CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Dynamic Response of Interlocking Plastic-Block Walls with Diaphragm using Numerical Approach

by

Hammad Bashir

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Dedicated this work to my parents, for always supporting and helping me throughout my education. Specially to my teachers who guided me to face the troubles with boldness.

CERTIFICATE OF APPROVAL

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Abstract

Economical earthquake-resistant housing is prudent in seismic active regions for developing countries. Because of lack of earthquake-resistant housing, there is significant loss of life in seismic regions. Rural areas often suffer loss of lives due to strong ground motions of earthquakes. Conventional masonry structures collapse in the result of large displacement and strong horizontal ground motions. Many of the methods are used to minimize the effects of the earthquakes. Earthquake-resistant housing needs to be built in developing countries. Interlocking block structure is among one of the possible alternative for earthquake-resistant structures.

The dynamic behavior of interlocking block structures are well-known by many researchers. But the interlocking plastic-block structures are still not completely explored. In this research work, the experimental results of interlocking plastic block structural components have verified with the numerical study. The specific goal of current research is to determine the dynamic behavior of structures using the numerical method. The structure consists of two plastic-block walls, wooden diaphragm and rubber band connection. Finite element method is used for modeling of structure in Ansys19 products.

Dynamic response in terms of acceleration-time and displacement-time histories of wooden diaphragm and interlocking plastic-block walls are observed. Base shear-displacement curves, energy dissipation, and damping has also calculated. Effect of diaphragm on walls and effect of wall with opening has determined in this research. As predicted, results are observed from graphs that by using wooden diaphragm relative displacement at top of interlocking plastic-block walls can be reduced and more energy can be dissipated.

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Abbreviations

1D	One Dimensional
3D	Three Dimensional
E	Energy Absorption
FEAP	Finite Element Analysis Program
FEM	Finite Element Modeling
IPBW	Interlocking Plastic-Block Wall
IPBWW	Interlocking Plastic-Block Wall with Window
MPa	Mega Pascal
Pa	Pascal
RB	Rubber Band
SDOF	Single Degree of Freedom
WD	Wooden Diaphragm

Symbols

$\ddot{u}_g$	Average accleration at base
$\ddot{u}_{t-E}$	Average experimental acceleration
$\ddot{u}_{t-N}$	Average numerical acceleration
$\ddot{u}_t$	Average accleration at top of Interlocking plastic-block strucure
$\ddot{u}_{t-IPBSW}$	Average accleration at top of solid wall
$\ddot{u}_{t-IPBWW}$	Average accleration at top of wall with window opening
$\dot{u}_{t-E}$	Average experimental velocity
$\dot{u}_{t-N}$	Average numerical velocity
u_{t-E}	Average experimental displacement
u_{t-N}	Average numerical displacement
$u_{t-IPBSW}$	Average displacement at top of solid wall
$u_{t-IPBWW}$	Average displacement at top of wall with window opening
CFRC	Coconut fiber reinforced concrete
CFRP	Carbon fiber reinforced polymers
ξ	Damping ratio
f_n	Fundamental frequency
g	Gravitational acceleration
Q	Base shear
t	Time period

Chapter 1

Introduction

1.1 Background

An earthquake is a catastrophic event that produces ground movement. Earthquake resistant houses are less in number and quality in most developed countries when compared with population growth. Earthquake's primary effect causes severe damage, including the failure of houses, highways, which was resulted the loss of the human beings [15]. Masonry buildings was seriously damaged by the earthquakes. More than 450,000 buildings were voluntarily or involuntarily damaged during the 2005 Kashmir, Pakistan earthquake [16]. In 2008 Sichuan, China's earthquake of greatest magnitude was resulted the collapse of 216,000 buildings and the killing of 70,000 people [17]. A significant quake enlisting a magnitude of 7.6 happened near the coast of west Sumatra. The main earthquake of Sumatra in 2009 had a devastating effect on a huge number of structures, including buildings and influenced on societies and infrastructures [18]. In 2010, the Haiti quake having a magnitude of Mw 7.00 caused deaths of 316,000 living being, more than 300,000 harmed. The Haiti government was proclaimed that 80 to 90 percent brick work structure fundamentally destroyed [19]. During Maule seismic event of 2010, 80,000 people were injured and 524 deaths was occurred [20]. In June 2018, the Lombok Earthquake caused serious damage in Indonesia and killed 154,000 people [21]. Its need to make earthquake resistant houses. A reasonable solution is required to provide the low-cost quake-resistant housing in rural areas for severe seismic zones [22]. In seismic regions, due to strong ground motion, these severe zones endure a huge loss of human life due to absence of earthquake resistant houses.

Most of the conventional masonry structure collapse due to deficiency in design and construction [23]. For development of quake-resistant buildings, one alternative is to use interlocking blocks to make earthquake-resistant buildings [24]. To get productive and low-cost solution, new development procedures were developed, using the mortar-free interlocking blocks structure [25]. Many researchers had worked to make earthquake-resistant buildings using interlocking blocks [26]. To reduce mass of interlocking blocks is a point of concern, Coconut fiber reinforced interlocking block was made to reduce the mass of interlocking block, but the mass of CFRC block was seen to increase [2]. Due to less weight of interlocking plastic blocks, interlocking plastic- block are examined in this research work. In seismic occasion, these interlocking plastic-blocks had dissipated more energy because of interlocking key of interlocking plastic blocks. Previous research was carried out by Fayyaz and Ali to determine the dynamic response of interlocking plastic blocks using column made up of interlocking plastic blocks [13]. However, there is need to examine the dynamic behavior of different element of interlocking plastic block structure. In this research, interlocking plastic block walls with wooden diaphragm are investigated for dynamic response. Roofs are provided in buildings to cover it from top, save it from rain, sun and many other disasters. Dynamic or seismic response of diaphragms depends upon the supports and connections [27]. Wooden diaphragms are used in rural areas due to its good performance during seismic events [28].

Numerical approach for harmonic response had been investigated by many researchers. Many masonry structures were modeled by using finite element method (FEM). The numerical model was proposed with the help of the discrete element method. The dynamic response of the proposed model minaret was developed [29]. Numerical analysis of multi-drum column had conducted to focus the crack behavior for the stability of the structure [30]. To the best of the author's knowledge, no work has been done to investigate the dynamic response of interlocking plastic-blocks walls with wooden diaphragm using a numerical method. Therefore, this study helps to understand the dynamic behavior of interlocking plastic block structure for practical use in design and construction.

1.2 Research Motivation and Problem Statement

The earthquake has caused genuine harm and significant loss of the economy. The damage was caused by an earthquake that allows houses, roads, and bridges to collapse, and can kill many residents. The work had carried out on multiple earthquakes that have shown the construction flaws and design were primarily responsible for the earthquake catastrophe rather than the disaster itself. The economical solution can minimize the losses due to earthquakes. The complex behavior of buildings during the earthquake have been analyzed in more depth with the goal of safer structures to fulfill social expectations. Ali et al. [31] have introduced an economical solution. However, the block mass also requires to be reduced. Due to the low density, the interlocking of the plastic block structure with fire-resistant paint can be used. Recycled plastic waste could be an economical alternative for this purpose. Thus, the problem statement is as follows:

Many of the masonry structures had collapsed during the past earthquakes due to structural deficiencies [32]. Either the structures are need to be reinforced or new techniques are required. Strengthening is still possible but is costly. Ali [31] established a mortar-free structure (advance construction technique) with coconut fiber reinforced concrete (CFRC) blocks for quake-resistant housing. However, the mass of coconut fiber reinforced concrete blocks is still a point of concern. Charalampakis et al. [33] introduce a new approach in the structural design category, which reduces the earthquake loading acting on the structure through the significant reduction of the effective seismic mass. Lighter the mass of the structure, lower the inertia force generated. For this, lightweight interlocking plastic-block is one solution along with fire-resistant paint. For such kind of structure (i.e. Mortar-free interlocking plastic-block structure), dynamic behavior should be studied. This can be done by numerical method. Therefore, it is important to investigate the behavior of the interlocking plastic-block structure under dynamic loading, using finite element method.

1.3 Overall Objective and Specific Aim

The overall objective of the research program is to precisely investigate the 3D seismic response of full-scale detail plastic block structure.

The specific aim of this MS research work is to investigate the dynamic response of a prototype interlocking plastic-block structure using finite element numerical method.

1.4 Scope of Work and Study Limitations

The interlocking plastic-block structure consist of 96 plastic blocks. fixed base will be provided at base of walls. Three random loading including 1.5, 2.0 and 2.5 Hz will be applied. The basic dynamic properties in terms of frequency and damping ratio will be determined for modal analysis. The harmonic response in terms of displacement-time and acceleration-time will be determined. Empirical equations using Ali [25] approach will be use with the help of single degree of freedom (SDOF) concept. In study limitations, includes finite element dynamic method in Ansys 19 and three harmonic loading frequencies (1.5, 2.0 and 2.5 Hz).

1.5 Research Significance of Current Study

In seismic active regions, economical earthquake-resistant housing is required in rural areas of developing countries. Interlocking plastic-block houses can be built without any engineering supervision, because to construct well-supervised earthquake resistant houses costs will more. The lightweight interlocking plastic blocks are used in this research to reduce inertial forces. The finite element method can provide better performance and safety to measure the seismic response of earthquakes. The numerical method has a cheap solution to determine the modal and harmonic results for interlocking plastic blocks. This study provides a comparison of experimental results with numerical results. Furthermore, this study will help researchers to identify research directions regarding the numerical approach.

1.6 Brief Methodology

Finite element software, Ansys 19 has used for modal and harmonic loading with different random frequencies, including 1.5, 2.0 and 2.5 Hz. The aim of this research is to predict dynamic behavior of interlocking plastic block structure with increment in frequencies. For this work, initially verification between previous experimental research of interlocking plastic blocks has made with numerical results. After verification, the structure has used for numerical approach. The Structure under study consists of two plastic-block walls, wooden diaphragm and rubber band connection. The finite element method are used for modeling of structure in Ansys19. Harmonic loadings with different frequencies are applied to get a dynamic response at the top of the structure.

The structural response is represented in terms of histories of acceleration-time and displacement-time. Base shear is being calculated using acceleration and displacement time histories. The energy absorption of the structure is also determined.Effect of diaphragm on interlocking block walls and Effect of opening in wall has determined. Empirical equations has used,keeping in mind the geometry of interlocking blocks, structure height, and input loading parameters. Rs is the reduction factor has added in empirical equations due to increased stiffness. [13] empircal equations was used for column structure. Their equations are little modified by incorporating the new variable i.e. reduction factor due to increased stiffness, denoted by Rs. Comparison of numerical and empirical results for energy dissipation, acceleration and displacement time histories of interlocking plastic block structure.

1.7 Thesis Outline

There are six chapters in this thesis, which are as follows:

Chapter 1 consists of introduction section. Masonry damages in past earthquakes are explained in this chapter. It also consists of research motivation and problem statement, objective and scope of work, methodology and thesis outline.

Chapter 2 contains the literature review section. It consists of background, masonry damages in past earthquakes, different interlocking block structures, finite element modeling of structures and summary.

Chapter 3 consists of numerical procedure. It contains background, finite element models including models for validations and structure under current study, finite element model validation results, study parameters including modal analysis,harmonic analysis procedure and summary.

Chapter 4 consists of numerical results. It contains background, basic dynamic properties, harmonic analysis results including acceleration and displacement time histories, base shear and displacement behavior, effect of diaphragm on behavior of wall having opening and effect of opening on behavior of interlocking plastic wall and summary.

Chapter 5 contains discussion section. It has background, empirical equations development and summary.

Chapter 6 includes the conclusions and future recommendations.

Chapter 2

Literature Review

2.1 Background

Earthquakes are a natural disaster that had caused significant damage to the masonry structural system. Annually, it kills many people. Most of the masonry structure had collapsed in the past earthquake due to design deficiencies and implementation in construction. Many studies had conducted in the past, and are also being carried out in the present to establish strategies to mitigate the adverse effects of the earthquakes. For the development of an earthquake-resistant structure, many studies had developed on interlocking block structures. The finite element method had to investigate the precise analysis of structure under dynamic loading. Hence, it can provide a good solution for the dynamic response of interlocking structures. The finite element method has been used in past researches for predicting the response of structures. Ground acceleration is transmitted from the ground to the foundation of the structure, which causes the shearing effect of masonry structures. The literature has indicated the solution to make earthquake-resistant housing, interlocking blocks is one solution. But the greater inertial mass is a point of concern for conventional masonry blocks. This chapter includes the literature review about masonry structure damages in past earthquakes, different interlocking block structures and finite element modeling of structures.

2.2 Masonry Structure Damages in Past Earth Quakes

An earthquake is a catastrophic event that produces ground movement. Earthquake resistant houses are deficient in quality in most developing countries. Earthquake's primary effect had caused serious damage, including the failure of houses, highways, which can result in the death of lives. During the earthquake of 2000, also called the Enggano earthquake, a magnitude of 7.9 was observed. Over 100 deaths and near to 2,585 injuries were happened due to the failure of masonry structures [34]. During the 2001 earthquakes, more than 75,000 homes in the Republic of El Salvador in Central America were completely damaged [35].The structural damage was isolated into three classifications; heavy, medium and low damage structures. In 2002, seismic event results most intensely damage, medium and low damage structures were 4,390, 1,730, and 9,556. Azeloglu et al. [36] have observed, that around 1,000 masonry structure has fallen, 122 people had injured and two people had died in turkey. In 2004, during the Sumatra, Indonesia earthquake approximately 131,000 people were dead, seismic damage was occurred due to poor seismic designs, many mosques had survived the disaster and also suffered to masonry walls [37]. In 2007, Pisco, the Peru's earthquake with magnitude 8.0 caused the collapse of masonry buildings and damage to reinforced building [38]. In 2009, during the LAquila earthquake in Italy, many buildings had damaged. The LAquila earthquake was collapsed many churches and destroyed historical monuments [39]. In 2010 yushu china earthquake, Wang et al. [40] have determined the seismic characteristic damage of building structures in china.Table 2.1 show the damages in past earthquakes. The Yushu earthquake had damaged around 27 seven cities in China and seven countries, including Shique, Nangqian, Qumalai, Zaduo. The magnitude of the Yushu earthquake was 7.1, it has destroyed about 94 percent masonry structures and resulted in several losses, including 2,697 people died, 12,134 injured. The earthquake had caused significant damages to a masonry structure. Motosaka et al. [41] had described the damage of buildings based on the damage survey to the Tohoku earthquake. Many buildings was collapsed.

FIGURE 2.1: Masonry building failure during severe earthquake in Italy [1].

TABLE 2.1: Damages in Past Earthquakes

Sr. No.	**Location**	**Year**	**Magnitude**	**Deaths**	**Comments**
1	Gorkha, Nepal [42]	2015	7.8	8,789	Due to lack of risk sensitivity planning and development, structural knowledge and lack of its awareness causes 141,495 damages of buildings.
2	Tohoku, Japan [43]	2011	9.03	15,878	The most difficult crisis faced by Japan after WWII, which damaged more than 129,225 buildings, caused fires and tsunamis as well.
3	Sichuan, China [44]	2008	8.0	69,197	It rendered almost 15 million people homeless and caused $146.5 billion.
4	Kashmir, Pakistan [45]	2005	7.6	73,000	Due to poor construction of work, there is US$5.2 loss by damages of 400,000 structures partly or fully
5	Izmit, Turkey [46]	1999	7.6	45,000	The absorb frequencies by buildings are more than its capacity due lack of design in return there is many losses of properties and life.

The collapse of masonry systems was in response to large support displacements and horizontal ground accelerations. Masonry buildings were seriously damaged by the earthquakes. More than 450,000 buildings were voluntarily or involuntarily damaged during the 2005 Kashmir, Pakistan earthquake [16]. In 2008 Sichuan, China's earthquake of greatest magnitude results collapses of 216,000 buildings and the deaths of 70,000 people. The earthquake caused more than 6.5 million buildings to collapse and destroyed some 23 million more structures [17]. In 2010, Haiti quake having a magnitude of 7.00 was results the death of 316,000 human beings, more than 300,000 harmed. The Haitian government was proclaimed that 80 to 90 percent brickwork structure fundamentally destroyed [19]. During the Maule seismic event of 2010, 80,000 people were injured and 524 death of people were occurred [47]. In the recent years, many countries were faced serious damage to masonry buildings. Fig .2.1 shows the building failure in Accumuli, [1] located in Italy during severe earthquake.

2.3 Different Interlocking Block Structures

There is need for a reasonable economical solution to provide low-cost earthquake-resistant housing in rural areas for severe seismic zones [22]. In seismic regions, due to strong ground motion, these severe zones endure a huge loss of human life due to the absence of earthquake-resistant houses. Most of the conventional masonry structures collapse due to design inaccuracy and construction issues [48]. For the development of the earthquake-resistant building, one alternative is to use interlocking blocks to make earthquake-resistant buildings [24]. To get a productive and low-cost solution, new development procedures were developed using the structure of mortar-free interlocking blocks [25]. Many researchers have worked to make earthquake-resistant buildings using interlocking blocks [26]. Fig.2.2 shows the proposed interlocking block [2] are able to recover its original location during seismic ground excitation due to the availability of inclined key shape in blocks. Fig.2.3 show the different type of interlocking block used for earthquake resistant structures.

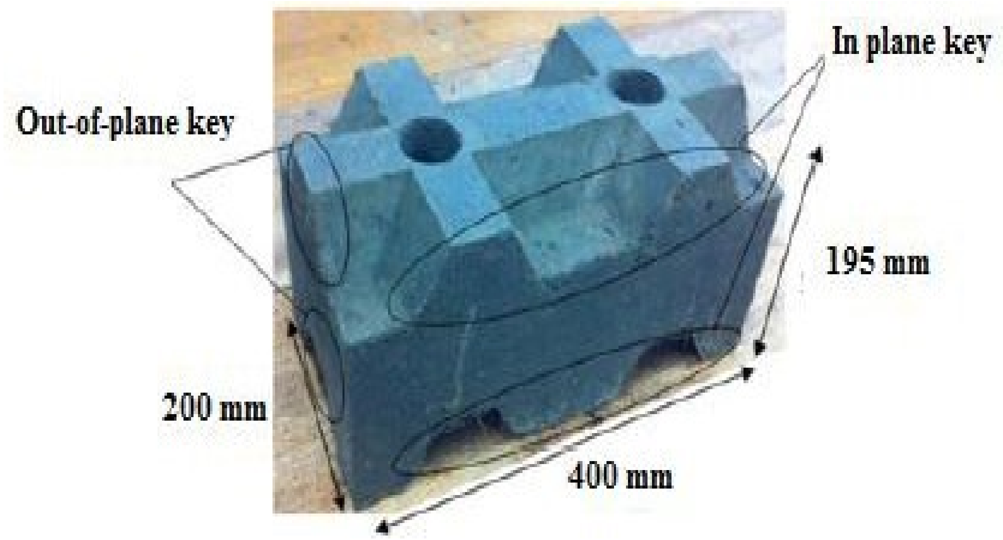

FIGURE 2.2: Coconut Fibre Reinforced Concrete (CFRC) interlocking block [2]

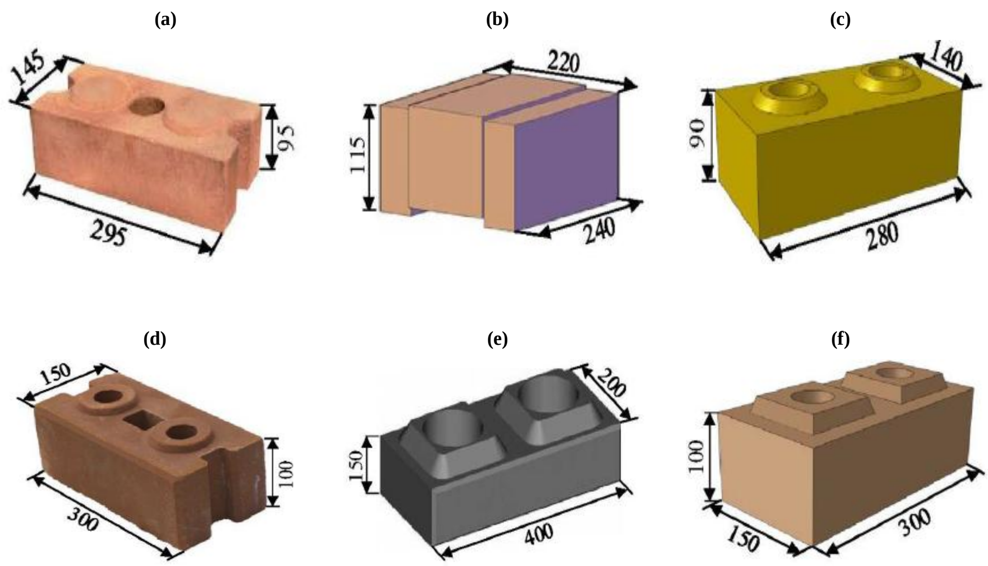

FIGURE 2.3: Various interlocking earth blocks; (a) Auram interlocking block[3], (b) Hydraform interlocking block [4], (c) HiLoTec interlocking block [5], (d) Thai Rhino interlocking block [6], (e) Hollow interlocking block [7], (f) Tanzanian interlocking block [8].

Qamar et al. [49] had observed the lateral resistance in the interlocking block walls with the use of natural fibers to make earthquake resistant structures.To reduce the mass of interlocking blocks is a point of concern, the Coconut fiber-reinforced interlocking block was made to reduce the mass of the interlocking block for reduction in inertial forces, but the mass of CFRC block was seen to increase [2].

TABLE 2.2: Summarized details of various interlocking compressed earth blocks proposed in previous researches

Reference	**Interlocking-block shape**	**Main findings**
Maini et al. [3]	Auram block	Dry compression, shear and bending compressive strength; absorption of water.
Uzoegbo et al. [4]	Hydraform block	Compressive strength of the masonry units; compressive strength of the dry-stack walls.
Sturm et al. [5]	HiLoTec block	Compressive and flexural strength of the units; compressive and shear behavior of masonry prisms.
Qu et al. [6]	Thai Rhino block	Stressstrain curves of prisms; seismic performance of flexure-dominated interlocking compressed earth block walls; the structural performance of interlocking compressed earth block walls under cyclic in-plane loading.
Fay et al. [7]	Hollow block	Resistance of compression, water absorption, and sizing of interlocking compressed earth blocks.
Bland et al. [8]	Tanzanian block	Block irregularity and implication for wall quality; the relationship between alignment and block geometric imperfection; stiffness of the interlocking block columns.

Due to less weight of interlocking plastic blocks, interlocking plastic- blocks are examined in this research work. In the seismic occasion, these interlocking plastic-blocks had absorbed more energy because of the interlocking key of interlocking plastic blocks. Previous research was carried out to determine the dynamic response of interlocking plastic blocks using columns made up of interlocking plastic blocks. Khan and Ali developed the use of interlocking plastic blocks, for earthquake-proof housing because of their lightweight in conjunction with energy

FIGURE 2.4: Various interlocking patterns/techniques for blocks; (a) eco-friendly interlocking block including holes and shapes [9], (b) sliding inter-locking block [10], (c) interlocking block including holes to provide steel re-inforcement [11]

dissipation due to uplifting the plastic block column [13]. Sudheer and Ali [14] developed the dynamic study of interlocking block wall with window. Table 2.2 show the Summarized details of various interlocking compressed earth blocks proposed in previous researches.

However, the study was based on experimental research. Fig. 2.4 show the various interlocking patterns/techniques for blocks; (a) eco-friendly interlocking block including holes and shapes [9], (b) sliding inter-locking block [10], (c) interlocking block including holes to provide steel reinforcement [11]. Interlocking blocks can be used for earthquake resistant structures. Khan and Ali [13] developed following empirical equations incorporating the geometry of interlocking blocks, column height, column response and input loading parameters:

$$\ddot{u}_t = \frac{\frac{a}{h^2}}{n} K^{(1+\frac{2n}{100})} \ddot{u}g.....(2.1)$$

$$u_t = \frac{\frac{a}{h^2}}{n} K^{(1+\frac{n}{100})} ug.....(2.2)$$

$$E = \frac{\frac{a}{h^2}}{n} \frac{0.85KH^2M}{t^2} \frac{u_t}{u_g}.....(2.3)$$

2.4 FE Modeling of Structures

The masonry structures are modeled utilizing finite element (FEM) method. The discrete element method had used to propose the three dimensional numerical model. The seismic response of the proposed model minaret was developed by Mordanova and Felice [50]. Numerical analysis of the multi-drum column had conducted to focus the crack effects on the stability of the system [30]. The numerical model had designed to predict the seismic response of structure made of bricks [51]. Timber connection was used in this research, the nonlinearity was evaluated in the constitutive behavior of the masonry structure. In the first place, the system was verified by fitting the statistical compared with the actual behavior of the dynamic tests. Subsequently, It was used for simulation study of the impact of the following criteria, the tensile and compressive resilience of the brickwork, the deformation energy of the brickwork in tension and compression [52]. In the recent times, as an option to traditional homogenization methods, multi scale designs had used to develop the dynamic response of masonry [53]. The advance modeling of various cracking phenomena in brittle materials, such as reinforced masonry, using coherent building design and multiple scales strategies, had received a great deal of interest due to its broad application and effectiveness [54]. Many nonlinear modeling are used to determine the mechanical behavior of material properties in both linear and nonlinear domains, with particular attention

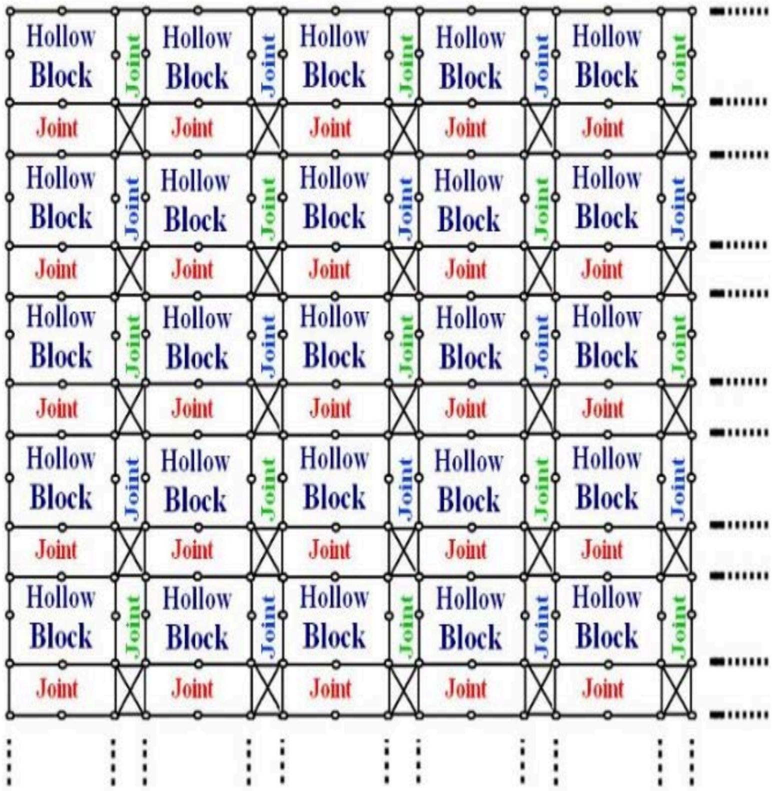

FIGURE 2.5: FE Model of mortar-less hollow block wall [12]

to fiber, polycrystals and concrete structures materials [55]. As an alternative, the best-established computational homogenization methods, the various variants of simultaneous multi-scale methods were first adapted for evaluation of masonry by few researchers [53]. The performance of structural concrete members strengthened with CFRP composites had predicted using a numerical approach in ansys 19 software [56]. The numerical modeling of the masonry wall had used for the determination of mechanical and thermal properties. A comparison of experimental results were made for the verification of mechanical and thermal properties [57]. Finite element (FE) models were used by many researchers to evaluate the nonlinear response of masonry walls and buildings, according to the use of a micro-modeling approach [58, 59]. A nonlinear macro-mechanical finite element model of traditional masonry was established based on material properties [60]. Table 2.3 shows the Finite element modeling for Dynamic response. The FE numerical method can be used for getting the dynamic response of structures. Hejazi et al. [12] proposed interfaces for horizontal and vertical surface interactions for FE modeling of mortar-less hollow blocks for seismic analysis as shown in Fig.2.4.

TABLE 2.3: Finite element modeling for dynamic results

Sr.No.	**Authors**	**Publication year**	**Structure Details**	**Conclusions**
1	Aleman et. al.[61]	2020	Nonlinear Model Unreinforced Masonry Buildings	Numerical tools for URM buildings indicated that finite element models can fully characterize the dynamics response of wood diaphragms over a very long computational time.
2	Thakur et. al.[62]	2020	Numerical Modelling of clay brick masonry assemblage	Finite element model proves very useful in light of identifying the dynamic amplification factor as it is an essential parameter required for designing the structure under
3	Joshi et. al.[63]	2019	3D Masonry Compressed Stabilized Earth Block and Brick Building Models	Results obtained from Finite element analysis by ANSYS-13 for Models are compared with experimental results and the variation is marginal.
4	Aldemir et. al. [64]	2018	Masonry building	The numerical model gave satisfactory predictions in terms of the diagonal cracks.
5	Hamdy et. al.[65]	2018	Masonry wall, Arches and Domes	The numerical results showed good agreement with published experimental results as regards crack patterns, failure mechanisms, maximum load and corresponding maximum deformation.
6	Sirajuddin et al. [66]	2011	Masonry building wall	Heterogeneous modelling gives more accurate results that homogeneous modelling using ANSYS-13.

2.5 Summary

Earthquake is one of the big structural health threats. The earthquake has done significant harm to the societies, the environment and the economy. It is clear from the above discussion that significant harm to the masonry structure is due to design and implementation deficiencies. The earthquake damage is often caused by inadequate understanding of the behavior of the system during the earthquake. The research has performed in depth to reduce damages and adverse effects related to earthquakes in the future. Ali et al. [2] have shown from his work that mortar-free interlocking block structure has the capability to dissipate earthquake force, but there is a need to reduce the mass of coconut fiber reinforced concrete block, that is still a concern point. As a result, new interlocking plastic blocks have been added, the lower mass of the structure can produce less inertia forces. The interlocking plastic block structure has the potential to dissipate earthquake energy due to block lifts. A comparative research can be done by numerical procedure and numerical analysis results. For numerical procedure and analysis, finite element of structures as literature has been found to be supportive in this regard.

Chapter 3

Numerical Procedure

3.1 Background

Interlocking plastic-blocks were analyzed due to its lighter weight and lower inertia forces resulting. Inertia force is commonly used for a structure capacity to endure effects induced by any external force like ground acceleration. The concept is governed by the laws of motion of Newton including the Law of Inertia forces with the Law of Action-Reaction. In response to these external force, heavy structures (materials) are more prone to their higher weight as compared to lighter systems

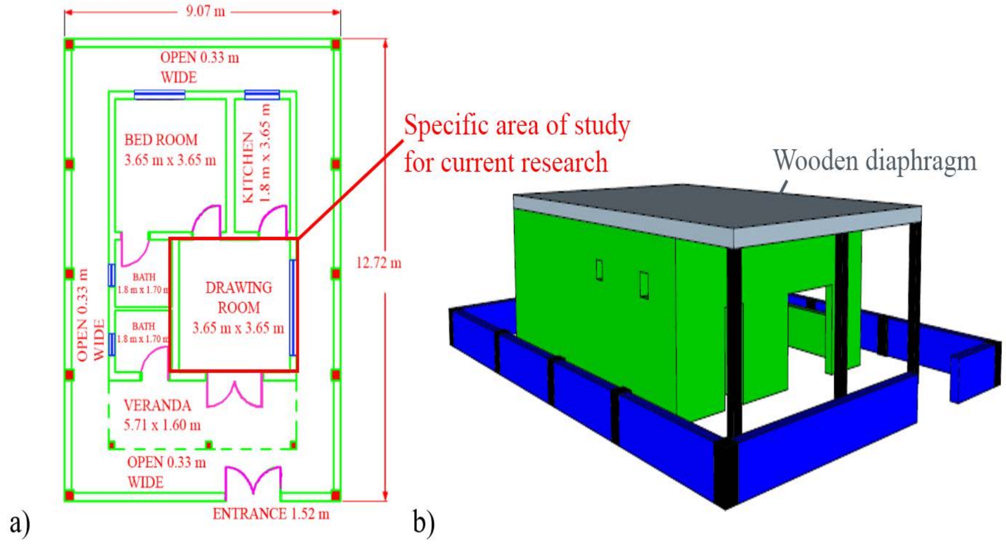

FIGURE 3.1: Proposed interlocking plastic block house [13], a) plan b) 3D structure.

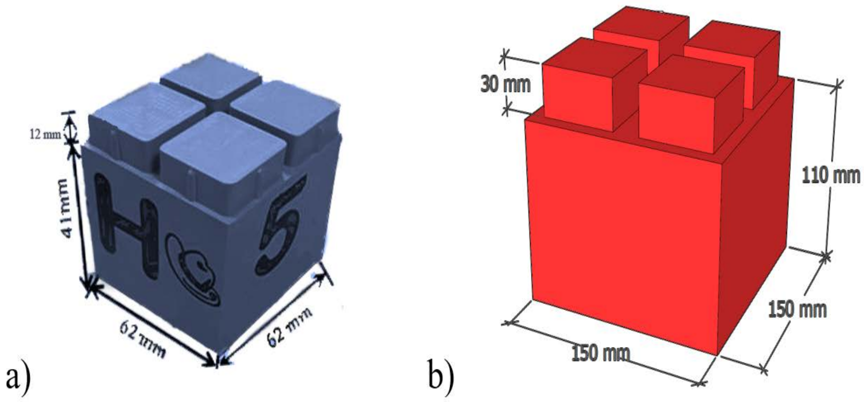

FIGURE 3.2: Interlocking plastic-blocks, a) prototype for research study, b) proposed for construction.

(materials), resulting in higher inertial forces. Present research is continuation of Khan [13] and Sudheer [14] study work has shown in Fig.3.1. The interlocking plastic blocks for real construction have a base dimension of 150 mm x 150 mm and have many keys at the top of building seismic-resistant housings. The total block height is 140 mm including the interlocking key height of 30 mm, as shown in Fig.3.2. The plastic block size is 2.5 times smaller than proposed interlocking plastic-block.

The interlocking key of the proposed plastic-block is made in such way that allows uplift during earthquake. This uplift is produced which is necessary for energy dissipation during ground motion. Key of interlocking plastic- block should be designed little bit inclined to allow uplift during harmonic loading. The previous research was on considered structure with respect to pretension. However, in real structures, these will be eccentric. For structures with the moment, pre-tensioning with rubber band through interlocking keys may be required. For current study, the randomly selected scale of 1/10th in for structure height is considered with simplified boundary conditions. Ali et al. [25] also used simplified boundary condition. Keeping in mind 1/10th scale of structure height and 2.5 scales for the block, a total of 52 blocks for IPBSW with 44 blocks for IPBWW are taken. In current research, verification of experimental study of previous researchers will made to verify the experimental results of IPBWW and interlocking plastic block column. Same scaling factor 1/10 has used for a structure scaling technique that was adopted by Sudheer and Ali [14] for out of plane dynamic experimental testing of plastic-block wall with window opening. Same scale down techniques are used for finite element modeling of structure to get response on top of the structure. The primary purpose of current research is to study the dynamic behavior of interlocking plastic blocks structure. For this, structural time period is an important parameter which depends on the structure height (UBC-97). That's why, scale down technique is mainly applied on elevation dimensions of structure.

3.2 Finite Element Models

To understand the structural dynamic behavior, a numerical modeling approach has been used for decades. For finite element modeling of interlocking plastic-block structure, Ansys 19 software has used. The Model has divided into finite elements interconnected at points common to two or more elements. The finite element model of simple and complex structures is built with the material and geometric characteristics of the interlocking plastic block structure. Three-dimensional structure is used for numerical modeling to get dynamic behavior. Fig. 3.3. show the flow chart for finite element analysis. For the geometry, space claim has used to model interlocking plastic structure. For modeling mortar-free interfaces. Ansys Design modeler is being used for plastic blocks horizontal and vertical interfaces. [12] used horizontal and vertical interfaces for FE modeling of mortar less hollow blocks for seismic analysis.

3.2.1 Models for Validations

The models for validations consist of columns and interlocking plastic block wall with the window. The material properties used in the numerical model has shown in Table 3.1. Material properties consist of density, elastic modulus, poissons ratio, bulk modulus and shear modulus. For current structure, three basic materials are selected. These materials are plastic, rubber and wood.

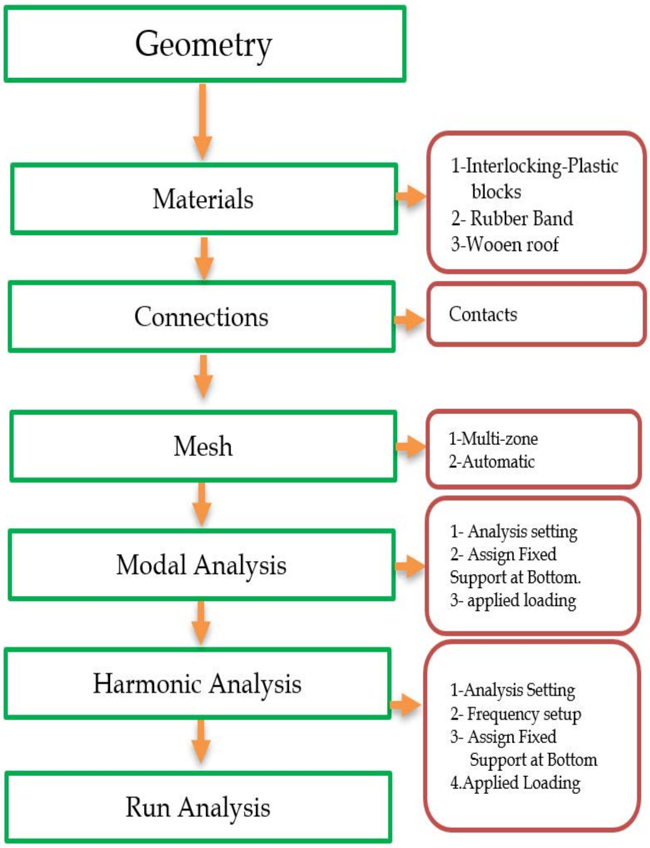

FIGURE 3.3: Flow chart for finite element analysis in Ansys.

For interlocking plastic blocks elastic modulus is selected from the experimental testing of Khan and Ali [13]. Density and poissons ratio of plastic blocks are selected through the range of plastic mechanical properties. ASTM D0695-02A standard is available in the compressive properties of plastic. For wood and rubber, material properties are available in material library of Ansys 19. These materials are essential mechanical properties of interlocking plastic-block structure. Density for mechanical properties of interlocking plastic blocks, rubber band and wood are 900,110 and 700 kg/m3, respectively. Elastic or youngs modulus includes 1.1e+09, 1.27e+06 and 2.5e+08 pascals are used for interlocking plastic blocks, rubber band and wooden items. The poisons ratio for description of expansion and contraction of material for wood, a rubber band and plastic blocks are 0.25, 0.4 and 0.42, respectively. Poissons ratio is unitless material property. On the basis of these previous materials properties, Bulk modulus and shear modulus of structural material are evaluated. Simple structures are modeled in computer aided product of Ansys 19. Interlocking plastic block column and IPBWW consist of 8 and 44 plastic blocks respectively. Experimental setup of column as used by Khan and Ali [13] and wall by Sudheer and Ali [14] converted into a numerical analysis model for validation of results. Respectively shows the conversion of experimental model to numerical model of column and interlocking plastic block wall with a window opening. Numbering are provided on structures, number one show the position of base where input loading has provided. Number two show the dynamic response at top of column due to input loading. Similarly, number one show the input loading at base of IPBWW, number three show the response at top of IPBWW due to input at the base of interlocking plastic block wall.

Table 3.1: Material properties for finite element modeling of prototype structure

Parameters	**Interlocking Plastic Blocks**	**Rubber Band**	**Wood**
Density (kg/m3)	900	110	700
Youngs modulus (Pa)	1.1E+09	1.27E+06	2.5E+08
Poissons ratio	0.42	0.4	0.25
Bulk modulus (Pa)	2.2917E+09	2.1167E+06	1.6667E+08
Shear modulus (Pa)	3.873E+08	4.5357E+05	1E+08

3.2.2 Model for Structure Under Current Study

The structure under study consist of finite element modeling of two parallel plastic block walls, including solid wall and wall with window opening. Table 3.2 shows the dimensions that are used for numerical modeling. Wooden diaphragms are attached to walls using plus symbol rubber band connection 3D model is shown in Fig 3.5. Same material, including young modulus, density and poissons ratio, shear and bulk modulus, has used as it was used in the finite element model of the structure has prepared, using space claim for models of validations. The design modeler has used for parts inner connection between interlocking plastic block walls with wooden diaphragm including rubber band plus symbol connections.

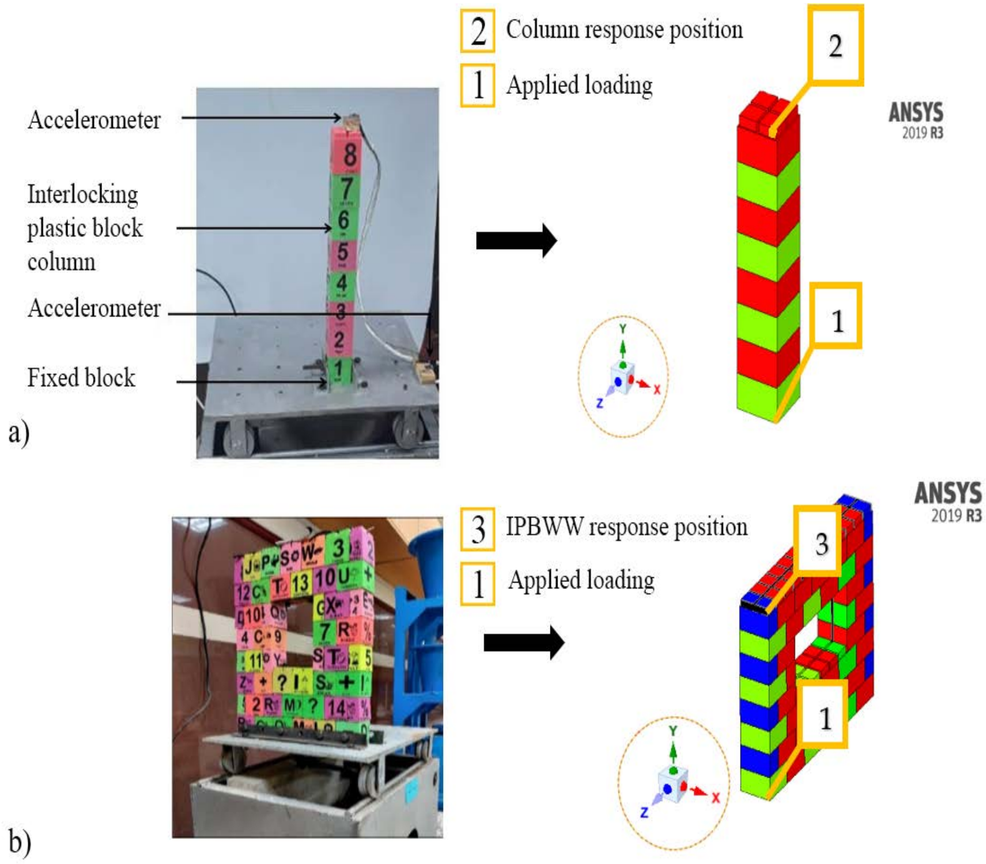

FIGURE 3.4: Finite element models for validation, a) column experimental idea from Khan and Ali [13] and b) IPBWW from Sudheer and Ali [14].

One interlocking plastic block has base dimension 62 mm x 62 mm with height 41 mm. In height interlocking key of 12 mm has added. Interlocking plastic block wall without opening, has height 328 mm with base dimensions 372 mm x 62 mm. IPBSW has an interlocking key of 12 mm. Interlocking plastic block wall with window opening has base dimensions of 372 mm x 62 mm, the height of interlocking plastic block wall with window (IPBWW) is 328 mm. Window opening dimensions are 186 mm x 62 mm with height 123 mm. Diaphragm used for structural response is made up of good and flexible material. The dimensions for wooden diaphragm have base of 372 mm x 496 mm with 25 mm thickness. Numbering are added to structure for well understanding of behavior of structure. Number one show the position of base where input loading has provided, number four show the position of response on top of the structure. Similarly, number five and six has shown the response at top of IPBSW and IPBSW, respectively. For modeling mortar-free interfaces.

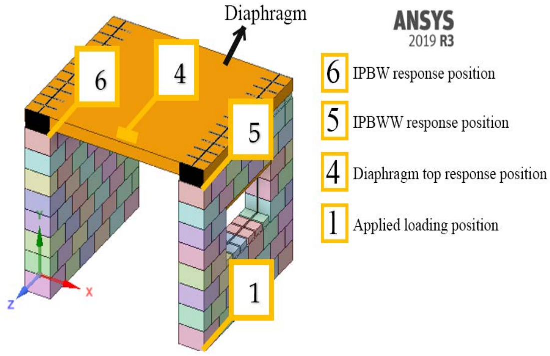

FIGURE 3.5: Structure under study.

TABLE 3.2: Dimensions of FE model structure

Structure elements	**Dimensions (mm)**	**Key height (mm)**	**Opening (mm)**
One block	62 x 62 x 53	12	-
Plastic-block wall without opening	372 x 62 x 328	12	-
Plastic-block wall with window opening	372 x 62 x 328	12	186 x 62 x 123
Wooden diaphragm	372 x 496 x 25	12	-

3.3 Finite Element Models Validation

To validate the experimental results of previous research of interlocking plastic-block structures. Experimental results are reproduced for numerical results verification. Fig 3.6 shows the proposed interlocking plastic-block column for dynamic response at the top of the structure. The interlocking plastic-block structure was tested under harmonic loading with an amplitude of around 3 cm and a frequency of 2.83 Hz. The response of interlocking plastic-block structure acceleration, velocity and displacement time histories during the period from 30 to 40 seconds are recorded. The interlocking plastic block column has modeled in Ansys 19. The same harmonic loading 3 cm with frequency 2.83 Hz has applied. The averaged acceleration, velocity and displacement of the base motion is taken as applied loading. These are 0.11 g, 150 mm/s and 3 cm, respectively. Similarly, the averaged acceleration, velocity and displacement at column top is taken as column response. Experimental results were 0.12 g, 160 mm/s and 3.2 cm. Numerical results are 0.123 g, 159 mm/s, 3.2 cm. Table 3.3 and Fig3.6 shows the comparison of column and IPBWW results between experimental and numerical results. Figure shows the experimental setup of the wall with a window (IPBWW). Prototype interlocking plastic-block wall with the opening was tested on a shake table under harmonic loading with an amplitude of around 3 cm and a frequency of 2 Hz. The response of interlocking plastic-block wall in terms of acceleration, velocity and displacement time histories during the period 30 s to 40 seconds are recorded. The averaged acceleration, velocity and displacement of the base motion is taken as applied loading. These are 0.08 g, 40 cm/s and 3 cm, respectively. Similarly, the averaged acceleration, velocity and displacement at IPBWW top is taken as IPBWW response. These are 0.095 g, 60 cm/s and 3.2 cm, respectively. Numerical results on top of IPBWW are 0.083 g, 59 cm/s, 3.19 cm. Results are showing that the numerical method can be used for the dynamic response of the interlocking plastic-block structure.

Table 3.3: Comparison of experimental results of column and IPBWW with numerical results

Interlocking plastic block column	**Experimental values**	**Numerical values**	**Percentage difference**
Column			
Acceleration (g)	0.12	0.123	2.5%
Velocity (mm/s)	160	159	0.62%
Displacement (mm)	32	32	0.3 %
IPBWW			
Acceleration (g)	0.095	0.094	1.05%
Velocity (cm/s)	60	59.725	0.45%
Displacement (cm)	3.2	3.1985	0.04%

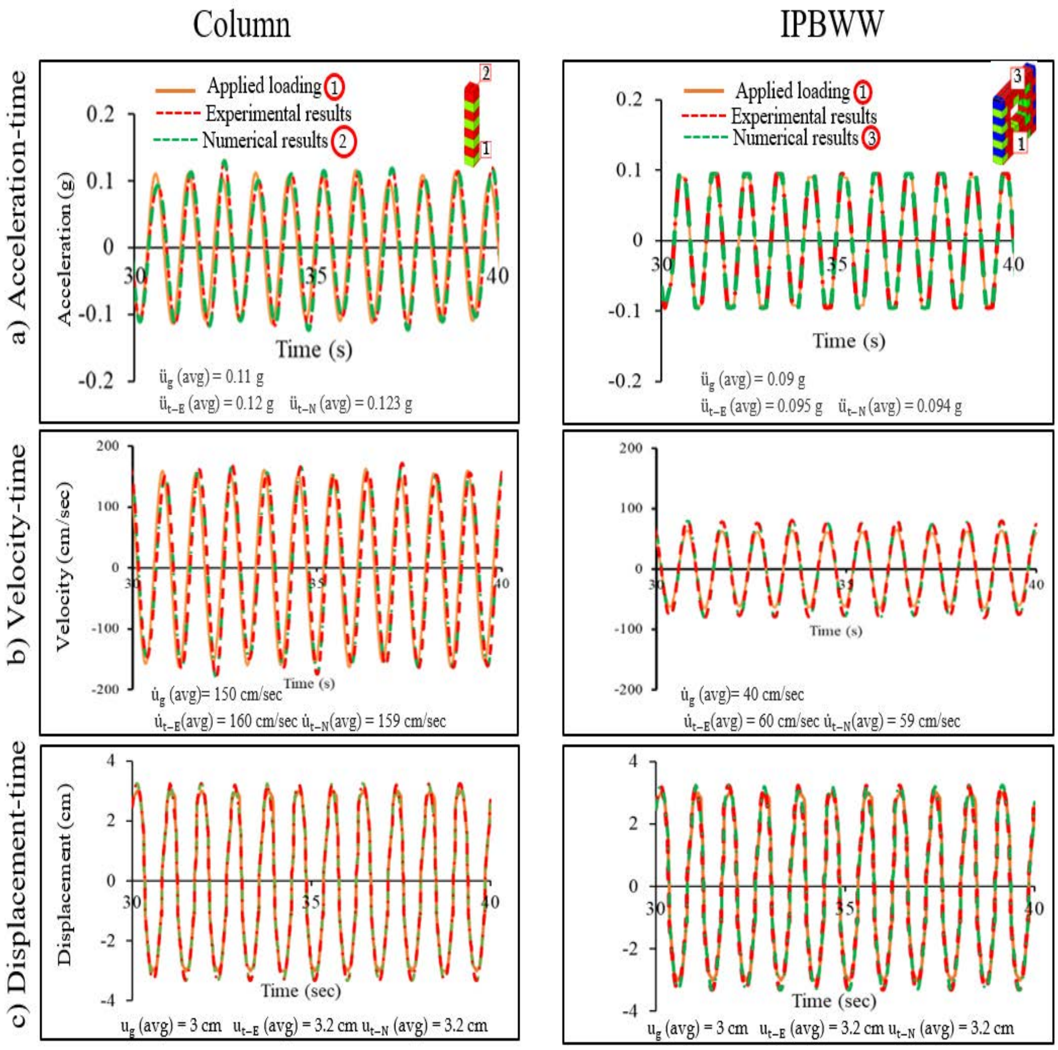

FIGURE 3.6: Verification of column and IPBWW results, a) acceleration-time, b) velocity-time and c) displacement-time histories.

3.4 Study Parameters

3.4.1 Modal Analysis Procedure

Modal Analysis is an important method of study of the vibration characteristics. Modal analysis has performed under the frequency domain to determine the mode shapes of interlocking plastic block structure. Modal analysis is used to determine the natural frequency and mode shapes of interlocking plastic structures. In the preprocessing phase, geometry and meshing are made using finite element methods. Analysis settings are made to set several modes and damping controls.

Fixed support is provided at the base of interlocking plastic-block walls. For natural fundamental frequency, free vibrations are applied with 25mm and 50 mm displacement.

3.4.2 Harmonic Analysis Procedure

Harmonic analysis is used to determine the dynamic time histories results of interlocking plastic block structures. Table 3.4 shows the magnitude considered for modal and harmonic analysis. In the preprocessing phase, geometry and meshing are made using finite element methods. Fixed support is provided at the base of interlocking plastic-block walls. In the analysis setting, harmonic loading with random frequencies are applied to get a response on top of the structure. Run the analysis to get time history results.

TABLE 3.4: Magnitude considered for modal and harmonic analysis

Test	**Amplitude**	**Structure**
Modal	ug = 25 mm	1
	ug = 50 mm	1
Harmonic	ug = 30 mm (f = 1.5 Hz)	1
	ug = 30 mm (f = 2 Hz)	1
	ug = 30 mm (f = 2.5 Hz)	1

3.5 Summary

This chapter highlights the numerical techniques adopted in this research work. Interlocking plastic-block experimental results has verified with numerical results. For verification, numerical model of IPBWW and column has modeled. In addition to that, numerical procedure of column and IPBWW has also studied. Comparison of experimental and numerical results has made. The detailed procedure for dynamic analysis using finite element software is also highlighted in this chapter. This chapter discussed the detailed numerical procedure. In study parameters, modal and harmonic analysis procedure has also discussed.

Chapter 4

Numerical Results

Previous chapter highlighted the numerical procedure verification with experimental procedure. In addition to that, numerical procedure in detail has discussed. This chapter explains the numerical results including basic dynamic properties of structure. The basic dynamic properties includes damping ratio and fundamental frequency. In addition to that, mode shapes of interlocking plastic block has also determined. Ansys 19, finite element software has used for evaluation of acceleration and displacement time histories of interlocking plastic block structure.furthermore, using acceleration and time history data of structure, base shear and displacement behavior of structure has also determined in this chapter. In addition to response of structure, comparison of effect of diaphragm on window opening wall and effect of opening in structure wall will be discussed.

4.1 Basic Dynamic Properties

In dynamics, basic properties are fundamental frequency and damping ratio. For determining these properties modal analysis has performed in Ansys 19 software using finite element method. Modal analysis has performed to understand that in which dynamic behavior interlocking plastic-block structure has responded, either it is stiffness control, damping control or mass control. Furthermore, for understanding resonance phenomena, it can help in modal analysis results. The

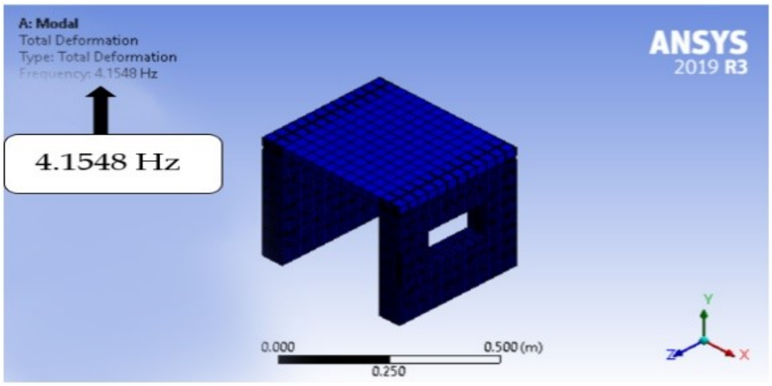

FIGURE 4.1: Mode shape of structure at fundamental natural frequency.

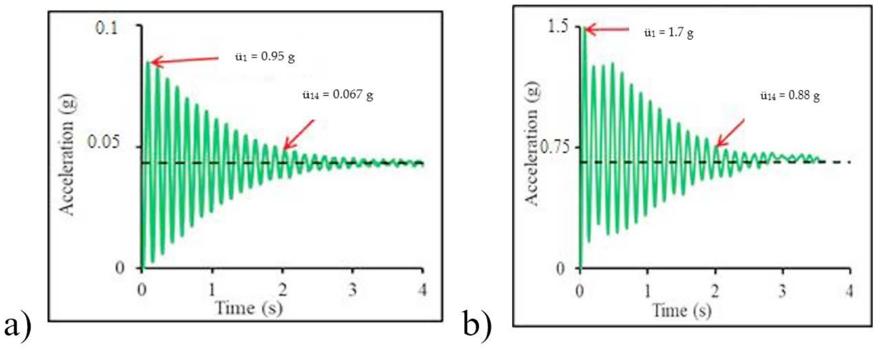

FIGURE 4.2: Modal analysis results having displacement at top mean position

fundamental frequency, damping ratio and mode shapes are obtained.Table 4.1 shows the results of the fundamental frequencies and damping ratio of interlocking plastic-block structure, including interlocking plastic block solid wall (IPBSW), interlocking plastic block wall with the window opening (IPBWW) and flexible wooden diaphragm. Fig.4.1 shows the fundamental frequency in mode shape of the structure. Fig.4.2 shows the acceleration with 25 mm and 50 mm displacement. In response of interlocking plastic-block structure against modal analysis, fundamental natural frequency has become 4.15 Hz with damping 4 percent. Acceleration-time response due to the natural frequency at 25 mm displacement initially it is 0.95 g with reduction in cyclic loading in 14th cycle it has become 0.067 g. Similarly, for 50 mm displacement its initial value is 1.7 g of acceleration and after the14th cycle it has reduced to 0.88 g. In modal analysis, fundamental frequency, damping ratio and acceleration due to 25 mm and 50 mm has obtained.

Table 4.1: Fundamental frequency and damping ratio of structure

Parameters	**Structure**
Fundamental frequency fn (Hz)	4.15
Damping ratio ξ (%)	4

4.2 Harmonic Analysis Results

4.2.1 Acceleration, Velocity and Displacement Time Histories

The response of interlocking plastic-block structure i.e. Acceleration, velocity and displacement time histories during the period from 30 s to 40 s are taken. The harmonic loading 3 cm with frequencies 1.5, 2 and 2.5 Hz has applied to the interlocking plastic block structure. For frequency 1.5 Hz the averaged acceleration, velocity and displacement of the base motion is taken as applied loading. These are 0.070 g and 2.6 cm, respectively. The average acceleration, velocity and displacement at interlocking plastic block structure top is taken as structure response. The numerical results are 0.072 g, and 2.89 cm. For Frequency 2 Hz, the averaged acceleration, velocity and displacement of the base motion is taken as applied loading. These are 0.085 g and 2.8 cm, respectively. The numerical results are 0.088 g, 3.03 cm. For Frequency 2.5 Hz, the average values of acceleration, velocity and displacement of the base motion is taken as applied loading. Their values are 0.095 g, and 3.15 cm, respectively. The numerical results are 0.097 g and 3.19 cm. Fig 4.3 show the displacement mode shapes due to harmonic loading in one cycle. Red color shows the extreme displacement at top of structure. Red color shows the extreme displacement and blue color shows no displacement. Other colors show the variation between maximum and minimum (no) displacement. Fig 4.4 shows the numerical results of harmonic loading for frequencies applied loading for structure is shown in orange line. For response at top of structure green dotted lines are shown.

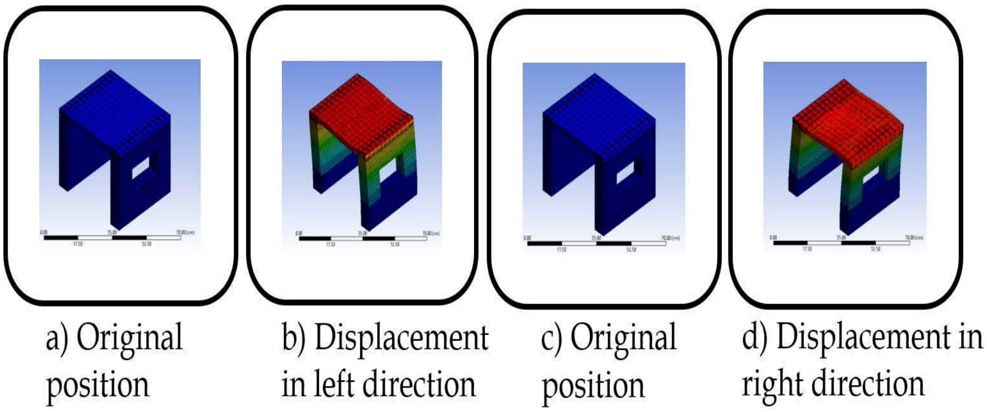

FIGURE 4.3: Displacement mode shapes due to the harmonic loading of one cycle.

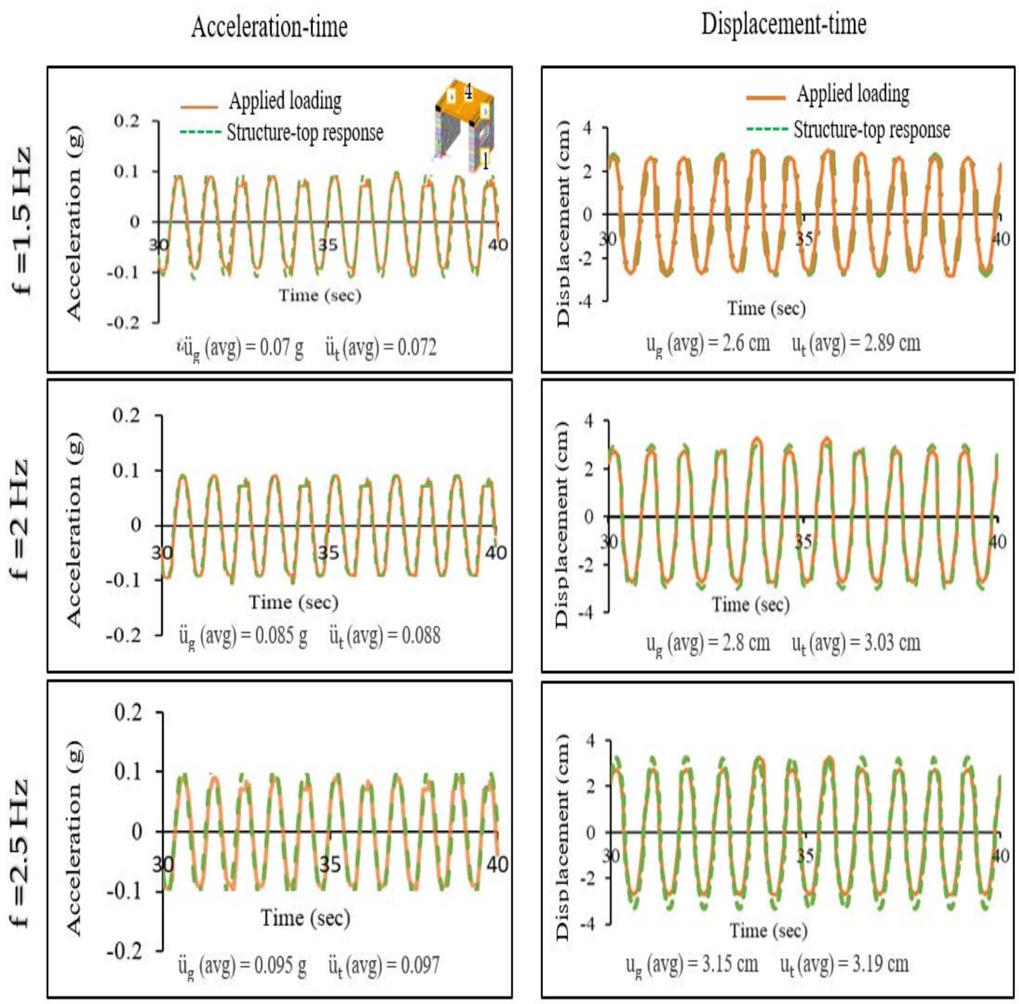

FIGURE 4.4: Acceleration and displacement time histories of structure during harmonic loading of frequency 1.5, 2.0 and 2.5 Hz.

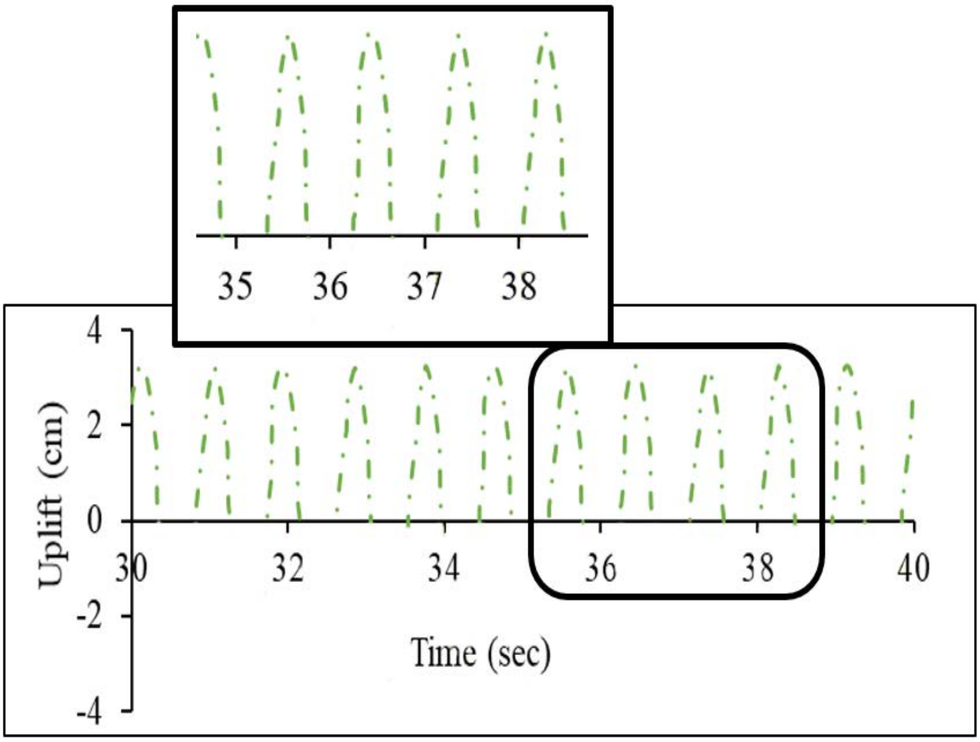

FIGURE 4.5: Uplift time of interlocking plastic block structure.

4.2.2 Base Shear and Displacement Behavior

At interlocking plastic block structure top, the mass of structure (M) is assumed to be lumped at top of structure where its response acceleration-time (i.e. u t-t) history is recorded. Base shear is calculated from harmonic time histories with displacement or amplitude of 3 centimeters. Base of structure is calculated from multiplication of total mass of structure to accelerations M. u-t. The typical base shear displacement results for a single cycle are shown in Figure 4.6. This is calculated as per working of [25]. Table 4.2 shows the averaged energy Dissipation in one cycle as well as total energy dissipation. Area in one loop is used for the performance in terms of energy absorption per cycle within structure. The energy dissipation would be greater the loop region more. Because of block uplift. Interlocking plastic-block structure can dissipate more energy during seismic event. In current study, the energy dissipation of structure increases with an increase in applied loading frequencies because of increase magnitude of uplift. Energy dissipation usually refers to uplifting, that may contribute to material properties, but uplifting works. Because it decreases the structure's secure stiffness and thus

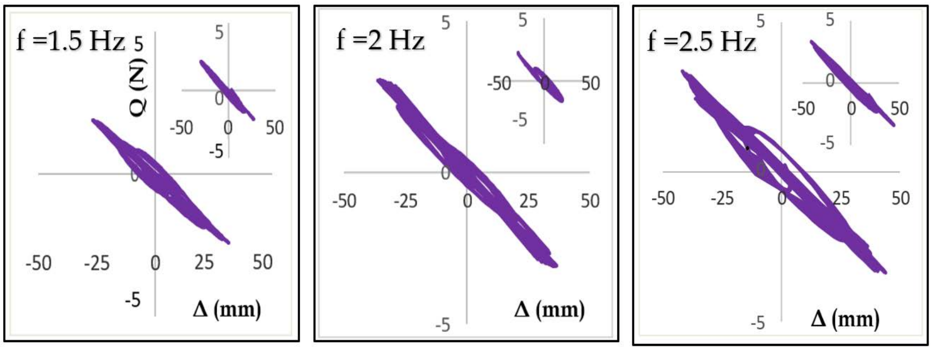

FIGURE 4.6: Base shear-displacement (Q-Δ) curves along with enlarged typical single loop for 1.5, 2.0 and 2.5 Hz.

TABLE 4.2: Average energy dissipation of interlocking block structure during harmonic loading

Frequency (Hz) ug= 30 mm	**Average Energy dissipation in one cycle (Nm)**	**Total number of cycles**	**Total energy absorbed (Nm)**
Structure			
1.5	1.88	78	146.64
2.0	2.9	80	232
2.5	5.9	90	538.2

disrupts the earthquake effect. The plastic-block structure has rubber band allows vertical relative moment during harmonic setting. Uplifts are noticed when the plastic block structure moves to one side, say the right side and top relative displacement is observed, at the left side. It was noted that rubber bands play an important role in energy dissipation during harmonic loading because rubber bands do not permanently allow structural deformation, individuals provide an integrity structure and allow the structure to arrive in its original position without damage. By increasing the frequency with rubber band in ANSYS 19 energy dissipation is also being increased in interlocking structure. Fig 4.5 shows the Uplift time of interlocking plastic block structure.Mortar-free interlocking structure allows vertical relative movement at the block interface during the applied harmonic loading. When the structure deflected towards one side. The block uplifts along the height during one cycle will be observed.

It was noted that during harmonic loading with frequencies 1.5, 2.0 and 2.5 Hz.

The interlocking of plastic-block structure with rubber band dissipates greater energy. It has observed with increasing frequencies from 1.5 to 2.0, 2.0 to 2.5 Hz, 54 and 106 percent increase in energy dissipation has occurred. The conclusion is that energy dissipation is enhanced by the use of rubber band in interlocking plastic-block structure. [25] also stated that the use of ropes improved the energy dissipation by providing pre-tensioning to the structure. It is concluded that pre-tensioning in mortar-free interlocking plastic-block construction, without pre-tensioning, will dissipate more energy than construction. Using rubber band, the pre-tensioning to interlock plastic-block structure is given.

4.3 Effect of Diaphragm on Behavior of Wall Having Window Opening

In applied displacement, the displacement value 3cm has used with frequency 2.5 Hz. It has observed from the results of Sudheer and Ali [14] the averaged acceleration, velocity and displacement at the IPBWW top (i.e. t, and ut, respectively) is taken as IPBWW response. These are 0.090 g and 3.0 cm, respectively, are applied loading at the base of interlocking plastic block wall with the window opening (IPBWW). The response on top of IPBWW are acceleration and displacement time histories. These values are 0.095 g and 3.2 cm. Orange line shows the applied loading. While for the response of interlocking plastic block wall, dotted lines are used in the graph. Green line shows the top response of IPBWW as used by Sudheer and Ali [14]. For IPBWW using the wooden diaphragm are represented by red dotted lines, it has observed that the displacement at top of interlocking plastic-block walls has reduced. In addition to lines numbers are added, number 1 show the applied loading, number 2 shows the numerical response of interlocking plastic block wall with window opening without diaphragm. Number 5 shows the numerical response of wall using wooden diaphragm, Acceleration and displacement time histories at top of interlocking plastic block wall with window opening has shown in Fig 4.7. However, using the flexible wooden diaphragm, has an effect to the displacement value has reduced to 3.12 centimeters. Acceleration

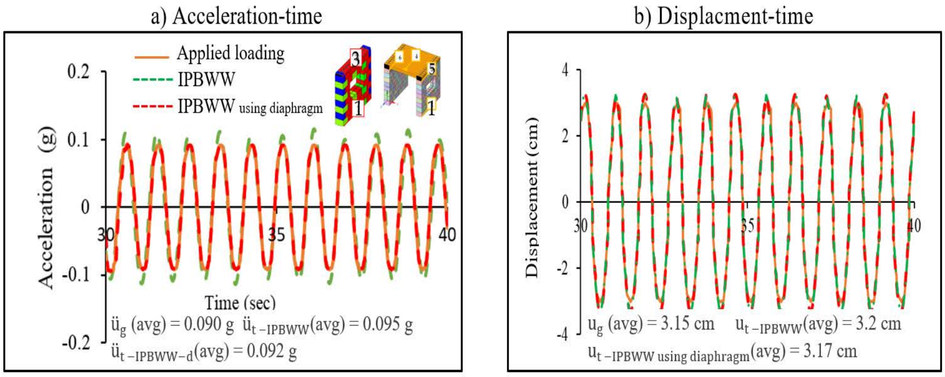

FIGURE 4.7: Effect of diaphragm on IPBWW [14]; a) acceleration-time histories, b) displacement-time histories.

value has reduced from 0.095 g to 0.092 g.In percentage, 4.68 percent reduction in displacement and 3.15 percent acceleration has reduced, it has observed due to wooden diaphragm on top of the structure. Use of flexible wooden diaphragm, has valuable effect in displacement reduction of interlocking plastic wall without opening. Furthermore, it has evaluated that previous research was conducted on only IPBWW structure. For the complete structure, IPBWW will be used with wooden diaphragm, it has noted that using diaphragm, acceleration and displacement time histories can be reduced

4.4 Effect of Opening on the Behavior of Interlocking Plastic Wall

For measuring the dynamic effect between interlocking plastic block walls, the input loading including the average acceleration and displacement has applied to interlocking plastic block walls. These values are 0.080 g and 3.0 cm, respectively. Both walls are tested in Ansys 19 with same applied loading including ground acceleration and displacement. The frequency 2.5 Hz has used for input loading of the structure. The orange solid line shows the applied to interlocking plastic block wall, the purple dotted line shows the response at top of interlocking plastic solid wall (IPBSW), red dotted lines are used for response top of IPBWW. Fig 4.8 shows the effect of IPBWW with IPBSW of interlocking plastic block structure.

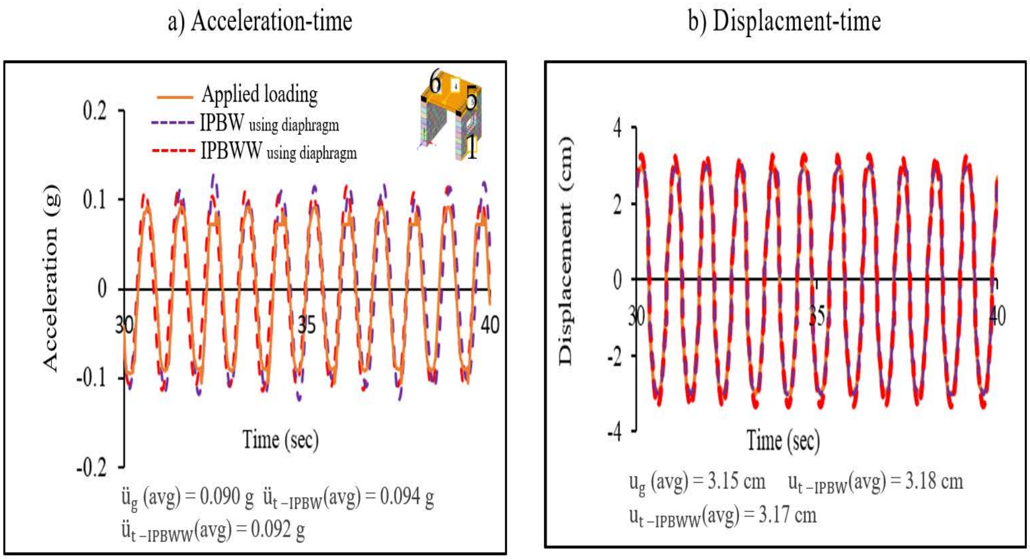

FIGURE 4.8: Effect of wall with opening; a) acceleration -time histories, b) displacement time histories.

In number figure, the number 1 shows the applied loading, while number 5 and 6 shows the response of wall with window opening and solid wall, respectively.

Comparison has made between wall of structure. The response on top of walls has observed after analysis completion, the acceleration and displacement values for IPBWW are 0.092 and 3.05 cm. For interlocking plastic block solid wall (IPBSW), the acceleration and displacement values are 0.094 and 3.13, respectively. It has noted from acceleration and displacement time histories during harmonic loading that interlocking wall with window opening has less value of acceleration and displacement, that show that it can dissipate more energy during seismic events. More energy can dissipate using interlocking plastic block wall with window opening.

4.5 Summary

In this chapter, numerical results of recorded data from structure response is presented. Finite element software, Ansys 19 has used for acceleration, velocity and displacement time histories. The response of structure has presented in terms of acceleration and displacement time histories. In addition to that base shear and displacement behavior of structure has represented. Energy absorption loops of structure are also plotted. Effect of diaphragm on window opening wall has also determined. furthermore, effect of opening in walls has also determined in acceleration and displacement time histories. Interlocking plastic block structure dissipated more energy with increasing frequencies.

Chapter 5

Discussion

5.1 Background

The results of the acceleration-time history, velocity-time history, displacement-time history, base shear-displacement curves are explained in detail in the previous chapter. Notable energy absorption is found in the plastic-block structure. In this chapter, the relationship between numerical and empirical values is established to predict the dynamic behavior of the plastic-block structure. In addition, the percentage difference between empirical and experimental values is also presented.

5.2 Empirical Equations using Structure Response Geometrical Parameters and Applied Numerical loading

Khan and Ali [13] have developed the empirical equations that integrate geometry of interlocking plastic block columns, column height, column response and input loading parameters. Following advanced based equations on Khan and Ali [13] approach developed for predicting the response of interlocking plastic-block structure by incorporating new variable R_s:

$$\ddot{u}_t = \frac{\frac{a}{h^2}}{n} R_s K^{(1+\frac{2n}{100})} \ddot{u}g.....(5.1)$$

$$u_t = \frac{\frac{a}{h^2}}{n} R_s K^{(1+\frac{n}{100})} ug.....(5.2)$$

$$E = \frac{\frac{a}{h^2}}{n} R_s \ \frac{0.85KH^2M}{t^2} \frac{u_t}{u_g}.....(5.3)$$

TABLE 5.1: Comparison between numerical and empirical results of structure

Frequency (Hz)	**Energy dissipation(Nm)**	–	**Percentage difference**
–	Numerical values	Empirical values	–
1.5	0.72	1.92	2.4%
2.0	2.90	2.95	1.7%
2.5	5.92	5.97	1.3%
Frequency(Hz)	**Acceleration (g)**	–	**Percentage difference**
–	Numerical values	Empirical values	–
1.5	0.072	0.072	0.2%
2.0	0.088	0.088	0.2%
2.5	0.097	0.097	0.2%
Frequency(Hz)	**Displacement (cm)**	–	**Percentage difference**
–	Numerical values	Empirical values	–
1.5	2.89	3.23	12%
2.0	3.03	3.48	15%
2.5	3.19	3.92	23%

where R_s is the reduction factor due to increased stiffness. The reason behind incorporating new variable is that, Khan and Ali [13] equations are for column structure, while the current study is about structure with walls response which has more stiffness as compared to the column structure. M, h, t, n, A, H, E are total mass of structure, key height, input loading period, number of blocks, base area,total height of structure, and total energy absorption of structure, respectively. Averaged ground acceleration, velocity and displacement are applied respectively. Their corresponding values are 0.08 g, 75 cm/s and 3 cm, respectively are response acceleration, velocity and displacement, respectively. a, h, n, and m are block base area, key height, total number of blocks, and number of blocks along the length of wall in a single layer, respectively. Their corresponding values are 62 mm x 62 mm, 12 mm, 8, 41 mm * 8 + 12 mm = 340 mm, respectively. K is coefficient having dimensionless value of 0.45. Khan and Ali [13] equation is little modified by incorporating the new variable i.e. reduction factor due to increased stiffness, denoted by R_s. In Table 5.1 shows the comparison of numerical and empirical values of interlocking plastic block structure. The value of R_s for current structure is 0.115. It can be noticed that empirical are in good agreement with empirical results. The percentage difference between numerical and empirical results is relatively large (even though acceptable) at higher frequency with respect to that at lower frequency. This may be due to dynamic characteristics of interlocking assembly. As Ali [31] percentage difference was up to 35 percent in predicting the structure response which could be attributed towards the complicated nature of the structure versus the simple approach developed.

FE work is done to see the behavior of mortar-free interlocking-plastic block structure having diaphragm with simplified boundary conditions. Empirical modeling is used to understand which parameters and how these are contributing towards the observed behavior. Empirical modeling is giving the absolute maximum values where an FE work is giving time history analysis.

5.3 Outcome of Study with Respect to Practical Requirement

The implementation of harmonic loading using easily finite element Ansys software is capable of generating accurate harmonic loading to some degree, such that the dynamic behavior of the system under study can be studied. Harmonic loading is considered to be the base ground motion and the structure's response is studied with regard to it.

The structure studied indicated good capability in the form of structural stability and energy absorption. And, in combination with other structural elements, it should be discussed in depth for the interlocking structures. In addition, the negative impact of the seismic can be minimized by using an interlocking plastic block for earthquake resistant construction. Table 5.2 provides comparisons of

TABLE 5.2: Comparison between numerical and empirical results of structure

Previous Study	**Current study**
Complex shake table was used to analyze dynamic behavior of mortar-free interlocking structure	Finite element modeling has used
More inertial force was generated in coconut fiber reinforced concrete block due to its weight	Less inertial force is generated in plastic block structure due to its light weight
Previous research of interlocking block was conducted on dynamic response using shake table.	Numerical method has used for dynamic response.

previous research with the current analysis. There is a strong similarity to observed patterns in energy dissipation in a mortar-free structures.

5.4 Summary

This chapter clarified the findings of the analysis in terms of functional criteria and empirical equations. The goal of constructing the empirical equations was to test the percentage difference. It is capable to some degree of producing precise harmonic loading such that the dynamic behavior of the structure under study can be studied. Interlocking plastic-block structure dissipated more energy during applied testing. This is attributable to energy dissipation due to uplifting and relative block motion at interfaces.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

Most earthquake-resistant construction methods for earthquake-prone areas are available in literature. Yet those are inexpensive. Developing countries cannot afford these strategies to reduce the damage done by the earthquake. In this pilot study, dynamic response of interlocking plastic block structure using numerical approach has verified with previous experimental results. finite element model of structure has prepared to determine the response at top of structure. For finding the fundamental frequency and damping of system modal analysis has performed. Following conclusions can be drawn from this research work:

- Models validations have made with previous experimental studies. For column, the percentage difference in results is less than the 5 percent. For IPBWW, the percentage difference in results is less than 2 percent. It shows model validation is acceptable. Because percentage difference is less than 5 percent.
- From modal analysis, natural frequency of structure is 4.15 Hz and damping 4% have determined. It shows that structural frequency is much more than applied frequency.

- From harmonic analysis, acceleration-time, displacement time and energy absorption of structure have obtained. It shows that structure energy absorption increases with increasing frequencies.

- Effect of diaphragm on wall with window opening, acceleration-time and displacement time results have obtained. The percentage difference of acceleration time is 3.15% and displacement time is 0.93 percent.

- Effect of opening in behavior of walls, acceleration-time and displacement-time results have obtained. The percentage difference of acceleration time is 2% and displacement time is 0.31 percent.

- Finite element modeling of structure provides safe and economical earthquake-resistant housing solution to public.

- Empirical equations results of structure response are in good agreement with numerical values. The percentage difference is less than 18%.

6.2 Future work

The complete interlocking plastic-block structure with different connection and type of diaphragm with foundation will be studied for well understanding of dynamic response of interlocking plastic block structures.

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