CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

# Dynamic Behavior of Prototype Interlocking Plastic-block Structure Using Locally Developed Low-cost Shake Table

by

Fayaz Khan

A thesis submitted in partial fulfillment for the degree of Master of Science

in the

Faculty of Engineering
Department of Civil Engineering

2019

*I want to dedicate this work to my family, who helped me throughout my education. This is likewise a tribute to our best teachers who guided us to go up against the troubles of presence with ingenuity and boldness, and who made us what we are today.*

# CERTIFICATE OF APPROVAL

## Dynamic Behavior of Prototype Interlocking Plastic-block Structure Using Locally Developed Low-cost Shake Table

by

Fayaz Khan

(MCE173011)

### THESIS EXAMINING COMMITTEE

| S. No. | Examiner | Name | Organization |
|---|---|---|---|
| (a) | External Examiner | Engr. Dr. Rao Arsalan Khushnood | NUST, Islamabad |
| (b) | Internal Examiner | Engr. Dr. Ishtiaq Hassan | CUST, Islamabad |
| (c) | Supervisor | Engr. Dr. Majid Ali | CUST, Islamabad |

Engr.Dr.Majid Ali
Thesis Supervisor
April, 2019

Engr. Dr. Ishtiaq Hassan
Head
Dept. of Civil Engineering
April, 2019

Engr. Dr. Imtiaz Ahmed Taj
Dean
Faculty of Engineering
April, 2019

# *Author's Declaration*

I, **Fayaz Khan** hereby state that my MS thesis titled "**Dynamic Behavior of Prototype Interlocking Plastic-block Structure Using Locally Developed Low-cost Shake Table**" is my own work and has not been submitted previously by me for taking any degree from Capital University of Science and Technology, Islamabad or anywhere else in the country/abroad.

At any time if my statement is found to be incorrect even after my graduation, the University has the right to withdraw my MS Degree.

**(Fayaz Khan)**

Registration No: MCE173011

# *Plagiarism Undertaking*

I solemnly declare that research work presented in this thesis titled "**Dynamic Behavior of Prototype Interlocking Plastic-block Structure Using Locally Developed Low-cost Shake Table**" is solely my research work with no significant contribution from any other person. Small contribution/help wherever taken has been duly acknowledged and that complete thesis has been written by me.

I understand the zero tolerance policy of the HEC and Capital University of Science and Technology towards plagiarism. Therefore, I (as an author of the above titled thesis) declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS Degree, the University reserves the right to withdraw/revoke my MS degree and that HEC and the University have the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized work.

**(Fayaz Khan)**

Registration No: MCE173011

# *List of Publications*

It is certified that following publication(s) have been made out of the research work that has been carried out for this thesis:-

## Conference Proceedings

1. Khan F. and Ali M. (2018). Behavior of interlocking plastic- block structure under harmonic loading using locally developed low-cost shake table. *Annual Australian Earthquake Engineering Society Conference,* Nov: 16-18. Paper 51.

**Fayaz Khan**
(MCE173011)

# *Acknowledgements*


- I would like to thank Almighty Allah for his countless blessing.
- I would like to pay special gratitude to Dr. Engr. Majid Ali for his guidance and supervision, without which, this was not possible.
- I also want to thank CUST for partial financial assistance.
- I am grateful to all who assisted me during this study especially Engr. Atta baik, Engr. Farhan, Dr. Engr. Munir Ahmad, Mr.Usman, Mr.Ishtiaq ,and Mr. M. Junaid for their kind help in lab work.
- I am also grateful to my family for their continuous moral support.

# *Abstract*

In area, most of the non-engineered structures are collapsed in earthquake due to strong ground motion of earth. In seismic active region there is significant loss of life due to lack of earthquake resistant-housing. In developing counties there is need to develop economic and earthquake-resistant housing. Interlocking plastic-block structure is good option for earthquake-resistant housing. Many researchers explored various interlocking techniques for construction, but there is a need to investigate the plastic-block structure.

The overall aim of this research is to control damages and save precious human lives in future earthquake. In this research work, interlocking plastic-block structure behavior is studied under harmonic loading by using simple 1D shake table. Prototype interlocking plastic-block structure made of eight blocks having fixed base is tested using simple shake table.Similar structure with rubber band is also tested to enhance the integrity of structure. To record the structure response two accelerometers are installed: one at top of structure to record structure excitation while other at shake table to record base response.

Response in terms of acceleration-time and displacement-time histories is recorded. Base shear- displacement curves, energy absorption, and damping are calculated. At the same time, empirical equations are established keeping in mind the interlocking plastic- blocks geometry, size, height of structure and input loading parameters. As expected, the structure having rubber band is stiffer than structure without rubber band. Column response without band has more relative displacement at top of structure compared to structure with rubber band.

# Contents

# List of Figures

# List of Tables

# Abbreviations

| | |
|---|---|
| 1 D | One dimensional |
| 3 D | Three dimensional |
| CFRC | Coconut fiber reinforced concrete |
| E | Energy absorption |
| $E_1$ | Energy absorption up to first crack/maximum load |
| $E_2$ | Energy absorption from first crack/max. load to ultimate load |
| FEAP | Finite Element Analysis Program |
| FEM | Finite Element Modeling |
| SDOF | Single degree of freedom |
| MDOF | Multiple Degree of Freedom |
| kN | kilo-Newton |
| RCC | Reinforced Concrete Structures, Reinforced Concrete |
| Up | Uplift |
| MPa | Mega Pascal |
| RB | Rubber band |
| IPB | Interlocking plastic-block |
| T.I | Toughness index |

# Symbols

| | |
|---|---|
| $\xi$ | Damping ratio |
| $\Delta$ | Displacement |
| $\epsilon_o$ | Strain |
| $\delta$ | Compressive strength |
| $\ddot{u}_g$ | Average acceleration at column base |
| $\ddot{u}_t$ | Average acceleration at column top |
| $u_g$ | Average displacement at column base |
| $u_t$ | Average displacement at column top. |
| $f_n$ | Fundamental frequency |
| $E_t$ | Total energy absorbed |
| K | Coefficient having dimensionless value |
| n | Number of interlocking plastic-blocks |
| A | Base area of interlocking plastic-block |
| h | Key height of interlocking plastic-block |
| H | Total height of interlocking plastic-block. |
| Q | Base-shear |
| Hz | Unit of frequency |
| g | Acceleration |
| t | Time period |
| P | Peak load |

# Chapter 1

# Introduction

## 1.1 Background

An earthquake is the natural disaster which produces strong ground motion. Primary effects of earthquake cause severe damages, such as collapsing of buildings, roads and bridges, which may kill many people. Due to design deficiencies most of the masonry structure collapsed during earthquake [1]. Sichuan (china) earthquake in 2008 having magnitude of 8.0 killed 70,000 people, 216,000 buildings collapsed, including 6890 school buildings [2]. In October 2005 a catastrophic earthquake having magnitude 7.6 hit Kashmir. The Kashmir earthquake killed more than 85,000 people and partially or fully destroyed more than 45,000 buildings [3]. Dujiangyan earthquake 55% of masonry structure collapsed (Su et al. 2011). In 2010 Haiti earthquake having magnitude 7.0 caused 316,000 deaths, more than 1.3 lacks homeless, 300,000 injured and it was declared by the government of Haiti that 80% to 90% masonry structure critically ruined or damaged [4]. During seismic event mortar-free interlocking block absorb more energy due to relative movement of block interfaces. More than 80,000 injuries, 524 deaths resulted during Maule earthquake in 2010 [5]. Chen et al. [6] reported the tremendous damage of masonry houses and loss of life in Nepal. In June 2018 more than

1,000 houses are damaged during Indonesia earthquake, displaced round about 154,000 people (Lombok earthquake).

In seismic active region the cost-effective earthquake resistant housing is required in rural area of developing counties. During strong ground motion these region frequently suffer a significant loss of human life because of lack of seismic resistant housing. Arya et al. [7] declared that most of masonry structure collapse due design deficiencies and implementation. To find an efficient and cost effective solution, new construction techniques were developed utilizing structure consists of mortar-free interlocking blocks [8] and Ali at al. [9]. Coconut fiber reinforced interlocking mortar-free block were used but the mass of CFRC block is more Ali et al. [10]. Mass of CFRC block is still point of concern. Due to light weight, interlocking plastic- block are investigated in this research. In seismic event these interlocking plastic-block dissipated more energy due to uplift of blocks.

For dynamic analysis complex 3 D shake table is used in developing countries. But undeveloped countries lack such type of facilities. Simple 1D shake table is good option to explore dynamic behavior of structure in earthquake engineering laboratories. To study the dynamic behavior of structures single 1 degree of freedom shake table is used because it is economical and low maintenance cost. From this view point, uni-axial shaking tables were designed at low cost. Under harmonic as well as random excitation the shake table is utilized to study the dynamic behavior of structural. Stavirdis et al. [11] performed a test on three story reinforced concrete frames with masonry infill walls by using complex 3 D shake table. The prototype solid infill walls were placed on shake table. Different sensors were used for record structure response. For recording structure response, eleven cameras were put on different position. After performing the test, some minor cracks in infill wall were appeared due to intensity of base motion. Ali et al. [10] studied the dynamic analysis of mortar-free interlocking blocks but block weight is still point of concern. Nadir et al. [12] performed 44 tests on single storey structure by using shake table to study the behavior of structure under harmonic loading. The flexible structure and rigid structure were tested under dynamic loadings. Responses of flexible and rigid structures were recorded under different earthquake loadings. This test was conducted to record the accelerations and displacements by using different sensors. The responses of the rigid and flexible structures were compared. After performing the test, some of the factors were increased like base shear, stiffness of the connection and only one thing was not enhanced that was lateral drift.

To the best of author knowledge, no study has been conducted to investigate the behavior of interlocking plastic-block structure under harmonic loading using locally developed low-cost 1D shake table.

## 1.2 Research Motivation and Problem Statement

Damages are occured due to earthquake which causes collapse of buildings, roads and bridges, which may kill many people. Theses losses are needed to be reduced by using any economical solution. Ali et al. [10] proposed an economical solution but the mass of block still needs to be reduced. Interlocking plastic-block structure with fire-resistant paint can be considered due to low mass. For this purposes, recycled plastic waste can be an economic solution. Thus the problem statement is as follows:

*"In earthquake, most of the masonry structures collapsed due to design deficiencies [7]. There is a need of either to strengthen the structures or to develop new techniques. Strengthening is already available but is expensive. Ali [10] developed a mortar free structure (a new construction technique) for earthquake-resistant housing) with CFRC blocks. However, the mass of coconut fiber reinforced concrete blocks is still a point of concern. Lighter the mass of structure, lower the inertia force generated. For this, light weight interlocking plastic-block is one solution along with fire-resistant paint. For economical and environmental aspects, plastic waste can be recycled for this purpose (note: for the time being, it is outside the scope of this work). For such kind of structure (i.e mortar-free interlocking plastic-block structure), dynamic behavior should be studied. This can be done with simple shake table. Therefore, the behavior of interlocking plastic-block structure is*

*needed to be investigated under dynamic loading by using locally developed low-cost 1D shake table."*

## 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 structure in laboratory and field.

*"The specific aim of this MS research work is to investigate the dynamic response of a prototype interlocking plastic-block structure using locally developed low-cost 1D shake table* in laboratory."

## 1.4 Scope of Work and Study Limitation

Prototype interlocking plastic-block structure consists of eight blocks. Fixed base will be provided. Three loadings such as 1.1 Hz, 1.3 Hz, and 1.5 Hz will be applied. Response in terms of displacement-time and acceleration-time histories will be recorded. Frequency and damping will be determined for snap-back test. Empirical equation for these will be developed based on Ali [10] approach.

Study limitations include the use of simple 1D shake table, two accelerometers only (one at the bottom and other at the top), and three loading frequencies (1.1 Hz, 1.3 Hz, and 1.5 Hz).

## 1.5 Brief Methodology

Shake table have been used for applying harmonic loading with varying frequency of 1.1 Hz. 1.3 Hz, and 1.5 Hz. The aim of testing is to explore behavior of interlocking plastic-block structure at some incremental frequencies. To start with, three lower frequencies (i.e. 1.1 Hz, 1.3 Hz and 1.5 Hz) are randomly selected.

Two accelerometers are attached to interlocking plastic-block structure. One accelerometer is attached to base of structure and other accelerometer is attached at top of interlocking plastic-block structure to record structure excitation under applied harmonic loading. The accelerometer is further connected to computer for recording structure response.

Raw data is recorded in the form of acceleration-time history. Initially noise is removed by using different filters in matlab. Further the recorded response of structure in the form of acceleration-time history is then converted into displacement-time history by using seismosignal software. Base shear (Q) is being calculated by using the displacement time-history and acceleration-time history of top accelerometer data. Average energy dissipation in single loop and total energy absorbed is also calculated. Empirical equation is being developed keeping in mind the geometry of interlocking plastic-block, height, size of block and loading input parameters.

## 1.6 Thesis Outline

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

Chapter 1 consists of introduction section. Damages during earthquake 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; damages during earthquake are explained, new technology for earthquake resistant housing, dynamic response during real earthquake and lab dynamic loading and summary.

Chapter 3 consists of experimental program. It contains background, proposed structure and prototype plastic-block, stress-strain curves for interlocking plastic-block, mortar-free interlocking plastic-block with and without pre-tensioning, test setup, snap-back test and instrumentation, harmonic loading, analyzed parameters, development of empirical equation and summary.

Chapter 4 consists of experimental evaluation. It contains background, damping and fundamental frequency, structure response against harmonic loading and summary.

Chapter 5 comprises of discussion. It classifies into background, relationship of empirical equations, and outcome of study with respect to practical requirements and summary.

Chapter 6 includes conclusion and recommendations.

References are presented right after chapter 6.

Annexures are given at the end. Annexure A explains the results from the harmonic loading testing of remaining time-history analysis. Annexure B explains the preparation of shake table and specification. Annexure C consists of acceleration, velocity, and displacement-time history and base shear –displacement graphs from accepted conference paper.

# Chapter 2

# Literature Review

## 2.1 Background

Earthquakes are the natural hazard which caused severe damages to masonry structure and kill thousands of people every year. Earthquakes are natural disaster that cannot be stopped, but using engineering knowledge, its negative effects can be minimized up to large extent. In earthquake most of masonry structure collapsed due to design deficiencies and implementation. Many studies have been carried out in the past, and are being done in the present as well to develop techniques to minimize the negative effects of earthquakes. Dynamic behavior of structure is investigated using 3 dimensional shake tables. Developed countries like America, News land, Canada, England, and Australia have complex 3 D shake table and many facilities to investigate the precise analysis of structure under dynamic loading. But unfortunately developing countries lack such type of facilities. Hence Simple 1 D shale table is good option to enhance the understanding of dynamic response of structure in earthquake engineering laboratories. For such type of research prototype structure have been developed for analyze the dynamic behavior of structure in laboratory by using low-cost shake table. Prototype structure is being analyzed in past researches .This chapter includes the literature review about damages caused to masonry structure due to past earthquakes. Literature review also includes the new technology for earthquake resistant housing, and also contains the dynamic response of structure during real earthquake and also about dynamic testing in laboratories.

## 2.2 Damages of Masonry Structure During Earthquake

During the earthquake of 2001, more than 75,000 houses were fully damaged in in the Republic of El Salvador in Central America [13]. In 2002 earthquake of magnitude 6.3 occurred in turkey. The structure damages is divided into three categories; heavily damaged, medium damaged and low damaged structure. In this earthquake numbers of heavily damaged, medium damaged, and low damages structures were 4,390, 1,730, and 9,556, respectively, and masonry structure having height less than 3 stories had survived during earthquake with minor damages Azeloglu et al. [14]. One thousand masonry structures collapsed, two people died and 122 people injured in turkey. In 1999, a magnitude of 7.4 hit Kocaeli (Turkey) and caused a lot of destruction. According to the survey, building damages were divided into three categories: such as heavily damaged, medium damaged and low damaged. In this earthquake the number of heavily damaged structure was 41,266, medium damages structure was 43,618 and low damage structure was 48,008 [15]. Sichuan (China) earthquake in 2008 having magnitude of 8.0 killed 70,000 people, 216,000 building collapsed, including 6,890 school building [16]. In 1935 a catastrophic earthquake having magnitude 7.7 hit Quetta city (Baluchistan). This earthquake caused a lot of destruction in Quetta. This earthquake killed about 30,000 to 60,000 peoples. A complete city was destroyed in Quetta earthquake [17]. The Kashmir earthquake killed more than 85,000 people and partially or fully destroyed more than 45,000 buildings [3]. Wang et al. [18] reported that devastating earthquake occurred in yushu China in 2010. Dujiangyan earthquake 55% of masonry structure collapsed [19]. In November 2011 van earthquake having magnitude of 7.2 badly destroyed the unreinforced masonry building. In van earthquake two earthquakes occurred of magnitude of 7.6 and 5.6. Approximately 2200 masonry structure collapsed during first earthquake, 4000 people injured and more than 644 people died [20]. In 2010 Haiti earthquake having magnitude 7.0 caused 316,000 deaths or missing, more than 1.3 homeless, 300,000 injured and it was declared by the government of Haiti that 80% to 90% masonry structure critically ruined or damaged [4]. Yushu earthquake effect 27 seven cities in China and seven countries including Shique, Nangqian, Qumalai, Zaduo. Ziduo. The magnitude of yashu earthquake was 7.1, damaged about 94 % structure and caused number of casualties including 2,697 people died, 12,134 injured and 260 missing. Earthquake has caused severe damages to masonry structure, which kill many people. In earthquakes, most of the masonry structures collapsed due to design deficiencies [16]. In 1992 a magnitude of 6.3 earthquakes occurred in Turkey. In Turkey earthquake damages is dived into three categories such as low damaged structure, medium damaged structure and heavily damaged structure. The total number of low damaged, medium damaged and heavily damaged structure were 4,867, 5,453, and 4,157, respectively [21]. In Nepal earthquake most of the masonry structure was damaged due to several reasons. A more intensity of earthquake hit Dinar (Turkey) in 1995, caused collapsed of 4,909 building [22]. In 1988 in Nepal, a catastrophic earthquake of magnitude 6.6 hit the Bihar-Nepal border. The focal depth of this earthquake was 71 km, which caused 281 deaths in Bihar and 650 deaths reported in Nepal. This earthquake destroyed 1.5 lacks houses in Bihar. In this earthquake more than 3,676 people were injured. In 1985 earthquake occurred in Mexico City. An estimated 50,000 were injured, 10,000 were killed and more than 250,000 people lost their shelter. In this earthquake 60 % of structures were fully or partially damaged. Bhuj earthquake in 1991 collapsed a lot of masonry structure, and total numbers of deaths were 19500. On 9th April 2009, Jaisalmer earthquake having magnitude of 5.1 occurred in India and duration of the earthquake was 15 sec to 30 sec. This earthquake caused cracks in 3,000 buildings. At least 7 people were injured. Jnemann et al. [5] investigated that more than 80,000 injuries, 524 deaths resulted during Maule earthquake in 2010. Pian [23] reported that more than 501,201 buildings are collapsed, 272,176 buildings are partially or fully damaged in Nepal earthquake. It is necessary to precisely investigate the dynamic behavior of structure to reduce the damages to structure and to save precious human lives. Chen et al. [6] reported the tremendous damage of masonry houses and loss of life in Nepal. In June 2018, more than 1,000 houses were damaged during Indonesia earthquake, displaced round about 154,000 people (Lombok earthquake).

## 2.3 New Technology for Earthquake Resistant Housing

After investigation, it was observed that most of the structures in 2005 earthquake damaged due to design deficiencies and implementation [17]. Even today, an effort is required to reduce loses during future earthquakes. To find an efficient and cost-effective solution, new construction techniques were introduced by various researchers in last decade [8] and Ali at al. [9]. Due to relative movement of block interfaces a mortar-free interlocking block structure has the ability to absorbed energy during seismic events. Interlocking blocks have been used in past for research purposes but the mass of CFRC (coconut fiber reinforced composite) block has been a point of concern due to its heavy weight Ali et al. [9]. Structure is also affected by its heavy weight during earthquake. Greater the weight of structure more will be inertia forces generated. So it is necessary to reduce the weight of structure. Structure having lighter weight, smaller will be in inertia force generated. For this, light weight interlocking plastic- block is one solution. In order to reduce inertia forces there is need to reduce the weight of coconut fiber reinforced concrete block. Hence interlocking plastic-block structure is alternative to explore. For economic and environmental aspects, plastic waste can be recycled to make useful interlocking plastic- blocks for this purpose study.

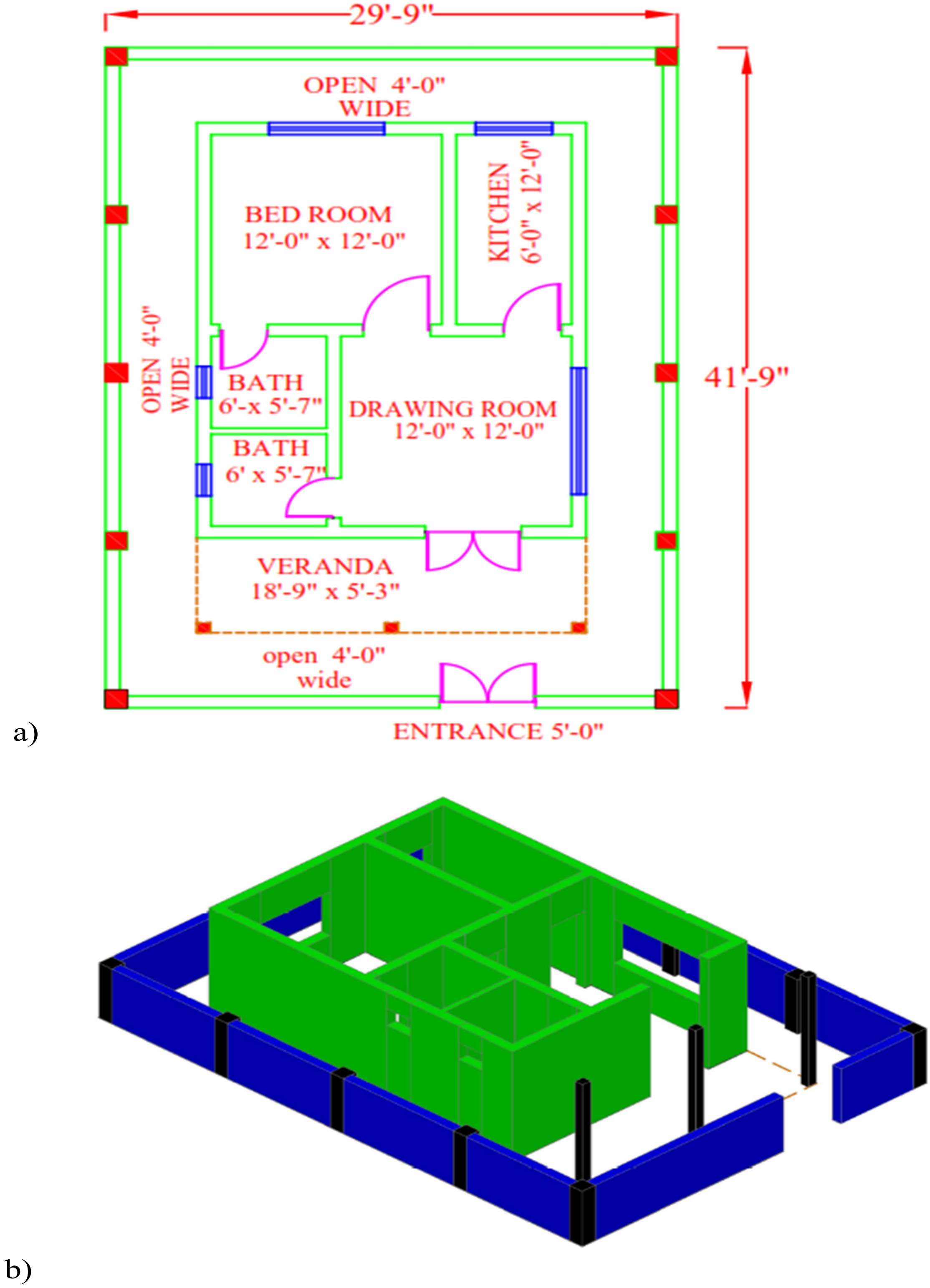



FIGURE 2.1: Proposed interlocking plastic-block house: a) plan and b) 3D view.

Figure 2.1 shows proposed interlocking plastic-block house: 1a) plan and 1b) 3D view. The proposed interlocking plastic-block structure is especially for poor people because the proposed house is economical. The total area of interlocking plastic-block is 1245 ft$^2$, consists of one bed room (12'-0" X 12'-0") having attached bath (6'-0" X 5'-7") , one kitchen (6'-0" X 12'-0"), drawing room (12'-0" X 12'-0") having attached wash room for guest (6'-0" X 5'-3"), verandah having dimension 18'-9" X 5'-3". The thickness of boundary wall is six inch and open wide area is 4'-0". The main entrance in proposed interlocking plastic-block house is 5 feet.

## 2.4 Dynamic Response of Structure During Earthquake and Lab Dynamic Loading

In order to generate real earthquake data a complex 3-D shake table having six degree of freedom is used in developed countries to precisely investigate the dynamic response of structure. But complex shake table is uneconomical and developing countries lacking such facility. Simple 1D shake table can be useful to understand dynamic behavior of prototype-structure in laboratory. Prototype structures are developed and used for such type of studies. Time history analysis is useful technique for determination seismic response of structure under dynamic loading [25]. Elvin and Uzoegbo [8] investigated the full scale structure under harmonic loading. Darshita and Anoop [26] conducted study on development of low cost shake table. The dynamic analysis of structure subjected to earthquake loading and reported that damage of structure during earthquake can be reduced if structure design in such way that it resists seismic forces [27]. This technique was carried out in steps to investigate the dynamic response of structure under the loading varying time [28]. It was reported that mortar-free interlocking block dissipated energy due to uplift of blocks.

Specifications of some shake tables are shown in Figure 2.1 [26]. It is noticed that different types of shake table such as one dimensional and three dimensional shake tables is used for dynamic analysis of structure. For precise dynamic analysis of structure 3 D shake table is being used.

TABLE 2.1: Specification of some shake table [26]

| Sr. no | Institute, Country | Year | Specifications | | | | |
|---|---|---|---|---|---|---|---|
| | | | Size (mm) | Direction | Amplitude (mm) | Frequency (Hz) | |
| | | | | | | X-Direction | Y-Direction |
| 1 | University of Canterbury New Zealand | 2005 | 10500 x 8000 | 1 D | ±75 | 4.4 | - |
| 2 | NED UET, Karachi, Pakistan | 2013 | 1830 x 1220 | 3 D | ±30 | 2.83 | 1.57 |
| 3 | NIED, Tsukuba, Japan | 2013 | 20000 x 15000 | 3 D | ±90 | 2.34 | 3.52 |
| 4 | University of Nevada, Reno | 2014 | 1829 x 1829 | 3 D | ±35 | 4.32 | 3.54 |
| 5 | University of California, San Diego | 2015 | 10100 x 4600 | 1 D | ±60 | 8 | - |

To the best of authors knowledge, no study has been reported on investigation of the interlocking plastic-block structure under dynamic loading by using uniaxial shake table. This study is done to know the dynamic characteristic of mortar-free structure that consists of the interlocking plastic-blocks. In this research work, experimental investigation is done to calculate the amount of energy dissipation of interlocking plastic-block column. At the same time, empirical equations are developed for predicting the column response. The dynamic characteristic of interlocking plastic-blocks column is studied in the following section. The intended outcome of this research is to (i) understand the dynamic behavior of mortar-free interlocking plastic-block structure (ii) to determine the damping of interlocking plastic-block structure under varying amplitude (iii) also to study the base-shear displacement relationship.

## 2.5 Summary

One of the major hazards to structural safety is earthquake. The occurrences of earthquake cause severe damages to both society, environment and economic. It is evident from the above discussion that severe damages of masonry structure are due to design deficiencies and implementation. The earthquake damages are also caused due to poor understanding of structure behavior during earthquake. Therefore study has been carried out in detail to reduce losses and adverse effect due to earthquake in future. Ali et al. [9] proved from his research that mortar-free interlocking block structure has the ability to dissipate energy of earthquake but there is need to reduce the mass of coconut fiber reinforced concrete block, which is still point of concern. Therefore new interlocking plastic-block has been introduced, lighter the mass of structure lower will be inertia forces generated. Interlocking plastic-block structure has ability to dissipate earthquake energy due to uplift of blocks. To start with, a comparative study can be done through experimental and empirical analysis. For experiment simple one dimensional shake table is used as literature has been found supportive in this regard.

# Chapter 3

# Experimental Program

## 3.1 Background

In chapter two, damages during earthquake, dynamic response of structure during real earthquake and new technology for earthquake resistant has been explained. This chapter includes many topics such as proposed structure and plastic-block, stress-strain curve of interlocking plastic-block, mortar-free interlocking plastic-block without and with pre-tensioning, test setup, snap back test, harmonic loading, analyzed parameters and development of empirical equations. To reduce the effect of earthquake on structure, many techniques are being studied. Ali et al. [10] investigated the mortar-free interlocking dissipate energy due to uplift of blocks and relative movement at block interfaces. The structural damage can be reduced to change the mode shape of structure during earthquake. The mode shape of structure during earthquake can be changed by using interlocking plastic-block.

## 3.2 Proposed Structure and Plastic-block

Figure 3.1 shows the interlocking plastic-block for proposed construction and its prototype for current research. For construction of earthquake resistant housing the proposed interlocking plastic-block has total height of 140 mm including key height of 30 mm and base area is 150 mm x150 mm is shown in Figure 3.1 (a). There are four keys in proposed plastic-block for construction. The prototype interlocking plastic-block is shown in Figure 3.1 (b). It has mass of around 25 g. The overall dimensions are 62 mm x 62 mm x 53 mm. The height of interlocking key is 12 mm.

For current research work, the prototype block size is 2.5 times smaller than proposed interlocking plastic-block. The interlocking key of 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 considered structure is prototype concentric column with respect to pre-tensioning. However, in real structures these will be eccentric columns. For columns with moment, pre-tensioning with rubber band through interlocking keys may be required. For current study, the randomly selected scale of $1/10^{th}$ in for structure height is considered with simplified boundary conditions. Ali et al. [9] also used simplified boundary condition. Keeping in mind $1/10^{th}$ scale of structure height and 2.5 scales for block, a total of eight blocks is taken."

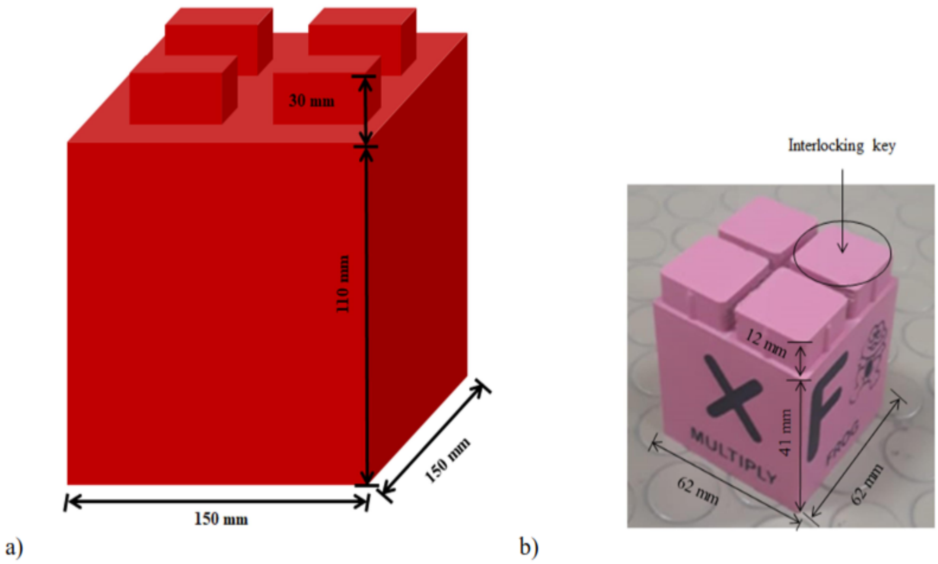



FIGURE 3.1: Interlocking plastic-block: a) proposed for construction, and b) prototype for current study.

### 3.2.1 Stress-strain Curve for Interlocking Plastic-block

Fig 3.2 shows the Stress-strain curve of single and multiple interlocking plastic-blocks. The full green line indicates stress-strain curve of single interlocking plastic-block while red dotted line shows stress-strain curve of multiple interlocking plastic-block. It is also noticed that ultimate load for multiple interlocking plastic-block is more than the ultimate load of single interlocking plastic block. No failure is observed in the key of interlocking plastic-block during compressive test but however some cracks are found in other parts of interlocking plastic-block. It means that key of interlocking plastic-block has sufficient strength and with stand with greater compressive load. No yielding has been noticed in interlocking plastic-block while performing the compressive strength test.

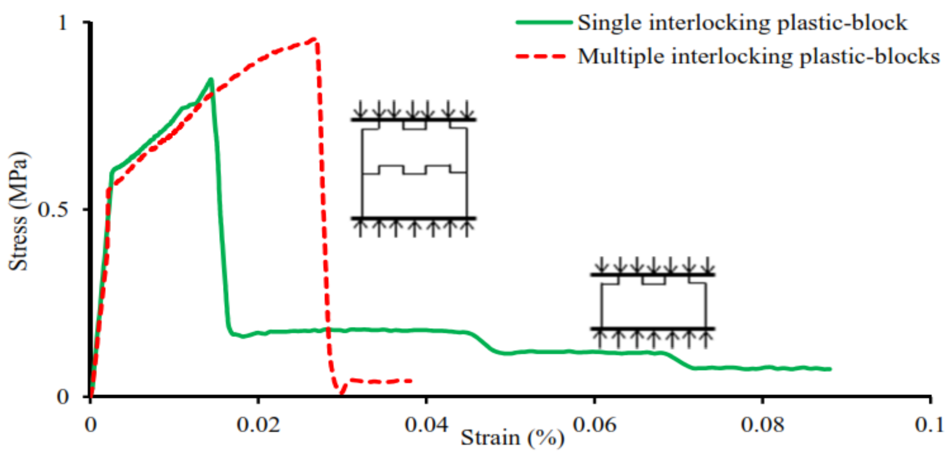
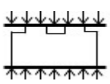
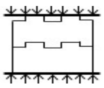



FIGURE 3.2: Stress-strain curve of single and multiple interlocking plastic-blocks.

Table 3.1 shows the investigated properties of single and multiple interlocking plastic-block such as compressive strength ($\sigma$), peak load, strain, energy absorption, and toughness index. It has been noticed that multiple interlocking plastic-blocks have greater compressive strength. It is also observed that more energy is absorbed in case of multiple interlocking plastic-blocks (0.03 kN-mm) while single interlocking plastic-block absorbed (0.02 KN-mm). It is also noticed that peak load for multiple interlocking plastic-block is 3.67 kN, which is more than the peak load (3.15 kN) of single interlocking plastic block. Energy absorption capacity under compressive strength is enhanced by 50% in case of multiple interlocking-plastic blocks. No failure or cracks is observed in the key of interlocking plastic-block during compressive test.

TABLE 3.1: Properties of interlocking plastic-block

| **Sr.no** | **No. of blocks** | **Peak load (kN)** | $\sigma$ **(MPa)** | $\epsilon_o$ **(-)** | $\mathbf{E_1}$ **(Nm)** | $\mathbf{E_2}$ **(Nm)** | $\mathbf{E_t}$ **(Nm)** | **TTI (-)** |
|---|---|---|---|---|---|---|---|---|
| 1 |  | 3.15 | 0.85 | 0.015 | 10 | 10 | 20 | 2.07 |
| 2 |  | 3.67 | 0.91 | 0.027 | 20 | 10 | 30 | 1.67 |

## 3.3 Mortar-free Interlocking Plastic-block

The considered structure is prototype concentric column with respect to pre-tensioning. However, in real structures these will be eccentric columns. For columns with moment, pre-tensioning with rubber band through interlocking keys may be required. For current study, the randomly selected scale of $1/10^{th}$ in for structure height is considered with simplified boundary conditions. Ali et al. [9] also used simplified boundary condition. Keeping in mind $1/10^{th}$ scale of structure height and 2.5 scales for block, a total of eight blocks are taken.

### 3.3.1 Without Pre-tensioning of Structure

For the evaluation of the dynamic characteristic of mortar-free interlocking, plastic-block column is considered without pre-tensioning. A prototype mortar-free interlocking plastic-block structure comprising of eight interlocking plastic-block (n=8) having total height (H) of 340 mm. Fixed base is provided. Column integrity can be availed by interlocking key height of 12 mm; otherwise collapse of column is expected. The overall weight of structure is 0.20 kg. Two accelerometers are used: on at the top of column to record structure response and other accelerometer is fixed with moving plate of shake table to record base excitation of structure. The two sensors (e.g. sensor 1 and sensor 2) are tightly attached to specified location otherwise if there is any movement found in sensor than data recorded will be incorrect. Structure response in term of acceleration-time history is obtained by connecting accelerometer to computer system ( i.e. by using software matlab). For connected hardware to computer system it is necessary to install simolink package in matlab. Initially noise is removed by designing a different filter in matlab. Displacement-time histories are obtained by using seismosignal software.

### 3.3.2 With Pre-tensioning of Structure

Similar mortar-free interlocking structure is considered for the determination of dynamic characteristic of interlocking plastic-block column. In addition, column integrity is availed by using rubber band, which can help to prevent the collapse of column. In real construction, waste tyres may be used instead of rubber-band to provide elastic pre-tensioning.

Figure 3.3 shows instrumentation of snap back test: a) schematic diagram and b) test setup. Damping and fundamental frequency of structure will be calculated from free vibration [10]. The main purpose of snap back test is to determine damping ratio ($\xi$) and fundamental frequency ($f_n$) of interlocking plastic-block structure.

## 3.4 Test Setup

### 3.4.1 Snap-back Test and Instrumentation

A total four tests are planned for snap-back including structure with rubber band and without rubber band. Only two tests for snap-back are performed for structure having rubber band and unfortunately the snap-back test for structure without rubber band is not performed due to some reasons. By sudden releasing of wire, a)

b)

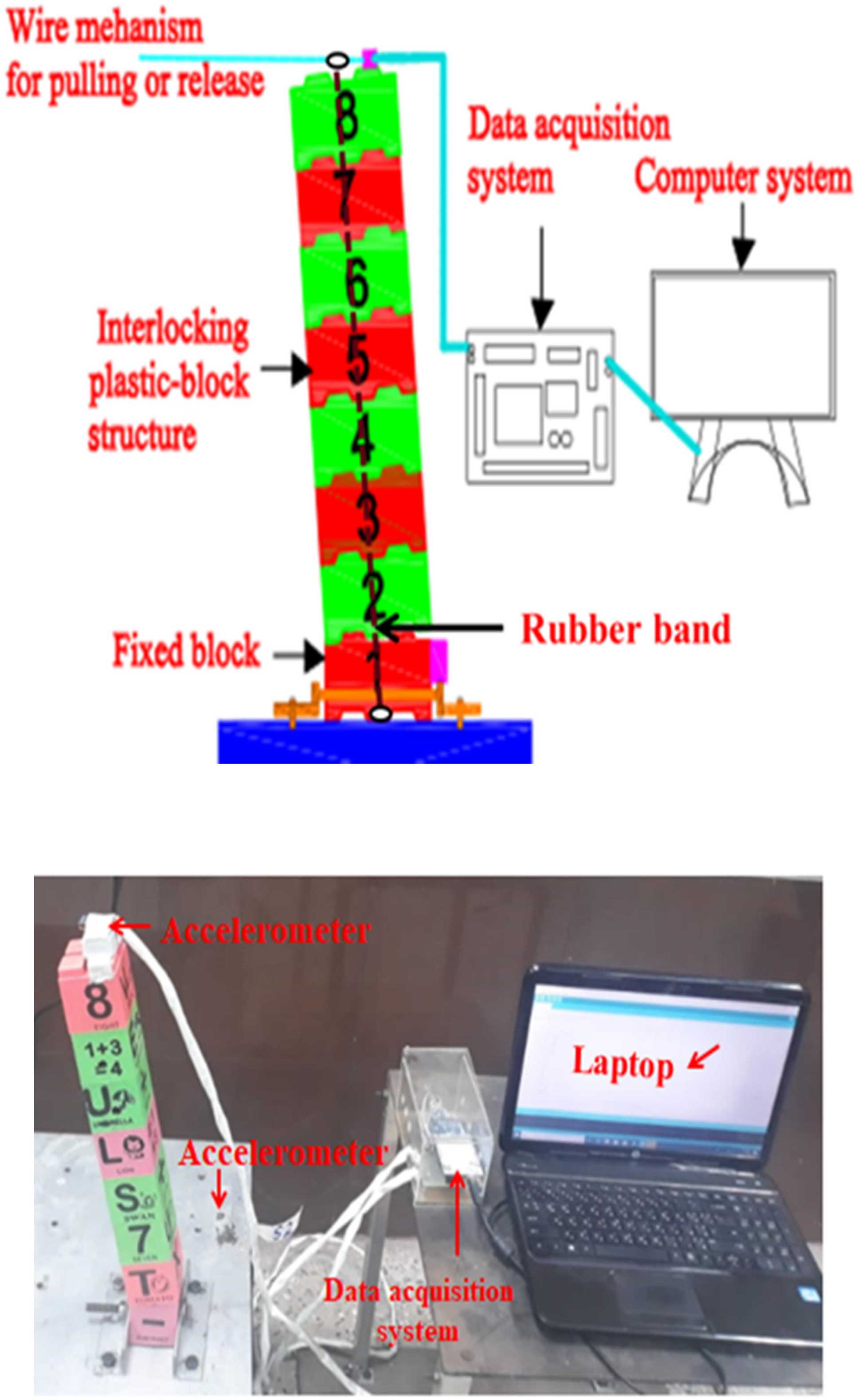



FIGURE 3.3: Instrumentation of snap back test: a) schematic diagram and b) test setup.

no free vibration is observed in structure without rubber band. The snap-back test setup is shown in Figure 3.3. A wire is attached at column top having length of 460 mm. Only one accelerometer is used to record free vibration of interlocking plastic-block structure. The accelerometer is attached with top of interlocking plastic-block structure to record structure response. By releasing of a wire, free vibration of interlocking plastic-block structure is observed. Basic response of structure is recorded in terms of acceleration- time histories. Damping ratio ($\xi$) and fundamental frequency of interlocking plastic-block structure with rubber band is calculated by using log decrement method.

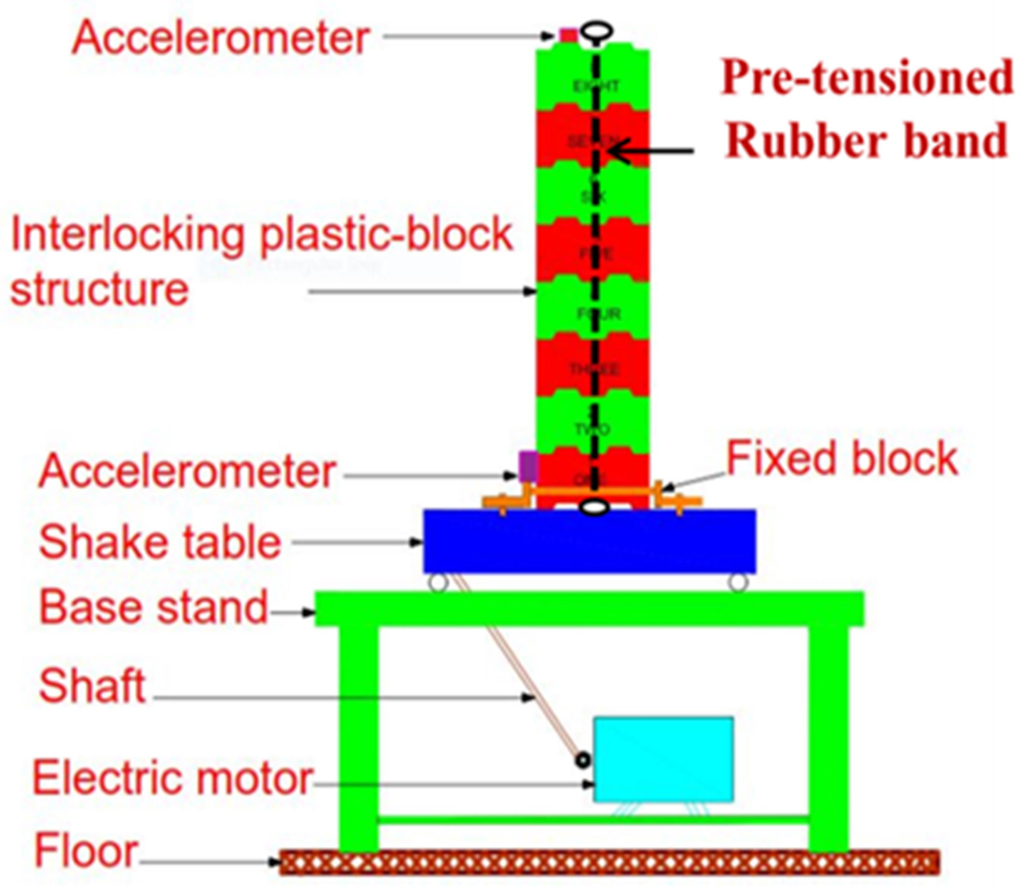
### 3.4.2 Shake Table Test and Instrumentation

Interlocking plastic-block structure consists of eight plastic- blocks (n=8) and total height (H) of column is 340 mm. The base area of column is 62 mm X 62 mm. The lower plastic-block column is fixed with shake table and the top of column no mass is provided. However the total mass of column is 0.20 kg. Figure 3.4 shows instrumentation of shake table testing: a) schematic diagram and b) test setup. Two accelerometers are used to record response at bottom and top of the structure. Structure response is obtained in term of acceleration-time history. By using seismosignal software acceleration-time history is converted to displacement-time histories.

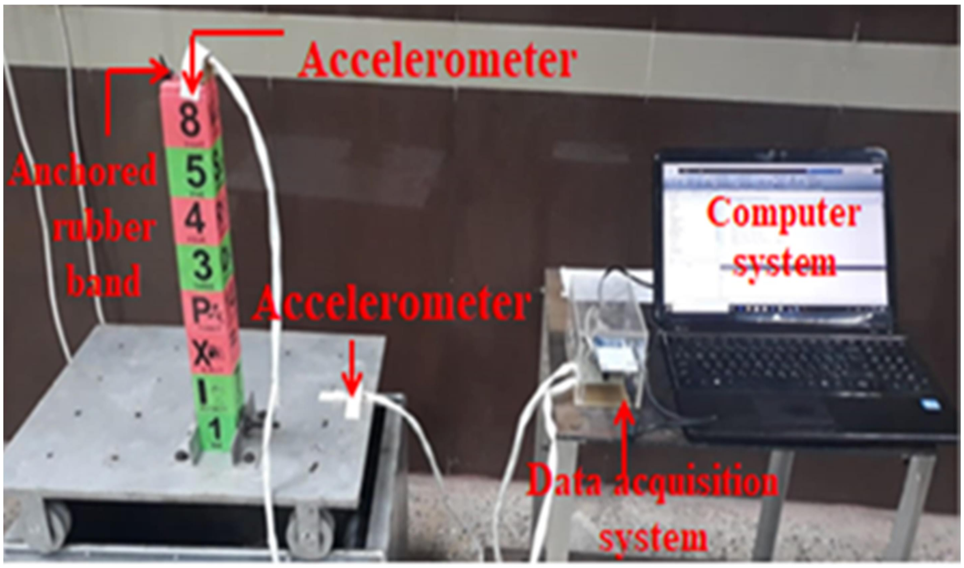
## 3.5 Loading

### 3.5.1 Snap Back

For snap back test, interlocking plastic-block structure was displaced by 25 mm and 50 mm respectively at top of structure and released structure suddenly to produce free vibration. The acceleration-time history for snap-back tests are shown in Figure 4.1. For calculation of damping ratio, load decrement method is used.




a)




b)

FIGURE 3.4: Instrumentation of shake table testing: a) schematic diagram and b) test setup.

### 3.5.2 Harmonic Loading

Table 3.2 shows magnitude of different tests considered. Total eight tests performed for this research work. Two snap back tests are carried out for structure having rubber band. Snap-back test is only performed for structure with rubber band. Different harmonic loading with varying frequencies such as 1.1 Hz, 1.3 Hz, and 1.5 Hz are considered. Six harmonic loading tests are conducted; three tests for interlocking plastic-block structure with rubber band and three harmonic tests were carried out for structure without rubber band. In harmonic loading the amplitude of structure is 30 mm. Acceleration time –history and displacement time –history of two sensor is compared to know the dynamic behavior of interlocking plastic-block structure under harmonic loading. It is expected that acceleration and displacement will be more in interlocking plastic-block structure having rubber band.

Table 3.2: Magnitude of different tests considered.

| **Test** | **Amplitude** | **Structure without rubber band** | **Structure with rubber band** |
|---|---|---|---|
| Snap back | $u_g$ =25 mm | - | 1 |
| | $u_g$ =50 mm | - | 1 |
| Harmonic | $u_g$ = 30 mm (f=1.1 Hz) | 1 | 1 |
| | $u_g$ = 30 mm (f=1.3 Hz) | 1 | 1 |
| | $u_g$ = 30 mm (f=1.5 Hz) | 1 | 1 |

## 3.6 Analyzed Parameters

### 3.6.1 From Snap-back Tests

Raw data of interlocking plastic-block structure is recorded in the form of acceleration-time history. After analysis it has been noticed that some noise is also recorded in acceleration-time history. Noise is removed by using seismosignal software. Seismosignal software have their own filter, like butterworth is used to removed noise and undesired value recorded during performing test. However some noise is also removed by designing a different filter in mat lab. Damping ratio ($\xi$) and fundamental frequency of interlocking plastic block- structure is calculated. For calculation of damping ratio and fundamental frequency log decrement method is used. It is expected that damping ratio of interlocking plastic-block structure will be more for greater displaced structure.

### 3.6.2 From Shake Table Tests

Structure response is studied by applied different harmonic loading with varying frequencies such as 1.Hz, 1.3 Hz, and 1.5 Hz. The structure response is recorded in the form of acceleration- time history. Acceleration time history is then converted into displacement-time history by using seismosignal software. Base shear (Q) –displacement curves are calculated by using acceleration time histories and displacement-time histories. Base shear (Q) is taken as M. $\ddot{u}_t$ , where M is the total mass of structure [9]. Similarly base shear (Q)-displacement ($\Delta$) is calculated as M. $\ddot{u}_t$. Here M is total mass of interlocking plastic-block structure and $\ddot{u}_t$ is acceleration at the top of interlocking plastic-block structure.

### 3.6.3 Development of Empirical Equations

Empirical equations are being established keeping in mind the interlocking plastic-blocks geometry , size of block, height of structure and input loading parameters. Different empirical equations are developed to check the percentage difference between empirical values and experimental values.

## 3.7 Summary

This chapter discussed the detailed experimental procedure. The prototype interlocking plastic-block structure is selected for research work. Plastic interlocking plastic-block is purchased from local market. Prototype interlocking plastic-block structure is selected for such type of study to investigate the dynamic behavior of structure in earthquake engineering laboratories. Integrity of prototype interlocking plastic-block structure can be availed by providing rubber band. By using rubber band in interlocking plastic-block lead the structure to greater energy dissipation. Stress-strain curve for interlocking plastic-block structure is also calculated. It is noticed that some cracks appear in the lower portion of interlocking plastic-block. It is also observed that no cracks or failure are found in the key of interlocking plastic- block after compressive strength. It means that key of interlocking plastic-block absorb more energy under compressive test. Key of interlocking plastic-block is ability to withstand in greater compressive load. It is concluded that interlocking plastic-block can be used in earthquake resistant housing.

# Chapter 4

# Experimental Evaluation

## 4.1 Background

In previous chapter, experimental procedure is explained in detail. This chapter is about experimental evaluation of damping ration ($\xi$), fundamental frequency of structure ($f_n$) and recording of structure response in term of acceleration-time history and displacement time history. Data is recorded in the form of acceleration-time history. Initially noise is removed by designing a different filter in matlab. Acceleration time-history is converted into displacement-time history and acceleration-time history.

## 4.2 Damping and Fundamental Frequency

Figure 4.1 shows snap back test results of column with rubber band having displaced top mean position by: a) 25 mm and b) 50 mm. Damping ratio ($\xi$) and fundamental frequency ($f_n$) for interlocking plastic-block structure were calculated by using log decrement method [9].

Table 4.1 shows snap-back test result of column with rubber band. The damping ratio ($\xi$) of structure is 2.02% and 2.05% for structure displaced 25 mm and 50

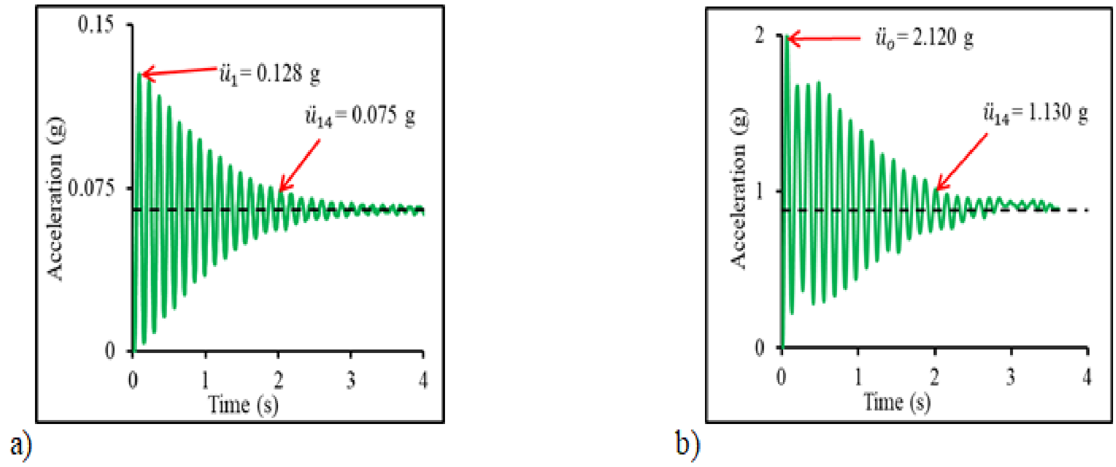



FIGURE 4.1: Snap back test results of column with rubber band having displaced top mean position by: a) 25 mm and b) 50 mm.

TABLE 4.1: Snap-back tests results of column with rubber band.

| **Sr.no** | **Amplitude** | **Frequency (Hz)** | **Damping ratio (%)** |
|---|---|---|---|
| 1 | 25 mm | 7.28 | 2.02 |
| 2 | 50 mm | 7.31 | 2.05 |

mm, respectively. The frequency calculated is 7.28 Hz and 7.37 Hz, respectively. It is observed that there is a little bit difference between damping values. The damping ratio for structure displaced 50 mm will be more than that of structure displaced 25 mm because free vibration time is more for greater displaced structure and frequency value is almost same because same structure is used for tests.

## 4.3 Structure Response Against Harmonic Loading

### 4.3.1 Acceleration-time Histories and Displacement-time Histories

The interlocking plastic-block structure response is recorded in term of acceleration-time history and displacement-time histories during the period of 40 s to 50 s are shown in Figure 4.2 and Figure 4.3. The blue full line shows the shake table movement or base excitation (applied loading) while the red line shows the response at top of interlocking plastic-block structure. The acceleration-time history and displacement time history obtained from analysis of result are acceptable to investigate the dynamic response of interlocking plastic-block column. Acceleration-time history is recorded and then by using seismosignal software the acceleration-time history is converted into displacement-time histories as described earlier. Since the locally low-cost shake table is good enough to apply harmonic loading precisely (constant amplitude of different cycles), the averaged acceleration and displacement of base excitation (i.e. $\ddot{u}_g$ and $u_g$, respectively) is considered applied loading. Similarly, the averaged acceleration and displacement at the interlocking plastic-block column top (i.e. $\ddot{u}_t$ and$u_t$, respectively) is considered as column response.

Acceleration-time histories of columns without and with rubber band during harmonic loadings of 1.1 Hz, 1.3 Hz, and 1.5 Hz between 40 s and 50 s are shown in Figure 4.2. The structure excitation can be classified into three phase: A. when the column started its vibration until it attained the steady-state, B. steady-state response of the structure, and C. free vibration of the structure [9]. For clarity, only portion of steady state response is shown in Figures 4.2 and 4.3. Averaged acceleration at base and top of structure is also mentioned. It has been noticed that the acceleration of interlocking plastic-block structure without rubber band is increased by increasing the frequency of shake table. Using rubber band, the acceleration at base and top of interlocking plastic-block structure is decreased. It is concluded that under harmonic loading the acceleration of structure can be reduced by using rubber band.

Displacement-time histories of columns without and with rubber band during harmonic loadings of 1.1 Hz, 1.3 Hz, and 1.5 Hz between 40 s and 50 s are shown in Figure 4.3. To check the response at the base and top of the structure, displacement time-history is shown between 40 s and 50 s. Averaged displacement at ground and top of structure is also mentioned. It has been noticed that the displacement of interlocking plastic-block structure without rubber band is increased by increasing the frequency of shake table.

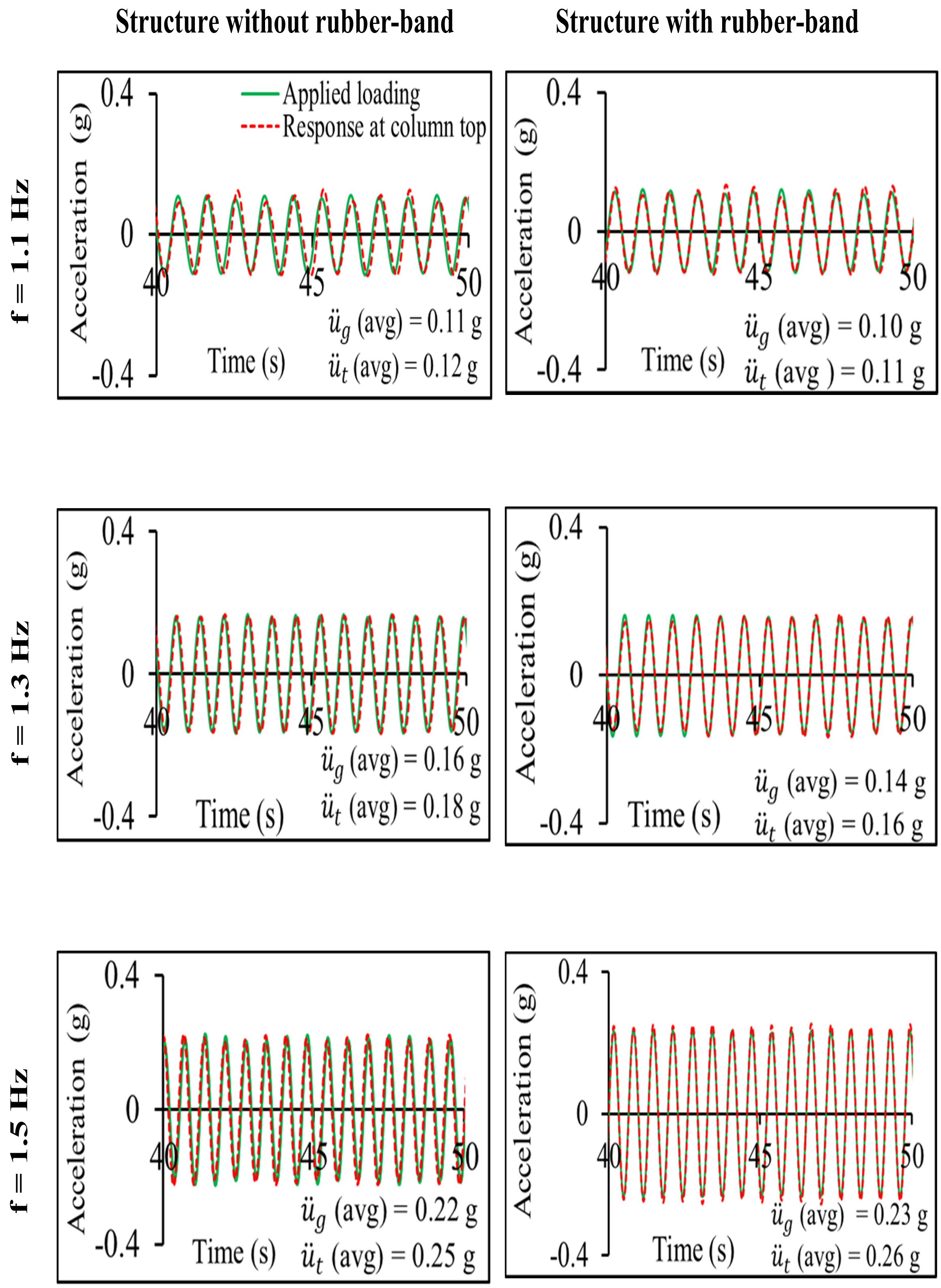



FIGURE 4.2: Acceleration-time histories of columns without and with rubber band during harmonic loadings of 1.1 Hz, 1.3 Hz, and 1.5 Hz between 40 s and 50 s.

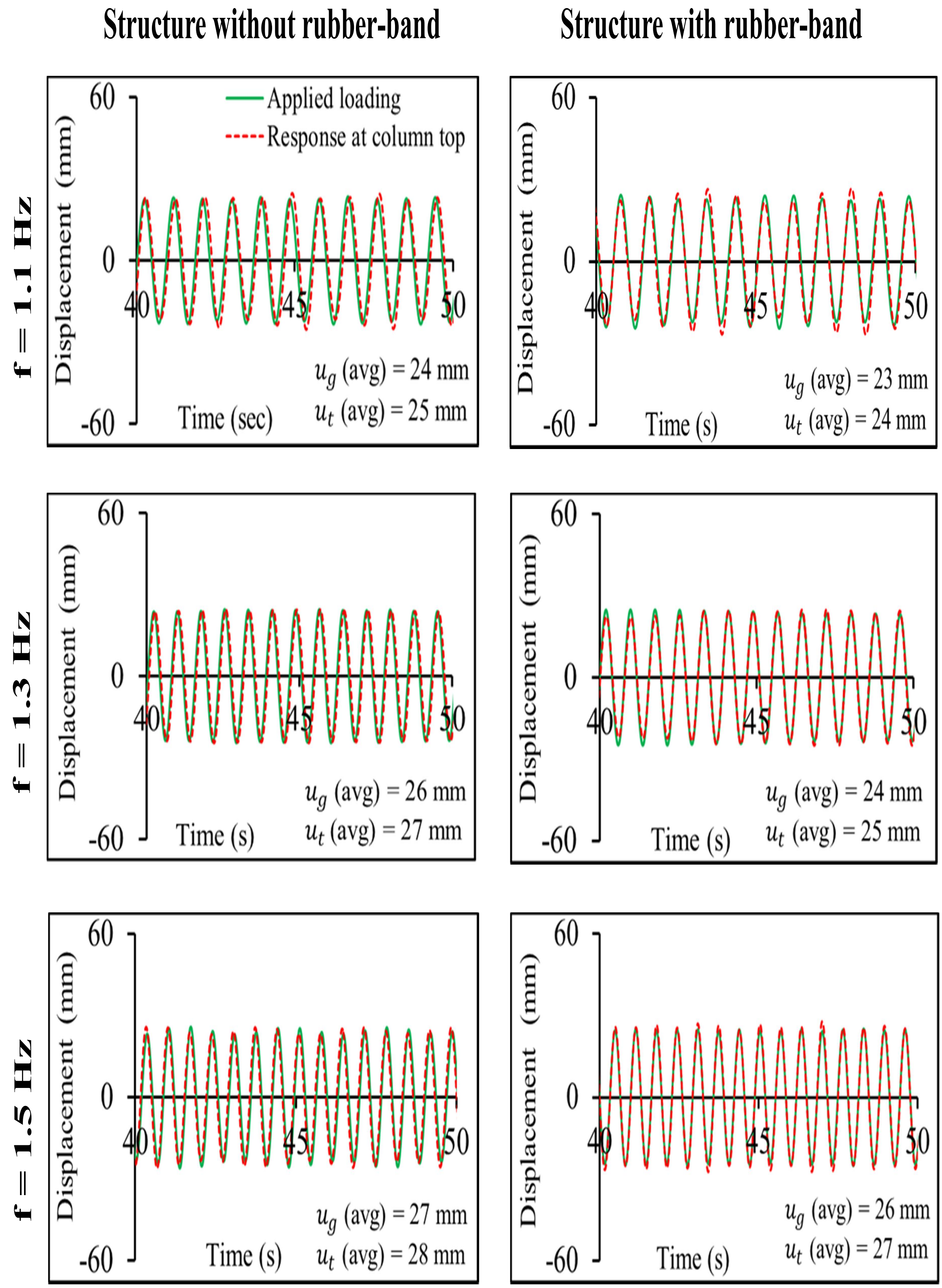



Figure 4.3: Displacement-time histories of columns without and with rubber band during harmonic loadings of 1.1 Hz, 1.3 Hz, and 1.5 Hz between 40 s and 50 s.

While the displacement at base and top of interlocking plastic-block structure is decreased. It is concluded that displacement of structure can be reduced by using rubber band in interlocking plastic-block structure.

## 4.4 Base Shear (Q) - Displacement (Δ) Curves and Energy Dissipation

At column top the mass of structure is presumed to be lumped where its response in term of acceleration-time history is recorded. Base shear (Q)-displacement (Δ) curves is produced from the harmonic test with amplitude of 30 mm and different frequencies (such as 1.1 Hz, 1.3 Hz, and 1.5 Hz) are shown in Figure 4.4. Base shear is calculated by multiplying total mass of structure to acceleration ($M.\ddot{u}_t$). Base shear (Q) - displacement (Δ) curves during harmonic loading along with enlarged typical single loop are shown in Figure 4.4. Ali et al. [9] technique is being used for calculation of base shear. Area within one loop is used for calculation of energy absorption within structure per cycle. Greater the loop area more will be the energy dissipation. Total energy absorbed and averaged energy absorbed in one cycle is shown in table 4.4. Interlocking plastic-block structure can dissipate more energy during seismic event because of uplift of block. Energy conservation generally applies to uplift and rocking behaviors, it is typically the rocking impacts that could lead to energy absorption, but rocking/uplift "works" because it reduces secant stiffness of structure and hence detune the effect of earthquakes. During harmonic loading the interlocking plastic-block structure having rubber band allows vertical relative moment. When column moved to one side (say right side), uplifts are noticed and top relative displacement is observed at left side. It has been noticed that rubber band play important rule in energy dissipation during harmonic loading because rubber band do not allow column buckling permanently, it provides integrity structure and enable the structure to come its original position without any damages . Increasing the frequency of shake table, energy dissipation is also increased in both structures with or without rubber band.

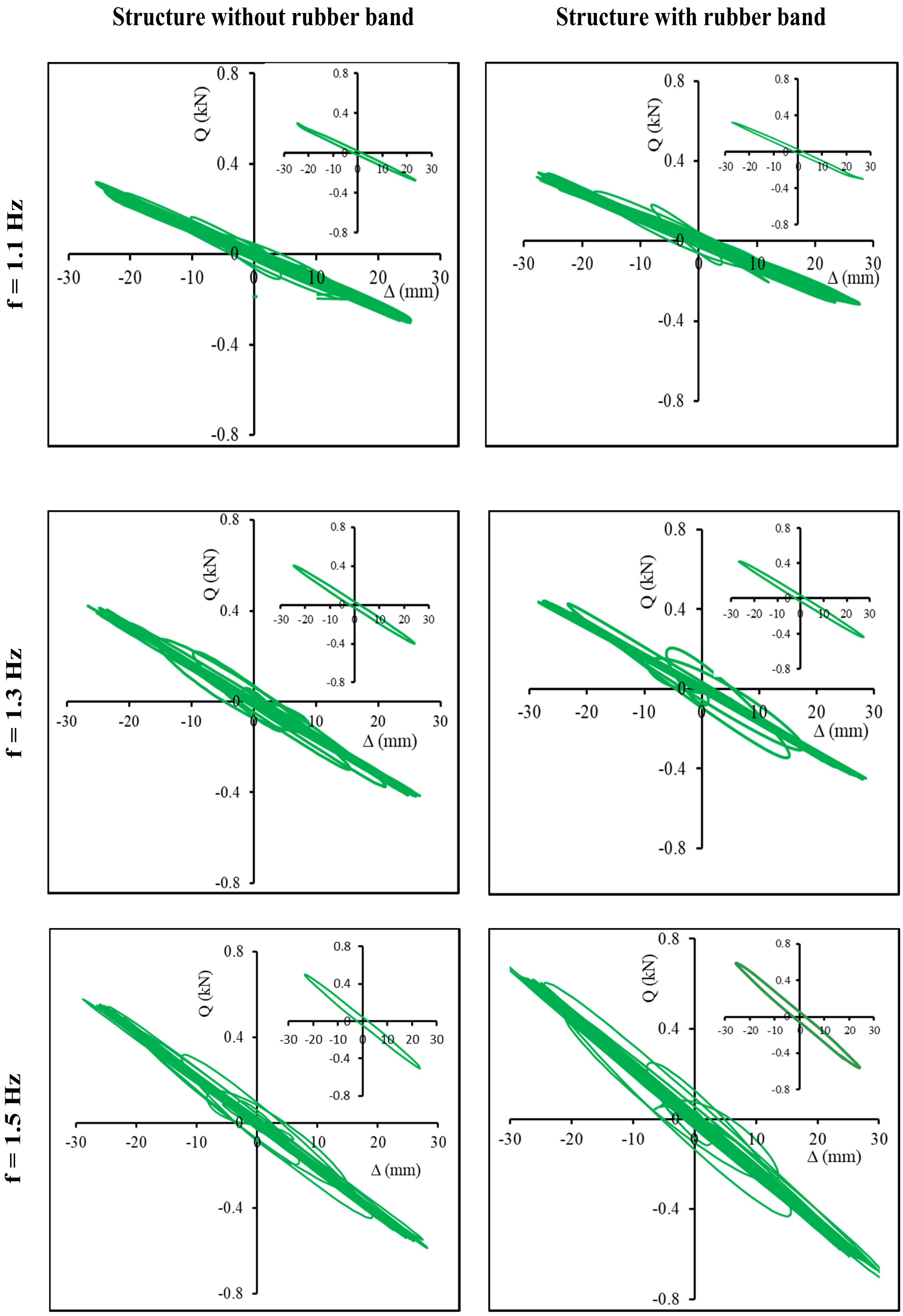



FIGURE 4.4: Base shear (Q) - displacement (Δ) curves during harmonic loading along with enlarged typical single loop.

TABLE 4.2: Energy absorption during the harmonic loading

| **Sr. no** | **Frequency (Hz) for $u_g$ = 30 mm** | **Averaged energy absorbed in one cycle (Nm) for structure without rubber band** | **Averaged energy absorbed in one cycle (Nm) for structure with rubber band** | **Total no.of cycles (n)** | **Total energy absorbed (Nm) for structure without rubber band** | **Total energy absorbed (Nm) for structure with rubber band** |
|---|---|---|---|---|---|---|
| 1 | 1.1 | 1.0 | 1.4 | 56 | 56 | 78 |
| 2 | 1.3 | 2.5 | 2.8 | 70 | 175 | 196 |
| 3 | 1.5 | 3.6 | 4.8 | 89 | 320 | 427 |

Table 4.2 shows energy absorption during harmonic loading. It has been noticed that interlocking plastic-block structure with rubber band dissipates more energy during harmonic loading with frequencies 1.1 Hz, 1.3 Hz, and 1.5 Hz. Interlocking plastic-block structure also dissipated energy without pre-tensioning. It is concluded that 40%, 12% 34% more energy is dissipated in structure with rubber band at 1.1 Hz, 1.3 Hz and 1.5 Hz. It is concluded that energy dissipation enhanced by using RB in structure. Ali et al. [9] also reported that by providing pre-tensioning to structure, using ropes enhanced energy dissipation. It is concluded that with pre-tensioning in mortar-free interlocking plastic-block structure can dissipate more energy than structure without pre-tensioning. Pre-tensioning to interlocking plastic-block structure is provided by using rubber band.

## 4.5 Summary

In this chapter experimental data is processed by using different software like matlab, seismosingal for converting acceleration-time history into displacement-time history. Acceleration and displacement-time histories graphs are produced.

The graphs of base shear (Q) –displacement curves under varying frequencies are also created. Relative comparison of result is also done. Empirical equation is being developed to check the percentage difference between experimental values and empirical values. It is concluded that acceleration, displacement, and base shear value is decreased in interlocking plastic-block structure with rubber band.

# Chapter 5

# Discussion

## 5.1 Background

The outcome of experimental testing such as acceleration-time history, displacement-time history, and base shear-displacement curve are already explained in chapter 4. Significant improvement in energy absorption is observed in pre-tensioning structure as compared to the without pre-tensioning structure. Now it's time to develop a relationship between experimental and empirical values to check the percentage difference.

## 5.2 Relationship Between Structure Response, Geometrical Parameters and Applied Loading.

To predict column response following empirical equation are developed.

$\ddot{u}_{\,t} = \frac{a/h^2}{n} K^{\left(1+\frac{2n}{100}\right)} \ddot{u}_g \ldots\ldots\ldots$ Eq(1)

u $_{\,t} = \frac{a/h^2}{n} K^{\left(1+\frac{n}{100}\right)} u_g \ldots\ldots\ldots$ Eq(2)

$E = \frac{a/h^2}{n} \; \frac{0.85 \; K \; H^2 M}{t^2} \frac{u_t}{u_g}$........ Eq(3)

In above equation $\ddot{u}_g$, $\dot{u}_g$, *and* $u_g$ are averaged applied acceleration, velocity, and displacement, respectively. The value of averaged applied acceleration, velocity, and displacement are 1.05g, 250 mm/s, and 24 mm respectively. $u_t$, $\dot{u}_t$, and $\ddot{u}_t$ are the response displacement, velocity, and acceleration. 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. Their corresponding values are 0.2 kg, 12 mm, 0.35 s, 8, 62 mm x 62 mm, and 340 mm, respectively. Where "K" is constant in all equation and its value are 1.05. The comparisons of experimental and empirical values of interlocking plastic-block structure response are shown in table 5.1. It has been observed that empirical values are in good agreement with experimental values. The percentage error is less than 15 % in all cases.

TABLE 5.1: Comparison of experimental and empirical values of column response (energy absorption 'Nm') at top

| **f (Hz)** | **Energy Absorption (Nm)** | | | | **Percentage difference** | |
|---|---|---|---|---|---|---|
| | **Experimental values** | | **Empirical values** | | | |
| | **Structure without rubber band** | **Structure with rubber band** | **Structure without rubber band** | **Structure with rubber band** | **Structure w/out RB** | **Structure with RB** |
| 1.1 | 1 | 1.4 | 1.12 | 1.44 | 12% | 2.8% |
| 1.3 | 2.53 | 2.83 | 2.6 | 2.86 | 2.7% | 1.2% |
| 1.5 | 3.63 | 4.81 | 3.83 | 4.87 | 5.5% | 1.2% |

Table 5.2 shows comparison of previous studies with current study. A significant resemblance of trends observed is noted regarding energy dissipation in mortar-free structure.

Table 5.2: Comparison with previous studies

| Previous study | Current study |
|---|---|
| Complex shake table was used to analyze dynamic behavior of mortar-free interlocking structure [10]. | Simple 1D shake table is used to analyze dynamic behavior of interlocking plastic-block structure. |
| More inertial force was generated in coconut fiber reinforced concrete block due to its weight [9, 10]. | While less inertial force is generated in interlocking plastic-block structure due to its light weight. |
| Energy is dissipated in mortar-free interlocking structure during dynamic loadings [9, 12, 17]. | Plastic-block interlocking structure also dissipates energy during harmonic loading. |
| Pre-tensioning of structure with coconut fiber ropes dissipated less energy compared to that without rope [9]. | While structure with pre-tensioned rubber band dissipates more energy compared to that without rubber. |
| In collapse of column, little bit damage was observed in interlocking block [9]. | Due to shake table limitation, no damage could be introduced in interlocking plastic-block structure. |

## 5.3 Outcome of Study with Respect to Practical Requirement

Locally developed low-cost shake table is capable of applying precise harmonic loading to some extent so that dynamic behavior of structure can be studied. Structure behavior can be investigated by applying base loading with help of shake table. Structure response is recorded in term of acceleration-time history and displacement-time history .Base shear-displacement curve is produced by using acceleration and displacement-time history. The observed dynamic behavior of interlocking plastic-block structure is more or less similar as that reported by other researcher .The adverse impact of earthquake can be reduced by using interlocking plastic-block structure. The mortar-free interlocking block used for earthquake resistant housing.

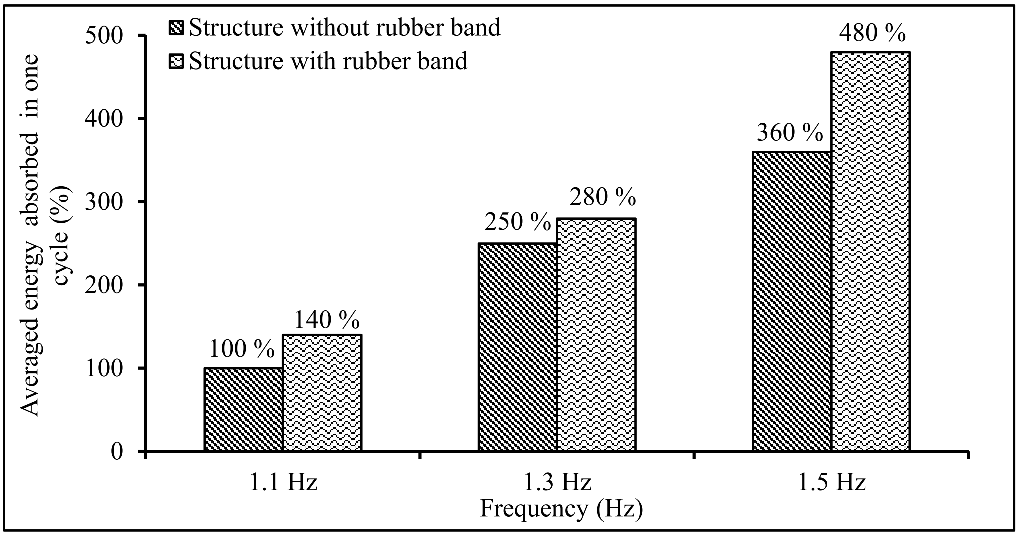



Figure 5.1: Averaged energy absorbed of one cycle (%) of column without and with rubber band during harmonic loading of 1.1 Hz, 1.3 Hz, and 1.5 Hz.

Figure 5.1 shows the percentage of averaged energy absorbed of one cycle for column without and with rubber band during harmonic loading of 1.1 Hz, 1.3 Hz, and 1.5 Hz. Energy absorption depend on loop area, greater the loop area more will be energy dissipation in interlocking plastic-block structure. It is observed that interlocking plastic-block structure with rubber band dissipated more energy during harmonic loading.

Figure 5.2 shows the comparison of total energy absorption without and with rubber band during harmonic loading of 1.1 Hz, 1.3 Hz, and 1.5 Hz. It is noticed that total energy absorption of interlocking plastic-block with rubber band is increased by 40%, 12 %, and 33% at frequency of 1.1 Hz, 1.3 Hz, and 1.5 Hz. It was also noticed that up to maximum 40 % maximum energy absorbed under harmonic lading at frequency of 1.1 Hz. It is concluded that energy absorption in structure is enhanced by using rubber band.

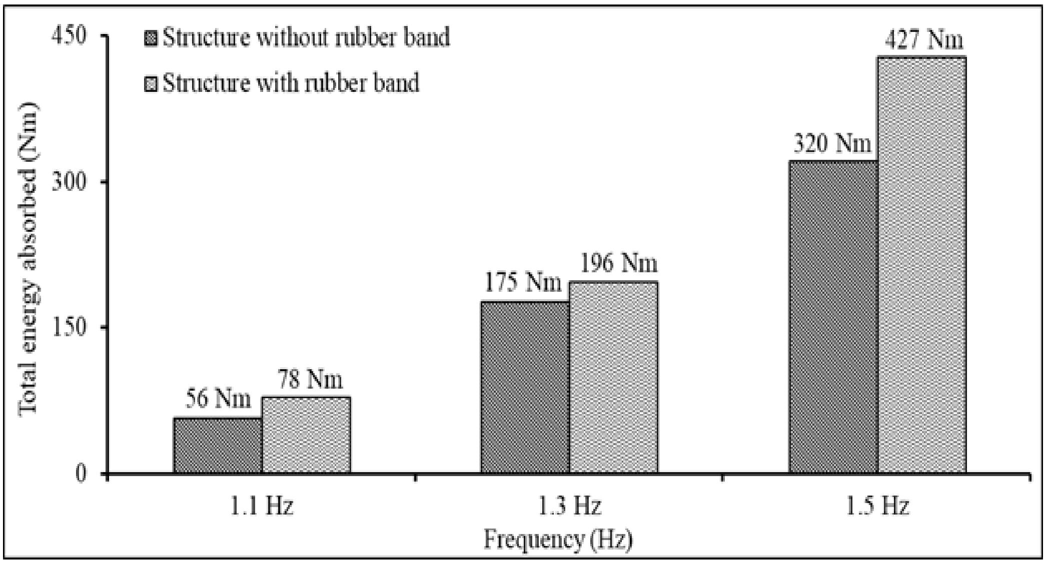



FIGURE 5.2: Total energy absorbed of column without and with rubber band during harmonic loading of 1.1 Hz, 1.3 Hz, and 1.5 Hz.

## 5.4 Summary

This chapter discusses the empirical equation and outcome of the study with respect to practical requirement. Empirical equation has been developed to check the percentage difference. It is also ensured that empirical equations are dimensionally correct. 3D shake table is used for precise dynamic analysis of structure but this facility is not available in developing countries. 3 D shake table is too much expensive and high maintenance cost. To overcome these problems locally low-cost shake table is prepared by using local human resources. Locally low-cost shake is not so much accurate but however it is good enough for apply harmonic loading precisely. Proposed interlocking plastic-block will be more useful for earthquake resistant housing. Proposed interlocking plastic-block structure will be dissipated more energy during future earthquake. The energy in proposed block will be dissipated by uplift and relative movement of block at interfaces.

# Chapter 6

# Conclusion and Future Work

## 6.1 Conclusion

For developing country, new construction techniques have been developed to construct safe earthquake- resistant housing but these are expensive. There is a need to develop more economical housing technique. In this pilot study, interlocking plastic-block structure is tested under different harmonic loadings to determine the response and their dynamic characteristic. Interlocking plastic-block structure is tested with or without pre-tensioning. For finding the fundamental frequencies ($f_n$ ) of the structure, the harmonic tests were found more accurate compared to snap back test. From this research work, following conclusion can be made:

- Brittle nature of plastic-blocks is observed in current study, it should have been of ductile nature.
    - ◇ Multiple plastic blocks have more strength as compared to single block.
- Damping was observed in structure with rubber band in spite of the fact that structure frequency was much more than that of loading.
    - ◇ It is likely that the proposed structure will have significant damping at resonant frequency (Note: This could not be performed due shake table limitations).

- Energy dissipation in pre-tensioning column with rubber band is more than that of without pre-tensioning column.
  - ◇ Column response (averaged acceleration and displacement) is increased a little bit at its top compared to applied loading at foundation.
  - ◇ Interlocking plastic-block column without rubber-band dissipate about 320 Nm was due to uplifts of block during applied harmonic loading. While structure with rubber band dissipates energy about 427 N-m at same frequency (1.5 Hz).
- Empirical values of column response are in good agreement with experimental values.

## 6.2 Future Work

Next step should be the dynamic behaviour of interlocking plastic-block wall along with diaphragm.

# Bibliography

[1] S. T. Maqsood and J. Schwarz, "Analysis of Building Damage during the 8 October 2005 Earthquake in Pakistan," *Seismological Research Letters*, vol. 79, no. 2, pp. 163–177, 2008.

[2] M. Zhang and Y. Jin, "Building damage in Dujiangyan during Wenchuan Earthquake," *Earthquake Engineering and Engineering Vibration*, vol. 7, no. 3, pp. 263–269, 2008.

[3] A. Naseer, A. N. Khan, Z. Hussain, and Q. Ali, "Observed Seismic Behavior of Buildings in Northern Pakistan During the 2005 Kashmir Earthquake," *Earthquake Spectra*, vol. 26, no. 2, pp. 425–449, 2010.

[4] R. Desroches, M. Comerio, M. Eberhard, W. Mooney, and G. J. Rix, "Overview of the 2010 Haiti Earthquake," *Earthquake Spectra*, vol. 27, no. 1. pp. 124-130, 2011.

[5] R. Jünemann, J. D. L. Llera, M. Hube, L. Cifuentes, and E. Kausel, "A statistical analysis of reinforced concrete wall buildings damaged during the 2010, Chile earthquake," *Engineering Structures*, vol. 82, pp. 168–185, 2015.

[6] H. Chen, Q. Xie, Z. Li, W. Xue, and K. Liu, "Seismic Damage to Structures in the 2015 Nepal Earthquake Sequences," *Journal of Earthquake Engineering*, vol. 21, no. 4, pp. 551–578, 2016.

[7] P. Farshidnia, "Behavior and analysis of masonry-infilled reinforced concrete frames subjected to lateral load," *Earthquake Resistant Engineering Structures*, vol. 65, no. 57, pp. 148-156, 2009.

[8] Y. Kim, T. Kabeyasawa, T. Matsumori, and T. Kabeyasawa, "Numerical study of a full-scale six-story reinforced concrete wall-frame structure tested at E-Defense," *Earthquake Engineering & Structural Dynamics*, vol. 41, no. 8, pp. 1217–1239, 2011.

[9] M. Ali, R. Briet, and N. Chouw, "Dynamic response of mortar-free interlocking structures," *Construction and Building Materials*, vol. 42, pp. 168–189, 2013.

[10] M. Ali, "Role of Post-tensioned Coconut-fibre Ropes in Mortar-free Interlocking Concrete Construction During Seismic Loadings," *KSCE Journal of Civil Engineering*, vol. 22, no. 4, pp. 1336–1343, 2017.

[11] A. Stavridis, F. Ahmadi, M. Mavros, P. B. Shing, R. E. Klingner, and D. Mclean, "Shake-Table Tests of a Full-Scale Three-Story Reinforced Masonry Shear Wall Structure," *Journal of Structural Engineering*, vol. 142, no. 10, pp. 615-624, 2016.

[12] M. Nader and A. Astaneh, "Dynamic behavior of flexible, semirigid and rigid steel frames," *Journal of Constructional Steel Research*, vol. 18, no. 3, pp. 179–192, 2018.

[13] D. Benedetti, P. Carydis, and M. P. Limongelli, "Evaluation of the seismic response of masonry buildings based on energy functions," *Earthquake Engineering & Structural Dynamics*, vol. 30, no. 7, pp. 1061–1081, 2001.

[14] C. O. Azeloglu, A. Edincliler, and A. Sagirli, "Investigation of Seismic Behavior of Container Crane Structures by Shake Table Tests and Mathematical Modeling," *Shock and Vibration*, vol. 2014, pp. 1–9, 2002.

[15] A. Ural, A. Doğangün, H. Sezen, and Z. Angın, "Seismic performance of masonry buildings during the 2007 Bala, Turkey earthquakes," *Natural Hazards*, vol. 60, no. 3, pp. 1013–1026, 2004.

[16] M. Zhang and Y. Jin, "Building damage in Dujiangyan during Wenchuan Earthquake," *Earthquake Engineering and Engineering Vibration*, vol. 7, no. 3, pp. 263–269, 2008.

[17] S. T. Maqsood and J. Schwarz, "Analysis of Building Damage during the 8 October 2005 Earthquake in Pakistan," *Seismological Research Letters*, vol. 79, no. 2, pp. 163–177, 2008.

[18] Y. Wang, Y. Yao, B. Cheng, and L. Wang, "The Seismic Damage Characteristic and Mechanism Analysis of Building Structure in Wenchuan Earthquake," *Advanced Materials Research*, vol. 28, pp. 1892–1895, 2010.

[19] Z. Qiang and S. Bai-Tao, "Study on Earthquake Damage Distribution of Multistory Masonry Buildings," *The Open Civil Engineering Journal*, vol. 9, no. 1, pp. 435–441, 2015.

[20] M. Khanmohammadi, P. L. Rad, and A. Ghalandarzadeh, "Experimental study on dynamic behavior of buried concrete rectangular liquid storage tanks using shaking table," *Bulletin of Earthquake Engineering*, vol. 15, no. 9, pp. 3747–3776, 2017.

[21] W. R. Li, Y. F. Du, S. Y. Tang, and L. J. Zhao, "Structural Damage Identification Based on the Minimum System Realization and Sensitivity Analysis," *Mathematical Problems in Engineering*, vol. 20, pp. 1–12, 2014.

[22] W. H. Chen, C. Y. Ding, B. Q. He, Z. R. Lv, and J. K. Liu, "Damage Identification Based on Power Spectral Density Sensitivity Analysis of Structural Responses," *Advanced Materials Research*, vol. 91, pp. 45–50, 2014.

[23] T. Pian, "Dynamic Response Of Thin Shell Structures," *Plasticity*, pp. 443–452, 2015.

[24] M. Ali, R. J. Gultom, and N. Chouw, "Capacity of innovative interlocking blocks under monotonic loading," *Construction and Building Materials*, vol. 37, pp. 812–821, 2012.

[25] S. Wilkinson and R. Hiley, "A non-linear response history model for the seismic analysis of high-rise framed buildings," *Computers & Structures*, vol. 84, no. 5-6, pp. 318–329, 2006.

[26] T. Baran, A. Tanrikulu, C. Dundar, and A. Tanrikulu, "Construction And Performance Test Of A Low-Cost Shake Table," *Experimental Techniques*, vol. 35, no. 4, pp. 8–16, 2010.

[27] "Dynamic Analysis Of Structures Subjected To Earthquake Load," *International Journal of Advance Engineering and Research Development*, vol. 2, no. 09, pp. 32-39, 2015.

[28] M. Betti, L. Galano, and A. Vignoli, "Time-History Seismic Analysis of Masonry Buildings: A Comparison between Two Non-Linear Modelling Approaches," *Buildings*, vol. 5, no. 2, pp. 597–621, 2015.

# Annexure A

### Velocity-time history data (Reaming time-history analysis graphs)

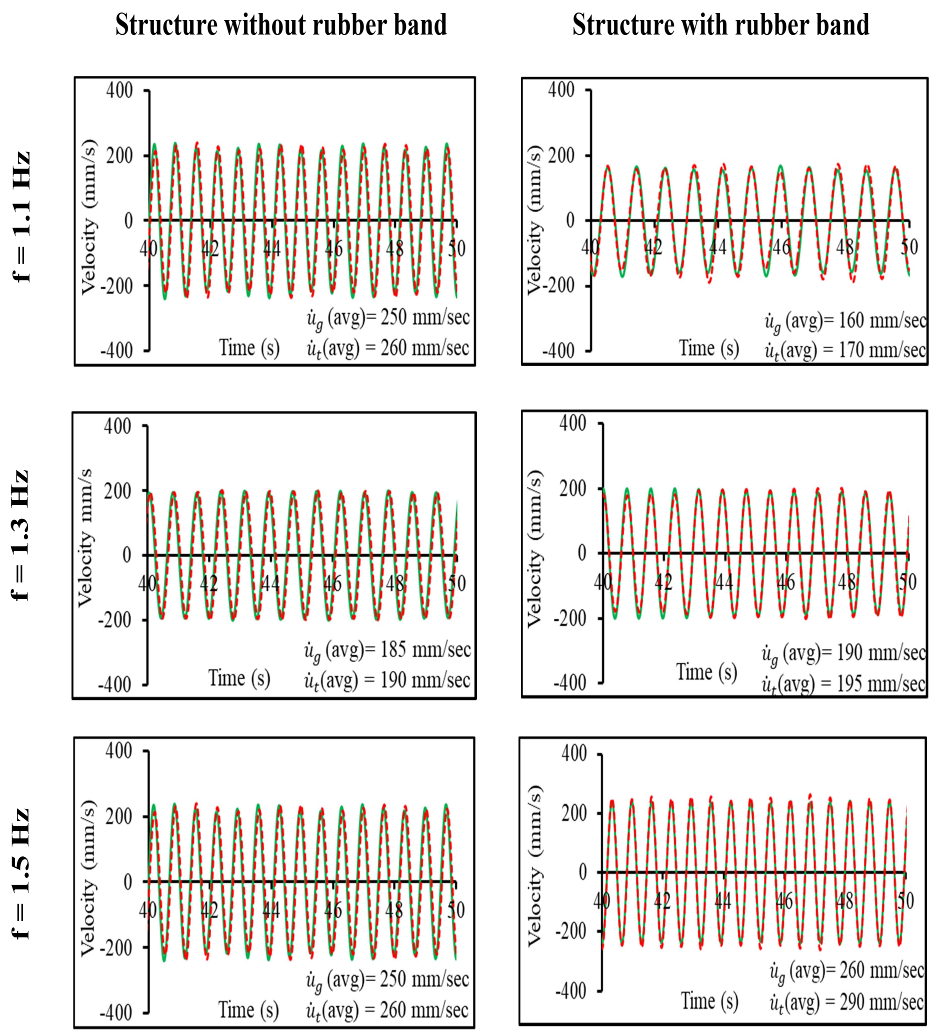



FIGURE A.1: Velocity-time histories of columns without and with rubber band during harmonic loadings of 1.1 Hz, 1.3 Hz, and 1.5 Hz between 40 s and 50 s.

# Annexure B

### Shake table preparation and specification

Locally low-cost shake table is prepared by using local human resources and local material for applying harmonic loading. It may be noted that the shake table is manually calibrated by running it at different frequencies. Shake table can be operated using an electric motor of 1 horse power having variable gear which can control the frequency of applied loading.

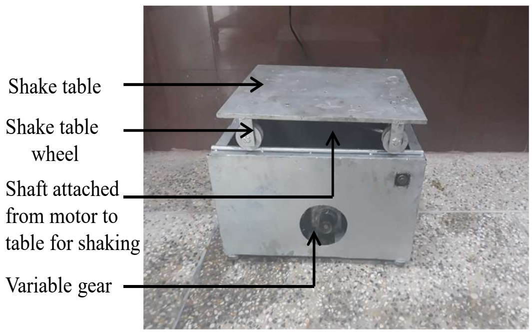



Figure B.1: Locally made shake table

### Specifications of shake table

| | |
|---|---|
| Size | 450 mm x 600 mm |
| Payload | 80 kg |
| Amplitude | ±30 mm |
| Frequency | 1-4 Hz |

# Annexure C

### Results from the from submitted conference paper in 2018 (Australian earthquake engineering society)

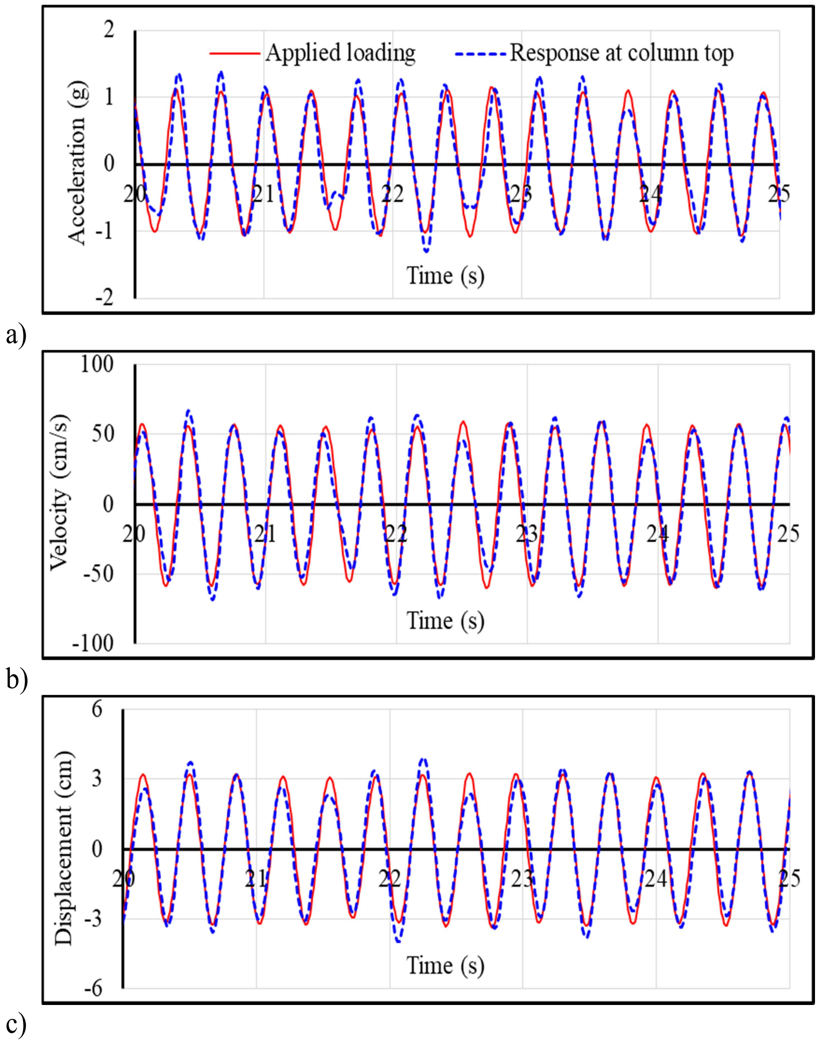



FIGURE C.1: Response of interlocking structure for intermediate 5 seconds, a) acceleration – time history, b) velocity – time history and c) displacement – time history

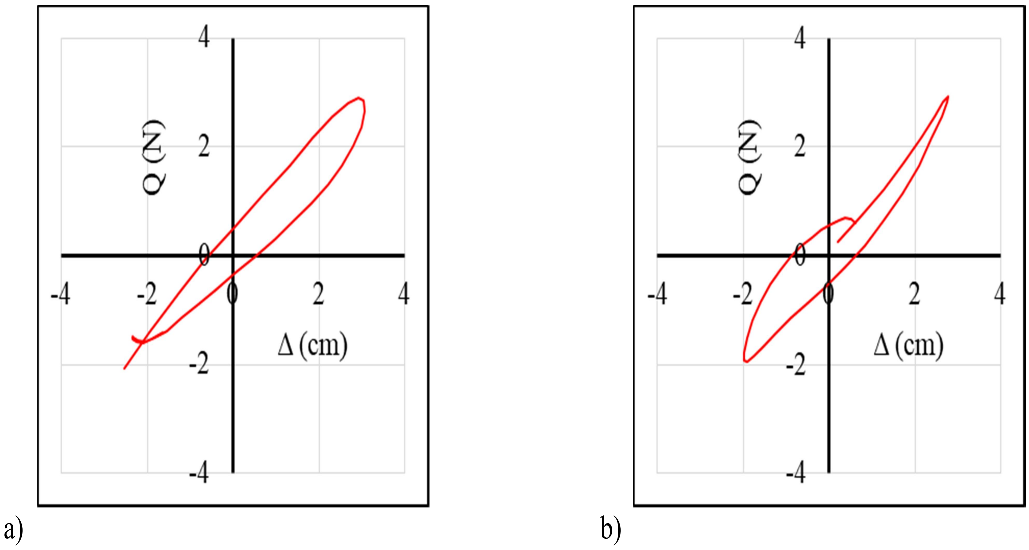



FIGURE C.2: Typical force displacement curves, a) maximum loop area in positive direction, and b) maximum loop area in negative direction.

TABLE C.1: Energy absorption during the harmonic loading

| **Structure** | **Averaged energy absorbed in one cycle (Nm)** | **Total energy absorbed (Nm)** |
|---|---|---|
| Eight-blocks column | 0.32 | 22 |

TABLE C.2: Comparison of experimental and empirical values of column response at top

| **Column response** | **Experimental values** | **Empirical values** | **Percentage difference** |
|---|---|---|---|
| Acceleration (g) | 1.3 | 1.3 | 0.3% |
| Velocity (cm/s) | 60 | 62.6 | 4.4% |
| Displacement (cm) | 3.6 | 3.65 | 1.3% |
| Energy absorbed (Nm) | 0.32 | 0.33 | 1.4% |