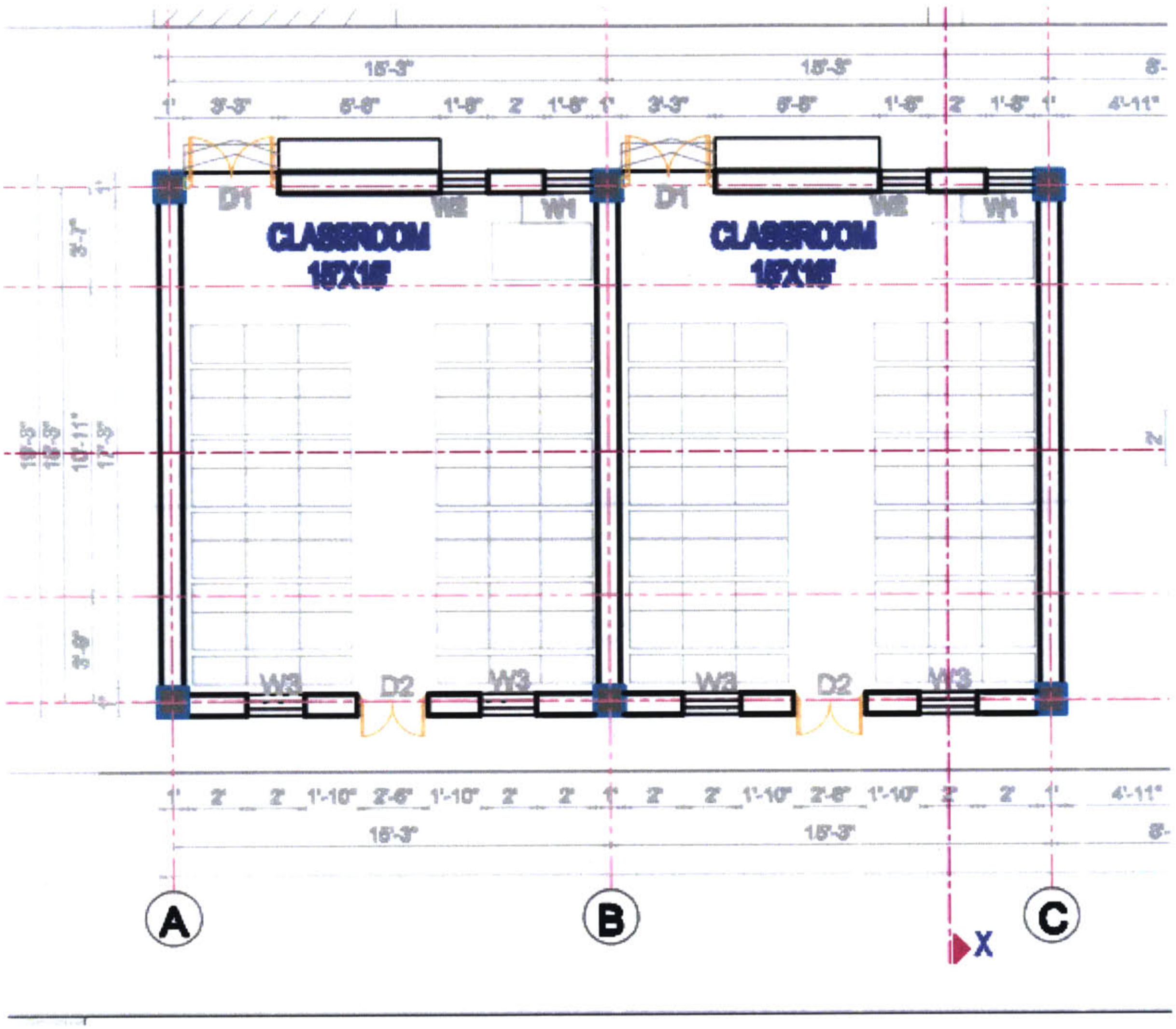


Figure 7-1: Kids of Kathmandu Plan

Figure 7-2: Kids of Kathmandu Elevation

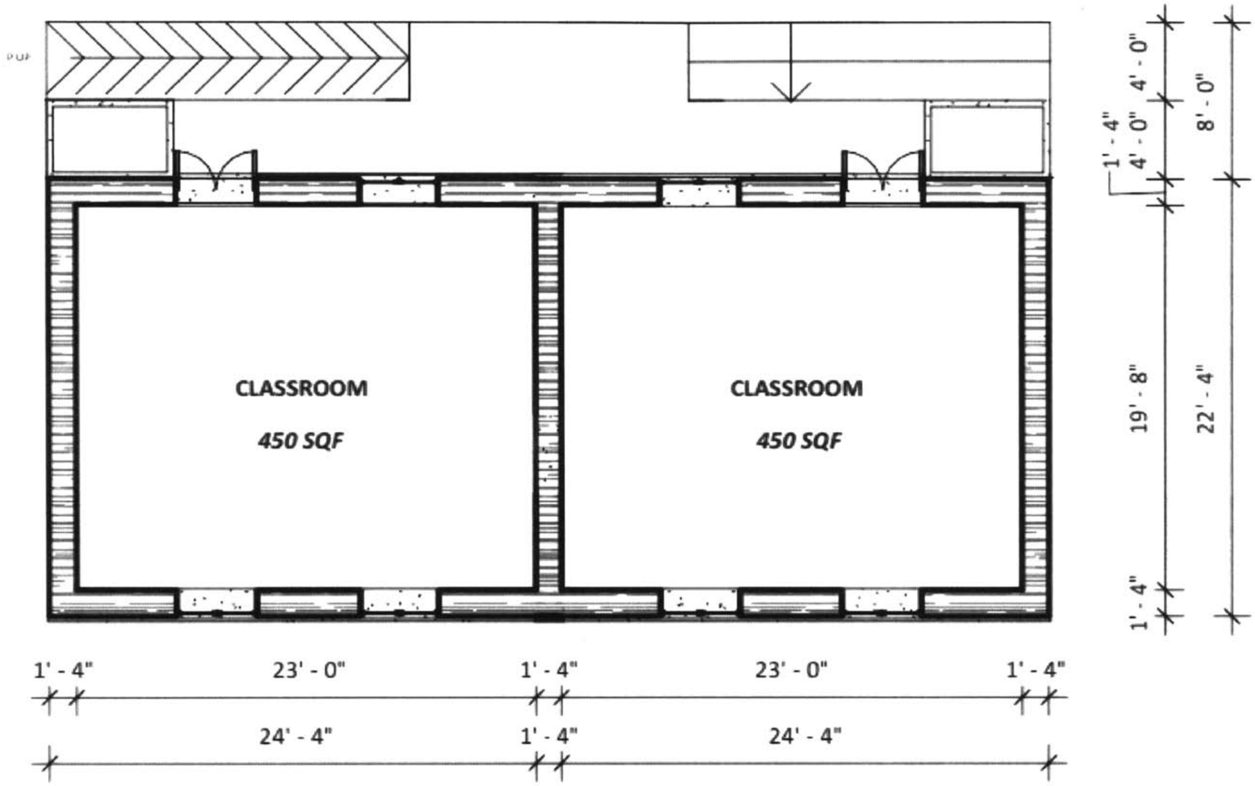


Figure 7-3: ABARI Plan

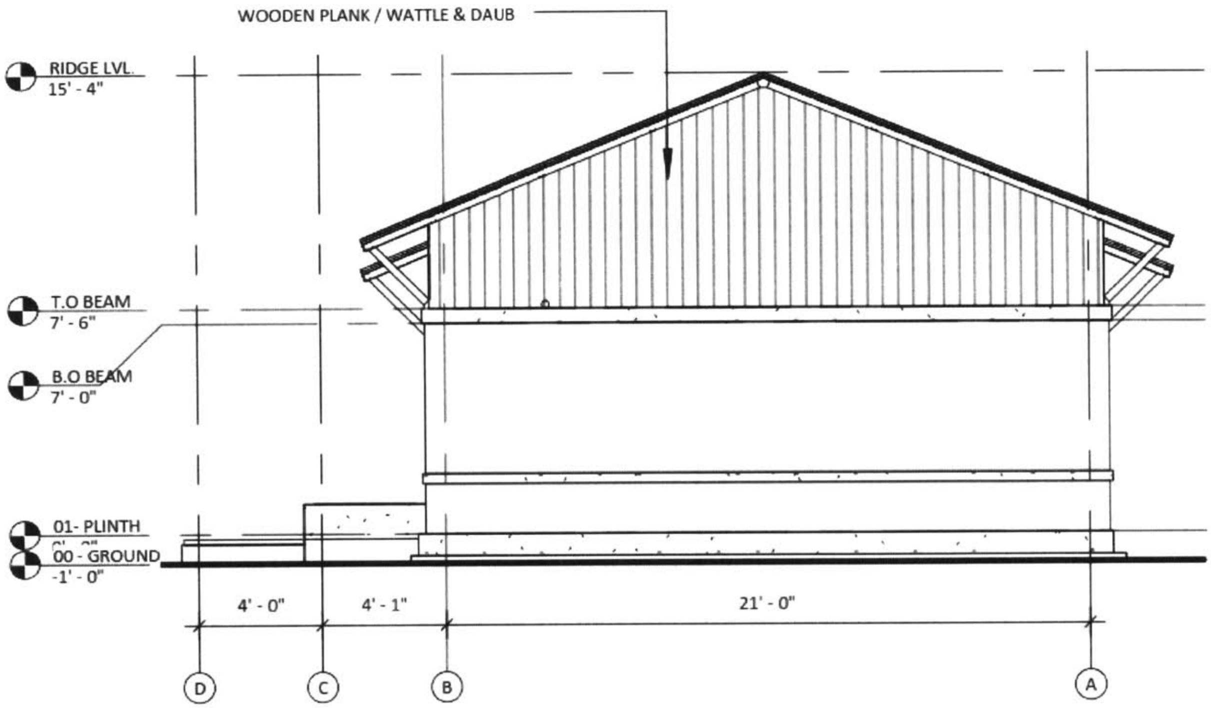


Figure 7-4: ABARI Elevation

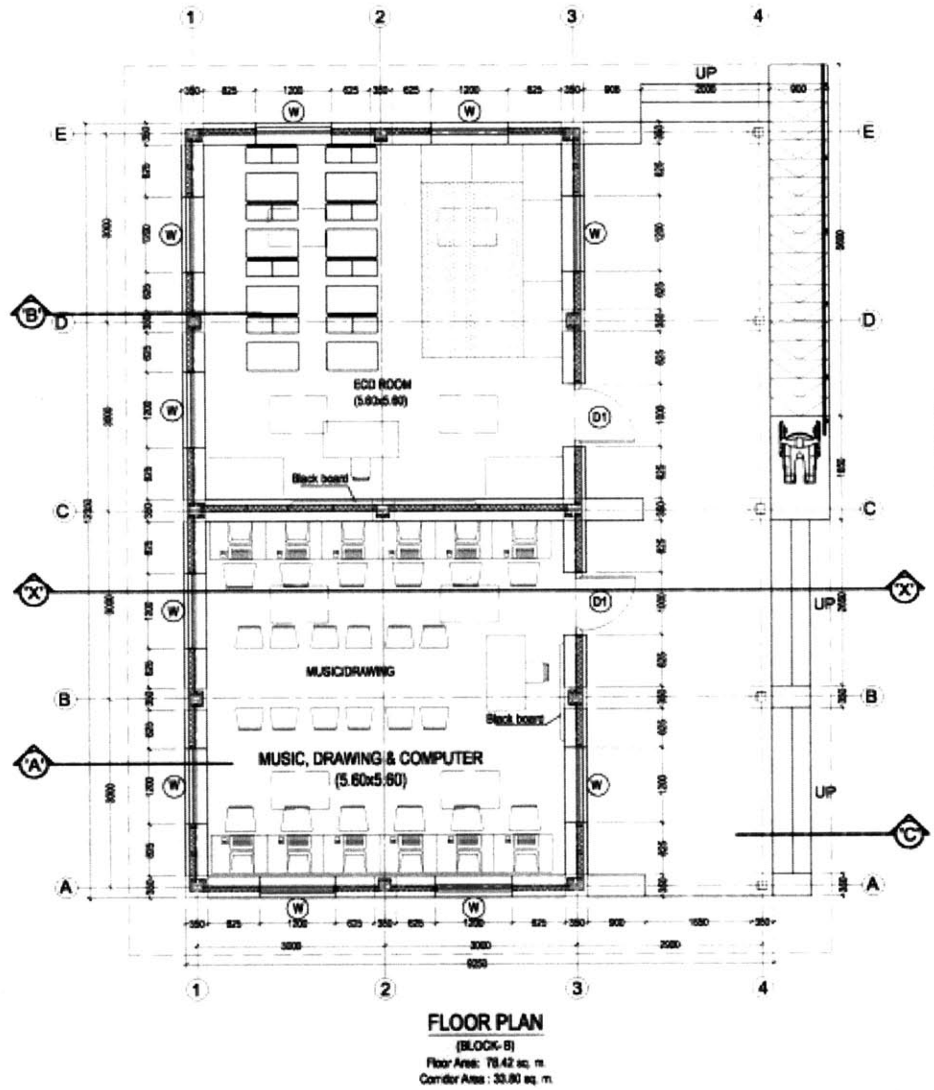


Figure 7-5: Asian Development Bank Plan

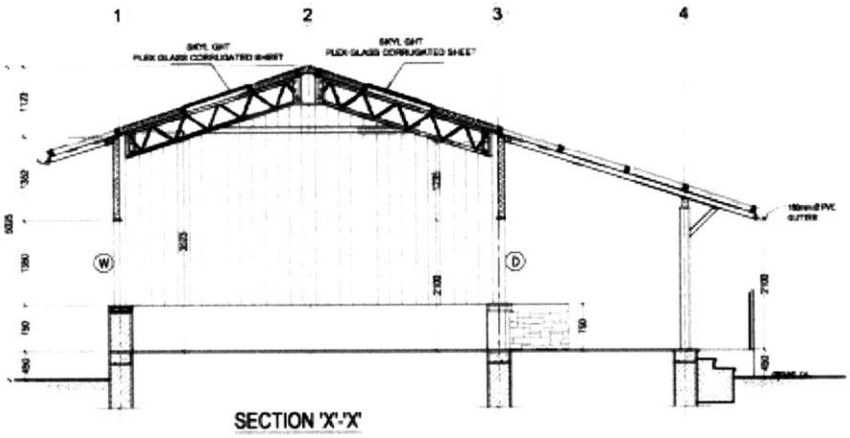
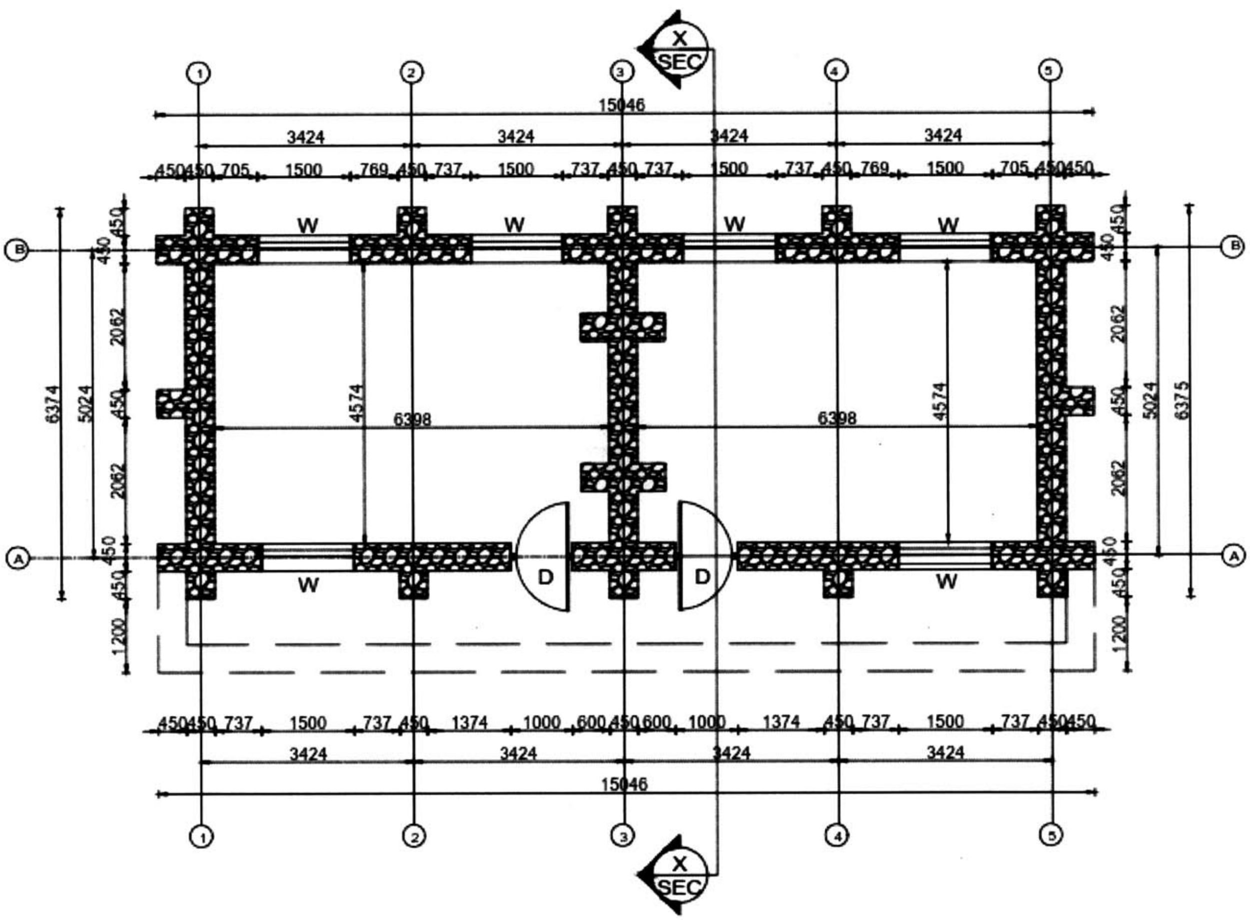


Figure 7-6: Asian Development Bank Elevation



PLAN

Figure 7-7: Edge of Seven Plan

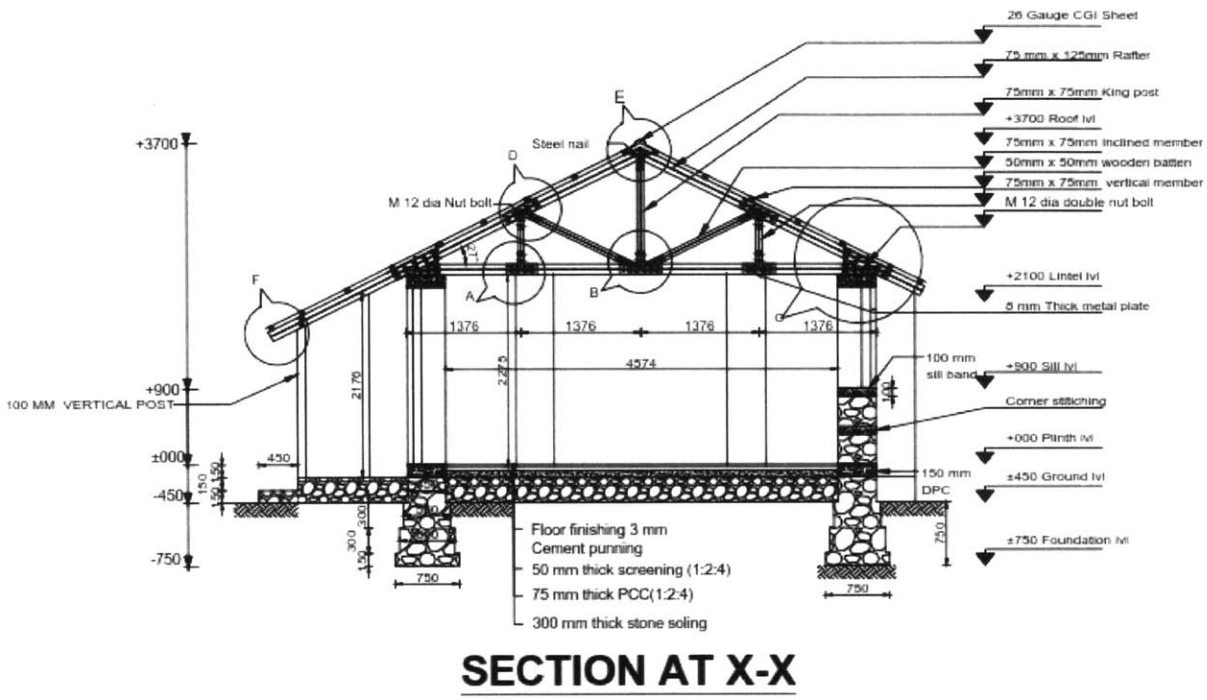


Figure 7-8: Edge of Seven Elevation

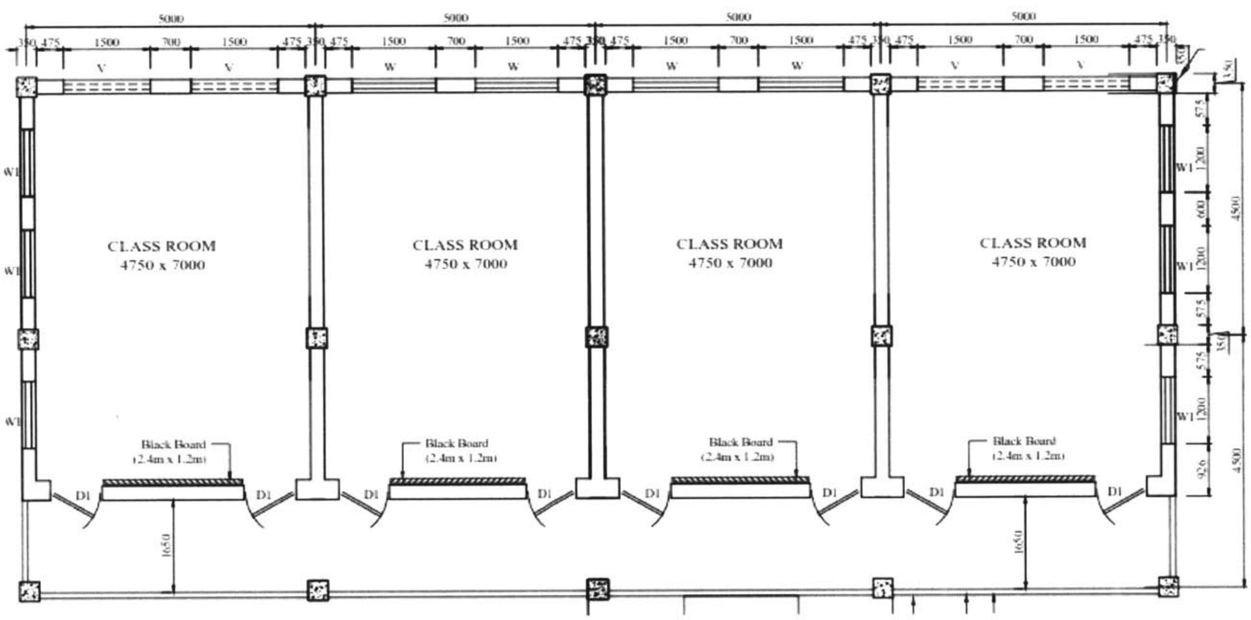


Figure 7-9: National Society of Earthquake Technology Plan*

** School design was incomplete. Building height was set as 2.75 meters arbitrarily.*