CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

# Out-of-Plane Dynamic Behavior of Double-Story Interlocking Plastic-Block Structure with Different Wall Patterns

by

Abu Bakar

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# CERTIFICATE OF APPROVAL

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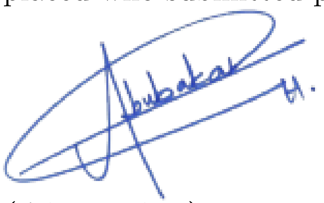

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# *Abstract*

The traditional masonry building construction particularly in non-engineered buildings is very vulnerable to collapse during intense ground vibration. In the seismically active areas, especially in the developing world, inexpensive and earthquake-resistant buildings are a great menace to human lives and infrastructure. There are a number of seismic mitigation plans; some of them are not cost-effective to be implemented on a large scale. Out-of-plane failure is a typical failure mode of masonry construction. Mortar-free interlocking plastic-block walls behavior with seismic loads, especially in the out-of-plane direction, is little studied. Such systems have the potential benefits of being light in mass and inertia and are useful in the low-cost construction of earthquake-resistant buildings. Studies indicate that basic low-cost shake table tests give promising outcomes to study such behavior. Therefore, the behavior of the double-story on a simple shake table should be investigated.

The ongoing study is directed towards the dynamic behavior of a 1:10 scaled-down full-size double-story building made of interlocking plastic blocks. The prototype double-story was made up of 120 plastic blocks, consisting of 12 layers and attached at the bottom using angle sections to stabilize the structure. To measure the structural response, five accelerometers were placed at certain points. Two on the top of the single-story, two on the top of the double-story, and one on the base plate to measure the base excitation. To measure the natural time period, frequency, and damping ratio, a snapback test was done by moving the wall in the X-direction with a 400 mm wire and releasing the wire to measure the natural time period, frequency, and the damping ratio using the logarithmic decrement method. The experiment used a locally constructed low-cost shake table with frequencies of 0.8 Hz, 1.0 Hz, and 1.2 Hz to provide seismic excitation. MATLAB software was used to collect acceleration-time history data, which was processed and refined in SeismoSignal software to remove noise and correct the baseline.

The natural frequency of the interlocking double-story was about 1.0 Hz on average, and the damping ratio was as high as 3.99%. The values of energy absorption were calculated using base shear displacement curves, with mass lumped on the top of the specimen. It is worth noting that the wall configuration, labeled Sequence A, had higher energy absorption with 1.39, 1.14, and 1.43 at frequencies of 0.8 Hz, 1.0 Hz, and 1.2 Hz, respectively, compared to the wall configuration, Sequence B. The nearly 25% difference between experimental and empirical data can be attributed to the complexity of the structure as compared to the simplicity of the equations. The research can be used in the investigation of the interlocking block systems with mortar-free, which are of the type of a double-story. It shows that the interlocking-plastic-block wall with a mortar-free double-story is a step towards a safe, economical, and resilient wall for seismic-resistant housing.

**Keywords:** Mortar-free construction, Interlocking-plastic block structure, Double-Story, Dynamic behavior

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# List of Abbreviations

| | |
|---|---|
| **1D** | One-dimensional |
| **3D** | Three-dimensional |
| **CBM** | Confined brick masonry |
| **cm** | Centimeter |
| **cm/s** | Centimeter per second |
| **CMU** | Conventional masonry unit |
| **Hz** | Hertz |
| **IPB** | Interlocking plastic block |
| **MFI** | Mortar-free interlocking |
| **mm** | Millimeter |
| **MMS** | Mortar-less masonry system |
| **Nm** | Newton meter |
| **PGA** | Peak ground acceleration |
| **PT** | Post-tensioned |
| **RB** | Rubber Band |
| **SDOF** | Single degree of freedom |

# Symbols

| | |
|---|---|
| $a$ | Base area of interlocking plastic-block |
| $E$ | Energy absorbed |
| $E_t$ | Total energy absorbed |
| $f_n$ | Fundamental frequency |
| $g$ | Acceleration |
| $Hz$ | Unit of frequency |
| $K$ | Coefficient having dimensionless value |
| $m$ | No. of blocks along the length of wall in a single layer |
| $n$ | No. of interlocking plastic-blocks |
| $Q(N)$ | Base-shear |
| $u_g$ | Average displacement at the base of specimen |
| $\dot{u}_g$ | Average velocity at the base of specimen |
| $\ddot{u}_g$ | Average acceleration at the base of specimen |
| $u_t$ | Average displacement at the top of specimen |
| $\dot{u}_t$ | Averaged velocity at the top of specimen |
| $\ddot{u}_t$ | Average acceleration at the top of specimen |
| $\Delta$ | Displacement in millimeter |
| $\zeta$ | Damping ratio |

# Chapter 1

# Introduction

## 1.1 Background

An earthquake is a natural disaster that produces strong ground motion [5]. The primary effects of an earthquake cause severe damage, such as the collapse of buildings, roads, and bridges, which may kill many people. Earthquake badly affects masonry structures [6]. During the Kashmir earthquake of 2005, more than 450,000 buildings were partially or fully damaged. Ground acceleration is transferred from the ground to the structure foundation, which causes shearing of masonry walls due to inertia [7]. Recently, an earthquake in 2018 in Indonesia (the Lombok earthquake) damaged more than 1000 houses. An effort is required to reduce losses during future earthquakes [8]. In seismically active regions, the economically earthquake-resistant housing is desirable, particularly for developing countries. During strong ground motions, these regions often suffer a significant loss of life because of the lack of such houses [9].

To enable an efficient and cost-effective solution, various researchers have investigated new construction techniques in the last decade. Structures consisted of mortar-free interlocking blocks. Mortar-free blocks used in the structure played an important role during strong ground motion. These blocks dissipated more energy during the seismic event because of the relative movement at the block interfaces. However, the mass of coconut fiber reinforced concrete blocks is still a point of concern. The lighter the mass of the structure, the lower the inertia force generated. There is a need to reduce the mass of the block in order to reduce inertia forces. For this, a lightweight interlocking plastic block is one solution. An electro-hydraulic shake table having six degrees of freedom is essential in order to generate real earthquake data. But such a table is very expensive. However, the dynamic behavior of structures can also be studied using a unidirectional shake table. During a seismic event, an interlocking structure can dissipate energy because of the relative movement of block interfaces. The lighter the mass of the structure, the lower the inertia force generated during the seismic event.

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 tables having six degrees of freedom are used in developed countries to investigate the dynamic response of the structure and to generate real earthquake data. On the other hand, developing countries cannot afford such sophisticated and expensive 3-D shake tables. But these countries are using simple 1-D shake tables to understand the dynamic behavior of prototype structures in the laboratory. The purpose behind the development of prototype structures in the laboratory is to conduct such studies. Many researchers have conducted dynamic testing of small and large-scale prototypes in the laboratory using a shake table. For small-scale testing, simplified boundary conditions have been adopted in these studies. These studies validated the conduct of prototype testing in the lab using a small-scale shake table. It is worth mentioning that the lesser inertial forces can be generated during the strong ground motions with the use of blocks having less weight. The interlocking plastic blocks are one option to explore. The dynamic response of such lighter structures needs to be explored.

In this work, the behavior of a double-story interlocking block structure is investigated. To the best of the author's knowledge, the investigation on mortar-free construction without steel reinforcement and the innovative use of interlocking plastic blocks for resisting earthquake loading has not been reported. This study was conducted to understand the dynamic characteristics of mortar-free structures comprising the newly developed interlocking plastic blocks.

### 1.1.1 Previous Researches

Adnan [10] in an investigation discovered that the elements of structure with two block widths had superior energy absorption and peak load capability during compressive loads compared to those with single block widths, which collapsed abruptly. A study conducted by Sudheer [11] found that interlocked plastic-block walls with windows were more resistant and absorbed more energy under lateral loads compared to unreinforced masonry walls. Khan [3] in a study came up with empirical equations indicating that the interlocking plastic-block structures with rubber bands were stiffer, and less top displacement was observed with harmonic loading. In a study, Shahzad [12] discovered that in harmonic loading of interlocking plastic-block walls, vertical reinforcement with rubber bands enhanced energy dissipation. As demonstrated by Afzal [13], unreinforced masonry (URM) solid masonry walls failed when subjected to loading following poor bonding of mortar and bricks. The lighter interlocking plastic block solid walls (IPBSW), on the other hand, were more effective in energy dissipation. According to Aslam [14], the interlocked plastic block walls exhibit adequate compressive strength to support their own weight, improve their structural behavior by controlling cracks, and dissipating energy.

In a study conducted by Bashir [15], it was found that a wooden diaphragm (elements that pass the structural load to vertical resisting elements such as frames or walls) minimized the top displacement and maximized the energy dissipation in interlocking plastic-block walls. Anwar [16] investigated the interlocking plastic-block walls with block-return and diaphragm exhibit high seismic performance, higher damping ratio, base shear, and energy dissipation, particularly with out-of-plane loading. A study conducted by Asad [17] has shown that block-return and rubber band reinforced interlocking plastic-block walls were effective in dissipating more energy under harmonic loading. Walls with openings, corners, intersections, and out-of-plane walls are sensitive areas, and experiments on in-plane and out-of-plane behavior of walls have been conducted; however, the use of double-story mortar-free interlocking masonry has not been explored yet. The present research aims to investigate the out-of-plane dynamic action of a type of mortar-free interlocking-plastic-block structure that is double-story.

## 1.2 Research Motivation and Problem Statement

Earthquakes are serious occurrences, which are devastating. When buildings collapse during or after an earthquake, a large number of people die in most of the countries, and a large number of them end up being homeless. All these damages and loss of human lives are manageable provided that the earthquake behavior of a structure is accurately studied which can be used to design appropriately. To this end a cost-effective and efficient solution is required. The use of mortar less block masonry can be a cost effective solution, but it is still too heavy. Interlocking plastic blocks may be a more appropriate choice to use since they are light in weight. Therefore, the problem statement will be as follows:

The construction of the seismic resistant houses using mortar-free interlocking block structures has been an innovative construction method. These blocks have the ability to absorb energy, however, because of their high mass, they remain an issue of concern since the mass increases as the inertial forces do during earthquakes. This could be alleviated by reducing block mass, so lightweight interlocking plastic blocks may be a good solution. The dynamic behavior of a double-story mortar-free interlocking plastic block structure should be studied in order to assess its performance. This implies that the dynamic performance of a interlocking-plastic-block structure that is without mortars and is a double story should be studied under dynamic loading.

### 1.2.1 Research Questions

i. What would be the natural frequency and damping ratio of the interlocking plastic-block structures (without mortar) in the shape of a double-story building?

ii. How would the out-of-plane behavior of plastic-block walls in interlocking affect the dynamic performance of the double-story?

iii. How well do past experimental investigations support the results of the current study?

iv. Which of the suggested sequences of wall configuration would quench the most energy under dynamic loading?

## 1.3 Overall Goal of the Research Program and Specific Aim of this Particular Study

The overall objective of the research program is to investigate the 3D seismic response of a full-scale structure in double-story mortar-free interlocking plastic-block structure in a laboratory.

The specific aim of this MS research work is to investigate the out-of-plane dynamic behavior of a scaled-down double-story interlocking plastic-block structure using a locally manufactured low-cost simple shake table in the laboratory.

## 1.4 Scope of Work and Study Limitations

A prototype of a double-story structure is designed in the research, in which the interlocking system is made of a mortar-free plastic block structure, which is designed of specifically designed blocks. The building is constructed on a fixed base because this renders in perfect simulation of real life situations. During the experiment, three different frequencies of load are applied. The optimum conditions of the two-story building are witnessed because under the seismic like conditions the response of the building to the load applied is anticipated both in displacement time history and acceleration time history. The snap-back test is done to measure the natural frequency and damping ratio of the wall. Based on the obtained data, empirical equations have been developed to define the behavior of the double-story walls and therefore give a better insight into the structure.

The research also has limitations, the first being that the simple one-dimensional shake table is used, which limits the testing to uniaxial loading. Also, it will involve only five accelerators at the top, bottom and the other at the central location of the wall and this restricts the range of data collection. The obtained data from MATLAB is only in the form of acceleration-time history, which needs further refining and conversion using seismic signal software. Also, the research will concentrate on three loading frequencies only. Although they might limit the scope of situations considered, these restrictions can facilitate a narrow and controlled exploration, which will enable future studies using more sophisticated equipment and a wider testing environment. The main limitations of the study include the use of scaled models, simplified boundary conditions, and restricted loading scenarios, which may not fully represent real construction behavior. Additionally, long-term effects such as creep, durability, and fire performance of plastic blocks were not considered. Exposure to fire significantly reduces the structural integrity of plastic block construction due to thermal softening, strength degradation, and loss of interlocking efficiency. In mortar-free systems, the reduction in friction and geometric stability further increases displacement and collapse risk, leading to substantial loss of load-carrying capacity and residual structural performance. The experimental scope was limited to idealized configurations.

### 1.4.1 Rationale Behind the Variable Selection

The current research is a subset of the larger research program. Double-story structure is yet to be studied, that's why a double-story structure is chosen. Elevation dimensions are scaled 1/10 only because of the method A of UBC-97 in respect to time period, which is dependent on the height of the structure. The wall length which is taken is 600 mm per side, which is far much more than the block return. 62 x 62 mm with 50 mm height and 12 mm key. The Interlocking plastic-block structural elements and a 1D shake table will be used to investigate out-of-Plane response of a double-story structure with a diaphragm. The laboratory shake table test is an inexpensive laboratory experiment to find out the fundamental frequency and maximum failure acceleration in a small-scale prototype structure. The rationale behind the choice of plastic-block structural elements that interlock in this research study is that the plastic blocks are light in weight and can absorb more energy in comparison to masonry walls.

## 1.5 Brief Methodology and Techniques to be Employed

A reduced two-story building with a scale of 1:10 made of interlocking plastic blocks. The prototype of the Interlocking plastic block wall was developed with 120 plastic blocks (n = 120), and the total height (H) was 600 mm. The wall structure is constructed in two stages. Sequence A is constructed in such a way that the out-of-plane behavior of solid walls is taken into account, whereas Sequence B constructs the walls in a way that out-of-plane behavior of the wall with an opening is taken into account. The wall is 6 layers thick. Rubber bands are vertically tied on the bottom to the top of the wall through the center of the blocks to increase the vertical stiffness of the wall. 20 stiffeners are used in the form of a rubber band, 5 in each wall.

In the snap-back test, the acceleration-time history was recorded by moving the wall in the X-direction with a 400 mm wire and releasing it. It was applied in the determination of natural time period, frequency, and damping ratio by the logarithmic decrement method. Five accelerometers were placed at certain points to measure the response of the structure. Two at the top of a single-story, two at the top of the double-story, and one on the base plate to measure the base excitation. A laptop running MATLAB software was connected to an Arduino setup to acquire data. To simulate seismic excitation, a one-dimensional shake table that was locally manufactured and had the capacity to run at a frequency of 0.8 Hz, 1.0 Hz, and 1.2 Hz was used. The data of acceleration-time history recorded in MATLAB software was processed and refined with the use of SeismoSignal software in order to eliminate noise and correct the baseline. The data of mass of the specimen x acceleration measured by an accelerometer on the top of the double-story is used to determine the base shear. Base shear-Displacement curves are used to determine energy consumption, with total mass lumped on the top of the specimen. The mean energy dissipation in the single loop and the overall energy absorbed is determined. Empirical equations were developed to predict the response by taking the double-story height, geometry of interlocking blocks, and structural response of the specimen. The results are compared between experimental and empirical and values are within reasonable percentages.

## 1.6 Research Impact on Industry

### 1.6.1 Research Novelty and Uniqueness

Various interlocking techniques have been investigated in recent years to improve the structural efficiency, constructability, and seismic resistance of masonry systems. While several studies have examined the performance of single-story interlocking masonry walls under static and dynamic loading conditions, research addressing the behavior of double-story interlocking structures remains limited. In particular, experimental investigations utilizing simple one-dimensional (1D) shake tables to assess the dynamic response of double-story systems are scarce. This limitation is especially evident in the context of out-of-plane dynamic behavior, which is a critical failure mode for masonry walls during seismic events. Consequently, the out-of-plane dynamic response and failure mechanisms of double-story interlocking structures constructed with plastic blocks are not yet well understood, highlighting a clear gap in existing experimental research and motivating the need for further investigation.

### 1.6.2 Research Significance and Benefit

The purpose of this study is to develop the insight of the inter-locking construction with mortar-free, which is constructed as a double-story and covers an important area of structural performance during dynamic loading. The results will help in creating more cost-effective and safe housing systems, especially in areas prone to earthquakes.

### 1.6.3 Practical Implementation

The research helps in the creation of affordable houses as it advocates the use of easy to assemble, cost effective and time saving construction methodologies. The solution provides a viable remedy to quick deployment in case of a disaster situation by working with the disaster relief agencies, which will add to the resilient and accessible housing in vulnerable communities. The scalability and flexibility to a variety of geographic and climatic environments, brought by the modularity of interlocking plastic blocks, have made it applicable both to temporary shelters and permanent housing. Moreover, the lightweight and recyclable materials used during the construction process are sustainable construction materials, which minimizes the environmental impact. This strategy does not only respond to short-term post-disaster housing but also promotes long term policies of inclusive and sustainable urban planning.

### 1.6.4 National and Global Impact with Emphasis on SDGs Relevance

The study will contribute to disaster resilience in terms of safety and loss of infrastructure. It also spurs innovation within the construction industry, employment, economic growth, as well as enhancement of national base of knowledge, and development of educational and training programs. The study encourages the communities to be inclusive participants in the rebuilding process by introducing modular, low-tech methods of construction to include unskilled labor, enhancing the involvement of the communities in the rebuilding process. Besides, the results can be used to develop policy on disaster risk reduction and urban planning, and advance evidence-based policies on resilient infrastructure. Implementing such innovative systems into the curricula of academic institutions can also create a new breed of engineers and planners who are interested in sustainable and resilient development.

### 1.6.5 Research Challenges

A small number of accelerometers and a 1D shake table are also a limitation of the study as they limit dynamical response data. A fixed base was used to simplify boundary conditions, potentially affecting the realism of structural behavior. The accelerator information also needs to be modified with the help of Seismo-signal, which only shows the acceleration histories without any displacement or velocity information. These constraints can influence the quality of the results, particularly in the ability to measure the entire range of dynamic responses in complex loading conditions. Future investigations could use multi-directional shake tables and more sensors to better understand the entire dynamic behavior of interlocking block systems. Also, more sophisticated numerical models and experimental results may assist in confirming and expanding the results as well as give a more detailed perspective on the displacement and velocity distributions.

### 1.6.6 Ethical and Management Considerations, including Risk Management

The research highlights transparency through reporting all the findings and limitations, thus maintaining ethical integrity. It seeks to ensure the developed technology is affordable to the housing sector and still upholds the rights of all its partners by paying them well. They adhere to the university health and safety regulations and have a coordinated timetable to ensure that all activities are carried out on time. Moreover, the study complies with the ethical provisions in terms of resource utilization, which makes it sustainable both environmentally and economically. The collaborative strategy will help create a culture of accountability and inclusivity, which will enable local communities and stakeholders to actively participate in developing and deploying the technology. The study will be an example of ethical innovation in housing development by ensuring such standards.

### 1.6.7 Research Deliverable, Sales and Marketing Potential

The study is oriented towards construction companies, developers of affordable houses, and disaster relief organizations, and the practical advantages, which are mentioned in the study, are ease of construction, cost-effectiveness, and the time of construction. It provides a scalable answer to quick and cost-effective housing, particularly in post-disaster and low-income situations. Relevance to different environmental conditions and needs of the community is also made possible by the modular design and the use of interlocking plastic blocks that allows flexibility. Additionally, the strategy helps local economies by using regionally specific resources and labor, enhancing self-sustenance and sustainability. This study does not only solve the problem of shortage of housing in the short term but also preconditions the long-term, sustainable solutions to the housing problem, enhancing the quality of life of vulnerable groups. The study is geared towards creating affordable and secure housing to the disadvantaged individuals. Development of awareness to the construction stakeholders regarding the ease of construction, safety, cost-effectiveness, and the possibility of minimizing time of construction.

## 1.7 Thesis Layout

Chapter 1 includes the introduction part, which consists of the background, research motivation, problem statement, overall objective, specific aims, scope of work, study limitations, methodology taken up, and the structure of the thesis.

Chapter 2 gives the literature review, which includes background information, damages observed in conventional masonry buildings during earthquakes, new techniques of mortar-free interlocking masonry, interlocking mechanism of mortar-free construction, and a final concluding summary.

Chapter 3 describes the experimental program, including background information, construction specifications of the two-story structure with interlocking plastic block wall, free of mortar, test setup, snap back test setup, harmonic loading with shake table, experimented variables, derivation of empirical equations and conclusion.

Chapter 4 is devoted to the experimental analysis, background, the results of a snap-back test, the wall response under harmonic loading, the calculation of the damping ratio, of the base shear, of the energy absorption, and a summary.

Chapter 5 is the discussion section that includes background, correlation of empirical equations, interpretation of findings in terms of real world applications and summary.

Chapter 6 provides the conclusions and recommendations. At the end of the thesis, there are references after chapter 6.

# Chapter 2

# Literature Review

## 2.1 Background

Masonry constructions frequently sustain major damage as a result of severe ground movements brought on by seismic activity. Seismic events have varying effects in different areas, often resulting in structural damage and, in the most severe situations, fatalities. Particularly, masonry structures in seismically active urban and rural areas pose a serious risk to public safety. The main reason for this is the ground accelerations being transmitted to the foundation of the structure, which results in inertial forces and masonry wall shear failure. Numerous studies in the literature demonstrate the use of different construction methods to increase the seismic resistance of masonry structures. Interlocking block construction has become a viable substitute among these. However, a major obstacle to seismic performance remains the high inertial forces generated by the larger mass of traditional masonry blocks. The literature on the seismic vulnerability of conventional masonry structures is thoroughly reviewed in this chapter, along with cutting-edge methods for creating earthquake-resistant systems and the function of stiffeners in enhancing the dynamic response and structural integrity of prototype masonry structures in lab settings.

## 2.2 Damages in Conventional Masonry and its solution

### 2.2.1 Failures in Conventional Masonry

During the earthquakes, numerous researchers from all over the world reported damage to traditional unreinforced masonry structures. Owing to their uncontained and weak diaphragm anchorage, much of the damage to masonry structures occurred [18]. Led survey research after the 2015 Gorkha earthquake in Nepal. Approximately 80000 partially or completely damaged buildings have been recorded [19]. Conventional masonry, usually unreinforced brick or block walls connected with mortar, has a low tensile strength and a brittle nature, which makes it susceptible to significant damage from wind, earthquakes, or settling in two-story buildings. In-plane lateral pressures often cause diagonal shear cracking in wall panels [20]. This cracking typically begins at the corners of openings such as doors and windows and spreads in an "X" pattern. Out-of-plane (i.e. acting perpendicular to the wall surface) failures, which occur frequently in upper floors where acceleration demands are larger, occur when parts of walls bulge, split, or collapse due to inadequate floor and roof anchoring [21]. Although slabs provide nominal top restraint, out-of-plane failure can still occur due to flexible slab behavior, inadequate wallslab anchorage, and sliding or rocking at dry joints. In mortar-free systems, the absence of bonding reduces rotational restraint, allowing bending and instability under lateral loading, which may lead to out-of-plane collapse. Inadequate inter-story floor-to-wall connections may cause separation fractures or even partial wall detachment. The study concludes that most of the mud mortar or lime mortar masonry buildings were badly damaged due to the poor strength of the bond. Due to the heavy bonding, masonry buildings with cement mortar are more resistant than others, according to the report.

Extreme dynamic or static stresses can still cause significant damage to reinforced masonry, even though it usually performs better than unreinforced masonry in double-story buildings when it has grouted cores and integrated steel reinforcement in masonry units [22]. Under severe seismic shaking, out-of-plane shear cracks may develop along mortar joints or through units due to the restraining effect of reinforcement [23]. Compared to unreinforced walls, these cracks usually show up as diagonal cracking that is thinner and more widely distributed. Flexural cracks may form toward mid-height or around wall bases, where bending forces are greatest [24]. Typically, these fractures begin vertically and grow toward the tension face. Inadequate anchoring of vertical reinforcement into floor diaphragms or foundations can cause pullout failures, which reduce the wall's overall stability. In compression zones, excessive drift requirements at inter-story levels may cause masonry crushing and vertical steel bars to give or buckle, particularly if confinement is insufficient [25]. Although less common than in unreinforced walls, out-of-plane damage can nonetheless cause localized bulging or panel separation if floor-to-wall connections are inadequate or if the reinforcement pattern varies between floors [26]. Although reinforced masonry is more ductile, inadequate detailing, a lack of lap splices, or corrosion of the reinforcement can significantly impair its seismic and structural performance in double-story buildings.

### 2.2.2 Typical Out-of-Plane Damages in Conventional Masonry Structure

The potential suggestion in the study was the use of the lintel band and the provision of steel reinforcement in corners and junctions of masonry structures [27]. Figure 1 shows the typical out-of-plane failures of conventional masonry under one-way and two-way bending. While the supply of lintel bands would decrease the in-plane failure of masonry walls, the study indicated that it would not be helpful during the occurrence of out-of-plane flexural failure [28]. Specifically, the out-of-plane failure results in flexural cracks that spread horizontally and finally into the lintel band, causing the lintel-band and corner failure. The influence of post-tensioned coconut fiber ropes in controlling uplift during earthquake loading of interlocking mortar-free block construction was studied [29]. Due to the inclined main shape, it was proven to an effective in regaining its first place after the ground motion. Research findings were used to strengthen the empirical relationship in the context of the peak soil acceleration function [30]. In predicting the actual seismic response of the structure, which may be complied with due to the complexity of the interlocking block column, a difference of 35 percent was seen. The study findings were satisfactory in order to provide cost-effective earthquake-resistant building strategies for homes.

FIGURE 2.1: Typical out-of-plane failures of conventional masonry under one-way and two-way bending [1].

Conventional masonry and reinforced masonry differ significantly in terms of construction method, structural performance, and suitability for seismic regions [30]. Conventional masonry involves stacking bricks or blocks with mortar and relies primarily on gravity and the bonding strength of mortar for stability [31]. It generally offers moderate structural strength and poor to moderate seismic performance. Its construction is relatively straightforward but slow, requiring skilled masons, and the structures are often not reusable or easily repairable after damage [32]. In contrast, reinforced masonry integrates steel reinforcement bars within the masonry units and mortar, significantly enhancing strength, ductility, and the ability to resist lateral loads such as those from earthquakes [27]. Although it provides better seismic performance and higher structural integrity, it requires more time, skilled labor, and incurs higher material costs due to the use of steel and cement. Additionally, while both systems have environmental impacts, reinforced masonry typically has a larger footprint due to its greater resource consumption.

The out-of-plane dynamic behavior of double-story masonry structures refers to the way that walls or other faade elements respond to seismic or dynamic loads that act perpendicular to their plane [33]. These types of buildings are particularly vulnerable to unreinforced or improperly linked masonry walls because of their poor tensile and flexural strength perpendicular to the wall surface [34]. The out-of-plane direction is considered because it represents the most critical and vulnerable response mode of masonry walls under lateral loading, where low tensile strength, slender geometry, and weak boundary restraint conditions combine to produce flexural instability and potential sudden collapse. Inertial forces cause wall panels, especially those not firmly attached to diaphragms or transverse walls, to vibrate or move outward during seismic excitation, potentially leading to cracking, detachment, or complete collapse [35]. Because of the varying stiffness and mass distribution between the two levels, the problem becomes more complex in double-story masonry buildings. Stiffness is the resistance of a structural element or system to deformation under applied loading, quantified as the ratio of applied force to the resulting displacement. In mortar-free interlocking construction, It is defined as the resistance of the block assembly to lateral deformation, primarily controlled by interface friction, interlocking geometry, and contact behavior between dry joints. Top-story walls often accelerate faster due to amplification effects, whereas lower-story walls may bend and rock more because of the inertia of the top walls.

### 2.2.3 Comparison between Conventional and Reinforced Masonry and its Innovative Solution

The majority of the traditional masonry houses generally collapse due to ignorance of adopting proper designs and engineering practices as well as following contemptible construction procedure [36]. Table 1 illustrates the properties of conventional and reinforced masonry. Unreinforced masonry (URM) walls are the basic load-bearing elements in masonry buildings. During earthquakes, the typical failure mode observed in these structures are junction failures and out-of-plane wall failures. This type of failure is typically marked by the formation of a masonry wedge, primarily caused by the combined effects of roof thrust and inertial forces [28]. To achieve the goal of producing safe houses by resisting ground motion an alternative and cheap solution is to produce interlocking blocks which could not only resist earthquake but could be a fast and low-cost construction solution. To get creative and economic solution, new techniques have been developed by using the mortar-free interlocking blocks to construct earthquakes resistance structure [2]. Many researchers have contributed in this regard and have presented many ways and solutions to make safe and earthquake resistant houses and medium tall buildings by using interlocking blocks [37]. The weight of interlocking blocks is a point of concern, to do so an effort was made by introducing fiber reinforced concrete interlocking block. Coconut fibers were added to reduce the weight of interlocking block, but ultimately the mass of fiber reinforced concrete block was observed to increase instead of decreasing [38].

Discontinuities that can create weak points and increase the risk of out-of-plane instability include openings, improper vertical wall alignment, and inadequate floor-to-wall anchorage [39]. For realizing this goal of creating safe homes through resisting motion on the grounds, another alternate and cheap option would be to create blocks, which could also resist earthquakes forces, which could also lead to fast, and cheap solution. Furthermore, flexible diaphragms (like timber flooring) that do not offer adequate lateral restriction may permit excessive movement [40]. Prior earthquake observations have documented significant out-of-plane failures in several double-story masonry buildings, when higher facade panels collapsed outward, sometimes resulting in progressive collapse. Out-of-plane behavior is generally more critical in masonry structures due to low tensile strength perpendicular to the wall thickness, high slenderness, and dependence on boundary restraints. Out-of-plane loading induces flexural instability and often leads to sudden brittle failure, making it a governing mode for collapse, particularly in unreinforced and mortar-free masonry systems. To combat this, proper detailing is required to ensure an integrative, box-like seismic reaction and increase the out-of-plane capacity [41]. This includes continuous wall-to-diaphragm anchorage, the use of

Table 2.1: Properties of conventional and reinforced masonry [4]

| **Aspect** | **Conventional Masonry** | **Reinforced Masonry** |
|---|---|---|
| Construction Method | Laid with mortar between units | Masonry units + reinforcement (steel bars) + mortar |
| Structural Strength | Moderate; relies on gravity and mortar | High; improved by reinforcement |
| Seismic Performance | Poor to moderate | Good; handles lateral forces better |
| Speed of Construction | Slow to moderate | Slow; reinforcement and curing required |
| Material Cost | Moderate | High; due to reinforcement and skilled labor |
| Labor Skill Requirement | Requires skilled masons | Requires highly skilled labor |
| Environmental Impact | High; uses cement and bricks | Higher steel and cement use |
| Reusability | Low; difficult to dismantle | Low; permanent with embedded steel |
| Maintenance and Repair | Moderate; cracks require repointing | Complex; needs structural assessment |
| Applications | Residential buildings, boundary walls | Load-bearing walls, seismic zones |

bond beams, and reinforcement or retrofitting using steel ties, FRP strips, or shotcrete.

## 2.3 New Techniques: Mortar-free Interlocking Masonry

### 2.3.1 Mortar-free Masonry System

Traditional brick masonry is laborious and tedious; modern techniques offer stiff competition to the conventional building methods [42]. Mortar-Less Masonry Systems (MMS) employ self-locking or dry-stack blocks that do not require mortar, offering a viable option for mitigating the dependency on skilled labor and enhancing efficiency [43]. MMS provides efficient load-carrying capacity, necessitating supplementary reinforcement to withstand cyclonic and seismic effects. Mortarless self-locking buildings demonstrate superior performance compared to other constructions concerning the resistance to gravity and lateral loads [44]. In gravity loading scenarios, the compressive strength of the block units determines the resistance and failure modes [31]. MMS offers a suitable alternative to traditional masonry, facilitating reduced labor intensity and improved efficiency while requiring supplementary reinforcement against cyclonic and seismic effects [45]. The effectiveness of MMS is mainly dependent upon the compressive strength of the block units.

Its mechanical block-to-block interlock and gravity-based stability, rather than the bonding strength of mortar joints, mostly control the out-of-plane dynamic behavior of mortar-free interlocking brickwork. These methods enable dry building without the use of cement by assembling carefully planned components, often with protrusions and recesses to create sturdy wall assemblies [46]. The self-weight, frictional resistance, and geometric interlock of the units, along with the presence or absence of vertical or horizontal post-tensioning devices, significantly influence the wall's response to out-of-plane dynamic loads, such as seismic shaking or blast pressure [47]. Because there is no mortar to preserve tensile continuity, walls may rock, slide, or partially separate between blocks when inertial forces exceed the frictional capacity. This is especially true at higher elevations, where there is a greater need for acceleration. However, the interlocking shape can help provide more fair weight distribution and prevent complete collapse by maintaining partial contact between blocks even after displacement [48]. The lightweight design of some interlocking systems can reduce out-of-plane inertial forces, but it may also increase their vulnerability to overturning if anchorage is inadequate. Plastic interlocking blocks exhibit lower stiffness compared to conventional masonry materials such as clay bricks and concrete blocks due to their reduced elastic modulus and dry joint behavior. Consequently, plastic block assemblies demonstrate higher deformation capacity, whereas traditional masonry systems provide greater rigidity. The stiffness difference typically results in larger lateral displacements but improved ductility and energy dissipation in plastic block construction.

The block design, frictional contact surfaces, and overall mass distribution, rather than the cohesive bond that mortar provides in traditional masonry, mostly determine the dynamic behavior of mortar-free interlocking brickwork [49]. These technologies use mechanical interlock to fit precisely designed blocks together, enabling the wall to act as a self-supporting structure. When exposed to dynamic loads like seismic shaking, wind gusts, or impact forces, the response is characterized by rocking, sliding, and a slight separation between blocks at the joints [50]. Because the connections are dry, the system can withstand minor relative displacements without breaking in the traditional sense; instead, energy is released through controlled movement and friction at the contact interfaces. This rocking motion may strengthen the wall's resistance to brittle failure by reducing the peak acceleration communicated through the wall.

### 2.3.2 Pros and Cons of Mortar-free Interlocking Masonry

Mortar-free interlocking masonry presents a modern and efficient alternative to traditional construction methods, offering several advantages along with certain limitations. One of its key benefits is the elimination of mortar, which simplifies construction, reduces reliance on skilled labor, and accelerates the building process [51]. This system also enhances sustainability by lowering the use of cement and water, making it an environmentally friendly option. Structurally, interlocking masonry performs well under gravity and lateral loads due to the precision of block alignment and the energy dissipation enabled by inter-block friction, especially during seismic events [52]. Energy dissipation is defined as the capacity of a structural system to absorb and dissipate externally supplied energy through inelastic deformation mechanisms, quantified as the area enclosed by the force-displacement hysteresis loops obtained under cyclic loading. In mortar-free construction, this dissipation is primarily governed by frictional sliding, rocking, and interface interactions between interlocking units. However, the system does have drawbacks. It often requires additional reinforcement to resist in-plane shear and out-of-plane flexure, especially in high seismic or cyclonic zones. Furthermore, the compressive strength of the interlocking blocks is crucial, as it directly affects the system's load-bearing capacity [44]. While mortar-free construction reduces construction time and material use, its long-term durability and structural integrity under complex loading conditions still require further research and standardization to ensure safe, widespread adoption.

Without the need for drying time, interlocking brickwork without mortar enables quick, clean construction and is easy to assemble and disassemble for reuse or repair [53]. It removes the need for specialized labor, prevents shrinkage and heat cracking often caused by mortar, and can maintain good dimensional accuracy and alignment due to precise block manufacturing. Some designs further improve earthquake resilience with controlled rocking mechanisms that release energy without causing catastrophic failure [54]. Since there is less inherent tensile strength due to the absence of mortar bonding, the structure relies more on friction and geometric stability, both of which can be compromised under heavy out-of-plane loads. Manufacturing tolerances that are too loose can create gaps that weaken stability [2]. Over time, surface wear, dirt in joints, and weathering can also reduce the effectiveness of interlocks. Without additional reinforcement or post-tensioning, frequent rocking and sliding during seismic events can lead to a progressive loss of contact and eventual instability. Mortar-free interlocking plastic block construction is considered economical due to elimination of mortar, reduced labor dependency, faster construction, lightweight transportation advantages, and lower lifecycle maintenance costs. The cumulative reduction in material, labor, and time-related expenses leads to a possible lower total construction cost compared to conventional masonry systems.

A contemporary and effective substitute for conventional building techniques, mortar-free interlocking brickwork has a number of benefits but also some drawbacks. The removal of mortar, which speeds up the building process, simplifies construction, and lessens the need for specialized labor, is one of its main advantages [55]. This technology is an environmentally beneficial choice that also improves sustainability by using less water and cement. Because of the accuracy of block alignment and the energy dissipation made possible by inter-block friction, interlocking brickwork works well structurally under lateral loads and gravity, particularly during seismic occurrences [52]. But there are problems with the system. To withstand in-plane shear and out-of-plane flexure, it frequently needs extra reinforcement, particularly in seismically active or cyclonic zones. Furthermore, because it directly impacts the system's ability to support loads, the interlocking blocks' compressive strength is essential [56]. Although mortar-free construction saves time and money, further research and standardization are still needed to ensure its long-term durability and structural integrity under complicated stress circumstances. The primary challenges in real construction using plastic blocks include low stiffness, creep-induced long-term deformation, poor fire resistance, thermal expansion effects, connection difficulties with conventional structural components, and a lack of standardized design guidelines. These factors influence structural reliability and currently limit widespread adoption in load-bearing applications.

### 2.3.3 Properties of Mortar-free Masonry

A new construction technique for earthquake-proofed housing has been introduced using mortar-less interlocking concrete blocks. Interlocking mortar-less masonry is an emerging construction material that promises great potential for future constructions, especially considering its sustainable and economical use for housing purposes. The characteristics of mortar-less masonry are detailed in Table 2 [4]. The walls consist of special mortar-less interlocking bricks that provide not only ease in positioning during construction but also improved shear resistance [57]. The walls were tested under in-plane cyclic loading conditions in order to evaluate their structural capabilities, which were compared to ordinary walls used in existing literature regarding their better capability to withstand earthquake loads and dissipate the energy produced by the earthquake. Mortar-less interlock-ing blocks are much heavier than regular interlocking blocks, and thus they produce stronger inertia forces due to their heavier nature [58]. Mortar-less interlocking blocks with slanted keys are capable of dissipating earthquake energy and resuming their positions after the earthquake due to the slanting keys used in them.

However, localized joint opening, partial panel dislodgment, or gradual overturning may occur if lateral forces surpass the geometric and frictional stability, especially in higher walls or those with inadequate vertical restraint [59]. Brick walls have been found to have greater seismic resistance than conventional CMU walls, where the brick friction is the main component of seismic resistance. The load resistance mechanism of connected bricks is considerably different owing to the interlocking effect. These systems can also automatically re-center after mild shaking because there are no stiff mortar joints; instead, the blocks are helped to return to their initial alignment by gravity and interlock geometry. While heavier variants of such systems improve stability by increasing self-weight but may cause larger base reactions, lightweight ones lower inertial demands [60]. MFI (Mortar-Free Interlocking) sliding and rotation in the OOP direction is helpful in 25 percent of energy dissipation as compared to conventional masonry dissipation. The relative motion of interfaces is increased owing to mortar-free construction. Overall, block accuracy, surface conditions, and the presence of supplemental measures, such as vertical reinforcement, post-tensioning, or tie elements, all of which can significantly improve stability and integrity during repeated dynamic loading, have a substantial impact on the dynamic performance of mortar-free interlocking masonry.

In terms of construction efficiency, cost-effectiveness, and seismic performance, mortar-free interlocking masonry provides a contemporary substitute for both traditional and reinforced masonry systems. By using specifically made blocks that fit together without cement, mortar-free interlocking systems enable speedier construction with fewer skilled workers than conventional masonry, which uses mortar to connect units [37]. Through energy dissipation at block interfaces and self-locking mechanisms, particularly in out-of-plane motion, interlocking masonry provides equivalent or higher seismic performance to reinforced masonry, which uses steel reinforcing to increase strength and seismic resistance. Interlocking systems are more cost-effective and ecologically friendly than reinforced masonry, particularly when lightweight or recyclable materials are used [61]. Moreover, interlocking structures are often more sustainable, allowing for easier disassembly, reuse, and repair. However, for high seismic zones, additional measures such as

TABLE 2.2: Properties of Mortar-free masonry [4].

| **Aspect** | **Mortar-free Masonry** |
|---|---|
| Construction Method | Dry stacked using interlocking blocks (no mortar). |
| Structural Strength | Variable; depends on interlock design and block material. |
| Seismic Performance | Good; joints allow movement and energy dissipation. |
| Speed of Construction | Fast; blocks stack easily and without curing time. |
| Material Cost | Low to moderate; plastic blocks can be recycled and reused. |
| Labor Skill Requirement | Low; user-friendly and simple assembly. |
| Environmental Impact | Low; often uses recycled plastic and no cement. |
| Reusability | High; can be disassembled and reused easily. |
| Maintenance and Repair | Easy; damaged blocks can be replaced individually. |
| Applications | Temporary shelters, low-cost housing, and disaster-prone areas. |

grout or external reinforcement may still be necessary to match the structural robustness of reinforced systems. Plastic blocks are utilized due to their lightweight characteristics, mold ability for interlocking geometries, enhanced deformation capacity, recyclability, and construction efficiency. These properties make them particularly suitable for mortar-free systems, enabling improved seismic performance, reduced construction cost, and sustainable material utilization.

## 2.4 Interlocking Mechanism of Mortar-free Construction

### 2.4.1 New Approach for Earthquake-Resistant Structure

The mortar-free unconfined block masonry systems with interlocking blocks with the self-locking capability can endure low to moderate seismic loads, acting as energy dissipation devices to prevent brittle shear failure. The mortar-free building technique facilitates effective energy dissipation during earthquakes owing to the movement of blocks relative to each other. The paste used in the adhesion of blocks proved to be very useful in increasing the compressive strength of the masonry prism [62]. In the case of both direct and diagonal shear tests, which involved the interlocking keys directly, it was observed that the use of adhesive paste and grout increased the shear strength. With the introduction of grout, steel reinforcement, and adhesive paste, there was an improvement in ductility and strength of the masonry structure subjected to various loads [63]. Because the interlocking process relies on specifically designed blocks that join via self-locking elements like projections, grooves, or keys, traditional mortar is not used in mortar-free construction. These blocks are easy to construct without sacrificing structural strength because of their exact fit [2]. By permitting controlled relative movement between blocks, the interlocking system distributes energy and lowers the chance of brittle fracture during seismic occurrences. Because of this movement and the blocks' restricted capacity for rotation and sliding, the structure is more ductile and better suited to absorb and recover from seismic shocks than conventional masonry. In some designs, grout, adhesive pastes, or minimum reinforcement can be used to boost shear capacity and strength without sacrificing the dry-stack principle [64]. In addition to simplifying construction and reducing the requirement for labor, the interlocking system provides a dependable, effective solution for resource-constrained and earthquake-prone areas.

The mortar-free blocks' interlocking system provides structural integrity without the need for cement by using precisely shaped blocks that fit together like puzzle pieces. These blocks often contain slanted keys, tongues, or grooves that enable them to interlock both horizontally and vertically, ensuring alignment and resistance against lateral and vertical loads. In the event of seismic stress, the relative movement between blocks allows for controlled rotation and sliding, dispersing energy and reducing the likelihood of brittle failure [65]. Lightweight materials, such as recycled plastic or modified concrete, further enhance this performance by reducing the overall mass of the structure, which reduces inertia forces during earthquakes. In addition to improving seismic resilience, this mechanism speeds up construction, simplifies handling, and may even be reusable, making it a viable and efficient alternative to traditional masonry systems. In addition to improving structural flexibility, this mechanism speeds up construction, simplifies handling, and may even be reusable, making it a viable and efficient alternative to traditional masonry systems. Structural flexibility is the measure of a structural system's deformation capacity under applied loading, representing the displacement produced per unit force and defined as the reciprocal of structural stiffness. It governs the dynamic response and drift characteristics of structures subjected to lateral or seismic loads.

### 2.4.2 Structure of Interlocking Blocks

Traditional mortar isn't necessary in mortar-free construction because the interlocking process depends on specially made blocks that connect through self-locking features like projections, grooves, or keys. Due to their precise fit, these blocks can be assembled easily while maintaining their structural strength. The interlocking mechanism disperses energy and reduces the risk of brittle fracture during seismic events by allowing controlled relative movement between blocks [37]. This movement, along with the blocks' limited rotation and sliding abilities, enhances the structure's ductility. It refers to the capacity of a structural system to sustain significant inelastic deformation while maintaining load-carrying ability. In mortar-free interlocking masonry, ductility is governed primarily by interface mechanics such as rocking, sliding, and joint opening. It is quantitatively evaluated through displacement ductility obtained from loaddisplacement response curves, representing the ratio of ultimate deformation capacity to yield deformation, and serves as a critical indicator of seismic resilience and energy dissipation capability, making it more capable of absorbing and recovering from seismic shocks than traditional masonry. In some designs, shear capacity and strength can be increased without compromising the dry-stack principle by adding grout, adhesive pastes, or minimal reinforcement [66]. The interlocking system not only makes construction easier and lessens the need for personnel, but it also offers a reliable, efficient solution for areas that are prone to earthquakes and have limited resources.

The unusual way that specifically shaped blocks transfer and resist forces without depending on a continuous mortar bond gives rise to the dynamic properties of the interlocking mechanism in mortar-free building. These systems restrict relative movement between neighboring units in both vertical and horizontal directions by use of mechanical interlocks such as protrusions, grooves, keys, or tongue-and-groove joints [67]. The interlock shape permits controlled micro-movements like rocking, sliding, or rotation at the joints while facilitating force transfer through direct contact and friction under dynamic loading conditions like earthquakes, wind gusts, or impact forces. When blocks re-engage following slight separations, the system can disperse seismic energy through impact restitution and frictional damping thanks to this partial freedom of movement.

After shaking, the self-aligning geometry and gravity-driven re-centering capacity assist the wall in regaining stability and minimizing any remaining deformations. Block manufacture requires precision; close tolerances guarantee that contact surfaces connect efficiently, reducing accidental looseness that might intensify vibrations. Furthermore, the interlock design improves stability under both in-plane and out-of-plane dynamic activities by offering resistance in various directions [63]. Block mass, surface roughness, and vertical restraint techniques like post-tensioning or strengthening, which can stiffen the structure and lessen excessive rocking or sliding, all have a significant impact on the dynamic response [68]. Because the interlocking mechanism in well-designed systems strikes a balance between stability, flexibility, and energy dissipation, mortar-free construction may be more resilient in dynamic environments than brittle, monolithic masonry. In mortar-free construction, flexibility refers to the deformation capacity of the interlocking block assembly governed by sliding, rocking, and joint opening at dry interfaces. The absence of mortar increases flexibility, enabling larger displacements and improved energy dissipation under dynamic loading, although it reduces initial stiffness.

### 2.4.3 Behavior of Interlocking Masonry

In terms of energy dissipation, structural behavior, and ease of assembly, mortar-free construction's interlocking mechanism has a number of advantages over traditional masonry. Using mortar to join blocks or bricks, traditional masonry produces a solid, monolithic structure that is mostly dependent on the strength of the mortar's connection and the craftsmanship of the individual blocks [31]. Because the structure lacks the flexibility to adapt to ground movement, this rigidity frequently results in brittle collapse under seismic loading. On the other hand, blocks with unique shapes that fit together using tongue-and-groove or other geometric locking features are used in mortar-free interlocking construction [69]. During seismic occurrences, this self-locking mechanism permits relative movement between blocks, allowing the structure to release energy through controlled deformation and friction. Because of this, interlocking systems are more resilient and ductile, especially when moving out of plane, when traditional masonry is more likely to break [57]. Furthermore, the dry stacking of interlocking blocks makes it possible to build more quickly, disassemble more easily, and require less specialized personnel, which makes it a more flexible and sustainable option for areas that are prone to earthquakes and have limited resources.

For achieving stability, transferring loads, and preventing movement, the interlocking mechanisms of conventional, reinforced, and mortar-free masonry are essentially different. In order to create mechanical engagement between units, mortar-free interlocking brickwork depends on the precise geometry of its blocks, which frequently have keys, grooves, or tongue-and-groove profiles. Geometric interlock, friction at contact surfaces, and the wall's self-weight without any bonding substance between joints are the main sources of stability [70]. This facilitates energy dissipation, controlled rocking and sliding under dynamic loads, and ease of assembly or disassembly; nonetheless, it necessitates excellent manufacturing accuracy and occasionally additional reinforcing for increased stability. Bricks or rectangular blocks joined by mortar, which fills in spaces, joins units, and offers shear resistance through adhesion and friction, are used in conventional (unreinforced) masonry. Because it is brittle, stability can be rapidly jeopardized when mortar joints shatter under tensile or shear pressures.

Nevertheless, the mortar joint acts as a leveling bed and a bonding agent, creating a continuous monolithic structure that resists displacement. Reinforced masonry provides tensile strength, ductility, and improved energy dissipation by combining the mortar-bonding process of traditional masonry with embedded steel reinforcement (horizontal joint reinforcement, vertical bars, and grouted cores) [71]. In this case, the interlock is structural due to reinforcement that connects the assembly to a load-resisting system and mechanical due to mortar and unit contact. This reinforcement reduces progressive failure after cracking and enhances both in-plane and out-of-plane performance. Essentially, to achieve structural integrity, mortar-free systems rely on geometry and friction, conventional masonry on mortar bonding and unit alignment, and reinforced masonry on the combined action of steel and mortar.

### 2.4.4 Interlocking Mechanism for Innovative Construction

Interlocking brick walls offer better seismic performance than conventional CMU walls, as their energy dissipation occurs via friction between the bricks. Due to the interlocking characteristics, the load transfer characteristics of brick joints vary from those of conventional masonry mortar joints. Moreover, the vertical ground motion component plays an important role in determining damage owing to the rocking response [72]. Figure 2 illustrates interlocking methods of the blocks used in different research studies. MFI blocks can slide and rotate in the out-of-plane direction by 25 percent more than conventional masonry in energy dissipation. Construction without mortar increases relative movement between blocks, which improves energy dissipation during earthquakes. Interlocking brick walls exhibit superior seismic performance than conventional CMU walls, as energy dissipation occurs via inter-brick friction [57]. Construction without mortar aids in improving energy dissipation through the relative motion of blocks.

The lack of stiff mortar joints permits some rocking, sliding, or rotation at the block interfaces in seismic or dynamic circumstances, which aids in energy dissipation and lowers stress concentrations. Because blocks tend to realign due to gravity and joint form, the interlocking design ensures that any movement is restricted and frequently self-correcting, limiting excessive displacement. The shape prevents total separation unless forces beyond the interlock capacity are applied, and load transfer mostly happens through compression in vertical joints and shear/friction in horizontal joints [73]. In addition to providing the opportunity for reinforcement integration, such as vertical rebar or post-tensioning, to further improve stability

FIGURE 2.2: Interlocking mechanisms for blocks [2].

and load resistance, this modular, dry-stacked method allows for speedy assembly, disassembly, and maintenance. To guarantee constant engagement and even load distribution throughout the structure, the mechanism's efficacy is largely dependent on manufacturing accuracy, surface quality, and block shape optimization.

Instead of relying on mortar's bonding properties, mortar-free construction relies on the precise geometric interlocking of masonry units [74]. Each block in this system is made with unique profiles, such as tongue-and-groove edges, protrusions (keys), grooves, or dovetail forms, which fit closely with neighboring units both horizontally and vertically. When layered, these interlocking features mechanically limit relative movement, enabling the direct passage of vertical loads through bearing surfaces and the resistance of lateral loads through geometric engagement and friction. Because the assembly's self-weight keeps the blocks firmly in contact and increases frictional resistance at the interfaces, gravity is essential to stability.

## 2.5 Previous Studies on Plastic Block Mortar -free Construction

Thanaya [75] studied the characteristics of plastic block as building block material, produced by dissolving waste plastic wrap, i.e., shopping bags (crackle plastics), aluminum-coated thin plastic waste, and other types of thin plastic waste, into waste engine oil, without and with rice husk ash as filling materials. Plastic wrap waste increases over time. Efforts are needed to utilize them as they are less demanded for recycling by the private sectors in Bali and Indonesia. This study describes an effort to describe a combination of waste thin plastic wrap as a plastic block for wall construction material. The plastic wrap wastes were cut into 5-10 mm size, then they were melted in a hot waste engine oil at 200C. The mixture was then poured into a metal mold, slightly cooled down, and compressed using a compression machine. The mixtures produced were without and with added rice husk ash as filling material.

Tchuigwa [76] studied the compressive strength of building blocks produced using two different processes: the traditional mold/press method and 3D printing with varying infill percentages. The results showed that while the mold/press prototype required the most time and resources, it had the weakest structural performance. In contrast, the 3D printed prototypes showed significantly better compressive strength, with the 90% infill prototype achieving the highest resistance. However, increased material consumption and longer production times remain challenges for 3D printing as a viable construction method. In light of these findings, future research should focus on optimizing manufacturing processes to improve efficiency and structural integrity. Finite Element Analysis (FEA) is a promising approach to reduce the need for extensive physical testing while allowing for in-depth numerical simulations. By integrating FEA, researchers can refine material selection and structural design before prototype fabrication, minimizing resource consumption and improving sustainability. Ultimately, this research highlights the potential of recycled polymer materials in sustainable construction and emphasizes the need for further development to overcome existing limitations and improve performance for real-world applications.

Ferreira [77] studied the development, manufacture, and characterization of PP and HDPE recycled polyolefin blocks as masonry components in civil construction. The rotational molding process manufactured these blocks. Besides this, the mechanical, physical, impact, and flammability properties of the blocks were studied. The lack of suitable destinations for plastic materials can be a global environmental problem. The alternative use of materials for sustainable construction encourages the standardization of waste, promotes effective social, environmental, and economic gains at the local level, and ensures savings and income for communities. In addition, polypropylene (PP) and high-density polyethylene (HDPE) are relevant polymer wastes because they are polyolefins used in foam sheets and can indicate satisfactory results even with 50% of granules replacing virgin materials.

Udhaya [78] studied the mechanical and physical properties of interlocking blocks made from mixtures of plastic and industrial waste materials, including fly ash, waste glass powder, and concrete debris. Billions of metric tonnes of solid waste are produced annually. This includes Polyethylene Terephthalate (PET) plastic waste and other industrial manufacturing by-products. This study assesses the durability of waste plastic blocks (WPB), which are made by repurposing scrap plastics from PET. Mechanical and fire resistance properties of WPB have been optimised by varying mixing proportions of PET plastic and mixtures of industrial waste materials like fly ash, waste glass powder, and concrete debris in ratios of (20:80, 30:70, and 40:60), respectively. This investigation integrates various wastes synergistically to produce blocks, aiming to replace traditional blocks made from cement and clay.

Ahmed [79] studied a comprehensive review of literature about the potential of mortar-less construction in local regions. This is accomplished by focusing on articles published in highly reputable journals over the last decade. Pakistan is currently facing an issue of housing demand due to 2.4% annual population growth. Mortar-less construction, being one of the vibrant techniques, has its own pros and cons. The mechanism of interlocking commonly depends on the block shape, applicable restraints, and interfacial angles. Interlocking blocks with lugs and keys have the ability to use their topology in maintaining the structural integrity. The peripheral boundary of a block is responsible for maintaining the structural stability by dissipating frictional forces at contact surfaces. Boundary constraints like lintels and tensioned ropes provide additional integrity to the whole structure. The interfacial angle between interlocked surfaces determines the resistance of block removal against lateral loading. Local regions in Asia, and particularly

Pakistan, face economic limitations in construction. Practical implementation of mortar-less interlocking structures can be economically beneficial, provided sufficient robustness for stability.

Ullah [80] studied the development and properties investigation of recycled plastic solid interlocking blocks. Plastic waste accumulation threatens the environment, yet high-density polyethylene (HDPE), a major constituent of this waste, can be recycled into building materials. This study fabricates solid interlocking blocks (SIBs) entirely from recycled-HDPE waste using extrusion molding. Molds were developed for manufacturing specimens for the characterization of material. Standardized mechanical tests (compression, shear, flexure, tensile) were conducted on recycled-HDPE as per ASTM standards. These blocks show ductile energy absorption in shear, indicating robustness under mechanical loading. By avoiding virgin polymer and mortar, i.e., no cement, they offer clear sustainability advantages for low-carbon mortar-free masonry.

Das [81] studied the sustainable development and assessment of low-strength/high-toughness recycled plastic rebars for structural elements under light loads. The construction sector faces growing pressure to adopt sustainable alternatives amid the global plastic-waste crisis. This study presents a novel use of mechanically recycled high-density polyethylene (HDPE) and polypropylene (PP) to manufacture full-scale plastic rebars for mortar-free, light-load construction applications. Unlike prior studies that confined recycled plastics to filler roles in composites, this work validates their direct application as full-section, load-bearing members. Additionally, a polynomial-based empirical model was formulated to predict the tensile behavior of the recycled rebars. The findings underscore the potential of mechanical extrusion as a low-emission, scalable solution to convert plastic waste into durable construction materials that support circular economic principles.

The limited research on plastic block construction is primarily attributed to the absence of standardized design codes, concerns regarding stiffness, creep, and fire performance, and the need for long-term durability validation. Additionally, manufacturing constraints and the novelty of the material have restricted extensive experimental and analytical investigations, particularly for multi-story structural applications.

## 2.6 Summary

Traditional masonry buildings are susceptible to seismic loads because of weak connections, poor material quality, and improper construction techniques. Although there have been some advancements in mortar-free interlocking (MFI) masonry systems with better block shapes and grouting that have improved their seismic response through energy dissipation, shear strength, and ductility, certain structural characteristics require further investigation. MFI systems permit the relative displacement of blocks to minimize damage to the building structure from an earthquake. The system is capable of dissipating up to 25% of energy by sliding and rotation. Nevertheless, the dynamic response of two-story mortar-free interlocking systems has not been extensively studied despite its importance in the structural stability of buildings subjected to earthquakes.

# Chapter 3

# Experimental Program

## 3.1 Background

A precise estimation of the behavior of structures in seismic zones is necessary for safe designing. Dynamic testing of prototypes of such structures in laboratory tests is common practice in the international community. The focus of this chapter is on the construction method of building an interlocking double story structure made out of plastic block walls, experimental set-up, snapback test instrumentation, dynamic loadings through shaking table, parameter estimation, and formulation of empirical relationships.

## 3.2 Continuation of Research Program

Khan [3] proposed the Interlocking-Plastic-Block (IPB) for earthquake resilient residential structures, with a plan and three-dimensional view of the proposed house presented in Figures 3.1(a) and 3.1(b). Because of its reduced mass and hence lower inertia forces, the technology has proven useful in scaled-down testing. The materials' weight and the corresponding inertial forces significantly influence the performance of seismic-resistant constructions. The resistance of a system to changes brought about by outside forces, like acceleration, is commonly referred to as inertial force. According to the Third Law (Action-Reaction principle), Newton's Law of Motion, and the Law of Inertia, systems with higher mass (heavier materials) react more strongly to external forces because of their increased weight. Compared to lighter systems, this leads to higher inertia forces.

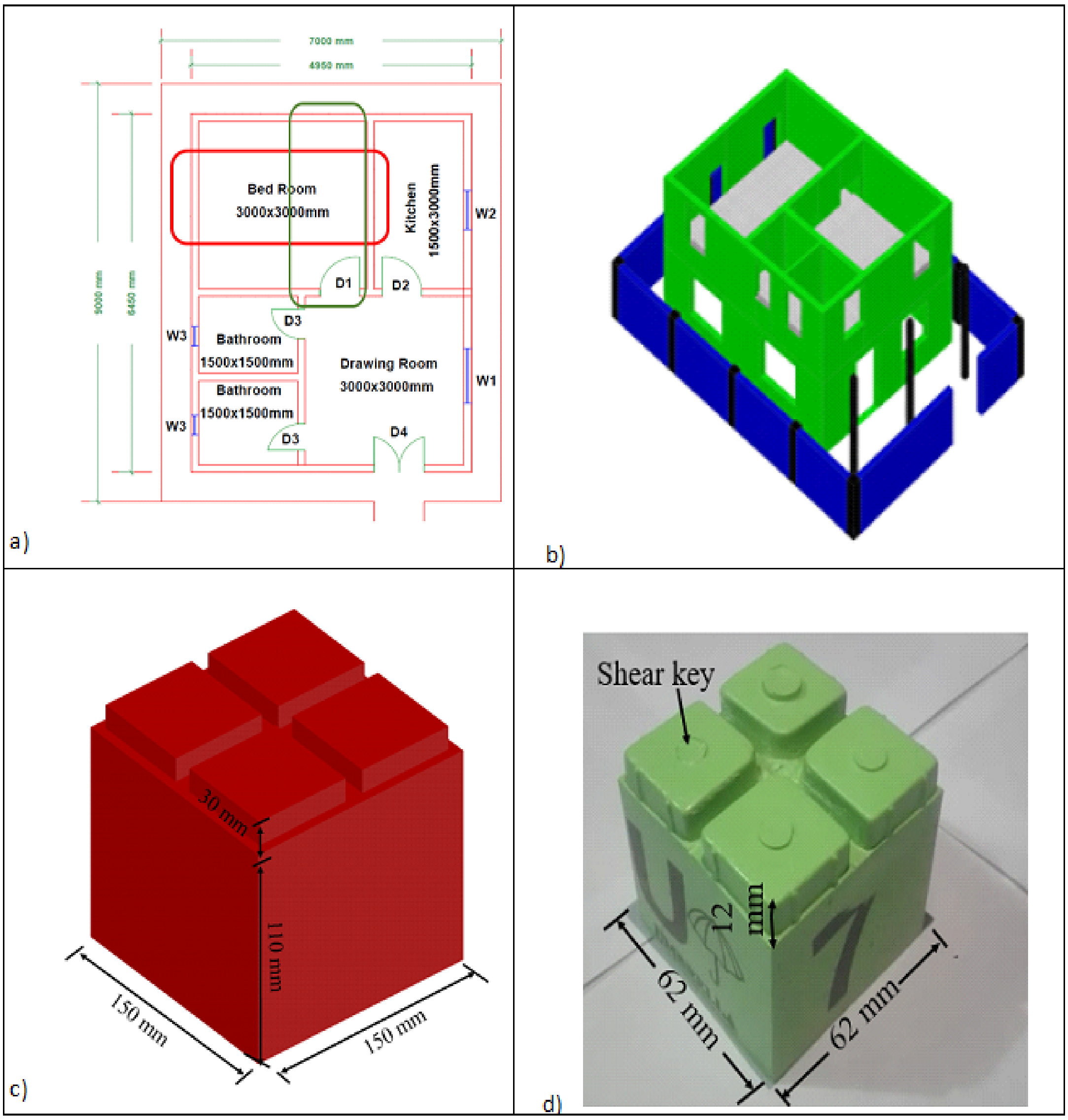



FIGURE 3.1: Proposed mortar-free interlocking-plastic-block house: a) plan, b) 3D view, c) proposed interlocking-plastic-block, and d) real plastic block Khan [3].

The suggested IPBs have a base dimension of 150 mm by 150 mm and are made with four interlocking keys on the top surface, as shown in Fig. 3.1 (c), to make it easier to build seismically resilient housing. As shown in Figure 3.1(d), the block utilized for the experiment is 62 mm tall and has an interlocking key that is 12 mm high. The blocks utilized in the study for the scaled-down construction were 62 mm by 62 mm and 50 mm tall overall. They included a 12 mm interlocking key that was intended to enhance block connectivity, as seen in Figure 3.1(d). This investigative work is an extension of a study conducted by Khan [3]. A square plastic block with four keys, a vertical joining key, and a groove interlocking is used in the current study to build a prototype.

A prototype double-story building made of interlocking plastic block walls is put through dynamic testing in this study. Instead of depending only on theoretical models, the main goal of the scaled-down testing is to provide specifications for a workable, real-world system. The methods used to scale and build the prototype walls in this study are entirely derived from accepted procedures described in the literature. The findings of these investigations advance our knowledge of how full-scale structures behave.

The goal of current research is to examine the double-story's dynamic nature. According to UBC-97, the structure is a significant factor that is dependent on its height during this time period. As a result, the scale-down method is mostly applied to structural wall elevation dimensions. It is significant to note that the prototype's units (i.e., the scaled-down double-story IPB walls without mortar) have somewhat different proportions. Figure 3.2(a) shows the house's plan and elevation, taking into account the original double-story. The simplified and reduced boundary requirements for the double-story are shown in Figure 3.2(b).

A scaled-down double-story in an interlocking plastic block wall without mortar, with wall configuration Sequence A and B, is depicted in Figure 3.2(c). A plate made of steel angle section is used to secure the double-story. In this study, walls of 6000 mm (double-story) in length and 6000 mm (double-story) in height are taken into consideration for the double-story. The wall length taken into account in this study is longer than the block-return length. A scaled-down length of 600 mm (double-story) and a height of 600 mm (double-story) are taken into account. Fixity at the bottom is guaranteed to replicate the real-world situation. The house plan appears to indicate the walls in question. Current research focuses on examining the double-story's behavior in the x-direction solely, assuming that the y-direction behavior would likewise remain unchanged according to the law of symmetry.

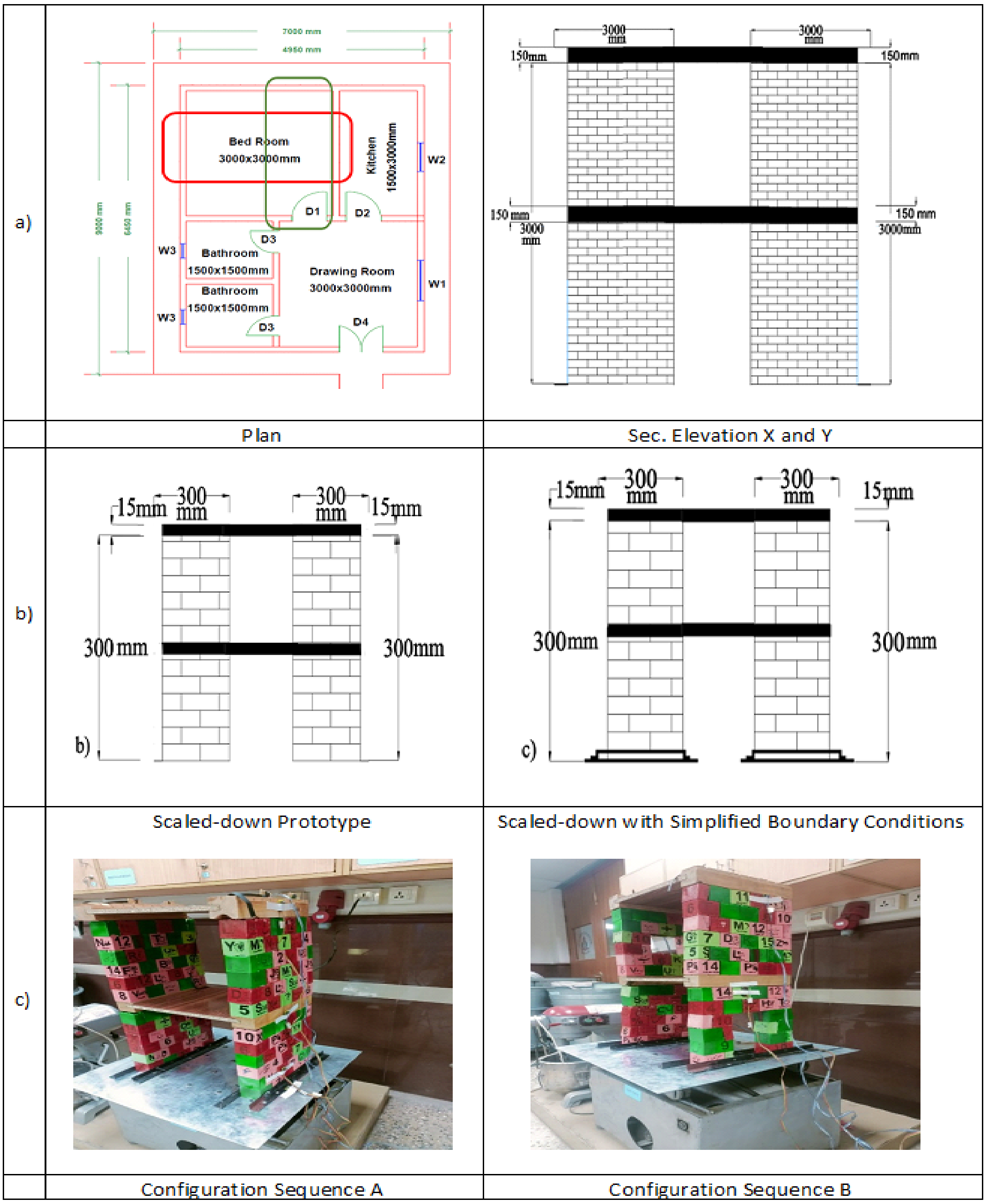



FIGURE 3.2: Consideration of double-story in out-of-plane direction; (a) plan and elevation of house with original double-story consideration, (b) scaled-down and simplified boundary conditions, and (c) double with configuration sequence A and B

## 3.3 Construction of Prototype Scaled-down

The double-story model of the interlocking plastic block wall can be produced by arranging 120 blocks of plastics (n = 120) with a height of 600 mm (double-story). The specimen comprises plastic blocks, a wooden diaphragm, angle sections connected to the base plate using nutbolt assemblies, and rubber stiffeners, which

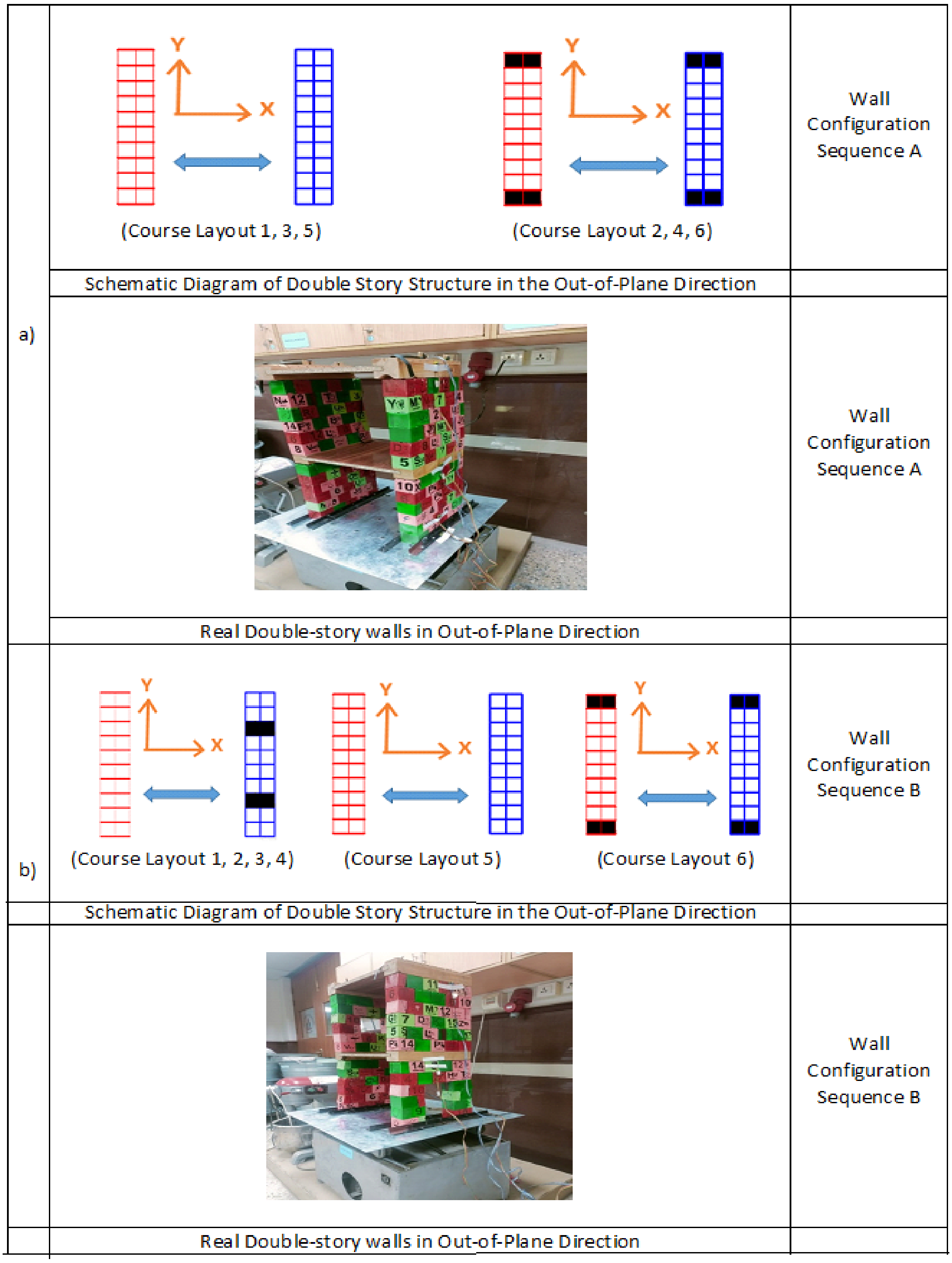



FIGURE 3.3: Out-of-plane Construction Details, a) Schematic diagram and real diagram of Double-story structure in out-of-plane direction (Wall Configuration Sequence A), b) Schematic diagram and real diagram of Double-story structure in out-of-plane direction (Wall Configuration Sequence B).

collectively form the structural configuration used for testing. The arrangement is performed in two sequences as follows. The first sequence, namely Sequence

A, has the double-story walls with the out-of-plane behavior of solid walls while Sequence B has the walls, which exhibit the out-of-plane behavior of the wall with a door opening in the ground story, and the wall with a window opening in the top story. The wall contains twelve layers. In order to increase the wall's vertical stiffness, rubber bands have been tied vertically from the bottom to the top via the middle of the blocks.

The shake table is fixed to the base, ensuring that the structure is fixed for uniform loading to be applied. The diaphragm is attached on top. The weight of the double story structure is 10.45 kg. In order to increase stability to the double story structure, which would not easily collapse, twenty stiffeners, made up of rubber bands, are attached at key points, five on each wall. This will be the real situation that is to be simulated in the experiment. Two wall structures are used during experimentation.

The lateral fixation of the double story in the interlocking plastic block wall is achieved by the shake table through the use of nut bolts and angle sections such that the double story may be duplicated to experiment in the real world scenario. The testing process of the double story is only conducted in the X direction while the testing process in the Y direction falls outside the scope of this research study since it is similar to the testing of X direction since of the principle of symmetry of the structure. It is expected that the result obtained from this research study will provide useful information regarding the determination of the seismic performance of interlocking blocks in the construction of the structure.

## 3.4 Test Setup

### 3.4.1 Snapback Test Setup and Instrumentation

Figure 3.4 below is the illustration of Snapback test apparatus. As illustrated in Figures 3.4a and 3.4b, the Snapback test apparatus for sequence A and sequence B are given respectively. A 400 mm long wire is tied at the top of double story located within the interlocking plastic block wall to perform free vibration. An accelerometer is used at the top of the structure to record the dynamic response of IPB double story structure. This is accomplished through displacing the wall with the help of a wire. The displacement of double story structure in the interlocking plastic block wall is done twice, namely, 25 mm and then 50 mm.

The test will be done using two wall configurations, A and B. Wall configurations A and B are pulled in the X direction. This is because of the symmetry law where behavior in the Y direction is assumed to be similar. Behavior in the Y direction will be discussed later. The behavior of the double-story structure made up of interlocking plastic block walls is measured in terms of acceleration against time using the data from the accelerometer. After that, the damping ratio ($\zeta$) and fundamental frequency (fn) of the tested system are computed using the logarithmic decrement approach. For this to happen, the number of cycles and maximum acceleration levels (maximum or amplitudes) need to be established as well. $\zeta$ is determined from the following equation for the double-story:

$$\zeta = \frac{1}{2\pi N} \ln \left( \frac{x_0}{x_1} \right) \times 100 \tag{3.1}$$

The initial value and the final value of acceleration in each cycle will be denoted as xo and x1, respectively. Moreover, N refers to the total number of cycles. The natural vibration frequency of the structure is referred to as the fundamental frequency. If there is an approach of the fundamental frequency towards the dominant frequency of the earthquake, then there is resonance, resulting in the increased vibrations of the structure.

### 3.4.2 Shake Table Setup and Instrumentation

From the figure 3.5, instrumentation of the shake table test is given in two ways: a) Schematic diagram, and b) Experimental test setup diagram. The building that is designed using interlocking walls of plastic blocks is connected with the shake table by means of angle and nut/bolt connection methods. In all, five accelerometers are needed for the experimental test setup. Two accelerometers are fixed to the upper side of walls in order to monitor the contribution made by walls to the joints and failure. Similarly, another two accelerometers are fixed to the top of the first floor of the two story building to monitor the relative motion and deformation of the building. The fifth accelerometer is placed on the base of shake table in order

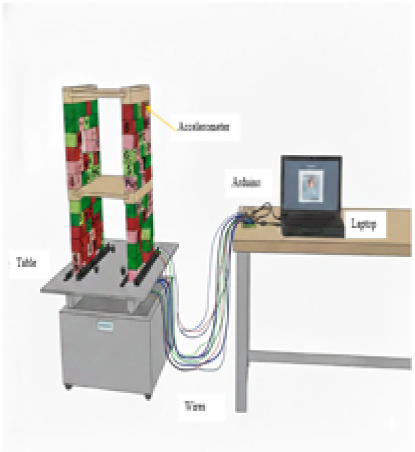
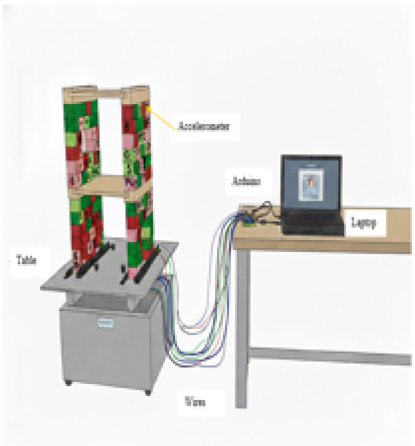
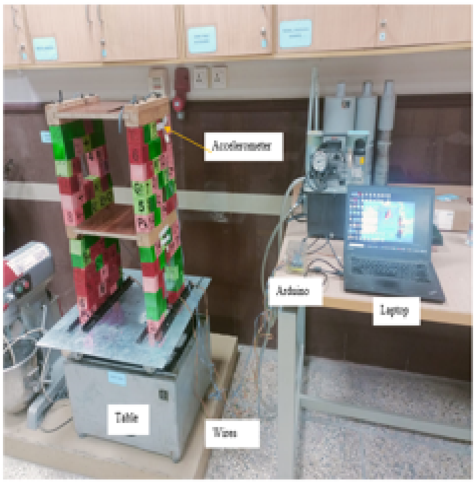
| | | |
|---|---|---|
| a) |  |  |
| | Schematic Diagram | Real Test Setup |
| b) |  |  |
| | Schematic Diagram | Real Test Setup |

FIGURE 3.4: Snapback test instrumentation and testing: schematic diagram and real test setup for a) sequence A and b) sequence B

to monitor the ground excitation below the structure. The performance of the building is analyzed from the basis of acceleration versus time response data.

## 3.5 Dynamic Loading

### 3.5.1 Snap Back

Displacement of the double-story in mortar-free interlocking plastic block wall in horizontal direction was made up of 25 mm and 50 mm, respectively, using attached wires. The displacement was made possible through releasing the wire

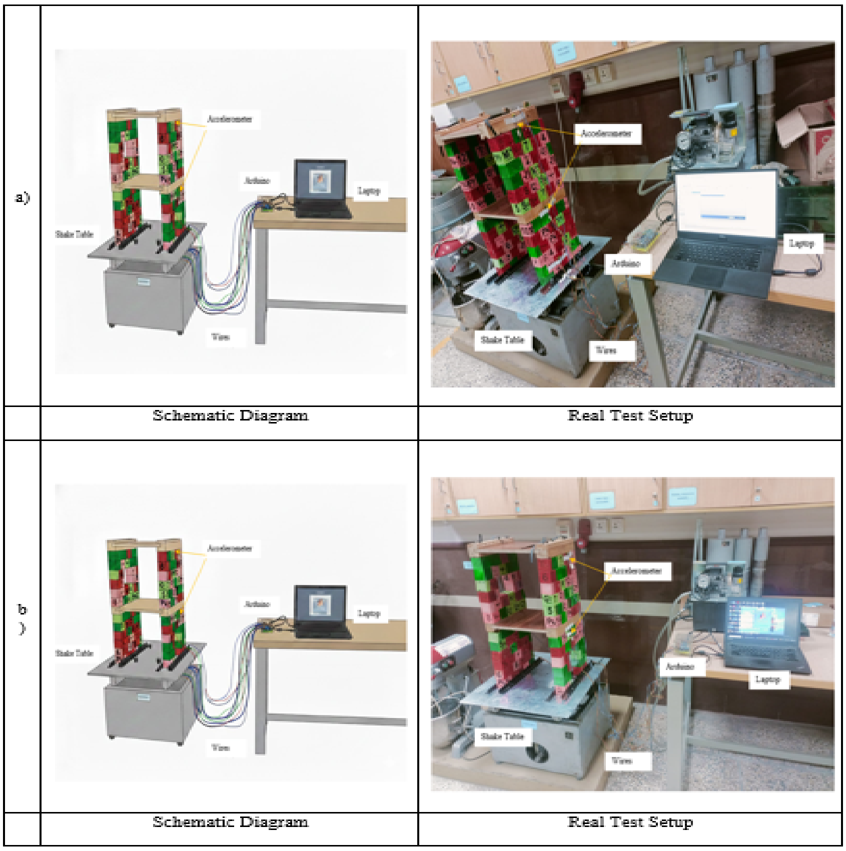



FIGURE 3.5: Shake table instrumentation and testing: schematic diagram and real test setup for: a) sequence A and b) sequence B

suddenly, resulting in free vibration. Acceleration-time history data for the reaction thus generated were collected using an accelerometer installed on the wall's top surface. Test on walls with Seq. A and B were carried out in the X-direction, while the reaction in the Y-direction will be the same because of the law of symmetry, which is not within our scope currently. Damping ratio and fundamental frequency of the double-story in mortar-free IPB wall were calculated using the log decrement technique from the acceleration-time history data. Table 3.1 shows the magnitude of snap-back loading.

TABLE 3.1: Loading Details of Test Specimens

| **Sr. No.** | **Specimen** | **Loading Direction** | **Amplitude (mm)** |
|---|---|---|---|
| 1 | A | X | 25, 50 |
| 2 | B | X | 25, 50 |

### 3.5.2 Harmonic

The harmonic magnitudes for the six tests performed in the current study are shown in Table 3.2. Harmonic excitations were performed at 0.8 Hz, 1.0 Hz, and 1.2 Hz, while the magnitude remains constant at 25mm of the double story of the interlocking plastic block wall. The results on acceleration-time history, velocity-time history, and displacement-time history were recorded for both the top and bottom ends of the shake table in terms of their dynamic characteristics under the harmonic loadings. It can be seen that the double story of interlocking plastic block wall could show extremely high values of acceleration, velocity, and displacements as a result of the structure itself. 1/2 plastic block was used so that there would be no overlapping of joints successively. This applies to all normal brick masonry, including stretcher bonds. Based on the table, combinations using the blocks will only have up to 2. The two solid walls in sequence A are subjected to loads out-of-plane, as shown by the x-direction. The two walls in sequence B that have openings for doors, as well as the wall with an opening for the window, are also subjected to out-of-plane loads as indicated by the x-direction. This is the only difference between the two sequences with regard to the loading conditions. In sequence A, the two-story wall firmly attaches the shake table through a steel angle iron. The major frequency at 1.0 Hz, indicated in bold letters, was determined through the snap-back test conducted on the models, showing that this is the natural frequency since it corresponds to the major dynamic response. Khan studied a column with a major frequency of 0.2 Hz, Afzal did the same for a solid wall at 0.5 Hz, while Sudheer & Ali used a frequency of 0.5 Hz. In the present study, the value for fundamental frequency (fn) is established through the Snapback test, where frequencies of about 1.0 Hz and 0.2 Hz are chosen for the higher and lower frequencies respectively. In terms of loading, 25 mm of harmonic load amplitude in the X- direction in both Wall Configurations (Seq. A and Seq. B) represents an input value used to conduct tests that realistically simulate dynamic excitations. Furthermore, the test apparatus allows consistency in applying boundary and loading conditions so that a comparative analysis can be conducted between Seq. A and Seq. B configurations. Table 3.2 shows the magnitude of harmonic load used for the test.

Table 3.2: Harmonic Loading Details of Wall Configurations

| **Sr. No.** | **Wall Configuration** | **Harmonic Loading Direction** | **Amplitude (mm)** | **Frequency (Hz)** |
|---|---|---|---|---|
| 1 | Seq. A | X | 25 | 0.8, 1.0, 1.2 |
| 2 | Seq. B | X | 25 | 0.8, 1.0, 1.2 |

## 3.6 Parameters to be Evaluated

### 3.6.1 Parameters Evaluated under Snapback Loading

The acceleration-time history data were obtained for the mortar-free interlocking plastic block wall double-story building. During data collection, some noise was recorded in the form of acceleration. To improve the quality of the data, the seismo signal software was used to remove the noise. For this, a bandwidth filter was applied in the seismo signal software to clean the collected acceleration-time history data. In the early stage of data collection, MATLAB software was used to remove excessive noise from the data to obtain clean data. Moreover, the natural frequency (fn) and damping ratio ($\zeta$) for the mortar-free interlocking plastic block wall double-story building were determined from the acceleration-time history data [82, 83].

The critical values for system dynamics would include the damping ratio and the natural frequency because they can reveal the conditions for energy dissipation and resonance of the system respectively. The processed data and parameters obtained are significant in the assessment of the system's dynamic response for seismic activities because they help in making an informed prediction about the performance of the building in the future. Moreover, alterations and analysis of the data ensure that they are credible representations of actual conditions experienced by the double-story building.

### 3.6.2 Parameters Evaluated under Harmonic Loading

Loads according to frequencies of 0.8 Hz, 1.0 Hz, and 1.2 Hz were applied to the IPB wall, and the acceleration time history response was observed. The velocity and displacement responses were derived from the results through numerical integration of the data with the aid of SeismoSignal program. Moreover, the acceleration response was important in deriving the Q-displacement curve. This was vital in that it was necessary in determining the dynamic stiffness and energy dissipation capabilities.

## 3.7 Procedure for Empirical Equation Formation

The development of equations for estimating the dynamic behavior of the double-story structure made up of in-masonry interlocking plastic-block walls depends on interlocking plastic block's shape, block size, height of the structure, and load parameters as discussed by Khan [3]. In addition, the percentage of difference between the experimental and empirical results will be obtained. This will help in determining the efficiency of the formulated equation. To decrease the difference between experimental and empirical results, the value of the K parameter is taken to be 1.20. This will help in increasing the reliability of the empirical equations such that they become more realistic when compared with experimental results. This empirical model may estimate the behavior of the structure in an accurate manner.

## 3.8 Summary

This chapter provides an overview of the methodologies and procedures for testing that were utilized in the experiment. Testing will primarily focus on the dynamic behavior of a prototype of a double-story building constructed using interlocking plastic blocks. The performance of the double-story structure will be assessed through testing and compared to the results obtained from empirical formulas. This chapter will provide an explanation of the test setup and instrumentation to provide more information regarding the equipment and procedures used in conducting the tests. Furthermore, the various parameters tested will also be described to provide information about the factors that influence the performance of the double-story structure. Emphasis will be placed on the displacement, acceleration, and failure modes of the structure under dynamic loads.

# Chapter 4

# Experimental Evaluation

## 4.1 Background

In the last chapter, the investigatory techniques of snapback and dynamic loading tests are explained in detail, as well as the parameters analyzed. The present chapter gives the experimental results of the data that was recorded during testing. Based on the acceleration time history, the fundamental frequency (fn) and damping ratio of two-story walls in the out-of-plane direction are determined. Initially, MATLAB software was used to collect the data in raw form, and then seismo-signal software was used to remove extraneous noise. The seismo-signal data were also used to derive acceleration and displacement time histories. The calculation of energy absorption at each loading frequency is also done.

## 4.2 Damping Ratio and Fundamental Frequency

A natural period or frequency produced by a structural element is known as the fundamental frequency. When the frequency is too near the dominating frequency in an earthquake, resonance can occur, resulting in a strong vibration in the structure. The fundamental frequency is carefully chosen in a seismic-proof structure to avoid resonance with normal seismic motions. Figure 4.1 shows the results from snap- back tests for a double-story out-of-plane direction wall constructed of interlocking plastic blocks, top of double-story wall using chord was moved out of its mean position by 25 mm and 50 mm. Fundamental frequency (fn) and damping ratio of the double-story interlocking plastic block wall is determined using log decrement method.

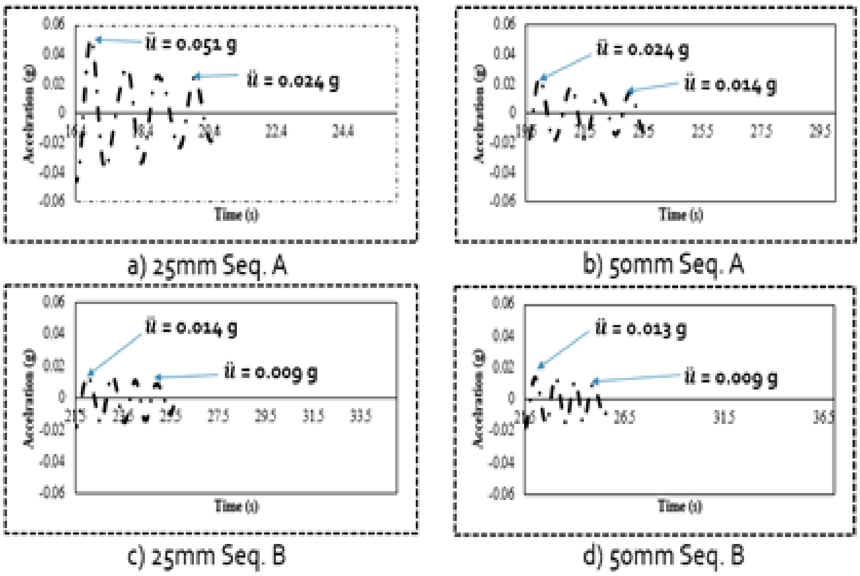



FIGURE 4.1: ü-t from snap back test; a) 25mm wall seq.A, b) 50 mm wall seq.A, c) 25mm wall seq.B, d) 50mm wall seq.B

Table 4.1 shows the evidence of the snap-back test results. It must be noted that the rate of the reduction in the amplitude of the structure is high, signifying the increased damping ability when the double-story walls in the structures get displaced from the mean position. Damping is the rate of decrease in the vibration of structures. The high damping ratio signifies the increased ability to dissipate the vibrations, thereby preventing major damage to the structures. The materials that are used in seismic-resistant constructions are chosen in such a manner that the structures have the maximum damping ability, thereby preventing unnecessary vibrations. In relation to wall configuration, Seq. A, the damping for the displacement of the double-story out-of-plane wall by 25 mm was calculated at 3.99 percent, while for the 50 mm displacement of the double-story out-of-plane wall, the damping was determined to be 2.85 percent. Likewise, the frequency of the double-story out-of-plane wall displaced 25 mm was determined to be 0.98 Hz, while the frequency of the 50 mm double-story out-of-plane wall was found to be

0.99 Hz. On the other hand, concerning wall configuration, Seq. B, the damping for the displacement of the double-story out-of-plane wall by 25 mm was calculated to be 2.34 percent, while that of the 50 mm displacement of the double-story out-of-plane wall was found to be 1.95 percent. Furthermore, the frequency of the double-story out-of-plane wall displaced 25 mm was determined to be 1.02 Hz, while that of the 50 mm double-story out-of-plane wall was found to be 1.04 Hz.

TABLE 4.1: Results from Snapback Test

| **Wall Configuration** | **Amplitude (mm)** | **Frequency (Hz)** | **Damping (%)** |
|---|---|---|---|
| Seq. A | 25 | 0.98 | 3.99 |
| – | 50 | 0.99 | 2.85 |
| Seq. B | 25 | 1.02 | 2.34 |
| – | 50 | 1.04 | 1.95 |

In the current study, attention is paid to the product and element, and the material properties are not a matter of interest. Damping variations by a slight percentage could occur based on some of the following concerns; for instance, the nonlinearity in material, joint friction, and boundary conditions. On the other hand, it is possible to have a slight damping value of 20% occurring in a particular structure based on the effects of amplitude, where, in this case, the mechanisms of viscous damping may depend slightly on the amplitude.

## 4.3 Behavior of Prototype Double-story Structure under Harmonic Loading

### 4.3.1 Behavior in Terms of Acceleration-time and Displacement-time Histories

The performance of the double-story out-of-plane wall made from the interlocking plastic block material has been observed based on the acceleration time history and displacement time history within a particular period from 30s to 35s, as depicted in Figures 4.2 and 4.3. As illustrated in Figures 4.2 and 4.3, the red solid line indicates the base excitation used as (applied loading), the green dotted line shows the reaction of the top of the ground floor of the double-story out-of-plane wall 1 of interlocking plastic block material. On the other hand, the blue line shows the top of the 1st floor double-story out-of-plane wall 1. The purple dotted line indicates the reaction of the top of the ground floor of the double-story out-of-plane wall 2, while the brown line represents the reaction of the 1st floor of the double-story out-of-plane wall 2. The experimental acceleration time history and displacement time history are adequate to conduct the dynamic analysis of the double-story out-of-plane wall prototype. The data will be transferred to the displacement time history at the seismosignal software by using the acceleration-time history.

As the cheaply manufactured shake table is capable of applying harmonic loading with accuracy in respect to uniform amplitude of the cycle, the average of the acceleration and the displacement of the base excitation is considered as the loading condition. Acceleration and displacement of the top of the double-story out-of-plane wall of the interlocking plastic block structure are considered as the behavior of the model. Figure 4.2 illustrates the graphs of the accelerations with time histories of a double-story out-of-plane wall under harmonic loading with frequencies of 0.8, 1.0, and 1.2 Hz from 30 to 35 seconds. Structural excitation can be categorized into three different stages: (A) Initial stage, where the vibration process is initiated until a steady-state condition is attained; (B) Steady-State response; and (C) Free vibration, where the external loading condition is terminated [83].

For the purpose of understanding the regular state behavior, a partial regular state behavior is presented in Figures 4.2 and 4.3. The average accelerations of the base and top of double-story out-of-plane walls are illustrated. It can be seen that the acceleration increases due to an increase in frequency of the shake table when the second harmonic loading was applied, which is equivalent to 1.0 Hz. The double-story out-of-plane wall without mortar in interlocking plastic block was vibrated strongly with considerable deformation. The top of the corer, having a wedge shape, separates from the above discussion, which agrees with some previous studies regarding the dominance of the bending effect without any vertical loads or slab loading. The damages noted in the experiment are seen due to the cumulative effects of earlier frequency excitation. Figure 4.3 below is the displacement-time history of double-story out-of-plane walls under dynamic loads at 0.8 Hz, 1.0 Hz, and 1.2 Hz. These results were obtained from 30 to 35 seconds. Additionally, the displacement time history of the structure from the base is presented, and this is because an analysis of this particular area is needed. Moreover, the average displacement values are taken into consideration from the ground level as well as from the top of the double-storied buildings. This is because, for the walls, there was an increase in displacement value due to the increase in frequency value in the input of the shake tables. Homemade shake tables are useful when it comes to dynamic loading processes. As it can be seen from the figure above, minor variations in amplitude occur. The average acceleration, velocity, and displacement of the base movement are taken into consideration. As the first and second dynamic loads were applied at frequencies of 0.8 Hz and 1.0 Hz, the plastic block interlocking walls deformed extensively.

It was clearly shown by the data, and this is illustrated by the graph depicted in Figure 4.3. The rise in displacement was extremely important, as it could be deduced from the results that in dynamic loading scenarios with such frequencies, the interlocking plastic block system would not effectively act as an oppositional force to the loads. This could have been a result of some characteristics present within its interlocking aspect or component, which may not favor its performance under such circumstances. The conclusions drawn from the observations include that, in these frequencies, the wall becomes unstable and thus moves greatly, and this may pose a threat to issues of natural catastrophes or disasters, such as earthquakes. In addition to the fact that the aforementioned loads led to the displacement of the structure from its initial location or plane, it became clear that the in-plane load resistance of the wall was significantly lowered when the dynamic loading at 1.0 Hz was conducted. It was therefore evident that the wall had the ability to withstand in-plane or surface loads but this was hindered due to the application of dynamic loads at 1.0 Hz frequency. The out-of-plane stiffness needs to be taken into account since this is one of the factors that must be considered to determine whether or not the wall can resist lateral forces. In cases where there are earthquakes, it might cause damage due to these lateral loads.

Although these results reveal high levels of deformations and reduced in-plane stiffness for particular frequencies, the results clearly suggest that the use of interlocking plastic block for construction is still a valid alternative for housing programs that require earthquake-resistance features. Although the wall may become vulnerable to high deformations for some particular dynamic loadings, the capacity of absorbing energy exhibited by this material, particularly at high frequencies, can be considered advantageous.

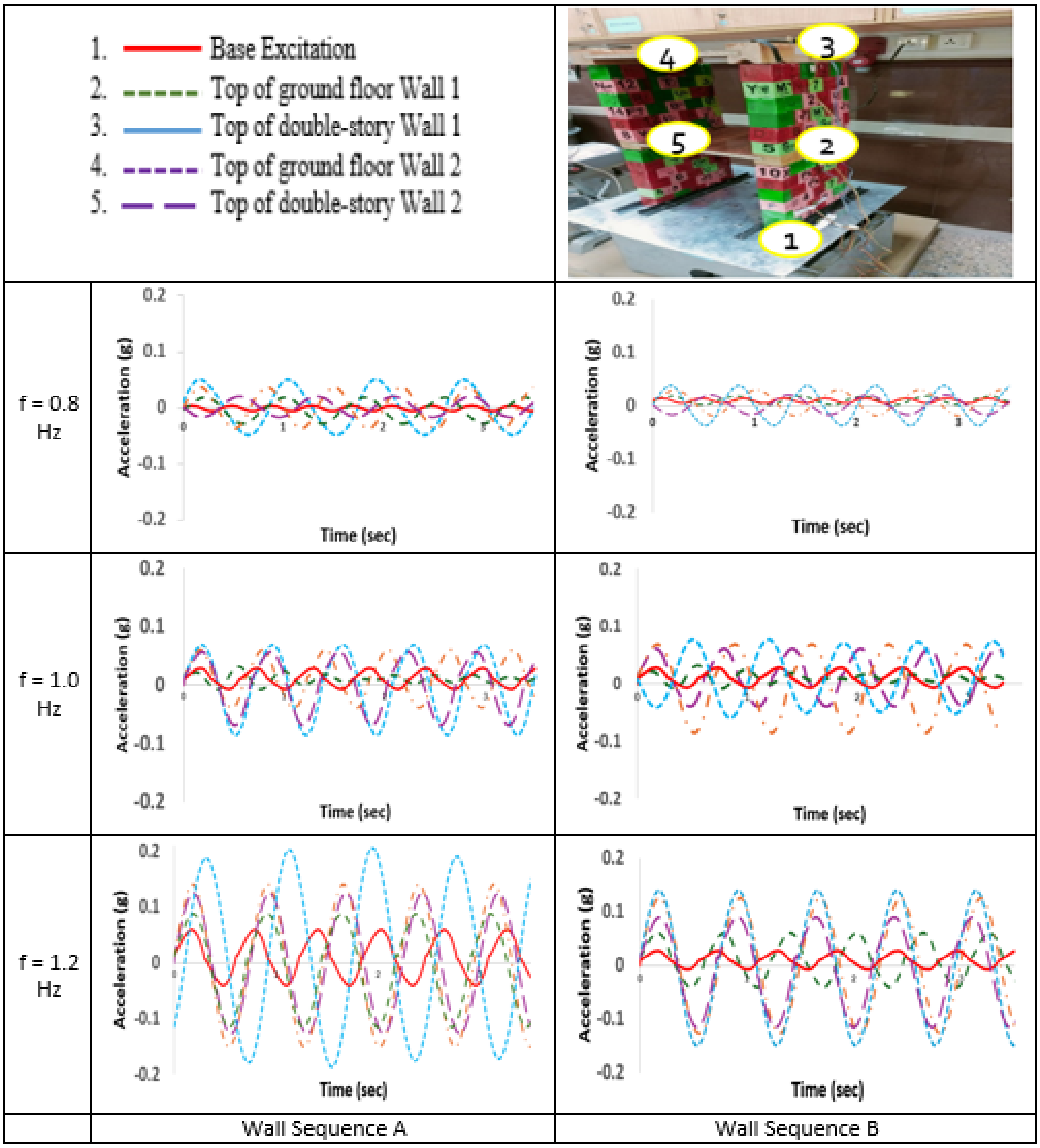



FIGURE 4.2: ü-time history curve of double-story

Therefore, this implies that by making further improvements in design, such as improving the interlocking system or changing the physical attributes of the blocks, the efficiency of interlocked plastic blocks walls can be greatly improved. Despite

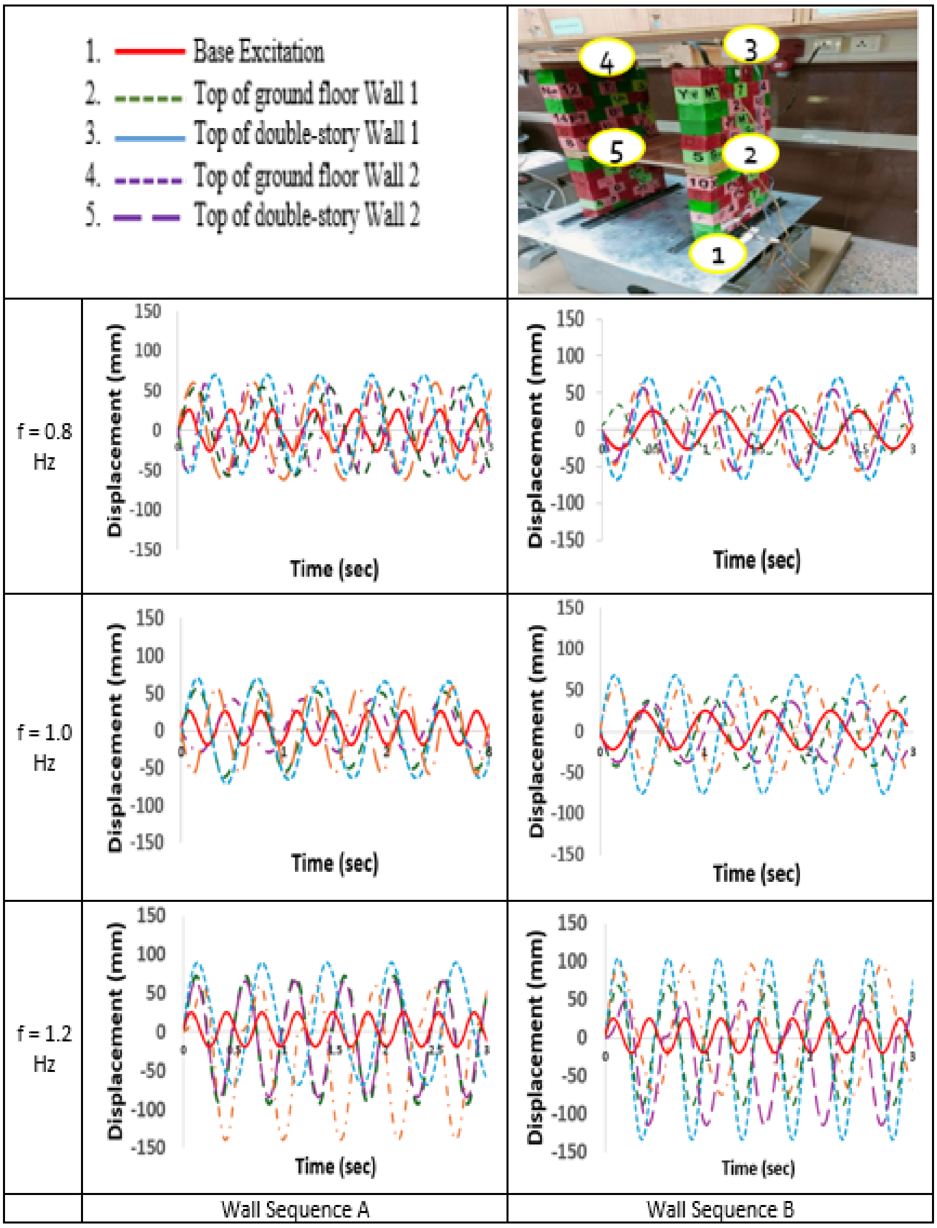



FIGURE 4.3: △-time history curve of double-story

the fact that this wall deformed excessively at frequencies of 0.8 Hz and 1.0 Hz, it nevertheless has promising potential for becoming a flexible, elastic, and energy-absorbing structure in areas that are prone to earthquakes. In order to make sure that this plan for building safe homes through motion resistance is fulfilled, one cheap alternative to achieve this is to build blocks that can resist the force of earthquakes.

Table 4.2 depicts the contribution made by the wall towards the double story phenomenon. In sequence A, wall one under the action of OOP load experienced movements equal to 74 mm, 138 mm, and 124 mm at 0.8 Hz, 1.0 Hz, and 1.2 Hz respectively. Likewise, for sequence B, under OOP load wall 1 experienced movements of 80 mm, 115mm, and 159 mm. This implies that the OOP wall sequence B has contributed more compared to the sequence A.

Table 4.2: Wall contribution to double-story response

| **Wall Configuration** | **Frequency (Hz)** | **OOP (mm)** |
|---|---|---|
| Sequence A | 0.8 | 74 |
| – | 1.0 | 138 |
| – | 1.2 | 124 |
| Sequence B | 0.8 | 80 |
| – | 1.0 | 115 |
| – | 1.2 | 159 |

### 4.3.2 Base shear-Displacement Curves and Energy Absorption

The total energy absorbed by the structure in dynamic loading is estimated by assuming that the total mass of the interlocking plastic block double story is located at the top of the double story. This estimation can be carried out according to the time-history analysis of its acceleration. The base shear is taken as M. Figure 4.4 shows the base shear-displacement curves. It is computed based on the work of [83]. Base shear is plotted along the X-axis and displacement along the Y-axis. The area inside hysteresis loops corresponds to the absorbed energy of the specimen under cyclic loads. The results of energy absorption are provided in Table 4.3, along with the total number of hysteresis loops, energy absorbed per loop, and equivalent damping. The equivalent damping ratio is determined according to the equation.

$$\zeta = \frac{E}{2\pi Q_{\max}\Delta_{\max}} \tag{4.1}$$

Equivalent damping is determined as work done by [84]. Where E is the energy absorbed in a cycle, $Q_{max}$ and $\delta_{max}$ are the maximum shear and displacement,

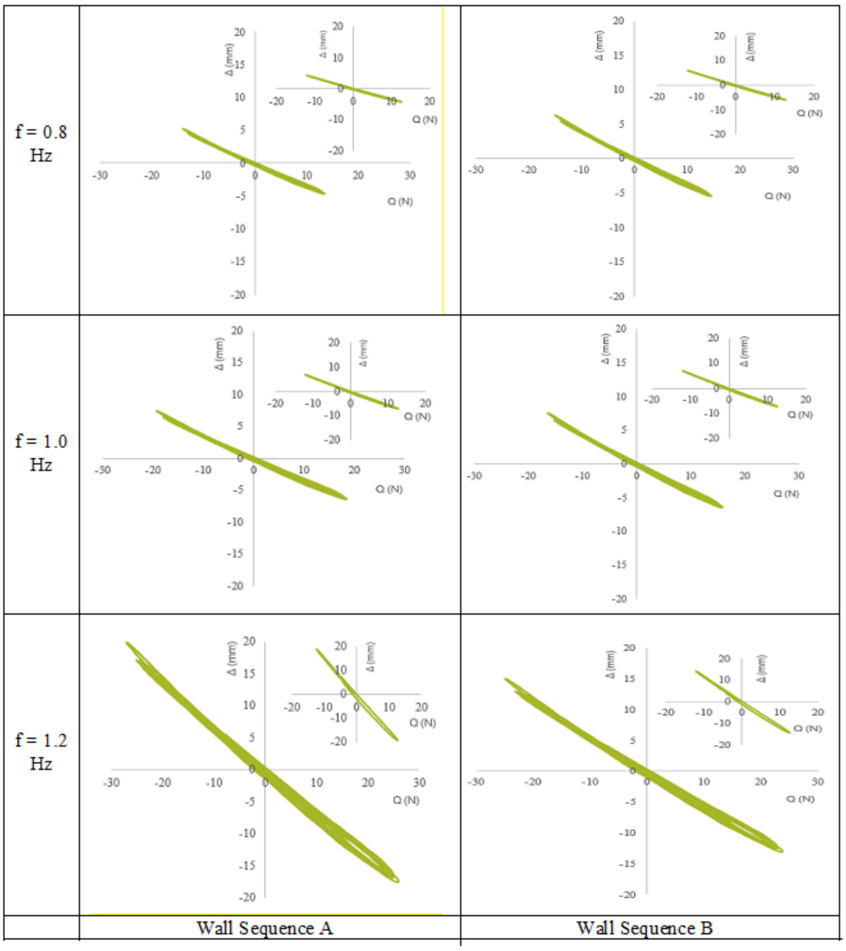



FIGURE 4.4: Q-△ curves of double-story

respectively, in one cycle. The graph of energy absorbed at various loading frequencies is given in Figure 4.4. Energy absorbed is higher at higher frequencies of loading.

TABLE 4.3: Energy absorption during dynamic loading

| **Wall Config.** | **Freq. (Hz)** | **Avg. Energy /Cycle (Nm)** | **No. of Cycles** | **Total Energy Absorp. (Nm)** | **Equiv. Damping (%)** |
|---|---|---|---|---|---|
| Seq. A | 0.8 | 1.33 | 65 | 86.7 | 19.50 |
| – | 1.0 | 2.02 | 83 | 168 | 19.51 |
| – | 1.2 | 5.38 | 118 | 635 | 19.52 |
| Seq. B | 0.8 | 1.49 | 81 | 121 | 21.47 |
| – | 1.0 | 1.54 | 95 | 147 | 19.72 |
| – | 1.2 | 3.92 | 113 | 443 | 19.81 |

The data in Table 4.3 provides a complete perspective regarding the energy absorption capability of the double-story structure in an interlocking plastic block wall system subjected to dynamic loadings. The definition of energy absorption (E) can be considered as the energy dissipation in a single cycle of loading, whereas the total energy absorption (ET) can be considered as the accumulation of energy dissipation through multiple cycles of harmonic loadings. One important observation from the analysis is that there is a difference in the value of energy dissipation based on the frequency of excitation. It can be seen that the double-story structure exhibits a higher capability to dissipate energy in high-frequency excitations of 1.2 Hz than low frequencies of 0.8 Hz and 1.0 Hz.

This shows that the frequency is a critical determinant of the damping properties and the dynamic behavior of the block construction. In quantitative terms, at a 1.2 Hz frequency, the structure absorbs 7.3 times more energy than at 0.8 Hz in wall sequence A. Similarly, at a 1.2 Hz frequency, a double-story absorbs 3.96 times more energy than at 0.8 Hz in sequence B. The significant rise in the amount of energy consumed in higher frequencies could be a result of greater cyclic deformations, more internal friction within the interlocking units, and frequent movement among the plastic blocks. All these factors become pronounced in higher loading frequencies, which enhance friction and material damping, leading to more energy losses. Furthermore, when comparing wall Sequence B to wall Sequence A in 0.8 Hz, there is a 1.39% difference in energy consumption.

Just like Wall Sequence B, 1.14% more energy dissipation was found when comparing to Wall Sequence A at 1.0 Hz. Similarly, in relation to Wall Sequence A at 1.2 Hz, Wall Sequence B had 1.43% more energy dissipation. From the results, the hypothesis that increases in excitation frequency can result in increases in energy dissipation in this case was supported, even by modest increases. Sequence B is considered superior because it demonstrated greater displacement capacity without premature collapse, indicating enhanced ductility, improved energy dissipation, and more stable load redistribution between stories. These characteristics reflect a controlled out-of-plane response, which is preferable for seismic resilience compared to the behavior observed in Sequence A. These results have significant implications as far as designing and assessing structural performance is concerned, especially since high-frequency excitations will mostly be encountered during seismic and impact loadings on structures. It becomes clear from the increased energy dissipation at 1.2 Hz that the interlocking joint systems can be used as efficient absorbers of energy in such cases. Designers can take advantage of this to enhance performance of non-mortared wall structures in areas where such structures can benefit from flexibility and low density. Further, due to the sensitivity to frequency of the double-story joint configuration, the importance of dynamic testing in assessing these new types of joint configurations becomes apparent.

## 4.4 Summary

In this chapter, the data on the behavior of the dynamic captured behavior are experimentally analyzed, giving significant insight into the behavior of the double story wall out-of-plane wall subjected to dynamic loading. Seismoignal software is used to analyze the data on acceleration-time graph. These values are converted to velocity-time and displacement-time graphs. Graphical analysis of this data reveals some information regarding the dynamic behavior of the wall. Base shear-displacement graph and Energy Absorption are drawn to obtain more information about the structural performance of the wall subjected to harmonic loading. From the analysis above, it is evident that dynamic loads close to the natural frequencies of the structure can deform the double story. In spite of this, this behavior does not cause the failure of the entire structure. This indicates that the joints in the double story can absorb the forces from dynamic loads without failing because of the flexible movement between the double story and the base of the structure. This helps in absorbing the energy from dynamic loads, thus saving the structure from possible failure.

# Chapter 5

# Discussions

## 5.1 Background

The last chapter provides a discussion of the results of acceleration time history, velocity time history, displacement time history, and base shear displacement relationships. It is important to note that the significant energy uptake was recorded at the interlocking plastic-block wall system at its double-story. In this chapter, a relationship between the experimental values and the empirically determined values is also established in order to approximate the behavior of the interlocking plastic block double-story. In addition, the difference in the percentage of the empirical and experimental values is quantified and examined.

## 5.2 Formation of Empirical Equations considering Geometrical Parameters, Structure Behavior and Input Loading Conditions

An empirical equation formulated by Khan [3] when the geometry of interlocking blocks is used, as well as the height of the double-story, its response, and other input loading parameters. For predicting the response of a double-story interlocking plastic-block wall, empirical equations are made by including an additional new variable:

$$\ddot{u}_t = \frac{a}{h^2 n} \times m \times k^{\left(1+\frac{2n}{100}\right)} \times \ddot{u}_g \tag{5.1}$$

$$\dot{u}_t = \frac{a}{h^2 n} \times m \times k^{\left(1+\frac{2n}{100}\right)} \times \dot{u}_g \tag{5.2}$$

$$u_t = \frac{a}{h^2 n} \times m \times k^{\left(1+\frac{2n}{100}\right)} \times u_g \tag{5.3}$$

In which K is dimensionless Coefficient, n is Number of interlocking plastic block, m is Number of blocks which are arranged along the length of the wall of the double-story in single layer, a is base area of IPB. ($\ddot{u}_g$) is mean acceleration at bottom of specimen, ($\acute{u}_g$ ) is mean velocity at bottom of specimen and ug is mean displacement at bottom of specimen. ($\ddot{u}_t$ ) average acceleration at the top of the specimen, ($\acute{u}_t$ ) average velocity at the top of the specimen, and $u_t$ average movement at the top of the specimen. Their respective values are 62 mm x 62 mm, 12 mm, 120, and 12. The coefficient K is 1.20, which has no dimensions.

Motion parameters are measured at the base and at the top of the double-story to measure the dynamic response. Table 5.1 represents the comparison of experimental and empirical values of the double-story IPB wall's response. Different Values of K are being used in past research, i.e., Khan [3] used 1.05, Afzal [13] used 0.45, Sudheer and Ali [85] used 0.5, Akram [86] used 1.14, and Ullah [87] used 0.98 for columns, OOP solid wall, OOP wall with window, corner joint, and T-junction, respectively, keeping in mind the geometries and loadings of the specimen. For the current scenario of the double story, the value of K is taken as 1.20, which resulted in a difference of -25% to -17%. The presence of complex behavior of the structure can explain the percentage difference between experimental and empirical values.

In an experiment by Nasery [88], reported differences of experimental and empirical values of up to 30%. Ali [29] gave a percentage range of up to 35% as the difference in experimental values and empirical ones, noting the complex behaviour of mortar-free interlocking columns with various uplift mechanisms, and seeking to give an approximate estimate of the induced accelerations. Thus, the current research having variation from -25% to -17% due to the complex nature of structure, can help in understanding the behavior of double-story in mortar-free interlocking plastic block wall. in Modular Wall Systems.

TABLE 5.1: Variation in experimental and empirical values for double-story of interlocking-plastic-block wall in out-of-plane direction

| **Config.** | **Freq. (Hz)** | **Joint Response** | **Exp. Values** | **Emp. Values** | **Diff. (%)** |
|---|---|---|---|---|---|
| **Seq. A.** | | | | | |
| | | Acceleration (g) | 0.05 | 0.062 | -19.38 |
| | 0.8 | Velocity (mm/s) | 45.2 | 56.06 | -19.38 |
| | | Displacement (mm) | 13 | 16.13 | -19.38 |
| | | Acceleration (g) | 0.07 | 0.088 | -20.96 |
| | 1.0 | Velocity (mm/s) | 159.4 | 193.7 | -17.74 |
| | | Displacement (mm) | 18.5 | 22.94 | -19.38 |
| | | Acceleration (g) | 0.19 | 0.249 | -23.95 |
| | 1.2 | Velocity (mm/s) | 311.1 | 393.6 | -20.96 |
| | | Displacement (mm) | 25.96 | 32.84 | -20.96 |
| **Seq. B.** | | | | | |
| | | Acceleration (g) | 0.06 | 0.078 | -23.37 |
| | 0.8 | Velocity (mm/s) | 44.7 | 58.33 | -23.37 |
| | | Displacement (mm) | 14.4 | 18.79 | -23.37 |
| | | Acceleration (g) | 0.07 | 0.087 | -19.70 |
| | 1.0 | Velocity (mm/s) | 161.3 | 202.4 | -20.34 |
| | | Displacement (mm) | 15.8 | 19.72 | -19.91 |
| | | Acceleration (g) | 0.15 | 0.194 | -22.78 |
| | 1.2 | Velocity (mm/s) | 322.4 | 425.5 | -24.23 |
| | | Displacement (mm) | 23.8 | 31.41 | -24.23 |

## 5.3 Comparison of Prototype Double-story and Single-story Structures Behaviors

Harmonic loading by a shaking table, which is produced locally, can produce relatively realistic harmonic motion that can be used to study the dynamic behavior of the observed structure. The reason behind this is that the harmonic loading applied is considered the base ground motion, and the structural response is considered with respect to it. The behavior of the double-story mortar-free in-

Table 5.2: Comparison with previous researches

| **Previous Researches** | **Current Research** |
|---|---|
| The mortar-less interlock building was tested using a complicated shake table to evaluate its dynamic response [89]. | The one-dimensional simple shake table method is applied to investigate the dynamic performance of the two-story building interlocking plastic block wall. |
| Out-of-plane walls, walls with openings, corners, and junctions are critical locations, and studies on the out-of-plane behavior of single-story walls have been carried out, but double-story mortar-free interlocking masonry remains unexplored. | The current study focuses on exploring the out-of-plane dynamic behavior of a double-story mortar-free interlocking plastic block structure. |
| The concrete blocks reinforced with coconut fibers were heavier and therefore experienced more inertia forces [29]. | Inertial force is less produced in a two-story building because of the light interlocking structure. |
| Semi-interlocking brickwork systems exhibited excellent energy dissipation characteristics under dynamic loading [90]. | The interlocking plastic block system showed considerable energy dissipation and damping capacity, with the double-story having superior performance at high frequencies. |
| The energy is absorbed in the mortar-less interlock system under dynamic loading [83]. | The double-story within the mortar-less interlocking plastic block wall also acts as an energy absorber. |
| Concrete with natural fiber reinforcement exhibited high capacity to absorb seismic energy [91]. | The energy intake was also comparable for interlocking plastic block, with few cracks at higher frequencies of stimulation. |
| The pre-stressing of the structure using coconut fiber ropes led to a decrease in energy absorption relative to that of the rope-less structure [29]. | The use of rubber bands on the interlocking plastic block wall improved the energy absorption capacity under harmonic loads for the double-story structure. |
| As the column failed, a minor degree of damage was noted in the interlocking blocks [29]. | The damage could not be caused in the specimen because of the limitation of the shake table. |

terlocking plastic-block wall is similar to that reported in previous studies, which further confirms its usefulness. The double-story demonstrated offering promising performance under dynamic loading conditions, regarding structural stability and energy dissipation. This implies that these joints may be critical to increasing the resilience of structures, particularly in seismic areas. Using interlocking plastic blocks, the negative impact of earthquakes could be reduced, and the alternative construction technique would be sustainable and damage-resistant.

A comparative profile of the results of earlier research and the present study is provided in Table 5.2, and shows a steady pattern in the energy dissipation behavior observed in mortar-free systems. This supports the increasing trend on the feasibility of interlocking block technologies in earthquake resistant construction systems. Moreover, these systems demonstrate a tremendous potential in saving the cost of construction as a whole and the requirement to use heavy reinforcement and thus, they are more cost-effective as well as environmentally sustainable. With the world rising demand of resilient infrastructure, these results indicate that the use of mortar-free interlocking block technology may play a key role in safer and more resilient buildings in seismic-prone areas.

In addition, these systems are also compatible with performance-based design philosophies, which focus on controlled damage and energy dissipation, as opposed to absolute rigidity. They are typically easy to construct, repair and scale, especially important in resource-constrained environments due to their modular nature. A combination of these innovative materials and systems would therefore be a paradigm shift in sustainable seismic design in terms of affordability, resilience, and the ease of deployment.

## 5.4 Challenges in Seismic Resilience of Masonry and Remedial Measures

The low mass causes less inertial forces during an earthquake hence it is a good seismic design strategy. According to UBC 1997, the weight of the building is directly proportional to the base shear. Hence, lowering the weight of a building has a considerable effect of minimizing seismic demand. Mortar-free interlocking-plastic-block provides an alternative that is lightweight and with efficient energy dissipation particularly in double-story out-of-plane walls. Their dry assembly technology improves the speed of construction, reusability and minimises the reliance on skilled labour. This renders them applicable in large-scale and earthquake-resistant buildings in earthquake prone regions. Such systems have been studied in application in recent work, such as [92].

## 5.5 Summary

This chapter summarizes the results of the research with accent on practical implementation and elaboration of an empirical equation. The empirical equation was developed to confirm the results of the experiment, and the consistency between the prediction of the theoretical results and the behavior. The difference between experimental and empirical values could be explained by the sophistication of the structure that was used during the testing, as well as through the employment of a simplified empirical equation. A locally developed shake table was used to provide harmonic loading and is cost effective, but has been found to have drawbacks in ensuring a constant amplitude at different frequencies. Despite the limitations, the shake table was effective in producing consistent harmonic loading which could be sufficient to evaluate the dynamic response of the structure. These findings allowed conducting a significant evaluation of the structural behavior in dynamic conditions. The experimental results were also supported and reinforced by the empirical equation, which added more credibility to the study. Finally, the combination of experimental and analytical methodologies makes the research more practical and provides the insights that are applicable to the real-world applications.

# Chapter 6

# Conclusion and Future Work

## 6.1 Conclusions

This study investigates the dynamic behaviour of a 1:10 scaled interlocking plastic block double-story. The model was made up of 120 plastic blocks organized into 12 layers attached at the bottom with angle sections. The structural response was measured using five accelerometers, which were two on top of the walls on a double story, two on top of the ground floor, and one on the base. A snap-back test was also done to find the natural frequency, time period, and damping ratio using the logarithmic decrement method. The experiment was performed on a one-dimensional shake table that was locally made and was used at frequencies of 0.8 Hz, 1.0 Hz, and 1.2 Hz. MATLAB data were refined in SeismoSignal to filter noise and remove baselines. According to this study, one can make the following conclusions:

i) The mean fundamental frequency is about 1.0 Hz, and the damping ratio of the double story is still as high as 3.99%.

ii) The prototype double-story was subjected to evaluation of the response in the form of acceleration time and displacement time histories.

   a. The OOP wall on sequence B adds more to the behaviour of the double-story with greater displacements at sequence A wall harmonic loading.

b. Wall Sequence A takes in energy 1.4 times more than Wall Sequence B in frequencies 0.8 Hz, 1.0 Hz, and 1.2 Hz, respectively.

iii) The deviation of up to 25% between the empirical and experimental values in predicting the structural response can be attributed to the complexity of the structure under consideration and the simplicity of the approach used for this research. However, the findings from this study would help explain the behavior of double-story buildings without mortar in interlocking blocks.

iv) The use of the double-story mortar-less interlocking plastic block wall is effective in absorbing energy, hence proving its worth as an earthquake-resistant building material.

Energy dissipation in the harmonic loading is increased in the lightweight two-story building made up of mortar-less interlocking plastic block walls that are efficient in ensuring structural security. This environmentally friendly housing solution can offer an affordable and resilient answer to endangered communities during earthquakes in order to guarantee their quality of life.

## 6.2 Future Recommendations

The following may be considered as an attempt to further investigate the nature of the interlocking plastic block configuration:

i) Optimized Design of Double Story Systems for a Uniform Response in Seismic Activities with Interlocking Blocks.

ii) Optimized Model for the Study of Double Story Dynamics within Modular Walls.

# Bibliography


[1] G. Vlachakis, E. Vlachaki, and P. B. Loureno, "Learning from failure: Damage and failure of masonry structures, after the 2017 lesvos earthquake (greece)," *Engineering Failure Analysis*, vol. 117, p. 104803, 2020.

[2] M. T. Gazkoh, X. Lin, and A. Zhou, "Advancing topological interlocking structures: recent developments, applications, and challenges in civil engineering," *International Journal of Civil Engineering*, vol. 18, no. 1, p. 91, 2024.

[3] F. Khan, "Dynamic behavior of prototype interlocking plastic-block structure using locally developed low-cost shake table," Master's thesis, Capital University of Science and Technology, Islamabad, Pakistan, 2019.

[4] B. Ghiassi, A. Vermelfoort, and P. B. Loureno, "Masonry mechanical properties," in *Numerical modeling of masonry and historical structures.* Elsevier, 2019, pp. 239–261.

[5] M. D. Trifunac, "Site conditions and earthquake ground motion: A review," *Soil Dynamics and Earthquake Engineering*, vol. 90, pp. 88–100, 2016.

[6] M. Abbas, K. Elbaz, S.-L. Shen, and J. J. Chen, "Earthquake effects on civil engineering structures and perspective mitigation solutions: a review," *Arabian Journal of Geosciences*, vol. 14, no. 14, p. 1350, 2021.

[7] A. Naseer, A. N. Khan, Z. Hussain, and Q. Ali, "Observed seismic behavior of buildings in northern pakistan during the 2005 kashmir earthquake," *Earthquake Spectra*, vol. 26, no. 2, pp. 425–449, 2010.

[8] V. Tsimopoulou, T. Mikami, T. T. Hossain, H. Takagi, M. Esteban, and N. A. Utama, "Uncovering unnoticed small-scale tsunamis: field survey in lombok, indonesia, following the 2018 earthquakes," *Natural Hazards*, vol. 103, no. 2, pp. 2045–2070, 2020.

[9] R. J. Spence, "Saving lives in earthquakes: successes and failures in seismic protection since 1960," *Bulletin of Earthquake Engineering*, vol. 5, no. 2, pp. 139–251, 2007.

[10] M. Adnan, "Effect of slenderness on the behavior of interlocking plastic-block structural elements under compression," Master's thesis, Capital University of Science and Technology, Islamabad, Pakistan, 2022.

[11] M. Sudheer, "Out-of-plane behavior of prototype interlocking plastic-block wall with opening under harmonic loading," Master's thesis, Capital University of Science and Technology, Islamabad, Pakistan, 2020.

[12] K. Shahzad, "Effect of block-return on out-of-plane behavior of interlocking plastic-block walls under harmonic loading," Master's thesis, Capital University of Science and Technology, Islamabad, Pakistan, 2020.

[13] S. Afzal, "Out-of-plane behavior of prototype interlocking plastic-block solid wall under harmonic loading," Master's thesis, Capital University of Science and Technology, Islamabad, Pakistan, 2020.

[14] M. S. Aslam, "Compressive behavior of interlocking plastic block structural elements," Master's thesis, Capital University of Science and Technology, Islamabad, Pakistan, 2021.

[15] H. Bashir, "Dynamic response of interlocking plastic-block walls with diaphragm using numerical approach," Master's thesis, Capital University of Science and Technology, Islamabad, Pakistan, 2020.

[16] S. Anwar, "Effect of diaphragm on dynamic behavior of interlocking plastic block structure with different elements pattern," Master's thesis, Capital University of Science and Technology, Islamabad, Pakistan, 2021.

[17] S. J. Asad, "Consequences of block-return on dynamic in-plane behavior of interlocking plastic block walls," Master's thesis, Capital University of Science and Technology, Islamabad, Pakistan, 2021.

[18] S. Bhattacharya, S. Nayak, and S. C. Dutta, "A critical review of retrofitting methods for unreinforced masonry structures," *International Journal of Disaster Risk Reduction*, vol. 7, pp. 51–67, 2014.

[19] B. Lizundia, R. A. Davidson, Y. M. Hashash, and R. J. Olshansky, "Overview of the 2015 gorkha, nepal, earthquake and the earthquake spectra special issue," *Earthquake Spectra*, vol. 33, no. 1_suppl, pp. 1–20, 2017.

[20] P. Zhang, L. Chen, T. Wei, P. Huang, H. Wang, and X. Chen, "Multi-hazard assessment of masonry buildings: A state-of-the-art review," *Buildings*, vol. 14, no. 12, p. 3711, 2024.

[21] R. E. Sedgh, "Interaction between structural walls, flooring slabs and gravity frames in reinforced concrete buildings," Ph.D. dissertation, University of Canterbury, 2018.

[22] A. Ahmed, K. Shahzada, S. M. Ali, A. N. Khan, and S. A. A. Shah, "Confined and unreinforced masonry structures in seismic areas: Validation of macro models and cost analysis," *Engineering Structures*, vol. 199, p. 109612, 2019.

[23] B. Behera and R. P. Nanda, “In-plane shear strengthening of brick masonry panel with geogrid reinforcement embedded in bed and bed-head joints mortar,” *Engineering Structures*, vol. 227, p. 111411, 2021.

[24] P. A. Korswagen, M. Longo, and J. G. Rots, “High-resolution monitoring of the initial development of cracks in experimental masonry shear walls and their reproduction in finite element models,” *Engineering Structures*, vol. 211, p. 110365, 2020.

[25] C. M. Nadian, “Seismic design guide for low-rise confined masonry buildings,” Earthquake Engineering Research Institute (EERI), Tech. Rep., 2011.

[26] M. Garrido, J. R. Correia, T. Keller, and F. A. Branco, “Connection systems between composite sandwich floor panels and load-bearing walls for building rehabilitation,” *Engineering Structures*, vol. 106, pp. 209–221, 2016.

[27] S. A. Babatunde, “Review of strengthening techniques for masonry using fiber reinforced polymers,” *Composite Structures*, vol. 161, pp. 246–255, 2017.

[28] A. K. Thomoglou, P. Jagadesh, and M. E. Voutetaki, “Review of out-of-plane strengthening techniques of unreinforced masonry walls,” *Buildings*, vol. 11, no. 9, p. 78, 2023.

[29] M. Ali, “Role of post-tensioned coconut-fibre ropes in mortar-free interlocking concrete construction during seismic loadings,” *KSCE Journal of Civil Engineering*, vol. 22, no. 4, pp. 1336–1343, 2018.

[30] W. Wang, D.-Q. Li, Y. Liu, and W. Du, “Influence of ground motion duration on the seismic performance of earth slopes based on numerical analysis,” *Soil Dynamics and Earthquake Engineering*, vol. 143, p. 106595, 2021.

[31] T. Zahra, J. Thamboo, and M. Asad, “Compressive strength and deformation characteristics of concrete block masonry made with different mortars, blocks

and mortar beddings types," *Journal of Building Engineering*, vol. 38, p. 102213, 2021.

[32] H. S. A. Varum, "Seismic assessment, strengthening and repair of existing buildings," Ph.D. dissertation, Universidade de Aveiro, Aveiro, Portugal, 2003.

[33] L. Fiorino, V. Macillo, and R. Landolfo, "Shake table tests of a full-scale two-story sheathing-braced cold-formed steel building," *Engineering Structures*, vol. 151, pp. 633–647, 2017.

[34] F. Yavartanoo and T. H.-K. Kang, "Retrofitting of unreinforced masonry structures and considerations for heritage-sensitive constructions," *Journal of Building Engineering*, vol. 49, p. 103993, 2022.

[35] S. Kallioras *et al.*, "Experimental seismic performance of a full-scale unreinforced clay-masonry building with flexible timber diaphragms," *Engineering Structures*, vol. 161, pp. 231–249, 2018.

[36] V. Kumar, "Traditional and modern disaster resistant house construction techniques," *Journal of Progress in Engineering*, vol. 3, no. 1, pp. 13–22, 2024.

[37] S. K. Tan, H. Ma, and Q. Ma, "A review of interlocking earth block: material modification, block structural system, and seismic performance," *International Journal of Masonry Research and Innovation*, vol. 49, no. 4, pp. 3275–3291, 2025.

[38] Z. Tang, M. Ali, and N. Chouw, "Residual compressive and shear strengths of novel coconut-fibre-reinforced-concrete interlocking blocks," *Construction and Building Materials*, vol. 66, pp. 533–540, 2014.

[39] W. Roser, "Seismic performance of nonstructural cold-formed steel framed exterior walls with drift-compatible details in a 10-story mass timber building," Master's thesis, University of Nevada, Reno, 2025.

[40] J. Vilotijevi and M. Premrov, "Assessment of in-plane timber floor stiffness as structural diaphragms: A numerical approach to lateral load response," *Forests*, vol. 16, no. 1, p. 56, 2024.

[41] R. Almeida, H. Rodrigues, M. G. Gomes, and A. Furtado, "Financial incentives for energy and seismic retrofitting of reinforced concrete buildings: a review of an integrated approach," *Infrastructure Innovation and Sustainability*, vol. 10, no. 8, p. 329, 2025.

[42] R. Dindorf and P. Wos, "Challenges of robotic technology in sustainable construction practice," *Sustainability*, vol. 16, no. 13, p. 5500, 2024.

[43] A. Ullah, "Performance of confined dry-stacked block masonry against blast loading," Master's thesis, University of Engineering & Technology Peshawar, Peshawar, Pakistan, 2020.

[44] P. Debnath and S. C. Dutta, "Seismic retrofitting and strengthening of structures," in *RC structures strengthened with FRP for earthquake resistance*. Springer, 2024, pp. 141–176.

[45] A. Sen, L. Halder, and P. Debnath, "Seismic strengthening of masonry structures using sustainable reinforceing materials: A comparative analysis," in *Structures*, vol. 77. Elsevier, 2025, p. 109091.

[46] R. Martins, R. do Carmo, H. Costa, and E. Jlio, "A review on precast structural concrete walls and connections," *Advances in Structural Engineering*, vol. 26, no. 14, pp. 2600–2620, 2023.

[47] J. K. Bhaskar, D. Bhunia, J. Karthik, and A. Samadhiya, "A state-of-the-art review on the evolution of performance of masonry infill walls under lateral

loadings," *ASCE Journal of Civil Engineering*, vol. 23, no. 7, pp. 973–1028, 2022.

[48] T. Shi, X. Zhang, H. Hao, and C. Chen, "Experimental and numerical investigation on the compressive properties of interlocking blocks," *Engineering Structures*, vol. 228, p. 111561, 2021.

[49] S. Ahmed and M. Ali, "Development and engineering evaluation of interlocking hollow blocks made of recycled plastic for mortar-free housing," *Buildings*, vol. 15, no. 17, p. 2996, 2025.

[50] S. M. Harle, "Exploring the dynamics of vibration and impact loads: a comprehensive review," *International Journal of Structural Engineering*, vol. 14, no. 1, pp. 1–24, 2024.

[51] R. S. K. Mandala and R. R. Nayaka, "A state of art review on time, cost and sustainable benefits of modern construction techniques for affordable housing," *Clean Engineering and Technology*, vol. 25, no. 2, pp. 363–380, 2025.

[52] Y. F. L. Hermans, K. E. M. Kamel, O. Debeir, G. Milani, and T. J. Massart, "Image-based structural kinematic limit analysis for historical masonry structures," *Journal of Masonry*, pp. 1–18, 2025.

[53] Y. Xu, S. Liu, and F. Heisel, "Towards sustainable construction waste management: Study on a disassemblable brick partition wall for the architecture, construction, and engineering industry," *Circular Economy*, vol. 3, no. 1, p. 100078, 2024.

[54] Z. Chang, H. Chunni, and S. Wanghua, "Resilience of rock engineering: concept, mechanism, evaluation and enhancement," *Geo-Energy and Disaster Reduction*, vol. 12, no. 1, p. 21, 2025.

[55] S. Sakir, S. N. Raman, M. Safiuddin, A. A. Kaish, and A. A. Mutalib, "Utilization of by-products and wastes as supplementary cementitious materials in

structural mortar for sustainable construction," *Sustainability*, vol. 12, no. 9, p. 3888, 2020.

[56] N. Kashfia, "Seismic performance of flat plate structures in punching shear modelled with non-layered and layered shell elements," Ph.D. dissertation, University of Alberta, 2023.

[57] G. Xie, X. Zhang, H. Hao, T. Shi, L. Cui, and J. Thomas, "Behaviour of reinforced mortarless interlocking brick wall under cyclic loading," *Engineering Structures*, vol. 283, p. 115890, 2023.

[58] J. Y. Xue, Y. Yang, and L. Qi, "Restoring force model of steel-reinforced recycled concrete frames infilled with recycled concrete blocks," *Journal of Building Engineering*, vol. 60, p. 105173, 2022.

[59] S. A. M. El-Beshlawy, "A review of analysis of rc shear walls with cutting out opening," *The Egyptian International Journal of Engineering Sciences and Technology*, vol. 47, no. 1, pp. 33–47, 2024.

[60] H. Z. Hassan and N. M. Saeed, "Advancements and applications of lightweight structures: a comprehensive review," *Developments in Civil Engineering*, vol. 1, no. 1, p. 47, 2024.

[61] S. K. Bhattarai, N. Karmacharya, S. Arayal, U. Neupane, and G. K. Joshi, "Enhancing residential construction efficiency: Evaluating interlock blocks as a sustainable alternative to traditional brick construction (a case study of private housing in setipakha height, lalitpur)," *Journal of Housing and Community*, vol. 10, no. 1, pp. 6–22, 2024.

[62] G. Xie, X. Zhang, H. Hao, K. Bi, and Y. Lin, "Response of reinforced mortarless interlocking brick wall under seismic loading," *Bulletin of Earthquake Engineering*, vol. 20, no. 11, pp. 6129–6165, 2022.

[63] V. Baneshi, S. M. Dehghan, and R. Hassanli, "An experimental study on the in-plane behavior of interlocking blocks with different interconnection mechanisms," *Materials*, vol. 57, no. 4, p. 90, 2024.

[64] A. Ullah and M. Ali, "Understanding the dynamic behavior of junctions in mortar-free interlocking block walls through literature research," 2025, unpublished research.

[65] G. Mifsud, "Comparative analysis of the seismic performance of unreinforced masonry buildings using globigerina limestone and hollow concrete blockwork," Master's thesis, University of Malta, 2024.

[66] M. Sathurshan *et al.*, "Compressive strength in grouted dry-stack concrete block masonry: Experimental and analytical predictions," *Construction and Building Materials*, vol. 467, p. 140411, 2025.

[67] N. Usukhbayar, "Geometric ornamentation for self-assembly guidance in planar interlocking joint system," Ph.D. dissertation, Iwate University, 2024.

[68] U. Murugesan, "Seismic strengthening of reinforced concrete structures using external lateral post tensioning," Master's thesis, The British University in Dubai, 2020.

[69] I. Shufrin, E. Pasternak, and A. Dyskin, "Environmentally friendly smart construction: Review of recent developments and opportunities," *Applied Sciences*, vol. 13, no. 23, p. 12891, 2023.

[70] A. Al-Fakih, B. S. Mohammed, M. A. Al-Shugaa, and M. A. Al-Osta, "Experimental investigation of dry-bed joints in rubberized concrete interlocking masonry," *Journal of Building Engineering*, vol. 58, p. 105048, 2022.

[71] Z. Wang *et al.*, "Evaluation of the effects of grouting rate and flanges on the seismic performance of mortarless mortise-and-tenon masonry walls," in *Structures*, vol. 76. Elsevier, 2025, p. 108851.

[72] Z. Wang, "Experimental and numerical study of structural frames with semi-interlocking masonry (sim) infill panels," Ph.D. dissertation, The University of Newcastle, Newcastle, Australia, 2016.

[73] W. Zhao, T. Zheng, Y. Li, Y. Yang, and Q. Wang, "Shear behavior of keyed vertical joints with lap splices for precast rc frame-shear wall structures," *Engineering Structures*, vol. 343, p. 121100, 2025.

[74] T. Shi, X. Zhang, H. Hao, and G. Xie, "Numerical derivation of homogenised constitutive relation for masonry wall made of mortar-less interlocking bricks," *Advances in Structural Engineering*, p. 13694332251322588, 2025.

[75] I. N. A. Thanaya, I. N. K. Mataram, and M. Fathan, "Plastic block for building construction material," *Journal of Engineering Science*, vol. 22, no. 4, pp. 718–726, 2024.

[76] P. F. T. Tchuigwa and K. Ssov, "Building blocks made from recycled plastics," *Proceedings of International Structural Engineering*, vol. 12, p. 1, 2025.

[77] T. Ferreira, G. A. Mendes, A. M. de Oliveira, and C. G. B. T. Dias, "Manufacture and characterization of polypropylene (pp) and high-density polyethylene (hdpe) blocks for potential use as masonry component in civil construction," *Polymer Testing*, vol. 14, no. 12, p. 2463, 2022.

[78] K. T. Udhaya and M. Jayadurgalakshmi, "Development of light weight green efficient interlocking blocks using waste plastics and industrial wastes for low cost housing construction," in *Materials Science Forum*, vol. 1144. Trans Tech Publ, 2025, pp. 71–76.

[79] S. Ahmed and M. Ali, "Mortarless structures with hollow interlocking blocks–a," working Paper/Manuscript.

[80] S. Ullah and M. Ali, "Development and properties investigation of recycled plastic solid interlocking blocks," *Case Studies in Construction Materials*, p. e05342, 2025.

[81] A. J. Das and M. Ali, "Sustainable development and assessment of low-strength/high-toughness recycled plastic rebars for structural elements under light loads," *Sustainability*, vol. 17, no. 11, p. 4997, 2025.

[82] K. Twigden, R. Henry, and Q. Ma, "Pseudo-static cyclic, snap back and shake table testing of prewec self-centering wall systems," in *10th US National Conference on Earthquake Engineering*, Anchorage, Alaska, 2014.

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

[84] H. Rodrigues, A. Arde, H. Varum, and A. Costa, "Energy dissipation and equivalent damping of rc columns subjected to biaxial bending: An investigation based in experimental results," in *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, 2012, pp. 24–28.

[85] M. Sudheer and M. Ali, "Dynamic response of an interlocking plastic-block wall with opening," *Journal of Structural Engineering*, vol. 19, no. 4, pp. 595–613, 2024.

[86] W. Akram and M. Ali, "An overview on recent developments in making efficient corner joints in mortar free interlocking block walls against lateral loading," 2025, unpublished research.

[87] A. Ullah and M. Ali, "Understanding the dynamic behavior of junctions in mortar-free interlocking block walls through literature research," 2025, unpublished research.

[88] M. M. Nasery, M. Hsem, F. Y. Okur, and A. C. Altuniik, "Numerical and experimental investigation on dynamic characteristic changes of encased steel profile before and after cyclic loading tests," *International Journal of Civil Engineering*, vol. 18, no. 12, pp. 1411–1431, 2020.

[89] M. Kohail, H. Elshafie, A. Rashad, and H. Okail, "Behavior of post-tensioned dry-stack interlocking masonry shear walls under cyclic in-plane loading," *Construction and Building Materials*, vol. 196, pp. 539–554, 2019.

[90] K. Thanushan, Y. Yogananth, P. Sangeeth, J. G. Coonghe, and N. Sathiparan, "Strength and durability characteristics of coconut fibre reinforced earth cement blocks," *Journal of Natural Fibers*, vol. 18, no. 6, pp. 773–788, 2021.

[91] W. Wang and N. Chouw, "An experimental study of coconut fibre reinforced concrete under impact load," in *New Zealand Society for Earthquake Engineering (NZSEE) Annual Technical Conference*, 2014, pp. 1–7.

[92] A. K.-L. Jnr, L. Mohammed, T. A. Tagbor, S. K. Tulashie, and C. Cheeseman, "Recycling waste plastics into plastic-bonded sand interlocking blocks for wall construction in developing countries," *Sustainability*, vol. 15, no. 24, p. 16602, 2023.