CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Out-of-plane Behavior of Prototype Interlocking Plastic-block Solid Wall Under Harmonic Loading

by

Sohail Afzal

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

in the

Faculty of Engineering
Department of Civil Engineering

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I dedicate my dissertation work to my family and teachers.

CERTIFICATE OF APPROVAL

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Sohail Afzal

(MCE183046)

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(b)	Internal Examiner	Engr. Dr. Shujaa Safdar	CUST, Islamabad
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October, 2020

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(Sohail Afzal)

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(Sohail Afzal)

Registration No: MCE183046

Abstract

Earthquake is one of the natural disaster that cause several damages i.e. failure of buildings, roads, bridges and other civil works. Earthquakes also causes the floods and landslide. Masonry structures effects most during the earthquake activity due to weak bonding of bricks and mortar. In developing countries, it is the need of time to build up a new construction technique for earthquake-resistant housing in earthquake prone areas. Mortar-free interlocking construction have gained popularity due to its speedy erection and energy dissipation. However, its progress at local level in developing countries is quite limited from dynamics point of view. Many researchers have done the researches on mortar free interlocking structures for the economical earthquake resistant structures in earthquake prone areas. But mortar free interlocking plastic block structure is yet to be explored.

Prototype interlocking plastic-blocks solid is considered for making the mortar-free structure. In this study, behavior of prototype interlocking plastic-block solid wall is examined against harmonic loading in comparison with prototype unreinforced masonry solid wall using locally developed shake table. Interlocking plastic-block wall consists of forty-eight plastic blocks and interlocking with rubber band. Fix base is provided by the help of nut bolts for the both prototype walls. Small bricks are used for unreinforced masonry solid wall. Three accelerometers are used: one is attached on the top of shake table to record the ground excitation, one each is attached on the top of interlocking plastic block solid wall and unreinforced brick masonry solid wall.

The behavior of walls in terms of acceleration-time, velocity-time, and displacement-time histories are recorded. Energy absorption, damping and base shear displacement curves are calculated. Empirical equations are developed keeping in mind the geometry of interlocking blocks, wall height and input loading parameters. Unreinforced brick masonry solid wall collapsed during the app.lied loading, due to conventional issue of weak bond between bricks and mortar. Interlocking plastic-block solid wall dissipated total energy of 490 Nm at the same frequency, at which unreinforced brick masonry solid wall collapsed.

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Abbreviations

1 D	One Dimensional
3 D	Three Dimensional
IPBSW	Interlocking Plastic-block Wall with Opening
MDOF	Multiple Degree of Freedom
MPa	Mega Pascal
RB	Rubber Band
SDOF	Single Degree of Freedom
UBMSW	Unreinforced Brick Masonry Wall with Opening
Up	Uplift

Symbols

ξ	Damping ratio
Δ(mm)	Displacement in millimeter
E	Energy absorbed
E_t	Total energy absorbed
f_n	Fundamental frequency
K	Coefficient having dimensionless value
n	No. of interlocking plastic-blocks
m	No. of blocks along the length of wall in a single layer
a	Base area of interlocking plastic-block
Q (kN)	Base-shear
H_z	Unit of frequency
g	Acceleration
$\ddot{u}_{\ g}$	Average acceleration at base
$\dot{u}_{\ g}$	Average velocity at base
$u_{\ g}$	Average displacement at base
$\ddot{u}_{\ t}$	Average acceleration at top of IPWW
$\dot{u}_{\ t}$	Averaged velocity at top of IPWW
$u_{\ t}$	Average displacement at top of IPWW
$\ddot{u}_{\ t'}$	Average acceleration at top of UBMWW
$\dot{u}_{\ t'}$	Averaged velocity at top of UBMWW
$u_{\ t'}$	Average displacement at top of UBMWW

Chapter 1

Introduction

1.1 Background

Earthquake is a natural disaster which produces strong ground motion. Major effects of earthquake cause severe damages, such as failure of building, roads, and bridges, which may affect many people. Earthquake can also cause landslide and floods. Building can literally sink when water content is high in soil because soil having high percentage of water content behaves like fluid and lose their mechanical strength when soil shake violently. Earthquake happens to underneath the ocean floor; they can cause tsunami. Structure is frequently affected during forceful earthquake and damage. Most of structures are often affected during intense earthquake and collapse. Earthquake badly effect masonry structures due to strong ground motion. In Gorkha earthquake, number of 0.5 million masonry buildings were entirely collapsed and other 0.2 million were partially damaged [1]. In Nepal earthquake of 2015, 0.15 million people were displaced due to severe structural damages in the affected region [2]. Sichuan earthquake in 2008, caused 70,000 casualties, 216,000 structural failures, including 6890 school structures [3]. More than 86000 causalities and 80000 injuries were reported in the Kashmir earthquake of October 2005 with the total economic loss of $5.2 billion [4]. The out-of-plane behavior of masonry structures is more critical than the in-plane behavior. During the earthquakes of 2010 and 2011 in Canterbury, 72% of the identified walls were damaged due to out of the plane damages and 28% were due to in plane damages [5].

In seismic regions the inexpensive earthquake resistance housing is necessary in rural area of developing counties. During strong ground motion these regions often suffer a significant loss of lives because of lack of seismic resistance housing. To qualify an efficient and cost-effective solution, new construction techniques were investigated, applying on structure, comprises of interlocking plastic-blocks. Interlocking plastic-block used in structure play significant role during intense ground motion, these interlocking plastic-block dissolve more energy during seismic event, because of the comparative movement at the block boundaries.

An electro-hydraulic shake-table of six degree of freedom is needed to produce real earthquake data. We cannot use hydraulic shake-table of six degree of freedom because it is not cost-effective and need more functioning and maintenance cost. To overcome these difficulties, 1D shake table can be used in earthquake engineering laboratory. It is very challenging to develop shake-table for the earthquake engineering laboratory at low cost. To study the dynamic behavior of structures, one degree shake-table is used because it is cost-effective. From this point, uni-axial shaking tables were designed at short cost. Under harmonic along with random excitation the shake-table is developed to study structural behavior of structure. By using local low-cost shake-table, the earthquake simulation can be found in laboratory. To produce earthquake simulation shake-table is used to test scale model and prototype. To the best of author knowledge, no study has been conducted to investigate the behavior of interlocking plastic-block solid wall under harmonic loading using locally developed low-cost 1D shake table.

1.2 Research Motivation and Problem Statement

Earthquake causes severe damages, such as failure of buildings, roads, and bridges, which may kill many peoples. Such sufferers can be abridged if specific behavior of structures during earthquake is considered which can help in its appropriate design. Developed countries have such services, but on the other hand, developing countries are requiring these facilities. Shake-table is one of the solutions. To start with, performance of structure may be studied with locally developed low-cost shake table (operating in one direction). Secondly, confined brick structures are little expensive. A cheap solution is desired. Ali [6] proposed an inexpensive solution but the mass of block still needs to be reduced. Interlocking plastic-block structure can be one solution with concern of fire-resistant paint. For financial and environmental aspects, plastic waste can be recycled for this cause (note: for time beings, it is outside the scope of this work). Thus, the problem statement is as follow.

In earthquake, most of the masonry structures collapsed due to design deficiencies [7]. Khan and Ali [8] developed a mortar free structure (a new construction technique) for earthquake-resistant houses. A mortar-free interlocking plastic-block structure has the capability to dissipate energy of earthquake. Though, the mass of coconut fiber reinforced concrete blocks is still a point of concern. Lighter the mass of structure, lower the inertia force produced. For this, light weight interlocking plastic-block is one option towards the solution together with fire-resistant paint. For financial and environmental aspects, plastic waste can be recycled for this cause (note: for the time being, it is outside the scope of this work). For suck kind of structure (i.e mortar-free interlocking plastic-block structure), dynamic behavior should be considered. This can be done with simple shake-table. So, the behavior of interlocking plastic-block structure is needed to be examined under dynamic loading by using locally developed low-cost 1D shake-table.

1.2.1 Research Questions

How much energy will dissipate during the earthquake testing of prototype interlocking plastic block solid wall? How much energy will dissipate during the earthquake testing of prototype interlocking masonry solid wall? Which wall will withstand the higher frequency during the earthquake testing?

1.3 Overall Objective of the Research Program and Specific Aim of this MS Thesis

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 solid wall using locally developed low-cost 1D shake table in laboratory.

1.4 Scope of Work and Study Limitation

Two prototype solid walls (mortar free interlocking plastic-block solid wall and unreinforced brick masonry solid wall) is constructed as the scope of this research work. Fixed base is provided for both walls with the help of nut bolts. Four dynamic loading frequencies of 1.5 Hz, 2 Hz, 2.25 Hz and 2.5 Hz are applied on both walls. Response in terms of acceleration-time, velocity-time, and displacement-time histories are documented with the help of data extracted and then refine it by removing the noise with the help of sismo-signal software. Empirical equations developed to predict the dynamic behavior of mortar free interlocking plastic block solid wall. Empirical equation is advanced based on Ali (2018) approach.

Study limitations include the use of simple one-dimensional shake table, only three accelerometers are used. One accelerometer is used at the base of shake table to record base excitation, and one each is used at the top of prototype walls. Four loading frequencies are applied on both walls (1.5 Hz, 2 Hz, 2.25 Hz and 2.5 Hz). Wind and fire effect are out of the scope of this study. Only out-of-plane behavior of both walls under consideration. The diaphragm effects on wall is outside the scope of this MS work. Walls with simplified boundary conditions are under consideration. Scale-down technique is only applied on elevation dimension but not on wall width.

1.4.1 Rationale Behind Variable Selection

To reduce the damage of structures during seismic activity due to the uplift behaviour of mortar-free interlocking structures.

Energy dissipation is possible in mortar-free interlocking structures.

Khan (2019) proposed mortar-free interlocking plastic block structure for earthquake resistant housing. Mortar free interlocking plastic block structures with rubber band dissipates more energy.

1.5 Research Novelty, Research Significance and Practical Implementation

To the best of author knowledge, no study has been conducted to investigate the out-of-plane behavior of prototype interlocking plastic-block solid wall under harmonic loading using locally developed low-cost 1D shake table. The significance of current research is the understanding of dynamic behavior of interlocking plastic-block structure in out-of-plane direction with simplified boundary conditions. This along with other parallel studies can lead towards understanding of complete interlocking structure. The previous work of Khan [23] and Sudheer [29] have shown favorable results. This work is a step forward in developing interlocking structure with plastic-blocks. The proposed housing scheme has the potential to provide respectable living standard for underprivileged people.

1.6 Brief Methodology

Shake table have been used for applying harmonic loading with varying frequency of 1.5 Hz, 2 Hz, 2.25 Hz and 2.5 Hz. The aim of testing is to explore behavior of interlocking plastic-block solid wall at some incremental frequencies.

Three accelerometers are attached. One accelerometer is attached at the base of shake table to record the base excitation, and one each is attached at the top of interlocking plastic-block solid wall and unreinforced brick masonry solid wall. The accelerometer attached at base of shake table because both prototype walls are fixed on the shake table to record the structure excitation under applied harmonic loading. The accelerometer is further connected to data requisition device that was connected to computer software for recording structure response as well as the base excitation under the applied harmonic loading.

Raw data is recorded in the way of acceleration-time history. It may be noted that noise is removed with different filters using MATLAB. Further the recorded response of structure in the way of acceleration-time history is then converted into displacement-time history by using seismo-signal software. Base shear (Q) is being calculated by using the displacement-time history and acceleration-time history of top accelerometer data. Comparison of percentage differences of acceleration, velocity and displacement between experimental and empirical values also made. Average energy dissipation in single loop is calculated. At the end total energy absorbed is also calculated. After that, the comparison between energy absorption of mortar free interlocking plastic block solid wall and unreinforced brick masonry solid wall is also addressed. Empirical equation is being improved keeping in mind the geometry of interlocking plastic-block, height, size of block and loading input parameters, and introduce a new variable 'R_s' having the value of 0.12 that is the reduction factor due to increased stiffness of interlocking plastic block solid wall as compared with the stiffness of interlocking plastic block column structure. Energy absorption of interlocking plastic block solid wall is also checked.

1.7 Thesis Outline

This study has six chapters, 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, objectives and scope-of-work, methodology and thesis outline.

Chapter 2 contains the literature review section. It consists of background; damages of typical masonry-structures during Ground-motion are explained, new approach for earthquake-resistant structures is described in the view of previous studies, Out-of-plane behavior of mortar free interlocking plastic block walls, and summary.

Chapter 3 consists of experimental program. It contains background, proposed structure and prototype mortar free interlocking plastic-block solid wall, unreinforced brick masonry solid wall, real prototype walls and scale down technique with the help of diagrams, schematic diagram of test setup, real test setup 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, test results in the form of time-acceleration graph, time-displacement graph, base shear-displacement graph, and summary.

Chapter 5 comprises of discussion. It classifies into background, relationship of empirical equations, comparison between energy absorption of mortar free interlocking plastic block solid wall and unreinforced brick masonry solid wall and outcome of study with respect to practical requirements, comparison of percentages differences between mortar free interlocking plastic-block solid wall and unreinforced brick masonry solid wall and summary.

Chapter 6 includes conclusion and recommendations.

References are presented right after chapter 6.

Chapter 2

Literature Review

2.1 Background

Earthquake is one of the natural and life-threatening disaster which majorly effects the buildings, roads, and bridges etc. Unreinforced masonry structures are one of the most affected structures during the ground motion produced by the earthquakes. Out-of-plane failure are more crucial during the seismic activity. Earthquakes badly effect the masonry structures due the conventional week bonding of bricks and mortar and the strong ground motion. Earthquake in Pakistan occupied Kashmir region in 2005, caused more than 72000 causalities, more than 68000 injuries, more than 450000 buildings damages and the losses to a total cost of US $5.2 billion [9]. During the earthquake of Laquila, the city of Central-Italy in 2009 damages about 10000 buildings, 328 deaths and more than 1500 injuries [10]. Earthquake in Nepal in 2015, 50000 peoples dislocated after the severe damages of the earthquake [11]. The major reason of the damage of masonry buildings is the use of typical un-constrained masonry system. In-addition, during the earthquakes most brick masonry buildings are collapsed due to the design deficiencies. The earthquake in Doubayazt, the district of Province Agr of Turkey, caused 1000 masonry building damages and 100 houses badly affected [12]. In the earthquake of Christchurch in 2011, about 650 unreinforced buildings of clay brick masonry and 90 unreinforced buildings of stone masonry were damaged [13]. More than 25000 peoples were homeless due to the severe damages of unreinforced masonry buildings in the earthquake of Abruzzo in 2009 [14]. Unreinforced-masonry buildings are being classified as most of the earthquake prone constructions in New Zealand [15]. In the earthquake of Haiti in 2010, most of the unreinforced masonry structures were damaged severely [16].

Earthquake-resistant and cost-effective houses are the need of present times for the earthquake-prone regions in developing countries. Due to the lack of earthquake-resistant development techniques, the developing countries are suffering of severe structure damage and social loss during the earthquakes. However, literature shows that different earthquake-resistant development methods and techniques have been adopted for the said purpose. For example, provide the plinth and lintel beams, vertical stiffeners in masonry structures. Ali et al. [17] proposed mortar-free interlocking-block structure as modern construction technique for the earthquake-resistant housing. Mortar-free block structure of coconut-fiber reinforced interlocking with post-tensioned ropes of coconut fiber was being tested for the dynamic loading [6]. Out-of-plane behavior of unreinforced-masonry structures is more crucial than the in-plane behavior. Most of the damages of masonry structures have been occurred due to the out-of-plane failure. Sometimes, no, or poor anchorage of walls with diaphragm causes the severe damages. Out-of-plane failure appeared very quickly.

Out of 182 damages to unreinforced masonry cavity wall construction, 72% damages were due to the out- of-plane failure 28% were caused by the in-plane failure [5]. During the earthquake of Darfield, Christchurch in 2010, the out-of-plane failure of walls was the first one to appear on the television-screen right after the earthquake [18]. As shown in figure 1, the primary reasons of such brick-masonry collapses were stated as lowly construction, poor materials usage, non-designed building walls, gable walls without confinement, and cracking started from edges of the openings. All the damages were occurred due to the out-of-plane failure of the said structures. The 2017 Lesvos earthquake induced severe damage to old URM structures at the 534 southwestern part of the island, and especially in the traditional settlement of Variss [32]. During the Bhuj earthquake of January 2001, most common found failures in the masonry structures were out-of-plane collapse [33]. Maule earthquake in 2010 resulted in about 524 deaths, more than 800,000 injuries, and caused an estimated 30 billion dollars direct and indirect economic loss [34]. The Kashmir earthquake of October 2005 caused more than 86,000 causalities [35]. During the earthquake of 2005, many masonry structures were partially or fully damaged in Kashmir [36]. Some examples of out-of-plane failures in solid masonry walls are shown below in figure 1. Different types of wall collapse, and corner failure are shown.

FIGURE 2.1: Masonry wall damages; (a) corner failure; (b) wall collapse; (c) wall collapse at 1st story; and (d) out-of-plane collapse [18]

2.2 Damages of Typical Masonry-structures During Ground-motion

Damages to typical unreinforced masonry structures during the earthquakes are being stated by different researchers from all over the world. Most of the damages to masonry structures occurred due to their un-confinement and poor anchorage

with diaphragm. Sharma et al. [19] lead survey study after the Gorkha earthquake in Nepal in 2015. Approximately 80000 partially or fully damage buildings were reported. Jagadish et al. [20] carried out a study for the behavior of unreinforced-masonry structures during the Bhuj earthquake in India in 2001. It is concluded in the study that most of the masonry building of mud mortar or lime mortar were being severely damages due to the low bond strength. According to the study, masonry buildings with cement mortar resist more than the others due to the strong bonding. Use of lintel band and provision of steel reinforcement in corners and junctions of masonry structures were being suggested as the future recommendation in the study. The research recommended that, although the provision of lintel bands will reduce the in-plane failure of masonry walls, but it will not be helpful during the occurrence of out-of-plane flexural failure. Particularly, in the flexural cracks which propagates horizontally and ultimately results the out-of-plane failure. Lintel-band failure and corner failure due to the out-of-plane failure are shown below in Figure 2a and Figure 2b, respectively.

Javed et al. [21] conducted a research on the behavior of masonry structure after the earthquake of 2005 in Pakistan occupied Kashmir. The study included that many damages were occurred due to the shear forces produces during the in-plane behavior in walls and out-of-plane flexure of the walls. Most of the in-plane diagonal cracks and the X-diagonal cracks were the results of shear forces produces in the plane of the wall. Typical diagonal cracks originating from the corners of the opening due to non-provision of the corner reinforcement. Toe crushing failure of masonry piers occurred due to the cyclic nature of seismic forces. Inertial forces were the main cause of collapse of masonry houses due to

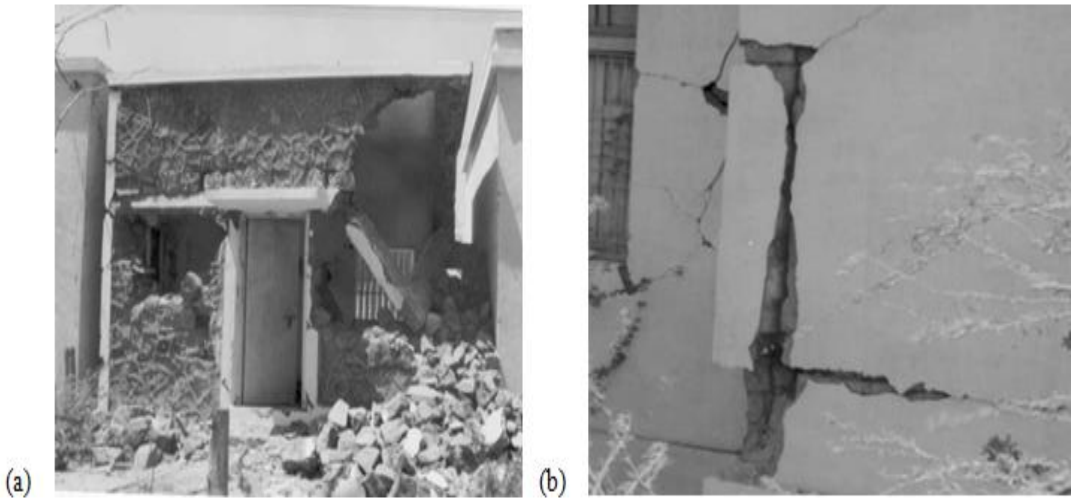


FIGURE 2.2: Damages in walls having horizontal and vertical stiffeners; (a) lintel-band failure; and (b) corner reinforcement failure [20]

the out-of-plane failure. Out-of-plane overturning of gable walls was also noted in different localities. Diagonal compressive forces caused the non-structural masonry walls. Collapse of masonry bridges and water tank on the roof of houses was also reported. Poor quality of cement mortar and the undressed stone masonry was concluded as the major reason behind the all said damages and collapses.

2.3 New Approach for Earthquake-resistant Structures

Ali [6] studied the impact of post-tensioned ropes of coconut-fiber in governing uplift of interlocking mortar-free blocks-construction during earthquake loading. It was stated that suggested interlocking block shown in Fig. 3 is accomplished of regaining its first position after the ground motion due to providing inclined key shape in the block. Investigational results were used to improve the empirical relation in the form of function of peak ground acceleration. A difference of 35% was witnessed in predicting the actual seismic response of the structure, which may obey due to the difficulty of the interlocking block column. Results of the study appeared satisfactory in-order to have cost-effective earthquake-resistant houses construction techniques. A coconut-fiber-reinforced-concrete interlocking block is shown in Figure 3 [6].

Qamar et al. [22] carried out a study for the improvement of lateral resistance in mortar-free interlocking walls with plaster by using nature fibers. The major reason of the failure of mortar-free interlocking wall system is the out-of- plane lateral resistance. Increase in lateral peak load is noted in this study and further increase also noted for rice straw and sisal fiber reinforced plastered wall system. Khan [23] suggested use of interlocking plastic-blocks for earthquake proof houses due to their less-weight with the combination of energy dissipation because of uplift of blocks. Liu et al. [24] studied the cyclic behavior of non- interlocking mortar-less brick and interlocking mortar-less brick. During the study of cyclic behavior, the effects of different interlocking forms, loading compression stress levels and loading cycles were considered. With the help of hysteresis loop method, a mechanical model was established. The shear failure modes of all the tested joints were well-defined by using Mohr-coulomb failure method. Increase in the loading cycle, decrease in the friction coefficients of all the joints was observed carefully. With the reduction of the flatness of the surface of the interlocking, a significant increment has been seen in the degradation of the friction.

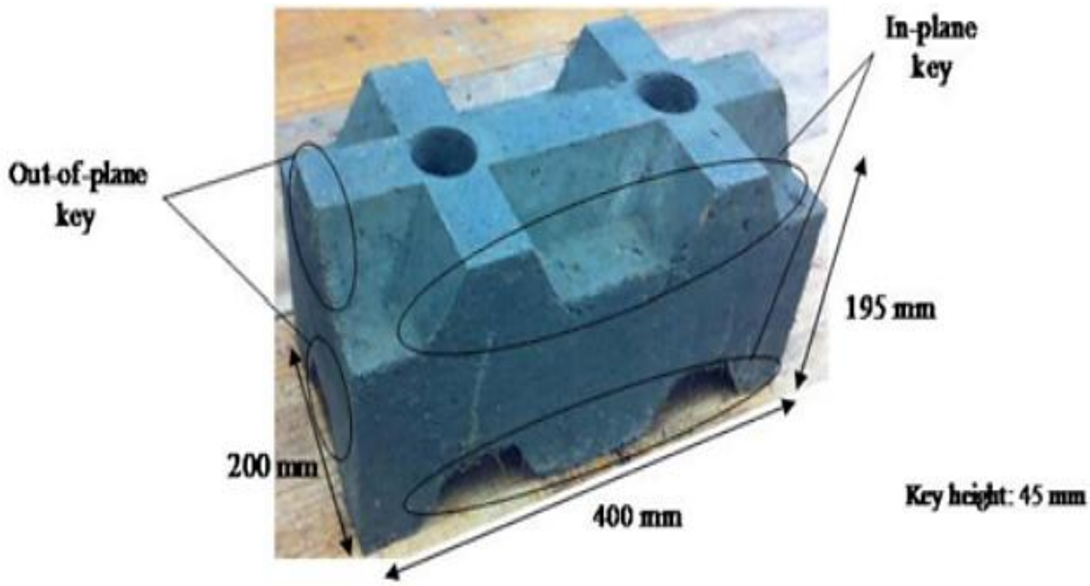


Figure 2.3: Coconut-fiber-reinforced-concrete interlocking block [6]

Shakir et al. (2020) constructed eco-friendly hybrid blocks for earthquake resistant houses to replace conventional construction practices [37]. Jeba Jeslin and I. Padmanaban, Experimental studies on interlocking block as wall panels, Materials Today: Proceedings, 2019 [38]. Liu et al. (2016) studied the cyclic behavior of mortar-less bricks and interlocking mortar-less bricks [39]. In seismic event, the damages in structure can be reduced due to uplift behavior of mortar-free interlocking columns [40]. Fay et al. [41] proposed innovative interlocked soil cement block for the construction of masonry to eliminate the settling mortar. Jan et al. [42] proposed interlocking masonry block construction with steel reinforcement for sustainable housing in Thailand. Khan and Ali [8] developed following empirical equations incorporating the geometry of interlocking blocks, column height, column response and input loading parameters:

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

$$\dot{u}_t = \frac{(\frac{a}{h^2})}{n} \mathrm{K}^{(1+\frac{2n}{100})} \dot{u}\mathrm{g} - - - 2.2$$

$$u_t = \frac{(\frac{a}{h^2})}{n} \mathrm{K}^{(1+\frac{n}{100})} ug - - - 2.3$$

Where $\ddot{u}_t$, $\dot{u}_t$ and u_t are averaged IPBSW response acceleration, velocity, and displacement, respectively. $\ddot{u}_g$, $\dot{u}_g$ and u_g are averaged ground acceleration, velocity and displacement, respectively. a, h, and n, are wall base area, key height, and number of blocks along the height of wall, respectively. K is constant and its value is 0.45.

2.4 Out-of-plane Behavior of Mortar Free Interlocking Plastic Block Walls

Out-of-plane behavior is more critical than the in-plane behavior. Many researchers reported that most of the damages and collapse in unconfined masonry structures had been occurred due to the failure in out-of-plane behavior. Various studies have been conducted on the out-of-plane behavior effects. Kallioras et al. [25] delivered a single data set that captures at full-scale the in-plane and out-of-plane performance of un-reinforced masonry walling. And provided a dynamic global response of a building under earthquake loading. Saifee et al. [26] concluded that the walls behavior was majority controlled by large horizontal displacement and dry-joint opening about at mid height of the wall (location of extreme moment). Figure 4 shows the interlocking mortar less wall exposed to out-of-plane loading. Martinez and Atamturktur [27] mortar-less masonry wall was experienced under out of plane loading to understand the performance of wall. Enhancement in crucial lateral load capacity was assessed because of rise in block compressive-strength and effect of wholly or partly grouted wall was compared. Out-of-plane response of mortar-free walls by different researchers are shown in Table 1. Diverse studies had been carried out to examine the ot-of-plane behavior of mortar-free walls by the different researchers.

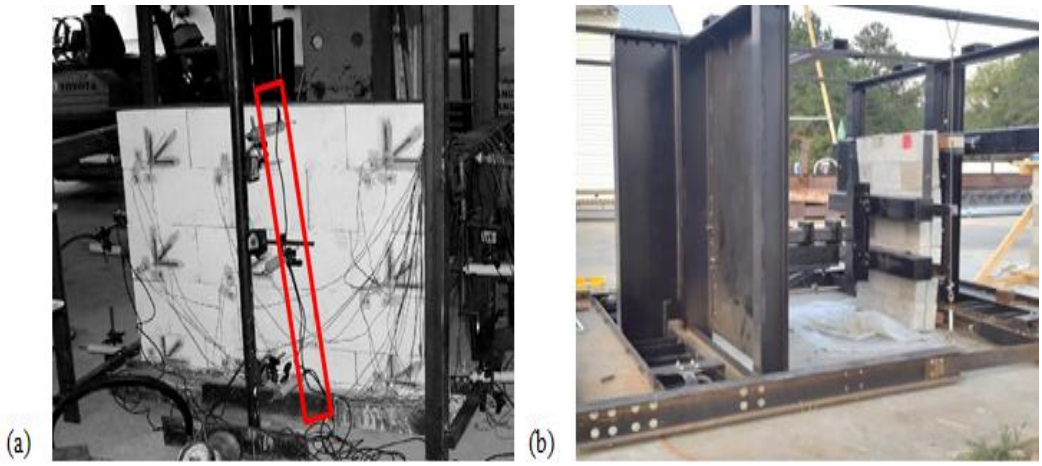


FIGURE 2.4: Out-of-plane testing of mortar-free wall; (a) Saifee et al. [26] and (b) Martinez and Atamturktur [27]

Large scale shaking-table tests were performed on the 3 and 7 storey buildings for the prediction of the seismic response of timber buildings [43]. Ceccotti et al. [44] carried out a study on dynamic response of cross-laminated timber building concluded upper stories have maximum acceleration and displacement. Stavridis et al. [45] concluded that In filled reinforced concrete structures can respond safe during earthquake if infill walls as provided sufficiently. Nader et al. [46] carried

Table 2.1: Out-of-plane response of mortar-free walls by different researchers

Reference	**Study**	**Conclusions**
Ali et al. [17]	Dynamic behavior of mortar-free interlocking structures	Mortar free walls were collapsed in bending in out-of-plane direction as one of the bottom interlocking keys broken and partly shear-off, producing uncertainty in the structures
Saifee et al. [26]	Experimental study was examined to investigate the structural behavior of mortar less interlocking load bearing hollow block wall under out of plane loading	Out-of-plane load capacity, mode of deformations and dry joint opening in the wall were extremely affected by grout and the reinforcement and pre-compressive load
Thanoon et al. [28]	Structural response of mortar less interlocking masonry system under the eccentric compressive loads	Interlocked walling system is a possible alternate to conventional brick-mortar-masonry as it showed better and comparable structural presentation under the axial and eccentric loading

out the study on structure stiffness, base shear and lateral drift for flexible, semi rigid and rigid steel frame and concluded Maximum energy can be dissipated where flexible connections are developed. The earthquake and harmonic base motion energies were dissipated through inter-brick friction [47]. Alshawa et al. [48] carried out a study on out-of-plane behavior of unreinforced-masonry wall proposed a nonlinear equation of motion of a single-body wall. Alshawa et al. [48] carried out a study on out-of-plane behavior of unreinforced-masonry wall proposed a nonlinear equation of motion of a single-body wall. Nezhad [49] carried out an experimental investigation on out-of-plane behavior of GFRP retrofitted masonry panels. Mathematical model provides reasonable results based on the shake table tests results [50]. Mendes et al. [51] carried out a study on methods and approaches for predictions of out-of-plane behavior of masonry walls. Cavaleri et al. [52] presented numerical procedure for out-of-plane behavior of walls.

2.5 Summary

Earthquakes are the major natural disasters that severely affects the buildings. Typical unreinforced masonry structures are prone to earthquake loading and seismic damages due to their conventional weak bonding of bricks and mortar. Developed countries has adopted the confined masonry structures technique to avoid such failures and collapses of the masonry structures. However, confined masonry structures are also not enough to avoid the severe damages and collapse of building and structures during the earthquake activity. In developing countries, it is the need of time to adopt the modern techniques for the earthquake resistant housing. However, in developing countries the modern approaches are quite limited from economical point of views as well as dynamic point of view. A cheap new modern technique for earthquake resistant housing for developing countries is needed. For this purpose, the researchers from all over the world are focusing on the new technique of mortar-free interlocking structures at cheap cost for the developing countries. The in-plane and out-of-plane behaviors of solid-walls play an important role to avoid overall structure collapse by resisting earthquake forces. Out-of-plane behavior is crucial than the in-plane behavior. Through the literature research to understand the behavior of mortar-free interlocking plastic block solid wall is explored in the light of the previous research from throughout the world researchers. Available literature has included plenty of sizes, shapes and interlocking-techniques for such blocks. An output of higher-level accuracy in laboratory can be achieved by examining the dynamic behavior interlocking mortar free solid walls prototypes. The behavior of these interlocking mortar free plastic block solid wall prototypes against harmonic loading can be more accurately predicted by conducting small scale testing. The provided literature has the significant studies of the researchers which proposed the different types and sizes of interlocking mortar-free structures for the earthquake resistant housing in developing countries. Behavior of these interlocking mortar-free block prototypes against earthquake loading can be predicted well by considering the small-scale dynamic testing in the laboratory. Their analytical endorsement can be used to improve empirical relations to perform basic testing with the identification of error percentages. A lot of research support and authenticate the results get from the testing of these prototype structures. In present, most of the researchers have motivated on concrete block or masonry block approaches for the said purpose.

Chapter 3

Experimental Program

3.1 Background

While talking about the earthquake resistant design of structures, it is critically important to predict or calculate the reaction and response of building during the seismic activity. For this particular purpose, different approaches have been practiced throughout the world. Dynamic testing of prototype structures in laboratory is the one of the practices. This chapter describes the techniques of constructing the interlocking plastic-block solid wall, unreinforced brick masonry solid wall, snap back test, test setups, their instrumentations, applications of harmonic loading by using simple shake table, parameters analysis and empirical equations development.

3.2 Continuation of Research Program

Khan [23] suggested the interlocking plastic-block for earthquake resistant houses (plan and 3D view of proposed house is shown in Figure 3.1) and prototype testing, because they result less inertial forces due to their light weight. The role of weight of used material and the resulting of inertia forces are very important in earthquake resistant housing.

(a)

(b)

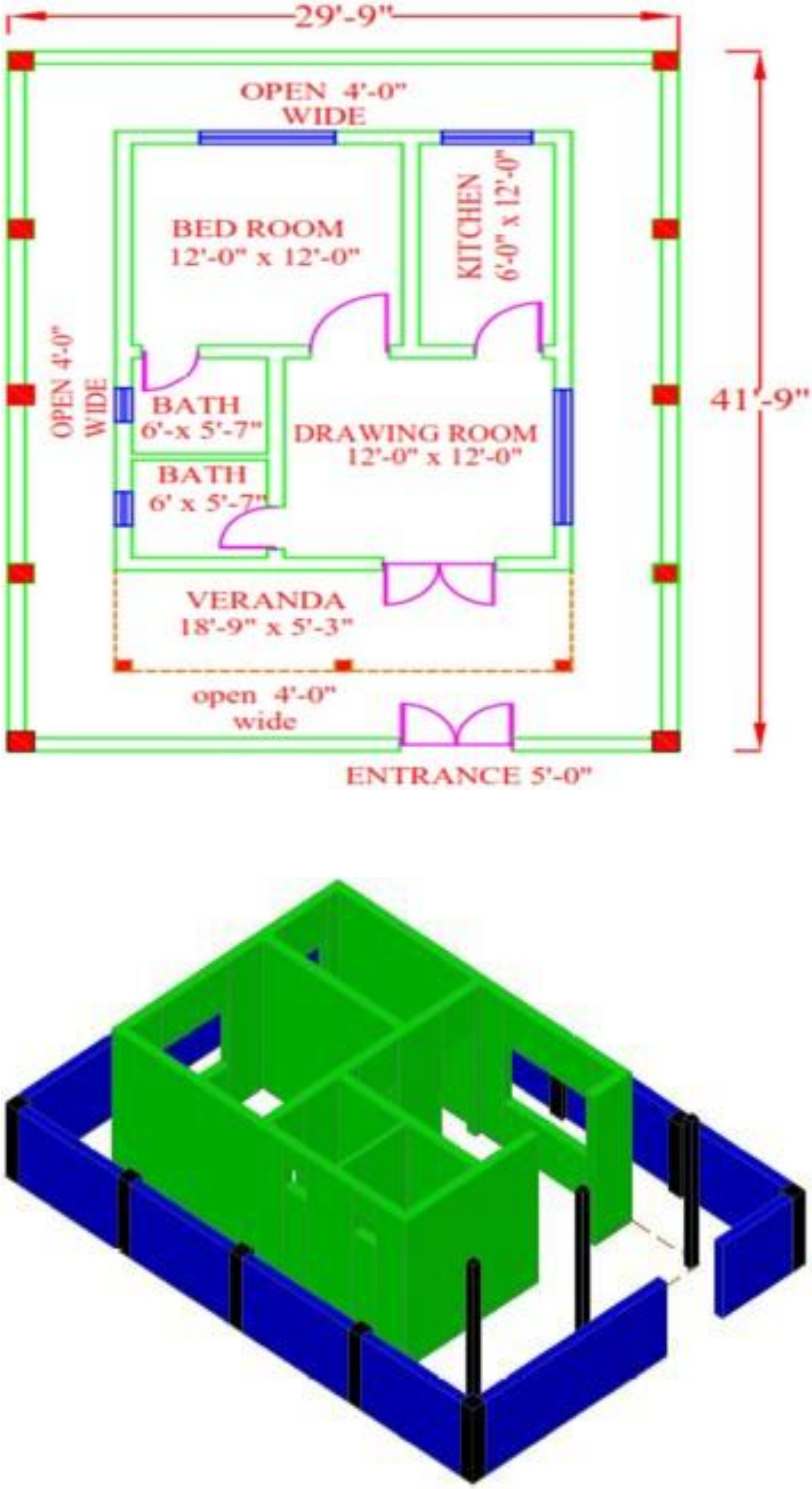


FIGURE 3.1: Proposed interlocking plastic-block house: a) plan and b) 3D view [23]

Inertia force is generally taken as a systems ability to resist changes caused by some external force (acceleration). This approach is built on Newtons Laws of Motion, also including the Inertial Law and the Action-Reaction Law. In response to such external force, heavy systems respond more due to their greater weight in comparison with lighter systems, thus causing greater inertia forces. The specific aim of this experimental study is the comparison of out-of-plane behavior of mortar-free interlocking plastic block solid wall and unreinforced brick masonry solid wall under harmonic loading by using 1D shake table. Earthquake forces can be resolved into three components i.e. x, y, and z directional components. It would be relatively easier to understand the behavior in one direction. In one direction, the behavior can be studied with different magnitudes which can then be used to make the respective behavior by taking resultant with consideration of different magnitudes acting in x, y, and z directional components. In this study, behavior is studied with different magnitudes in one direction. Structural time period is an important aspect that depends on the structure height. Thats why, the 1/10 scale is done for elevation dimensions only and wall width is not considered for scaling.

For construction of earthquake resistant housing, the proposed interlocking plastic blocks have the cross-sectional dimension of 150 mm x150 mm and 4 keys at the top. Total height of block is 140 mm including the 30mm height of interlocking key as shown in Figure 3.2 (a). Similarly, for prototype construction, the used dimensions in the study was 62 mm x 62mm with a height of 41 mm including the 12 mm height of interlocking key as shown in Figure 3.2 (b). The sizes of plastic block and small brick are not same. Small bricks of different sizes are available in market. To start with, in this study, small bricks used for UBMSW prototype construction have dimensions of 124 mm x 62 mm x 25 mm. Current research work is continuation of Khan [23] research work.

In this study, prototype interlocking plastic block solid wall is considered for dynamic testing. Prototype testing serve to provide specifications for a real or proposed working system rather than a theoretical one. Prototype walls scaling and construction technique adopted in this research work is purely based on research practices mentioned in literature [30-31]. Outcome of such studies help to understand behavior of full-scale structures. This research has the purpose to study the dynamic behavior of structural solid walls. For this, structural time-period is an important parameter which depends on the structure height (UBC-97). That is why scale down technique is primarily applied on elevation dimensions of structural walls. It might be noted that the dimensions of units used in both prototypes (i.e., scaled down solid wall samples) are slightly different. However, the elevation dimensions in both prototypes are approximately the same.

Figure 3.3 (a) shows schematic diagram of proposed real solid wall made-up of interlocking plastic-blocks. It will have some grooved block mechanism for foundation and roof diaphragm. Figure 3.3 (b) shows scaled downed schematic diagram of prototype interlocking plastic block solid wall, using 1/10 scale factor. Figure 3.3 (c) shows schematic diagram of prototype interlocking plastic block solid wall with simplified boundary conditions.

Figure 3.4 (a) shows schematic diagram of real-life unreinforced brick masonry solid wall. Figure 3.4 (b) shows scaled downed schematic diagram of prototype unreinforced brick masonry solid wall, using 1/10 scale factor. Figure 3.4 (c) shows schematic diagram of unreinforced brick masonry solid wall with simplified boundary conditions.

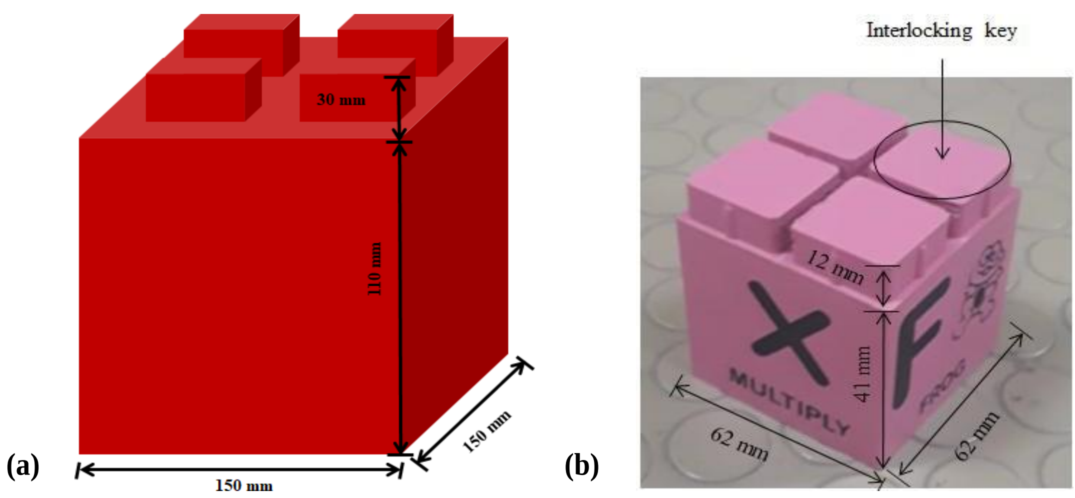


FIGURE 3.2: Proposed interlocking plastic-block: a) for earthquake resistant construction, and b) for prototype construction [23]

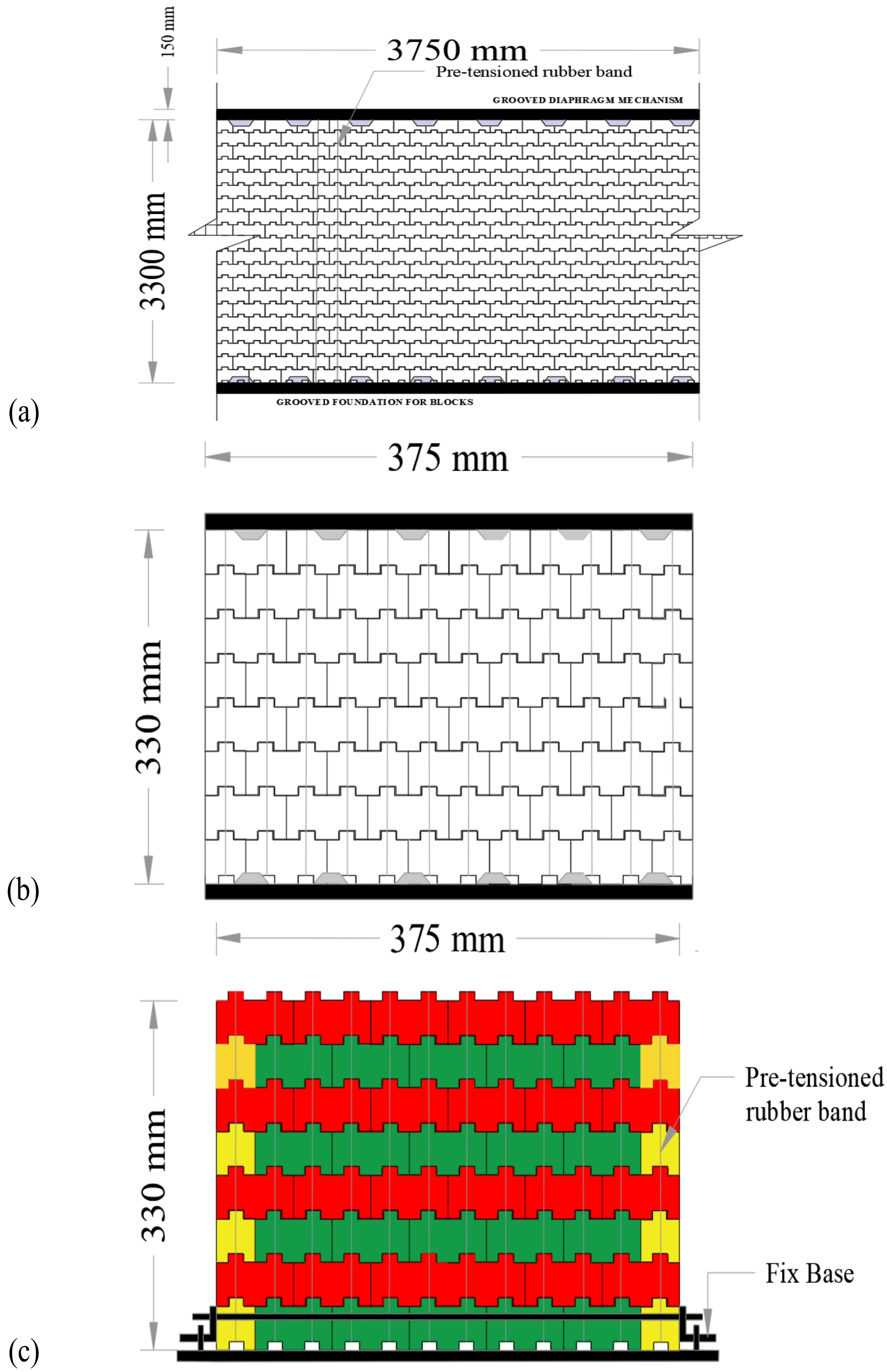


FIGURE 3.3: Schematic diagram of interlocking plastic block solid wall a) proposed real life solid wall b) scaled downed prototype solid wall c) prototype solid wall with simplified boundary conditions

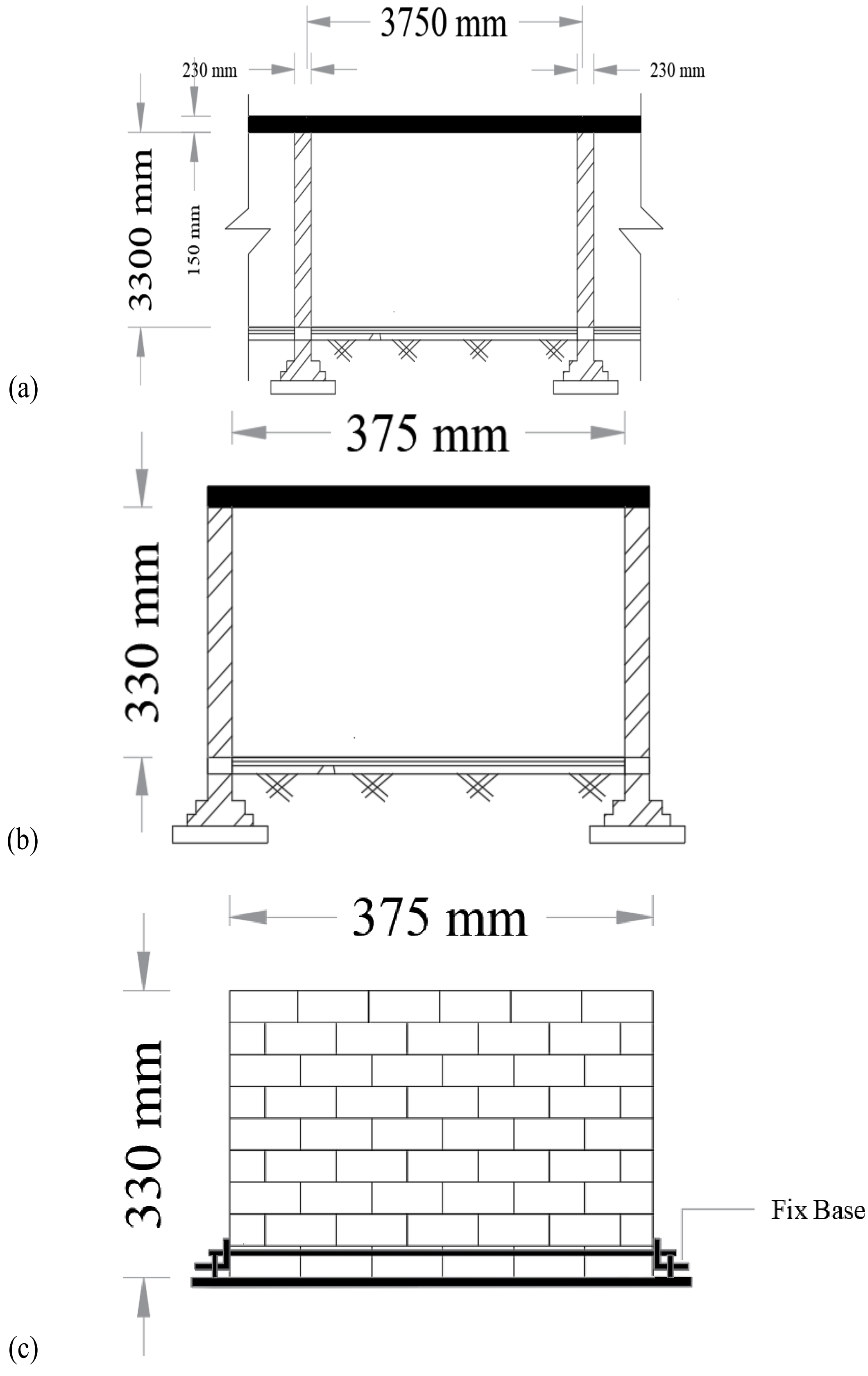


FIGURE 3.4: Schematic diagram of unreinforced brick masonry solid wall a) proposed real solid wall b) scaled downed prototype solid wall c) prototype solid wall with simplified boundary conditions

3.3 Prototype Walls

Prototype interlocking plastic block solid wall consists of forty-eight interlocking plastic blocks (n=48, making a total height (H) of 330 mm as shown in Figure 3.5 (a). It is a solid wall with no opening like window or door. Rubber band are tied up from bottom to top through mid of blocks to provide vertical stiffness in the wall. Fixed base with the help of base plates and nut bolts is provided. No mass is provided on top. However, the total mass of wall (M) is 1.60 Kg. Unreinforced brick masonry solid wall was constructed using small bricks. It was water cured for ∼10 days and the cement sand mortar ratio was 1:3. It has a total height of 330 mm as shown in Figure 3.5 (b). Fixed base with the help base plates and nut bolts is provided. No mass is provided at the wall top.

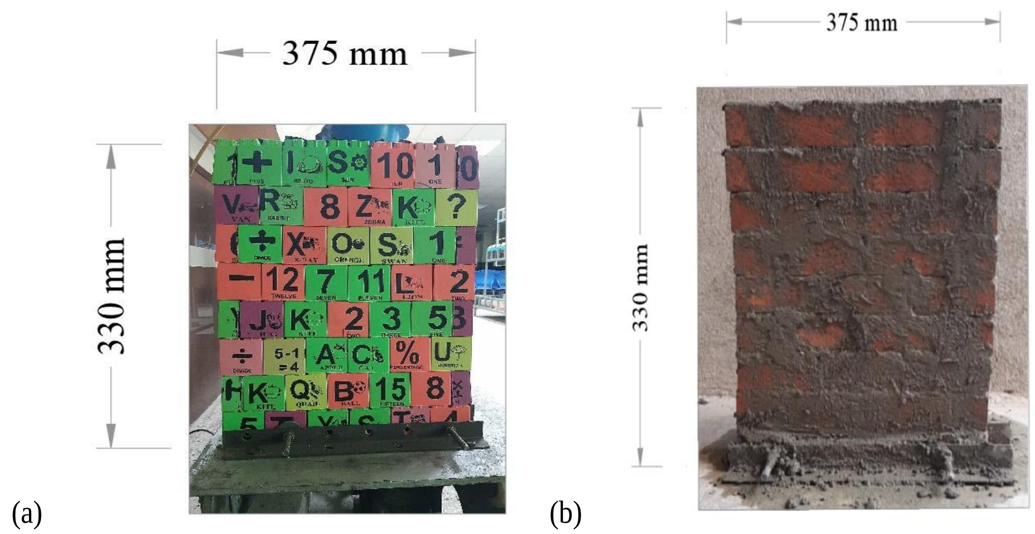
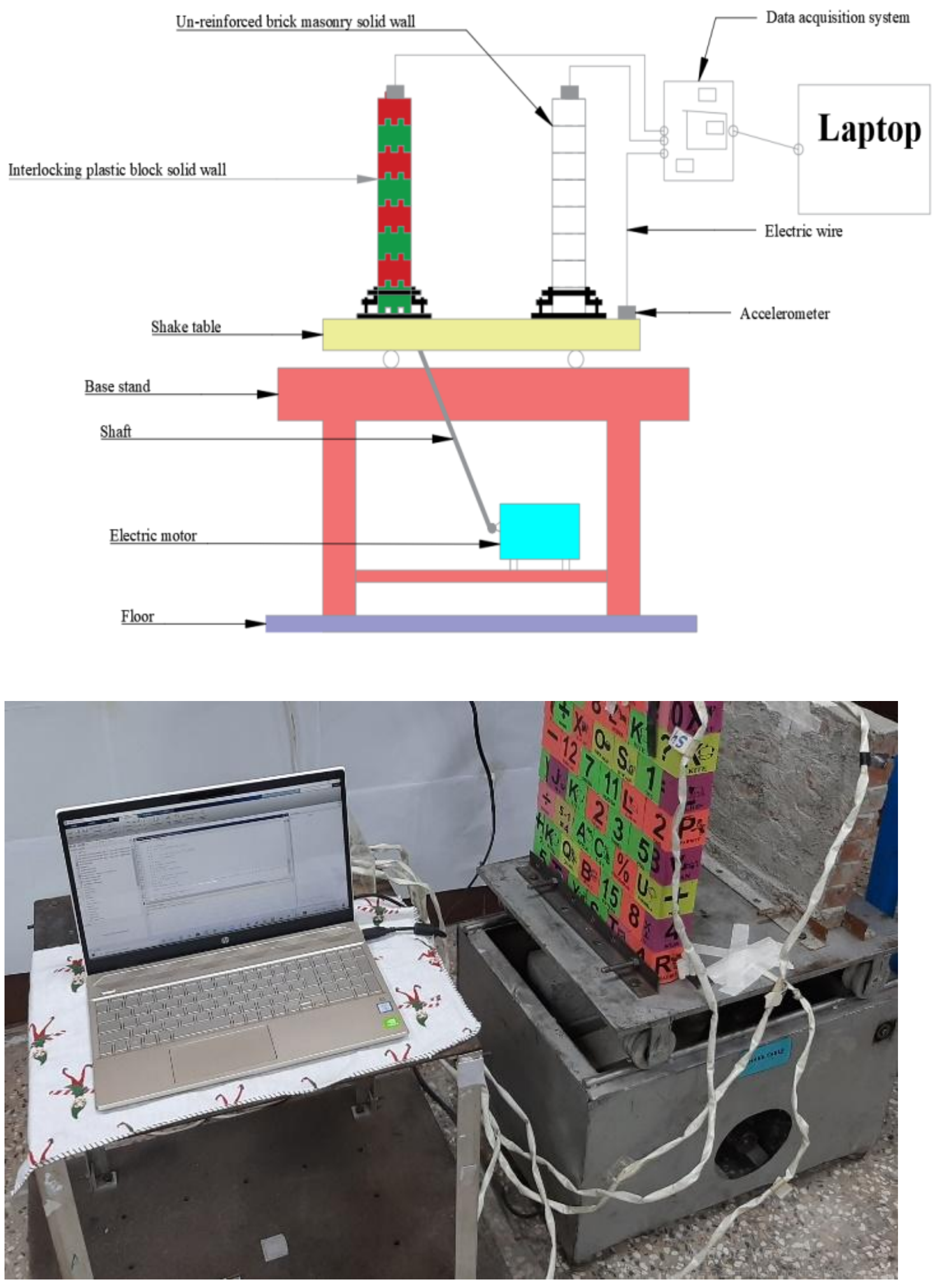


Figure 3.5: Prototype a) interlocking plastic block solid wall, b) unreinforced brick masonry solid wall

3.4 Test Setup and Considered Loading

3.4.1 Shake Table Test and Instrumentation:

Figure 3.6 shows instrumentation of shake table testing: a) schematic diagram and b) test setup. Both walls (interlocking plastic-block solid wall and unreinforced masonry solid wall) are mounted on the shake table using base plates and nut bolts. Total three accelerometers are used. One is attached on the top of plastic block solid wall. One is attached on the top of masonry solid wall while the one is attached on the shake-table. Response of both walls is recorded in the terms of acceleration-time history. Then this data is converted into velocity time history and displacement time history using the seismo-signal software.



(a)

(b)

FIGURE 3.6: Shake table instrumentation and testing: a) schematic diagram and b) real test setup

3.4.2 Harmonic Loading:

Magnitude of different tests considered are shown in Table 3.1. Two tests are performed. In this research work, two tests are performed i.e., snap back test and harmonic loading test. Snap back test is only performed for interlocking plastic-block solid wall. For harmonic loading, frequencies of 1.5 Hz, 2 Hz, and 2.5 Hz are considered. For harmonic loading, the amplitude of interlocking plastic-block solid wall is taken as 30 mm. Displacement-time history, velocity-time history, and acceleration-time history at the top of both walls and base of shake table is compared to evaluate the dynamic response of walls under the influence of harmonic loading. It is predicted that the displacement-time history, velocity-time history, and acceleration-time history will be greater for the case of interlocking plastic-block solid wall.

Table 3.1: Detail of magnitude of tests considered

Test	**Amplitude**	**Interlocking plastic-block solid wall**	**Unreinforced brick masonry solid wall**
Harmonic	ug = 30 mm (f = 1.5 Hz)	1	1
	ug = 30 mm (f = 2 Hz)	1	1
	ug = 30 mm (f = 2.25 Hz)	1	1
	ug = 30 mm (f = 2.5 Hz)	1	1

3.5 Analyzed Parameters

3.5.1 From Snap-back Test

Sudheer [29] determined the damping ratio and fundamental frequency of the same research program. The same data is supposed for this research.

3.5.2 From Shake Table Tests

Harmonic loading having frequencies of 1.5 Hz, 2 Hz, 2.25 Hz and 2.5 Hz was applied to both walls. Response of these walls in terms of acceleration-time history was recorded. Displacement-time history and velocity-time history was calculated then, using the seismosignal software. Similarly, with the help of acceleration-time history data, base shear (Q) displacement curves were also obtained for both walls. Base shear is taken as M . $\ddot{u}_t$, where M is the mass of respective wall and $\ddot{u}_t$ is the acceleration at the top of respective wall.

3.5.3 Improvement in Empirical Equations

For understanding the dynamic behavior of interlocking plastic-block solid wall, empirical equations are developed. The difference between the percentages of the experimental and empirical values was also calculated.

3.6 Summary

This chapter includes the detailed experimental techniques implemented in this re- search study. Prototype interlocking plastic-block solid wall was tested under the harmonic loading. Furthermore, behavior of prototype of typical unreinforced brick masonry solid wall was also examined. Behavior of these both walls was also compared. The detailed test setup and instrumentation of all test conducted in this research study is also included in this chapter. And details about parameters to be analyzed is also presented.

Chapter 4

Experimental Evaluation

4.1 Background

Previous chapter included the experimental procedure in detail. This chapter describes experimental evaluation of the data recorded through experimentation. Damping ratio ξ and fundamental frequency (f_n) of the interlocking plastic- block solid wall was calculated by using the acceleration-time history. Furthermore, seismosignal software was used to remove this noise from test data. Bandwidth filter of seismosignal software was used to remove undesired data. But on primarily basis, noise from the recorded data was eliminated by the MATLAB filter. Similarly, velocity-time history and displacement-time history was determined using the acceleration-time history data. Seismosignal software was used for this purpose.

4.2 Damping Ratio (ξ) and Fundamental Frequency (f_n)

Sudheer [29] determined the damping-ratio and fundamental-frequency of the same research program. Table 4.1 depicts the results of snap back. The top of the wall is displaced from mean position by: a) 25 mm and b) 50 mm. By using log decrement method, damping ratio (ξ) and fundamental frequency (f_n) were calculated.

TABLE 4.1: Snap back test results

Sr.no	**Amplitude**	**Frequency (Hz)**	**Damping (%)**
1	25 mm	4.853	1.34%
2	50 mm	5.154	1.36 %

4.3 Prototype Walls Response Against Harmonic Loading

4.3.1 Acceleration-time Histories and Displacement-time Histories

Response of interlocking plastic-block solid wall and unreinforced brick masonry solid wall are recorded in terms of displacement time history and acceleration time history during the time of 55 s to 60 s as shown in Figure 4.1 and Figure 4.2. The red dashed dotted line represents the shake table movement or base excitation (applied loading), the orange solid line represents the response at the top of the interlocking plastic-block solid wall and the green dotted line repents the response at the top of the unreinforced brick masonry solid wall. The acceleration-time history and displacement time history attained from analysis of result that are acceptable to investigate the dynamic response of both prototype walls. Acceleration time history is recorded and then it is converted to displacement time history by using the seismosignal software as described earlier. Meanwhile the locally made low-cost shake table is acceptable to apply harmonic loading accurately i.e., constant amplitude of different cycles, the averaged acceleration and displacement of base excitation (i.e. $\ddot{u}_g$ and u_g respectively) is measured applied loading. The averaged acceleration and displacement at the top of interlocking plastic-block solid wall (i.e. $\ddot{u}_t$ and u_t respectively) is considered as IPBSW response. Similarly, the averaged acceleration and displacement at the top of unreinforced brick masonry solid wall (i.e. $\ddot{u}_t$ and u_t respectively) is considered as UBMSW response.

Acceleration-time histories of both walls during harmonic loadings of 1.5 Hz, 2 Hz, 2.25 Hz and 2.5 Hz between 55 s and 60 s are shown in Figure 4.1. The structure excitation can be classified into three stages: A. when the structure started its vibration till it reached the steady state, B. steady state response of the structure, and C. free vibration of the structure [17]. For clarity, only portion of steady state response is shown in Figures 4.2 and 4.2. Averaged acceleration at base and top of walls is also mentioned. It has been noticed that the acceleration of these band is increased by increasing the frequency of shake table. Initially it was planned to consider only three frequencies i.e 1.5 Hz, 2 Hz, and 2.5 Hz. But during the application of third frequency i.e 2.5 Hz the shake table got damaged (shake table wheels displaced from the rail) due to high frequency. Then the both walls tested again on the previous frequency of 2 Hz for long enough time-period about three minutes and the on 2.25 Hz frequency. Displacement-time histories of both walls during harmonic loadings of 1.5 Hz, 2 Hz, 2.25 Hz and 2.5 Hz between 55 s and 60 s are shown in Figure 4.2. During the application of 2.25 Hz frequency the unreinforced brick masonry solid wall damaged and collapsed as shown in fig 4.3. Deflection of interlocking plastic block solid wall after testing is shown in fig 4.4. This damage was accumulative incorporating the effects of previous frequency. To check the response at the base, displacement time-history is shown between 55s and 60s. Averaged displacement at ground and top of walls is also stated. It has been noticed that the displacement of walls is increased by increasing the frequency of shake table. And UBMSW collapsed at 2.25 Hz frequency.

As described before, locally made shake table is only able to apply precise harmonic loading. There is a little variation exists in amplitude of different cycles. The averaged acceleration, velocity and displacement of base motion (i.e. $\ddot{u}_g$, and u_g, respectively) is taken as applied loading. For the case of unreinforced brick masonry solid wall, it is undoubtedly visible that initial values of acceleration, velocity and displacement was relatively less than values of interlocking plastic-block solid wall.

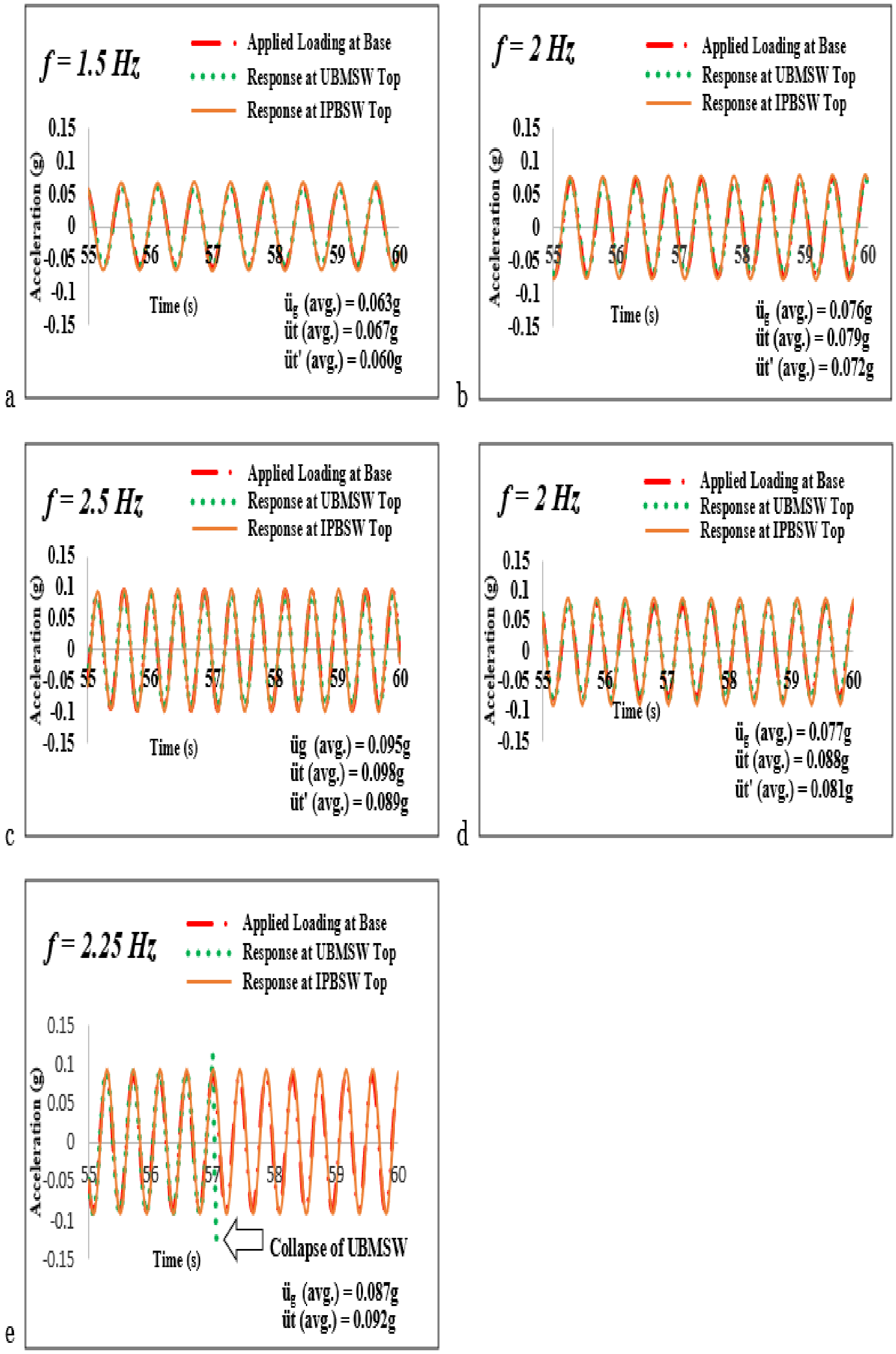


FIGURE 4.1: Behavior of Interlocking plastic-block solid wall and un-reinforced brick masonry solid wall for 5 seconds in terms of acceleration-time history: a) for 1.50 Hz, b) for 2.00 Hz, c) for 2.50 Hz, d) 2.00 Hz, and e) 2.25 Hz

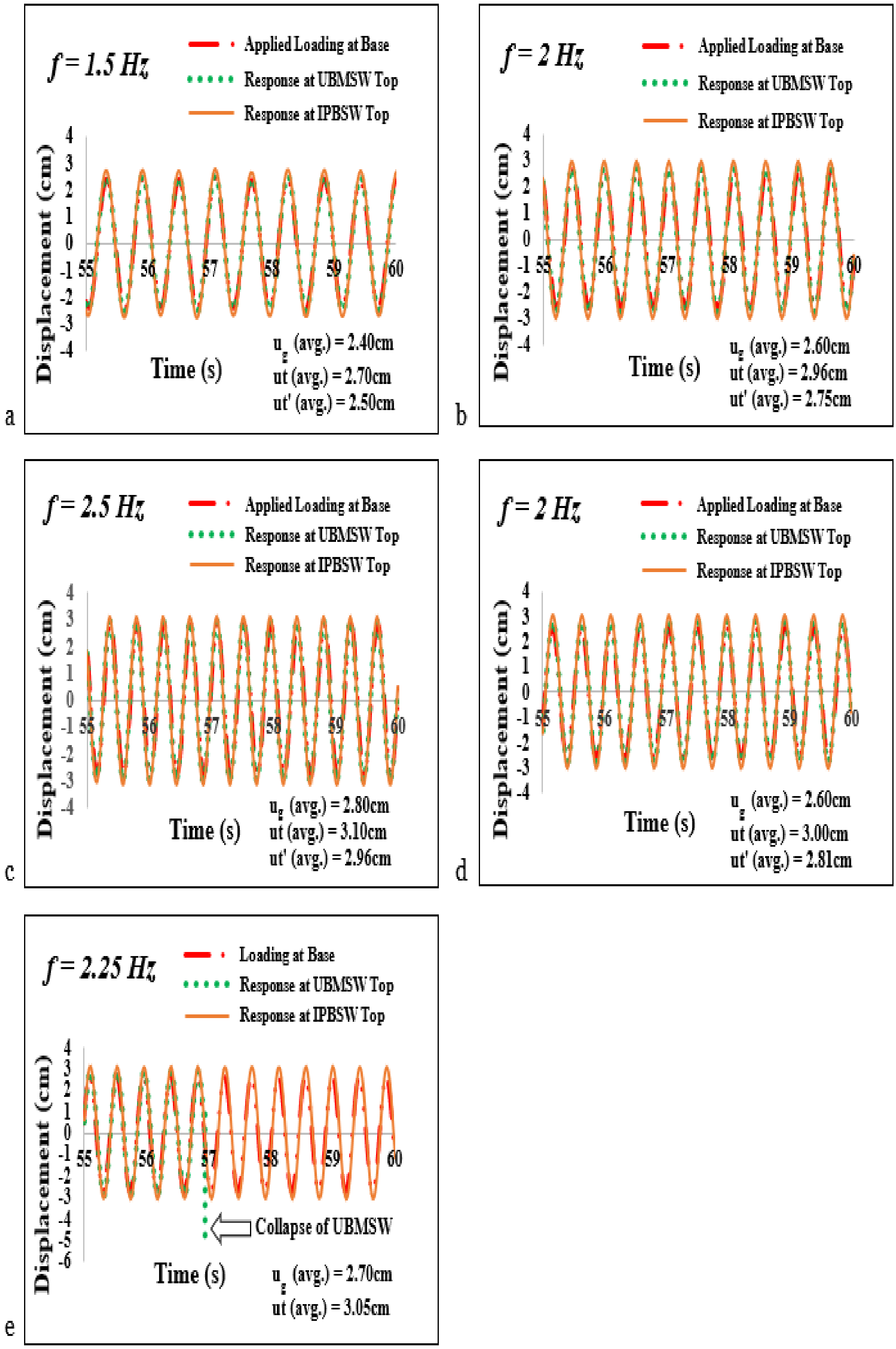


Figure 4.2: Behavior of Interlocking plastic-block solid wall and un- reinforced brick masonry solid wall for 5 seconds in terms of displacement-time history: a) for 1.50 Hz, b) for 2.00 Hz, c) for 2.50 Hz d) 2.00 Hz and e) 2.25 Hz

FIGURE 4.3: Failure of unreinforced brick masonry solid wall during testing

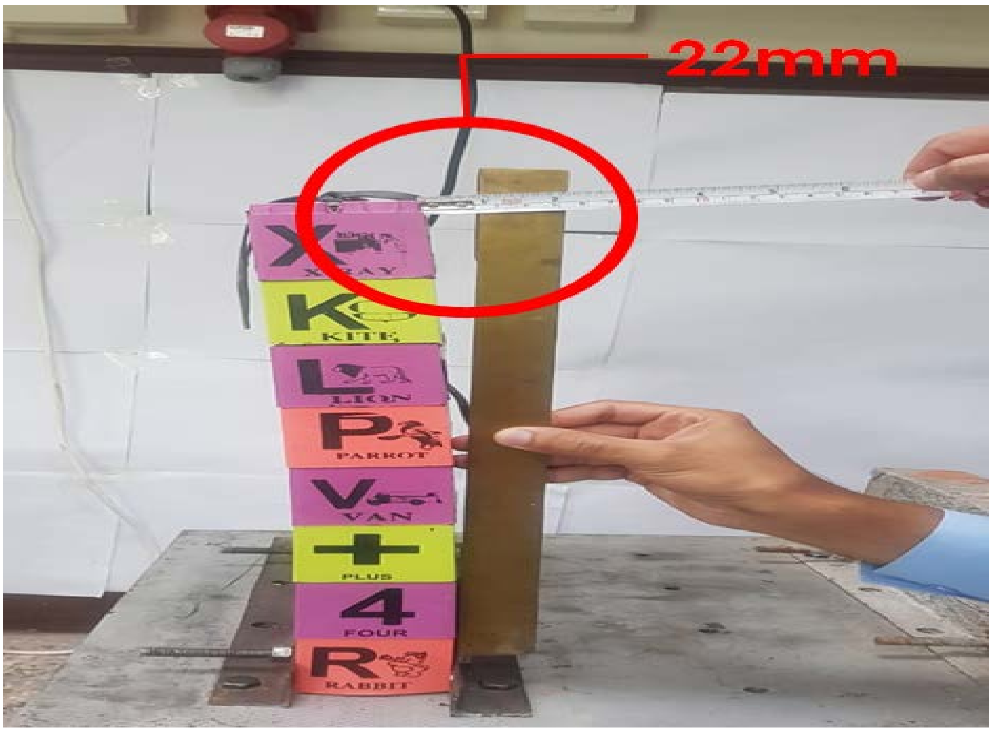


FIGURE 4.4: Deflection in interlocking plastic block solid wall after testing

4.3.2 Base Shear (Q) Displacement (Δ) Curves and Energy Absorption:

It is assumed that the total mass of interlocking plastic block solid wall (M) is lumped at walls top where its response acceleration time (i.e., $\ddot{u}_t$-t) history is recorded. Base shear is computed as M. $\ddot{u}_t$. Typical base shear (Q) displacement (Δ) curves are shown in Figure 4.4 and Figure 4.5. This is calculated as per working of Ali et al. [17].

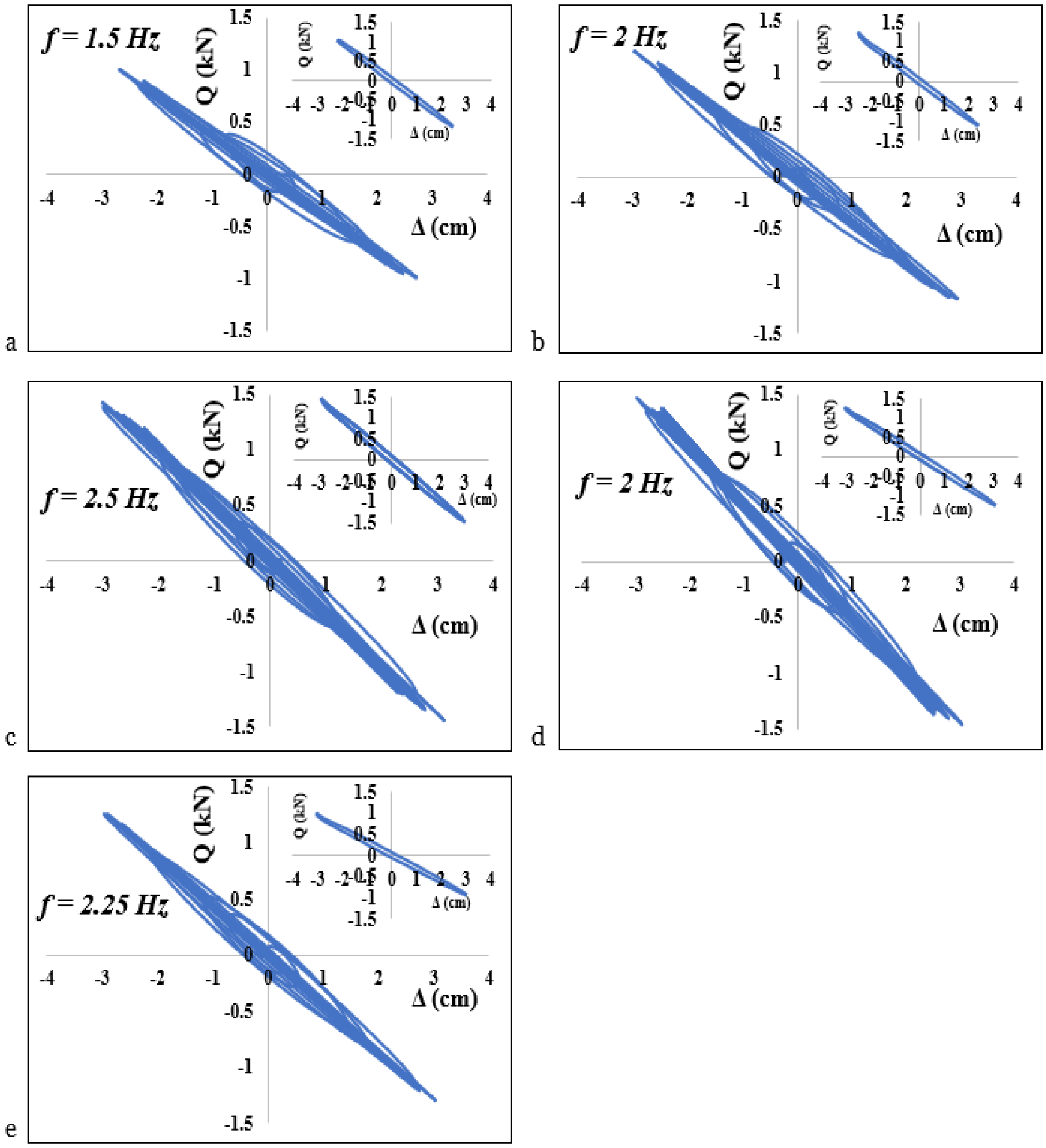


FIGURE 4.5: Base shear - displacement curves of interlocking plastic-block solid wall for: a) 1.50 Hz, b) 2.00 Hz, c) 2.50 Hz, d) 2.00 Hz and e)2.25 Hz

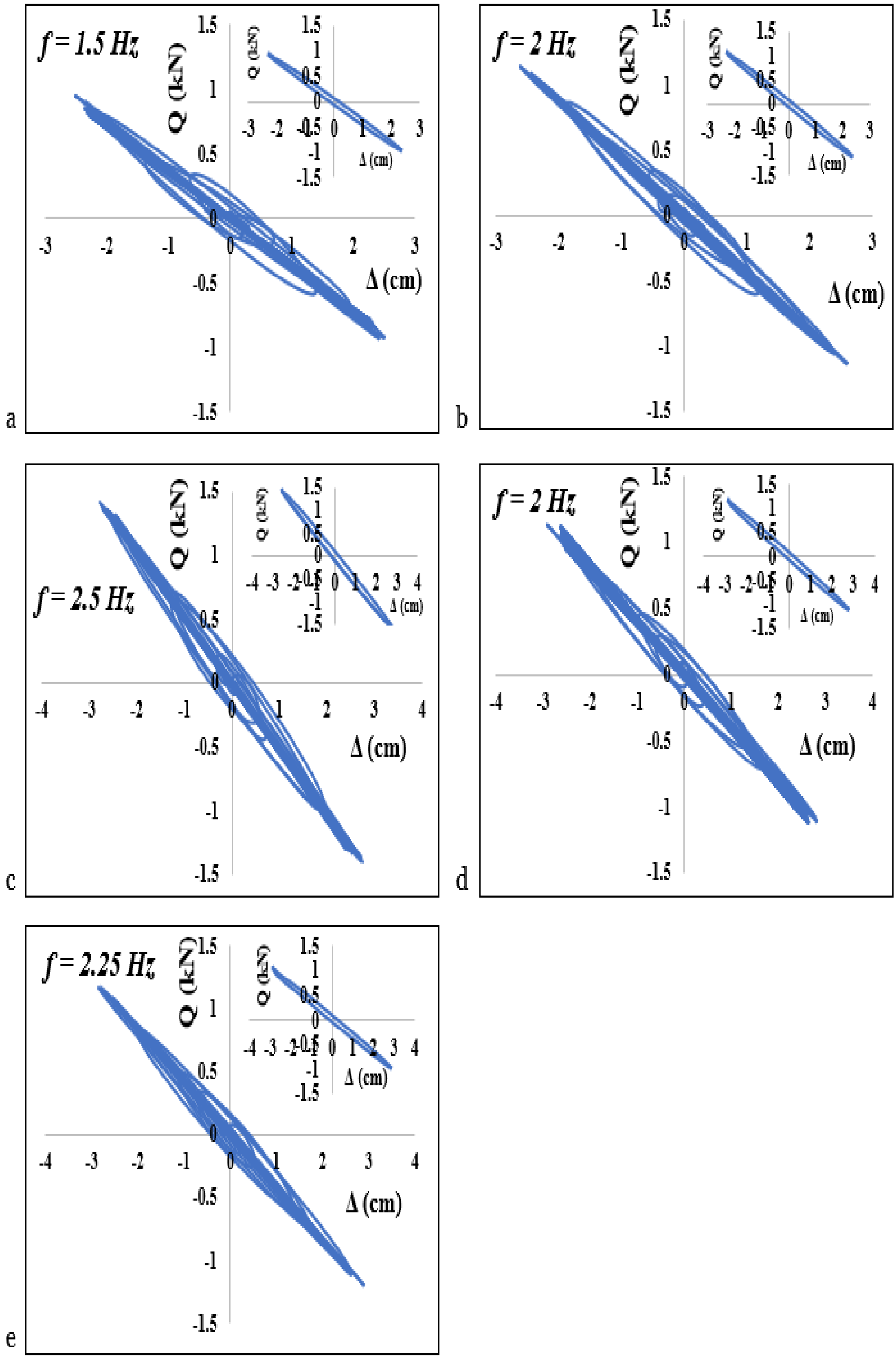


FIGURE 4.6: Base shear-displacement curves un-reinforced brick masonry solid wall for: a) 1.50 Hz, b) 2.00 Hz, c) 2.50 Hz, d)2.00 Hz and e) 2.25 Hz

TABLE 4.2: Energy absorption during harmonic testing

Frequency (Hz)	**Averaged energy absorbed in one cycle (Nm)**		**Total no. of cycles (n)**	**Total energy absorbed (Nm)**	
—	IPBSW	UBMSW		IPBSW	UBMSW
1.5	2.4	2.1	92	221	193
2.0	2.8	2.4	121	339	290
2.5	3.9	3.4	153	597	520
2.0	3.4	3.1	121	411	375
2.25	3.6	3.2	136, 129*	490	412

* Total number of cycles for UBMSW under harmonic loading of 2.25 Hz up-to collapse.

Table 4.2 shows the averaged energy absorption (E) in one cycle as well as total energy absorbed (ET). Area within the loop is taken as energy absorption (E). It has been noticed that interlocking plastic-block solid wall dissipates more energy during harmonic loading at all frequencies compared to UBMSW. Averaged energy increases with an increase in applied frequency. It can be seen in Table 4.2 that 14%, 16%, 15%, 10% and 12.5% more energy is dissipated in interlocking plastic-block solid wall at the frequency of 1.50Hz, 2.00 Hz, 2.50 Hz, 2.00 Hz and 2.25 Hz, respectively, in comparison with that of unreinforced brick masonry solid wall. In seismic event, interlocking plastic-block solid wall can absorb more energy, because of the block interfaces relative movement. Experimentation is being done with observation that energy dissipation is because of relative movement or uplift of block which will be studied in future. It is concluded that interlocking plastic-block solid wall dissipates more energy than unreinforced brick masonry solid wall.

4.4 Relationship Between Structure Response, Geometrical Parameters, and Input Loading Conditions

Khan and Ali [8] developed empirical equations incorporating the geometry of interlocking blocks, column height, column response and input loading parameters. Following advanced based equations on Khan and Ali [8] approach developed for predicting the response of interlocking plastic-block solid wall by incorporating a new variable 'R_s':

$$\ddot{u}_t = \frac{(\frac{a}{h^2})}{n}\ \mathrm{R}_s K^{(1+\frac{2n}{100})} \ddot{u}\mathrm{g} - - - 4.1$$

$$\dot{u}_t = \frac{(\frac{a}{h^2})}{n}\ \mathrm{R}_s K^{(1+\frac{2n}{100})} \dot{u}\mathrm{g} - - - 4.2$$

$$u_t = \frac{(\frac{a}{h^2})}{n}\ \mathrm{R}_s K^{(1+\frac{n}{100})} ug - - - 4.3$$

Where 'R_s' is the reduction factor due to increased stiffness. The reason behind incorporating new variable is that Khan and Ali [8] equations are for column structure, while the current study is about solid wall response which has more stiffness as compared to the column structure. And $\ddot{u}_g$, $\dot{u}_g$ and u_g are averaged ground displacement, velocity and acceleration, respectively. $\ddot{u}_t$, $\dot{u}_t$ and u_t are averaged IPBSW response displacement, velocity and acceleration, respectively. a, h, and n are wall base area, key height, and total number of blocks respectively. Their corresponding values are 62 mm x 62 mm x 6, 12 mm, 48, respectively. K is coefficient having dimensionless value of 0.45 and value of 'R_s' is 0.12. In Table 4.3, comparison of the experimental and empirical values of wall response in terms of acceleration, velocity and displacement of all applied frequencies is shown. It is observed that the experimental values have good relationship with empirical values. The percentage difference is upto 17%. It can be because of the complicated interlocking solid wall structure (in terms of its dynamic characteristics) and the simple empirical equation. However, this can help towards predicting the dynamic response of interlocking plastic-block solid wall. It may be noted that such structures are very easy to build.

TABLE 4.3: Percentage difference in experimental and empirical values for interlocking plastic-block solid wall

f	Parameter	Experimental Wall response	Experimental Base response	Empirical	% Difference
1.5	Acceleration	0.067	0.063	0.068	-1
	Velocity	37	35	38	-2
	Displacement	2.70	2.40	3.11	-15
2.0	Acceleration	0.079	0.076	0.082	-3
	Velocity	41	38	41	0
	Displacement	2.96	2.60	3.37	-14
2.5	Acceleration	0.098	0.095	0.102	-4
	Velocity	50	47	51	-1
	Displacement	3.10	2.80	3.63	-17
2.0	Acceleration	0.088	0.077	0.083	6
	Velocity	42	39	42	0
	Displacement	3.00	2.60	3.37	-12
2.25	Acceleration	0.092	0.087	0.094	-2
	Velocity	45	42	45	0
	Displacement	3.05	2.70	3.5	-15

4.5 Summary

This chapter includes the experimental evaluation of recorded data is. Seismosignal software is used to convert acceleration-time history data into velocity time history and displacement time history. Graphs of acceleration time history, velocity time history and displacement time histories are produced. In addition to that, base shear-displacement curves and energy absorption loops are also plotted. It is concluded that during the application of harmonic loading the unreinforced brick masonry solid wall collapsed, whereas interlocking plastic-block solid wall showed relative movement with respect to base. Similarly, interlocking plastic-block solid wall dissipated more energy than unreinforced brick masonry solid wall.

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. This chapter includes the development of relationship between experimental and empirical values to check the percentage difference.

5.2 Comparison of Current Study with Previous Studies

A comparison has been made of present study with the previous studies of past 7 years. Table 5.1 shows comparison of previous studies with current study. A significant resemblance of trends observed regarding energy dissipation in mortar-free structure. The tends show that previous studies are on complex shake table while the current study is done on the locally made low-cast 1-D shake table on interlocking plastic block solid wall.

Table 5.1: Comparison of current study with previous studies

Previous study	Current study
For analyzing the behavior of mortar-free interlocking structure the complex shake table was used [30].	For analyzing dynamic behavior of interlocking plastic block solid wall, simple 1D shake table is used.
Coconut fiber reinforced concrete block face more inertial forces due to its weight [6].	Due to the light weight of IPBSW, less inertia forces generated.
Energy is dissipated in mortar-free interlocking structure during dynamic loadings [17].	Interlocking plastic-block solid wall also dissipates energy during harmonic loading.
Pre-tensioning of structure with coconut fiber ropes dissipated less energy compared to that without rope [6].	Rubber band in the interlocking plastic-block solid wall helped in energy dissipation during the harmonic loading.
Little bit damage was observed in interlocking block during collapse of column [6].	Due to shake table limitation, no damage could be introduced in interlocking plastic- block structure.

By applying the empirical equations of current study on Sudheer [29] work, the percentage difference is 18%. Variable 'R_s' is increased to 0.13 because of the fact that Sudheer [29] work is based on mortar-free interlocking plastic-block wall with window opening while the current study is based on interlocking plastic-block solid wall.

5.3 Outcome of Study with Respect to Practical Requirement

This procedure and instrumentation are adopted because the simple locally made low cast shake table is good enough to give the fair results of harmonic loading. The applied harmonic loading is taken as the ground response on shake table, while the prototype walls response is studied with respect to it. The studied prototype interlocking plastic block solid wall shown the noteworthy increase in energy absorption as related to un-reinforced brick-masonry solid wall. So, it should be explored in detail for wall in connection with other structural elements. Furthermore, the effects of earthquake also be reduced by using the interlocking technique with the help of rubber band.

5.4 Summary

In this chapter the outcome of study with respect to experimental and empirical values is addressed. The reason behind the development of empirical equations is to check the percentage difference of values with respect to experimental values. Empirical values are dimensionally accurate as compare to experimental values. Experimental values are less accurate due to shake table limitations and human error. However, simple locally made low cost shake table is good enough to produce simple harmonic loading to check and analysis the effects of harmonic loading. Prototype interlocking plastic block solid wall is more efficient during the applying harmonic loading as compare to unreinforced brick masonry solid wall. Interlocking plastic block solid wall dissipates more energy than the unreinforced brick masonry solid wall. This is because of energy dissipation due to uplift and relative movement of block at interfaces.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

Earthquake resistant houses is the need of earthquake prone areas. Different earthquake resistant housing construction techniques are developed and being used in developing countries, but these techniques are very expensive. It is the need of this era to develop the less expensive techniques for the developing countries. In this study, to address this gap simple locally made 1D shake table is used to analyze the effects of harmonic loading. Prototype interlocking plastic block solid wall and unreinforced brick masonry solid wall was made to compare their responses against the harmonic loading. Prototypes of both walls are tested under different harmonic loading to determine the response and their dynamic characteristics.

- Unreinforced brick masonry solid wall collapsed during the applied loading, due to conventional issue of weak bond between bricks and mortar.
- Interlocking plastic-block solid wall dissipated total energy of 490 Nm, which was due to uplifts of block during applied harmonic loading at same frequency (2.25 Hz), at which unreinforced brick masonry solid wall collapsed.
- The energy dissipation capacity of the interlocking plastic-block solid wall is increased by using rubber band in wall.

- Empirical values for response of interlocking plastic-block solid wall are in good agreement with experimental values.

Due to the lighter weight of prototype interlocking plastic block solid wall, energy dissipation of IPBSW was more than the unreinforced brick masonry solid wall.

6.2 Future Work

Next step should be to study the dynamic behavior of interlocking plastic-block solid wall with diaphragm. Wind and fire effects should also be studied.

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