CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

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

by

Mehran Sudheer

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 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

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International Refereed Conference Articles

1. M. Sudheer and M. Ali, "Behavior of interlocking block structures under dynamic loading: A review," in *Proceedings of 2nd International Conference on Sustainable Development in Civil Engineering*, MUET, Jamshoro, Pakistan, December 05-07 2019, p. 231.
2. M. Sudheer and M. Ali, "Behavior of interlocking plastic-block wall with opening under harmonic loading using locally developed shake table," in *Proceedings of 11th International Civil Engineering Conference*, NED, Karachi, Pakistan, March 13-14 2020, p. 58.

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Abstract

Earthquake is one of the dangerous and life-threatening natural disaster. Earthquakes produce different damaging impacts to the zones they act on. This incorporates harm to structures and in worst scenarios the loss of human life. Specifically, masonry buildings in seismic zones of rural and urban regions throughout the world constitutes a hazard to human life. Because strong ground motions generated by earthquake badly damage the masonry structures. In developing countries, earthquake resistant and economical housing in the earthquake prone areas is the demand of time. Researchers have investigated many mortar-free interlocking techniques. But interlocking plastic-block structures are still not explored.

To start with, prototype interlocking plastic-blocks wall having opening in the form of window is considered for making the mortar-free structure. In this study, behavior of prototype interlocking plastic-block wall is examined against harmonic loading in comparison with prototype unreinforced masonry wall with opening using locally developed shake table. Interlocking plastic-block wall consists of forty-two plastic blocks having window opening in the middle and bottom blocks layer fixed with the shake table. Three accelerometers are used: one is attached at the shake table to record the base excitation and one each is attached at the top of both walls to record the respective walls response.

The behavior of walls in terms of acceleration-time, velocity-time and displacement-time histories is 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. As foreseen prototype interlocking plastic-block wall with opening depicted more resistant to earthquake loading in comparison with simple masonry prototype wall. This study can be used to further understand the in-depth behavior of interlocking plastic-block structures in future.

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Abbreviations

1 D	One Dimensional
3 D	Three Dimensional
IPWW	Interlocking Plastic-block Wall with Opening
MDOF	Multiple Degree of Freedom
MPa	Mega Pascal
RB	Rubber Band
SDOF	Single Degree of Freedom
UBMWW	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 (N)	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 one of the dangerous and life-threatening natural disaster. Earthquakes produce different damaging impacts to the zones they act on. This incorporates harm to structures and in worst scenarios the loss of human life. The impacts of the vibrations generated by earthquakes normally prompts the destruction of civil engineering structures such as buildings, bridges, and dams etc. Specifically, masonry buildings in seismic zones of rural and urban regions throughout the world constitutes a hazard to human life. Because strong ground motions generated by earthquake badly damage the masonry structures. The Kashmir earthquake of October, 2005 caused more than 86,000 causalities, more than 80,000 human injuries and an estimated total economic loss of $5.2 billion [1]. Sichuan earthquake in 2008, having magnitude of 8.0 caused 70,000 casualties, 216,000 structural failures, including 6890 school structures [2]. In Nepal earthquake of 2015, 0.15 million people were displaced due to severe structural damages in the affected region [3].

The primary reason behind the destruction of masonry buildings either partial or full, is usage of conventional unconfined masonry technique. In addition, because of design deficiencies the majority of the brick masonry buildings face severe damages during earthquakes. In 2010 Haiti earthquake, 80% to 90% of the masonry structures were declared partially or fully damaged by the Haiti government [4]. In the 2010 Darfield earthquake, damage to chimneys, collapse of parapet walls, out-of-plane failure, failure of facade wall, partial in-plane and mid height damages were observed in unreinforced masonry walls of the city [5]. In Gorkha earthquake, number of 0.5 million masonry buildings were entirely collapsed and other 0.2 million were partially damaged [6]. During the quakes 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 [7].

In developing countries, earthquake resistant and economical housing in the earthquake prone areas is the demand of time. Due to absence of earthquake resistant construction techniques, these countries grieve from huge human loss during strong ground motion. The literature indicates that, various construction techniques in the form of structural components for the construction of earthquake resistant masonry buildings have been adopted. For example, provision of vertical stiffeners and lintel beams in the masonry walls. Similarly, Ali et al. [8] developed mortar free interlocking block structure as a new construction technique for earthquake resistant houses and reported energy dissipation due to comparative movement at the interlocking block edges. Coconut fiber reinforced interlocking mortar-free block with post-tensioned coconut fiber ropes were tested against dynamic loading [9]. Khan [10] proposed usage of interlocking plastic blocks for seismic proof housing due to their less weight in combination with energy dissipation due to uplift of blocks.

For dynamic analysis, usage of shake table in the laboratory is very well known. Modern countries are using complex 3D shake tables, while developing countries are mostly using 1D shake table because of its low cost. Dynamic behavior of prototype structures has been investigated by many researchers by using the shake table. Available literature withholds various scale down techniques to convert a real-life structure to prototypes with simplified boundary conditions. Testing of prototype structures along with analytical validation has been done by many researchers. The percentage error gives the accuracy of analytical validation as well as predicts the probable actual scenario in case of real earthquake phenomena. Nadir et al. [11] performed 44 tests on single storey structure by using shake table to study the behavior of structure under harmonic loading and reported increase in base shear. Chen et al. [12] conducted experiments on a quarter scale frame structure using shake table and indicated that the proposed control strategy of prototype was useful in oppressing the drift between storeys and acceleration of the structures floors. Similarly, a lot of researches have been done in the past, conducting the small-scale tests to study the actual dynamic behavior in the laboratory.

To the best of author's knowledge, no study has been conducted to examine the performance of interlocking plastic-block wall having opening under harmonic loading using locally developed low-cost 1D shake table.

1.2 Research Motivation and Problem Statement

Earthquakes are destructive. Consistently, a large number of individuals in unindustrialized countries die due to building failures, and many thousands more are left destitute. It's not the tremor that slaughters individuals, it's the failure of structures that were inadequately planned and manufactured. But these problems have solutions. Such losses can be reduced if precise behavior of structures during earthquake is studied which can help in its proper design. In this regard, interlocking block structures is a potential solution for earthquake resistant housing. But the greater mass of blocks is a point of concern, because of the resulting greater inertial forces during the earthquake. Therefore, the mass of the interlocking blocks needs to be reduced. Thus, the problem statement is as follow.

"Mortar free interlocking block structures have emerged as a new construction technique for earthquake resistant housing. Literature states that these blocks have the ability to dissipate the energy during earthquake loading. However, the greater mass of these blocks is still a point of concern. Lighter the mass of block, lower

the inertial forces generated during earthquake. For this, light weight interlocking plastic-block is one solution along with fire-resistant paint. For economic and environmental aspects, plastic waste can be recycled for this purposes (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 wall with opening 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 wall with opening in laboratory and field.

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

1.4 Scope of Work and Study Limitation

Scope of this study includes construction of two prototype walls (interlocking plastic block wall and unreinforced masonry wall). Both walls are having opening in the form of window. These walls are fixed on the shake table with the help of nut bolt to provide fixed base. Loading frequency on both walls is employed. Behavior of both walls in terms of acceleration-time, velocity-time, and displacement-time histories are recorded. With the help of data extracted through dynamic testing, frequency and damping are determined. In the end, empirical equations to predict the dynamic behavior of prototype interlocking plastic-block wall are established.

Study limitations include the usage of simple 1D shake table, use of three accelerometers only (one at the base of shake table and one each at the top both walls) to record dynamic excitation, study of only out of plane behavior of both walls, and application of three loading frequencies. Wind and fire effects are out of scope of this research.

1.5 Methodology

Firstly, both walls (interlocking plastic block wall and unreinforced masonry wall) are constructed and mounted on shake table. Harmonic loading is applied. This purpose of testing is to study the response of walls at incremental frequencies. To begin with, three randomly selected frequencies are applied, keeping in mind the dynamic loading capacity of the shake table. Three accelerometers are used: one at shake table to record ground motion and one each at wall top of both walls to record the walls response. Accelerometers are connected to computer system and data from accelerometers to computer is transferred using two types of software such as arduino and MATLAB.

Response of both walls in out-of-plane direction in terms of acceleration-time is recorded in the raw form. MATLAB filters are used to remove the noise. Then velocity-time and displacement-time histories are obtained using seismosignal software. With the help of displacement vs time-history and acceleration vs time-history of top accelerometer data, base shear (Q) is calculated. The averaged energy absorption in one cycle as well as total energy absorbed is also calculated. And empirical equations for interlocking plastic-block wall with opening are developed for predicting the wall response.

1.6 Thesis Outline

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

Chapter 1 consists of introduction section. It includes background, research motivation, problem statement, overall objective, specific aims, scope of work, study limitations, methodology adopted to conduct the study, and thesis outline.

Chapter 2 contains the literature review section. It consists of background, damages of conventional masonry structures during earthquake, new approach for earthquake-resistant structures, effect of stiffeners on masonry construction, dynamic performance of prototype structures in lab, and summary.

Chapter 3 consists of experimental program. It contains background, technique to construct interlocking plastic block wall with opening and unreinforced masonry wall with opening, test setup, snap back test with instrumentation, application of harmonic loadings using shake table, analyzed parameters, development of empirical equations, and summary.

Chapter 4 consists of experimental evaluation. It contains background, results of snap back test, response of walls against harmonic loadings, calculation of base shear, damping ratio and energy absorption, and summary.

Chapter 5 comprise of discussion. It contains background, relationship of empirical equations, 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.

Chapter 2

Literature Review

2.1 Background

Strong ground motions generated by earthquake badly damage the masonry structures. Earthquakes produce different damaging impacts to the zones they act on. This incorporates harm to structures and in worst scenarios the loss of human life. Specifically, masonry buildings in seismic zones of rural and urban regions throughout the world constitutes a hazard to human life. Because strong ground motions generated by earthquake badly damage the masonry structures. Ground acceleration is transferred from ground to structure foundation which causes shearing of masonry walls due to inertia. The literature indicates that, various construction techniques in the form of structural components for the construction of earthquake resistant masonry buildings have been adopted. Interlocking block construction is one of these new earthquake resistant techniques. But the greater inertial forces due to greater mass of these conventional construction blocks is an issue. This chapter includes the literature review about damages of conventional masonry structures during earthquake, new approach for earthquake-resistant structures, effect of stiffeners on masonry construction and dynamic performance of prototype structures in lab.

2.2 Damages of Conventional Masonry Structures During Earthquake

Destruction of conventional masonry buildings in the form of various failures have been reported by many researches. Sharma et al [13] conducted reconnaissance study after the April 25, 2015, Gorkha earthquake in Nepal. Approximately 0.8 million partial or full collapsed buildings were reported. A severe seismic event followed by major aftershock struck the whole district having hilly area, which resulted in the destruction of many brick masonry buildings. Many people were died, injured and remained homeless till the rescued operations done by the governing authorities. Apart from this, country faced a huge economic loss from this catastrophe. Various brick masonry failures in the form of vertical cracks near the corner, crosswise cracking initiated from edges of the openings, out of plane failure, gable wall failure, and separation of wall vertically and opening in short wall were reported as shown in the Figure 2.1. The major reasons behind these brick masonry failures were reported as poor construction practices, poor materials usage, non-designed building walls, gable walls without confinement, and cracking initiated from edges of the openings. For retrofitting of partially damaged masonry buildings, reinforcement or provision of verticals and horizontal bands was suggested. It was also recommended to enforce code compliance and to involve experienced engineers in all design phases of the building.

Jagadish et al. [14] reported that traditional masonry structures suffered considerable damage during the Bhuj earthquake of January 2001. Most of the masonry structures were reported had zero earthquake resistant features, due to which these structures faced severe damages. Most common found failures in the masonry structures were out-of-plane collapse, cracks below bands, out-of-plane failure of wall leading to collapse of lintel band, collapse of wall between openings and rigid box-like behavior above lintel band. It was highlighted that mud mortar or lime mortar usage resulting in weak bond strength was the primary cause of these failures. In case where cement mortar was used in masonry, bond strength was not sufficient to resist the earthquake vibrations. The most concerned issue was

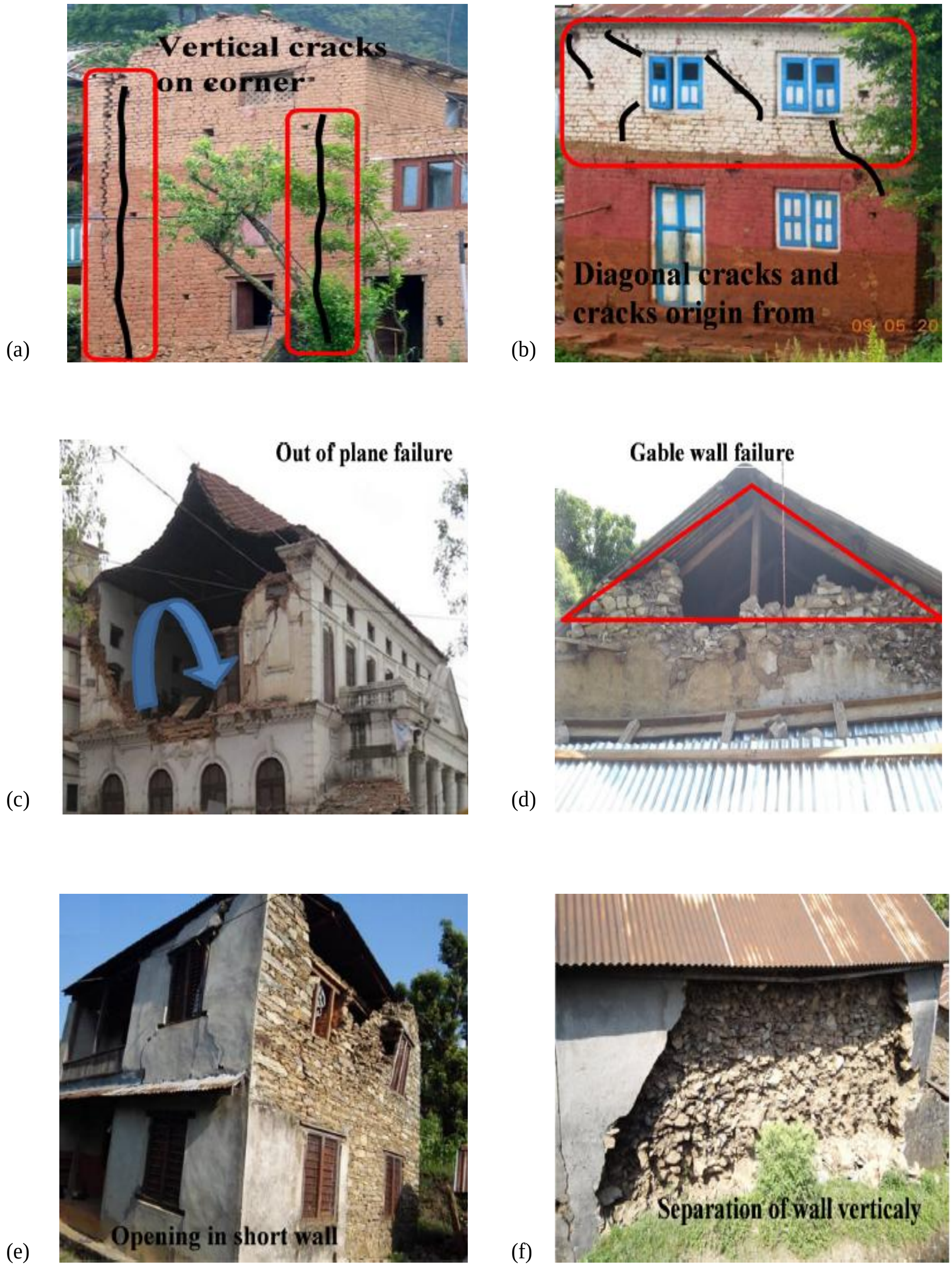


FIGURE 2.1: Conventional masonry failures; (a) Vertical cracks near the corner, (b) Crosswise cracking initiated from edges of the openings, (c) Out of plane failure, (d) Gable wall failure, (e) Opening in short wall, (f) Separation of wall vertically [13].

the failure of confined brick masonry in the form of cracks below lintel band and collapse of lintel band. Because properly designed confined brick masonry having horizontal/verticals bands with corner reinforcement properly resists the earthquake shaking. It was found during the survey that lintel bands were not properly designed and were having deficient longitudinal reinforcement. The study suggested that, though the horizontal bands lessens the in-plane shear and verticals cracks but these may not be helpful in case of out-of-plane flexure failure. Especially flexure cracks which propagates horizontally and results in out-of-plane failure of the wall.

Fiorentino et al. [15] stated that the consequence of the two seismic events of August 24th 2016 on the district of Amatrice was exceptionally disastrous. There were 298 fatalities, 386 harmed, around 5000 homeless people, and the ancient hub of the town suffered an extraordinary destruction. 260 recorded strong ground motions were analyzed, plotted in the shake map and later on compared with the large-scale damage surveys conducted in the vicinity areas. Based on an assessment study made in September 2016, a guide of the failure patterns of the structures in the ancient hub of the town was explained as per European Macroseismic Scale (EMS-98). The harm level was found extremely high with over 60% of the investigated structures demonstrating minor or complete failure. The high degree of destruction was fundamentally brought about by the high ineffectiveness of the masonry structures resulted due to poor quality material usage, absence of connections between the walls and improper connection between walls and floors. The study suggested that the importance of good engineering evaluations in the design involvements on existing buildings is very much important, which cannot just be done in light of standard methods. Perhaps, it requires a point by point assessment of local and global behavior of the building along with material testing.

Yon et al. [16] studied failures of masonry structures during eleven high intensity earthquakes caused by Anatolian fault line in Eastern Turkey. They have also presented rupture reasons of fault lines, updated data on active fault regions and seismic maps for future studies. They have reported corner damages, in plane wall and out of plane wall damages as major cause of masonry failure during these earthquakes. Similarly, traditional masonry structures suffered considerable damage during the Gorkha earthquake of 2015. Figure 2.2 highlights horizontal and vertical cracks initiated from openings caused severe damages to conventional masonry buildings [17].

(a)

(b)

Figure 2.2: Masonry building failures; (a) Horizontal cracks between openings, (b) Vertical cracks between openings [17]

Su et al. [18] studied damages of masonry structures during 2008 Wenchuan earthquake. A severe seismic event followed by major aftershock struck the whole district, which resulted in the destruction of many brick masonry buildings. Many people were died, injured and remained homeless till the rescued operations done by the governing authorities. Apart from this, country faced a huge economic loss from this catastrophe. Various brick masonry failures in the form of cross cracks between openings, diagonal cracks initiated from openings, out of plane failure etc were reported as shown in the Figure 2.3. The major reasons behind these brick masonry failures were reported as poor construction practices, poor materials usage, and non-designed building walls.

FIGURE 2.3: Masonry wall failures; (a) Cross cracks between openings, (b) Diagonal cracks initiated from openings [18]

2.3 New Approach for Earthquake-resistant Structures

Ali [9] examined influence of post-tensioned coconut-fiber ropes in governing uplift of interlocking mortar free block structure during earthquake loading. It was reported that proposed interlocking block shown in Figure 2.4 is capable of regaining its original position afterwards the induced ground excitation due to provision of inclined key shape in blocks. To imitate single degree freedom system, mass of 200 kg was lumped at columns top made up of interlocking blocks. The dynamic behavior of interlocking blocks column was recorded in terms of tempted accelerations, block uplift, top relative displacement and rope tension. It was found that tempted acceleration was amplified up to mid-height of the column and afterwards reduced a little bit at the column top. The drifts of uplift of blocks and tension of rope were found fairly alike. Experimental results were used to develop the empirical relation in the form of function of peak ground acceleration. 35% difference was observed in predicting the actual seismic response of the structure, which may comply due to the complexity of the interlocking block column. Results of the study seemed promising in order to have economical earthquake resistant housing construction.

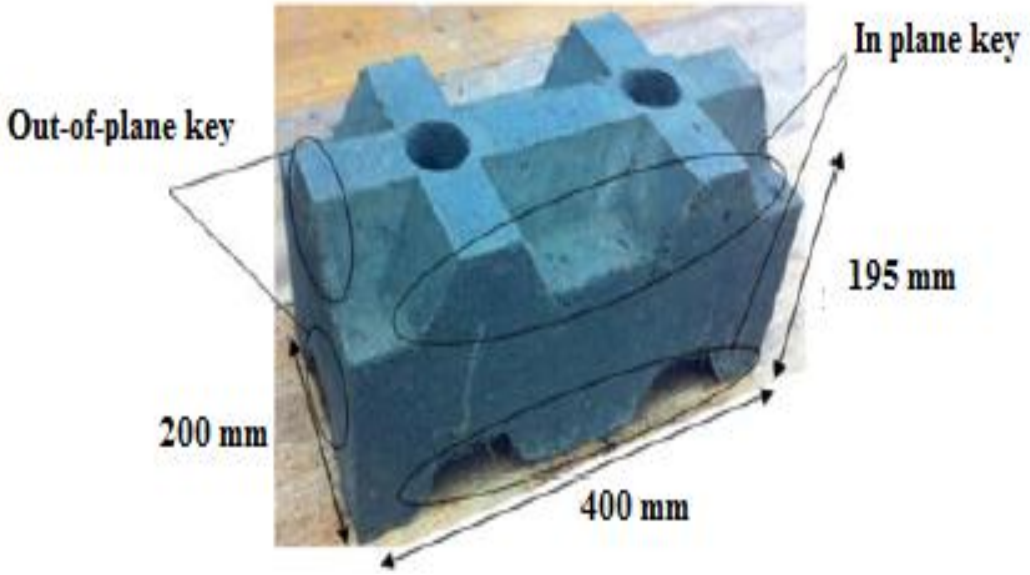


Figure 2.4: Coconut Fibre Reinforced Concrete (CFRC) interlocking block [9]

Liu et al. [19] examined the cyclic behavior of non-interlocking mortar less brick and interlocking mortar less brick shown in Figure 2.5. The properties of interlocking shapes, loading compression stress levels and loading cycles were considered during the investigation of cyclic behavior. With the help of hysteresis loop method, a mechanical model was established. Shear failure modes of all of the inspected joints were described by using Mohr-Coulomb failure method. With an upsurge in the loading cycle, there was a reduction in the friction coefficients of all of the joints. With the reduction in the smoothness of the interlocking surface, there was an increase in the degradation rate of the friction coefficients.

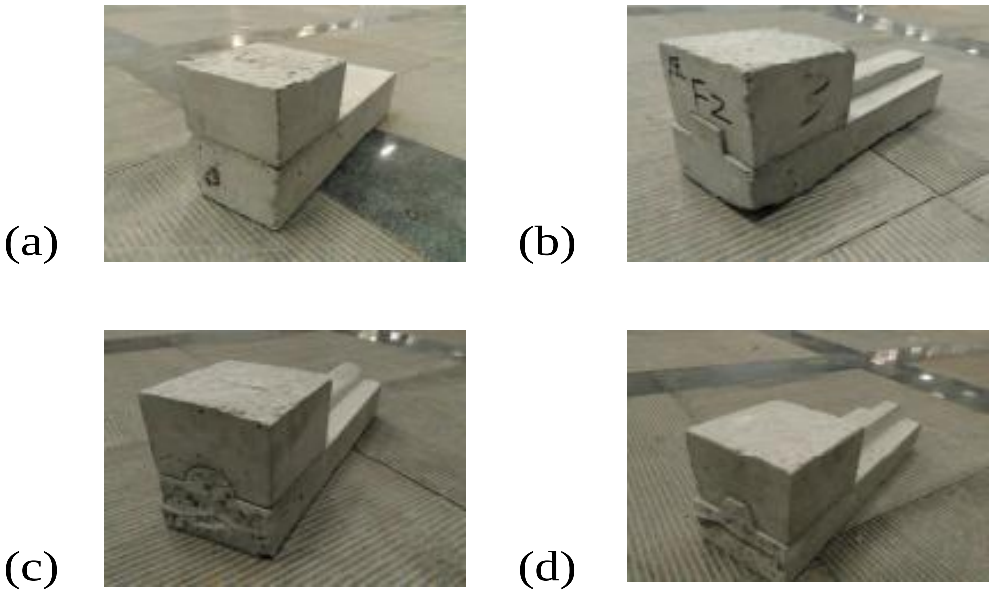


Figure 2.5: Interlocking blocks with non/various interlocking patterns; (a) non-interlocking, (b) rectangular interlocking, (c) circular interlocking, (d) trapezoidal interlocking [19].

Many researchers have proposed different shapes of interlocking compressed earth block as shown in the Figure 2.6. These blocks provide resistance to the movement both in horizontal and transverse direction to the wall surface. Expect, hydraform interlocking units provide straight movement and restricts crosswise one. Although these interlocking blocks have different forms, shapes and sizes but their interlocking mechanism is quite similar, consisting of protrusions and depressions also known as male and female features. Because of the complex arrangement of these blocks, the soil characteristics and curing conditions caused difficulty in keeping the precise shape and size of these interlocking blocks. A probable procedure needs specific apparatus and excellent mud choice, mix design and good curative conditions. But usage of such apparatus is uneconomical and not available in developing countries. The study suggested another useful solution in the form of simplifying the interlocking block configuration keeping control of the geometry during the manufacturing phase. The governing factor to make straight and stable block wall is effective locking of these blocks which can resist the governing forces [20].

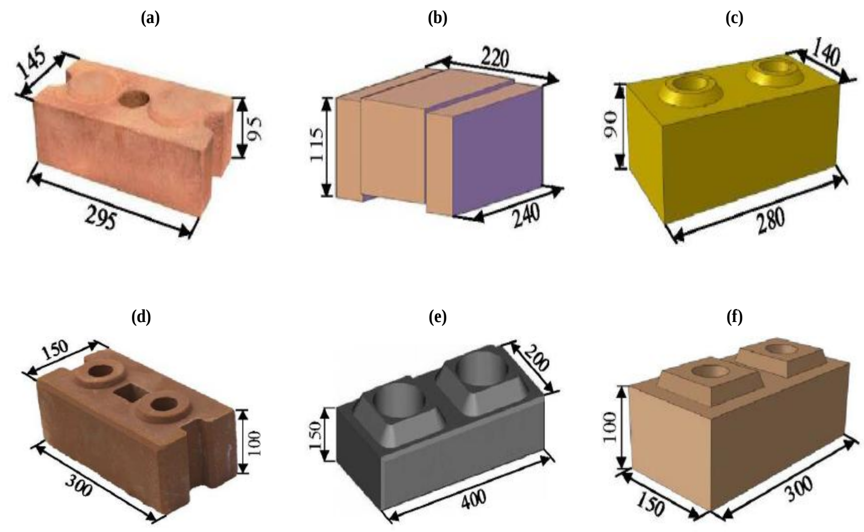


Figure 2.6: Various interlocking earth blocks; (a) Auram interlocking block [21], (b) Hydraform interlocking block [22], (c) HiLoTec interlocking block [23], (d) Thai Rhino interlocking block [24], (e) Hollow interlocking block [25], (f) Tanzanian interlocking block [26].

Table 2.1: Summarized details of various interlocking compressed earth blocks proposed in previous researches

Reference	Interlocking block shape	Surface area of holes %	Cement content	Main findings
Maini et al. [21]	Auram block	9.2	5	Dry compression, shear and bending compressive strength; absorption of water.
Uzoegbo et al. [22]	Hydraform block	0	5-20	Compressive strength of the masonry units; compressive strength of the dry-stack walls.
Sturm et al. [23]	HiLoTec block	10	9	Compressive and flexural strength of the units; compressive and shear behavior of masonry prisms.
Qu et al. [24]	Thai Rhino block	12.7	6.2	Stressstrain curves of prisms; seismic performance of flexure-dominated interlocking compressed earth block walls; the structural performance of interlocking compressed earth block walls under cyclic in-plane loading.
Fay et al. [25]	Hollow block	28.2	9	Resistance of compression, water absorption, and sizing of interlocking compressed earth blocks.
Bland et al. [26]	Tanzanian block	8.72	7.1	Block irregularity and implication for wall quality; the relationship between alignment and block geometric imperfection; stiffness of the interlocking block columns.

Shakir et al. [27] constructed innovative eco-friendly interlocking block shown in Figure 2.7(a) made from locally available waste materials like palm oil clinker, palm oil fuel ash, and quarry dust for construction of earthquake resistant houses. Jeslin et al. [28] compared conventional brick and interlocking block shown in Figure 2.7(b) on the basis of strength aspects. The study reported 15%-30% increase in mechanical properties for the case interlocking block. Jan et al. [29] proposed interlocking masonry block construction with steel reinforcement for sustainable housing in Thailand shown in Figure 2.7(c).

(a)

(b)

(c)

FIGURE 2.7: Various interlocking patterns/techniques for blocks; (a) eco-friendly interlocking block including holes and shapes [27], (b) sliding interlocking block [28], (c) interlocking block including holes to provide steel reinforcement [29]

Mortar less interlocking block construction has been adopted partially in different countries but with limited research background. The primary problem associated with these blocks is their production, which needs sophisticated machineries. But the salient features of the interlocking masonry are very well acknowledged in the literature. And very limited simplified and economical production techniques are proposed by the researchers. The construction industries of developed countries are acknowledging the benefits of these interlocking blocks for masonry construction. This new interlocking technique is less laborious and does not require mortar pasting activity, ultimately speeding up the construction time. In these countries, the available interlocking blocks in industry differ in shape, size, and material usage. These blocks have been categorized as ones, which confirm vertical and horizontal or only partial vertical interlocking. In some cases, to improve the lateral resistance, plain and reinforced grouting in combination with surface bonding is also in practice in masonry construction works. Previous researches have strongly recommended interlocking block masonry scheme as a possible alternate to mortar masonry, since it speeds up the construction procedure and likewise shows improved or similar structural behavior. But the point of concern about the usage of these earth compressed or concrete blocks is their high mass, causing greater inertia forces.

2.4 Effect of Stiffeners on Masonry Construction

Brick masonry is one of the oldest and extensively adopted construction technique. The provision of brick masonry structural members in ancient buildings is also abundant. Throughout the world, unreinforced brick masonry buildings are continuous threat to mankind, due to their high vulnerability to seismicity [30]. The economic and human losses in the past earthquakes was mostly due to these vulnerable structures. These structures were constructed with conventional materials and by considering the gravity loading only [31]. These materials in majority of the cases are bricks, stones and wood, which are not earthquake-resistant [32]. In October 2005 earthquake of Pakistan, most of the conventional unreinforced buildings including concrete block brickwork, conventional brickwork and stone masonry were fully or partially damaged [33]. Similarly, separation between the roof diaphragms and the masonry walls (in the out-of-plane direction) and damage to masonry piers at upper levels of unreinforced masonry buildings were observed in the 2010 Darfield (Christchurch, Nz) Earthquake [34].

A French structural engineer and contractor, Paul Cottancin, introduced stiffeners to reinforce the masonry buildings [35]. Seismic performance of masonry buildings is studied in laboratory by many researchers in the past. Immense non-linear behavior of unreinforced masonry was observed in the laboratory testing under time-scaled Nahnni earthquake 1985 [36]. On contrary, reinforced brick masonry in the form of concrete stiffeners usage enhanced strength and stiffness of the masonry buildings [37]. These phenomena have been confirmed not only through lab testing but also in the case of real earthquake loading. The failure modes during the laboratory testing changed from diagonal tension or shear slip into a combination of diagonal tension and toe-crushing. Incorporation of reinforcing elements in mortar joints prevented the structure from cracking [38]. Confined masonry walls with horizontal stiffeners performed well compared to non-confined walls when subjected to lateral loading in laboratory. Masonry walls with vertical stiffeners in terms of steel ties had significant enhancement in seismic capacity in comparison with unreinforced walls [39].

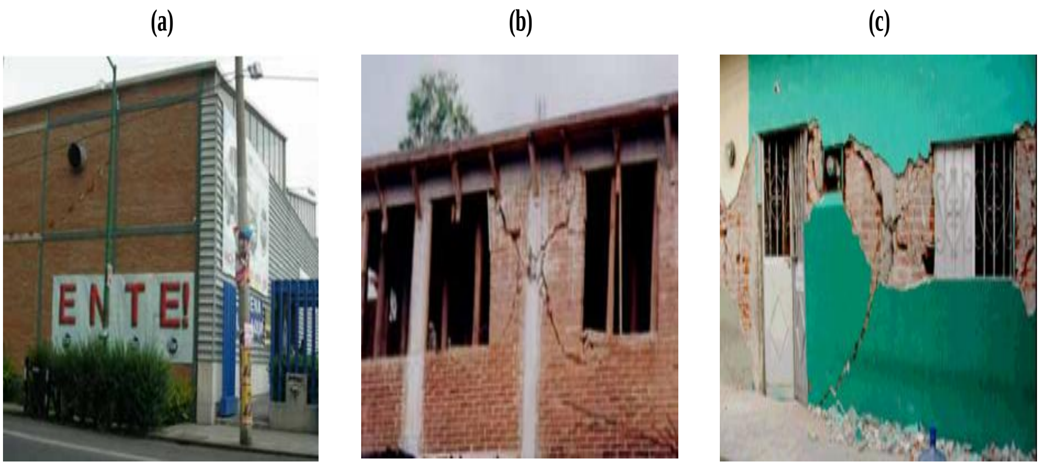


Figure 2.8: Confined masonry construction in Mexico (a) an engineered structure in the industrial zone (b) minor damage of confined masonry (c) major damage of confined masonry due to inadequate confining elements and their arrangement [40].

Mexico country has a long record of using confined masonry technique in their housing construction. It is the most common construction practice in the country, and is extensively used in the country. Confined masonry is usually practiced in the form of engineered and non-engineered construction all over the country. Most of the undersigned construction found in the rural and sub urban areas, whereas engineered constructed buildings found in the industrial areas and developed housing schemes as shown in the Figure 2.5 (a). During the 2003 earthquake of Tecomn having magnitude 7.6, designed masonry structures performed significantly well than un-designed brick masonry buildings; majority large number of designed masonry buildings were unharmed or grieved only slight damage as shown in Figure 2.5 (b). Some cases of catastrophe were detected when the quantity and arrangement of design elements were insufficient as shown in Figure 2.5 (c) [40].

(a) (b) (c)

FIGURE 2.9: Behavior of confined masonry during the 2001 El Salvador earthquakes, (a) confined masonry structures in city of Santa Cruz Analquito survived, whereas nearby conventional structures was destroyed, (b) a confined masonry school building survived the earthquake without damage (c) soft story construction (confined masonry construction at the ground floor level) [42].

Similarly, confined masonry buildings performed exceptionally well in the El Salvador earthquakes of 2001 [41]. Confined masonry structures are very common in El Salvador. Almost 60% of the structures in El Salvador were constructed from mixto. Mixto is a type of confined masonry having tie-beams and small tie-column spacing. Most of these buildings were undamaged, only limited ones faced few repairable damages and very few were found unrepairable. There were a few cases of wall shear failure, as well as out-of-plane wall failures, where the wall toppled outwards in spite of the confining elements. The study concluded that maximum of the failed structures during the tremors were of conventional masonry construction [42].

2.5 Dynamic Performance of Prototype Structures in Lab

Significant research has been conducted in the past to study the behavior of real-life structures with the help of scaled down prototypes in the laboratory. 3-D shake table having six degree of freedom is used in developed countries to investigate the dynamic response of structure, in order to generate real earthquake data. On the other hand, developing countries lack in affording such sophisticated and expensive complex 3-D shake table. But these countries are using simple 1-D to understand dynamic behavior of prototype-structures in laboratory. The purpose behind development of prototypes structures in laboratory is to conduct such studies. Many researchers have conducted dynamic testing of small- and large-scale prototypes in the laboratory using shake table. For small scale testing, simplifies boundary conditions had been adopted in these researches. These studies validate the conduction of prototype testing in the lab using shake table. Table 2.2 summarized details of dynamic testing of various small scale prototype structures with simplified boundary conditions. For determination of seismic behavior of these prototypes under dynamic loading, time history analysis is a useful technique [43]. Elvin et al. [44] studied the behavior of full-scale structure under harmonic loading. The dynamic analysis of a prototype structure was conducted in laboratory. And it was reported that structural damages due to earthquake can be reduced, if structure is properly designed to resist earthquake loading [45].

Table 2.2: Summarized details of dynamic testing of various prototype structures using shake table in previous researches

Reference	Prototype structure	Main findings
Elvin et al. [46]	Dry-stack masonry wall	The earthquake and harmonic base motion energies were dissipated through inter-brick friction, and in some cases by bricks cracking and crushing. The fact that the bricks were dry-stacked allowed them to move and hence dissipate energy.
Kallioras et al. [47]	Unreinforced clay-masonry building	The study provided a unique data set that captures at full scale the in-plane and out-of-plane behavior of unreinforced masonry walls, and the influence of flexible diaphragms on the dynamic global response of a complete building under dynamic loading.
Saifee et al. [48]	Interlocking mortar less wall	Interlocking mortar less wall was subjected to out of plane loading. The behavior of dry joint openings the wall was judged. The dry joint opening mechanism around mid-height of wall was reported to be dominant.
Velazquez-Dimas et al. [49]	Unreinforced Masonry wall with Glass Fibre Composite strips	URM wall strengthened with the help of glass fibre strips was tested and results was compared with the developed analytical model. The study suggested to limit maximum service load to a corresponding strain of 0.004.
Ali [9]	Mortar-free Interlocking block column with post tensioned Coconut-fibre ropes	In this study, coconut fiber reinforced interlocking mortar-free block with post-tensioned coconut fiber ropes were tested against dynamic loading. Energy dissipation because of the relative movement at the block interfaces was reported.

Antonellis et al. [50]	Bridge columns supported on rocking shallow foundations	The test protocols included up to six historical ground motions and resulted in peak drift ratios up to 13.8%. For peak drift ratios up to 6.9%, the rocking foundations performed very well, with residual drift ratios between 0.5 and 0.9%.
Kohail et al. [51]	Full-scale DSIM shear walls	An experimental study conducted to evaluate the in-plane behavior of full-scale DSIM shear walls under cyclic in-plane loading and to explore the effectiveness of using post-tensioning (PT) instead of grout and reinforcement.
Xie et al. [52]	Historical masonry towers	The dynamic characterization and the seismic performances of historical masonry towers, a 1/8-scale masonry model representative of an ancient Chinese tower was studied by shaking table tests.
Keivan et al. [53]	Steel dampers for inter story drift and displacement	In this study, steel dampers for inter story drift and displacement were tested against dynamic loading. Energy dissipation because of the relative movement at the dampers interfaces was reported.

2.6 Summary

Conventional masonry structures are prone to earthquake. Modern countries have adopted the practice of confined masonry in their construction techniques. But these are also prone to earthquake vibration up to some extent. Researchers are focusing on interlocking mortar free blocks as a replacement of brick masonry. Available literature has featured a lot of sizes, shapes and interlocking techniques for these blocks. In the laboratory, examining the dynamic behavior of interlocking block prototype structures using the shake table gives output at a higher accuracy level. The behavior of these interlocking block prototypes against dynamic loading can be predicted better by conducting small scale testing. Their analytical validation can be used to develop empirical relations in order to perform simplified testing with the identification of error percentages. A lot of researches support and validate the results obtain from the testing of these prototype structures. Most of the researchers till date have focused on concrete block or masonry block studies. But usage of any other lightweight material can play a vital role in reducing the inertial forces. In this research, usage of interlocking plastic-blocks for prototype wall is such an example of lightweight materials.

Chapter 3

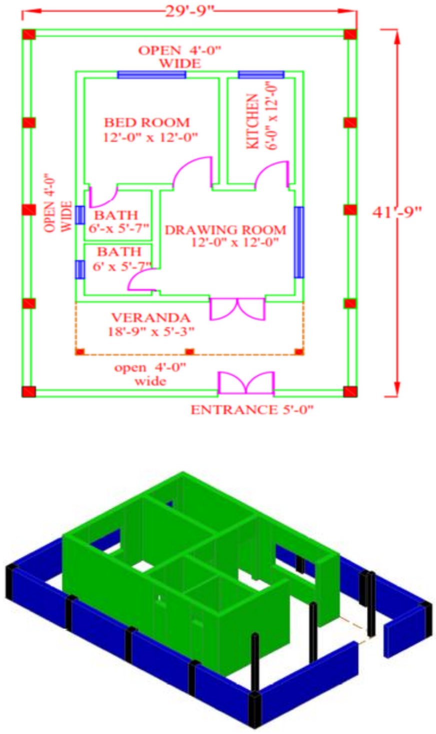
Experimental Program

3.1 Background

For earthquake-resistant design, it is very important to predict the response of structure during earthquake loading. For this purpose, dynamic testing of prototype structures in laboratories is a common practice all-around the world. This chapter highlights technique to construct interlocking plastic block wall with opening and unreinforced masonry wall with opening, test setup, snap back test with instrumentation, application of harmonic loadings using shake table, analyzed parameters, development of empirical equations etc.

3.2 Continuation of Research Program

Khan [10] proposed the interlocking plastic-block for earthquake resistant housing (plan and 3D view of proposed house is shown in Figure 3.1) and prototype testing, due to its lighter weight and resulting lesser inertia forces. The role of materials weight and resulting inertia forces is very crucial in earthquake resistant structures. Inertia force is generally taken as a systems ability to resist changes caused by some external force (acceleration). The concept is based on Newton's Laws of Motion, including the Law of Inertia and the Action-Reaction Law. In response to such external force, heavy systems (materials) responds more due to their greater weight in comparison with lighter systems (materials), thus causing greater inertia forces.



(a)

(b)

FIGURE 3.1: Proposed interlocking plastic-block house: a) plan and b) 3D view [10]

For construction of earthquake resistant housing, the proposed interlocking plastic blocks have base dimension of 150 mm x150 mm and having 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 53 mm including the 12 mm height of interlocking key as shown in Figure 3.2(b). Current research work is continuation of Khan [10] research work.

In this study, prototype interlocking plastic block wall with opening 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 [51-53]. Outcome of such studies

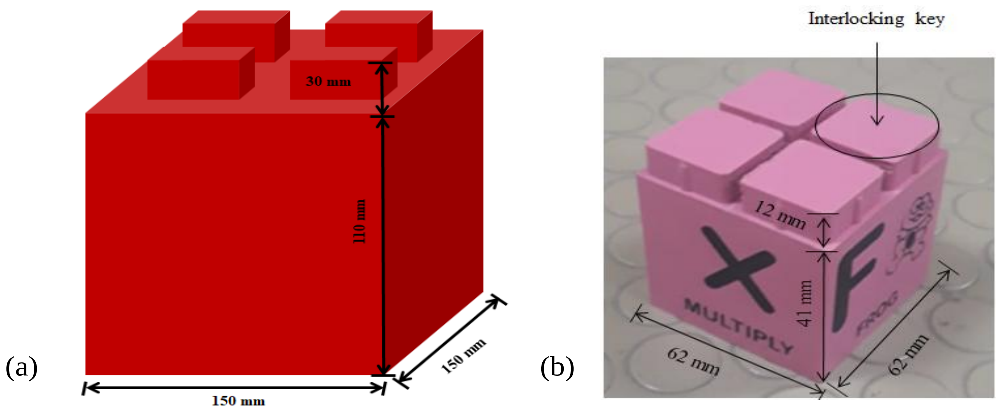
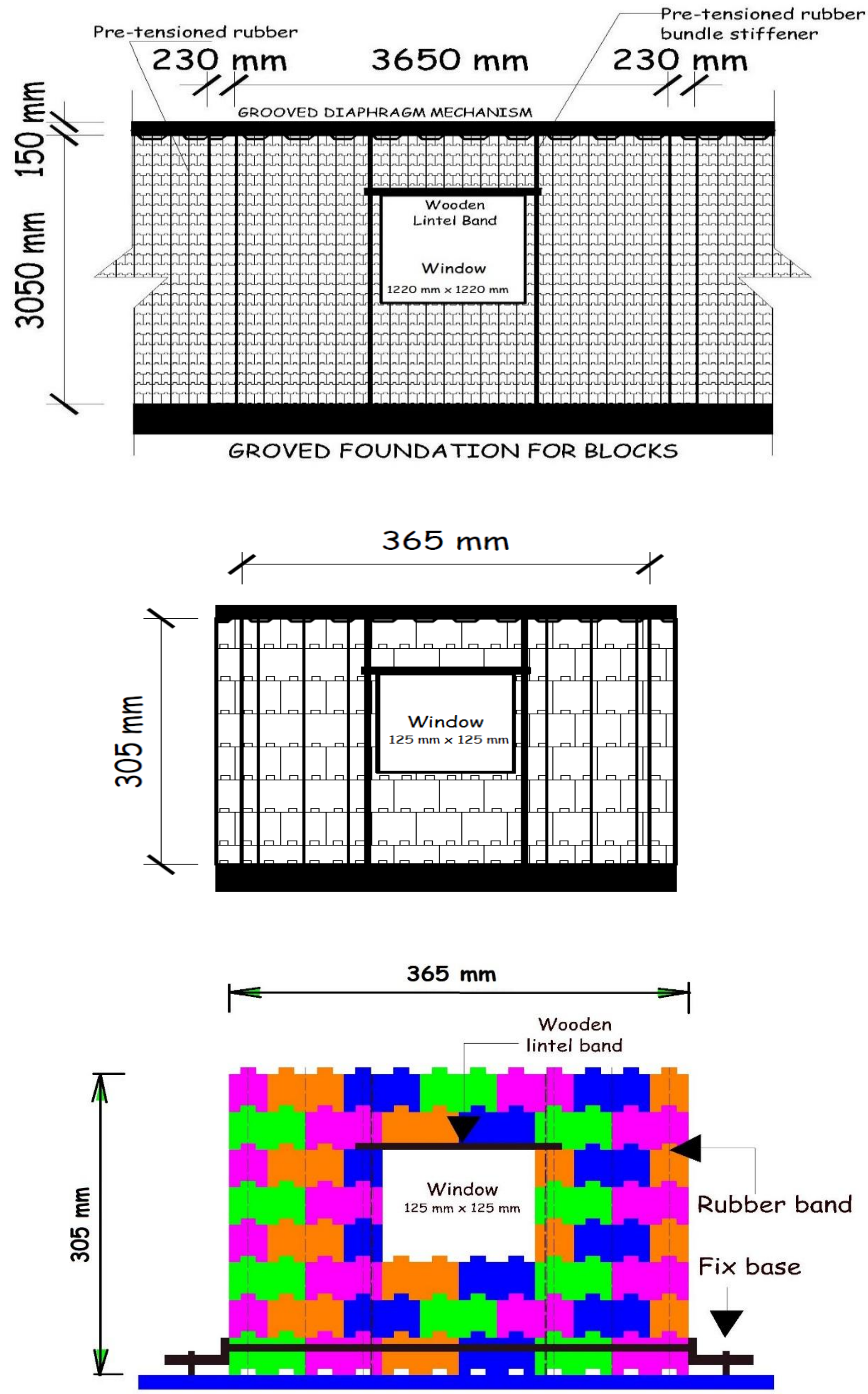


FIGURE 3.2: Proposed interlocking plastic-block: a) for earthquake resistant construction, and b) for prototype construction [10]

help to understand behavior of full scale structures. The primary purpose of current research is to study the dynamic behavior of structural walls having opening. For this, structural time period is an important parameter which depends on the structure height (UBC-97). Thats why, scale down technique is mainly applied on elevation dimensions of structural walls. It may be noted that the dimensions of units used in both prototypes (i.e., scaled down wall samples having window opening) are slightly different. However, the elevation dimensions in both prototypes are approximately the same as shown in Figure 3.5.

Figure 3.3(a) shows schematic diagram of proposed real wall with opening 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 wall with opening, using 1/10 scale factor. Figure 3.3(c) shows schematic diagram of prototype interlocking plastic block wall with opening with simplified boundary conditions.

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



(a) **(b)** **(c)**

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

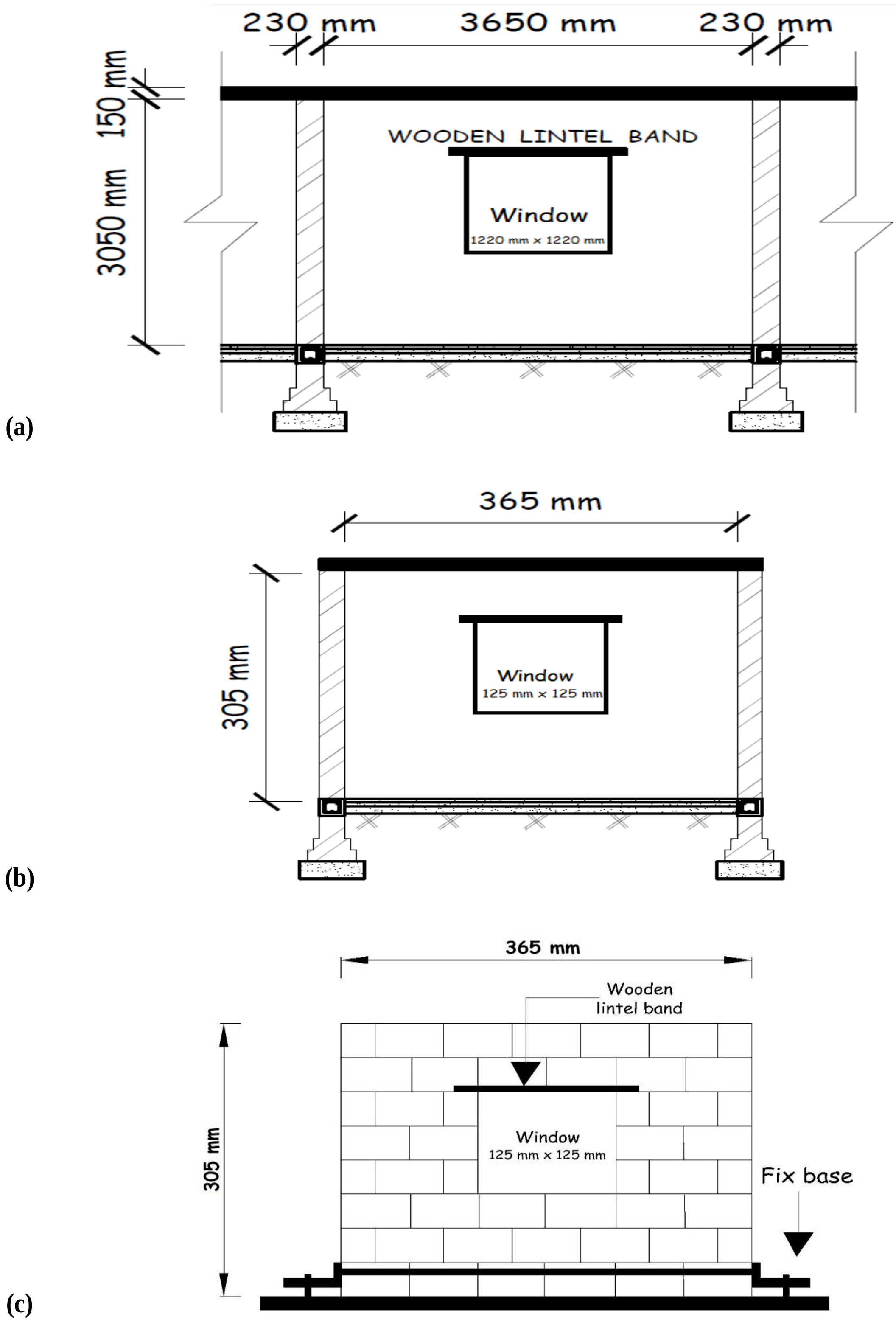


Figure 3.4: Schematic diagram of unreinforced brick masonry wall with opening a) proposed real wall b) scaled downed prototype wall c) prototype wall with simplified boundary conditions

3.3 Construction of Prototype Walls

Prototype interlocking plastic block wall with opening consists of forty two interlocking plastic blocks (n=42, making a total height (H) of 330 mm as shown in Figure 3.5(a). It is having an opening in form of window in the middle. The dimensions of opening are 125 mm x 125 mm. Wooden lintel band is provided above the opening for support mechanism. In addition, 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 base plates and nut bolts is provided. No mass is provided at the wall top. However, the total mass of wall (M) is 1.295 Kg. Unreinforced brick masonry wall with opening was constructed using small bricks. It was water cured for almost 10 days. It has a total height of 330 mm as shown in Figure 3.5(b). It is having an opening in form of window in the middle. The dimensions of opening are 125 mm x 125 mm. Wooden lintel band is provided above the opening for support mechanism. Fixed base with the help base plates and nut bolts is provided. No mass is provided at the wall top.

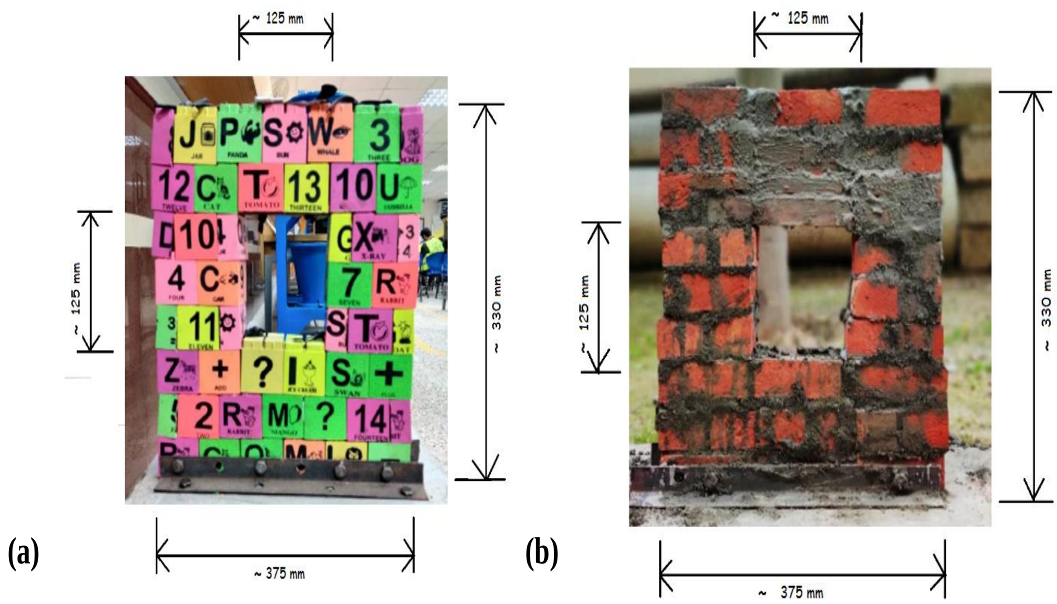


FIGURE 3.5: Prototype a) interlocking plastic block wall with opening, b) unreinforced brick masonry wall with opening

3.4 Test Setup

3.4.1 Snap Back Test and Instrumentation:

Figure 3.6 shows the test setup of snap-back test. A wire having length of 400 mm is attached at the top of interlocking plastic-block wall having opening. To record the response of the wall, an accelerometer is attached at the top of the wall. Free vibration of the interlocking plastic-block wall having opening is observed by freeing the attached wire. Response of the wall is recorded in terms of acceleration-time history using the accelerometer data. Log decrement method is used to calculate the damping ratio (ξ) and fundamental frequency (fn) of the interlocking plastic-block wall with opening.

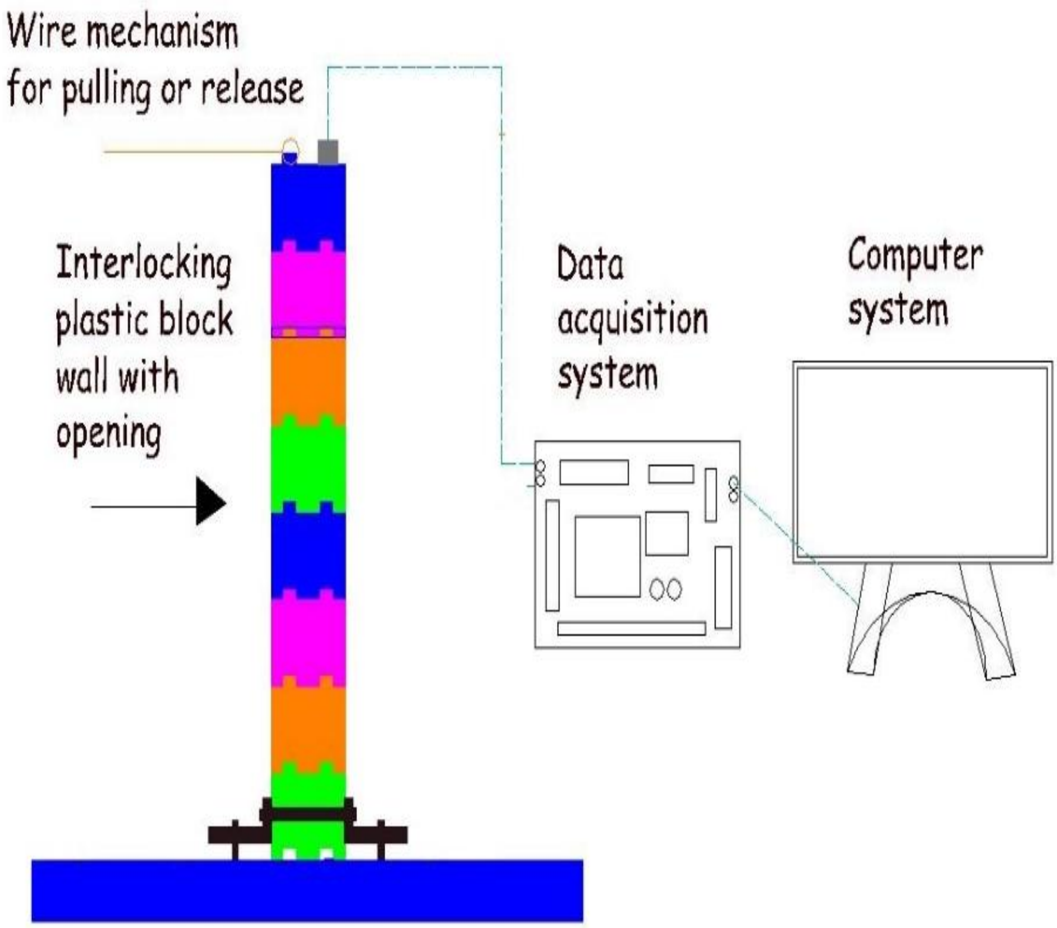
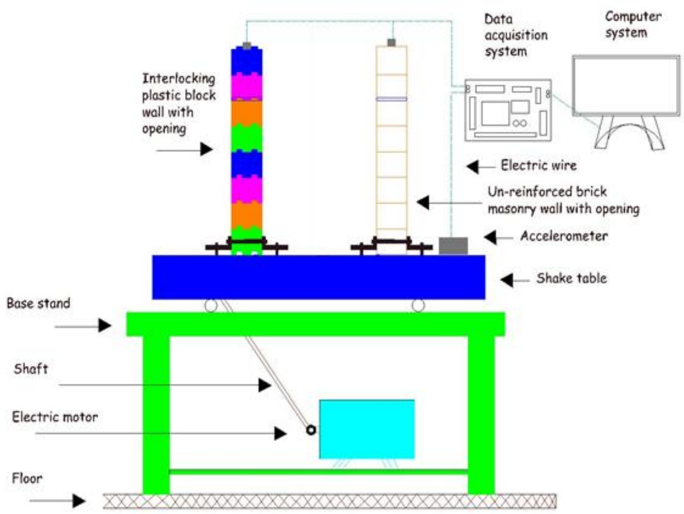


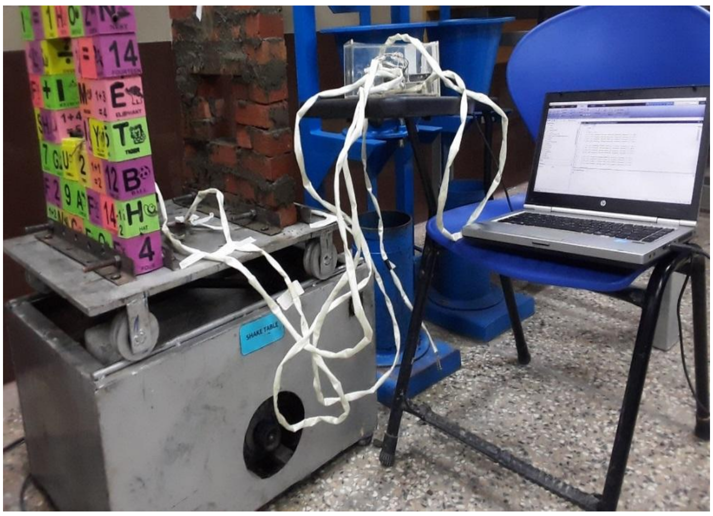
FIGURE 3.6: Schematic diagram of snap back test setup and instrumentation

3.4.2 Shake Table Test and Instrumentation:

Figure 3.7 shows instrumentation of shake table testing: a) schematic diagram and b) test setup. Both walls (interlocking plastic-block wall with opening and unreinforced masonry wall with opening) are mounted on the shake table using base plates and nut bolt. Total three accelerometers are used. One each is attached at the top of the both walls and one is attached at the base of the shake table. Response of both walls is recorded in terms of acceleration-time history. Then this data is converted into velocity-time history and displacement-time history using the seismosignal software.



(a)



(b)

FIGURE 3.7: Shake table instrumentation and testing: a) schematic diagram and b) real test setup

3.5 Loading

3.5.1 Snap Back:

To perform snap back test, interlocking plastic-block wall was displaced by 25mm and 50 mm respectively from the top with the help of attached wire. Then the wire was suddenly released to produce free vibration. Acceleration-time history data was recorded with the help of accelerometer attached at the top of the wall. With the help of log decrement method, damping ratio and fundamental frequency was calculated.

3.5.2 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 wall having opening. 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 wall having opening is taken as 30 mm. Acceleration-time history, velocity-time history, and displacement-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 acceleration-time history, velocity-time history, and displacement-time history will be greater for the case of interlocking plastic-block wall having opening.

Table 3.1: Detail of magnitude of tests considered

Test	Amplitude	Interlocking plastic-block wall with opening	Unreinforced brick masonry wall with opening
Snap back	ug = 25 mm	1	-
	ug = 50 mm	1	-
Harmonic	ug = 30 mm (f = 1.5 Hz)	1	1
	ug = 30 mm (f = 2 Hz)	1	1
	ug = 30 mm (f = 2.5 Hz)	1	-

3.6 Analyzed Parameters

3.6.1 Analyzed Parameters from Snap-back Test

For both walls (interlocking plastic-block wall with opening and unreinforced brick masonry wall with opening), raw data is recorded in terms of acceleration-time history. During the recording period, some noise was also recorded in acceleration-time history data. Seismosignal software was used to remove this noise from test data. Bandwidth filter of seismosignal software was used to remove undesired data. But on initially basis, MATLAB filter was used to remove excessive noise from recorded data. Furthermore, damping ratio (ξ) and fundamental frequency (fn) of the interlocking plastic-block wall with opening was calculated by using the acceleration-time history. It is predicted that the damping ratio of the interlocking plastic-block wall with opening will be more as compare to unreinforced brick masonry wall with opening, for greater displaced structure.

3.6.2 Analyzed Parameters from Shake Table Test

Harmonic loading having frequencies of 1.5 Hz, 2 Hz, and 2.5 Hz was applied to both walls. Response of these walls in terms of acceleration-time history was recorded. Velocity-time history and displacement-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.

3.6.3 Development of Empirical Equations

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

3.7 Summary

This chapter highlights the detailed experimental techniques adopted in this research work. Prototype interlocking plastic-block wall with opening was tested under the influence of harmonic loading. In addition to that, behavior of prototype of conventional unreinforced brick masonry wall with opening was also studied. Behavior of these both walls was also compared. The detailed test setup and instrumentation of all test conducted in this research work is also highlighted in this chapter. And details about parameters to be analyzed is also provided.

Chapter 4

Experimental Evaluation

4.1 Background

Previous chapter heighted the experimental procedure in detail. This chapter explains experimental evaluation of the data recorded through experimentation. Damping ratio (ξ) and fundamental frequency (f_n) of the interlocking plastic-block wall with opening was calculated by using the acceleration-time history. In addition, seismosignal software was used to remove this noise from test data. Bandwidth filter of seismosignal software was used to remove undesired data. But on initially basis, MATLAB filter was used to remove excessive noise from recorded data. Similarly, velocity-time history and displacement-time history was calculated using the acceleration-time history data. For this purpose, seismosignal software was used.

4.2 Damping Ratio (ξ) and Fundamental Frequency ($\mathbf{f}_n$)

Figure 4.1 depicts the results of snap back test conducted on interlocking plastic block-wall with opening. 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) for interlocking plastic-block wall with opening were calculated.

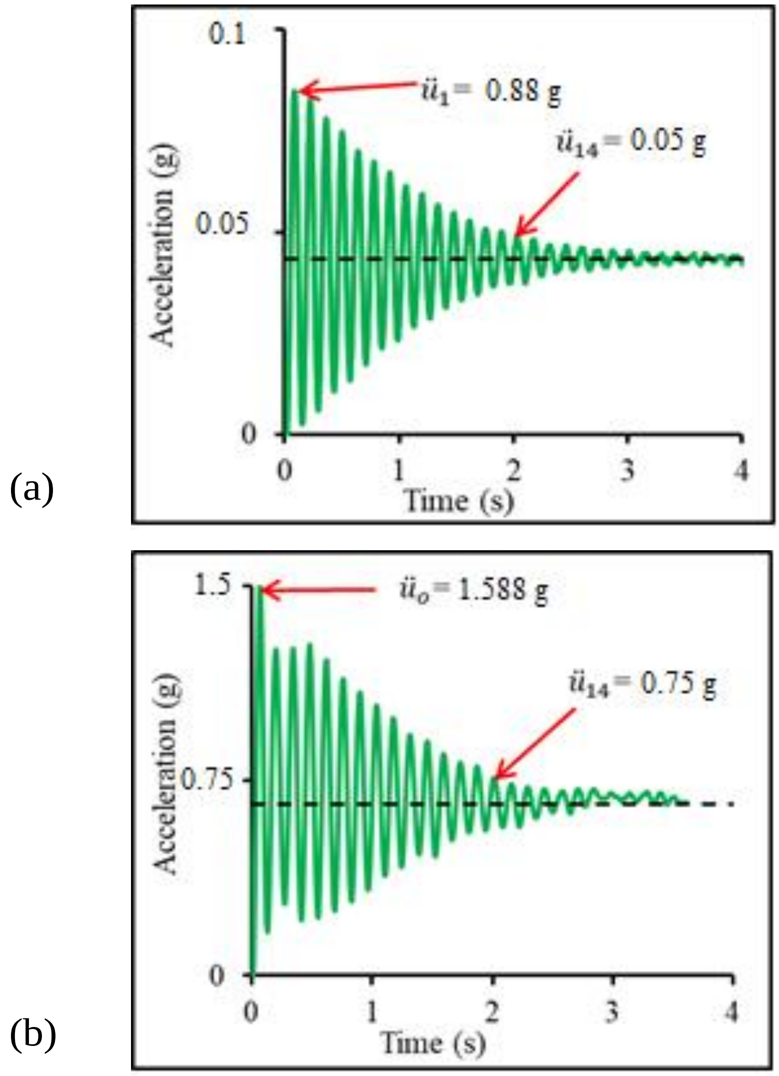


Figure 4.1: Result of snap back test conducted on interlocking plastic block wall with opening, top of the wall is displaced from mean position by: a) 25 mm and b) 50 mm

Table 4.1: Snap back test result of interlocking plastic-block wall with opening

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

Table 4.1 show snap back test result of interlocking plastic-block wall with opening. The damping ratio (ξ) of structure is 1.34% and 1.36% for wall top displaced by 25 mm and 50 mm, respectively. The frequency calculated is 4.853 Hz and 5.154 Hz, respectively. It is observed that there is a little bit difference between damping value. The damping ratio for wall top displaced by 50 mm found more than that of wall top displaced by 25 mm because free vibration time is more for greater displaced wall top and frequency value is almost same because same wall is used for tests.

4.3 Response of Prototype Walls Against Harmonic Loading

4.3.1 Response in Terms of Acceleration-time and Displacement-time Histories

Response of interlocking plastic-block wall with opening and unreinforced brick masonry wall with opening are recorded in terms of acceleration time history and displacement time history during the time period of 30 s to 35 s as shown in Figure 4.2 and Figure 4.3. The blue solid line represents the shake table movement or base excitation (applied loading), the red dash dotted line represents the response at the top of the interlocking plastic-block wall with opening and the grey dash line repents the response at the top of the unreinforced brick masonry wall with opening. The acceleration-time history and displacement time history obtained from analysis of result are acceptable to investigate the dynamic response of both prototype walls. 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 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 considered applied loading. The averaged acceleration and displacement at the top of interlocking plastic-block wall with opening (i.e. $\ddot{u}_t$ and u_t respectively) is considered as IPWW response. Similarly, the averaged acceleration and displacement at the top of unreinforced brick masonry wall with opening (i.e. $\ddot{u}_t$ and u_t respectively) is considered as IPWW response.

Acceleration-time histories of both walls during harmonic loadings of 1.5 Hz, 2 Hz, and 2.5 Hz between 30 s and 35 s are shown in Figure 4.2. The structure excitation can be classified into three phase: A. when the structure started its vibration until it attained the steady-state, B. steady-state response of the structure, and C. free vibration of the structure [8]. For clarity, only portion of steady state response is shown in Figures 4.2 and 4.3. 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. At application of second harmonic loading i.e., 2 Hz, the unreinforced brick masonry wall with opening initially oscillated and then collapsed suddenly as shown in Figure 4.2(b). The failure in unreinforced brick masonry prototype wall occurred around point of opening and above the third layer. This damage was accumulative incorporating the effects of previous frequency. Displacement-time histories of both walls during harmonic loadings of 1.5 Hz, 2 Hz, and 2.5 Hz between 30 s and 35 s are shown in Figure 4.3. To check the response at the base, displacement time-history is shown between 39 s and 35 s. Averaged displacement at ground and top of walls is also mentioned. It has been noticed that the displacement walls is increased by increasing the frequency of shake table. And UBMWW collapsed at 2Hz frequency as shown in Figure 4.3(b).

As described earlier, locally developed 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. $\ddot{u}_g$, $_g$, and u_g, respectively) is taken as applied loading. For the case of unreinforced brick masonry wall with opening, it is clearly visible that initial values of acceleration, velocity and displacement was relatively less than values of interlocking plastic-block wall with opening. But after the application of first harmonic loading i.e., 1.5

(a)

(b)

(c)

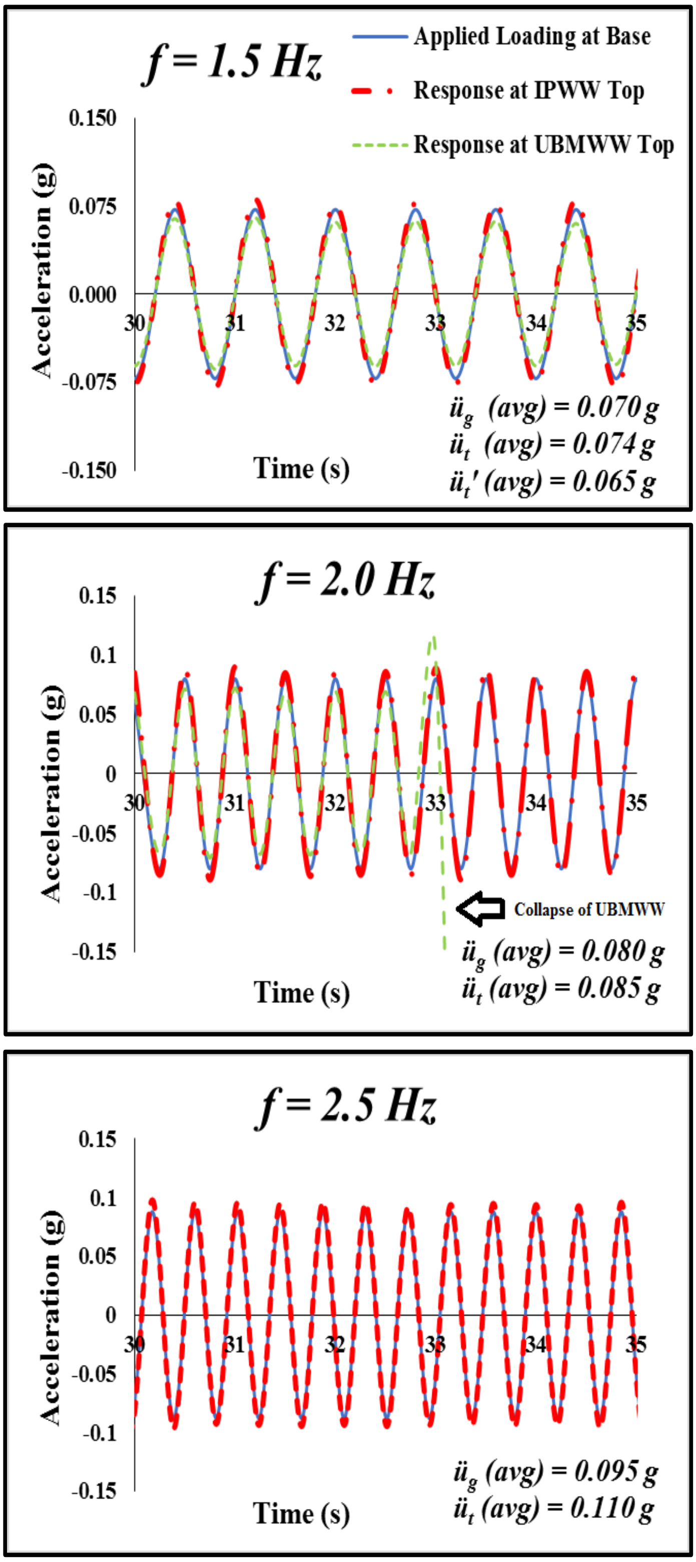
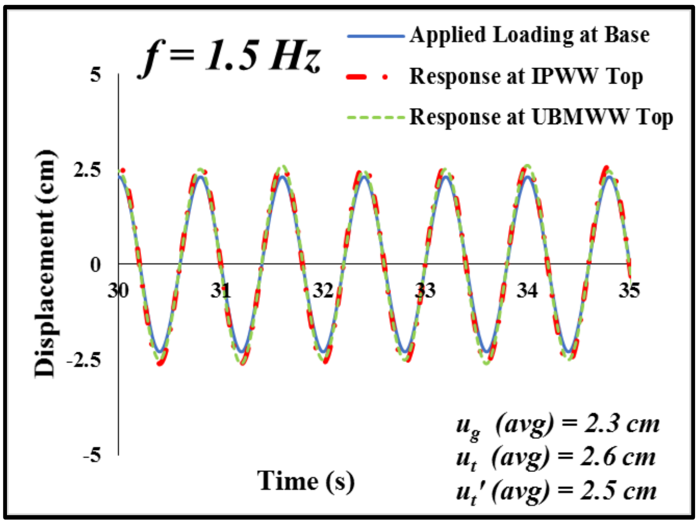


FIGURE 4.2: Behavior of Interlocking plastic-block wall with opening and unreinforced brick masonry wall with opening for intermediate 5 seconds in terms of acceleration-time history: a) for 1.5 Hz, b) for 2 Hz and c) for 2.5 Hz

(a)



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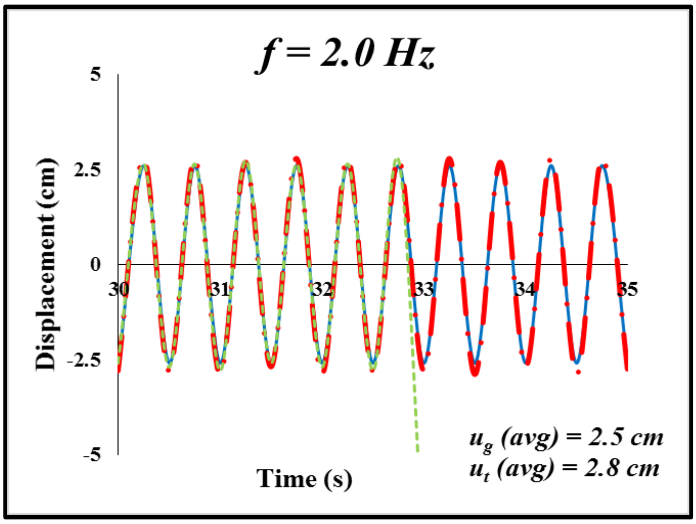

(c)

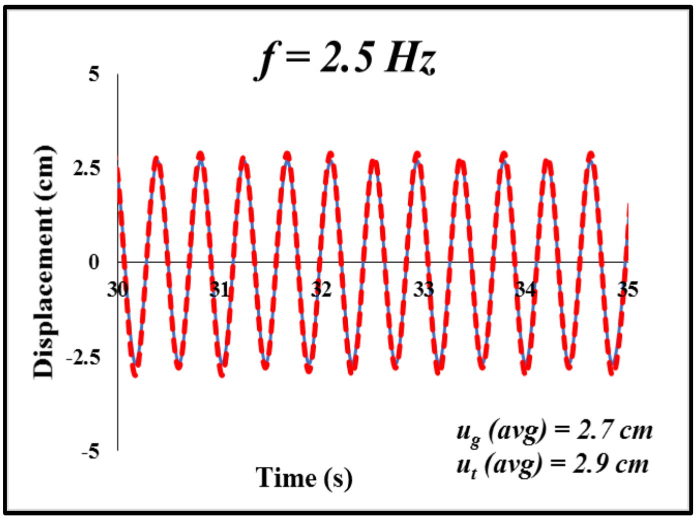

FIGURE 4.3: Behavior of Interlocking plastic-block wall with opening and unreinforced brick masonry wall with opening for intermediate 5 seconds in terms of displacement-time history: a) for 1.5 Hz, b) for 2 Hz and c) for 2.5 Hz

Hz and during the application of second harmonic loading i.e., 2 Hz, wall suddenly collapsed as shown in Figure 4.4. It is concluded that interlocking plastic-block construction is a potential solution for earthquake resistant housing schemes.

FIGURE 4.4: Failure of unreinforced brick masonry wall with opening during the application of harmonic loading

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

It is assumed that the total mass of interlocking plastic block wall with opening (M) is lumped at wall's top where its response acceleration time (i.e., $\ddot{u}_t$ - t) history is recorded. Base shear is calculated 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. [8].

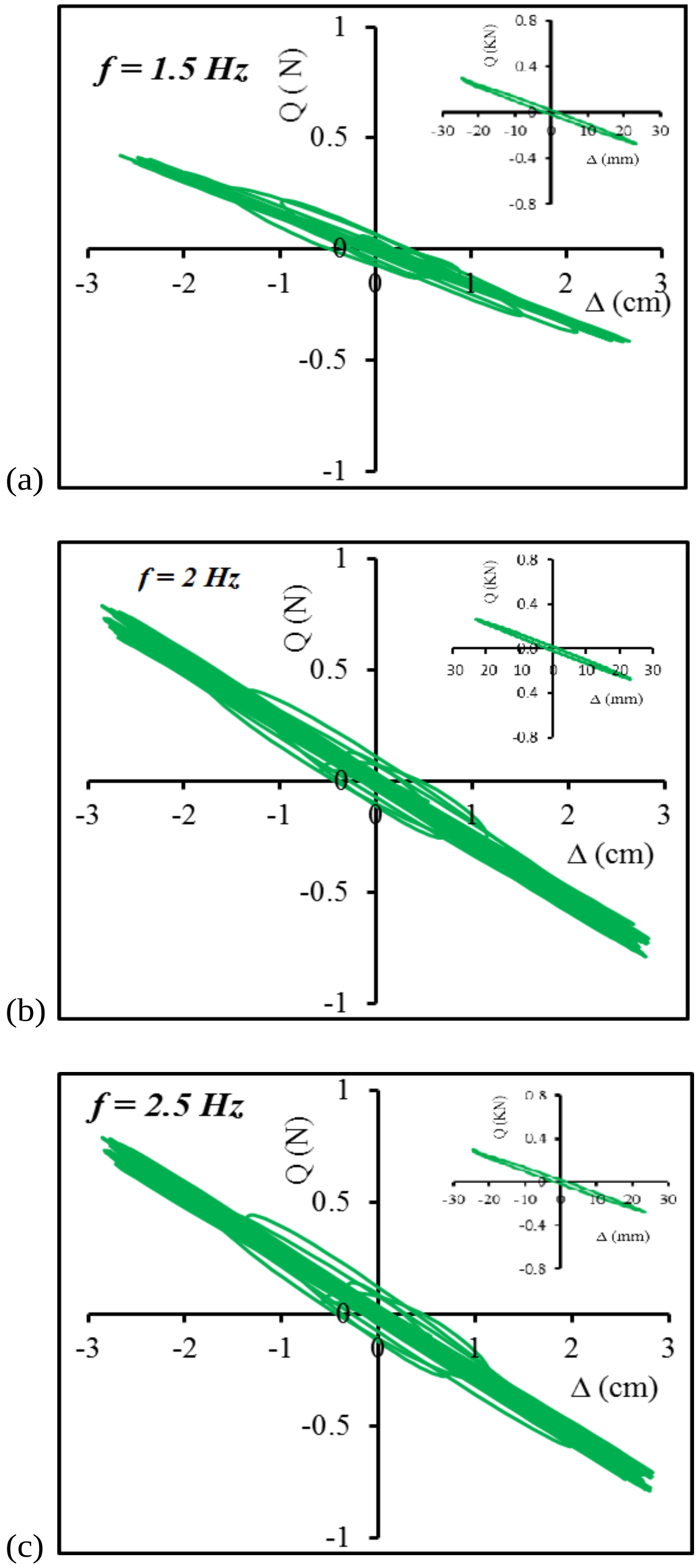

FIGURE 4.5: Base shear - displacement curves of interlocking plastic-block wall with opening for: a) 1.5 Hz, b) 2 Hz and c) 2.5 Hz

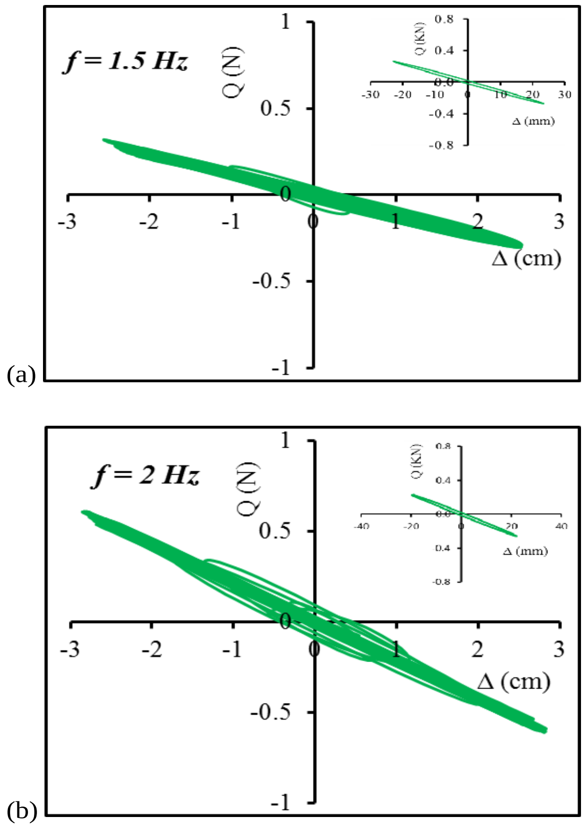

FIGURE 4.6: Base shear - displacement curves of unreinforced brick masonry wall with opening for: a) 1.5 Hz and b) 2 Hz

TABLE 4.2: Energy absorption during the harmonic loading

Frequency (Hz) for ug = 30 mm	Averaged energy absorbed in one cycle (Nm)		Total no. of cycles (n)	Total energy absorbed (Nm)	
	IPWW	UBMWW		IPWW	UBMWW
1.5	1.8	1.4	65	117	91
2	3.2	2.9	82, 67*	262	194
2.5	5.2	–	95	494	–

* Total number of cycles for UBMWW under harmonic loading of 2 Hz upto collapse.

Table 4.2 shows the averaged energy absorption (E) in one cycle as well as total energy absorbed (E_T). Area within the loop is taken as energy absorption (E). It has been noticed that interlocking plastic-block wall having opening dissipates more energy during harmonic loading with frequencies 1.5Hz, 2 Hz, and 2.5 Hz. It is concluded that 33% more energy is dissipated in interlocking plastic-block wall having opening at 1.5 Hz in comparison with unreinforced brick masonry wall having opening. And for the case of single cycle under 2 Hz frequency loading, interlocking plastic-block wall having opening dissipated 10% more energy. The reason behind comparing single cycle for 2 Hz is because unreinforced brick masonry wall having opening collapsed during the load application. In seismic event, interlocking plastic-block wall with opening can absorb more energy, because of the relative movement at block interfaces. 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 wall having opening dissipates more energy than unreinforced brick masonry wall having opening.

4.5 Summary

In this chapter, experimental evaluation of recorded data is presented. 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 wall with window collapsed, whereas interlocking plastic-block wall with opening showed relative movement with respect to base. Similarly, interlocking plastic-block wall with opening dissipated more energy than unreinforced brick masonry wall with opening.

Chapter 5

Discussion

5.1 Background

In the previous chapter, results of acceleration-time history, velocity-time history, displacement-time history, base shear-displacement curves are explained in detail. Noteworthy energy absorption is observed in interlocking plastic-block wall with opening is observed. In this chapter, relationship between experimental and empirical values is developed to predict the behavior of interlocking plastic-block wall having opening. In addition to that, percentage difference between empirical and experimental values is presented.

5.2 Development of Empirical Equations using Structure Response, Geometrical Parameters and Input Loading Conditions

Khan and Ali [54] developed empirical equations incorporating the geometry of interlocking blocks, column height, column response and input loading parameters. Following empirical equations are developed for predicting the response of interlocking plastic-block wall having opening by incorporating further new variable:

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

$$\dot{u}_t = \frac{(\frac{a}{h^2})}{n} \text{ mK}^{(1+\frac{2n}{100})}\dot{u}\text{g}$$

$$u_t = \frac{(\frac{a}{h^2})}{n} \text{ mK}^{(1+\frac{2n}{100})}ug$$

Where $\ddot{u}_g$, $\dot{u}_g$, and u_g are averaged ground acceleration, velocity and displacement, respectively. Their corresponding values are 0.08 g, 75 cm/s and 4.5 cm, respectively. $\ddot{u}_t$, $\dot{u}_t$, and ut are response acceleration, velocity and displacement, respectively. a, h, n, and m are block base area, key height, total number of blocks, and number of blocks along the length of wall in a singke layer, respectively. Their corresponding values are 62 mm x 62 mm, 12 mm, 42, 41 mm * 8 + 12 mm = 340 mm, respectively. K is coefficient having dimensionless value of 0.5. In Table 2, comparison of experimental and empirical values of wall response is shown. It can be noted that experimental values ar good agreement with empirical values. The percentage difference is less than or equal to 7%.

Table 5.1: Percentage difference in experimental and empirical values for interlocking plastic-block wall having opening

Wall response	Experimental values	Empirical values	Percentage difference
Acceleration (g)	0.085	0.091	7%
Velocity (cm/s)	90	95.86	6.51%
Displacement (cm)	3.2	3.40	6.25%

5.3 Outcome of Study with Respect to Practical Requirement

Application of harmonic loading using locally developed shake table is able to produce precise harmonic loading to some extent so that the dynamic behavior of structure under observation can be studied. This is so because the applied

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 [51].	Simple 1D shake table is used to analyze dynamic behavior of interlocking plastic-block wall with opening.
More inertial force was generated in coconut fiber reinforced concrete block due to its weight [9].	While less inertial force is generated in interlocking plastic-block wall with opening due to its light weight.
Energy is dissipated in mortar-free interlocking structure during dynamic loadings [8].	Interlocking plastic- block wall with opening also dissipates energy during harmonic loading.
Pre-tensioning of structure with coconut fiber ropes dissipated less energy compared to that without rope [9].	Rubber band in the interlocking plastic-block wall helped in energy dissipation during the harmonic loading.
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.

harmonic loading is taken as the base ground motion and response of the structure is studied with respect to it. On the other hand, the observed behavior of interlocking plastic-block wall with opening is more or less same as that reported in other researches. The studied wall has shown positive potential in form of structural stability and energy absorption. So, it should be explored in detail for wall in connection with other structural elements. In addition, the adverse impact of earthquake can be reduced by using interlocking plastic-block for earthquake resistant construction. 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.

5.4 Summary

This chapter explained the outcome of the study with respect to practical requirement and the empirical equation. The purpose of developing empirical equation was to check the percentage difference. Empirical equations are dimensionally correct. Application of harmonic loading using locally developed shake table is not much accurate with respect to different frequencies and fixed amplitude. However, it is able to produce precise harmonic loading to some extent so that the dynamic behavior of structure under observation can be studied. Prototype interlocking plastic-block wall with opening is more useful for earthquake resistant housing in comparison with unreinforced brick masonry wall with opening. Interlocking plastic-block wall with opening dissipated more energy during the applied loading. 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

Many earthquake resistant construction techniques are available in literature for earthquake prone areas. But these are uneconomical. Developing countries cannot afford such techniques to lessen the earthquake damages. In this pilot study, dynamic behavior of interlocking plastic-block wall with opening is compared with unreinforced brick masonry wall with opening. Prototypes of both walls are tested under different harmonic loading to determine the response and their dynamic characteristics. For finding the fundamental frequencies of the structure, the harmonic tests were found more accurate compared to snap back test. Following conclusions can be drawn from this research work:

- Unreinforced brick masonry wall with opening collapsed during the applied loading, due to conventional issue of weak bond between bricks and mortar.
- Interlocking plastic-block wall with opening dissipated total energy of 262 Nm, which was due to uplifts of block during applied harmonic loading at same frequency (2 Hz), at which unreinforced brick masonry wall with opening failed.

- The energy dissipation capacity of the interlocking plastic-block wall with opening is increased by using rubber band in wall.
- Empirical values for response of interlocking plastic-block wall with opening are in good agreement with experimental values.

On overall basis, prototype interlocking plastic block wall with opening performed exceptionally well against harmonic loading in comparison with prototype unreinforced brick wall with opening.

6.2 Future Work

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

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