KYAMBOGO UNIVERSITY

FACULTY OF ENGINEERING

DEPARTMENT OF CIVIL & BUILDING ENGINEERING

EFFECT OF THE EDGE SUPPORT CONDITIONS ON THE PERFORMANCE OF MASONRY INFILL WALLS SUBJECTED TO OUT OF PLANE LOADING

By

TULIRABA FREDRICK DANIEL

(B. Eng, Civil Engineerin,. KYU)

Registration Number: **16/U/13474/GMES/PE**

A dissertation submitted to Kyambogo University Graduate School in partial fulfillment for the award of a degree of Master of Science in Structural Engineering of Kyambogo University

October 2018

CERTIFICATION

The undersigned certify that they have and hereby recommend for acceptance by the Kyambogo University a dissertation entitled **"Effect of the Edge Support Conditions on the Performance of Masonry Infill Walls Subjected to Out of Plane Loading"** in fulfillment of the requirements for the award of degree of Master of Science in Structural Engineering of Kyambogo University

Dr. Michael Kyakula..

Date..

Dr. Rodgers Mugume..

Date..

DECLARATION

I, Tuliraba Fredrick Daniel, the undersigned, declare that to the best of my knowledge, this research has never been submitted before for the award of any degree in this or any other higher institution of learning.

Signature....................................

Date..

DEDICATION

I dedicate my dissertation work to my family and many friends. A special feeling of gratitude to my parents, whose words of encouragement and push for tenacity ring in my ears.

ACKNOWLEDGEMENT

I'm indebted to a number of individuals and entities for various reasons. Foremost, the supervisors Dr Michael Kyakula and Dr Rodgers Mugume, without whose time and effort, this research would not have been possible. The management of Kyambogo University and in particular the head of school Dr. Nyende Jacob, Professor Jo Yong Su and the entire staff of the faculty of engineering for provide an enabling environment for the study.

The consulting engineering firms and more particular Engineer Steven Kawuma of Associated Engineering Services for Corporation given while gathering data

Last but not least in importance, special thanks to my family members, without whom I would never have had any reason to return to school to pursue this course.

TABLE OF CONTENTS`

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AC	Australian Codes
2-D	Two Dimension
3-D	Three Dimension
C3D8R	Eight-node three-dimensional reduced integration elements
CAE	Computer Aided Engineering
CNC	Canadian National Codes
et al	And others
Euro-codes	European codes
FEMA	Finite Element Method Approach
IC	Indian Codes
KCCA	Kampala City Council Authority
Kg/mm^3	Kilograms per cubic millimeter
Mm	Millimeters
N/mm^2	Newton per square millimeter
NIV	New International Version
RC	Reinforced concrete
U1	Displacement in the x- axis
U2	Displacement in the y- axis
U3	Displacement in the z –axis
X	X- Axis
Y	Y-Axis
Z	Z-Axis
UACE	Uganda Association of Consulting Engineers

ACRONYMS

λ_h	Ultimate strength in N/mm^2
D	Panel diagonal length in mm
H	Height of column in mm
T	Panel thickness in mm
E	Young's modulus in N/mm^2
E_s	Young's modulus in N/mm^2
E_b	Elastic modulus in N/mm^2
θ	The angle between the infill diagonal and the horizontal plane in degree
I	Moment of inertia in mm^4
ν	Poisons ratio
W	Effective width of diagonal strut in mm
γ	Density kg/m^3
%	Percent
g	Maximum gap that could exit at the infill-bounding frame interaction in mm
Δg	Out-of-plane displacement caused by the exiting gap in mm
L	Length of infill in mm
h	Height of the infill in mm
t	Thickness of infill in mm
w	Applied out of plane load in N/mm^2
γ	A factor that accounts for depth of compression with value of 0.9

ABSTRACT

Serious damage and loss of stability of masonry infill walls can be realized when the infill panel is subjected to in-plane and out of plane loading. To improve their performance, the edge support conditions between the infill walls and the bounding frames needs to be properly investigated and improved. A survey of fifty (50) structures under construction in the Kampala City Council Authority revealed that 94% of the structures construct an RC frames and incorporate masonry infills. The four observed methods of infill construction are; Wall supported on beam at the bottom and bonded by mortar to the side columns and top beam (20%), wall bonded to side columns by mortar but top beam cast with its soffit directly on the wall (28%), side columns cast with infill wall panel in place and the soffit of the top beam cast directly on the wall (36%), side column cast with Infill panel in place forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall (10%) and infill wall panel built into structural steel frame connected by metal plates (6%). A questionnaire of twenty (20) leading consultancy firms in Uganda revealed that 19 has never incorporated infill edge support in design and construction but only design for bracing beams in infills to prevent failures. Four different configurations of the edge support conditions above were evaluated using the general finite element software, ABAQUS. An out of plane distributed load was applied to the wall panels to cause out of plane failure for each of the four selected configurations. The results showed that masonry infill walls that have the soffit of the beam constructed directly on the wall and restrained by saw toothing RC columns yield better performance.

Key words: *Masonry infill walls, out of plane loading, edge support conditions, performance, and stability of masonry.*

CHAPTER ONE: INTRODUCTION

1.1 Background Information for the use of masonry

In the early stages of civilization, construction of buildings was based on low-engineered and empirical approaches with masonry as the main building component. Masonry is a homogeneous material consisting of artificial or natural units, which are normally laid with mortar (EN 1996).

The first record of building referred to in the bible consider attempts made to build a skyscraper using masonry. "They said to one another, Come, "let us make bricks and dry them with fire". They used bricks for stone and bitumen for mortar. Then they said, "Let us build ourselves a city and a tower with its top in the sky" (NIV Bible, Genesis 11:3-4) and this proves that building with masonry engaged people's attention from early days. The early Egyptians, Romans and Greeks built lots of monumental structures from masonry such as the pyramid of Cheops in Egypt, the Great Wall of China, and the Pharos of Alexandria. The masonry walls of that time were different: Romans built walls from two leaves of masonry and rubble mixed with mortar in the middle. Greeks used mostly natural stone, Chinese built masonry walls mostly from sun dried clay bricks (Fódi, A., Bódi, I. - 2010).

The effective use of masonry construction is seen in structures where it is performing a variety of functions such as supporting loads, dividing space, providing thermal insulation and weather protection.

In a number of cases of modern construction, masonry walls are used as infills between concrete frame members. Unfortunately, the masonry infill-concrete frame interaction is not well defined due the variant edge support conditions. It is imperative that these various edge support conditions are studied and analyzed to realize the most optimum case.

1.1.1 Masonry Infill

In the current construction practices, one of the most feasible choices of erecting multilevel buildings is to construct framed structure as it allows the contractors to follow a smooth pattern of work with ease and appreciable economy during the various construction stages. These framed structural members are later infilled with masonry units out of burnt clay bricks or concrete blocks.

However the incorporation masonry infills into the structural frame can cause undesirable effects during seismic actions resulting into damage to masonry itself or to the main structure. These effects are categorized in three stages namely:

i. In plane failure whereby only the walls are damaged and with eventual reduction of the induced stiffness in the structure.

ii. Out of plane failure whereby the walls are damaged and a possibility of damage to other non-structural elements like fittings and partitions as well as injury to the occupants.

iii. Short column, torsion and soft storey failure arising from materials form, connections and arrangement of walls in plan and elevation. This type of failure causes structural damage to nonstructural elements like fittings and partitions as well as distress of columns.

This research concentrated on out of plane failure which occurs when the applied forces are perpendicular to the wall (out of plane loading). Field observations from the notable earthquakes in Uganda have shown that out of plane failure of masonry infills occurred quite often leading to loss of life and property and hence indicating the need to introduce improved construction techniques [Earthquake report.com].

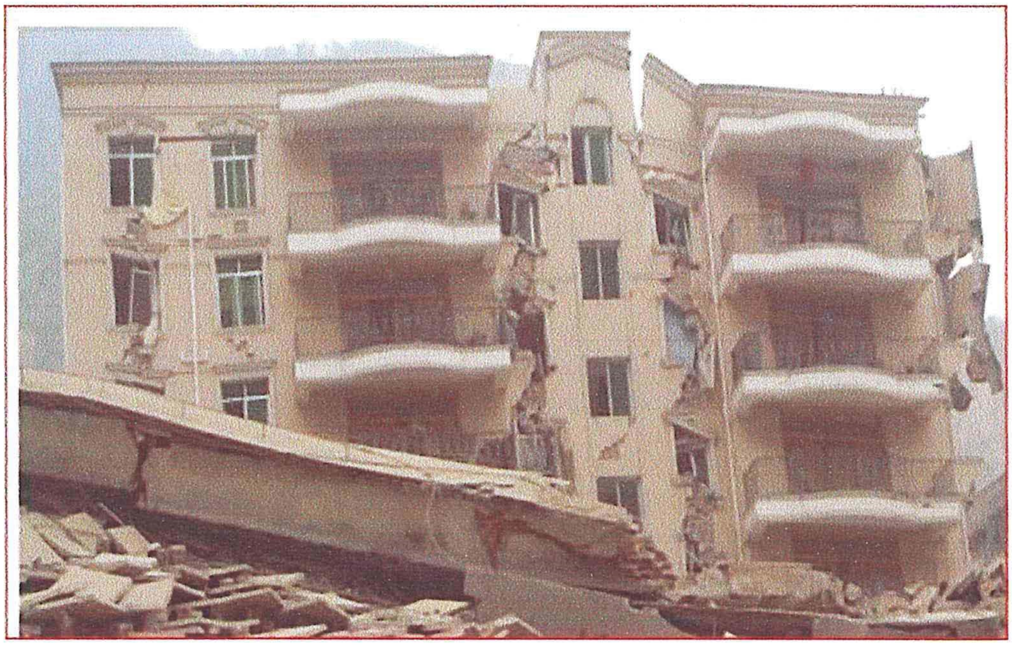

Figure 0-1: Failure in masonry infill due to seismic actions

The factor of great importance to consider is the edge support conditions of masonry infill walls with the surrounding frame. The interaction of masonry wall units with the adjoining frame members may not be significant during static load analysis procedure, but when the frame undergoes lateral drifts due to dynamic forces, the response of the infill walls can lead to significant risks. (Fiorato et al., 1970; Broken and Bertero, 1981; Calvi and Bolignini, 2001; Negro and Verzeletti, 1996; Zarnic et al., 2001; Hashemi and Mosalam, 2006)

Framed structures-masonry infill construction has been greatly adopted in the Uganda's construction industry for majority of the multilevel buildings and it forms a common landmark in the Kampala Capital City Authority.

Figure 0-2: Reinforced Concrete framed structure with burnt clay bricks infills.

The categorization of the masonry infill - concrete frame interaction is dependent on the type of edge support condition adopted. There are varied masonry edge support conditions but the most common types in the Uganda Construction Industry will investigated in this research.

1.2 Problem Statement

The current design practices usually consider masonry infill walls as non-structural elements whereby structural engineers only take into account their weight during structural analysis and design (Rodrigues et al., 2010; Noorifard et al., 2014; Noorifard et al., 2015). Infill walls are considered to have a no load-bearing function but when the under unusual excitation a case of seismic actions, they contribute significantly to its performance by increasing the stiffness and strength of the structural members (Moghaddam and Dowling, 1987) and thus supplementing the response of the overall structure. However one of the factors to consider in the performance of the masonry units in the reinforced concrete frame members is their interaction with the main structural frame which is not well defined due the variant edge support conditions (Noorifard et al., 2016). This has created uncertainties in ascertaining the worst case scenario during out of plane collapse resulting from out of plane loading.

The need for reliable analysis procedures capable of predicting damage evolution and failure in structures in order to design efficient repairs and maintenance is worth undertaking. It is therefore imperative that the various edge support conditions are studied and to avert the associated risks due to out of plane failures involving loss of property and life.

1.3 Objective

1.3.1 Main objective

To investigate the effect of the edge support conditions on the performance of masonry infills walls when subjected to out of plane loading.

1.3.2 Specific objectives

1. To determine the different types of the edge support conditions for masonry infills used in the Uganda construction industry;
2. To ascertain how leading structural engineering consultants to treat masonry infills in RC framed structures;
3. To develop a theoretical finite element model capable of predicting stresses and deformations for the different edge support conditions;
4. To check for the performance of the Masonry Infill walls in terms of spatial displacements and stress distribution for each individual edge support conditions.

1.4 Justification of the Research

In the present research the proposed model was employed to simulate the behavior of the masonry infill walls within the framed structure during structural analysis with focus on the failure criterion against out of plane motion.

This was to allow for more accurate predictions concerning the effect of the infill walls on the overall structural response of RC frame structures under static and earthquake loading conditions.

Several studies on the performance of masonry infills has been going on for the past six decades by various researchers (Smith 1966; Smith and Carter1969; Mehrabi et al. 1996: Dhanasekar and Page 1986; Asteris 1996; Rodrigues et al., 2010; Noorifard et al., 2014; Noorifard et al., 2015), their input data and the analytical tools developed are based on the nationally developed parameters for the individual countries and these may not be applicable to the Ugandan situation. These researches where based on the indigenous materials types in the location of research, customized construction methodologies and controls and building codes like Canadian National Codes (CNC), Indian Codes (IC), Australian Codes (AC) and may others.

It was therefore important to have proper analytical tools which can ease the assessment of the performance of infill walls based on the locally available materials, construction methods and controls in the Uganda construction industry.

1.5 **Significance of Research**

From the historical perspective, masonry structures were erected by the time-honored method of trial and error. This was based on traditional methods and rules-of-thumb which were in most cases done secretively and kept on passing from one generation to the other. All these were done irrespective of mathematical nor predictive methods, but with experience and great skill, an impressive empirical wisdom was obtained.

In the present research the proposed model will be employed to simulate the behavior of the infill walls within the framed structure during structural analysis by providing a failure criterion against out of plane motion. This is expected to improve the predictions of already decided strut models currently used to model only the in-plane behavior of infill walls. This will allow for more accurate predictions concerning the effect of the infill walls on the overall structural response of RC frame structures under static and earthquake loading conditions. The analysis will be able to provide better predictions regarding the redistribution of the internal stresses and deformations developed within the structural elements of the frame due to their interaction with the infill walls. The development of accurate stress and deformation analyses will aid in easy substantiation of the stability of masonry constructions under adverse seismic actions and in particular the existing structures in the design of effective strengthening and repair interventions.

1.6 Scope of the Research

Baseline data was from Geographical location of Kampala City Council Authority where a multitude of multi levels constructions was taking place and consultancy firms were concentrated in Uganda. Emphasis was on construction levels 3 to 5 and consultancy firms dealing with building and civil engineering designs and supervision.

The content scope was limited to Reinforced concrete as the main supporting frame, standard burnt Clay bricks for infills (75*115*230mm). Edge support conditions which were predominantly used as per results got from the baseline surveys and interview questionnaires.

Loading consideration was out of plane loading and gravity loading conditions on simplified micro modeling and analysis. Key attention was on the spatial nodal displacements in the infill and stress distribution within the infill and structural frame resulting from the uniform out of plane loading on the masonry infills. The structural RC frame was expected not to take on any load during the analysis and was fully restrained in all directions. And time scope was 13months from 1st September 2017 up to 31st October 2018.

CHAPTER TWO: LITERATURE REVIEW

2.1 Background

In multistorey buildings, the ordinarily occurring vertical loads, dead or live have design approaches based on standard design codes (EN 1991-9, British Standards codes). These codes have been tested over time and they can accommodate standardized materials and edge support conditions.

In many developing countries; a case of Uganda, structural frames are fully or partially infilled by brick/block masonry panels. Infill panels may enhance both the in-plane stiffness and strength of the frame and thus leads to frame failures during seismic actions. However these effects are often not taken into account due to lack of knowledge of their composite behavior with the frame.

Analytical and experimental studies on the behavior of masonry walls when subjected to in-plane static or dynamic loads have been the focus of activity for the past six decades (Polyakov 1957 Smith 1966; Smith and Carter1969; Mehrabi et al. 1996: Dhanasekar and Page 1986; Asteris 1996; Rodrigues et al., 2010; Noorifard et al., 2014; Noorifard et al., 2015). These studies concentrated mainly on experimental investigations by necessity, but these were hampered by the large number of variables that must be considered in the overall behavior of the masonry. The main influencing factors which include dimension, anisotropy, joints, constituent material properties and workmanship, have made the simulation of plain masonry infills extremely difficult and hence the continued research. A review of the available literature on the finite element modeling of masonry reveals that two-dimensional plane stress formulations have so far been adopted for the analysis of masonry structures.

Further, in the absence of a suitable model to represent its behavior, masonry was assumed to be an isotropic elastic continuum in the past (Dhanasekar et al. 1986).

2.2 **Previous research on masonry**

Beginning with the first study conducted by Polyakov (1957), analytical and experimental studies on infills have been conducted for nearly sixty years. During his studies, Polyakov observed diagonal cracks in the center region of the infill, separation over a finite length of the beam and the column between the frame member and the infill at the unloaded corners and full contact between them adjacent to two opposite loaded corners. In the 1960's, Smith (1962, 1966, 1967, 1968) and Smith and Carter (1969) developed analytical techniques to calculate the effective width of the strut, and cracking and crushing loads, as a function of the contact length between frame and wall elements. They also developed equations by which the properties of these struts, such as initial stiffness and ultimate strength, were calculated where, the following relationship was suggested for masonry infills prior to cracking as illustrated in equation (i) below:

$$\frac{w}{d} = 0.175(\lambda_h h)^{0.4} \sin\vartheta \qquad \text{...(i)}$$

In which w, d and h is the effective width of diagonal strut, panel diagonal length and height of column respectively and λ_h is given by Equation (ii) below:

$$\lambda_h = \sqrt[4]{\frac{E_b t \sin 2\vartheta}{4E_s I h}} \qquad \text{..(ii)}$$

In which E_b, t and h are the elastic modulus, thickness and height of the brick masonry infill respectively; E_s and I are the Young's modulus and moment of inertia of the surrounding frame member; and θ is the angle between the infill diagonal and the horizontal.

This approach proved to be the most popular over the years because of the ease with which it could be applied and Figure 2-1 below illustrates this relationship

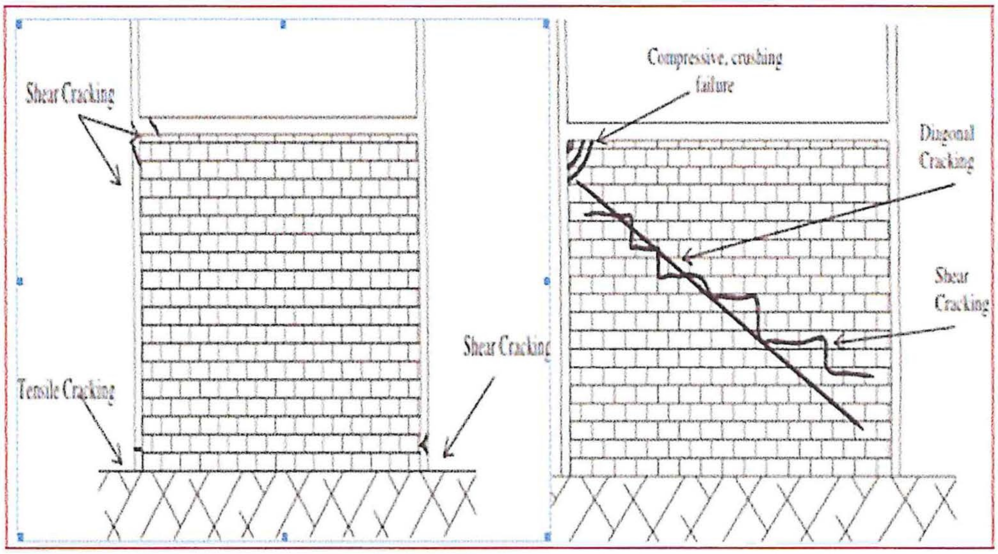

Figure 0-1: Failure mode of RC Frame and the infills due to in-plane loading.

The above relationship fits well for the in-plane loading condition but may not suffice in the out of plane loading condition due to non-linearity and hence a need for further research.

Further experimental and analytical studies were conducted on the infill walls by, Mainstone and Weeks (1970); Mainstone (1974); Paulay and Priestley (1992); Angel et al. (1994); Al-Chaar, (2002); El-Dakhakhni et al., (2003) to enhance a better understanding of the infilled frame behavior. Analytical results obtained by Smith and Carter (1969) showed similarity to experimental results obtained by Mainstone (1974) and Al-Chaar (2002). At this stage, a line drawn from one loaded corner to the other represents the direction of the principal compression indicating that the panel transfers compression along this line.

It was assumed that the infill behaves as a diagonal strut and the structure can be analyzed with equivalent struts replacing the infills as illustrated in Figure 2-2 below. A diagonal compression strut could adequately represent load transfer mechanism observed from the experiments and conducted finite element analysis. The equivalent compression strut was taken to have the same thickness as the infill it represented.

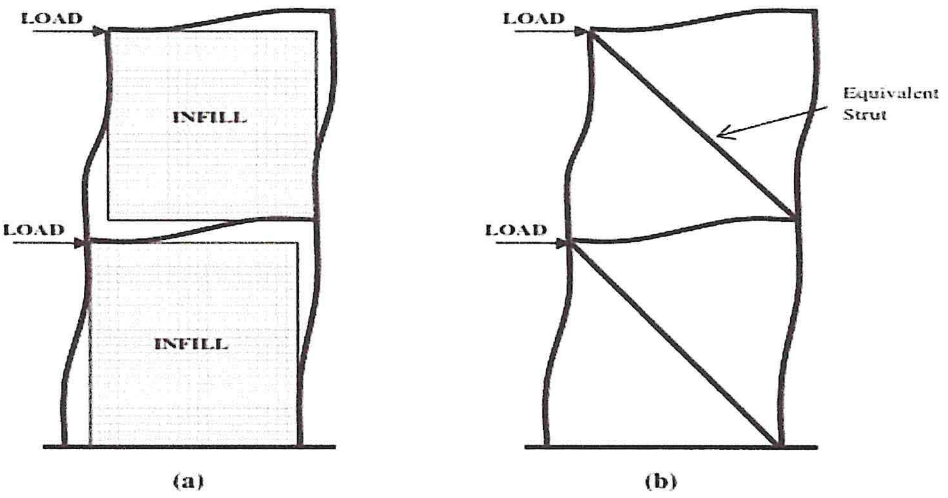

Figure 0-2: (a) Laterally loaded infilled frame and (b) Equivalent strut

2.3 General behavior of Masonry infills.

The primary objective of this research is to investigate the effect of the boundary conditions on the out-of-plane response of masonry infills with a focus nodal spatial displacement and stress distribution the surrounding frame. Out-of-plane resistance of masonry infills bounded by frames is derived largely by the arching action rather than conventional flexural behavior (McDowell et al. 1956). This model assumed that after the development of tension cracking at the supports and mid-height of an infill where maximum moments occur under the out-of-plane load, the wall acts as two rigid segments.

Each segment rotates about its end until either the masonry crushes or the two segments snap through as illustrated in Figure 2-3 below.

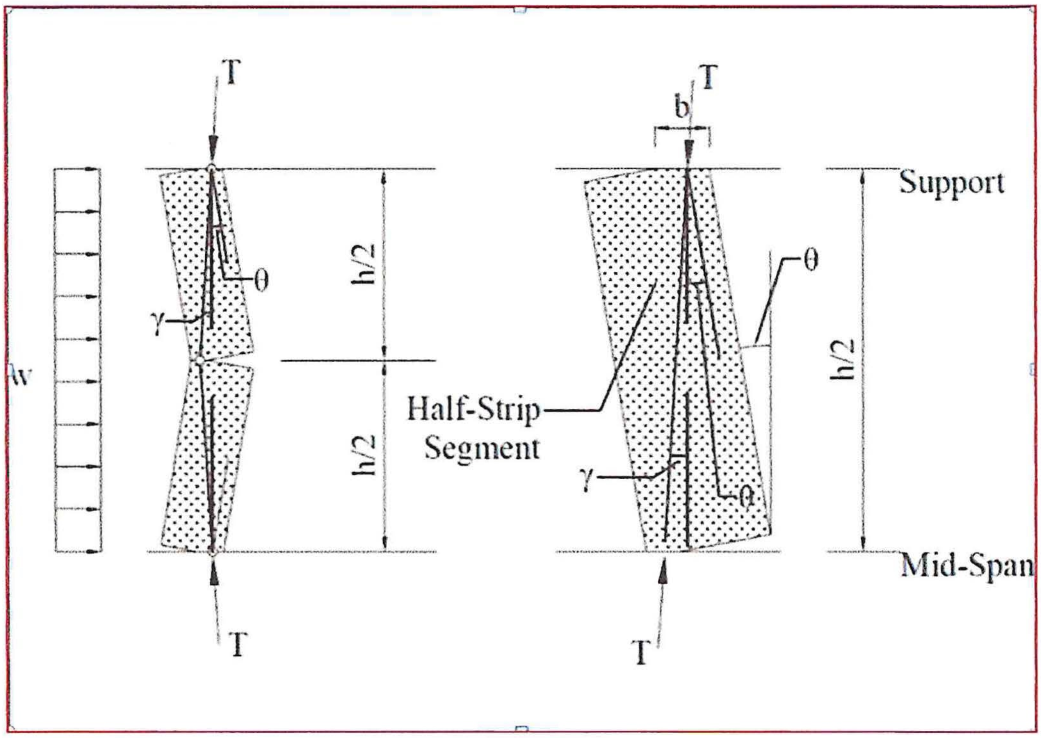

Figure 0-3: Idealized Model for Arching Action

In this case the rotation enabled by three hinges after cracking causes the rigid segments to push against either the rigid supports or each other and thus generating internal thrust forces (T) that resist the out-of-plane load. Using an idealized masonry material stress-strain relationship, the out-of-plane load could be estimated using equilibrium between the moment caused by internal thrust load and the external applied moment at the mid height. This mechanism, relying on thrust forces generated at two boundaries (top and bottom) with the frame, is considered as one-way arching action and most the developed analytical models are based on this mechanism.

Other studies (Dawe and Seah 1989; Angel 1994; Henderson et al. 2003) showed that a two-way arching action can develop but these results in a substantially higher ultimate load than one-way arching action.

However, they pointed out that the interfacial gap due to wall shrinkage and settlement affects the arching action and thus the out-of-plane strength of infills.

It was also shown that development of arching action enhanced the stability of infills even after the ultimate capacity was achieved (Flanagan and Bennett 1993). In this case the slipping or overturning of masonry infills is less significant than that of flexural masonry walls due to the improved stability of infills.

2.4 Parameters that influence out of plane behavior of masonry infills

Studies on masonry infills by various researchers (Anderson 1984; Angel 1994; Gabrielsen et al. 1975; Gabrielsen and Kaplan 1976) identified several geometric and material parameters that influence the arching action and out-of-plane strength of masonry infills. These include: slenderness of infills, gaps between infills and frames, strength of masonry, frame rigidity, and infill opening.

2.4.1 Slenderness Ratio of Infills

Anderson (1984) tested masonry wall panels subjected to out-of-plane loading through the application of hydraulic jacks. It was found out that the out-of-plane strength of masonry panels decreased with increases in the slenderness ratio of panels. Masonry panels with small slenderness ratio, their failure mode was governed by crushing due to the development of arching action. However, for slenderness ratios in the range of 35-40, the failure of masonry panels was governed by instability.

Angel (1994) tested eight masonry infilled RC frames that consisted of either clay brick or concrete masonry block infills to investigate the effect of slenderness ratio on the out-of-plane strength of infilled frames. His study indicated that if the slenderness ratio of infills was reduced in half (h/2t ratios), the out-of-plane strength of the infills increased by more than seven times. For the infills with a slenderness ratio larger than 30, arching action had significantly less effect on the out-of-plane resistance of masonry infills.

2.4.2 Gaps between Infills and Frames

A gap may exist due to defective workmanship, wall shrinkage and settlement, or an intentional movement joint placed between the infill and frame. Masonry walls having a top gap in the range 2.54 mm and 5.08 mm between the wall panel and the frame were tested under a uniform blast load (Gabrielsen et al. 1975). It was found that the gapped infills were considerably stronger than either cantilevered walls or walls pinned on two opposite edges due to the forming of arching action. However the gapped walls only resisted 1/6 to 1/8 of the load that sustained by ungapped infills.

Gabrielsen and Kaplan (1976) showed that the development of arching action was different in the infills with tight rigid supports (without gap) and with small gaps at the top wall boundaries. A symmetrical three-hinged arch was formed in an infill with tight rigid supports, while the infill with gaps needed to displace more in order to engage the support thus creating an unsymmetrical arch as shown in Figure 2-4 below.

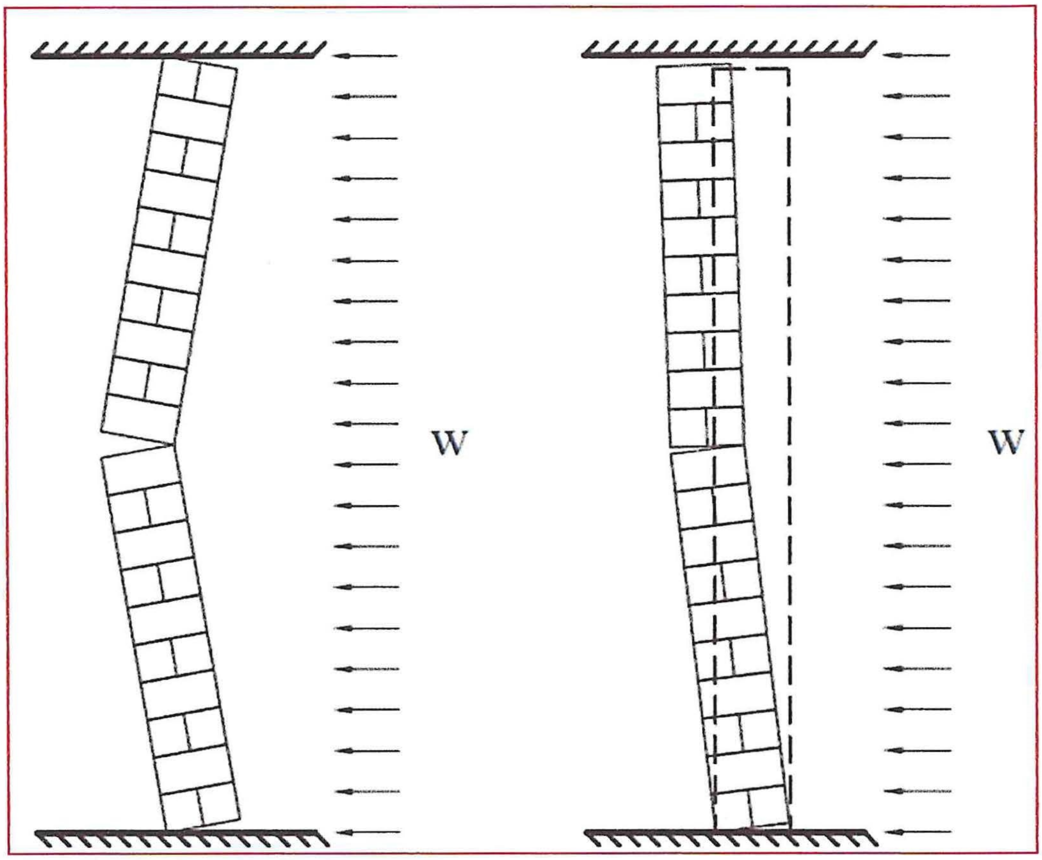

Figure 0-4: The differences in motion between rigid and gapped arching

A shaking table test to study the out-of-plane arching behavior of full scale masonry walls with a 3 mm gap between the top abutment and the infill was conducted by Dafnis et al. (2002). It was found out that during the dynamic loading, the gapped specimen experienced a larger deformation than the non-gapped counterpart before the arching action developed and the out-of-plane capacity was smaller.

Drysdale and Hamid (2005) investigated the development of arching action in gapped infills using mechanics of rigid body movement. They concluded that the maximum gap that could exist was controlled by the diagonal length between the compression forces at the hinges, and the maximum gap was expressed as:

$$g \leq \frac{4(\gamma t)^2}{L} \quad \text{(iii)}$$

Where L is the length of infills, and $\gamma=0.9$

Additionally, they also proposed the following equation for calculating the infill out-of-plane displacement, Δg, taking into account of the gap size, g.

$$\Delta g = \frac{g(L-g)}{4\gamma t} \quad \text{(iv)}$$

2.4.3 Compressive Strength of Masonry

Tests on clay brick infilled RC frames subjected to out-of-plane load applied through an air bag by Abrams et al. (1996). These tests showed that the out-of-plane strength of masonry infills increased as the compressive strength of masonry increased.

Experimental studies on masonry infilled RC frames to investigate the relationship between out-of-plane deflection of the infill panels and the compressive strength of masonry was conducted by Moghaddam and Goudarzi (2010). The results showed that the higher the masonry strength, the smaller the out-of-plane deflection and the out-of-plane strength of masonry panels increased linearly with an increase in the compressive strength of masonry.

2.4.4 Frame Rigidity

Experiments conducted by Monk (1958) and Gabrielsen and Wilton (1974) showed qualitatively that the out-of-plane strength of infills bounded by flexible frames was less than that of the infills bounded by rigid frames.

Investigations on masonry infilled steel frames having different frame stiffness, in particular column stiffness, under uniform pressure applied through an air bag were carried out by Dawe and Seah (1989).

It was found out that both the flexural stiffness and torsional stiffness of frame columns had an effect on the out-of-plane strength of infills. They in turn proposed an equation to include the effect of both the flexural and torsional stiffness in the calculation of the out-of-plane strength of the infills.

Angel (1994) studied the effect of stiffness of bounding frames on the out-of-plane strength of infills using numerical simulations. He concluded that the out-of-plane strength of an infilled frame can benefit more by using stiffer frame members. However, the increase in out-of-plane strength is insignificant when the flexural stiffness (EI) of the frame exceeds $2.6x10^{13}$ N/mm^2. He developed a flexural stiffness reduction factor based on the flexural stiffness of the frame to modify the strength of infill bounding in the less stiff frames.

2.4.5 Openings in infills

Akhoundi et al. (2016) investigated a brick masonry infilled frame having a center opening of 13% area of the infill under uniform out-of-plane pressure. The test results showed that the infill with opening did not show significant reduction in its out-of-plane strength.

2.4.6 In-plane damage

Angel (1994) investigated the effect of in-plane damage caused by lateral loading on the out-of-plane strength of infilled RC frames. It was found that the out-of-plane strength decreased in accordance with the magnitude of in-plane damage.

He developed an out-of-plane strength reduction factor in terms of the ratio of maximum in-plane applied displacement to the twice in-plane displacement at which the first crack occurred.

Porto et al. (2013) conducted out-of-plane tests on full scale clay masonry infilled RC frames with various levels of prior damage defined by in-plane deformation of the frame. They found that the out-of-plane strength of the masonry infilled frames can be related to the in-plane drift. Compared with the specimen with 0.5% in-plane drift, a 1.2% in-plane drift resulted in 39% and 19% reductions in the initial stiffness and out-of-plane strength respectively.

Furtado et al. (2016) tested three full scale clay masonry infilled RC frames with in-plane damages under cyclic out-of-plane loading. The specimen was loaded laterally to a 15 mm displacement which was twice the displacement at the ultimate load. Compared with the specimen with in-plane damage, the ultimate out-of-plane strength for undamaged specimen was four times higher and the displacement was also greater. It was also shown that the failure mode of the infilled frame under out-of-plane load was depended on the previous in-plane damage. Comparing with the specimen without prior in-plane damage, the development of arching action was not significant for the specimen with prior in-plane damage, and no cracking occurred in the middle of the infill.

Despite all the above parametric studies on masonry infills none considered the effect of the different edge support conditions on the performance of the masonry infills.

2.5 **Numerical Modeling**

The increasing complexity and multidisciplinary nature of the real engineering problems is continuously demanding for simplified methods of analysis. By implication the traditional approach need to be substituted with one which allows engineers to have increasing and stimulating analysis curves. Through the adoption of finite element methods, many efforts to develop analytical solutions like numerical models to supplement the experiments have been undertaken by many investigators (Smith 1966; Smith and Carter1969; Mehrabi et al. 1996: Dhanasekar and Page 1986; Asteris 1996).

Numerical modeling is a powerful technique for the solution of complex engineering problems. One of the significant requirements in the design of a scientific computing program is the ability to store, retrieve, and process data that maybe complex and varied.

2.6 **Models for masonry using the Finite Element Method**

Several investigators have dealt with the structural behavior of masonry using the finite element method. Most analyses considered masonry to be an assemblage of bricks and mortar with average properties. Isotropic elastic behavior has been assumed to simplify the problem by ignoring the influence of mortar joints acting as planes of weakness [Rosenhaupt 1965, Saw 1974]. Assumptions like these were useful in predicting deformations at low stress levels, but not at higher stress levels where extensive stress redistribution caused by non-linear material behavior and local failure would occur.

Dhanasekar et al. (1984) proposed a non-linear finite element model for solid masonry based on average properties derived from biaxial tests on brick masonry panels. The model was capable of reproducing the effects of material non-linearity and progressive local failure, but the masonry was modeled as a continuum with average properties, with each element in the finite element subdivision including several bricks and joints.

This model, had limitations when local effects were important and could not be used, to predict the behavior of masonry subjected to concentrated loads where local stresses and stress gradients were high. The model did not comprehensively account for other factors like the type, source of materials and the variant edge support conditions.

2.7 Constitutive models

The constitutive models for masonry, are categorized as;

i. The one-phase material models (micro), treating masonry as an ideal homogeneous material with constitutive equations that differ from those of the components; and
ii. The two-phase material models (macro) where the components are considered separately to account for the interaction between them.

Micro models are relatively simple to use and require less input data, and the failure criterion is of normally a simple form but their constitutive equations are relatively complicated. This type of model is suitable for the study of the global behavior of masonry whereby the mortar joints and interface elements are defined as individual elements to represent a contact areas as in Figure 5c below. The general geometry is maintained, but the individual elements that represent joints and interface are not able to describe the Poisson's effect of mortar over bricks.

Macro models are relatively costly to use due to the great number of the degrees of freedom, large amount input data, and their failure criterion are of a complicated form due to the brick-mortar interaction but the constitutive equations of the components are normally of a simple form, and hence suitable for the study of local behavior of masonry.

Lourenco 1995 et al) presented in detail the two approaches (Micro- and Macro-modeling) for the analysis of masonry structures. It was realized that the relative merits of various models and algorithms should be based on direct comparison of the methods when applied to identical problems.

They suggested that the adoption of the particular model should depend on the kind of problem, the degree of accuracy required for the problem at hand. Figure 2-3 below shows the different types of modeling techniques for masonry.

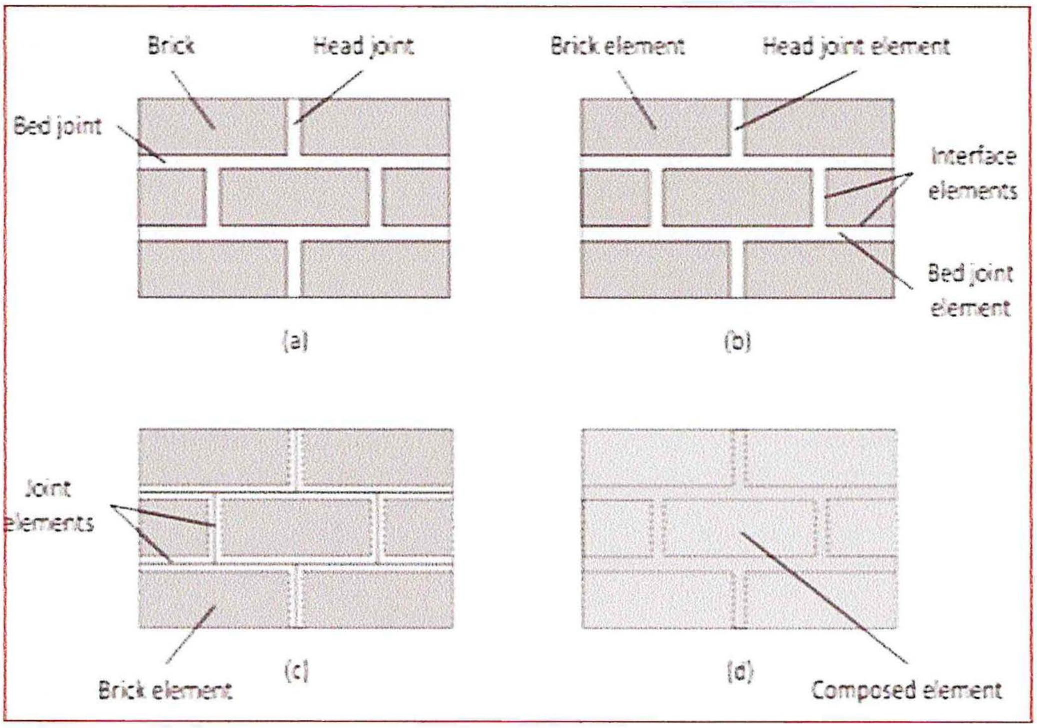

Figure 0-5: Modeling techniques for masonry

2.8 **Summary**

Despite several researches on the behavior of masonry infills, there is no clear indication of any research carried out on the wall-frame interaction in the Uganda's construction industry. The aim of this research is to investigate the effect of the different wall to frame edge support conditions on the performance of the masonry infill wall subjected to out of plane loading in the Uganda construction industry.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter presents the instruments used in the study and the analysis undertaken in the effort to provide answers to the research questions and the general objectives of the research.

3.2 Research design

The study adopts the baseline survey research approach, questionnaire and then numerical modeling and analysis. The survey design was adopted as it has been used by many researchers and has proven to be a useful tool for investigating trends and specific situations in many scientific disciplines.

The study started by gathering data from primary sources in order to achieve the research objectives This included a drive through on the major roads in the divisions of KCCA and contact with the leading structural engineering consulting firms in Uganda. The data acquired was used in the development of a computer models to enable the analysis.

3.3 Sample size and space for structures under construction

Consideration was made for the multi-level structures under construction of levels 3-5 within the Kampala City Council Authority. Out of the five divisions within the KCCA, the study covered only four divisions where there was concentration of multilevel construction of the considered level.-For each division, five (5) major roads randomly selected from the number of major roads in a division as in Table 3- 1below

A drive through was conducted and all the structures with masonry infills noted and the type edge support condition recorded using the survey tool shown in Appendix 3

Table 0-1: Number of major and sampled roads per division

Division	Number of major roads	Sampled roads
Nakawa	10	5
Kawempe	9	5
Rubaga	13	5
Makindye	7	5

3.4 Questionnaire guides to the structural engineering consulting firms

Questionnaire guides with both opened ended and closed ended questions was administered to the structural engineering consulting firms using a designed questionnaires shown in Appendix 5. Twenty (20) firms were randomly sampled out of the thirty one (31) in the register with the Uganda Association of Consulting Engineers (UACE) as shown in appendix 4.

3.5 Computer Modeling

For computer modeling and analysis, Abaqus-CAE 6.14 software used in this research. This software application is capable of both the modeling and analysis of mechanical components and assemblies (pre-processing) and visualization of result from static analysis.

3.6 Procedure for data collection and analysis of results

3.6.1 Baseline surveys

The baseline survey was conducted within the four selected divisions of Kampala City Council Authority and these comprised of Nakawa, Kawempe, Makindye, Rubaga division.

The purpose of this survey was to ascertain the construction techniques of multilevel structures with special attention to masonry infills. Factor to consider were:

i. The number of levels (3-5 levels);
ii. The type of infills adopted for use, and
iii. The adopted edge support conditions.

The process was a drive through the major community access roads by counting and taking photographs of the ongoing construction works with focus on:

i. The number of structures per selected road in the divisions;
ii. The different types of materials in use for the infills and
iii. The adopted construction methods and edge support conditions.

3.6.2 Questionnaires guides to the structural engineering consulting firms:

Questionnaires guides were used to interview the consulting firms who carry out structural Engineering designs with focus on:

i. The type of materials used for masonry infills and choice of preference;
ii. Whether masonry infills are considered in the designs to carry lateral or gravity loads;
iii. The adopted edged support conditions in the design of masonry infills and choice of preference,
iv. The loading conditions considered during the design of masonry infills

3.6.3 Categorization of the masonry infill – concrete frame interaction.

From the survey, the categorization of the masonry infill - concrete frame interaction was dependent on the type of edge support condition adopted. The frequently adopted types of edge support conditions in the Uganda Construction Industry include the following:

Case1- Infill panel constructed after frame construction and attached to the side RC columns and top beam by mortar. This was modeled as simply supported at the bottom and free on the other three sides.

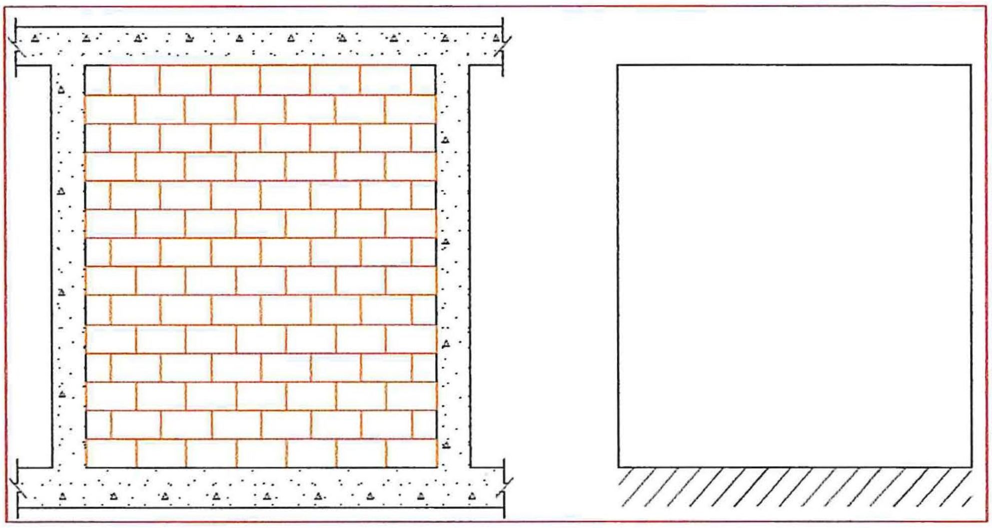

Figure 0-1: Wall simply supported at the bottom and free on the other three sides

Case 2- Side RC columns cast with Infill wall panels in place and the soffit of the top beam cast directly on the wall attached such that the load on the wall generates friction at the bottom and top to prevent lateral movement. This was modeled as wall restrained at the bottom and top but simply supported at the vertical sides.

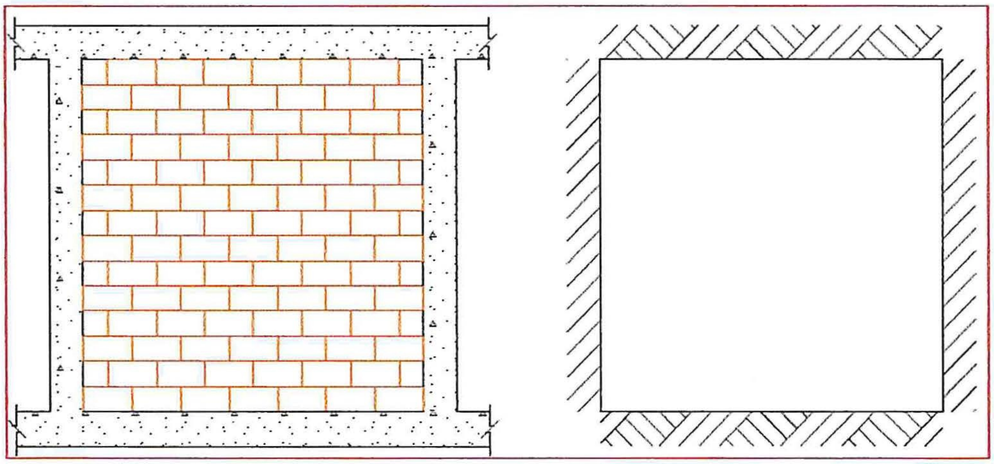

Figure 0-2: Fixed bottom and top to the RC frame, simply supported at the sides

Case 3-Infill wall panel built after construction of columns and attached to columns by mortar and soffit of the beam cast directly on the wall. The infill wall panel was modeled as restrained at the base and top beam but free on the two vertical sides.

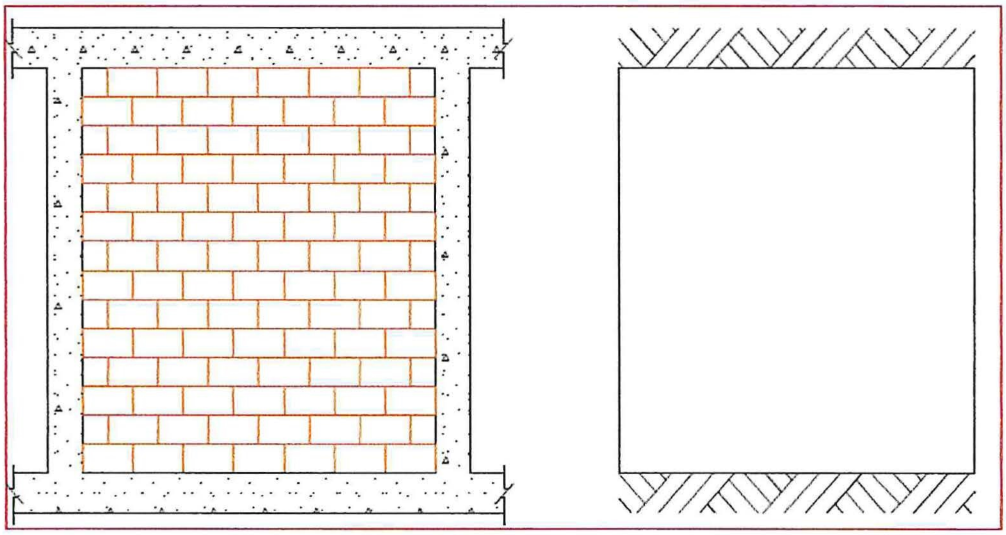

Figure 0-3: Fixed bottom, free on the two vertical sides, fixed to the RC beam

Case 4-Side column cast with Infill panel in place forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall. This was modeled as restrained on all the four sides.

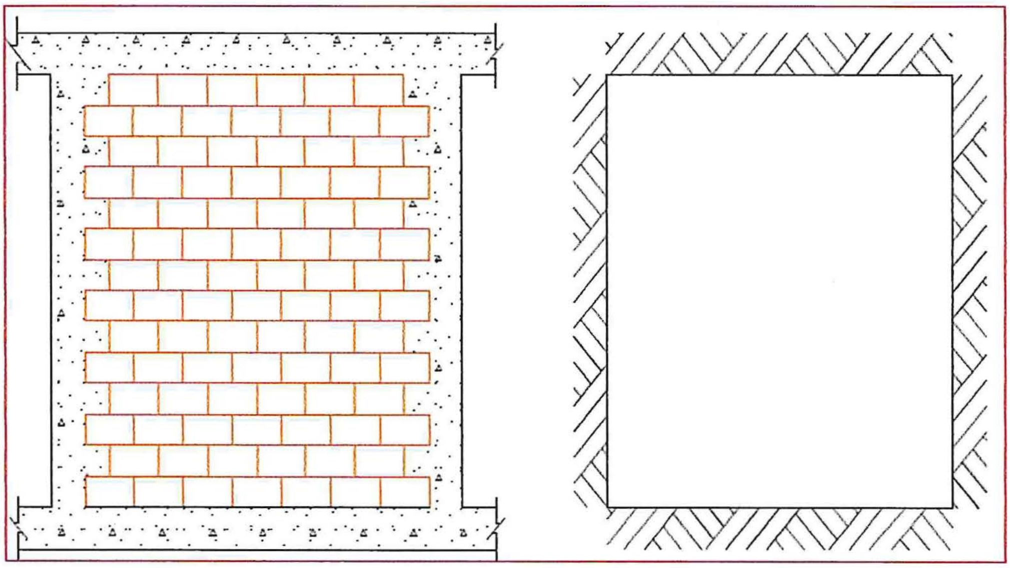

Figure 0-4: Fixed bottom and top to RC frame and on the sides by Saw toothing

3.6.4 Computer Modelling and Analysis

This work formulated constitutive models for constituent parts in the RC frame and Masonry infill and assembled them to perform the analysis. Consideration was made for the four different types of edge support conditions adopted for use in the Uganda construction industry.

Modeling and analysis was done on a reinforced concrete portal framed structure infilled with standard burnt clay brick using Abaqus Computer software version 6.14 and Finite Element Method (FEMA) Approach. The model consisted of two main materials; reinforced concrete and standard burnt clay bricks.

Using this technique, the interaction behavior of the masonry infill panel and concrete frame was investigated.

A parametric study was carried out using parameters such as aspect ratio with emphasis on the edge support conditions of the masonry infill panel with the frame. The variable parameter in the model assembly was the edge support conditions between the RC frame and the Masonry infill.

3.6.5 Model Development.

A 3-D arrangement was considered to develop the geometric model of 1000*1020mm infill out of 75*115*230mm burnt clay bricks with 10mm thick mortar interface and 300*300mm RC surrounding frame. The parts where positioned in a global coordinate system to create the assembly and the bricks were modelled together with 10mm thick mortar in joints. Figures 3-5 and 3-6 depict the different created parts for use in the assembly.

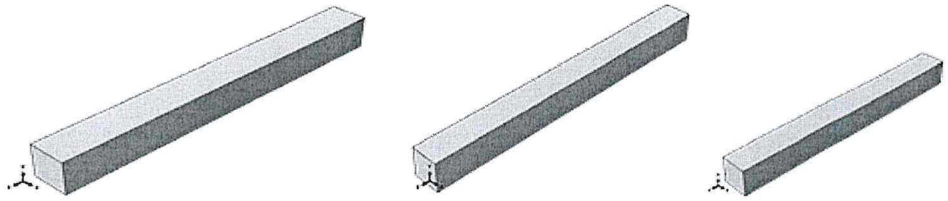

Figure 0-5: Parts of the concrete frame (Base beam, top beam and side columns)

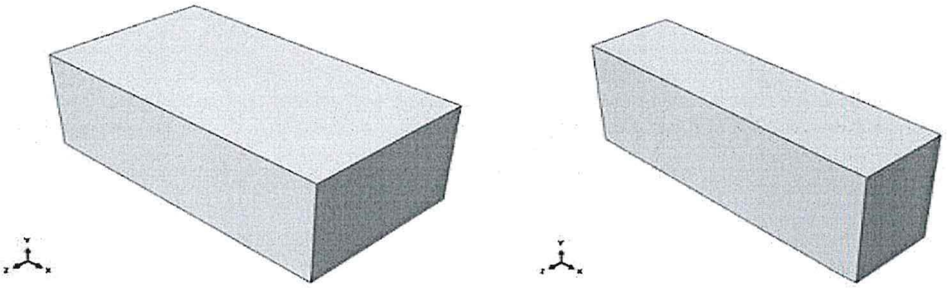

Figure 0-6: Parts of the masonry infill with 10mm mortar joint (Full and half brick)

3.6.6 Assigning of Material Properties

All materials of the reinforced concrete structure with mechanical nature were independently modelled, two material models were used, to represent the general and mechanical behaviour of reinforced concrete frame and masonry infill as homogenous isotropic elastic materials.

Table 0-2: Material Properties for reinforced concrete and burnt clay bricks

s/n	Description	Density γ (kg/mm^3)	Young's Modulus (N/mm^2)	Poisson's ratio ν
01	Reinforced Concrete	$2.4*10^{-6}$	$3*10^{4}$	0.2
02	Clay Bricks	$1.8*10^{-6}$	$1*10^{4}$	0.17

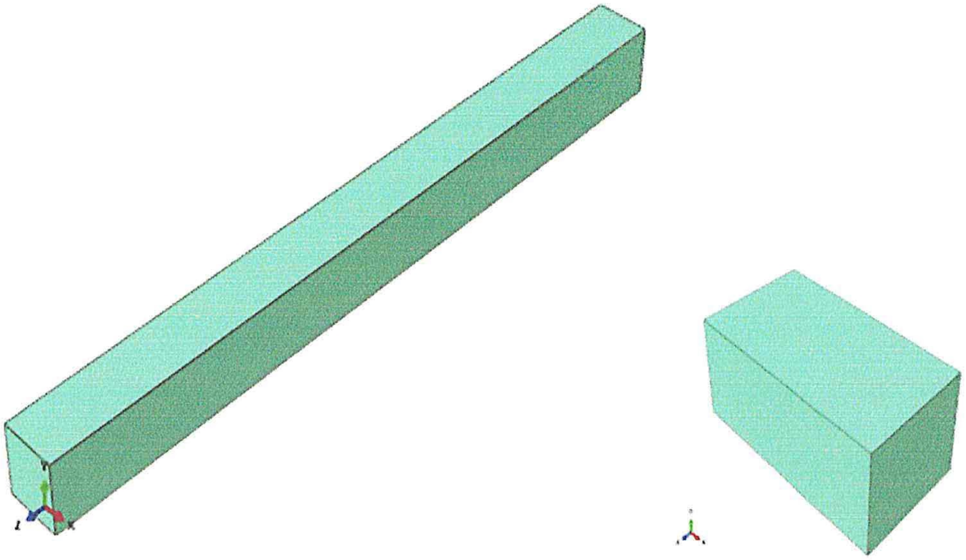

Figure 0-7: Concrete and brick sections assigned with properties

3.6.7 Model Assembly

The Assembly module was used to create instances of the parts which is a representation of the original parts. These parts instances where positioned in a global coordinate system to create the assembly. The assembly contained multiple instances of a single part and in this case the columns, bricks and half bricks were used repeatedly in the infill wall assembly.

The Reinforced concrete frame was filled with block units of 75mm by 115mm by 230mm thick connected in header bonding with 10mm thick mortar joint. However this mortar thickness was reduced to zero thickness due to the adapted model and the average unit dimensions increased by half the mortar thickness. The overall wall thickness was 230mm and infill panel size was 1000*1020mm as Figure 3-8 below.

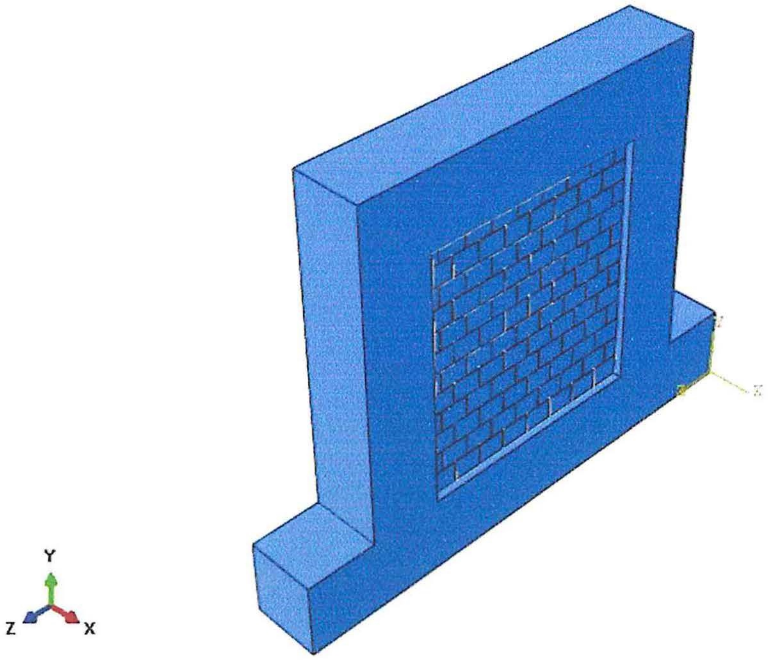

Figure 0-8: Geometric Model Assembly

3.6.8 Creation of step for analysis

The assembly was configured for analysis by creating a step and in this simulation interest was on the static response of the out of plane pressure load applied on the entire face of the brick work within the rigid RC frame.

Only a single analysis step was needed for the simulation and thus the analysis consisted of two steps:

i. An initial step, in which took care of the boundary conditions that constrained the ends of the RC frame.

ii. And the analysis step, in which applied a concentrated load on the entire face of the infill wall.

The initial step was generated automatically while the analysis step was created and the request output for the steps in the analysis was also made.

3.6.9 Creation interaction properties and constraints within the parts

Eight-node three-dimensional reduced integration elements with a Gaussian integration point in the element (C3D8R) were used to simulate the concrete frame and solid bricks.

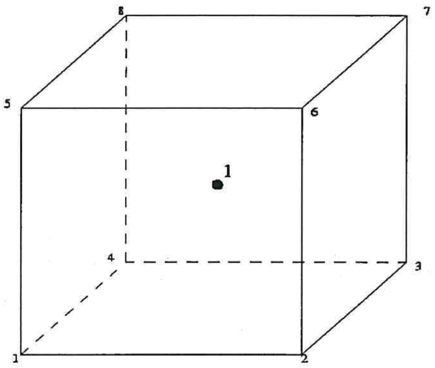

Figure 0-9: Eight node brick element indicating the integration point

The adjacent nodes in the concrete parts in the model were merged to have perfect connections. As a result, there was no failure in the connections between the columns and beam as these connections were merged into one unit and behaved ideally with no weakness as one reinforced concrete frame.

A micro modeling approach was adopted for this research whereby, the mortar joints and interface elements were defined as individual elements to represent a contact areas as in Figure 2-3c above. The interactions between the bricks were modeled by interface behavior in the form of contact elements as in Figure 3-11 below. Interactions between the masonry bricks were defined between the contact surfaces through adjusting the normal and tangential behaviors. The latter supported a friction feature by which the transmission of the shear forces in the interface was taken into account when two surfaces were in contact. In built system in the software were able to account for the friction coefficient as a function of contact pressure as Figure 3.12

below. In this research, penalty formulation with a variable friction coefficient for masonry interaction peaking at of 1.0 was used.

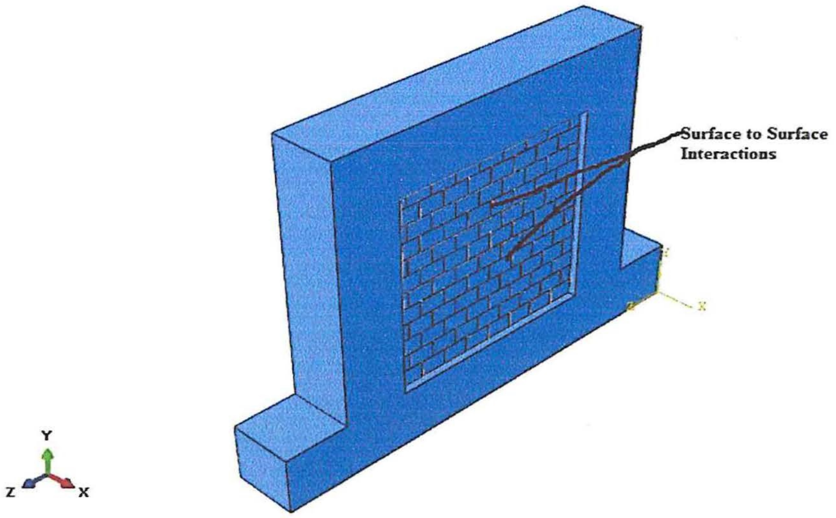

Figure 0-10: Created Interactions

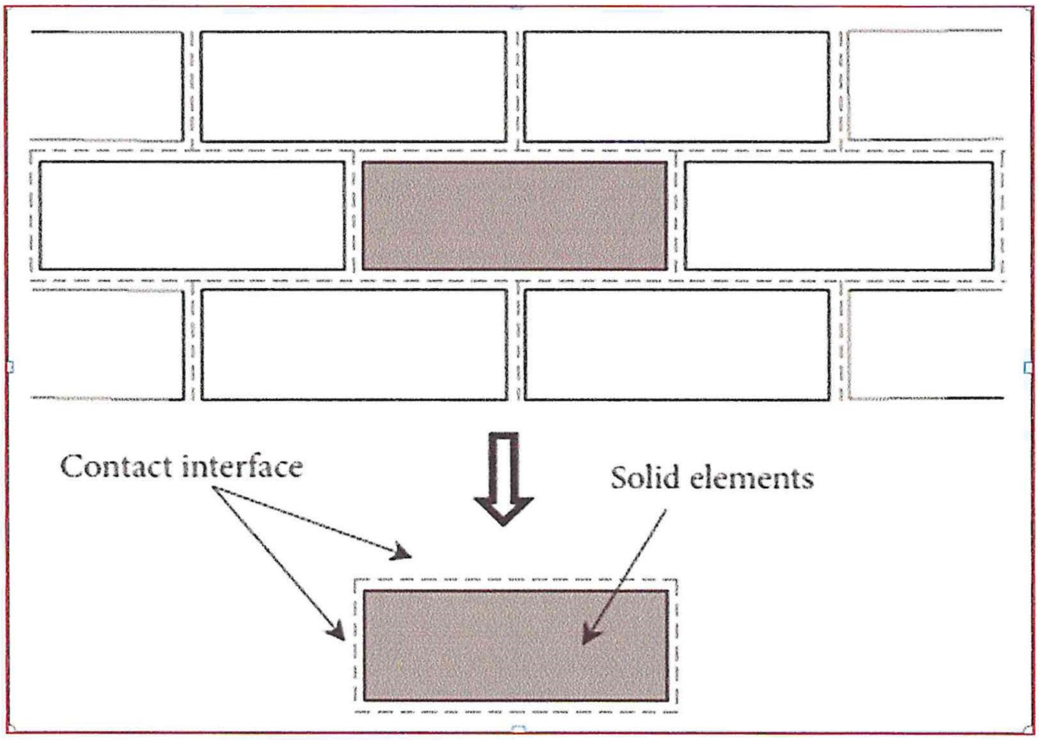

Figure 0-11: Contact interfaces between the masonry elements

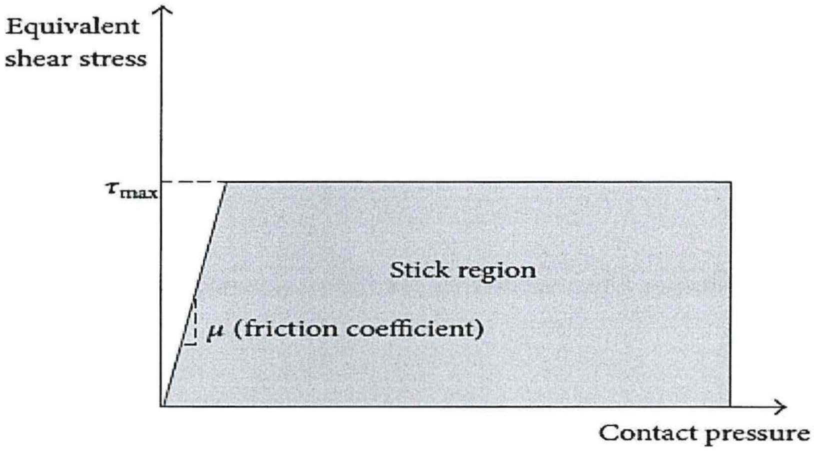

Figure 0-12: Schematic plot of tangential response

3.6.10 Application boundary conditions and loads to the model

Due to the difficulty of simulating restrained ends in the laboratory, it was decided to consider 3-d fixed translations for the entire frame in the research program.
The boundary conditions were applied to those regions of the model where the displacements and/or rotations were known. These regions where constrained to remain fixed with zero displacement and/or rotation during the simulation in all the three directions.

In this model the RC frame was constrained completely in all the three (3) directions (U1, U2 and U3). The frame was considered a rigid body whereby the effect of the pressure loading on the masonry caused insignificant effect.

After constraining the frame, a uniform out of plane load was applied to the face of the infill wall panel in the X-axis with an initial pressure force of $1.0*10^{-5}$N/mm^2 and subsequently in equal increments of 0. $5*10^{-5}$N/mm^2 until failure occurred for each edge support condition. A gravity load was also applied in the negative Y direction.

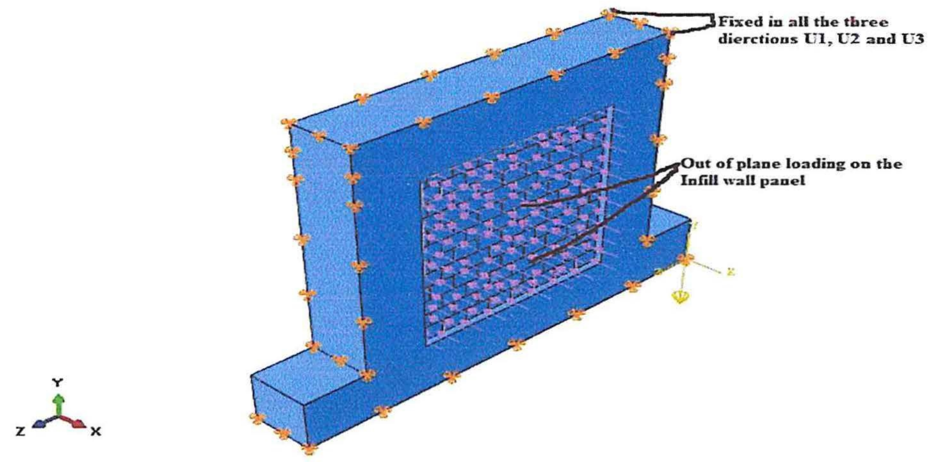

Figure 0-13: Boundary conditions and loading

3.6.11 Meshing the model

The frame and bricks was divided into a mosaic of small structural elements connected only at nodal points along the boundaries of the elements. An appropriate size was used to establish an optimal mesh for modelling the reinforced concrete frame and the bricks. In this model the RC frame and the brick were modelled independently using the following sizes.

Thus the following was considered in meshing.

Maximum edge length for the frame = 50mm

Maximum edge length for the bricks = 220mm

Maximum deviation factor =0.1mm

The Figure 18 below depicts the different meshes of the model parts and assembly

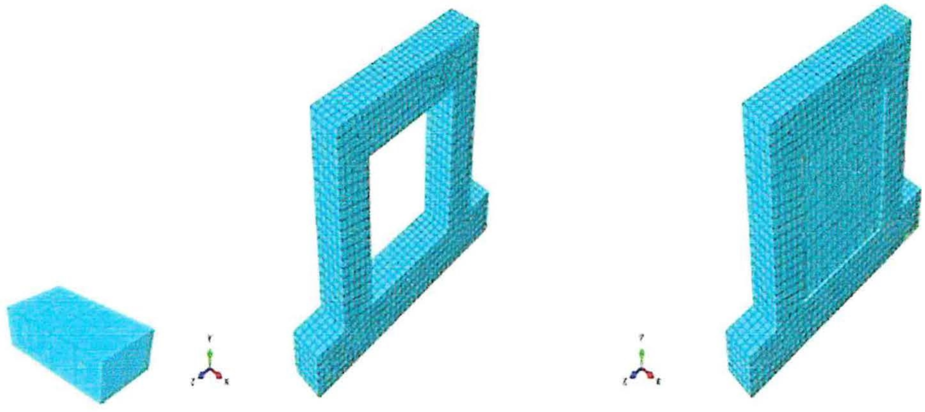

Figure 0-14: Meshed brick, RC frame and assembly

CHAPTER FOUR: DATA ANALYSIS AND DISCUSSIONS

4.1 Baseline surveys analysis

A sample of forty seven (47) for multilevel structures under construction in the Kampala City Council Authority (KCCA) was considered for analysis as in Table 4-1 below.

Table 0-1: Baseline survey results ongoing multi-level constructions in KCCA

Method of infill construction	**Division and corresponding number of structures**					
	Nakawa	Makindye	Rubaga	Kawempe	**Total**	**%age**
Infill wall panel constructed after frame constructed and attached to sides by mortar	03	03	02	02	10	**21.3**
Side RC columns cast with Infill wall panels in place and the soffit of the top beam cast directly on the wall	06	03	04	05	18	**38.3**
Infill wall panel built after construction of columns and attached to columns by mortar and soffit of the beam cast directly on the wall	04	05	02	03	14	**29.8**
Side column cast with Infill panel in place forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall	01	02	02	00	05	**10.6**
Total	**14**	**13**	**10**	**10**	**47**	**100**

The four observed methods of infill wall construction were;

1. Infill panel constructed after frame constructed and attached to the side RC columns and top beam by mortar comprised of 21.3%;
2. Side RC columns cast with Infill wall panels in place and the soffit of the top beam cast directly on the wall comprised of 29.8%;
3. Infill wall panel built after construction of columns and attached to columns by mortar and soffit of the beam cast directly on the wall comprised of 38.3%;
4. Side column cast with Infill panel in place forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall comprised of 10.6%;

4.2 Questionnaire guide analysis

Questionnaires guides were distributed to twenty (20) out of the thirty one (31) leading structural engineering consultancy firms in Uganda as given in appendix 4. The results revealed that 19 out of 20 (95%) do not design for masonry infill walls and do not account for the effect of edge support conditions on the performance of the masonry infill walls. However one firm reported that they had one case where they carried out a design review in a cracked wall and provided for bracing beams in the infills to prevent failures.

4.3 Computer model analysis

The four edge support conditions were subjected to the same loading and boundary conditions but visualisation was done independently for each load case. A uniform out of plane pressure load ranging from $1.0*10^{-5}$N/mm^2 upto $3.00*10^{-4}$N/mm^2 was applied laterally to the infill panel and the spatial nodal displacements and stress distribution for the individual job was visualised for each edge support conditions.

The spatial nodal displacements and stress distribution for first nine readings 1.0 to $5*10^{-5}N/mm^2$ were noted to determine and compare the rate of failure of the infills for each edge support condition as shown Table 4-2 and 4-3 below.

Table 0-2: Variation of spatial displacements ($mm*10^{-1}$)

Edge Support Condition	**Out of plane loads in N/mm^2*10^{-5}**									
	0.0	**1.00**	**1.50**	**2.00**	**1.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**
Displacements for infill panel constructed after frame construction and attached to the RC columns and beams by mortar.- Case1	0.0	1.24	1.86	2.49	3.11	3.73	4.35	4.97	5.60	6.32
Displacements for Side RC columns cast with infill wall panels in place and the soffit of the top beam cast directly on the wall - Case 2	0.0	0.90	1.35	1.80	2.25	2.79	3.14	3.58	4.01	4.50
Displacements for Infill wall panel built after construction of columns and attached to the columns by mortar and soffit of the top beam cast directly on the wall. Case 3.	0.0	1.04	1.55	2.08	2.59	3.11	3.64	4.15	4.66	5.19
Displacements for Side column cast with infill panel in place forming a saw tooth pattern with the columns and soffit of the top beam cast directly on the wall - Case 4	0.0	0.16	0.28	0.47	0.53	0.64	0.76	0.87	0.99	1.10

Table 0-3: Variation Von Misses stresses in N/mm^2*10^{-2}

	Out of plane loads in N/mm^2									
Edge support condition	**0.0**	**1.00**	**1.50**	**2.00**	**2.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**
Stress distribution for infill panel constructed after frame construction and attached to the RC columns and beams by mortar.- Case1	0.0	2.33	2.67	3.04	3.46	3.92	4.23	4.98	5.60	5.95
Stress distribution for side RC columns cast with infill wall panels in place and the soffit of the top beam cast directly on the wall - Case 2	0.0	2.01	2.18	2.35	2.54	2.76	3.09	3.30	3.60	3.91
Stress distribution for infill wall panel built after the construction of the columns and attached to the columns by mortar and soffit of the top beam cast directly on the wall. Case 3.	0.0	2.23	2.50	2.79	3.29	3.82	4.23	4.56	4.98	5.82
Stress distribution for side column cast with infill panel in place forming a saw tooth pattern with the columns and soffit of the top beam cast directly on the wall - Case 4	0.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0

The spatial displacements and stress distribution for each edge support condition was plotted against the applied out of plane loads and Figure 4-1 and 4-2 below shows the variation for each individual edge support condition

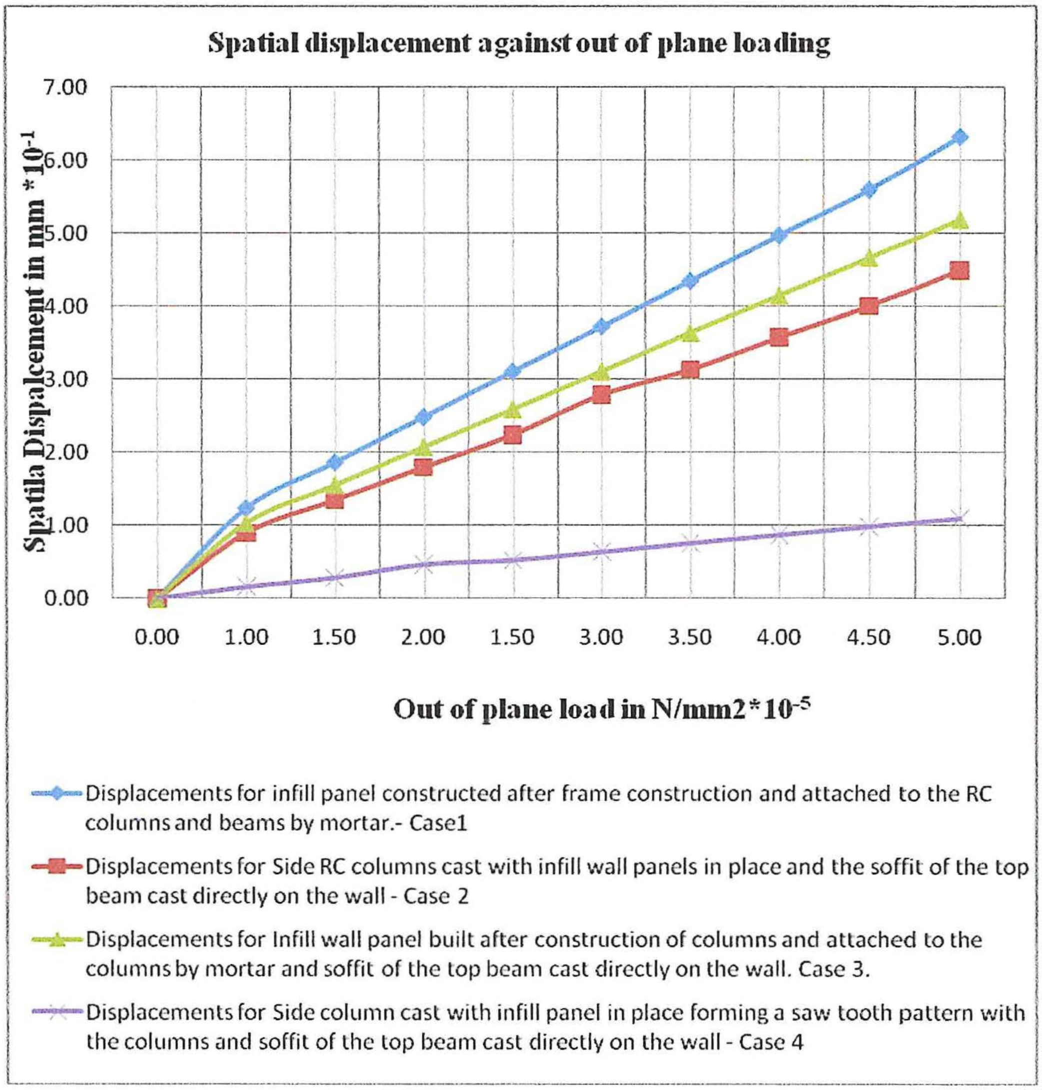

Figure 0-1: Variation of spatial displacements against out of plane loading.

Spatial displacements increased non-linearly with increase in the out of plane loading and were dependent on the edge support condition under consideration.

Infill panel constructed after frame is constructed and attached to the side RC columns and top beam by mortar (case 1) experienced the highest rate of spatial displacement which depicted early failure. While infill wall panel cast with frame forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall (case 4) experienced the lowest rate spatial displacement and thus depicting late failure.

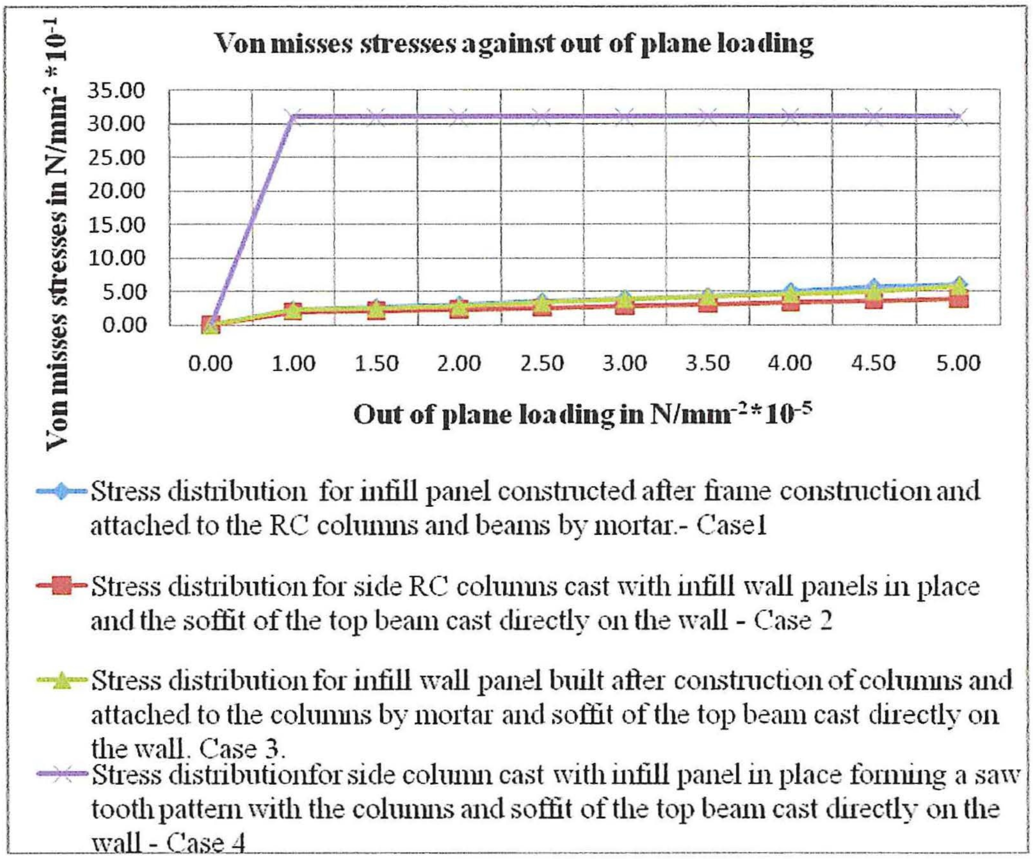

Figure 0-2: Variation of von misses stresses against out of plane loading.

The stress distribution increased non-linearly with increase in the loading for cases 1, 2 and 3 but for case 4 it remained a constant irrespective of the increase in the load intensity. Infill wall panel cast with frame forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall (case 4) induced the very high stresses in the supporting frame predicting increased stiffness in the beams and columns. The other three types of edge support conditions induced very low stresses.

Application of out of plane load continued on the infill wall panels until failure for each individual edge support condition. It was realized that panel failure depended on the type of edge support condition in use with different loading intensities as shown in the Figures 4-3 to 4-10 below.

Figures 4-3 and 4-4 show the nodal spatial displacement and stress distribution for infill panel constructed after frame construction and attached to the side RC columns and top beam by mortar- Case 1.

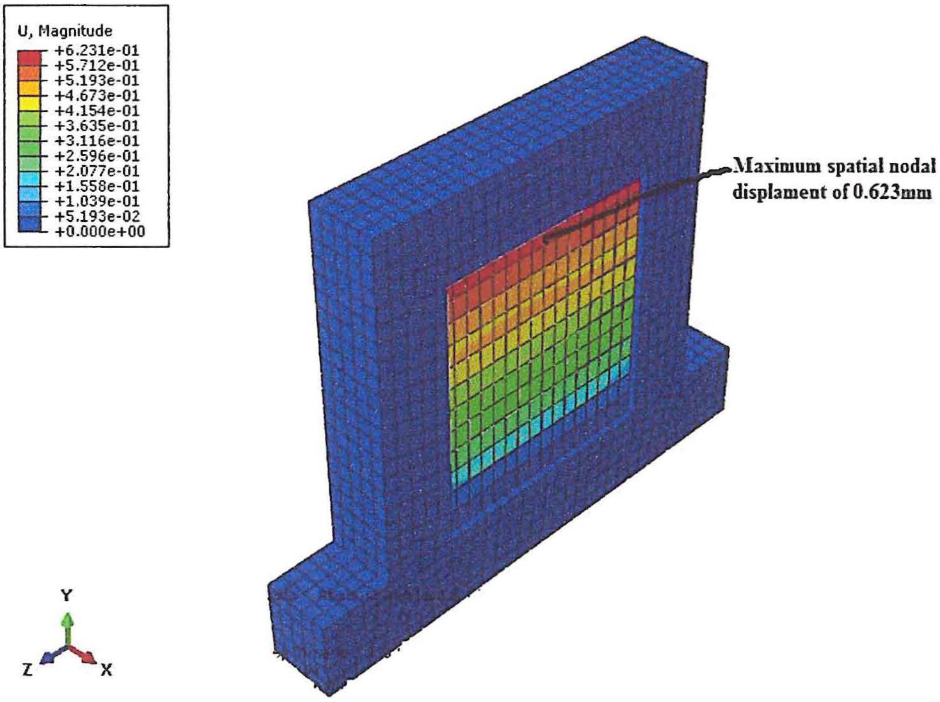

Figure 0-3: Nodal spatial displacements for case 1 under a load of $5.0*10^{-5}$N/mm^2

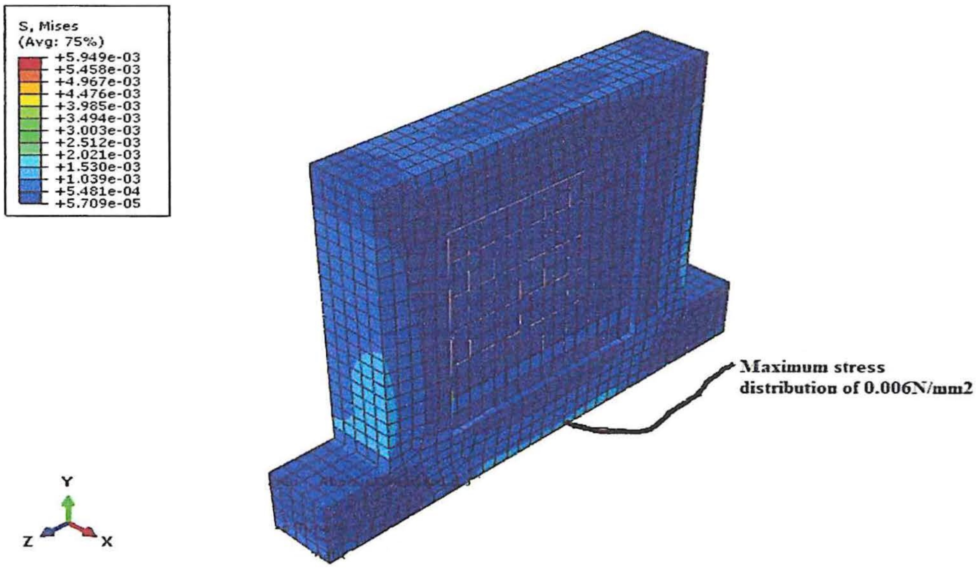

Figure 0-4: Stress distribution for case 1 under a load of $5.0*10^{-5}$N/mm^2

Figures 4-5 and 4-6 show the nodal spatial displacement and stress distribution for side RC columns cast with Infill wall panels in place and the soffit of the top beam cast directly on the wall attached such that the load on the wall generates friction at the bottom and top to prevent lateral movement- case 2.

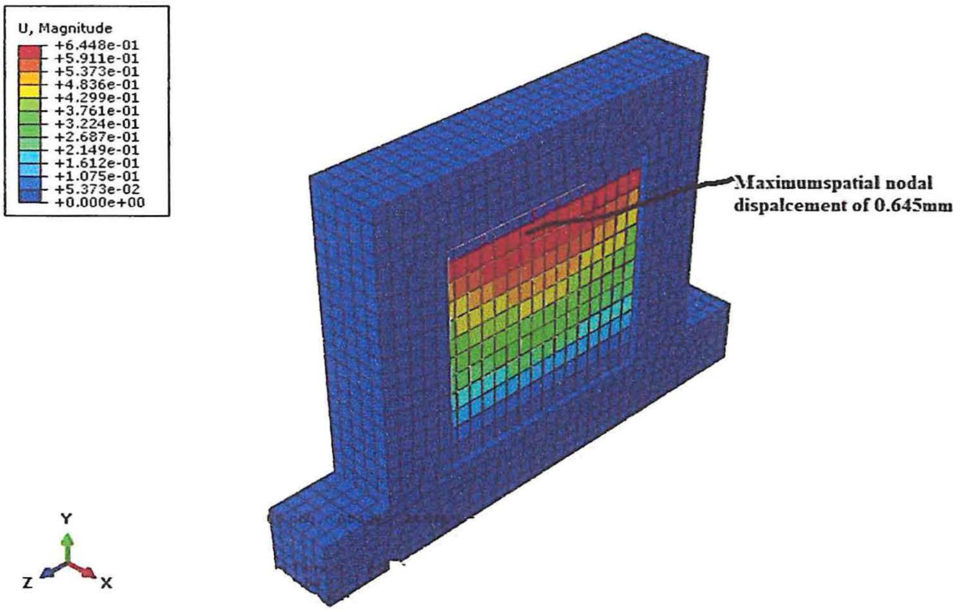

Figure 0-5: Nodal spatial displacement for case 2 under a load of $1.0*10^{-4}N/mm^2$

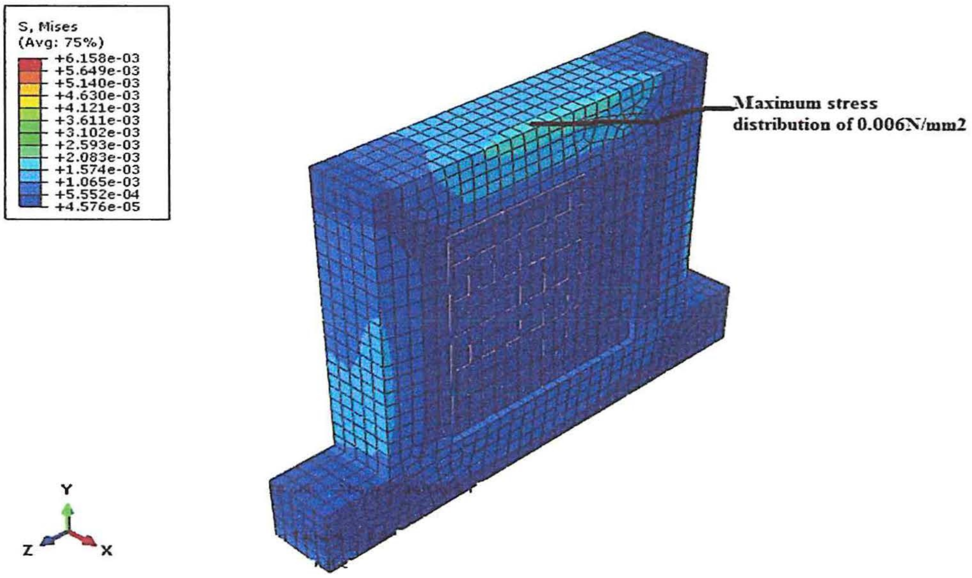

Figure 0-6: Stress distribution for case 2 under a load of $1.0*10^{-4}N/mm^2$

Figures 4-7 and 4-8 show the nodal spatial displacement and stress distribution for infill wall panel built after construction of columns and attached to columns by mortar and soffit of the beam cast directly on the wall - case 3.

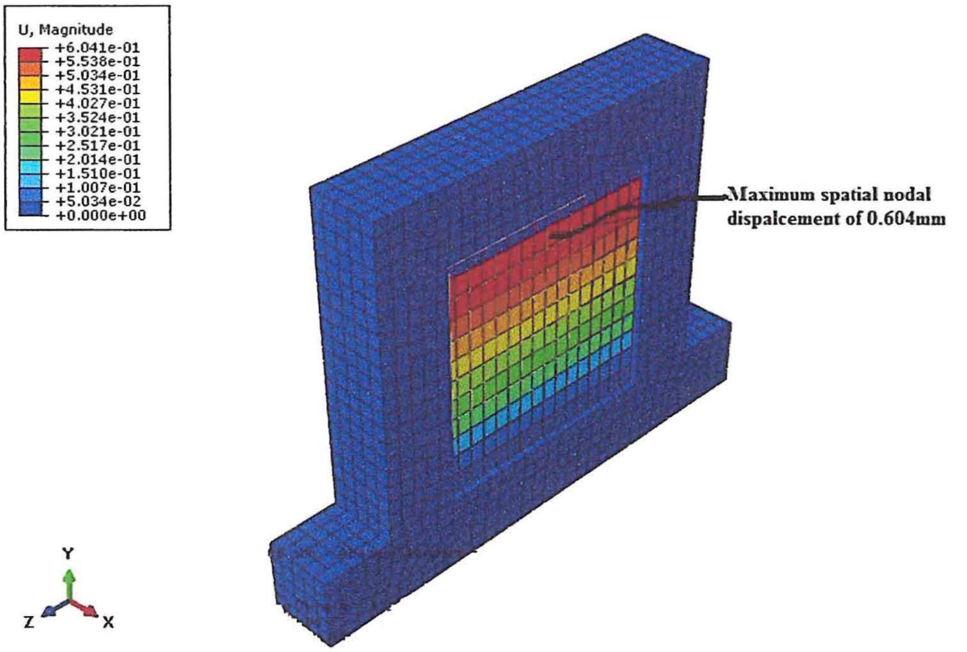

Figure 0-7: Nodal spatial distribution for case 3 under a load of 8.0*10^{-5}N/mm^2

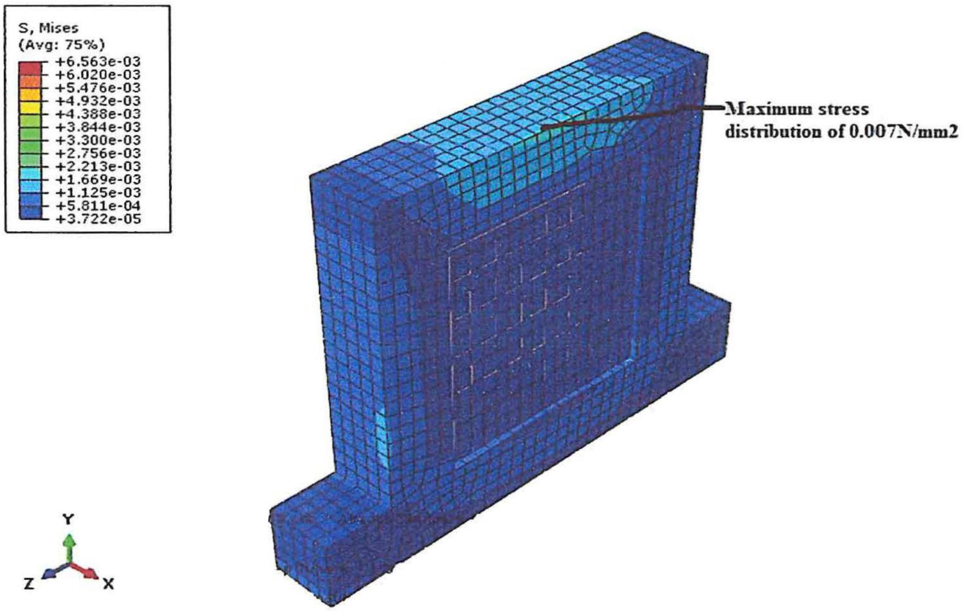

Figure 0-8: Stress distribution for case 3 under a load of 8.0*10^{-5}N/mm^2

Figures 4-9 and 4-10 show the nodal spatial displacement and stress distribution for side column cast with Infill panel in place forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall - case 4.

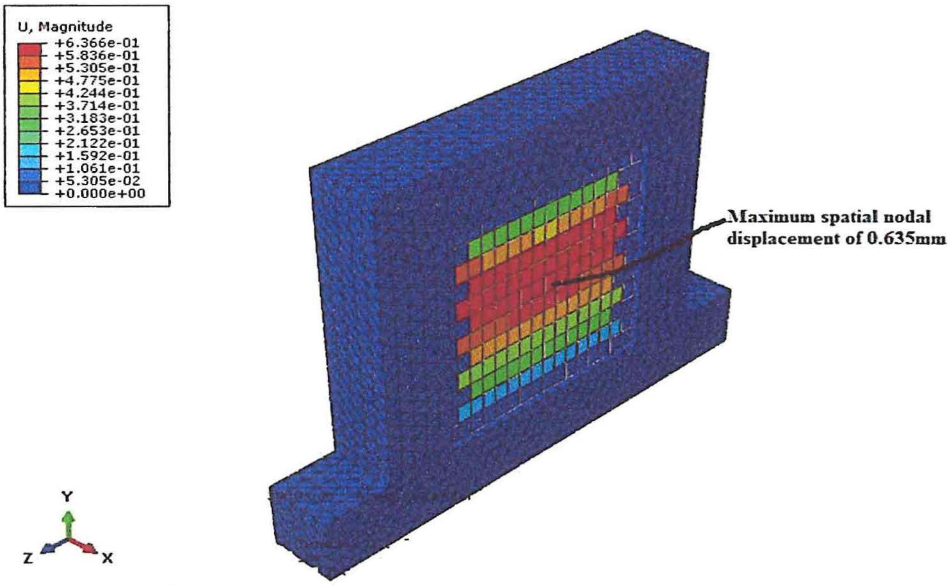

Figure 0-9: Nodal spatial displacement for case 4 under a load of $3.0*10^{-4}$N/mm^2

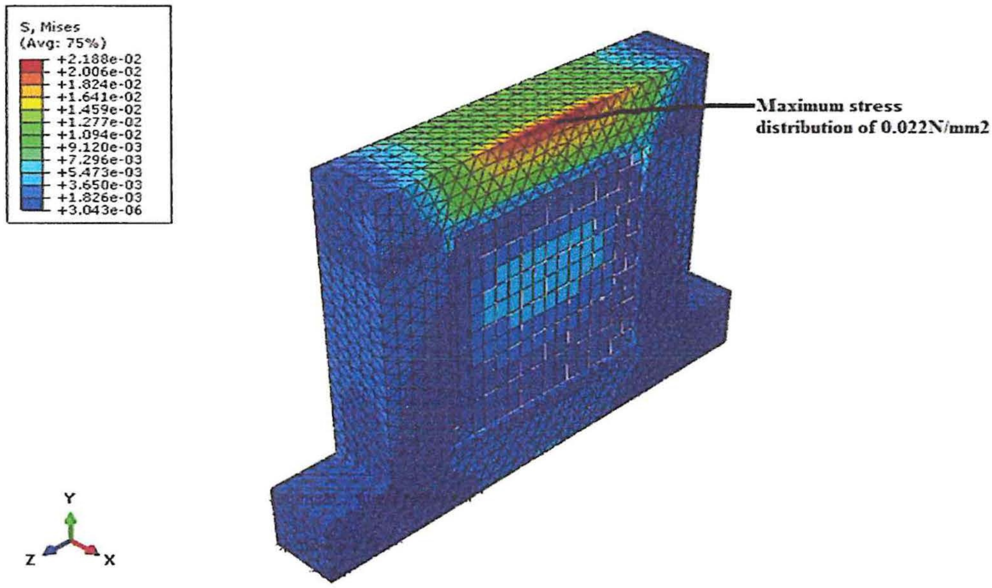

Figure 0-10: Stress distribution for case 4 under a load of $3.0*10^{4}$N/mm^2

Results of the spatial nodal displacement and the stress distributions for each edge support condition case at failure and the corresponding failure loads are shown it Table 4-4 below

Table 0-4: Results at out of plane failure with the corresponding out of plane load

Edge support condition case	**Maximum spatial nodal displacement in mm**	**Maximum stress distribution in the frame in N/mm^2**	**Pressure Load at failure in the panel in N/mm^2**
Case 1	0.623	0.006	0.00005
Case 2	0.644	0.006	0.0001
Case 3	0.604	0.007	0.00008
Case 4	0.635	0.022	0.0003

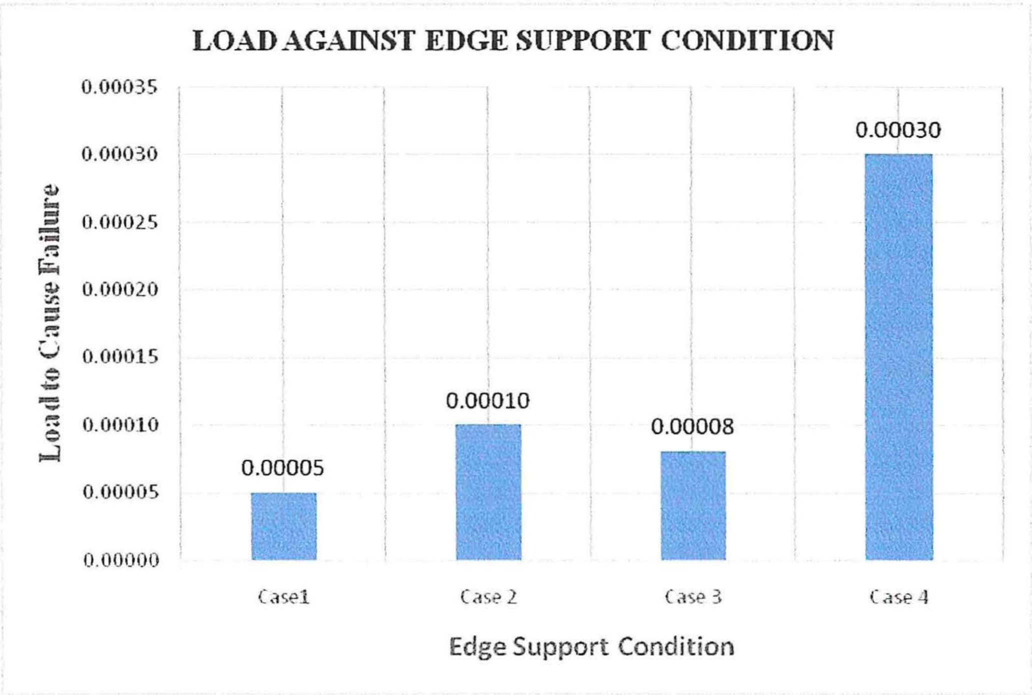

Figure 0-11: Out of plane failure loads for the different edge support conditions

From the analysis, the maximum nodal spatial displacement occurred in the range of 0.6mm for all the panels. However the out of plane loads to cause maximum displacement ranged from $5.0*10^{-5}N/mm^2$ for panel case 1 upto a maximum of $3.0*10^{-4}N/mm^2$ recorded for panel of case 4.

The individual out plane loads to cause failure loads for each edge support condition were:-

i. Infill panel constructed after frame constructed and attached to the side RC columns and top beam by mortar (Case 1) failed at $5.0*10^{-5}N/mm^2$ which was one sixth (1/6) of maximum analyzed load;

ii. Side RC columns cast with Infill wall panels in place and the soffit of the top beam cast directly on the wall (Case 2) failed at $1.0*10^{-4}N/mm^2$ which was one third (1/3) of maximum analyzed load;

iii. Infill wall panel built after construction of columns and attached to columns by mortar and soffit of the beam cast directly on the wall (Case 3) failed at $0.8*10^{-5}N/mm^2$ which was about one quarter (1/4) of maximum analyzed load;

iv. Side column cast with Infill panel in place forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall (Case 4) failed at $3.0*10^{-4}N/mm^2$ which was the maximum analyzed load;

From the above results, it is implied that the construction method where the side columns is cast with the Infill panel in place forming a saw tooth pattern with the columns and the soffit of the beam cast directly on the wall offers the highest resistance to out of plane loading and hence considered the best option.

It was also realized that the side column cast with the Infill panel in place forming a saw tooth pattern with the columns and the soffit of the beam cast directly on the wall induced highest stresses of $2.2*10^{-2}N/mm^2$ in the columns and beams which was about three times the other three edge support conditions. This implies that infill panel acts together with the beams and columns to resist the load.

CHAPTER FIVE: CONCLUSION AND RECOMEDATIONS.

5.1 Conclusion

In this research it was found out that there are four common types of edge support conditions used in the Uganda construction industry. The most dominant type was where the infill wall panel was built after construction of columns and attached to columns by mortar and the soffit of the beam cast directly on the wall (Case 3) with 36%. The least dominant type was where the side columns were cast with Infill panel in place forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall (Case 4) with 10%.

It was also found out that the choice of adoption of the edge support condition for use was not regularized as the consulting engineers do not account for them in design. This created uncertainties in choosing the most optimum type and enforcing proper construction controls and hence leaving the industry unguided.

During the computer modeling the four different infill edge support configurations were analysed and the results showed that:

i. Different failure patterns can occur for the infill walls depending on the support conditions and the interface with the main frame;

ii. The rate of spatial displacement was dependent on the individual edge support condition and loading.

iii. Infill wall panel cast with the frame forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall (Case 4) resisted the highest load before failure.

iv. This case was considered the best edge support condition for the performance of infill walls panel against out of plane loading.

A finite element model was successfully constructed and developed using ABAQUS software. It was observed that the edge support conditions positively contribute to the performance of masonry infill walls when subjected to out of plane loading and the net effect was dependent on the type of edge support condition adopted for use.

This knowledge will be useful for future applications of this model for the effective screening of seismically vulnerable RC buildings. The results from this research will also be useful to the policy makers in the formulation and final development of the Uganda National codes.

5.2 Recommendations

It is therefore recommended that:

i. Civil Engineering Consulting firms should make consideration for edge support conditions in their designs;

ii. Side column cast with Infill wall panels in place forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall is recommended as the best method to minimize out of plane failures.

iii. Further research should be done with other types of type of construction materials other than RC and burnt clay brick.

REFERENCES

- Noorifard A., Tabeshpour M. R., Saradj F. M. (2016), Experimental studies on preventing irregularity effects of infills through modifying architectural drawings, Architecture Civil Engineering Environment 9(2).
- Furtado, A., Rodrigues, and H., Arêde, A. (2016). Experimental evaluation of out-of-plane capacity of masonry infill walls. Journal of Engineering Structures, 111:48-63.
- Noorifard A., Tabeshpour M. R., Saradj F. M.(2015), Effect of infills on torsion and softstorey in a conventional residential building in Tehran-Iran, 7th International Conference on Seismology & Earthquake Engineering.
- Noorifard A., Tabeshpour M. R., Vafamehr M., Saradj F. M. (2014), Effective measures in design process of conventional medium-rise buildings to prevent detrimental seismic effects of walls, 2nd Seminar on Structural Investigation of Non- Structural Elements, Tehran, Iran.
- Porto, F.d., Guidi, G., Benetta, M.D., and Verlato, N. (2013) Combined in-plane/out-of-plane Experimental Behaviour of Reinforced and Strengthened Infill masonry walls. 12th Canadian Masonry Symposium.
- Rodrigues H, Varum H, Costa A (2010) Simplified macro-model for infill masonry panels. J Earthquake Eng 14:390–416.
- Fódi, A., Bódi, I. (2010), "Comparison of shear behavior of masonry walls with and without reinforcement", Pollack Periodical, Vol. 5, No. 3, pp.71-82.
- Hashemi, A. and Mosalam, K. M. (2006). Shake-Table Experiment on Reinforced Concrete Structure Containing Masonry Infill Wall. Earthquake Engineering and Structural Dynamics 35, 1827-1852.

- Drysdale, R.G., and Hamid, A.A. (2005). Study on masonry structures behaviour and design. Mississauga, Ontario: Canadian Masonry Design Centre.
- Henderson R. C., Fricke K. E., and Jones W. D. (2003). Summary of a large- and small-scale unreinforced masonry infill test Program. Journal of Structural Engineering, ASCE, 129(12): 0733-9445.
- El-Dakhakhni WW, Elgaaly M, Hamid AA (2003). Three-Strut Model for Concrete Masonry-Infilled Steel Frames. J. Struct. Eng., pp. 177-185.
- Dafnis, A., Kolsch, H., and Reimerdes, H. (2002). Arching in masonry walls subjected to earthquake motions. Journal of Structural Engineering, ASCE,128(2): 153-159.
- Al-Chaar G (2002). Evaluating Strength and Stiffness of Unreinforced Masonry Infill Structures. Construction Engineering Research Laboratory.
- Calvi G. M., Bolognini, D. (2001). Seismic Response of Reinforced Concrete Frames Infilled with Masonry Panels Weakly Reinforced. Journal of Earthquake Engineering 5: 2, 153-185.
- Euro code 6 EN 1996-1-1:2009, Design of Masonry Structures, 2009. European standard.
- Abrams, D. P., EERI, M., Angel, R., Uzarski, J., (1996). Out-of-plane strength of unreinforced masonry infill panels. Earthquake Spectra, 12(4)825-844.
- Asteris, P. G. (1996). "A method for the modeling of infilled frames (Method of Contact Points." Proc., 11th World Conf. on Earthquake Engineering, Paper No. 953, Acapulco, Mexico.
- Mehrabi, A.B., Shing, P.B., Schuller, M. and Noland, J. (1996). "Experimental evaluation of masonry-infilled RC frames", J. Struct. Eng., 122(3), 228-237.

- Lourenço, P. B., (1996). Computational strategies for masonry structures, Delft University Press, ISBN 90-407-1221-2.
- Negro P., Verzeletti, G. (1996). Effect of Infills on the Global Behavior of Frames: Energy Considerations from Pseudo dynamic Tests. Earthquake Engineering and Structural Dynamics, 25: 8, 753-773;
- Lourenco, P. B., J. G. Rots, J. Blaauwendraad,(1995) "Two Approaches for the Analysis of Masonry Structures: Micro-and Macro-Modeling", Heron, Vol. 40, No. 4, 1995, pp. 313-340.
- Angel, R. (1994). Behavior of reinforced concrete frames with masonry infill walls. Ph.D. Dissertation, the University of Illinois at Urbana-Champaign;
- Flanagan, R. D., and Bennett, R. M. (1993). Uniform lateral load capacity of infilled frames. 1994 ASCE Structure Congress.
- Mehrabi AB, Shing PB. (1994) Performance of Masonry-Infilled R/C Frames under In-Plane Lateral Loads: Analytical Modelling. Proceedings from the NCEER Workshop on Seismic Response of Masonry. San Francisco, California. p. 45-50.
- Angel, R., Abrams D.P., Shapiro D., Uzarski J. and Webster M. (1994), "Behavior of reinforced concrete frames with masonry infills", Structural research series report, 589, Department of Civil Engineering, University of Illinois.
- Paulay, T. and Priestley, M.J.N. (1992) "Seismic Design of Reinforced Concrete and Masonry Buildings" Wiley, 744pp.
- Dawe, J. L., and Seah C. K. (1989). Out-of-plane resistance of concrete masonry infilled panels. Canadian Journal of Civil Engineering, 16:854-864.

- Anderson, H., (1984). Arching action in transverse laterally loaded masonry wall panels. The Structural Engineer, 62B(1)12-23.
- Dhanasekar, M. and Page, A.W. (1986). "Influence of brick masonry infill properties on the behavior of infilled frames", Proc., Instn. Civ. Engrs., London, Part 2, 81, 593- 605.
- Dhanasekar 1984: Dhanasekar, M., A. W. Page, P. W. Kleeman, "A Finite Element Model for the In-Plane Behavior of Brick Masonry", Proc. 9th Australasian Conference on Mechanisms of Structures, 1984, pp. 262-267.
- Bertero V, Brokken S. Infills in seismic resistant building. Journal of Structural Engineering (ASCE). 1983; 109:1337–61.
- Gabrielsen, and Kaplan K. (1976). Arching in masonry walls subjected to out-of-plane forces. NBS Building Science Series 106, National Workshop on Earthquake Resistant Masonry Construction.
- Gabrielsen, B., Wilton C., and Kaplan K. (1975). Response of arching walls and debris from interior walls caused by blast loading. Report No 7030-23, URS Research Company, San Mateo, Ca.
- Mainstone RJ (1974). Supplementary Note on the Stiffness and Strengths of Infilled Frames. Building Research Station UK, Current Paper 13/74.
- Mainstone RJ, Weeks GA (1970). The Influence of Bounding Frame on the Racking Stiffness and Strength of Brick Walls. 2nd International Brick Masonry Conference held at Watford, England, pp. 165-171.
- Fiorato, A.E, Sozen, M.A., & Gamble, W.L. (1970) "An Investigation of the Interaction of Reinforced Concrete Frames with Masonry Filler Walls." Report No. UILU-ENG 70-100, University of Illinois, Urbana-Champaign, IL.

- Smith BS, Carter CA (1969). Method of Analysis for Infilled Frames. Proc. ICE., pp. 44: 31-48.
- Smith BS (1968). Model Test Results of Vertical and Horizontal Loading of Infilled Specimens. ACI J. August, pp. 618-624.
- Smith BS (1967). Methods for Predicting the Lateral Stiffness and Strength of Multi-Storey Infilled Frames. Build. Sci., 2: 247-257.
- Smith BS (1966). Behavior of Square Infilled Frames. ASCE J. Struct. Div., 92, ST.
- Rosenhaupt 1965: Rosenhaupt, S., Y. Sokal, "Masonry Walls on Continuous Beams", J. Structural Division, ASCE, Vol. 91, No ST1, 1965, pp. 155-171.
- Smith BS (1962). Lateral Stiffness of Infilled Frames. ASCE J. Struct. Div., 88: 183-199.
- Polyakov SV (1957). Masonry in Framed Buildings; an Investigation into the Strength and Stiffness of Masonry Infilling (English Translation), Moscow.
- Monk, C.B. (1958). Resistance of structural clay masonry to dynamic forces. Research Report No.7, Structural Clay Products Research Foundation, Geneva, Illinois. McDowell, E. L., McKee, K. E., and Sevin, E., (1956). Arching action theory of masonry walls. Journal of the Structural Division, Proceeding of ASCE, 82(2)915-1-915-18.
- Euro code 6 EN 1996-1-1:2009, Design of Masonry Structures.
- NIV Bible, Genesis 11:3-4.

APPENDICES

Appendix 1: Schedule

The research period was Thirteen (13) month see detail below

ACTIVITY	**1-Sep-31-Oct 2017**				**1Nov – 31 Dec 2017**				**1Jan -28 Feb 2018**				**1Mar – 30 Apr 2018**				**1May - 30Jun 2018**				**1Jul 31Aug. 2018**			**1Sept- 31Oct 2018**				
Introduction & Problem Statement	▨	▨	▨	▨	▨																							
Defense of proposal						▨																						
Literature Review							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
Methodology							▨	▨	▨	▨																		
Model Development											▨	▨	▨	▨														
Model Analysis															▨	▨	▨	▨	▨	▨								
Conclusion and Recommendations																					▨	▨						
Draft report and consultations																						▨	▨	▨				
Final Report																								▨	▨			
Submission To Post Graduate																										▨		
Corrections																										▨		
Defense of report																										▨		
Final Adjustment																											▨	
Final Submission																												▨

Appendix 2: Research Budget

The budget for this research will be as shown below:

Activity	*Cost in Ug Shs*
Computer and software	5,700,000
Downloads of literature from the internet	1,800,000
One year's subscription for relevant journals	2,200,000
Secretarial and type setting	450,000
Stationary including photocopies	900,000
Access to library materials from private libraries	750,000
Transport	1,750,000
Total	**10,985,000**

Appendix 3: Survey tool for the baseline surveys

Name of project	Type of Structural Frame	Type of Infill	Mode of Edge support

Appendix 4: Leading Consulting Firms in Uganda

S/N	Name of Firm	Action taken	Result
1	Structural Concepts ltd	C	R
2	Air Water Earth Ltd	C	R
3	Associated Engineering Services (AES)	C	R
4	Armstrong Consulting Engineers Ltd	C	R
5	Aurecon Engineering (U) Ltd	C	R
6	Emsult Engineers Ltd	NC	N/A
7	FBW Uganda Limited	C	R
8	Infrastructure Projects Limited (IPL)	C	R
9	CIC (U) Limited.	NC	N/A
10	KOM Consult Ltd	C	R
11	MBW Consulting Limited	C	R
12	M & E Associates Ltd	C	R
13	M & E Associates Ltd	NC	N/A
14	Newplan Limited	C	R
15	Professional Engineering Consultants Ltd	C	R
16	Gem Engineering Co. Ltd	NC	N/A
17	Prome Consultants	C	R
18	SEKA Associates	C	R
19	TB3 Global Ltd	C	R
20	UB Consulting Engineers Ltd	C	R
21	Kagga & Partners Ltd	C	R
22	Creek Consult Ltd	NC	N/A

23	COWI (U) Ltd	C	R
24	Fencon Consulting Engineers Ltd	NC	N/A
25	Gauff Consultants (U) Ltd	NC	N/A
26	Proman Consult Ltd	C	R
27	Multiplan Consulting Engineers	C	R
28	Multiplan Consulting Engineers	NC	N/A
29	Newplan Limited	NC	N/A
30	Technology Consults Limited	NC	N/A
31	Trio Consultants Limited	NC	N/A

Key:

C- Contacted

NC –Not Contacted

R- Responded

N/A –Not Applicable

Appendix 5: Questionnaire guides to Structural Engineering Consultancy Firms

1. During the design and construction of multilevel structures, the main structural frame is always filled with other non-structural elements.

		Rate of Application		
Sn	Material type	Mostly =2	Rarely = 1	Never = 0
I	Burnt clay bricks			
Ii	Burnt clay hollow blocks			
Iii	Solid concrete blocks			
Iv	Hollow concrete blocks			
V	Glass			
Vi	Any other			

2. What is the reason for preferring the most commonly used material in 1 above?

		Rate of consideration		
Sn	Choice	Mostly =2	Rarely = 1	Never = 0
I	Cost			
Ii	Availability			
iii	Strength			
Iv	Build ability			
V	Any other			

3. What are the applicable standards used in design of masonry infills?

		Rate of consideration		
Sn	Standard	Mostly =2	Rarely = 1	Never = 0

I	BS5628			
ii	Euro code 6			
iii	Euro code 8			
iv	In combination of i &iii			
v	In combination of ii &iii			
vi	Any other			

4. Are the infill walls designed to carry lateral loads (seismic, wind etc), gravity or any other load? YES or NO

5. How are these infill walls attached to the beams, columns and slabs?

		Rate of consideration		
Sn	Standard	Mostly =2	Rarely = 1	Never = 0
I	Infill panel constructed after frame construction and attached to the side RC columns and top beam by mortar. This is modeled as simply supported at the bottom and free on the other three sides. Figure a			
ii	Side RC columns cast with Infill wall panels in [lace and the soffit of the top			

	beam cast directly on the wall attached such that the load on the wall generates friction at the bottom and top to prevent lateral movement. This is considered as wall restrained at the bottom and top but simply supported at the vertical sides Figure b			
iii	Infill wall panel built after construction of columns and attached to columns by mortar and soffit of the beam cast directly on the wall. The infill wall panel is modeled as restrained at the base and top beam but free on the two vertical sides Figure c			
iv	Side column cast with			

	Infill panel in place forming a saw tooth pattern with the columns and soffit of the beam cast directly on the wall. This is modeled as restrained on all the four sides. Figure d			

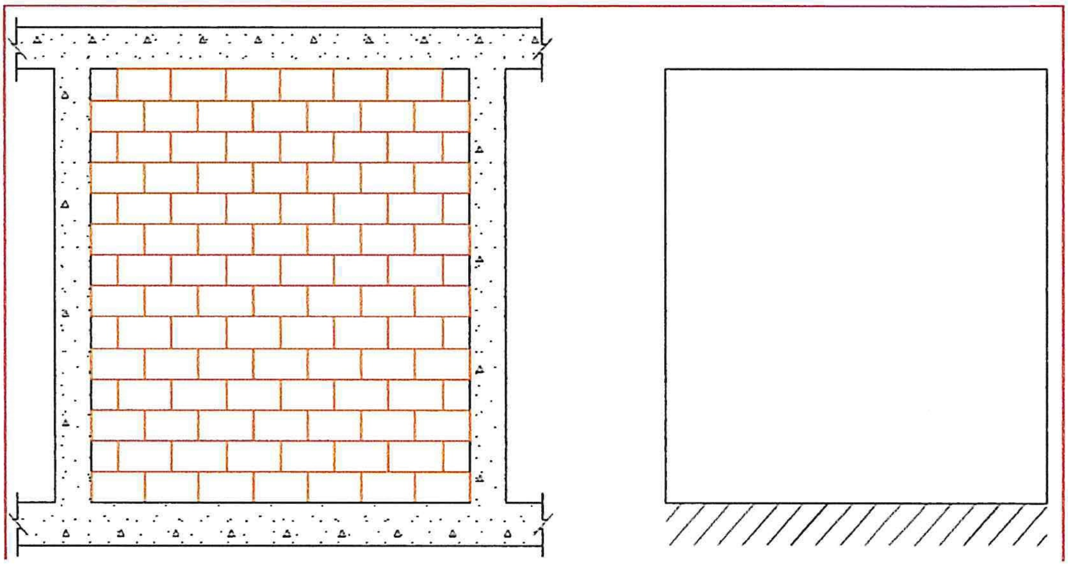

Figure a: Wall simply supported at the bottom and free on the other three sides

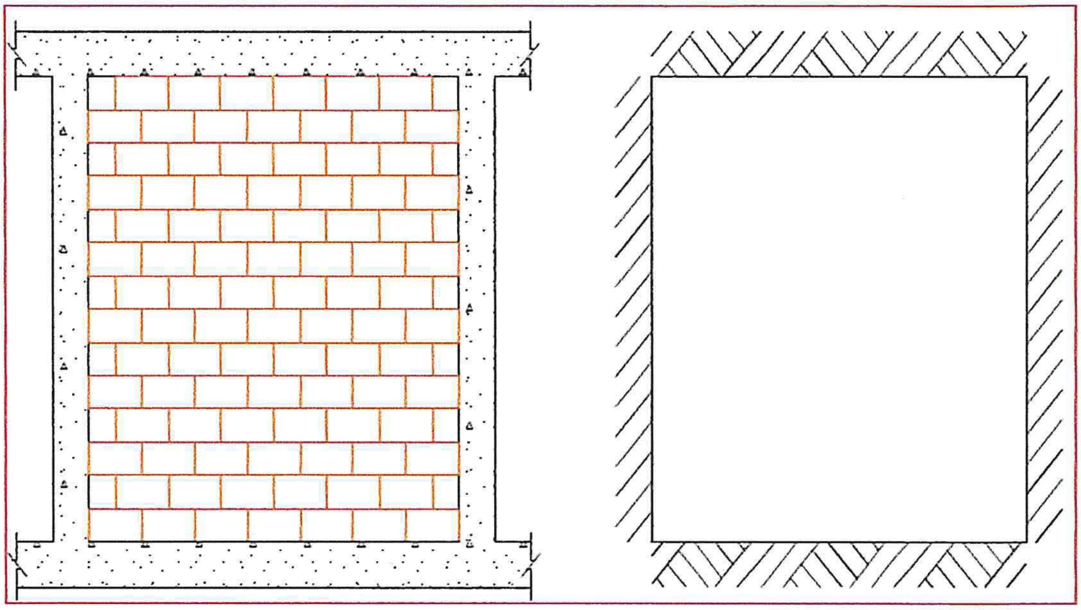

Figure b: Fixed at the bottom and top to the RC frame and simply supported at the sides

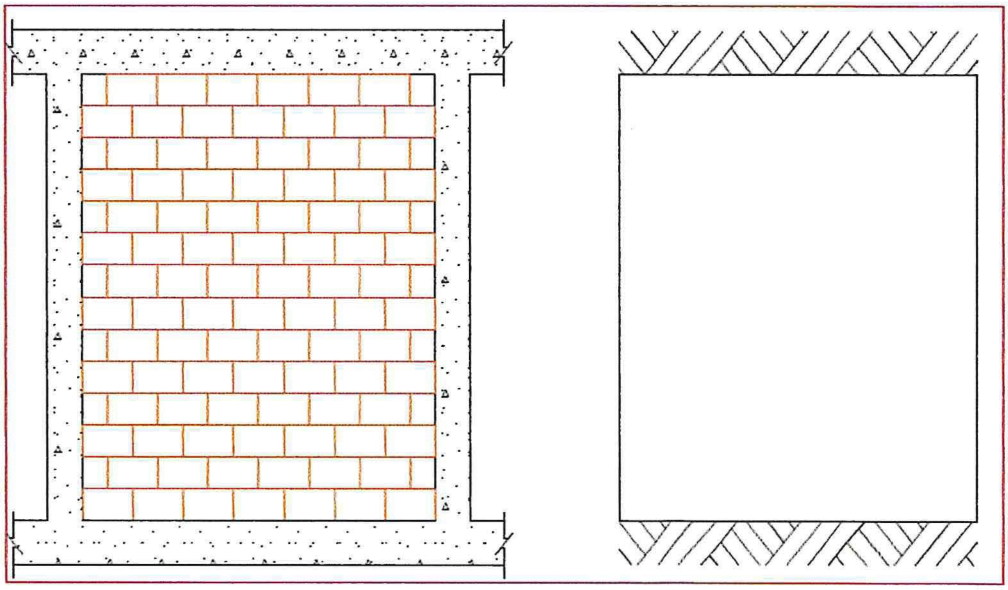

Figure c: Fixed at the bottom, free on the two vertical sides and fixed to the RC beam

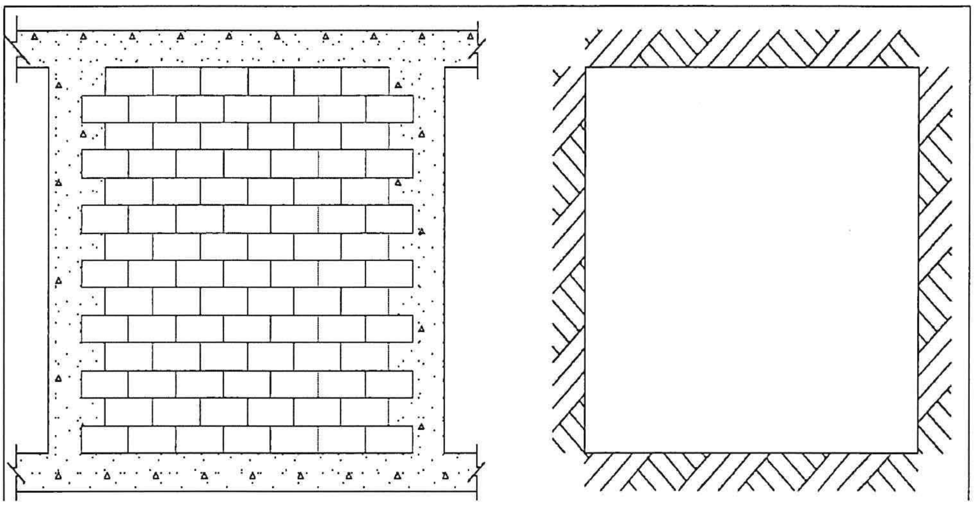

Figure d: Fixed at the bottom, fixed on the vertical sides by saw toothing and fixed on the top to the RC beam

6. In the design for the infill wall -frame interaction, what are loading conditions considered?

   i. In-plane Loading
   ii. Out plane loading
   iii. Both in plane loading and out of plane loading.

7. How many designs of multi-level structures (3-5 levels) have been made with consideration to masonry infills within the period 2012-2018 in the;

		Number of structures		
Sn	Locality	>10	5-10	0-5
I	KCCA Jurisdiction			
Ii	Outside KCCA Jurisdiction			

Appendix 5: Ongoing construction with masonry infills