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Response of Two Story Interlocking Plastic Block Structure Having Various Patterns Under In Plane Harmonic Loadings

by

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CERTIFICATE OF APPROVAL

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Jawad Nasar

Abstract

Mortar free interlocking block systems have gained significant attention as a viable alternative to conventional masonry for low-rise construction due to their modular configuration, rapid assembly, reusability, and enhanced seismic performance. These systems rely on mechanical interlocking rather than cementitious bonding, allowing controlled joint interaction and improved energy dissipation under dynamic loading. Despite these advantages, their structural response in multi-story configurations, particularly under in-plane harmonic excitation, remains insufficiently investigated, thereby limiting their adoption in practical structural applications. This study presents a comprehensive investigation that integrates a critical review of recent literature with an experimental evaluation of a double-story mortar-free interlocking plastic block wall system. The experimental program was conducted on a 1:10 scaled model consisting of 120 blocks arranged in 12 layers and rigidly fixed at the base. Dynamic properties were established through snap-back testing, while in-plane response was assessed using shake-table excitation at frequencies of 0.9 Hz, 1.1 Hz, and 1.3 Hz. Structural response was recorded using five accelerometers, and the acquired signals were processed using MATLAB and SeismoSignal to ensure accuracy through noise filtering and baseline correction. The results indicate that the system exhibits an average fundamental frequency of approximately 1.1 Hz and damping ratios of up to 5.4%, demonstrating moderate inherent energy dissipation. The in-plane dynamic response reveals pronounced frequency-dependent characteristics, with displacement amplification increasing by 71.4% for the SS-SS wall configuration and 54.7% for the DS-SW configuration, with an average increase of approximately 63%. Similarly, acceleration response shows significant amplification, with values at 1.3 Hz being 1.67 times higher than those at 0.9 Hz for the SS-SS configuration and 3.42 times higher for the DS-SW configuration. Displacement time-history analysis further confirms the frequency-sensitive behavior, indicating that responses at 0.9 Hz are 1.55 times and 1.7 times higher than those at 1.3 Hz for the SS-SS and DS-SW configurations, respectively. Energy dissipation characteristics, evaluated from in-plane base shear displacement relationships assuming an equivalent lumped roof mass, demonstrate that the DS-SW configuration consistently outperforms the SS-SS configuration, dissipating 55%, 7%, and 9.3% more energy at excitation frequencies of 0.9 Hz, 1.1 Hz, and 1.3 Hz, respectively. Furthermore, both configurations exhibit enhanced energy absorption at higher excitation levels, with increases of 1.71 times for the SS-SS configuration and 1.75 times for the DS-SW configuration at 1.3 Hz relative to 0.9 Hz. Comparison between experimental observations and empirical predictions indicates good agreement, with deviations ranging from 4.75% to 9.91%, reflecting the influence of nonlinear contact behavior and interlocking mechanisms while remaining within acceptable engineering limits. Overall, the findings establish that double-story mortar free interlocking wall systems exhibit stable and efficient in-plane seismic performance, characterized by significant frequency dependent response and reliable energy dissipation capacity, thereby supporting their applicability in sustainable and earthquake-resistant construction and highlighting the need for the development of standardized testing methodologies and design guidelines for multi story implementations.

Keywords: Mortar-free construction; Interlocking block systems; In-plane dynamic response; Shake table testing; Dry stack masonry; Seismic performance.

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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
Δ	Displacement in millimeter
ζ	Damping ratio

Chapter 1

Introduction

1.1 Background

The evolving demands of modular, seismic resilient, and sustainable construction have propelled the development of mortar free systems, particularly those relying on interlocking block assemblies. These systems offer substantial advantages in terms of reusability, speed of construction, and resource efficiency by eliminating the need for cementitious bonding materials. Their dry stack nature allows for greater ductility and energy dissipation, making them attractive for seismic zones [2,3]. In addition, the reduced construction time and potential for disassembly and reuse align with circular economy principles, making them ideal for post disaster reconstruction and environmentally conscious design. However, much of the research and experimental validation has been limited to single story prototypes or low rise applications. The extension of these systems into multi story configurations presents a range of unaddressed structural and dynamic challenges, especially when subjected to lateral or harmonic loading. Rocking behavior, joint instability, and the amplification of inter story drift are more pronounced in taller configurations, demanding careful analysis [4].

Among the most influential and least understood parameters in multi story mortar free assemblies is the behavior of interlocking joints under dynamic excitation.

While individual block designs such as tongue and groove or dovetail joints offer in plane restraint, their performance when stacked across floors introduces complexities related to load transfer and displacement compatibility. In high rise scenarios, the cumulative effect of minor deformations at each joint can lead to substantial top story displacements, compromising serviceability. Notably, floor-wall joint interfaces play a critical role in structural integrity, as they facilitate force redistribution between stories and influence overall seismic performance. In conventional masonry, such joints are monolithic due to continuous bonding, but in dry stack systems, they behave more like discontinuities. Failure at these joints, through slippage or uplift, can significantly degrade the structure's ability to maintain elastic behavior or recover post shaking [5, 6]. Additionally, variability in block manufacturing and installation tolerances may exacerbate joint inconsistencies, further complicating dynamic response prediction.

Despite the increasing interest in interlocking systems, a comprehensive design methodology that addresses the unique mechanical characteristics of dry stack masonry is still lacking. Unlike conventional bonded masonry, the absence of mortar in these systems eliminates tensile continuity, making the mechanical performance heavily reliant on the geometry and surface interaction of individual units. The lack of unified international codes or guidelines specific to mortar free systems further complicates widespread adoption in seismic prone regions. Therefore, this review not only assesses current technical advancements but also identifies critical research needs in joint mechanics, multi hazard performance evaluation, and monitoring technologies that can facilitate safe implementation at scale [7].

To the best of the authors' knowledge, studies utilizing full scale dynamic testing, incorporating floor-wall interlocking transitions, and deploying structural health monitoring (SHM) for multi story mortar free structures are rarely reported. Furthermore, most existing literature focuses on laboratory scale specimens under simplified boundary conditions, which may not represent the real behavior of tall structures exposed to multi directional seismic loads. The aim of this research is to explore the potential of interlocking, mortar free block systems for high rise structural applications, as reported in the literature. For this purpose, articles published in highly reputable journals in the last three years are reviewed in detail to gather all published information related to their dynamic performance, joint level mechanics, and current design limitations. First, the application of dynamic evaluation techniques such as shake table testing and nonlinear simulation for multi story configurations is discussed. Then, the behavior of interlocking joints, particularly at floor-wall transitions under lateral and harmonic loading, is reviewed. Finally, regulatory gaps and the role of modern SHM systems in advancing the safe adoption of these systems in tall buildings are explored [8]. This review aims to bridge the existing knowledge gap by highlighting both the opportunities and limitations of adopting mortar free construction methods in seismic prone urban environments.

1.1.1 Previous Researches

Research on mortar-free interlocking block systems has predominantly focused on their application in low-rise or single-story structures, where their modularity and energy dissipation capacity have demonstrated significant potential in seismic zones. Early studies highlighted the capacity of interlocking units to sustain rocking and re-centering behaviors under cyclic and earthquake-type loading, contrasting with the brittle cracking observed in conventional bonded masonry [2,3]. These investigations established the foundational understanding that eliminating cementitious mortar not only reduces construction time but also enhances reusability and alignment with sustainable, post-disaster construction needs.

Dynamic evaluation methods have been central to past research. Shake table testing, cyclic quasi-static protocols, and nonlinear finite element simulations have been widely employed to capture rocking mechanisms, uplift behavior, and slip at interfaces [4,5]. However, these techniques have largely been restricted to scaled or single-story prototypes, limiting their ability to replicate cumulative drift, gravity load effects, and floorwall interface complexities in tall structures [6]. Numerical models, particularly Discrete Element Method (DEM)-based approaches, have allowed simulation of block-to-block interactions and joint slip, but the accuracy of these models depends heavily on experimental calibration, which remains scarce [7,8]. At the component level, research has also emphasized the mechanics of interlocking joints. Various joint geometries such as key and slot and dovetail have been explored for their lateral resistance and energy dissipation capacity. Findings suggest that while such joints improve shear performance, they are prone to uplift and instability when scaled to multi-story applications [9, 10]. Floorwall interfaces have been identified as critical weak points, as unconfined joints concentrate drift and degrade structural integrity under cyclic lateral loads. Mitigation strategies such as shear keys, dowels, and friction-enhancing treatments have been proposed, but a standardized detailing framework is yet to emerge [11, 12].

Another important line of past research concerns design codes and monitoring. Current seismic design standards, developed for bonded masonry, do not recognize the unique mechanics of dry-stack systems. As a result, designers are forced to rely on conservative assumptions, restricting broader adoption of mortar-free systems in high-rise construction [8]. Structural Health Monitoring (SHM) has been explored in parallel, with advances in fiber optic sensing, smart bricks, and wireless sensors showing promise for tracking joint slip, rocking, and uplift in real time [12,13]. Nonetheless, these technologies remain underutilized, with challenges persisting in differentiating between functional joint motion and damage.

In summary, past research has demonstrated that mortar-free interlocking block systems hold considerable promise for seismic resilience, modular construction, and sustainability. However, their application has remained limited to single-story or small-scale studies. The absence of full-scale multi-story testing, standardized joint detailing, and performance-based monitoring frameworks continues to pose barriers to their widespread adoption in tall buildings. This body of work underscores the urgent need for bridging experimental, numerical, and regulatory gaps to transition these systems from laboratory prototypes to mainstream structural applications.

1.2 Research Motivation and Problem Statement

Conventional house leads to loss of human life due to its damages under earthquakes. The expensive solutions are available to safe human life and houses.

However, cheaper solutions are desirous in terms of mortar free construction, particularly multi story construction. This can also benefit in terms of much reduced rehabilitation cost in case of severe damages and losses.

House walls collapse due to resonance frequency. Less cost solutions are available in terms of mortar free interlocking construction. This is widely studied for single story construction, however as per authors best knowledge, no study is available on multi story construction.

1.2.1 Research Questions

Following are the research questions:

i. How do the fundamental frequency and damping ratio influence the in plane dynamic response and energy dissipation of mortar free interlocking block walls under harmonic loading?

ii. How do wall configuration and sequencing, including openings, influence in plane displacements and energy absorption of prototype mortar free interlocking block walls under harmonic loading across varying frequencies?

iii. Which structural and modeling factors contribute to the discrepancies between experimental results and empirical predictions of in plane behavior in mortar free interlocking block systems?

iv. How does the in plane behavior of mortar free interlocking plastic block walls enhance energy dissipation, and what are the implications for designing earthquake resistant masonry structures?

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

The specific objective of this study is to critically review and synthesize recent advancements in the dynamic behavior of double story mortar free interlocking block systems. The study particularly focuses on evaluating existing dynamic testing methodologies, understanding joint level mechanics with special emphasis on floor wall interaction, and identifying key structural design and long term monitoring challenges. Through systematic consolidation of these aspects, the research aims to delineate critical gaps in current knowledge and establish a robust foundation for future experimental, numerical, and monitoring based studies, ultimately contributing to the development of performance based seismic design frameworks for two story dry stack structural systems.

In this context, the experimental scope is scaled down to a controlled laboratory configuration, wherein the study specifically investigates the dynamic performance of double story in plane mortar free interlocking plastic block walls using a locally developed, low cost 1D shake table. This scaled down experimental approach enables a focused and controlled assessment of seismic response characteristics under idealized yet representative dynamic loading conditions, thereby supporting clearer interpretation of system behavior and governing mechanisms.

1.4 Scope of Work and Study Limitations

This study presents an experimental investigation of the dynamic behavior of a double-story mortar free interlocking wall configuration subjected to harmonic loading, with response evaluated in terms of acceleration-time and displacement-time histories.

The scope of the study is centered on an experimental program conducted on a prototype innplane double story walls configuration. The fundamental dynamic properties, including natural frequency and damping ratio, are determined using snap back testing. Subsequently, uni directional harmonic loading is applied in the X-direction to simulate controlled dynamic excitation. The structural response is recorded in the form of acceleration-time histories, which are further processed to obtain displacement-time histories. These results are used to evaluate the vibration characteristics, stiffness response, and energy dissipation behavior of the system. Based on the observed response, empirical relationships are developed to characterize and predict the in-plane dynamic behavior of the wall configuration under harmonic loading.

The study limitations arise from the controlled experimental setup. The system is investigated under uni directional loading only, which does not fully represent the complexity of real multi directional excitation. The structure is tested on a fixed base platform, which idealizes boundary conditions and does not account for soil structure interaction effects. Furthermore, harmonic loading represents a simplified and controlled form of dynamic excitation that may not fully replicate actual field conditions.

Overall, this study provides primary experimental evidence on the dynamic response of double story mortar free interlocking wall configurations under harmonic excitation, forming a foundation for further advanced experimental and analytical developments.

1.4.1 Rationale Behind the Variable Selection

The variables chosen in this study are directly linked to the core challenges of extending mortar free interlocking block systems from low rise to multi story applications. Unlike traditional bonded masonry, dry stack systems depend on joint geometry, surface interaction, and mechanical interlock to resist loads. This makes parameters such as joint detailing, floor wall interfaces, and dynamic loading regimes central to understanding their structural performance. Joint configurations strongly influence shear resistance, rocking behavior, and energy dissipation, but their effectiveness diminishes in taller assemblies where cumulative deformations can lead to instability. Floorwall interfaces represent another critical variable, as they govern load transfer between stories and often act as weak points under seismic excitation. Similarly, loading characteristics such as amplitude, frequency, and type of excitation dictate the extent of joint opening, uplift, and re-centering capacity, making them essential for evaluating system reliability. Additionally, monitoring related variables are necessary to establish whether joint movements represent safe, functional behavior or actual damage progression. Without incorporating these aspects, it becomes difficult to develop reliable performance-based design and validation strategies.

By addressing these variables, the study aims to bridge the gap between small scale laboratory findings and the requirements of real world multi story construction. This focus ensures that the research directly contributes to developing safer, more resilient, and scalable mortar free systems for seismic prone environments.

1.5 Brief Methodology

A comprehensive experimental program will be undertaken to evaluate the dynamic behavior of interlocking plastic block assemblies, with a particular emphasis on intersecting walls and floorwall interfaces. These regions represent critical structural connections that govern the overall seismic performance of mortarfree interlocking systems. The study aims to simulate realistic inplane loading conditions and identify the key response parameters influencing stiffness, energy dissipation, and joint stability under harmonic excitation.

The experimental setup will employ a one dimensional shake table, capable of applying controlled harmonic base motions to the test specimens. These motions will simulate seismic excitations at variable frequencies and amplitudes to observe nonlinear joint behavior, including slip, uplift, and re-centering phenomena. The interlocking block assemblies will be constructed at a reduced scale using plastic units that replicate actual geometry and interface characteristics. The floorwall interface will be modeled using a rigid wooden diaphragm to ensure effective load transfer between stories.

Instrumentation will include seven accelerometers strategically installed across the structure: two positioned at the base and top of the floor wall joint to capture boundary responses, two positioned at top and base of first floor, and three distributed along the wall panels to record local and global accelerations. The sensors will be connected to an Arduino based data acquisition system interfaced with MATLAB for real time recording and initial filtering of acceleration signals. The recorded acceleration time histories will then be processed using SeismoSignal software, which will perform baseline correction, filtering, and numerical integration to derive displacement time histories. From the processed data, base shear (Q) will be computed as the product of the effective mass and measured acceleration. The corresponding displacement data will be used to generate hysteresis loops, from which energy dissipation and total absorbed energy will be determined. Finally, the results will be utilized to develop empirical equations capable of predicting the dynamic response of both corner joints and floorwall interfaces in interlocking plastic block masonry systems, facilitating improved design and seismic assessment methodologies.

1.6 Research Impact on Industry

1.6.1 Research Novelty and Uniqueness

Although interlocking construction systems have been widely explored in previous studies, the majority of existing research is limited to single story configurations and static or quasi static loading conditions. The in plane dynamic response of double story mortar free interlocking wall configurations under harmonic loading conditions remains insufficiently investigated, particularly with respect to controlled experimental shake table studies. Furthermore, there is a lack of comprehensive understanding regarding the dynamic load transfer mechanisms, contact interaction behavior and energy dissipation characteristics double story interlocking assemblies subjected to repeated cyclic excitation.

In this context, the novelty of this research lies in the experimental investigation of a double story plastic interlocking wall system under harmonic loading using a one dimensional shake table, which provides systematic and controlled insight into its dynamic structural response. This study addresses a critical research gap by generating experimental evidence on the in plane behavior, deformation patterns, and failure progression of double story mortar free interlocking systems under dynamic excitation. Therefore, a clear research gap exists in the experimental investigation of in plane dynamic behavior of double story mortar free interlocking wall systems under controlled harmonic loading.

1.6.2 Research Significance and Benefit

The significance of this research lies in advancing the understanding of the dynamic in plane behavior of mortar free interlocking construction systems under harmonic loading conditions. By extending experimental investigation to a double story configuration, the study enhances current knowledge of structural response characteristics such as acceleration amplification, displacement behavior, and progressive failure mechanisms under cyclic dynamic loading.

This research contributes to the development of safer and more efficient alternative construction systems by providing experimentally validated insights into the performance of interlocking wall systems. It also strengthens the knowledge base in structural dynamics by addressing the limited availability of experimental data for double story modular interlocking structures subjected to controlled harmonic excitation. The findings are expected to support further development of innovative, economical, and sustainable housing systems, particularly in the context of low rise construction technologies.

1.6.3 Practical Implementation

From a practical perspective, the outcomes of this study are directly applicable to the development of cost effective and rapidly constructible housing systems using mortar free interlocking technology. The findings may be utilized by construction companies, housing developers, and contractors engaged in low cost and modular housing projects, particularly where speed of construction and material efficiency are critical considerations.

In addition, this research has significant relevance for disaster relief and emergency housing applications, where rapidly deployable and easy to assemble structural systems are required. The proposed interlocking system offers advantages such as reduced construction time, lower material and labor costs, and minimized dependency on skilled labor, making it a viable alternative for scalable housing solutions. Overall, the study supports the practical adoption of interlocking construction systems as a sustainable and efficient approach to modern housing challenges.

1.6.4 National and Global Impact with SDGs Relevance

At the national level, this research contributes to addressing the growing demand for affordable, rapidly constructible, and resource efficient housing systems, particularly in developing regions facing urban expansion and housing shortages. The study supports the advancement of alternative construction technologies that reduce dependence on conventional mortar based masonry systems, thereby promoting more economical and efficient building practices. This is particularly significant for regions where rapid housing provision is required due to population growth or infrastructure limitations.

From a global perspective, the research contributes to the broader field of sustainable and modular construction systems, which are increasingly being explored as part of international efforts toward resilient infrastructure development. The findings address a global research gap in experimentally validated dynamic performance data for double story interlocking wall systems under harmonic loading conditions, which is currently limited in existing literature. The outcomes of this study may assist researchers and practitioners worldwide in improving the design, analysis, and application of interlocking construction technologies, thereby supporting sustainable development goals related to affordable housing and resilient built environments. The study also aligns with SDG 9 (Industry, Innovation and Infrastructure) and SDG 11 (Sustainable Cities and Communities).

1.6.5 Research Challenges

The experimental investigation of the in plane dynamic response of double story mortar free interlocking wall systems under harmonic loading presents several methodological and technical challenges. One of the primary challenges is the accurate generation and control of harmonic excitation using a one dimensional shake table while ensuring consistent repeatability of test conditions across multiple trials. In addition, maintaining stable and realistic boundary conditions for a double story interlocking assembly is challenging, as minor variations in support constraints can significantly influence the dynamic response behavior of the system.

A further challenge lies in the instrumentation and data acquisition process, particularly in capturing precise acceleration and displacement responses at different levels of the structure under dynamic loading. The system also exhibits complex nonlinear behavior due to the nature of interlocking plastic blocks, where interface separation, localized slip, and partial loss of contact introduce uncertainties in load transfer mechanisms. These behaviors represent a research gap in accurately quantifying energy dissipation and contact dependent response mechanisms in double story interlocking systems under harmonic excitation. Moreover, laboratory scale shake table testing introduces scaling limitations, which makes it challenging to directly generalize experimental findings to full scale structural applications. The results are limited to laboratory scale conditions and should be interpreted considering scaling effects for real life applications.

1.6.6 Ethical and Management Considerations

This research will be conducted in alignment with academic and professional ethical standards. Ethically, care will be taken to ensure transparency in data collection, analysis, and reporting, with results presented objectively without fabrication or selective interpretation. Since the study involves laboratory scale experiments, no direct risks to human participants are involved; however, the safe use of laboratory resources, shake table equipment, and electrical instrumentation will be ensured through compliance with institutional safety protocols.

From a management perspective, effective time, resource, and team coordination will be essential. Proper scheduling of specimen construction, instrumentation setup, and experimental runs will minimize delays and optimize the use of equipment. Materials will be sourced responsibly to avoid unnecessary waste, aligning the study with principles of sustainability.

In terms of risk management, potential hazards include structural collapse of scaled models during shake table operation, electrical faults in instrumentation, and shake table malfunction. These risks will be managed by enforcing strict safety measures, such as restricting access during testing, providing protective barriers, conducting regular equipment checks, and having contingency plans for data backup and equipment maintenance. Fire safety and emergency response protocols will also be in place.

Overall, the study will uphold high ethical standards, ensure responsible resource management, and mitigate laboratory risks to guarantee a safe and reliable research process.

1.6.7 Research Deliverable, Sale and Marketing Potential

This research will deliver experimental data and empirical models on the seismic response of two story interlocking plastic block structures with different block patterns. The findings can be scaled from laboratory testing to real world applications, offering design insights for modular, low cost, and earthquake resilient construction. The marketing potential lies in the commercialization of interlocking plastic blocks as a sustainable, mortar free alternative to conventional masonry, suitable for affordable housing, disaster relief, and eco-friendly urban development.

1.7 Thesis Layout

This thesis consists of six chapters. A brief outline of each chapter is presented below:

Chapter 1: Introduction: This chapter explains the background of the research, defines the problem statement, specifies the aim and objectives, and outlines the scope and limitations of the study. It also describes the research motivation, novelty, and overall methodology adopted in the study.

Chapter 2: Literature Review: This chapter presents a detailed review of the previous studies relevant to this research. It summarizes the key findings of existing work and identifies the research gaps that led to the present study.

Chapter 3: Experimental Program: This chapter discusses the materials, prototype configuration, experimental setup, instrumentation, and testing procedures adopted in the current research program.

Chapter 4: Experimental Evaluation: This chapter presents and analyzes the experimental results, including acceleration time and displacement time responses, damping ratio, and energy absorption characteristics of the tested corner joint assembly.

Chapter 5: Discussions: This chapter interprets the experimental outcomes, develops empirical correlations, and discusses their practical implications for structural performance and resilience in interlocking plastic block systems.

Chapter 6: Conclusion and Future Work: This chapter concludes the research, highlights the major findings, and provides recommendations for future studies based on the outcomes of this investigation. At the end, references are provided.

Chapter 2

Literature Review

2.1 Background

Seismic events generate intense ground motions that often lead to extensive damage in masonry structures. The severity of this damage varies among affected regions but frequently results in the partial or complete collapse of buildings, posing a serious threat to human life and infrastructure [14, 15]. Masonry constructions, particularly those in seismically active rural and urban areas, are highly vulnerable due to their heavy mass and brittle behavior [16]. When ground accelerations are transmitted to the foundation, they induce significant inertial forces, leading to shear cracking and structural instability within masonry walls [17].

Over the years, numerous researchers have explored different construction techniques to enhance the seismic performance of masonry systems [18, 19]. Conventional bonded brick masonry, while widely used, demonstrates limited energy dissipation and low ductility under cyclic loading [20]. To address these weaknesses, the development of alternative systems such as mortar free interlocking block assemblies has gained considerable attention [21, 22]. These systems aim to simplify construction, improve reusability, and reduce the selfweight of structural components [23].

In spite of advancements, the inherent mass and stiffness characteristics of traditional masonry elements continue to present challenges for seismic resilience [24].

Consequently, ongoing studies have focused on refining the geometry, connection detailing, and reinforcement strategies of interlocking block systems [25, 26]. This chapter provides a detailed review of literature related to the seismic vulnerability of traditional masonry, examines recent innovations in interlocking construction, and evaluates the experimental and analytical investigations conducted to improve the dynamic performance and structural reliability of such systems under simulated earthquake conditions [27, 28]. Although both in plane and out of plane failure mechanisms have been reported in the literature, the present study primarily focuses on in plane dynamic behavior of mortar free interlocking block systems. The out of plane studies reviewed in this chapter are used only for comparative understanding of seismic failure patterns and for identifying broader masonry vulnerabilities. The research gap is therefore established mainly from in plane experimental and analytical investigations, particularly those related to single story and limited multi story configurations under dynamic loading.

2.2 Transition from Bonded Brick Masonry to Interlocking Block Construction

2.2.1 Fundamental Seismic Response Mechanisms in Masonry Walls

In plane and out of plane behaviors represent two fundamental modes of masonry structural response under lateral loading. In plane behavior refers to loading acting within the plane of the wall, where resistance is primarily governed by shear action, diagonal cracking, and racking deformation. In contrast, out of plane behavior occurs when lateral loads act perpendicular to the wall surface, resulting in flexural bending, instability, and potential overturning failure. In plane response is typically associated with shear dominated mechanisms, while out of plane response is governed by bending and stability loss. The present study is exclusively focused on the in plane dynamic behavior of mortar free interlocking block systems.

2.2.2 Limitations of Conventional Bonded Masonry

Conventional bonded masonry construction has been historically favored for its simplicity, availability of materials, and predictable load transfer mechanisms. It relies on mortar s to provide tensile and compressive pathways that ensure the overall integrity of the structure under static conditions [18]. However, under seismic or cyclic loading, these mortared s exhibit significant limitations. Brittle diagonal shear cracking and out of plane failure are common due to the lack of ductility and energy dissipation capacity [16]. The inability of bonded masonry to accommodate rocking or controlled displacement leads to sudden collapse, particularly in upper story walls, where load concentration is more pronounced [14].

FIGURE 2.1: Damage to Masonry Buildings after Earthquake

Moreover, once cracking occurs, the continuous load path through mortar s is disrupted, causing rapid degradation of stiffness and strength. This vulnerability was evident in several earthquake events where bonded masonry suffered partial or complete collapse due to the monolithic behavior of mortar s [17]. Although various retrofitting approaches have been suggested, including reinforced overlays or grout injection, these techniques do not address the inherent lack of flexibility. Consequently, traditional masonry remains susceptible to brittle failure when exposed to strong ground motions. Figure 1 illustrates typical seismic damage observed in conventional bonded masonry buildings. The left image shows partial wall collapse due to diagonal shear cracking and out of plane wall failure, while the right image depicts extensive upper story collapse and loss of vertical load bearing continuity. Such damage patterns are common in mortared masonry, where brittle failure modes and limited ductility lead to sudden strength degradation under dynamic loads.

Traditional bonded masonry offers predictable static performance but fails under seismic or cyclic loads due to brittle cracking and lack of ductility [19]. Mortar's restrict controlled movement, leading to sudden collapse [20]. The key gap is its poor adaptability under dynamic conditions, highlighting the need for flexible, energy dissipating alternatives [21].

2.2.3 Advantages of Interlocking Block Systems

Interlocking block systems have emerged as an innovative solution to overcome the structural limitations of traditional bonded masonry [22]. These systems rely on mechanical interlocking rather than mortar bonding, which allows for dry stacking and improved energy dissipation during lateral loading [23]. By transferring loads through geometry and surface friction, interlocking units provide self alignment and stability without relying on tensile continuity. The absence of cementitious bonding not only facilitates rapid construction but also enhances reusability and sustainability [24]. Studies have shown that interlocking masonry exhibits rocking and re-centering behavior under dynamic loads, thereby preventing brittle failure and allowing structures to recover post shaking [25].

Furthermore, interlocking systems significantly reduce the need for skilled labor and construction time compared to mortared masonry, offering advantages for low cost and post disaster reconstruction scenarios [26]. The modular nature of these blocks enables adaptability, making them suitable for prefabrication and reuse within the framework of circular economy principles. However, despite their potential, research remains primarily focused on low rise and single story applications. Experimental validation for taller configurations remains scarce, particularly concerning cumulative drift and slip behavior under seismic excitation [27]. Thus, the key research gap is the limited understanding of the dynamic behavior and scalability of interlocking block systems for multi story structures in seismic prone regions.

It is important to note that most available experimental and analytical studies on interlocking block systems primarily focus on single story in plane behavior, including lateral stiffness, energy dissipation, and rocking response under static, cyclic, or dynamic loading conditions. These studies provide a strong basis for understanding the fundamental in plane performance of such systems. However, limited research has been extended to double story or vertically stacked configurations, particularly in terms of in plane dynamic interaction, inter story drift transfer, and cumulative deformation effects under harmonic excitation. Therefore, this study extends the existing single story in plane investigations to a two story experimental model to evaluate the influence of vertical interaction on the overall in plane dynamic response.

Table 2.1: Comparison between Conventional Brick Masonry and Interlocking Block Systems

Aspect	**Conventional Bonded Brick Masonry**	**Mortar free Interlocking Systems**	**Evidence (2022-24)**
Load mechanism	Mortar provide continuous bonds tensile/compressive pathways	Mechanical interlock + friction at joints; no tensile continuity	[3, 28]
Failure mode	Diagonal shear cracking, brittle collapse	Joint Rocking, slip/uplift, re-centering potential	[2, 10]
Construction	Moderate; mortar laying skilled work	Faster; lower skill, modular assembly	[3, 28]
Sustainability	Low (demolition required)	High (disassembly, reuse)	[4–6]
Design status	Established codes and drift/limit states	Limited code guidance; need for performance-based	[20]
Monitoring	Damage = undesirable; SHM thresholds understood	Movement may be intentional: SHM must distinguish	[12]

The comparison in Table 2.1 underscores the fundamental shift in both structural philosophy and performance expectations when moving from bonded brick masonry to mortar free interlocking block systems. While the latter offer notable advantages in constructability, reversibility, and sustainability, their distinct load transfer mechanisms, nonlinear behaviors, and lack of standardized design provisions introduce new uncertainties in multi story applications [28]. These differences not only affect how such systems respond to lateral and harmonic loads but also necessitate the development of specialized evaluation methods to capture rocking, slip, and uplift phenomena with accuracy. As a result, dynamic testing protocols, advanced numerical simulations, and hybrid experimental computational approaches become essential for quantifying these behaviors [29].

Interlocking block systems transfer loads through geometry and friction, enhancing rocking stability and energy dissipation. They enable rapid, modular, and sustainable construction. However, their seismic scalability beyond single story structures remains underexplored, especially for multi story performance validation.

2.2.4 Challenges in Multi Story Applications

While the advantages of interlocking masonry are well recognized, scaling these systems to multi story configurations introduces several mechanical and analytical challenges [30]. In taller structures, minor displacements at each accumulate over multiple stories, resulting in significant inter story drifts that can compromise serviceability and safety [31]. The complex interaction between vertical and lateral loads creates nonlinear responses, which are difficult to capture accurately through conventional finite element modeling [32]. Additionally, variations in block manufacturing tolerances and surface roughness can lead to inconsistent frictional resistance, further complicating predictive modeling [33].

A major limitation is the absence of standardized design guidelines or international codes specific to dry stack masonry [34]. Current masonry design provisions assume monolithic behavior, neglecting the discontinuities and rocking mechanisms inherent to interlocking systems [35]. This lack of codified procedures results in conservative designs or reluctance to adopt mortar free technologies in seismic regions. Furthermore, existing experimental investigations are often limited to laboratory conditions that do not replicate realistic boundary effects or gravity loads. Therefore, the primary research gap lies in the absence of standardized methodologies and validated design frameworks that address the nonlinear, multi story behavior of interlocking masonry under dynamic excitation [36].

Extending interlocking systems to multi story use introduces complex stress distributions, nonlinear responses, and significant drift accumulation. The lack of standardized design codes and full scale validation hinders widespread adoption [37]. Developing reliable analytical and regulatory frameworks remains a priority [38].

2.3 Dynamic Evaluation Techniques for Multi Story Mortar Free Structures

2.3.1 Shake Table and Quasi Static Testing

Shake table and quasi static testing remain the most direct means of evaluating seismic performance in masonry systems [39]. Shake table tests simulate real earthquake ground motions, allowing assessment of rocking, uplift, and drift behavior in interlocking assemblies [40]. Quasi static cyclic testing, on the other hand, helps understand stiffness degradation and hysteretic energy dissipation [41]. However, most reported experiments have been performed on single story or small scale specimens, often neglecting the vertical load accumulation and frictional effects inherent to multi story systems [42].

Figure 2 illustrates a shake table test conducted to assess the seismic performance of a reinforced mortar less interlocking brick masonry wall [43]. The test setup includes a wall specimen mounted between a heavy top mass and a rigid base (footing), simulating realistic boundary conditions during earthquake loading. The wall is instrumented with Linear Variable Differential Transformers (LVDTs) and accelerometers to accurately record lateral displacements and accelerations throughout the dynamic excitation. The data obtained from such tests are crucial in understanding the nonlinear behavior and failure mechanisms of dry stack systems, particularly in multi story applications. This setup aligns with procedures described by Xie et al. [43], who conducted similar experiments to evaluate the seismic response of reinforced mortar less interlocking walls under lateral loading conditions.

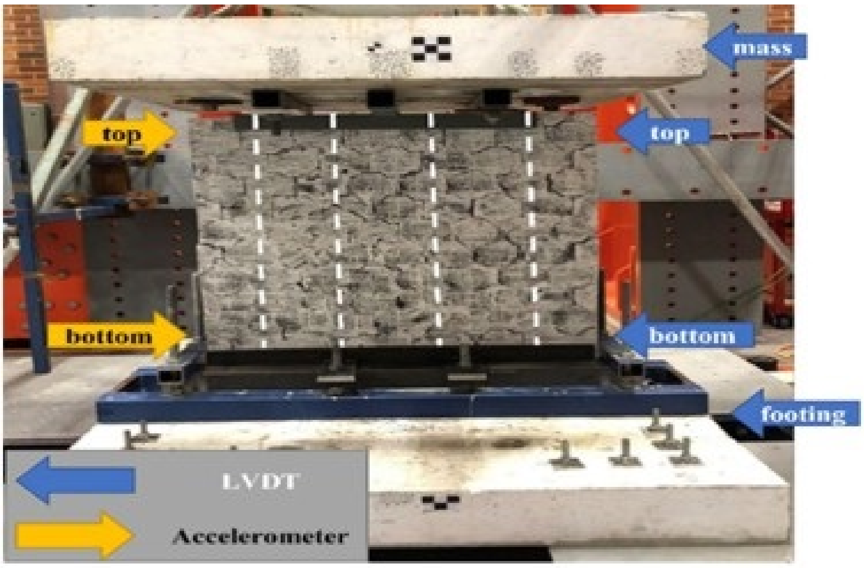


FIGURE 2.2: Shake Table Test for Interlocking Block Wall

Scaled models are particularly limited in replicating the realistic gravity induced stresses, leading to inaccuracies in evaluating cumulative drift or uplift at higher levels [44]. Furthermore, existing protocols vary widely in input motion, damping ratios, and interface conditions, making results across studies difficult to compare. Although shake table tests demonstrate the ability of dry stack systems to undergo rocking without collapse, the lack of full scale experiments restricts validation of their seismic resilience [45]. Hence, a critical research gap persists in the absence of large scale dynamic testing capable of capturing cumulative drift and energy dissipation in multi story mortar free systems. Shake table and quasi static tests provide insight into rocking, uplift, and drift behavior but are mostly limited to single story or scaled models [46]. These setups fail to capture cumulative drifts and realistic gravity effects. Full scale dynamic testing remains an essential research need [44–46]. A discussion on the scaled down modelling approach is included to justify the use of reduced scale specimens in experimental structural dynamics. Scaling allows the replication of prototype behavior under controlled laboratory conditions while ensuring geometric and dynamic similarity. This approach enables the study of structural response mechanisms that would otherwise be impractical to investigate at full scale.

2.3.2 Numerical Modelling Approaches

Finite Element (FEM) and Discrete Element Method (DEM) modeling have become essential tools for understanding the dynamic behavior of interlocking masonry [47]. FEM is effective in simulating global responses and stress distribution across walls, while DEM captures the motion, slip, and separation of individual blocks [48]. Nevertheless, these models depend heavily on input parameters such as friction coefficients, contact stiffness, and damping ratios, which vary across studies and materials [49]. Since experimental calibration is often based on small scale tests, predictive accuracy for multi story configurations remains limited [50]. Additionally, DEM models frequently underestimate energy loss and overestimate re-centering capacity because they do not account for surface irregularities and imperfect contact [51]. The interaction between floor diaphragms and wall assemblies introduces additional complexity, as most models assume rigid or perfectly bonded connections that do not exist in real dry stack systems [52]. The absence of standardized modeling protocols makes it challenging to establish consensus regarding performance prediction. Thus, the major research gap concerns the lack of experimentally validated, scalable numerical models that accurately represent slip, uplift, and drift accumulation in tall dry stack structures.

FEM and DEM techniques simulate global and block level behavior but depend on uncertain input parameters like friction and damping [47–52]. Their predictive accuracy declines for multi story systems due to limited calibration. Validated, scalable numerical models are needed for reliable performance prediction.

2.3.3 Hybrid Experimental Numerical Approaches

Hybrid testing methods integrate experimental observations with computational modeling to provide a more holistic understanding of structural response [51]. By combining physical shake table data with simulation based extrapolation, hybrid frameworks can reduce experimental costs while enhancing result accuracy [50]. These approaches are particularly useful for investigating nonlinear behaviors such as rocking and interface sliding, which are difficult to capture using a single technique [52]. Recent studies highlight that hybrid testing can effectively model the performance of small scale dry stack prototypes under cyclic loads [47]. However, its application to multi story interlocking block structures remains extremely limited [44].

Furthermore, hybrid frameworks have not yet been standardized for interlocking masonry, leading to inconsistencies in model validation and data fusion [45]. The integration of experimental and numerical data under multi hazard conditions, such as combined seismic and wind loads, is especially underexplored [49]. These gaps hinder the development of performance-based seismic design tailored to mortar free systems. Consequently, a clear research need exists for standardized hybrid experimental numerical protocols that combine physical testing with high fidelity simulations for multi story dry stack structures [44–49].

TABLE 2.2: Summary of Seismic Evaluation Techniques and Limitations

Technique	**Use**	**Limitation**	**Reference**
Shake Table Testing	Simulates real earthquakes	Limited to scaled models; vertical lacks load fidelity	[4]
Cyclic Quasi Static	Lateral load testing	Cannot capture dynamic effects	[5]
Time History Analysis	Seismic response modeling	Sensitive to model calibration	[8, 20]
DEM Simulation	Joint slip/uplift analysis	Limited full scale validation	[7, 19]
Hybrid Methods	Combines test and simulation	Rare in full scale use	[6, 26]

Table 2 provides a concise overview of the primary dynamic evaluation methods used to study multi story mortar free interlocking block structures. It reveals that while techniques like shake table testing, quasi static protocols, time history simulations, and DEM are effective for capturing rocking and slip behaviors, they are predominantly applied to single story or scaled models [46–52]. Limitations such as poor gravity scaling, sensitivity to interface assumptions, and lack of full scale validation reduce the reliability of these methods for tall configurations. The table emphasizes the need for hybrid experimental numerical approaches and standardized parameters to accurately assess the dynamic response of high rise dry stack systems under seismic and wind loads [47–52].

Hybrid frameworks combine testing and simulation for improved accuracy in dynamic assessment. Despite their promise, applications to interlocking systems remain rare and unstandardized. Developing integrated hybrid models is crucial for establishing performance-based design standards.

2.4 Structural Responses of Interlocking Assemblies and Floor Walls

2.4.1 Joint Geometry and Load Resistance

The geometry of interlocking s is one of the most critical factors governing lateral load resistance in mortar free systems. Common geometries include key slot, dovetail, and tongue and groove configurations, which resist in plane shear through mechanical interlock and surface friction [53]. While these designs improve energy dissipation, they remain vulnerable to uplift and slip under strong lateral loads [54]. The absence of tensile continuity across can lead to progressive separation between layers, especially in multi story configurations where vertical loads amplify interface stresses [55].

Experiments show that properly confined with dowel connections or boundary restraints exhibit enhanced rocking stability [56]. However, these reinforcement techniques reduce the inherent modularity and reusability of interlocking blocks. The challenge lies in balancing mechanical confinement with the system's sustainable and reusable nature. Therefore, the current research gap centers on developing geometries that combine effective uplift resistance and re-centering capacity without compromising modularity or reusability [53–56].

Table 3 outlines key structural issues associated with interlocking block geometries and floor walls under lateral loading in multi story configurations. It highlights that types such as key and slot or dovetail are effective against shear but prone to uplift and sliding if not properly restrained [53–55]. Floor wall interfaces emerge as critical zones of stress concentration, with experimental studies showing significant drift and loss of integrity when unconfined [56]. Although solutions like shear keys and dowels have been proposed, the non linear and history dependent nature of behavior complicates modeling efforts [53–55].

TABLE 2.3: Critical Focus Areas in Interlocking Masonry Systems

Focus Area	**Observation / Issue**	**Reference**
Joint Geometry	Key slot/dovetail shapes resist Shear but risk uplift/slip	[9, 24]
Floor Wall Joints	High stress at interfaces; prone to drift and detachment	[7, 19]
Interface Weakness	Lack of confinement leads to cyclic degradation	[3]
Proposed Solutions	Dowels, shear keys, friction enhancing treatments	[48]
Modeling Limitations	Joint behavior is nonlinear, history dependent	[8]
Simulation Needs	Spring dashpot models require calibration and empirical input	[8]

Geometry largely dictates shear resistance and stability in mortar free assemblies. While key slot and dovetail designs enhance performance, they remain prone to uplift and slip. Optimizing shapes for both strength and modularity is a key research direction.

2.4.2 Floor Wall Interfaces under Cyclic Loading

Floor wall interfaces are critical zones in multi story interlocking assemblies, as they transmit forces between horizontal diaphragms and vertical walls. Studies indicate that stress concentrations and inter story drift are most pronounced at these junctions [57]. When unconfined, floor walls experience sliding and detachment, leading to loss of stiffness and energy dissipation capability [58]. Experimental results show that introducing shear keys or friction enhancing surfaces can improve stability but may also complicate disassembly [59].

Since these experience cyclic opening and closing during dynamic excitation, their behavior is nonlinear and dependent on loading history [60]. Most existing models oversimplify this interaction, assuming rigid diaphragm behavior, which fails to capture realistic deformation patterns. Thus, the research gap lies in the lack of comprehensive experimental and analytical understanding of floor wall mechanics under dynamic conditions, particularly in multistory dry stack structures. Floor wall interfaces face high stress and drift accumulation under lateral loads, often leading to separation or degradation. Proposed solutions like shear keys and dowels improve strength but reduce modularity. More experimental validation is needed for realistic multi story conditions.

2.4.3 Modeling and Detailing Challenges

Accurately modeling the nonlinear behavior of interlocking remains a central challenge in advancing dry stack masonry. The interaction between vertical load, friction, and block geometry produces complex hysteretic responses that are difficult to replicate through simplified numerical models [61]. While spring dashpot models have been proposed to represent stiffness and energy loss, they require empirical calibration against experimental data [62]. Existing reinforcement measures such as dowels and shear keys improve confinement but lack standardized design formulations [63].

Additionally, the history dependent nature of slip complicates cyclic analysis, making fatigue and long term performance predictions unreliable [64]. The absence of full scale experimental programs means most models remain unverified for tall configurations. Hence, the research gap is defined by the absence of standardized, validated detailing and modeling approaches that can accurately predict multi story dynamic responses in mortar free systems. The nonlinear and history dependent nature of behavior complicates analytical modeling. Current models and reinforcement proposals lack standardization and large scale validation. Establishing consistent detailing and modeling protocols is critical for high rise applications.

2.5 Governing Parameters Influencing In Plane Behavior of Structural Wall Systems

2.5.1 Introduction

The in plane behavior of structural wall systems under static and dynamic actions is governed by the interaction of material properties, geometric configuration, loading characteristics, interface response, and global system dynamics. These interrelated parameters collectively control stiffness, strength, deformation capacity, energy dissipation, and failure mechanisms. Under harmonic and cyclic loading, the combined effects of inertia, boundary conditions, and interface interactions become particularly critical, necessitating an integrated understanding for accurate interpretation of structural response [65, 66].

2.5.2 Material Properties

Material properties form the basis of in plane resistance and deformation behavior. The elastic modulus governs initial stiffness, while the shear modulus influences shear deformation. Compressive strength controls resistance to crushing and diagonal compression, whereas tensile strength dictates crack initiation in brittle systems such as masonry. The damping ratio further governs energy dissipation and vibration attenuation under cyclic loading. Collectively, these properties define both the initial response and the evolution of stiffness degradation under repeated loading [65, 66].

2.5.3 Geometric Parameters

Geometric characteristics play a crucial role in governing load distribution and deformation patterns. Wall thickness enhances stiffness and shear capacity, while the height to thickness ratio influences slenderness and stability. The aspect ratio determines whether behavior is predominantly shear or flexure controlled. Openings reduce effective load bearing area and introduce stress concentrations, often leading to localized damage. Boundary conditions significantly affect displacement profiles and stiffness distribution, thereby controlling overall structural response and failure modes [67].

2.5.4 Loading Characteristics Harmonic Behavior

Loading characteristics are critical in defining structural response under dynamic conditions. The amplitude of excitation governs inertial force magnitude, while excitation frequency controls resonance effects relative to the system's natural frequency. Repeated loading cycles contribute to cumulative damage and stiffness degradation. Moreover, the loading mode force or displacement controlled strongly influences nonlinear behavior and failure progression. Thus, harmonic loading governs both peak response and the rate of structural degradation [65, 68].

2.5.5 Interface Behavior

Interface behavior is particularly significant in dry stacked and interlocking systems. Friction governs sliding resistance and shear transfer, while interlocking geometry enhances mechanical stability. Cohesion and bond strength resist separation, and contact stiffness influences load transmission. Joint opening capacity facilitates nonlinear deformation and energy dissipation. Consequently, interface properties are central to damping behavior, post cracking stability, and overall system performance under cyclic loading [66, 67].

2.5.6 Global Structural System Parameters

At the system level, mass distribution governs inertia forces, while stiffness distribution controls deformation patterns and mode shapes. Damping regulates vibration attenuation, and natural frequency determines susceptibility to resonance. Modal participation further defines the contribution of individual modes to overall response. These parameters collectively integrate local behaviors and ultimately govern the dynamic stability and performance of the structure [65, 68].

2.5.7 Damage and Nonlinear Behavior

The in plane response under cyclic loading is dominated by progressive damage mechanisms. Crack initiation marks the onset of nonlinearity, followed by stiffness degradation and strength reduction. Residual strength governs post cracking capacity, while hysteresis behavior reflects energy dissipation potential. Progressive softening under repeated loading ultimately leads to failure. Therefore, damage evolution is fundamental to understanding the nonlinear response and ultimate performance of structural wall systems [66, 67]. The governing parameters influencing in plane behaviour are summarized in Table 2.4 based on established structural dynamics and masonry mechanics literature [65–68].

Table 2.4 presents a structured classification of the key parameters governing in plane structural behavior, encompassing material, geometric, loading, interface, system, and damage related factors. Material and geometric properties primarily control stiffness, strength, and deformation modes, while loading characteristics influence dynamic amplifications and resonance response. Interface behavior is critical in mortar free systems, governing shear transfer, sliding resistance, and post cracking stability. Overall, system and damage parameters define the global dynamic performance, including stiffness degradation, energy dissipation, and failure progression under cyclic loading.

Table 2.4: Key Parameters Influencing In Plane Behaviour of Structural Systems

Category	**Key Parameters**	**Influence on In Plane Behavior**	**Supporting Literature**
Material Properties	Elastic modulus, shear modulus, compressive strength, tensile strength, damping ratio	Controls initial stiffness, cracking resistance, deformation capacity, and energy dissipation under cyclic loading	[66, 68]
Geometric Parameters	Wall thickness, aspect ratio, height to thickness ratio, openings, boundary conditions	Governs stability, stiffness distribution, load path, and deformation mode (shear or flexure)	[65, 66]
Loading Characteristics	Amplitude, frequency, number of cycles, loading type (force/displacement control)	Influences dynamic amplification, resonance effects, fatigue damage, and nonlinear response development	[65, 68]
Interface Behavior	Friction coefficient, interlocking geometry, bond strength, contact stiffness, joint opening capacity	Controls sliding resistance, shear transfer mechanism, post cracking stability, and energy dissipation	[66, 67]
System Parameters	Mass distribution, stiffness, damping ratio, natural frequency, mode shapes	Governs global dynamic response, vibration characteristics, and resonance susceptibility	[1, 7]
Damage & Nonlinear Behavior	Crack initiation threshold, stiffness degradation, residual strength, hysteresis energy dissipation	Defines failure progression, post cracking behavior, and cyclic degradation response	[67, 68]

2.6 Summary

The reviewed literature highlights that while mortar free interlocking block systems offer superior modularity, reusability, and seismic resilience compared to traditional bonded masonry, their large scale application remains underdeveloped. Experimental research is mostly confined to small scale or single story models, with limited validation for multi story configurations. Numerical and hybrid modeling techniques show potential but lack standardized calibration and integration. Furthermore, the absence of seismic code provisions and tailored monitoring frameworks hinders their adoption in high rise structures. Overall, significant progress is needed in full scale testing, detailing, and intelligent sensing integration to establish performance-based design standards and enable the safe, sustainable use of mortar free interlocking systems in dynamic environments [1, 63, 64, 69–72].

Chapter 3

Experimental Program

3.1 Background

For the safe design of structures in seismic regions, accurate prediction of structural response under earthquake loading is essential. To achieve this, dynamic testing of prototype structures in laboratory environments is widely carried out worldwide. This chapter focuses on the construction methodology of interlocking in plane (IP) plastic block wall systems, the experimental setup, instrumentation used for snap back testing, application of dynamic loading using a shake table, evaluation of key response parameters, and the development of empirical equations for performance prediction.

3.2 Continuation of Research Program

The concept of using lightweight construction systems to improve seismic performance has gained significant attention in recent years. In this regard, Khan [1] introduced the Interlocking Plastic Block (IPB) system as a suitable solution for earthquake resilient residential buildings. The architectural plan and three dimensional representation of the proposed housing unit are illustrated in Figs. 3.1(a) and 3.1(b). Experimental investigations carried out on scaled down models confirmed that the proposed wall system exhibits satisfactory performance when subjected to harmonic loading. This behavior is primarily associated with the reduced self weight of the structure, which directly lowers the inertia forces generated during ground shaking.

Material weight and the corresponding inertial forces are among the most critical factors governing the seismic response of structures. Inertial force is defined as the resistance offered by a structural system when it is subjected to acceleration or sudden movement. Based on Newton's Laws of Motion, particularly the Law of Inertia and the Action Reaction principle, structures with higher mass tend to experience larger forces during earthquakes. Consequently, heavier construction materials are subjected to greater inertia effects compared to lighter alternatives.

As a result, increased mass leads to higher inertia forces, which may cause severe damage or even collapse under strong seismic excitation. Lightweight systems, on the other hand, generate comparatively lower inertia forces and therefore perform better during earthquakes. The IPB system, due to its reduced mass, presents a promising alternative for minimizing seismic demand and enhancing overall structural safety [65].

To facilitate the construction of seismically resilient housing, the proposed IPBs have a base dimension of 150 mm x 150 mm are designed with four interlocking keys on the top surface, as shown in Fig. 3.1(c). The block used for experimental work has a height of 62 mm, which includes a 12 mm high interlocking key, as illustrated in Fig. 3.1(d).

For scaled down construction, the blocks used in this study have dimensions of 62 mm 62 mm with an overall height of 50 mm, including a 12 mm interlocking key to improve connectivity between blocks, also shown in Fig. 3.1(d). This investigation is an extension of the study carried out by Khan [1]. The current study employs square plastic blocks with four keys and a vertical joining key and groove interlocking system for the construction of the prototype.

In this study, a prototype in plane structure constructed from IPB walls is subjected to dynamic testing. The main purpose of scaled down testing is to develop specifications applicable to real world systems rather than relying solely on theoretical models. The scaling and construction techniques adopted for the prototype walls are fully based on previously established methods reported in the literature.

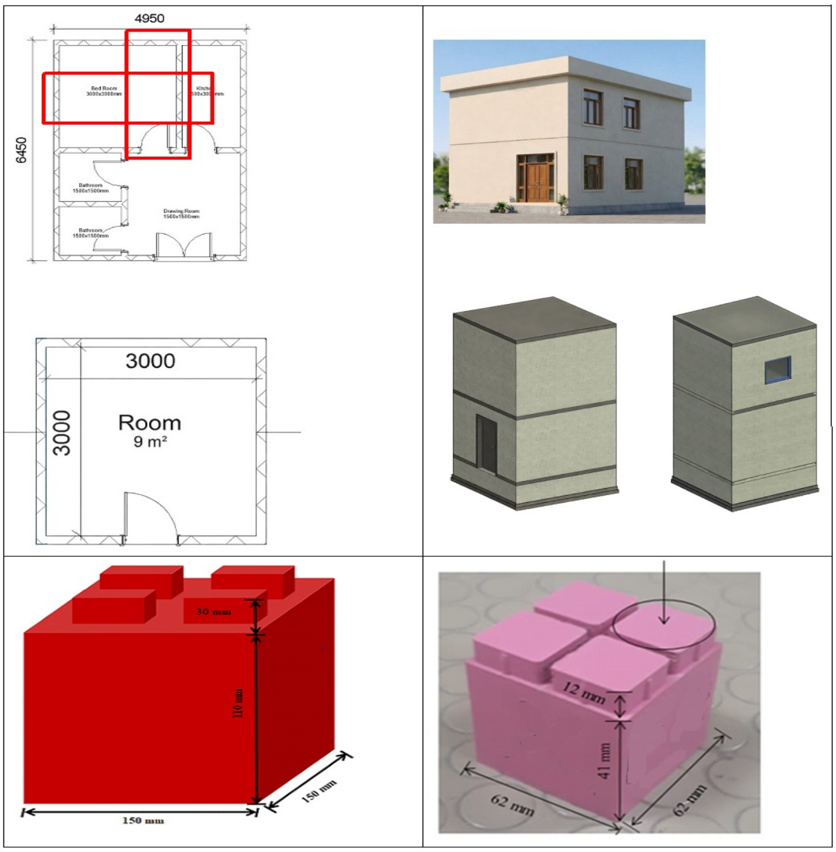


FIGURE 3.1: Proposed mortar free interlocking plastic block house: a) GF & FF plan, b) 3D Isolated View c) Enlarged bedroom plan, d) Front and side 3D view of Bedroom e)Back and side 3D view of Bedroom & f) Real plastic block Khan [1].

The results obtained from these studies contribute to a better understanding of the behavior of full scale structures.

The aim of the current research is to study the dynamic behavior of the in plane walls. For this purpose, the time period of the structure is considered an important parameter, which mainly depends on the height of the structure, as per UBC-97. Therefore, the scale down approach is primarily applied to the elevation dimensions of the structural walls. It should be noted that the dimensions of the units used in the prototype (i.e., scaled down in plane walls in mortar free IPB construction) are slightly different from the full scale structure.

The plan and elevation of the house with the original in plane consideration are presented in Fig. 3.2(a). Fig. 3.2(b) shows the scaled down and simplified boundary conditions of the in plane wall. Fig. 3.2(c) shows the scaled down in plane wall in mortar free IPB construction with wall configuration Sequence A and Sequence B.

The in plane wall is fixed with a base plate using a steel angle section. For the full scale structure, a wall length of 1350 mm and height of 6000 mm (double story) are considered. The scaled down prototype uses a length of 450 mm and height of 600 mm. The wall length in this research is greater than the block return length. To simulate real world conditions, fixity is ensured at the bottom of the wall. The in plane wall under consideration is shown in the plan of the house. The current research focuses on studying the behavior of the in plane wall along the x direction only, assuming that, due to symmetry, the behavior in the y direction will be similar.

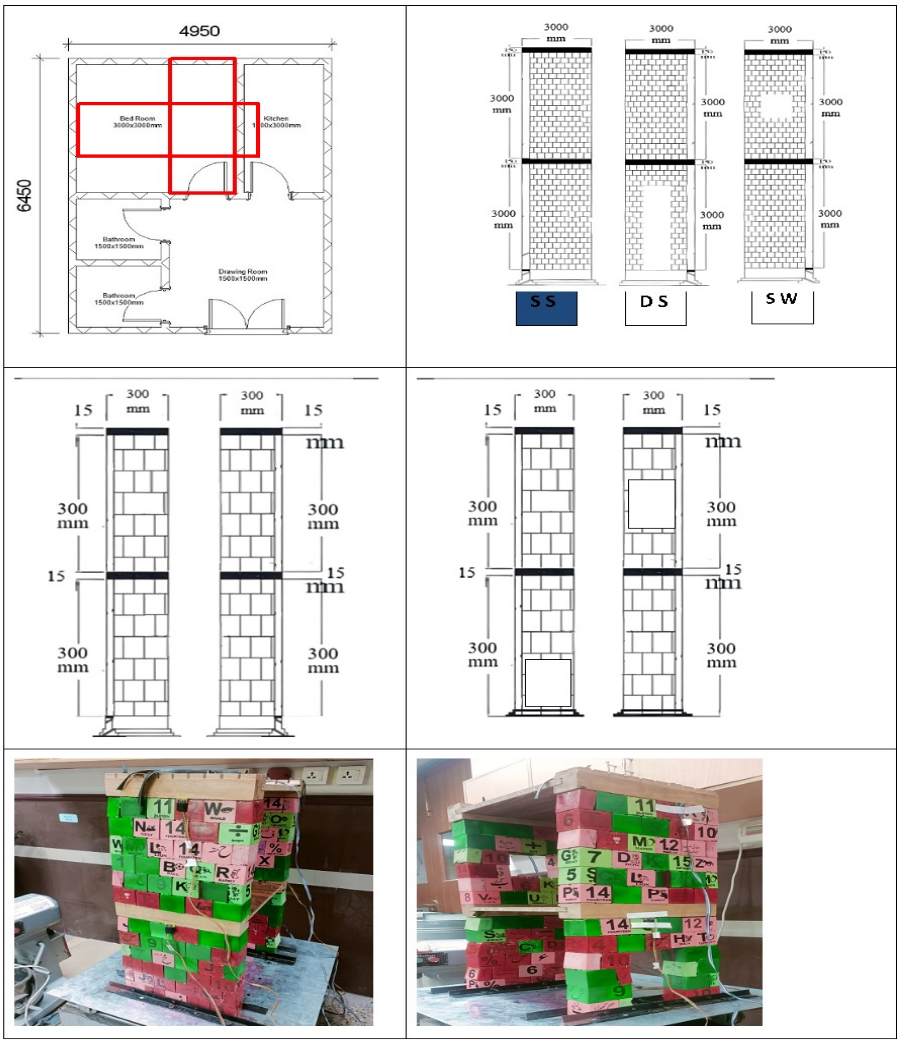


FIGURE 3.2: Consideration of In Plane: (a) plan and elevation of house with original In Plane consideration, (b) scaled down and simplified boundary conditions and (c) In Plane with configuration sequence A and B.

3.3 Construction of Prototype Scaled Down In Plane

For the experimental program, a prototype in plane Interlocking Plastic Block (IPB) wall system was assembled using a total of 120 interlocking plastic blocks (n = 120). The overall height of the specimen was maintained at 1000 mm, as illustrated in Figure 3.3. The wall assembly was constructed in two distinct configurations to evaluate its in plane dynamic response characteristics.

Configuration A comprises both walls constructed entirely with solid blocks at the ground and first floor levels. In contrast, Configuration B consists of one wall incorporating a door opening at the ground floor and solid construction at the first floor level, while the parallel wall comprises solid blocks at the ground floor and a window opening at the first floor level. The complete wall system consisted of 12 layers.

To enhance vertical rigidity and ensure effective load transfer throughout the structure, rubber band restraints were installed vertically from the base to the top through the central openings of the blocks. A total of five vertical stiffening elements were provided, including two bands in each wall panel of each floor. These stiffeners were introduced to improve interlocking efficiency and to control relative displacement during dynamic excitation.

The base of the specimen was rigidly anchored to the shake table to ensure uniform transmission of input motion across the structure. No additional mass was applied at the top of the in plane wall, and the self weight of the assembled wall system with provided slab was measured as 10.45 kg. To improve overall stability and delay potential collapse mechanisms, the five rubber band stiffeners were strategically positioned at critical locations along the wall height and at the interface. This configuration was selected to closely simulate practical construction conditions. Both configurations were tested independently under identical experimental procedures.

The in plane wall system was laterally restrained on the shake table using angle sections and nut and bolt connections, enabling controlled simulation of real world seismic loading conditions. Dynamic excitation was applied only in the X direction, while the response in the Y direction was excluded from the scope of this study. Based on structural symmetry considerations, the behavior in the Y direction is assumed to be comparable to that observed in the X direction.

The findings of this study are expected to provide valuable insights into the in plane seismic performance and structural reliability of interlocking plastic block wall systems, thereby contributing to the development of safer and more resilient construction practices.

3.4 Test Setup

3.4.1 Snap Back Test Setup and Instrumentation

The Snapback test setup is shown in Figure 3.4. Fig. 3.4(a) shows both the schematic and actual test setup for Sequence A, while Fig. 3.4(b) shows the schematic and real test setup for Sequence B. A 400 mm long wire is fixed to the top of the in plane in the IPB wall to start free vibration. To monitor the dynamic behavior of the in plane , an accelerometer is installed at the top of the structure.

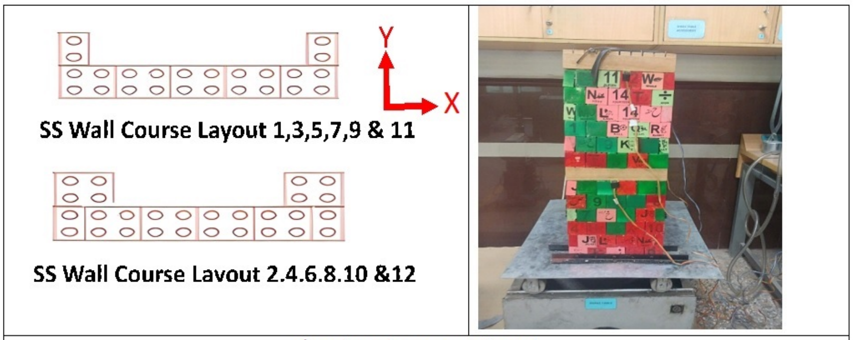
The free vibration behavior of the in plane is observed by displacing the wall using the wire and then releasing it, so the system oscillates freely. The in plane made of IPB wall was displaced twice, first for 25 mm and then for 50 mm.

Tests are performed for both wall configuration sequences, Sequence A and Sequence B. Both are pulled in X direction. Behavior in Y direction is assumed same because of the law of symmetry. Behavior in Y direction is not considered in this study.

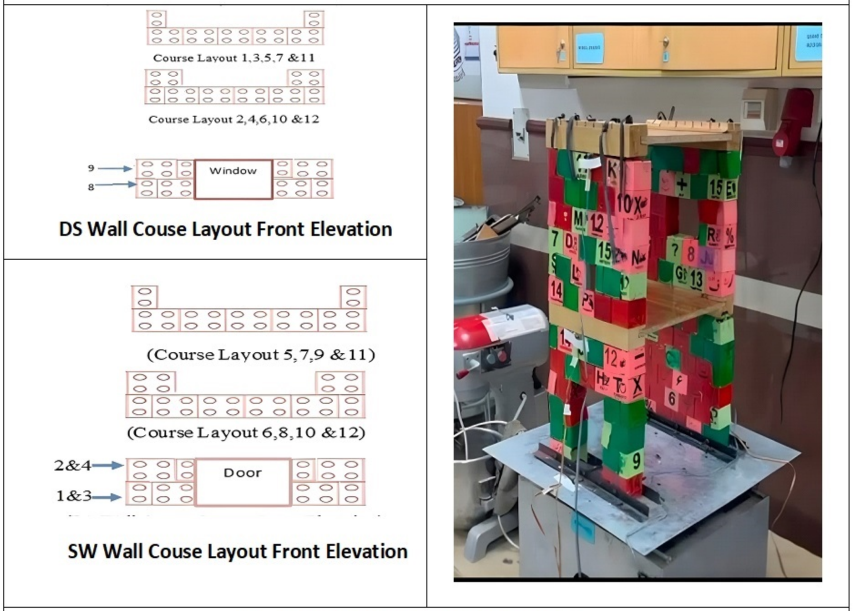
The response of the in plane, constructed from interlocking plastic block walls, is recorded as acceleration time history using the data from the accelerometer. Using the logarithmic decrement method, damping ratio (ζ) and the fundamental frequency (fn) of the system are calculated. For this, the number of cycles and their maximum acceleration values (amplitudes) are also determined. ζ is calculated using the formula for the in plane:

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

Where xo and x1 represent the acceleration values of first and last cycle. The fundamental frequency represents the natural vibration frequency of a structure. If it is too close to the dominant frequency of an earthquake, resonance can happen, which can amplify structural vibrations and increase the risk of failure. A properly designed seismic resistant structure should have a fundamental frequency that avoids resonance with normal seismic excitations. Frequency that avoids resonance with typical seismic excitations.



a) Wall Configuration A (SS-SS)



b) **Wall Configuration B (DS-SW)**

Figure 3.3: In Plane construction details; a) wall configuration sequence A and b) wall configuration sequence B.

3.4.2 Shake Table Test Setup and Instrumentation

As shown in Figure 3.5, the instrumentation used for shake table testing is illustrated through (a) a schematic representation and (b) the actual experimental test

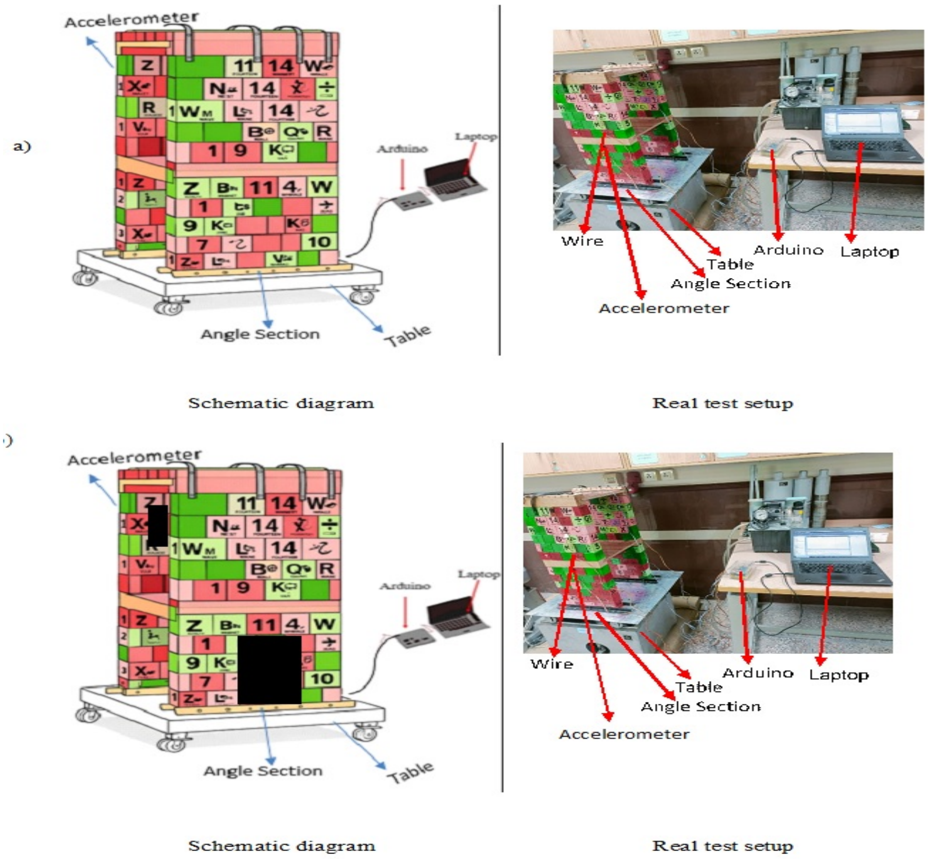
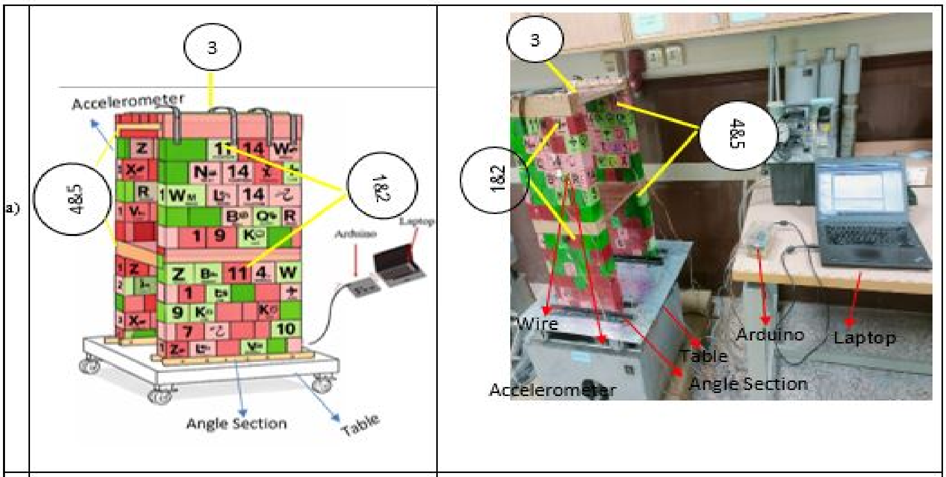


FIGURE 3.4: Snapback test instrumentation and testing; schematic diagram and real test set up for a) sequence A and b) sequence B.

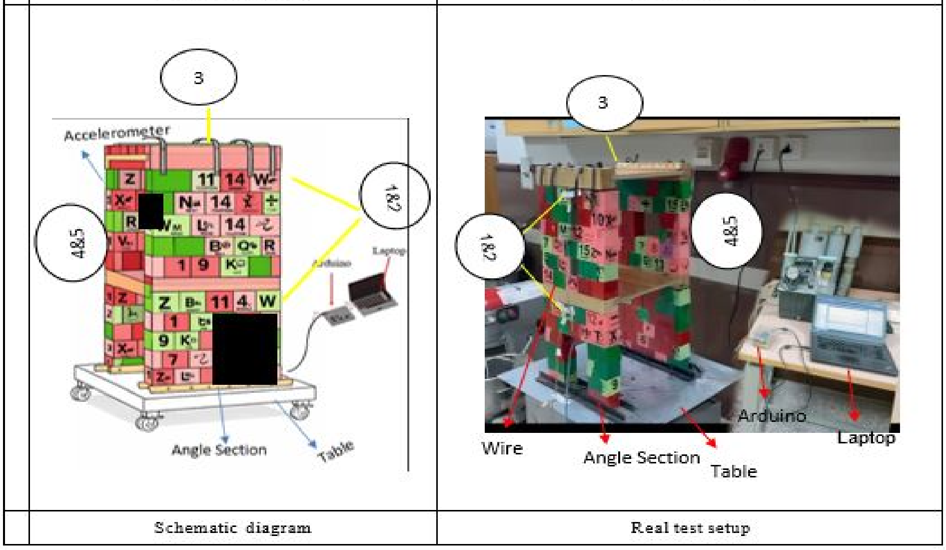
arrangement. The in plane , formed using interlocking plastic block wall panels, is assembled directly on the shake table with the help of angle sections and nut and bolt fixings, ensuring proper restraint during dynamic excitation.

For monitoring the dynamic response, a total of five accelerometers were installed in the testing setup for each wall configuration. One accelerometer was mounted at the base of the shake table to record the applied ground motion input, while the remaining four accelerometers were positioned at the top of each wall panel at both the ground and first floor levels. This instrumentation arrangement enabled the measurement of the dynamic response of individual wall panels and their contribution to the overall structural behavior and potential failure mechanisms. Furthermore, the selected placement facilitated the capture of acceleration distribution along the height of the wall system under in plane dynamic excitation.

The response of the in plane is primarily evaluated using the acceleration time history obtained from the sensors. This recorded data is further processed to determine the velocity time and displacement time histories by using SeismoSignal software. These processed results help in understanding the deformation pattern and overall seismic response of the assembled wall system under dynamic loading conditions.



Schematic diagram | Real test setup



Schematic diagram | Real test setup

FIGURE 3.5: Shake table instrumentation and testing; schematic diagram and Dynamic Loading

3.5 Dynamic Loading

3.5.1 Snap Back

For the Snap back test, the in plane in mortar free IPB wall was laterally displaced by 25 mm and 50 mm at the top using a connected wire. The wire was abruptly released to initiate free vibration. The resulting response of the wall was recorded as acceleration time history data using an accelerometer mounted at the top of the wall. Both wall configuration Sequence A and Sequence B were tested in X direction. The response in Y direction is assumed to be similar because of the law of symmetry, which is currently out of the scope of this research.

Using the logarithmic decrement method, both the damping ratio (ζ) and the fundamental frequency (fn) of the in plane in the mortar free IPB wall were calculated from the acceleration time history data. The Snap back loading magnitudes for both wall configurations are listed in Table 3.1.

Table 3.1: Snap back loading magnitude

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

3.5.2 Harmonic

Table 3.2 presents the harmonic magnitudes used for the six experimental tests conducted in this research work. Harmonic excitations are applied at three different frequencies, namely 0.9 Hz, 1.1 Hz, and 1.3 Hz, while keeping the displacement amplitude constant at 25 mm at the in plane of the IPB wall system. In this context, frequency refers to the number of loading cycles per second (Hz), which governs the rate of cyclic excitation applied to the structure. It is defined as the reciprocal of the time period of one cycle (f=1/T).

During testing, acceleration time, velocity time, and displacement time histories are recorded at both the top of ground as well first floor of double story and base of the shake table, and these records are later analyzed to examine the dynamic response of the in plane under harmonic excitation. The arrangement of plastic blocks corresponding to each wall configuration is summarized in Table 3.1. To avoid the alignment of vertical joints in successive layers, a half plastic block is introduced, similar to the stretcher bond pattern commonly used in conventional brick masonry. Based on this arrangement, two wall configurations are adopted for the experimental program.

In Sequence A and B, both parallel walls are subjected to in plane loading in the X direction. In both sequence A and B the in plane wall is rigidly anchored to the shake table using a steel angle iron section, which helps maintain stability and ensures repeatable test conditions throughout the experimental process. The harmonic loading parameters listed in Table 3.2 are selected based on both experimental observations and findings reported in earlier studies. In particular, the dominant frequency of 1.1 Hz is obtained from a Snap back test, indicating the approximate natural frequency governing the main dynamic response of the system.

Earlier investigations include the work of Khan [1] on columns, Afzal [73] on solid walls, and Sudheer and Ali [59] on wall panels with openings, where frequency intervals of 0.2 Hz, 0.5 Hz, and 0.5 Hz, respectively, were employed. In the present study, the fundamental frequency (fn) is identified from the Snap back test as approximately 1.1 Hz, and a frequency range of 0.2 Hz is selected to define the upper and lower bounds for harmonic excitation.

The imposed harmonic displacement amplitude of 25 mm in the X direction for both wall configurations, Sequence A and Sequence B, represents a controlled loading input that aligns with established experimental practices for simulating realistic dynamic actions. Moreover, the testing arrangement maintains consistent boundary conditions and loading parameters, enabling a reliable comparison between the two configurations. These selected parameters play an important role in evaluating how the initial wall positioning influences interaction, dynamic behavior, and the overall seismic performance of the IPB wall system.

TABLE 3.2: Harmonic loading magnitude

Sr. No.	**Wall Config.**	**Harmonic Loading Dir.**	**Amplitude (mm)**	**Frequency (Hz)**
1	Seq. A	X	25	0.9, 1.1, 1.3
2	Seq. B	X	25	0.9, 1.1, 1.3

It is noted that stiffness differences between conventional masonry systems and interlocking plastic block systems are inherent to their material characteristics. In this study, no artificial modification was applied to equalize stiffness. The experimental program was conducted under consistent boundary conditions and identical loading configurations for all test cases. The analysis focuses on comparative in-plane dynamic response parameters, including displacement, frequency, damping ratio, and stiffness degradation behavior, where stiffness variation is treated as an inherent property of the system.

3.6 Parameters Evaluated

3.6.1 Parameters Evaluated under Snap Back Loading

Dynamic loading was applied to the in plane at excitation frequencies of 0.9 Hz, 1.1 Hz, and 1.3 Hz. During each test, the structural response was primarily recorded in the form of acceleration time history, which serves as the basic measured output of the shake table experiment. These acceleration records reflect the direct response of the and connected wall segments under harmonic excitation.

The recorded acceleration time data were further processed using SeismoSignal software. Through numerical integration procedures, the corresponding velocity time and displacement time histories were obtained. These time histories provide a clearer understanding of how the in plane moves and deforms with time under different loading frequencies, especially near the system's dominant frequency.

In addition to response histories, the acceleration time data were also used to generate base shear (Q) versus displacement (δ) curves, which are important for evaluating the dynamic behavior of the . The base shear was calculated using the relation Q = M x ü(t), where M represents the effective mass associated with the top portion of the corresponding wall, and ü(t) is the measured acceleration at a given time. This formulation allows the conversion of inertial forces into shear forces acting at the base of the.

The resulting Q-δ curves provide useful insight into the stiffness characteristics, deformation capacity, and hysteretic response of the in plane . These curves also help in assessing the energy dissipation behavior under cyclic dynamic loading. By comparing responses at different excitation frequencies, the influence of loading rate on performance can be clearly observed.

Overall, the combined use of acceleration histories, derived displacement data, and base shear displacement relationships enables a comprehensive comparison of the in plane behavior under varying dynamic conditions. This approach helps in understanding how the stiffness, deformation demand, and energy dissipation capacity change with frequency, which is essential for evaluating its performance under seismic type loading.

3.6.2 Parameters Evaluated under Harmonic Loading

Dynamic loading utilizing frequencies of 0.9 Hz, 1.1 Hz, and 1.3 Hz was applied to the In Plane , and the structural response was recorded in terms of acceleration time history. Subsequently, velocity time and displacement time histories were derived using Seismosignal software through numerical integration.

Additionally,acceleration time data facilitated the development of base shear (Q) versus displacement curves, where base shear was computed as Q=Mxüt , with M representing the top acceleration of the corresponding wall. These parameters were essential in characterizing the dynamic stiffness and energy dissipation capacity of the In Plane , providing a comparative basis for evaluating performance under varying excitation frequencies.

3.7 Procedure for Empirical Equation Formation

To understand dynamic response of the in plane in mortar free IPB walls, empirical equations are developed considering the geometry of IPB, block size, wall height, and input loading parameters based on Khan [1]. The percentage difference between experimental and empirical values is calculated to assess accuracy.

To reduce discrepancy, a factor of K = 1.14 is applied, improving reliability of the empirical equations. This refined model provides better prediction of structural performance and offers useful insights into IPB wall behavior under dynamic loads, which can help in optimizing designs for better seismic resilience.

3.8 Summary

This chapter describes the experimental methodology and testing procedures used in the study. The focus was on testing a prototype in plane made from interlocking plastic blocks under dynamic loads. The behavior of the in plane was recorded and compared with results from empirical equations.

Detailed descriptions of test setup and instrumentation are provided, explaining the equipment and methods used. Parameters evaluated during testing, such as acceleration, velocity, displacement, damping, and fundamental frequency, are discussed to understand the factors affecting performance. Special attention was given to dynamic response, failure modes, and overall behavior of the in plane.

This chapter provides a complete guide to the experimental approach and demonstrates reliability of the results, forming a foundation for validating analytical and numerical models in the later part of the study.

Chapter 4

Experimental Evaluation

4.1 Background

In previous chapter, the investigatory methods used for Snap back and dynamic loading tests were explained in detail along with the parameters that were analyzed. In this chapter, we focus on the actual experimental findings obtained from the data recorded during the tests. The main purpose here is to understand how the In Plane behaves under different dynamic loading conditions.

It is important to clarify that the present experimental investigation was conducted using controlled harmonic loading applied through the shake table, rather than actual earthquake ground motion records. The harmonic excitation, characterized by sinusoidal input at selected frequencies, was intentionally adopted to enable a systematic evaluation of the dynamic characteristics of the system, including frequency dependent response, stiffness degradation, and energy dissipation behavior. Although harmonic loading does not fully replicate the irregular and multi frequency nature of real seismic excitations, it provides a simplified and controlled framework to investigate the fundamental dynamic response of the structure. Therefore, the results obtained from this study are interpreted as representative of the structural behavior under idealized dynamic loading conditions, while offering meaningful insights into its potential seismic performance.

For the analysis, fundamental frequency (fn) and damping ratio (ζ) were calculated for the In Plane by using the acceleration time history recorded during the tests. To clean this data and make it more usable, SeismoSignal software was later used. Using SeismoSignal, the extra noise was filtered out so that the acceleration time history could be interpreted more accurately. From the same processed data, displacement time histories were also obtained by numerical integration.

Furthermore, energy absorption for the In Plane was calculated for each loading frequency. This step is very important because it helps in understanding how much seismic energy the In Plane can absorb before it reaches any significant deformation. All of these steps combined give a clear picture of the dynamic performance of the In Plane made from interlocking plastic blocks. It also provides insight into how the wall might behave in real earthquake situations.

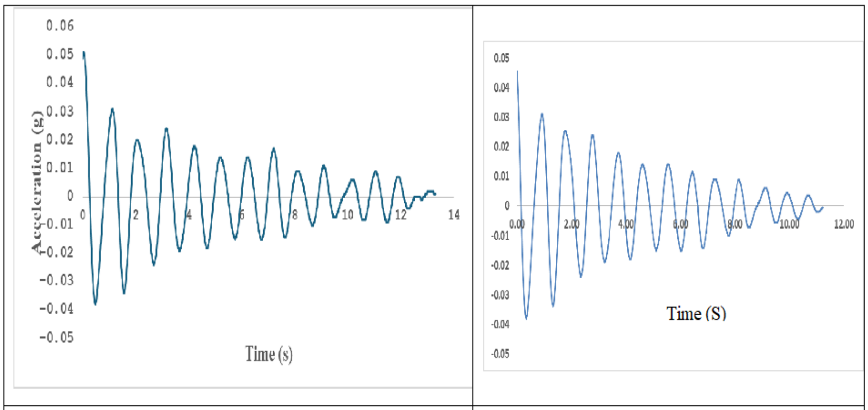
4.2 Damping Ratio and Fundamental Frequency

Figure 4.1 presents the snap back test response of the in plane IPB wall system. In these tests, the top of the in plane wall was laterally displaced from its equilibrium position by two controlled amplitudes, i.e. 25 mm and 50 mm. The displacement was applied using a chord system and then suddenly released, allowing the structure to undergo free vibration.

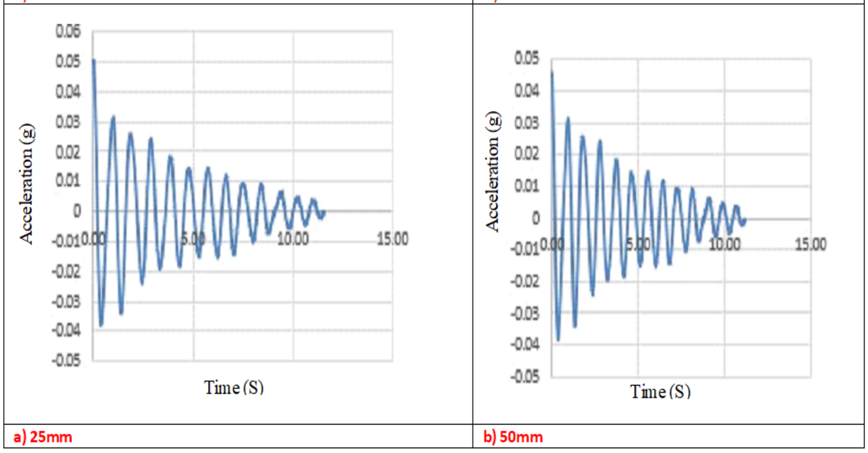
The dynamic characteristics of the system were evaluated using the logarithmic decrement method applied to the acceleration time history. This method was used to determine the fundamental frequency (fn) and damping ratio (ζ) of the system. The damping ratio represents the rate at which vibration amplitude decays, where a higher value indicates greater energy dissipation capacity and faster attenuation of vibrations.

The results indicate that the vibration amplitude of the in plane wall decays rapidly, demonstrating effective inherent damping behavior. This confirms the ability of the IPB wall system to dissipate dynamic energy, which is an important characteristic for improving seismic performance.

The quantitative results obtained from the snap back tests are summarized in Table 4.1, which presents the variation of damping ratio and fundamental frequency



a) 25mm b) 50mm



a) 25mm b) 50mm

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

for both wall configurations (Sequence A and Sequence B) under 25 mm and 50 mm displacement amplitudes. For Sequence A, as shown in Table 4.1, the damping ratio increases from 4.5% at 25 mm displacement to 5.4% at 50 mm displacement, while the corresponding fundamental frequency remains nearly constant, varying slightly from 1.09 Hz to 1.11 Hz. Similarly, for Sequence B, Table 4.1 indicates that the damping ratio increases from 4.05% to 4.63% with increasing displacement, while the fundamental frequency shows a marginal increase from 1.12 Hz to 1.14 Hz.

TABLE 4.1: Results from Snapback Test

Wall Configuration	**Amplitude (mm)**	**Natural Frequency (Hz)**	**Damping (%)**
Seq. A	25	1.09	4.5
–	50	1.11	5.4
Seq. B	25	1.12	4.05
–	50	1.14	4.63

These minor variations in damping ratio and frequency are expected in experimental systems. They can be attributed to nonlinear material behavior of the interlocking blocks, localized slip at interfaces, micro cracking effects, and slight construction imperfections. Boundary conditions and contact interactions also contribute to these observed variations.

In general, real structural systems do not exhibit perfectly constant dynamic properties, and small amplitude dependent variations are physically realistic. The dominant frequency content is consistently observed around 1.1 Hz for both wall sequences, confirming the stability of the fundamental frequency of the system.

Overall, the results demonstrate that the in plane IPB wall exhibits stable dynamic behavior, with moderate damping and consistent natural frequency. This indicates effective energy dissipation and controlled vibration response, which are essential characteristics for earthquake resistant structural systems.

4.3 Behavior of Prototype In plane under Harmonic Loading

4.3.1 Behavior in Terms of Acceleration Time and Displacement Time Histories

The dynamic behavior of the In Plane constructed from interlocking plastic blocks (IPB wall) was carefully captured using acceleration time histories and displacement time histories over a time period of 40 s to 45 s, as illustrated in Figures 4.2 and 4.3. In these figures, the red solid line represents the base excitation of base plate, which is the applied input loading. The brown dotted line depicts the response of top of ground floor of wall 1. The blue line represents the movement at the top of the first floor wall, while the green dotted line shows the movement of top of ground floor Wall 2, and the purple dotted line indicates the in plane movement of top of first floor Wall 2.

To capture the distributed response of the system, five sensors were installed at critical locations along the prototype. Sensor 1 was placed at the base plate to

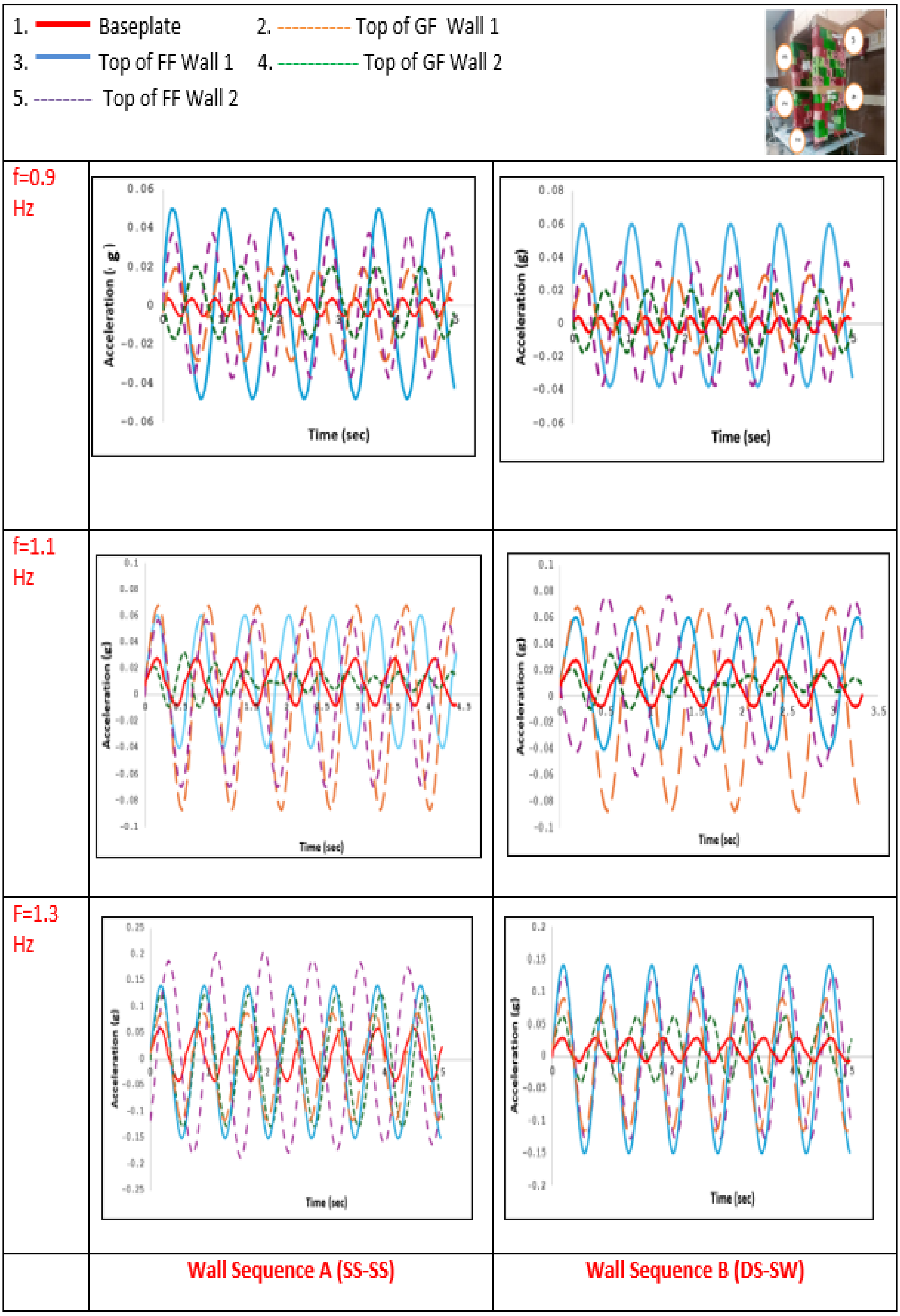


Figure 4.2: Ü-Time history of in plane double story

record the input base excitation. Sensor 2 was installed at the ground floor (GF) of Wall 1, while Sensor 3 was positioned at the top floor (FF) of Wall 1. Similarly,

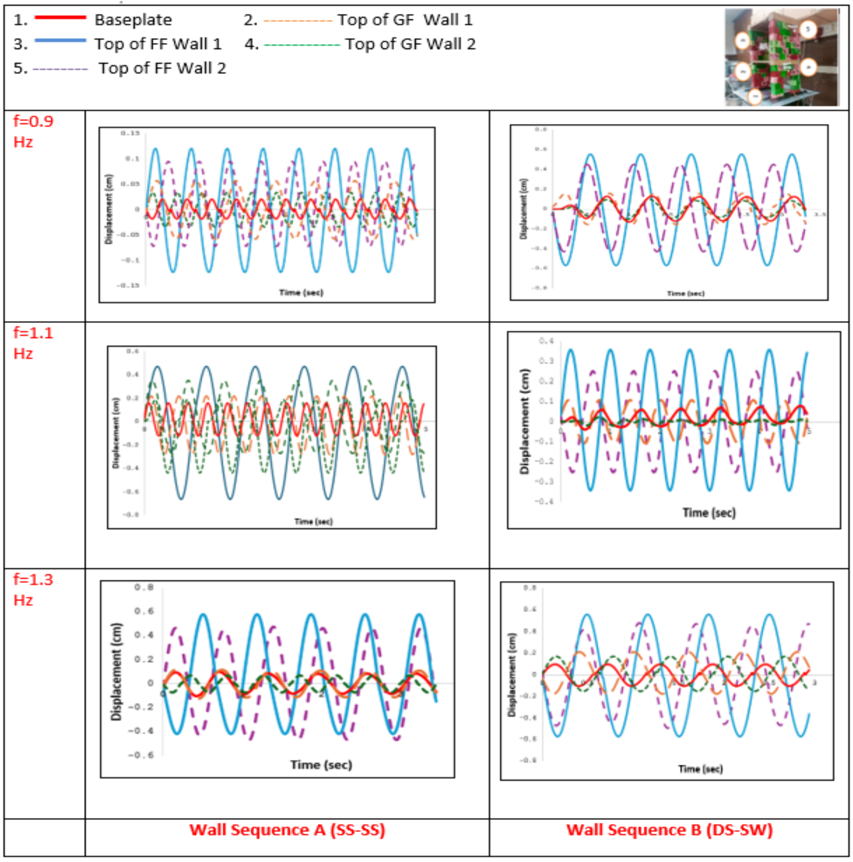


FIGURE 4.3: Ü-Time history in plan double story

Sensor 4 was placed at the ground floor of Wall 2, and Sensor 5 was installed at the top floor (FF) of Wall 2. This arrangement enabled detailed monitoring of base motion, inter story transfer behavior, and top amplification effects under harmonic loading conditions.

The recorded response data clearly distinguish between the imposed base excitation and the structural response at different levels of the system. For analytical purposes, the average acceleration and displacement at the base (denoted as ü-b, ù-b, and u-b, respectively) were considered as the applied loading, while the acceleration and displacement at the top (denoted as ü-t, ù-t, and u-t, respectively) were taken to represent the actual dynamic response of the structure. This formulation provides a consistent framework for evaluating input and output relationships under harmonic excitation.

The recorded acceleration data were processed using SeismoSignal software to derive displacement time histories from raw acceleration signals, enabling a more comprehensive assessment of the system's dynamic characteristics.

The shake table generated controlled harmonic excitation at 0.9 Hz, 1.1 Hz, and 1.3 Hz with nearly uniform amplitude across cycles, ensuring consistent and repeatable loading conditions.

TABLE 4.2: In Plane Displacement Response of Double Story Wall Configuration under Harmonic Loading

Wall Structure	**Freq. (Hz)**	**IP (mm)**	**Percentage Impact**
Seq A	0.9	21.0	-
	1.1	29.0	+38.1%
	1.3	36.0	+71.4%
Seq B	0.9	22.5	-
	1.1	28.6	+27.1%
	1.3	34.8	+54.7%

The results indicate a clear frequency dependent behavior in both displacement and acceleration responses. The in plane displacement contribution decreases with increasing frequency, indicating reduced participation of global deformation at higher excitation levels. This trend is clearly reflected in Table 4.2, where Sequence A shows a 71.4% increase in displacement at 1.3 Hz compared to 0.9 Hz, while Sequence B exhibits a 54.7% increase over the same range. On average, this corresponds to an approximate 63% increase, confirming strong frequency dependent amplification of in plane displacement under harmonic loading conditions.

In contrast, acceleration demand at the top of the specimen increases significantly with frequency. For Wall Configuration A, the acceleration response at 1.3 Hz is 1.67 times higher than at 0.9 Hz, while for Wall Configuration B, the increase is more pronounced, reaching 3.42 times. This indicates that Configuration B is more sensitive to higher frequency excitation and exhibits stronger resonance related amplification compared to Configuration A.

The displacement time histories further confirm that lateral deformation increases with excitation frequency, indicating a reduction in effective in plane stiffness under higher dynamic demand. Sequence dependent behavior is also observed, where Sequence B generally exhibits higher displacement values compared to Sequence A.

The observed behavior suggests that repeated harmonic loading induces progressive stiffness degradation, primarily due to localized sliding and interface slip within the interlocking block connections. These mechanisms reduce frictional resistance and contribute to nonlinear structural response under dynamic loading.

Despite frequency dependent stiffness reduction and localized deformation, the interlocking plastic block system demonstrates stable dynamic performance without brittle failure. The friction based interlocking mechanism provides inherent energy dissipation capacity, enabling controlled deformation and gradual attenuation of oscillations.

Overall, the results indicate that the prototype in plane wall exhibits higher displacement participation at lower frequencies, while acceleration amplification dominates at higher frequencies, particularly in Configuration B. This confirms that the system is sensitive to frequency variation and near resonance effects, yet maintains satisfactory dynamic stability due to its inherent energy dissipation characteristics.

4.3.2 Base Shear - Displacement Curves and Energy Absorption

The energy dissipation behavior of the in plane wall was evaluated using base shear displacement (Q-$\triangle$) hysteresis curves, as shown in Figure 4.4. This figure is presented at this point because it directly represents the force deformation response of the system under cyclic harmonic loading.

For analytical purposes, the total mass of the structure was assumed to be concentrated at the top of the wall, and the base shear was computed using the measured top acceleration response as:

$Q = M \text{ x } \ddot{u}_t$

Where:

Q = Inertial force (also representing base shear or dynamic force demand)

M = Mass of the structure

$\ddot{u}_t$ = Acceleration at the top of the in plane wall (structural response acceleration)

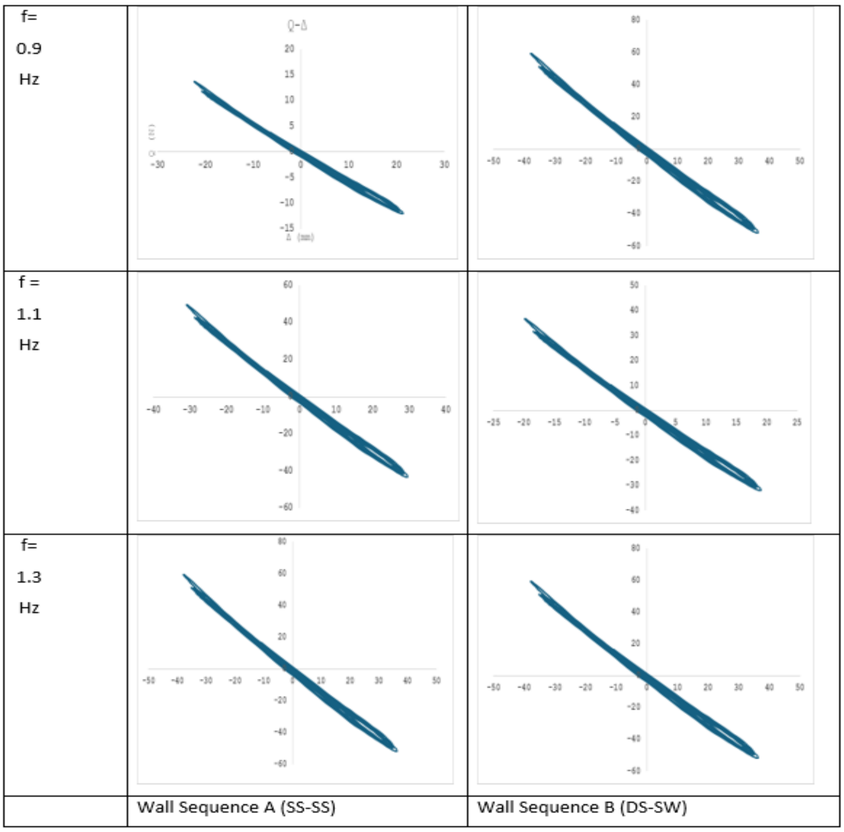


FIGURE 4.4: Q-△ curves of in plan double story

In the present experimental setup, a plywood slab was used as a rigid loading platform to represent the lumped mass at the top of the structure. The slab was assumed to behave as a rigid body, ensuring uniform distribution of mass and consistent transfer of inertial forces to the wall system. It is important to note that the inertial force developed in the system is directly proportional to the mass of the slab. Therefore, any increase in slab weight would result in a corresponding increase in base shear demand and displacement response. This highlights the significant role of mass in governing the dynamic behavior of the system under harmonic excitation.

The resulting Q-△ relationship shown in Figure 4.4 illustrates the cyclic force deformation behavior of the walls. The enclosed area within each hysteresis loop represents the energy dissipated during one loading cycle, while the cumulative area represents the total energy absorbed over multiple cycles of harmonic excitation. The shape and stability of the loops also provide insight into stiffness degradation and frictional sliding within the interlocking mechanism. A gradual widening of loops with increasing frequency indicates enhanced energy dissipation.

It is important to note that the peak base shear values observed from the hysteresis curves indicate that the shear resistance of the mortar free interlocking system is relatively lower compared to conventional bonded masonry systems. This reduction is primarily due to the absence of mortar bonding, which eliminates tensile continuity and reduces the overall shear transfer mechanism. Instead, the system relies on frictional resistance and mechanical interlocking between blocks, which allows controlled sliding and rocking at the interfaces. Although this leads to a reduction in peak shear resistance, it significantly enhances ductility and energy dissipation, as reflected by the stable and widening hysteresis loops. This behavior prevents sudden brittle failure and promotes a more stable and resilient structural response under dynamic loading conditions.

The equivalent damping ratio was calculated using the following expression [62].

$$\zeta = \frac{1}{2\pi N} \ln\left(\frac{x_0}{x_1}\right) \times 100 \tag{4.1}$$

TABLE 4.3: Energy absorption under harmonic loading

Wall	**Freq. (Hz)**	**Mean Energy per Cycle (Nm)**	**Number of Cycles**	**Total Energy (Nm)**	**Equiv. Damping (%)**
Seq A	0.9	4.3	78	367	19.9
	1.1	19.5	96	1874	20.28
	1.3	22.6	122	2760	20.35
Seq B	0.9	8.4	67	569	19.72
	1.1	21.49	81	1741	22.04
	1.3	27.67	109	3017	22.23

As also evident from Figure 4.4, the area enclosed by the hysteresis loops increases with excitation frequency, confirming higher energy dissipation at higher loading rates. This trend is consistent with the numerical results presented in Table 4.3.

The results show that energy absorption increases significantly with excitation frequency. For Sequence A, total energy increases from 367 Nm at 0.9 Hz to 2760 Nm at 1.3 Hz, while Sequence B increases from 569 Nm to 3017 Nm over the same range.

Sequence B demonstrates higher energy dissipation compared to Sequence A, particularly at lower frequencies. However, both configurations follow a similar increasing trend with frequency. The equivalent damping ratio remains relatively stable between approximately 20% and 22%, indicating consistent energy dissipation performance.

The increase in energy dissipation observed in Figure 4.4 is attributed to enhanced cyclic deformation, increased frictional interaction between interlocking blocks, and progressive sliding at contact interfaces. These mechanisms contribute to stable hysteretic behavior and prevent sudden brittle failure, thereby improving the dynamic performance of the system.

4.4 Summary

This chapter presented an experimental investigation of the dynamic behavior of a prototype in plane system constructed using mortar free interlocking plastic blocks (IPB). The system was tested under controlled harmonic excitation using a shake table at three excitation frequencies (0.9 Hz, 1.1 Hz, and 1.3 Hz) to evaluate its frequency dependent response. The raw acceleration time history data were processed using SeismoSignal software to remove noise and improve signal clarity. Velocity and displacement time histories were subsequently obtained through numerical integration, providing a complete representation of the structural response. In addition, base shear displacement (Q-$\triangle$) hysteresis curves were developed to assess energy dissipation characteristics of the system.

The snap back test results indicated stable dynamic properties, with the fundamental frequency remaining nearly constant at approximately 1.1 Hz and damping ratios ranging between 4% and 5.5%. Under harmonic loading, the system exhibited clear frequency dependent behavior, where both displacement and acceleration responses increased with increasing excitation frequency. This response is attributed to gradual stiffness degradation and localized nonlinear effects, including interface slip and frictional sliding between interlocking blocks.

The energy dissipation capacity of the system increased with excitation frequency, as evidenced by the progressive enlargement of hysteresis loop areas. The equivalent damping ratio remained relatively stable in the range of approximately 20% to 22%, indicating consistent dissipation performance across loading conditions. Although the peak base shear capacity of the mortar free system is lower than that of conventional bonded masonry, this reduction is offset by enhanced ductility and controlled deformation mechanisms governed by frictional interlocking and sliding behavior.

Overall, the experimental results confirm that the in plane IPB wall system exhibits stable dynamic performance, effective energy dissipation, and frequency sensitive response characteristics without structural instability. The observed behavior demonstrates the potential of mortar free interlocking systems as ductile, energy efficient, and earthquake resilient structural solutions under dynamic loading conditions.

Chapter 5

Discussions

5.1 Background

This chapter provides a detailed examination of the dynamic response of interlocking plastic block (IPB) walls when subjected to in plane harmonic loading. The evaluation is founded on experimentally obtained response histories, including acceleration, velocity, and displacement as functions of time, together with the corresponding base shear displacement (Q-δ) relationships. The experimental investigation demonstrates that the IPB wall system exhibits considerable capacity for energy dissipation under in plane loading conditions. To assess the reliability of predictive methodologies, the experimental findings are systematically compared with values estimated through empirical formulations. The discrepancy between the experimentally measured responses and the empirically predicted values is expressed in percentage form, enabling a quantitative assessment of the accuracy and practical applicability of the empirical models in predicting the in-plane behavior of the system.

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

Empirical equations are widely employed to estimate the dynamic response of in-plane (IP) walls of double-story interlocking plastic block (IPB) structures, particularly when analytical solutions are difficult due to complex interactions betwee blocks. In this study, the formulation builds upon prior work by Khan [6], which accounts for block geometry, wall height, and applied lateral loading. To improve predictive accuracy for the double-story wall, additional parameters reflecting the wall's height, number of blocks, and base dimensions were incorporated.

The dynamic response at the top of the in-plane wall can be estimated using the following empirical relations:

$$\ddot{u}_t = K\frac{h^2 n}{a} mk(1+2n)\ddot{u}_g \tag{5.1}$$

$$\dot{u}_t = K\frac{h^2 n}{a} mk(1+2n)\dot{u}_g \tag{5.2}$$

$$u_t = K\frac{h^2 n}{a} mk(1+2n)u_g \tag{5.3}$$

For the current double-story wall, the IPB dimensions are 62 mm 62 mm, arranged in 12 layers with a total of 120 blocks. A coefficient K=1.14K was selected to minimize the discrepancy between empirical predictions and experimental measurements.

Table 5.1 presents a comparison between experimental observations and empirical predictions for the in-plane wall. Previous studies have reported different values of K depending on wall geometry and loading conditions: Khan [1] used 1.05, Afzal [73] reported 0.45, and Sudheer and Ali [57] used 0.5 for columns and out-of-plane walls.

In the current study, the percentage differences between experimental and empirical values ranged from -4.75% to -9.91%, reflecting the complex structural behavior of mortar-free IPB walls. For instance, at 0.9 Hz (sequence A), the experimental acceleration was 0.13g, whereas the empirical prediction was 0.1365g (-4.79%), with velocity and displacement deviations of -4.79%. At 1.3 Hz (sequence B), the experimental acceleration was 0.58g, and the empirical value was 0.6317g (-8.18%), with corresponding velocity and displacement differences of -9.91%. These results indicate that, despite moderate deviations, the empirical equations provide a reasonable approximation of the in-plane dynamic response of double-story IPB walls, which can be effectively used for preliminary design and structural analysis [63,64].

Table 5.1: Variation in experimental and empirical values for In Plane of interlocking plastic block wall

Freq. (Hz)	**Response**	**Experimental Values**	**Empirical Values**	**Percentage Difference**
Seq. A				
0.9	Acceleration (g)	0.13	0.1365	-4.79
–	Velocity (mm/s)	49.7	52.1981	-4.79
–	Displacement (mm)	21.4	22.4756	-4.79
1.1	Acceleration (g)	0.48	0.5115	-6.16
–	Velocity (mm/s)	164.1	167.8342	-2.22
–	Displacement (mm)	29.6	31.0878	-4.79
1.3	Acceleration (g)	0.57	0.6298	-9.49
–	Velocity (mm/s)	316.6	337.3953	-6.16
–	Displacement (mm)	36.3	38.6843	-6.16
Seq. B				
0.9	Acceleration (g)	0.26	0.2855	-8.94
–	Velocity (mm/s)	49.2	54.0310	-8.94
–	Displacement (mm)	19.4	21.3049	-8.94
1.1	Acceleration (g)	0.41	0.4304	-4.75
–	Velocity (mm/s)	166.2	175.8005	-5.46
–	Displacement (mm)	36.3	38.4574	-5.61
1.3	Acceleration (g)	0.58	0.6317	-8.18
–	Velocity (mm/s)	327.3	363.3120	-9.91
–	Displacement (mm)	38.3	42.5141	-9.91

5.3 Comparison of Prototype Single Story and Double Story Structure Behavior

The use of harmonic excitation generated through a locally fabricated shake table provides a controlled and repeatable method for simulating base motion in experimental investigations. Although simplified compared to advanced multi axial

TABLE 5.2: Comparative Assessment of Previous Studies and Present Investigation

In Plane Behavior Parameter	**Previous Research**	**Present Research**
Scope of in plane response	Predominantly focused on global or single wall in plane response under seismic or cyclic excitation [72, 74]	Dedicated evaluation of in plane dynamic response at a two story structural scale
Loading characterization	Broad spectrum, seismic, or cyclic loading with limited control over excitation frequency content [68, 72]	Prescribed harmonic excitation enabling controlled, frequency specific response assessment
Structural configuration	Simplified wall assemblies or single story systems typically considered [72]	Double story configuration incorporating inter story interaction effects
Governing deformation mechanism	Frictional sliding and intermittent contact at block interfaces dominate lateral response [68, 74]	Friction driven interlocking interaction governs stable in plane deformation behavior
Mass inertia influence	Higher mass systems induce increased inertial demand and reduced dynamic responsiveness [68, 74]	Reduced mass system exhibits enhanced dynamic sensitivity and responsiveness
Energy dissipation mechanism	Dissipation primarily through frictional slip and hysteretic interface behavior [74]	Controlled frictional dissipation facilitated by interlocking geometry under cyclic excitation
Confinement and pre compression effect	Pre tensioning using fiber based confinement enhances stability but restricts inter block movement, leading to reduced frictional energy dissipation capacity [68]	Elastic confinement provides controlled pre compression while allowing limited inter block mobility, resulting in improved energy dissipation without compromising structural stability

Table 5.2: Continued from Previous Page

In Plane Behavior Parameter	**Previous Research**	**Present Research**
In plane stiffness evolution	Progressive stiffness degradation observed under repeated cyclic loading [68, 72]	Stiffness response assessed under steady state harmonic conditions with emphasis on response stability
Damage evolution	Localized cracking, joint opening and interfacial degradation reported at elevated drift levels [68]	Structural response maintained within serviceability limits without visible in plane damage
Frequency response characteristics	Resonance effects reported but not systematically isolated or quantified [68, 74]	Clear identification of frequency dependent response and resonance behavior under controlled excitation
Instrumentation strategy	Multi sensor configurations used to capture distributed in plane response [72, 74]	Targeted instrumentation capturing dominant lateral response at critical location
Damping characterization	Often inferred indirectly with limited consistency across studies [74]	Direct and consistent damping evaluation using logarithmic decrement methodology
Boundary condition representation	Rigid or idealized boundary constraints influencing in plane response interpretation [72]	Controlled and scaled boundary conditions with applied pre compression for realistic confinement simulation
Research gap addressed	Limited investigation of double story interlocking systems under controlled in plane dynamic loading [68]	Addresses gap through systematic evaluation of two story interlocking system under harmonic excitation

testing systems, the setup is effective for evaluating the in plane dynamic behavior of the structural system. In this study, the imposed harmonic motion is treated as the base excitation, and the structural response is analyzed relative to this input.

The experimental program included double story wall configurations, consisting of both solid walls and walls with openings such as doors and windows. While Table 5.2 summarizes the general in plane response, the behavior of walls with openings is discussed in detail in Chapter 4. Preliminary observations indicate that openings slightly modify local stiffness and displacement patterns; however, the overall trends in energy dissipation, fundamental frequency, and first mode response characteristics remain consistent with those observed in solid walls. This indicates that the mortar free interlocking system exhibits robust dynamic behavior across varying wall geometries.

The observed response of the in plane wall demonstrates stable performance under harmonic loading, with energy dissipation primarily governed by frictional interactions between interlocking blocks, consistent with prior reports on mortar free systems [61]. The results indicate that such interfacial mechanisms, rather than rigid bonding, dominate the dynamic energy absorption process.

The inclusion of confinement effects highlights the critical balance between stability and interfacial mobility in governing in plane energy dissipation of interlocking systems. Unlike rigid pre tensioning approaches reported in literature, the controlled confinement mechanism adopted in the present study enables enhanced frictional interaction while maintaining structural integrity, thereby improving overall dynamic response characteristics.

The present study contributes further by incorporating quantitative damping evaluation, providing a rigorous assessment of energy dissipation. While no visible damage was observed due to shake table limitations, the system's response remained within the elastic/serviceable range, confirming the suitability of the mortar free interlocking system for moderate dynamic excitations.

From a structural engineering perspective, these findings reinforce the potential of mortar free interlocking walls to enhance seismic resilience through controlled deformation and energy absorption. Additionally, the lightweight, modular nature of these units facilitates ease of construction, cost efficiency, and sustainability, making them particularly advantageous for resource constrained or rapid deployment applications.

Overall, the results of this study, combined with prior research, provide a comprehensive understanding of in plane dynamic behavior for both solid walls and walls with openings in double story configurations, supporting the broader application of mortar free interlocking systems in earthquake resistant construction.

5.4 Challenges in Seismic Resilience of Masonry and Remedial Measures

The seismic performance of a structure is significantly influenced by its mass, as the base shear generated during earthquake excitation is directly proportional to the building weight (UBC 1997). Reducing structural mass therefore lowers inertial forces and overall seismic demand, making lightweight construction an effective earthquake resistant strategy. Mortar free interlocking plastic block systems present a viable solution, combining reduced mass with high modularity. These systems rely on mechanical interlocking instead of cementitious bonding, enabling dry assembly, rapid construction, and reusability. Moreover, their modular design reduces dependence on skilled labor while enhancing construction efficiency and sustainability.

In double story applications, in plane behavior is critical to ensure lateral stability and structural integrity under seismic loading. Interlocking plastic blocks are capable of sliding, rotation, and shear deformation at the block interfaces, which facilitates energy dissipation during cyclic lateral forces. The absence of mortar eliminates brittle failure modes typical of traditional masonry, providing a ductile response that enhances resilience. Proper vertical alignment and optimized block geometry are essential to control story drift, in plane stiffness, and load distribution between stories, ensuring predictable performance under seismic excitations.

Figure 5.1 illustrates the in plane response of a double story interlocking plastic block wall subjected to lateral seismic forces. As shown, base shear acts at the foundation, while lateral forces induce progressive shear deformation, sliding, and rotation within block interfaces. These mechanisms allow significant energy dissipation without compromising the overall stability of the system. The interlocking design distributes lateral loads efficiently across stories, mitigating stress concentrations and minimizing the risk of catastrophic failure. The ability of individual blocks to slide and rotate contributes to structural ductility, enhancing the building's performance during earthquakes. Beyond mechanical performance, the lightweight nature of these systems reduces foundation loads and overall construction costs. The modular and dry assembly approach allows for rapid deployment and post event reparability, supporting sustainable and resilient construction practices. Recent studies [69] confirm that double story interlocking plastic block systems can endure multiple cycles of in plane lateral displacement with minimal loss of load carrying capacity, making them suitable for low to mid rise buildings in seismic prone regions. By integrating mass reduction, energy dissipation, ductility, and modularity, these systems represent a promising approach for earthquake resistant construction.

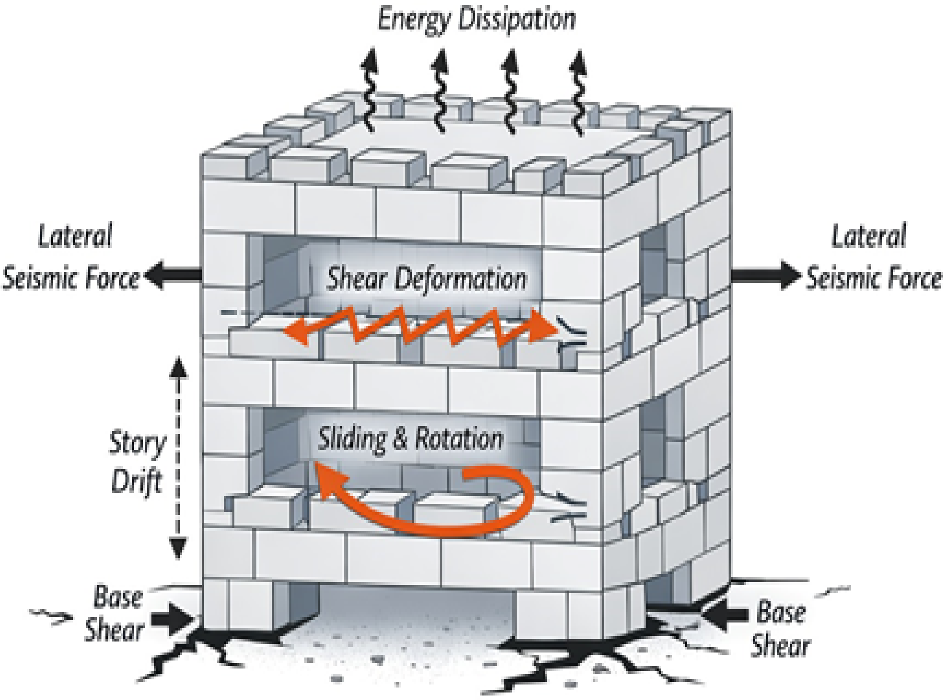


FIGURE 5.1: In Plane Behavior of Double Story Interlocking Plastic Block System, showing base shear, story drift, sliding & rotation, and energy dissipation at block interfaces

It is important to acknowledge that the structural response observed under controlled harmonic loading may differ from that under actual earthquake ground motion. Real seismic excitations are inherently irregular, multi frequency, and transient in nature, which can induce more complex response patterns and varying peak demands compared to the steady state sinusoidal input used in this study. Consequently, the deformation characteristics, force distribution, and energy dissipation mechanisms may exhibit variations under real earthquake conditions. Nevertheless, the present investigation provides a fundamental understanding of the dynamic response, stiffness behavior, and energy dissipation characteristics of the interlocking system under controlled excitation, thereby offering valuable insight into its expected seismic performance.

Building upon the above discussion, the following aspects require further consideration to facilitate the practical implementation of mortar free interlocking block systems in seismic regions. The findings of this study underscore the necessity for developing simplified analytical models and design oriented frameworks tailored to mortar free interlocking systems. Such frameworks should enable the translation of experimental observations into reliable engineering practice by incorporating key response parameters, including damping characteristics, energy dissipation capacity, and frequency dependent behavior identified in this research.

Furthermore, there is a clear need to extend the present investigation to full scale multi story structures subjected to realistic seismic loading conditions. While the current study provides valuable insights under controlled laboratory excitation, comprehensive validation under multi directional dynamic loading is essential to establish the scalability, structural reliability, and field applicability of the proposed system.

In addition, the potential of mortar free interlocking construction should be actively explored for seismic resilient applications, particularly in low cost and rapidly deployable housing. The inherent advantages of modularity, reusability, reduced construction time, and minimal reliance on skilled labor position this system as a promising solution for sustainable construction and post disaster reconstruction initiatives.

5.5 Summary

This chapter presents the principal findings of the study, highlighting both the practical execution of experiments and the development of an empirical model. Dynamic excitation was applied using a locally developed, cost effective shake table. Although the device exhibited some limitations in maintaining uniform amplitudes across varying frequencies, it successfully generated repeatable harmonic loads adequate for evaluating the structure's dynamic response. These experiments produced reliable data, demonstrating the effectiveness of the setup and providing a solid foundation for understanding structural behavior under realistic dynamic conditions.

An empirical equation was formulated to validate the experimental results, ensuring consistency between theoretical predictions and observed behavior. Minor discrepancies between experimental and empirical values are attributed to the structural complexity and the simplifications inherent in the model. The empirical model reinforced the experimental findings, adding confidence and robustness to the results. By integrating analytical and experimental approaches, the study not only enhances its practical relevance but also provides insights that can inform future structural design and dynamic analysis, highlighting the broader significance of the research.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This study systematically investigates the in plane dynamic behavior of a 1:10 scaled, two story interlocking plastic block (IPB) wall under harmonic excitations. The experimental model comprises 120 interlocking plastic blocks arranged in 12 layers, with the base rigidly anchored using angle sections. Structural responses were captured using five accelerometers as two at the top of each floor wall and one at the base. Both snap back tests and harmonic excitations were performed on a locally manufactured one dimensional shake table at frequencies of 0.9 Hz, 1.1 Hz, and 1.3 Hz. The snap back tests were employed to determine the natural frequency, time period, and damping ratio using the logarithmic decrement method, whereas harmonic tests enabled detailed characterization of the in plane response under continuous excitation. The acquired data were processed in MATLAB, and SeismoSignal was applied for noise filtering and baseline correction. The key findings are summarized as follows:

i. The average fundamental frequency of the two story system is approximately 1.1 Hz, while the in plane damping ratio attains values up to 5.4%, demonstrating moderate inherent energy dissipation.

ii. The in plane dynamic response of the walls was quantified in terms of acceleration and displacement time histories:

    a) In plane displacements increased by 71.4% for the SS-SS wall configuration and 54.7% for the DS-SW wall configuration, averaging 63%, reflecting significant frequency dependent amplification in the two story system.
    b) In plane acceleration amplification across frequencies was evident as for the SS-SS wall configuration, values at 1.3 Hz were 1.67 times higher than at 0.9 Hz, while for the DS-SW wall configuration, accelerations at 1.3 Hz were 3.42 times higher than at 0.9 Hz, highlighting pronounced frequency dependent intensification.
    c) In plane displacement time history analysis indicates that the contribution of the SS-SS wall configuration at 0.9 Hz is 1.55 times higher than at 1.3 Hz, and for the DS-SW wall configuration, the in plane contribution at 0.9 Hz is 1.7 times higher than at 1.3 Hz, confirming strong frequency sensitive behavior in the double story walls.

iii. The DS-SW wall configuration dissipates 55% and 9.3% more energy than the SS-SS wall configuration at excitation frequencies of 0.9 Hz and 1.3 Hz, respectively, and 7% more energy at 1.1 Hz.

    a) In plane base shear displacement analyses reveal that for the SS-SS wall configuration, the two story in plane wall absorbs 1.71 times more energy at 1.3 Hz than at 0.9 Hz.
    b) Similarly, the DS-SW wall configuration absorbs 1.75 times more energy at 1.3 Hz than at 0.9 Hz, demonstrating significant frequency dependent in plane energy dissipation.

iv. The percentage deviations between experimental and empirical predictions range from -4.75% to -9.91%, reflecting the inherent complexity of two story mortar free interlocking plastic block walls relative to simplified empirical models, and underscoring the need for cautious interpretation of empirical estimates in dynamic design.

The results demonstrate that two story mortar free interlocking plastic block walls exhibit substantial in plane energy dissipation, frequency dependent amplification in both displacement and acceleration, and robust dynamic stability under snap back and harmonic loading conditions. The lightweight, modular construction, combined with predictable damping characteristics, underscores the potential of these systems for cost effective, earthquake resilient housing solutions in seismic prone regions. These findings provide a strong foundation for further optimization of block patterns, structural configurations, and empirical modeling approaches in modular interlocking wall systems.

6.2 Future Recommendations

Based on the findings of this research, several recommendations are proposed to guide the further development and practical application of mortar free interlocking block systems. These recommendations emphasize the need for advancing theoretical frameworks, validating structural performance under realistic conditions, and promoting practical implementation in seismic resilient construction.

i. Development of Design Oriented Frameworks: Establish simplified analytical models and comprehensive design guidelines to ensure reliable and efficient integration into engineering practice.

ii. Full Scale Multi Story Validation: Conduct experimental evaluation of full scale structures under realistic seismic loading conditions to verify structural performance and scalability.

iii. Application in Seismic Resilient Construction: Implement the proposed system in low cost, sustainable, and earthquake resistant housing, particularly for rapid construction and deployment in post disaster scenarios.

In summary, these recommendations aim to bridge the gap between experimental investigation and practical implementation, thereby contributing to the advancement of innovative, sustainable, and resilient construction technologies.

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