

**CAPITAL UNIVERSITY OF SCIENCE AND
TECHNOLOGY, ISLAMABAD**



**Performance of Interlocking-Plastic-Block
Cross-Junctions Under Dynamic Loadings for
Utilization in Double-Story Mortar-Less
Structures**

by

Abdullah Ashraf

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

in the

Faculty of Engineering

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CERTIFICATE OF APPROVAL

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Abstract

The poor seismic performance of conventional masonry buildings results from their brittle behavior, limited ductility and inefficient load transfer at wall intersections where stress concentrations often start a failure. Although mortar-free interlocking plastic block (IPB) masonry is increasingly seen as an environmentally friendly, lightweight and economical material for low-rise construction, its seismic performance of double-storey cross-junctions, which connect the blocks and are critical for multi directional load transfer and global structural stability, has not been sufficiently understood. The absence of experimental evidence restricts the application of reliable design methods and the gradual adoption of mortarless interlocking masonry in seismic areas. To fill this void, the static and dynamic response of a scaled double storey mortar-free IPB cross-junction was investigated through the tests of lateral stiffness, modal properties, damping behavior, displacement response, capacity for energy dissipation, the effects of the construction structure and the development of empirical relationships for predicting the dynamic response.

A comprehensive experimental program was performed including pushover, snap-back, hammer impact and harmonic shake-table tests to assess the structural performance of the proposed system under static and dynamic loading. All acceleration responses were processed in MATLAB and SeismoSignal to gain insight of the natural frequencies, damping ratio, displacement response, hysteretic energy dissipation characteristics. Lateral stiffness and modal properties under free-vibration and impact loading were quantified with pushover testing and identified with snap-back and hammer impact testing, respectively. Then harmonic excitation was applied to study the effect of loading frequency on the structural response. Geometric, structural and loading parameters were also taken into account to build up empirical equations and validate those equations with the experimental results.

The experimental results revealed the stability of the static and dynamic behavior of the mortar-free IPB cross-junction for the investigated loading conditions. The average lateral stiffness was 2.192.22 N/mm for configurations A(X) and B(Y), and 1.891.91 N/mm for A(Y) and B(X). This indicates that higher lateral resistance is

not fixed to a specific axis, but rather depends on orientation, as complete in-plane blocks provide greater sliding resistance than half-blocks. The fundamental natural frequencies found at 1.371.42 Hz with 4.45.0% damping ratios by snap-back testing were between 4.17 and 5.43 Hz with 7.028.80% damping ratios obtained by hammer impact testing. It was found that the displacement responses under harmonic excitation were larger with increasing frequencies with a maximum value of 13.9 mm, and the corresponding damping ratios were between 16.5% and 18.9%, and hysteretic energy dissipation was improved. The structural performance of both construction structures was similar, and the developed empirical equations showed that the percentages of difference between the predictions and actual acceleration, velocity, and displacement responses were around 2833%, respectively, which were considered acceptable predictive ability. The results have been useful for the analytical model calibration and formulation of seismic design guidelines for sustainable mortar-free interlocking masonry structures.

Key Words: Interlocking Plastic Blocks (IPB); Mortar-free masonry, Cross-junction, Seismic performance, Dynamic response, Shake table testing, Energy dissipation, Empirical equations.

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List of Abbreviations

AD	Acceleration Data
AISC	American Institute of Steel Construction
FFT	Fast Fourier Transform
FRCM	Fabric Reinforced Cementitious Matrix
FRP	Fiber Reinforced Polymer
Hz	Hertz
IPB	Interlocking Plastic Block
MATLAB	Matrix Laboratory
mm	millimeter
MPa	Megapascal
OOP	Out-of-Plane
PBD	Performance-Based Design
RMS	Root Mean Square
SSI	SoilStructure Interaction
TRM	Textile Reinforced Mortar
URM	Unreinforced Masonry

Symbols

a	Area of interlocking plastic-block
d	Displacement
f_n	Fundamental Frequency
K	Lateral Stiffness / Structural Coefficient
m	No. of blocks in a single layer
n	No. of interlocking plastic-blocks
Q	Base shear
S	Number of stories
T_n	Natural time period
u_g	Average displacement
$\dot{u}_g$	Average Velocity
$\ddot{u}_g$	Average acceleration
Δ	Displacement in millimeter
ζ	Damping ratio

Chapter 1

Introduction

1.1 Background

Seismic vulnerability of residential structures is largely governed by the behavior of masonry systems, where failure frequently initiates at wall intersections due to stress concentration, discontinuous load paths, and poor transfer of lateral forces under earthquake loading [1]. Conventional masonry, reliant on mortar joints for bonding, typically exhibits brittle failure characterized by diagonal cracking, joint separation, and rapid stiffness degradation, particularly in multi-story configurations where increased mass and inter-story drift amplify demand on connection zones [2]. In response to these limitations, mortar-free construction systems such as interlocking plastic block assemblies have emerged as sustainable alternatives due to their lightweight nature, ease of assembly, recyclability, and potential for rapid construction in both normal and post-disaster scenarios; [3] however, their seismic performance remains insufficiently understood, especially at critical junction regions where structural walls intersect [4]. These systems rely entirely on geometric interlock and frictional resistance for load transfer rather than mortar bonding, resulting in fundamentally different dynamic behavior characterized by sliding, rocking, stickslip response, stiffness degradation, and hysteretic energy dissipation under cyclic loading [5]. Among all structural components, cross-junctions represent the most vulnerable zones because they function as multi-directional load

transfer nodes where shear, torsional, and rotational effects interact, making them highly sensitive to interface degradation, loss of friction, and progressive separation under seismic excitation [6]. In double-story interlocking plastic block structures, these effects are further intensified due to cumulative drift, increased overturning moments, and redistribution of stresses to lower levels, which significantly influence global stability and failure progression [7]. Despite growing interest in dry-stack and modular masonry systems, limited experimental data exists on the dynamic response of cross-junctions under realistic seismic simulation conditions, particularly for plastic-based interlocking blocks [8]. Therefore, this study focuses on evaluating the seismic performance of a double-story interlocking plastic block structure with special emphasis on cross-junction behavior using snap-back and shake-table testing [9], where key dynamic parameters such as natural frequency variation, damping ratio, stiffness degradation, displacement response [10], and failure mechanisms are assessed through experimental measurements and signal processing using MATLAB and SeismoSignal.

Despite these developments, a critical socioeconomic issue still exists: the need for resilient, reasonably priced housing that can endure high earthquake loads in developing countries. The Cross-joint junction mechanics of IPB assemblies in two-story masonry structures are a key structural vulnerability that has been disregarded despite the emergence of several mortar-less interlocking configurations in recent research. The current paper presents a novel IPB construction methodology in order to address this omission. These blocks efficiently absorb energy during a seismic event by enabling controlled interfacial sliding, providing a useful and effective solution for the upcoming generation of earthquake-resistant residential building.

1.1.1 Background of the Adopted IPB Configuration

Masonry construction has been extensively studied due to its widespread application in residential and heritage structures and its vulnerability under seismic and extreme loading conditions. Previous research has mainly focused on improving the structural performance of masonry walls through optimized block systems,

interlocking mechanisms, strengthening techniques, and advanced numerical mod-

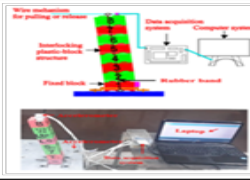
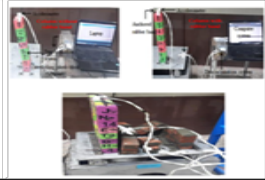
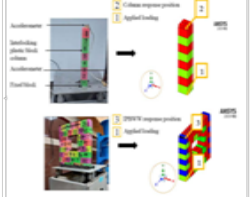
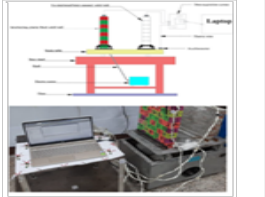
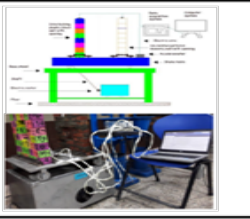
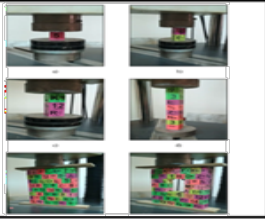
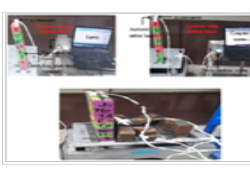
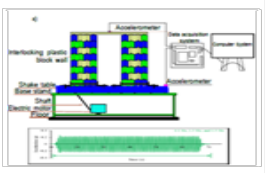
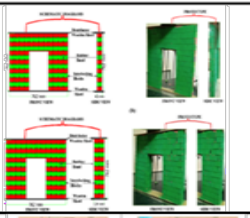
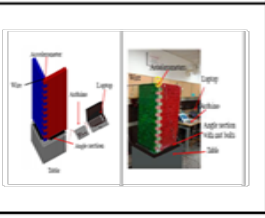
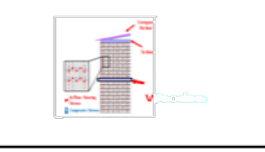
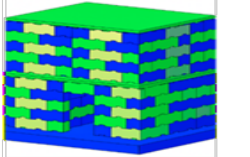
Fayaz Khan 2019	Dynamic Behaviour of Prototype Interlocking Plastic-block Structure		Khurram 2020	Effect of Block-Return on Out-of-Plane Behaviour of Interlocking Plastic-Block Walls	
Hammad 2020	Dynamic Response of Interlocking Plastic-Block Walls with Diaphragm		Sohail Afzal 2020	Out-of-plane Behaviour of Prototype Interlocking Plastic-block Solid Wall	
Mehran 2020	Out-of-plane Behaviour of Prototype Interlocking Plastic-block Wall		M. Sajid Aslam 2020	Compressive Behaviour of Interlocking Plastic Block Structural Elements	
Sardar Junaid 2020	Block-Return on Dynamic In-Plane Behaviour of Interlocking Plastic Block Walls		Shaukat Anwar 2020	Effect of Diaphragm on Dynamic Behaviour of Interlocking Plastic-Block Structure	
M. Adnan 2020	Effect of Slenderness on the Behaviour of Interlocking Plastic-Block		Waseem Akram 2025	Dynamic Performance of Corner-Joints in Mortar-Free Interlocking-Plastic-Block Walls	
Arshad Ullah 2025	Behaviour of Mortar-Free Interlocking-Plastic-Block Walls at Junctions		Jawad Nasar 2025	Compressive Behaviour of Interlocking Plastic Block Structural Elements	
Abu Bakar 2025	Out-of-plane Dynamic Behaviour of Double-Story Interlocking Plastic-Block				

FIGURE 1.1: Previous Research Progress on Interlocking Blocks and Masonry Structural Systems

eling approaches. Studies have investigated the behavior of masonry units under compressive, shear, cyclic, and dynamic loading conditions, while recent developments have introduced innovative materials such as fiber-reinforced composites, polymer-based mortars, recycled aggregates, and dry-joint interlocking systems.

Interlocking masonry technology has gained attention because it can reduce mortar dependency, improve construction speed, enhance modularity, and provide sustainable alternatives to conventional masonry. However, research on plastic-based interlocking blocks, particularly for double-story load-bearing masonry structures, remains limited. Existing literature primarily addresses conventional masonry units, recycled materials, and strengthening systems, leaving significant scope for evaluating the mechanical performance, durability, seismic behavior, and long-term structural reliability of plastic interlocking blocks in multi-story construction.

Building on these advancements, recent studies have increasingly focused on mortar-free interlocking plastic block (IPB) systems because of their lightweight nature, improved energy dissipation capacity, and enhanced seismic performance. Unlike conventional unreinforced brick masonry (URM), where brittle mortar joints often initiate cracking and collapse during strong ground motions, IPB walls rely on mechanical interlocking and controlled friction between blocks to accommodate structural movement and dissipate seismic energy. Experimental investigations have shown that interlocking plastic-block walls, including those with window openings, maintain satisfactory load-carrying capacity while exhibiting reduced crack propagation and greater resistance to lateral loading than traditional URM systems. Furthermore, block-return arrangements and diaphragm action have been reported to improve structural continuity, increase base shear resistance, and enhance damping characteristics by permitting controlled relative movement between adjacent blocks. These findings demonstrate the significant potential of dry-stacked IPB masonry for earthquake-resistant construction and provide a strong foundation for investigating the seismic behavior of more complex structural components, such as double-storey cross-junctions.

1.2 Research Motivation and Problem Statement

Conventional forms of residential house construction in seismically active zones are often associated with significant damage to the structure, owing to inherent deficiencies in masonry-based systems, especially where wall junctions are involved.

While engineered systems may be employed to upgrade the performance of structures, these are often associated with considerable cost implications, making them highly impractical for low-cost housing projects. As such, there is an urgent need for cost-effective yet innovative construction techniques that are capable of enhancing the performance of structures, especially in seismically active zones, without imposing significant cost implications. Interlocking plastic block construction, based on its lightweight features, rapid construction, and sustainable material usage, has emerged as an alternative form of construction. However, as this form of construction is based largely on geometric interlocking, its performance, especially in double-storey residential construction, is yet to be adequately understood. Thus, the problem statement is as follows:

Traditional masonry is a proven and highly effective standard for residential housing, yet mortar-free Interlocking Plastic Block (IPB) systems offer an opportunity to further optimize structural flexibility and energy dissipation. Because IPB construction relies on geometric interlocking rather than rigid joints, it naturally accommodates dynamic lateral forces. However, existing research on these plastic blocks has almost entirely focused on single-storey buildings with relatively light axial loads. Scaling up to a double-storey configuration fundamentally changes the stress distribution, particularly at complex intersecting nodes like cross-junctions where forces tend to concentrate. Since the dynamic response of double-storey IPB cross-junctions remains largely unexplored, this research physically evaluates these specific structural configurations to understand their load-transfer mechanics, derive calibrated empirical equations, and validate the system as a safe, advanced option for double-storey residential design.

1.2.1 Research Questions

- i. How does the geometric configuration of a two-storey mortar-free interlocking plastic block (IPB) cross-junction influence its lateral stiffness and directional response along the X- and Y-axes?
- ii. What are the fundamental dynamic characteristics, including the natural frequency and structural damping ratio, of a double-storey mortar-free IPB

cross-junction under free-vibration conditions, and how effectively do these properties contribute to energy dissipation?

- iii. How does impulsive loading through hammer impact affect the modal response, vibration characteristics, and damping performance of a double-storey mortar-free IPB cross-junction?
- iv. How do different interlocking structures (Structure A and Structure B) influence the dynamic response, displacement behavior, energy dissipation capacity, and hysteretic performance of a mortar-free IPB cross-junction subjected to harmonic loading?
- v. To what extent can empirical relationships accurately predict the acceleration, velocity, and displacement responses of mortar-free IPB cross-junctions when compared with experimentally measured results?

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

The primary objective of the present research is to investigate the structural response of a double-story residential building constructed using mortar-free interlocking plastic blocks through a well-controlled experimental investigation. The research aims to investigate the structural stability, behavior of load transfer, junction behavior, variation in stiffness, and dissipation of energy in the structure under simulated seismic loading conditions. The present research aims to create a database on the suitability and reliability of mortar-free plastic block structures for residential buildings through experimental investigations. The research is expected to bridge the gaps in the available literature and pave the way for the development of affordable and sustainable residential structures in seismic zones.

The specific objective of this Master's study is to critically assess the dynamic performance of cross junctions in a double-story residential structure made of mortar-free interlocking plastic blocks, with special emphasis given to their performance

when subjected to simulated seismic input in a laboratory environment. Snap-back and shake table testing of this structure is expected to determine critical response parameters such as natural frequency variation, damping characteristics, stiffness reduction, slip behavior, and failure mechanisms in these four-way intersections. By investigating the performance of this structure in these critical load transfer points, this study hopes to determine the stability of mortar-free plastic block structures when built to double-story heights. This study also hopes to bridge the existing knowledge gap regarding the behavior of mortar-free interlocking plastic block structures when built to double-story heights, thus paving the way for a safer and more viable use of mortar-free construction practices for double-story residential buildings in seismic zones.

1.4 Scope of Work and Study Limitations

This particular study is focused on carrying out an experimental investigation of a scaled model of a structure that represents a cross junction in a mortar-free double-story interlocking plastic block (IPB) residential construction system. In this regard, a specimen is developed using special interlocking blocks to accurately represent a realistic construction scenario, which is then fixed to a rigid base to simulate a fixed boundary condition. Dynamic analysis of the structure is carried out using snap-back and controlled harmonic excitations to test its response to seismic loading. Displacement-time and acceleration-time histories are recorded to analyze the stiffness characteristics, damping properties, slip characteristics, and stability of the structure. In addition, the effect of increasing levels of excitation on the structure is also examined to identify critical response characteristics and failure mechanisms. Empirical relationships are developed based on the results obtained to accurately model the dynamic characteristics of mortar-free IPB double-story residential construction systems for future design purposes.

The scope of this investigation is restricted to laboratory-scale experimentation via a unidirectional shake table, which only allows for a single direction of excitation in the horizontal plane, not accurately capturing the multi-directional characteristics

of seismic ground motions as they would be encountered in a real-world scenario. Furthermore, it should be noted that instrumentation is restricted to a limited set of displacement sensors and accelerometers located in key areas, which could impact the spatial resolution of structural response measurement. Data acquisition is restricted to displacement-time histories and acceleration-time histories, with detailed analysis requiring post-processing via software tools such as MATLAB for signal processing and SeismoSignal for response interpretation and dynamic parameter extraction. Furthermore, it should be noted that this investigation is restricted to a set of selected excitation levels and frequencies, as opposed to a wide range of seismic inputs. While these restrictions impact the scope of test scenarios that can be valuated, it should be noted that this approach does provide a fundamental basis for evaluating the dynamic performance of mortar-free plastic block double-story systems that could form a basis for future work utilizing more sophisticated equipment and analytical tools.

1.4.1 Rationale Behind the Variable Selection

The goal of developing mortar-free interlocking plastic block (IPB) construction for enhanced seismic performance in double-story residential buildings is strategically linked with the variables chosen for this study. The cross-junction arrangement, where four orthogonal walls contact and transfer multidirectional loads, was chosen because it represents a crucial and relatively understudied structural node in multi-story systems. The prototype's horizontal dimensions were kept constant to prevent distortion of in-plane behavior and load distribution, while the height was scaled down to a 1:10 ratio. This 1:10 scale was chosen to maintain similarity between the structural height and its dynamic response, and also because of the limited size of the available laboratory equipment. To ensure the walls interacted properly at the cross-junction despite this small space, wall lengths of about 200 mm on each side were chosen. The physical model was built using interlocking plastic blocks that have a 62 x 62 mm base, a 50 mm height, and a 12 mm key. These lightweight units provide superior energy dissipation compared to conventional masonry, substantially improving the seismic performance of the

overall structure [11]. Since vertical stress directly affects interface slip resistance and stiffness characteristics, controlled axial compression was included to simulate the gravity loading effects common in double-story architecture. To ascertain fundamental frequency, response amplification, and possible failure acceleration under dynamic excitation, laboratory testing on a scaled prototype was used as a controlled and economical method. Based on the facilities that were available, unidirectional loading and simplified boundary conditions were used. This allowed for a concentrated assessment of junction behavior and laid the groundwork for further research utilizing more sophisticated multi-directional testing equipment.

1.5 Brief Methodology

A 1:10 scaled prototype was constructed to investigate the performance of Interlocking Plastic Block (IPB) cross-junctions under dynamic loadings, specifically evaluating their utilization in double-story mortar-less structures. The experimental specimen consisted of dry-stacked plastic blocks assembled into two different construction layouts, Structure A and Structure B, to examine the influence of block arrangement on the structural response. The base of the cross-junction was rigidly connected to the shake table using steel angle sections and anchor bolts to simulate fixed-base boundary conditions and prevent unwanted foundation movement during testing. To monitor the dynamic response of the specimen, five accelerometers were strategically installed. One sensor was mounted on the shake table to record the input ground motion, while the remaining four were positioned at the wall base, the centre of the cross-junction, and the free ends of the intersecting walls to capture the propagation of vibration throughout the structure. An Arduino-based data acquisition system interfaced with MATLAB continuously recorded the acceleration responses during all experimental stages.

The experimental programme consisted of static stiffness, snap-back, hammer impact, and harmonic shake-table tests to evaluate both the static and dynamic characteristics of the proposed system. Static stiffness testing was first performed to determine the lateral load-displacement behavior, stiffness, and load-carrying

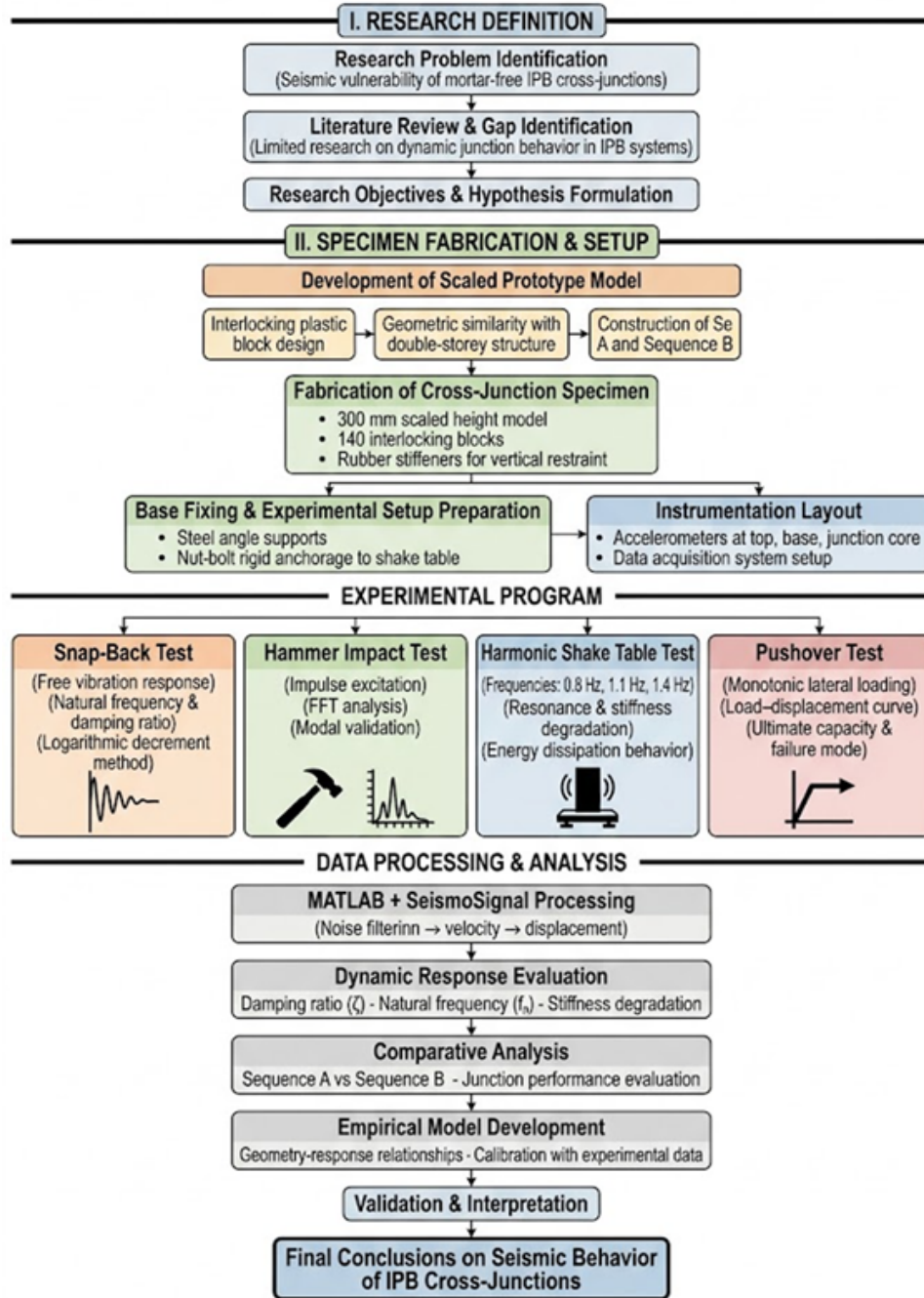


FIGURE 1.2: Brief Methodology of Proposed Research

capacity of the cross-junction. Free-vibration snap-back tests were then conducted by laterally displacing the specimen and suddenly releasing it to determine the fundamental natural frequency and damping ratio using the logarithmic decrement method. The modal properties were further verified through a hammer impact test using a pendulum hammer that generated a repeatable impulse load. Finally, the specimen was subjected to continuous harmonic excitation at 1.2 Hz, 1.4 Hz, and

1.6 Hz using a unidirectional shake table to investigate resonance, displacement amplification, damping characteristics, and energy dissipation. The recorded acceleration histories were processed in SeismoSignal to obtain velocity and displacement responses after baseline correction and filtering. Base shear was calculated from the measured acceleration response, and hysteresis loops were developed to evaluate equivalent damping and energy dissipation. Based on the experimental observations, empirical relationships incorporating the geometric characteristics of the cross-junction and structural parameters were formulated and validated using a calibrated structural coefficient of $K = 1.55$, providing a practical framework for predicting the seismic response of mortar-free IPB cross-junction systems. Configuration, and dynamic response indicators, enabling predictive assessment of seismic performance of IPB cross-junction systems.

1.6 Research Impact on Industry

1.6.1 Research Novelty - Uniqueness

While the application of mortar-free interlocking construction systems has been suggested as an economical and environmental-friendly option for residential housing construction, the existing literature on the subject has mostly been limited to single-story buildings, isolated wall panels, and simple joint configurations. However, the behavior of cross-junctions in double-story buildings, especially in the context of a 1 Kanal (90 ft x 50 ft) house, has not been explored in detail. This is because the cross-junctions in buildings are considered to be the major nodes of load transfer, where two orthogonal wall systems meet and intersect, and their behavior under seismic-type excitations is considered to have a direct impact on the stability of the global structure.

The novelty of this research lies in the fact that the study provides an in-depth investigation of the behavior of the cross junctions in the context of the seismic behavior of the double storey 1 Kanal residential configuration using scaled laboratory testing. By incorporating the realistic geometric details and dynamic excitation, the study provides a novel and experimental-based methodology to evaluate the seismic behavior of mortar-free plastic block housing. The results

of this research study are expected to provide new insights into the behavior of junctions and the corresponding resonance in the context of multi-storey systems, thus filling the existing gap in the literature and contributing to the development of affordable earthquake-resistant residential buildings.

1.6.2 Research Significance and Benefits

This study is significant because it enhances the understanding of the structural performance of cross joints in mortar-free interlocking construction systems. Cross joints are crucial places of connection that affect a multi-story building's overall stiffness, strength, and seismic stability. The study intends to investigate the seismic behavior of these joints, including their natural frequency, damping characteristics, energy absorption capacity, and potential failure pathways, by experimental inquiry under dynamic loading circumstances. The results will help design safer and more dependable building techniques and improve knowledge of how cross joints affect the overall reaction of interlocking buildings during earthquake events.

The design and construction of reasonably priced, earthquake-resistant structures utilizing mortar-free interlocking technology are anticipated to benefit from the research's conclusions. Engineers will be able to increase the structural performance and dependability of these systems while preserving cost-effectiveness with a better understanding of cross joints behavior. Wider use of mortar-free interlocking construction can also promote the use of sustainable, lightweight, and reusable building materials, reduce maintenance and post-earthquake repair costs, and shorten construction timeframes. This work will advance practical engineering knowledge and encourage the creation of robust, ecologically friendly, and financially feasible housing solutions by addressing the paucity of research on cross-joint performance under seismic loading.

1.6.3 Practical Implementation

The results of the present research can be applied directly for the implementation of the mortar-free interlocking plastic blocks for the construction of double-storey

residential buildings, especially for earthquake-prone zones. The experimental investigation of the dynamic behavior of the critical cross-junctions for a practical 1 Kanal residential scenario is useful for providing insights into the load transfer behavior, stiffness characteristics, and stability of the structure, which can be useful for the construction of the structure, especially for the details of the junctions, the arrangement of the blocks, and the construction structure, etc. The proposed mortar-free system is highly suitable for rapid housing development, as its simple, dry-stack assembly significantly reduces overall construction time.

In practical terms, the modular and light nature of the interlocking plastic blocks will provide ease in transporting the blocks, reduce the construction period, and minimize the cost of the materials used. The system can be used to construct permanent double-story residential homes as well as flexible shelter solutions based on the specific needs of the community. In addition, the recyclable nature of the plastic blocks will provide a positive contribution to the sustainability of the environment. The incorporation of experimentally validated performance data will enable the development of cost-effective, structurally sound, and earthquake-resistant homes that can be used to cater to the needs of areas experiencing urban expansion as well as disaster zones.

1.6.4 National and Global Impact with Emphasis on SDGs Relevance

This research has both national and global implications, as it advocates the development of affordable, structurally sound, and seismically resilient housing structures using the system of mortar less interlocking plastic blocks. In the context of the nation, the research has implications for the development of seismically sound housing structures in seismically active regions of the country by offering experimentally informed perspectives on the dynamic behavior of double-storey housing structures. The development of seismically sound structures will result in a reduction of life losses, as well as costs associated with post-disaster reconstruction efforts. Additionally, the use of mortar less construction techniques has

the potential to promote the development of the plastic blocks used in the housing structures, thereby providing employment to the semi-skilled workforce of the country.

At the global level, the research addresses the following challenges: disaster vulnerability, rapid urbanization, and the shortage of affordable housing. The proposed system provides a flexible and adaptable construction method that may be applied on a global scale. The proposed research is significantly aligned with the following Sustainable Development Goals of the United Nations: SDG 11 - Sustainable Cities and Communities, which improves the resilience of the housing system; SDG 9 - Industry, Innovation, and Infrastructure, which advances the innovation of construction technology; SDG 8 - Decent Work and Economic Growth, which advances job creation through the practice of sustainable construction; and finally, SDG 13 - Climate Action, which advances the practice of using recyclable materials that have less effect on the environment due to their light weight. The integration of experimental results into the design guidelines and the academic curriculum supports the decision-making process that enhances long-term resilience and sustainable urban development on the national and international levels.

1.6.5 Research Challenges

There are several challenges which are likely to be encountered in the implementation of this study. Firstly, the major limitation in the implementation of this study is the limitations in the laboratory facilities, especially the one-dimensional shake table, which can only be excited in one direction along the horizontal axis and not in all the directions as in the case of natural earthquakes. Data acquisition is another challenge which is likely to be encountered in this study, especially due to the limited number of accelerometers which may not cover the whole spatial response of the system, especially in the displacement and velocity response at the junction region. Processing and filtering of the raw data from the accelerometers using software such as MATLAB and SeismoSignal may also pose some uncertainties which may affect the results in the determination of the damping ratios, stiffness characteristics, and energy dissipation.

At the same time, scaling factors can also create complexities since the scaled model of 1:3 might not behave identically to the actual materials' behavior and the friction between the contacting surfaces and the load transfer mechanisms in mortar-free systems. The precise alignment of the blocks and the integrity of the joints during the process of repeating dynamic loading cycles can also create difficulties during the experimentation process due to the lightweight nature of the plastic blocks. Finally, the precise calibration of the experimental results with the empirical equations and the possible numerical results also requires careful attention to avoid discrepancies.

1.6.6 Ethical and Management Consideration Including Risk Management

This research follows the ethical principles that have been widely accepted to promote transparency, precision, and responsible reporting of the results obtained from the experiment. All the results obtained from the experiment, including the limitations and uncertainties, are recorded and documented objectively without any manipulation of the data or results obtained from the experiment. Proper recognition is given to the contributors, supervisors, and technical staff who assisted in the experiment conducted in the laboratory. Adherence to the health and safety regulations of the institution is strictly followed during the experiment using the shake table, handling the specimen, and setting up the equipment to ensure the safety of all personnel involved. This research also promotes the responsible use of materials and resources to support the concept of environmentally conscious research, which is aligned with the principles of sustainable construction.

From the management point of view, the project is guided by an outlined research plan with set milestones in the construction of the prototype, carrying out the dynamic test, processing the data, and analyzing the results to complete the project on time. There is also the integration of the researchers, laboratory technicians, and supervisors to coordinate the workflow and accountability in the implementation of the research. There is also the consideration of the risk management measures in the outlined framework of the research to help in the management of

the possible risks in the implementation of the project. These risks may include the malfunctioning of the instruments, errors in the calibration of the sensors, and the consistency of the results in the scaling process, which can be managed through the constant calibration of the instruments, the repeated test process, and the validation of the results through the cross-checking process. There is also the consideration of the contingency plans in the management of the delays in the laboratory access and the availability of the resources in the implementation of the project.

1.6.7 Research Deliverable, Sales and Marketing Potential

This research will produce academic as well as practical outcomes that will help in the development of the mortar-free interlocking plastic block (IPB) construction technique in the context of double-story residential buildings. Some of the outcomes that will be produced as a result of this research include the collection of comprehensive data on the dynamic properties of the cross-junctions that are created when two walls intersect. Some of the parameters that will be covered in the research include the fundamental frequency, damping ratio, variation in the stiffness, amplification in the responses, as well as the failure mechanisms that occur in the system. In addition to the above, the research will also produce practical outcomes that will help in the safe design of mortar-free IPB systems in earthquake-prone areas. Furthermore, the development of a scaled prototype that will show the structural feasibility, as well as the ease of assembly, will also be a practical outcome of the research.

The results of this research also have a high potential for commercialization and implementation, especially in the affordable housing and disaster-resilient construction fields. The IPB system's modularity and absence of mortar enable quick construction, shorter construction periods, and lower labor requirements, which can be highly beneficial for affordable housing developers, construction companies, and the government in addressing the housing shortage. The system's lightweight and recyclable characteristics also increase its potential in a society where green building practices are becoming more prominent. The marketing strategies for

this system can highlight three major benefits: safety during seismic events, cost-effectiveness, and sustainability. Potential partnerships with NGOs, disaster-relief organizations, and government housing institutions can provide opportunities for implementation projects in disaster-stricken communities. This research work validates the experimental performance of the IPB system, creating a platform for its potential expansion into the national and international markets for housing systems.

1.7 Thesis Outline

This thesis is organized into five chapters, each addressing a specific component of the research related to the seismic performance of mortar-free interlocking plastic block (IPB) systems, with particular emphasis on cross-junction behavior in double-storey residential structures.

Chapter 1 presents the overall background of the study, highlighting the research motivation and problem statement associated with the seismic vulnerability of mortar-free masonry systems. It defines the main research objectives and specific aims of this MS thesis, outlines the scope and limitations of the study, and provides a brief description of the adopted methodology. The chapter concludes with the structure of the thesis.

Chapter 2 provides a comprehensive literature review on seismic behavior and strengthening approaches in masonry construction, with a focused discussion on mortar-free systems and interlocking plastic blocks. It examines structural performance, damage mechanisms, interface behavior, and cross-junction response under seismic loading. The chapter also reviews experimental and numerical methods used in previous studies, identifying key research gaps that form the basis of the present investigation.

Chapter 3 describes the research methodology adopted in this study. It includes the development of the scaled cross-junction prototype using interlocking plastic blocks, details of material properties, and construction configurations. The chapter further explains the experimental setup, instrumentation, and testing procedures,

including snapback, harmonic shake-table, hammer impact, and static stiffness tests, along with data acquisition and analysis techniques.

Chapter 4 presents the results obtained from the experimental investigation of the seismic performance of mortar-free interlocking plastic block systems. The chapter reports the findings from dynamic and static testing, including snap-back tests, harmonic shake-table responses, hammer impact assessments, and static stiffness analysis. The observed structural responses, deformation patterns, natural frequencies, damping characteristics, load-displacement behavior, stiffness degradation, and failure mechanisms of the cross-junction specimens are systematically presented and analyzed.

Chapter 5 discusses the experimental findings in relation to the existing literature and theoretical expectations. The chapter interprets the influence of interlocking mechanisms, cross-junction configuration, interface behavior, and block connectivity on the seismic performance of IPB systems. Comparisons with conventional masonry and other mortar-free construction systems are provided to evaluate the effectiveness and potential applicability of interlocking plastic blocks for double-storey residential structures.

Chapter 6 summarizes the major conclusions derived from the research and highlights the key contributions of the study. The chapter discusses the overall performance of mortar-free interlocking plastic block systems under seismic loading and provides recommendations for future research. Potential future directions include full-scale structural testing, numerical modeling improvements, long-term durability assessment, environmental performance evaluation, and practical implementation of IPB systems in sustainable earthquake-resistant construction.

Chapter 2

Literature Review

2.1 Overview

Mortar-free masonry systems, particularly interlocking plastic block assemblies, have emerged as an innovative and sustainable alternative to conventional bonded masonry due to their dry-stack construction, rapid assembly potential, and reduced dependency on cementitious materials; however, their seismic behavior is fundamentally governed by interface mechanics rather than material continuity, making their structural response highly sensitive to contact conditions, geometric interlocking, and frictional resistance at block interfaces [1]. In these systems, load transfer occurs primarily through direct block-to-block contact, where friction and mechanical keying govern force transmission instead of mortar bonding, leading to distinct behavioral characteristics such as sliding-dominated hysteresis, rocking mechanisms, and localized separation at joints, especially under cyclic seismic loading [2]. Experimental and numerical studies consistently show that interlocking plastic blocks exhibit nonlinear stickslip behavior, where initial stiffness is governed by contact engagement but progressively degrades as interface slip initiates, resulting in energy dissipation through controlled frictional sliding rather than brittle cracking typical of conventional masonry [3]. The structural performance of such systems is strongly influenced by axial pre-compression, which enhances normal contact forces at interfaces, thereby increasing frictional resistance and delaying sliding initiation; however, variations in axial load due to seismic vertical

acceleration can significantly alter stability conditions, making multi-directional loading effects critical in performance assessment [4]. Interface stiffness and confinement conditions further govern the global response, as increased confinement through mechanical restraints, tie elements, or boundary framing improves load redistribution and reduces excessive displacement demand, while insufficient confinement leads to localized instability and progressive joint degradation [5]. In addition, the bi-directional nature of seismic excitation introduces complex interaction between in-plane and out-of-plane responses, where vertical motion amplifies rocking and separation at critical junctions, particularly at cross-junctions where multiple load paths intersect and stress concentrations develop [6]. These cross-junctions in interlocking plastic block systems represent the most vulnerable regions due to combined shear, torsion, and rotational effects, making them primary initiation points for damage and stiffness degradation under cyclic loading [7]. Furthermore, sliding-dominated hysteretic behavior, while beneficial for energy dissipation and ductility, also introduces progressive wear at contact surfaces, leading to reduction in frictional capacity over repeated loading cycles and potentially increasing residual deformations if not adequately restrained [8]. The dynamic response of multi-storey configurations further complicates this behavior, as inter-storey drift accumulation and overturning effects amplify demand at lower-level junctions, particularly in double-storey residential systems where load redistribution becomes highly sensitive to interface degradation [9]. Numerical simulations and shake-table experiments confirm that neglecting joint-level behavior leads to significant underestimation of seismic vulnerability, emphasizing that global response is governed by local interface performance rather than bulk material properties [10]. Consequently, interlocking plastic block systems demonstrate a complex balance between flexibility and stability, where their inherent ability to accommodate deformation through sliding and rocking enhances seismic resilience but simultaneously necessitates careful design of interface geometry, confinement mechanisms, and junction detailing to prevent excessive displacement and instability [12]. Therefore, the seismic reliability of mortar-free interlocking plastic block structures is fundamentally controlled by cross-junction behavior, interface stiffness variation, and frictional load transfer efficiency, establishing that

accurate evaluation of these parameters is essential for validating their suitability in multi-storey residential construction in seismic-prone regions.

2.2 Seismic Behavior of Masonry Structures

Masonry construction, commonly composed of bricks or blocks bonded with mortar, has been widely adopted due to its economic feasibility and ease of construction; however, its mechanical behavior is governed by low tensile strength and limited ductility, which significantly influence its performance under seismic loading [1]. The material heterogeneity and weak interfacial bonding between masonry units and mortar result in anisotropic behavior, making such structures highly susceptible to cracking when subjected to lateral forces [2]. During earthquake excitation, masonry walls experience combined in-plane shear and compressive stresses, leading to brittle failure mechanisms such as diagonal cracking and sliding along mortar joints [3]. Furthermore, masonry infill walls, often treated as non-structural components, contribute significantly to global stiffness and modify the dynamic characteristics of framed systems by altering load distribution and increasing lateral resistance [4]. Despite this beneficial increase in stiffness, the interaction between infill walls and structural frames introduces stress concentrations and irregular force paths, which may accelerate damage initiation [5]. Observations from past seismic events also indicate that irregular distribution of masonry elements leads to soft-storey mechanisms and localized failures, particularly in lower story [6]. Additionally, simplified analytical approaches often fail to capture the complex interaction between masonry panels and surrounding structural elements, limiting the accuracy of seismic assessment [7]. Therefore, the seismic behavior of masonry structures is primarily governed by their inherent material limitations and structural configuration, demonstrating that their vulnerability is strongly linked to both micro-level properties and macro-level interactions.

Analytical studies employing finite element modelling have shown that stress concentrations, particularly tensile and shear stresses, are critical in governing failure in masonry systems, as observed in cases where damage localizes at geometric transition Zones (Table 2.1) [8].

TABLE 2.1: Summary of Previous Studies on Seismic Behavior of Masonry Structures [4, 13]

Structural System	Research Method	Key Findings	Significance
Masonry minaret	Pushover and nonlinear dynamic analysis	Nonlinear response increases with displacement demand and damage progression	Demonstrates the importance of dynamic analysis for seismic assessment.
Masonry infilled frames	Experimental and numerical analysis	Infill walls improve lateral stiffness but reduce structural ductility	Highlights the influence of infill walls on seismic performance.
Masonry buildings strengthened with TRM	Nonlinear seismic assessment	Strengthening improves lateral resistance and crack control	Confirms the effectiveness of TRM for seismic retrofitting.
Masonry walls strengthened with FRCM	Cyclic loading tests	Increased shear strength, stiffness, and load transfer capacity	Demonstrates improved structural performance under cyclic loading.
Masonry walls strengthened with fiber nets	Experimental investigation	Improved crack control and deformation capacity	Validates fiber reinforcement for seismic strengthening.
Unreinforced masonry walls	Pushover analysis	Identifies damage mechanisms and probable failure modes	Provides insight into seismic vulnerability of masonry structures.
Masonry churches	Analytical assessment	Structural components significantly influence seismic response	Emphasizes the role of geometry in earthquake resistance.
Masonry walls with polymer strengthening	Experimental testing	Increased strength and energy dissipation	Shows the benefits of advanced strengthening materials for seismic applications.

Comparative analyses indicate that nonlinear dynamic methods provide a more realistic representation of structural response by capturing time-dependent effects, whereas pushover analysis tends to produce conservative estimates and cannot fully simulate cyclic degradation [9]. Experimental and numerical studies on infilled frame systems demonstrate that masonry infill walls enhance lateral stiffness and load-carrying capacity; however, they simultaneously reduce ductility and introduce brittle failure modes depending on connection characteristics [10]. Case studies involving strengthened masonry systems reveal that appropriate reinforcement configurations significantly reduce inter-storey drift and prevent collapse mechanisms [12]. Field observations from past earthquakes further confirm recurring damage patterns, including diagonal cracking, detachment of infill panels,

and shear sliding failures [13]. Moreover, parametric investigations highlight that factors such as aspect ratio, axial load, and mortar strength play a crucial role in determining stiffness, strength, and failure modes of masonry walls. These findings collectively emphasize that the seismic response of masonry structures is highly sensitive to both modelling approaches and structural parameters, indicating the necessity of integrating experimental validation with advanced numerical techniques.

Various retrofitting techniques have been proposed to address the inherent deficiencies of masonry, including the use of reinforced cores, polymer-modified mortars, fiber-based systems, and precast reinforced concrete panels [14]. Experimental studies demonstrate that the incorporation of reinforced cores within masonry walls delays crack initiation and limits crack propagation, thereby improving overall structural integrity and energy dissipation capacity [15]. Similarly, the application of polymer mortar and steel-based strengthening systems has been shown to significantly enhance load-bearing capacity and ductility, with notable increases in strength and energy dissipation depending on anchorage and configuration [16]. Strengthening with precast reinforced concrete panels further improves shear resistance and stiffness by facilitating effective load transfer between structural components [17]. In addition, the use of advanced materials such as textile-reinforced systems contributes to improved deformation capacity and mitigation of brittle failure modes [18]. However, the efficiency of these techniques is highly dependent on proper design, compatibility of materials, and execution quality [19]. Consequently, retrofitting strategies play a critical role in reducing seismic vulnerability, and their appropriate implementation can substantially improve the safety and resilience of existing masonry structures.

2.2.1 Mechanical Characteristics of Masonry Structures

The mechanical characteristics of masonry arise from its heterogeneous and composite nature, where different constituents such as blocks, mortar, grout, reinforcement, and their interfaces collectively govern the overall structural response

under loading conditions [20]. This complexity makes masonry behavior highly nonlinear and dependent on the interaction between materials with different mechanical properties [21]. The structural response is not only controlled by the strength of individual components but also by the quality of contact, bonding, and load transfer mechanisms between them [22]. Experimental observations indicate that masonry assemblages exhibit different stress-strain responses depending on whether they are grouted or ungrouted and on the configuration of the units, which directly relates to load transfer efficiency and stiffness variation [23]. In addition, numerical investigations are frequently required to complement experimental studies because capturing full stress-strain behavior in such heterogeneous systems is challenging [24]. The presence of multiple interfaces leads to variations in stiffness, energy dissipation, and failure patterns under different loading conditions, which is particularly relevant for dry-stack and interlocking systems where bonding is absent [25]. These interface-controlled mechanisms are critical when assessing junction behavior, especially in cross-junctions where stress redistribution and localized deformation govern performance. The interaction between units becomes more dominant in mortar-free systems, where mechanical interlocking and friction replace traditional bonding. Consequently, the behavior of masonry cannot be idealized as a homogeneous material but must be interpreted as an interaction-driven system influenced by contact mechanics [26]. This understanding is essential for evaluating dynamic response parameters such as stiffness degradation and energy dissipation under seismic loading. Therefore, the mechanical behavior of masonry is fundamentally governed by composite action and interface-dependent mechanisms that directly influence its structural performance at both element and junction levels.

The compressive and tensile behavior of masonry shows a strong contrast due to the inherent difference in load-carrying mechanisms under these stress states [27]. Under compression, masonry assemblages generally demonstrate higher load-bearing capacity because the applied load is transferred through direct contact between units and mortar or grout, allowing redistribution of stresses within the system [20]. Experimental findings indicate that ungrouted prisms may show higher

peak compressive stress; however, their deformation capacity and post-peak behavior differ significantly compared to grouted systems, especially in terms of stability and crack evolution [22]. In contrast, tensile behavior is considerably weaker due to the limited tensile strength of masonry constituents and the brittle nature of interfaces, which leads to early crack initiation and rapid propagation [23]. Studies further show that improved confinement, such as boundary elements or reinforcement, enhances tensile resistance and fracture energy, which is important for maintaining integrity at critical locations such as cross junctions [24]. In mortar-free and interlocking systems, tensile resistance is even more dependent on contact conditions and mechanical interlock, making them sensitive to separation under dynamic loading. Additionally, tensile failure is typically governed by interface cracking, which can propagate quickly across joints and reduce stiffness significantly. This difference between compressive strength and tensile weakness becomes more critical in seismic conditions where cyclic loading induces repeated tension-compression reversals. As a result, junction regions, particularly four-way intersections, are more vulnerable due to stress concentration and multidirectional force transfer [28]. Therefore, masonry exhibits strong compressive resistance but limited tensile capacity, emphasizing the need to improve tensile performance for enhanced seismic stability.

The shear friction mechanism in masonry plays a critical role in determining its structural stability, especially under lateral and seismic loading conditions [29]. Shear resistance is primarily governed by frictional interaction at interfaces, normal compressive stress, and the bonding condition between masonry units and mortar or grout [21]. Experimental investigations demonstrate that ungrouted masonry exhibits significantly lower shear strength compared to grouted configurations, highlighting the importance of interface cohesion in resisting sliding failure [27]. The shear behavior is also influenced by bonding patterns, where continuous vertical joints tend to promote sliding and increase shear deformation, whereas staggered configurations improve resistance [20]. In mortar-free and interlocking masonry systems, shear resistance is mainly provided by geometric interlocking and frictional resistance, making the system highly dependent on contact conditions and axial pre-compression [22]. This is particularly important

for cross-junctions, where load transfer occurs in multiple directions and frictional resistance governs stability. Studies also indicate that interface stiffness, friction coefficient, and cyclic degradation significantly affect shear response, leading to progressive stiffness reduction and energy dissipation under repeated loading [23]. Strengthening techniques, including confinement and reinforcement, improve shear capacity by enhancing joint integrity and delaying crack propagation [24]. However, without sufficient confinement, shear failure remains brittle and may lead to sudden loss of load-carrying capacity. The behavior becomes more complex in double-storey systems where accumulated deformation at junctions influences global response [25]. Therefore, shear behavior in masonry is predominantly governed by frictional mechanisms and interface performance, making it a key factor in assessing seismic resistance and ensuring structural safety of interlocking systems.

2.3 Damage at Cross Junctions in Masonry Structures

Damage at cross-junctions in masonry structures is consistently identified in the reviewed studies as a critical and highly vulnerable response zone under seismic loading [30]. The literature shows that wall intersections interrupt uniform load paths and create strong stress concentrations where orthogonal walls meet, making these regions more susceptible to cracking and separation during earthquakes [31]. Under cyclic lateral loading, damage typically begins with micro-cracks forming at the internal corners of junctions due to combined shear, bending, and compatibility demands between intersecting walls [32]. These cracks gradually grow into interface sliding and openingclosing behavior, indicating progressive loss of continuity (Figure 2.1) [33]. Field investigations from earthquake-affected regions further confirm that poor connections between perpendicular walls, lack of bond beams, and weak mortar significantly intensify this damage [34]. In addition, inadequate wall openings and irregular masonry units contribute to early structural degradation at these junctions by disturbing stress distribution [35]. Several studies also highlight that tensioncompression imbalance and weak tensile resistance of

masonry accelerate crack initiation at cross-junctions [32]. As damage progresses, localized crushing and spalling occur at highly compressed edges, reducing stiffness and deformability capacity of the junction region [33]. The literature further emphasizes that these processes ultimately lead to partial separation of intersecting walls, weakening the overall structural integrity [34]. These findings collectively indicate that junction regions behave as critical stress concentration zones where multiple failure mechanisms interact simultaneously. Such behavior becomes even more pronounced in mortar-free and interlocking systems where bonding is replaced by contact-based load transfer. Therefore, cross-junctions play a governing role in controlling damage initiation and structural response under seismic loading.



FIGURE 2.1: Seismic Damage in Conventional Masonry House Highlighting Failure at Wall Intersections (Cross-Junction Regions) [31].

Damage progression at cross-junctions is further governed by complex interaction effects and leads to severe structural instability when seismic loading continues [36]. The studies indicate that in-plane and out-of-plane interaction plays a major role in accelerating damage, where out-of-plane deformation reduces in-plane resistance and alters failure patterns at wall intersections [37]. Torsional effects in irregular masonry layouts further intensify stress concentration at junctions, especially when stiffness distribution is non-uniform [31]. The degradation of box action is repeatedly observed, where initially connected walls begin to act independently due to joint failure and loss of anchorage [34]. Numerical and experimental investigations show that failure at cross-junctions often triggers a chain reaction,

spreading from localized cracking to global instability of wall systems [32]. In hybrid and non-engineered structures, insufficient reinforcement such as missing seismic bands and weak stirrups further worsens junction performance under lateral loads [36]. Finite element studies also confirm that poor junction connectivity significantly increases shear demand and reduces load-carrying capacity of adjoining structural members [32]. Retrofit studies demonstrate that improving connectivity through reinforcements such as reinforced bands or fiber-based materials can significantly reduce vulnerability at these intersections [37]. Observations from historical masonry structures also reveal that material degradation and environmental effects can further weaken junction integrity over time, increasing long-term seismic risk [35]. The combined influence of these mechanisms highlights the sensitivity of junctions to both geometric and material irregularities. This behavior indicates that once junction integrity is compromised, the overall system response becomes highly unstable and prone to progressive collapse. In conclusion, cross-junction damage evolves through interacting in-plane, out-of-plane, and torsional mechanisms, and its progression highlights the necessity of strong connectivity and reinforcement to prevent global collapse of masonry systems.

2.3.1 Structural Vulnerability of Masonry under Seismic Loading

The structural vulnerability of masonry under seismic loading is governed by highly nonlinear response mechanisms that are strongly influenced by material behavior, boundary conditions, and interaction effects [38]. Across multiple studies, out-of-plane response of unreinforced masonry is identified as one of the most critical and least predictable failure modes due to uncertainties in triggering acceleration, velocity, and collapse initiation (Table 2.2) [39]. Experimental and numerical evidence consistently shows that unrestrained wall-to-wall and wall-to-diaphragm connections can lead to hybrid two-way bending, where rocking and horizontal bending occur simultaneously under seismic excitation [40]. This behavior is activated early in the loading process and evolves through alternating phases of one-way bending and sudden rocking, highlighting unstable transition mechanisms [42].

TABLE 2.2: Summary of Previous Studies on Structural Vulnerability of Masonry under Seismic Loading [38, 41]

Structure	Method	Key Finding	Main Observation
URM buildings	Shake-table testing	Hybrid bending and multiple collapse mechanisms observed	High out-of-plane (OOP) vulnerability
URM walls	Experimental & numerical	Wall interaction strongly influences seismic response	Increased vulnerability when interaction is neglected
Historic masonry walls	Shake-table cyclic testing	Strengthening improves deformation capacity	Better seismic performance after retrofitting
RC frame with brick infill	Cyclic loading	Stiffness degradation and damage progression occur during loading	Frame-wall interaction governs failure
Irregular RC buildings	Numerical analysis	Structural irregularity increases seismic demand	Higher collapse risk
Existing masonry walls	Field investigation	Weak anchorage causes OOP failures	High safety risk during earthquakes
Ancient masonry structures	Experimental & analytical	Cracks initiate around openings under seismic loading	Increased overturning vulnerability
Full-scale masonry walls	Experimental testing	Rapid stiffness degradation after cracking	Reduced seismic resistance

The role of interface stiffness and damping is repeatedly observed as a governing factor in controlling activation, progression, and near-collapse stages [43]. In reinforced and masonry systems, variations in reinforcement ratio, axial load, and detailing significantly affect deformation capacity and moment-rotation response, while stiffness degradation leads to period elongation and loss of translational dominance in dynamic behavior [44]. These findings collectively indicate that seismic vulnerability is fundamentally controlled by coupled material nonlinearity, interface behavior, and progressive stiffness degradation, which govern the transition from stable response to collapse.

In addition to inherent material response, structural vulnerability is significantly amplified by interaction effects and progressive failure mechanisms within masonry systems [45]. In-plane, out-of-plane, and torsional interactions play a central role

in damage development, where coupling effects and flange actions lead to bidirectional degradation and redistribution of seismic forces [46]. Weak inter-unit connections in masonry aggregates and hybrid frame systems result in uneven shear distribution, localized damage, and brittle failure chains that can trigger near-collapse conditions, while stronger connections improve load sharing and reduce displacement demand [47]. Torsional irregularities, particularly in asymmetric and L-shaped buildings, further intensify seismic demand, especially when combined with soilstructure interaction effects [48]. Strengthening interventions such as steel cords, engineered cementitious composites, and infilled masonry systems enhance stiffness distribution, deformation capacity, and crack resistance, although their effectiveness depends strongly on connection stiffness and material compatibility [49]. Failure progression studies consistently show that masonry structures undergo staged degradation starting from crack initiation at openings and weak joints, followed by stiffness loss, shear concentration, and eventual collapse through rocking, sliding, or hybrid mechanisms [41]. Masonry vulnerability under seismic loading is governed by the combined effects of interaction-driven damage localization, progressive stiffness degradation, and connection failure, which collectively control collapse mechanisms and structural performance limits.

2.3.2 Failure Mechanisms at Structural Wall Intersections

Failure mechanisms at masonry wall intersections under seismic loading are primarily governed by interaction effects between orthogonal walls, where stiffness discontinuities and connection quality control the overall load transfer mechanism [50]. Studies consistently show that intersection zones become critical stress concentration regions during seismic excitation because deformation compatibility between connected walls is not maintained (Table 2.3), especially in unreinforced masonry systems [51]. Weak inter-unit bonding and inadequate connection detailing lead to uneven shear transfer at junctions, which results in localized damage initiation and progressive stiffness reduction [52]. Experimental and numerical investigations further indicate that the interlocking efficiency of masonry aggregates significantly influences whether intersecting walls behave as a unified structural

system or as independent components under dynamic loading [53]. In cases where connectivity is weak, seismic forces are redistributed toward more flexible wall segments, intensifying deformation demand at intersections [54]. Strengthening techniques such as composite reinforcement, steel cords, and improved bonding systems enhance load transfer capacity, but their effectiveness strongly depends on interface stiffness and material compatibility [55]. Overall, intersection behavior is identified as a governing factor in seismic response, where connection integrity directly controls stress redistribution and damage initiation patterns.

TABLE 2.3: Case Study-Based Seismic Vulnerabilities and Failure Mechanisms of Masonry Structures [50,61]

Structural System	Loading Type	Key Finding
URM walls	Seismic loading	Brittle behavior with poor energy dissipation and early collapse.
Historic masonry	Out-of-plane loading	Strengthening improves stability and load resistance.
Brick veneer systems	Shake-table testing	Veneer detachment increases earthquake damage risk.
Interlocking masonry	Dynamic loading	Better force transfer and improved seismic performance.
ECC-strengthened URM	Cyclic loading	Higher ductility and energy dissipation than conventional URM.
Composite-strengthened masonry	Shear loading	Seismic performance depends on bond quality.
Aged masonry	Environmental exposure	Material degradation reduces structural capacity.
Ancient masonry structures	Lateral loading	Global instability governs structural failure.
RC irregular structures	Earthquake loading	Torsion significantly increases seismic demand.
Earthquake-damaged URM buildings	Field observations	Lack of reinforcement leads to severe structural damage.

The failure evolution at masonry wall intersections progresses through a structure of damage stages beginning with micro-cracking and advancing toward interface separation and local collapse under increasing seismic demand [56]. Research shows that initial cracking typically occurs at intersection corners due to geometric discontinuities and high stress concentration under cyclic loading conditions [57].

Once cracking initiates, sliding shear along mortar joints becomes dominant, leading to progressive loss of bonding between intersecting walls [58]. Experimental studies on masonry aggregates and hybrid systems indicate that weak connections can trigger brittle failure chains, where damage propagates rapidly from the intersection zone into adjacent structural elements [59]. Out-of-plane instability is frequently observed after interface weakening, particularly when lateral restraint from connecting walls is insufficient [60]. At advanced stages, local crushing and spalling develop at contact edges due to repeated loading reversals and loss of confinement [61]. It is concluded that intersection failure is a staged process governed by crack initiation, shear sliding, and progressive interface degradation leading to global instability.

2.3.3 Dynamic Response of Structural Junctions under Seismic Loading

The seismic response of masonry junctions is governed by complex interactions between material heterogeneity, interface behavior, and dynamic excitation characteristics (Table). Masonry systems composed of brick, stone, timber, and hybrid assemblies exhibit pronounced nonlinear behavior when subjected to seismic loading, where stiffness degradation, energy dissipation, and damage localization occur simultaneously [62]. Experimental and numerical investigations consistently demonstrate that junction regions act as critical transfer zones for stress redistribution, making them highly sensitive to vibration-induced effects and cyclic loading demands [61]. In structures such as timbermasonry connections, masonry arch bridges, and confined masonry systems, seismic loading modifies both global and local response mechanisms, leading to progressive changes in dynamic properties. These changes are strongly influenced by loading type, including quasi-static, cyclic, and full dynamic excitations, which collectively reveal the evolving nature of structural response under earthquake conditions [60]. Additionally, the interaction between structural elements and non-structural components significantly contributes to the overall seismic behavior. Consequently, the dynamic response

of masonry junctions is fundamentally controlled by the evolution of stiffness, damping, and interface integrity under seismic excitation.

Another important aspect governing the seismic performance of masonry junctions is the influence of multi-directional ground motion and structural configuration. Earthquake excitations rarely act in a single direction, and the simultaneous presence of horizontal and vertical components introduces complex stress states within masonry assemblies [63]. This leads to coupled deformation mechanisms that are highly dependent on geometry, boundary conditions, and material discontinuities at junction interfaces. Numerical simulations and experimental studies show that variations in loading direction significantly affect displacement patterns, stress distribution, and failure initiation [64]. In multi-storey masonry systems, these effects are further amplified by irregular stiffness distribution, resulting in localized deformation and damage concentration. The presence of soilstructure interaction also modifies dynamic response by altering boundary stiffness and frequency characteristics. As a result, seismic demand in masonry junctions cannot be evaluated using simplified unidirectional assumptions, as directional coupling plays a decisive role in defining structural vulnerability [65]. Therefore, a comprehensive understanding of multi-directional seismic response is essential for accurately characterizing masonry junction behavior under earthquake loading.

2.4 Innovative Techniques for Enhancing Structural Seismic Performance

Innovative seismic strengthening concepts in masonry systems are increasingly shifting from material-based enhancement to interface-driven performance improvement, with particular attention given to critical discontinuity regions such as cross-junctions, wall intersections, and load transfer nodes where stress concentration and damage initiation are most severe under seismic excitation [59]. However, recent developments extend beyond conventional masonry retrofitting and are now strongly aligned with the behavior of interlocking plastic block systems, where mortar is eliminated and structural continuity is governed entirely by

geometric interlock and frictional contact at dry interfaces [39]. In these systems, cross-junctions are not secondary connection zones but primary load transfer hubs where multi-directional forces interact, making their stability the key determinant of global structural performance [18]. Experimental and numerical studies on interlocking assemblies show that failure is primarily governed by interface sliding, rocking, and separation at these junctions under cyclic loading, particularly when subjected to bidirectional seismic excitation [54]. Unlike traditional masonry, where mortar governs joint behavior, interlocking plastic blocks rely on engineered geometries that control contact stability and delay stress localization at intersection points [26]. At cross-junctions, specially designed interlocking profiles enhance mechanical engagement between orthogonal walls, improving shear transfer continuity and reducing abrupt stress concentration, thereby directly influencing seismic resilience.

In interlocking plastic block systems, the role of cross-junctions becomes even more critical in double-storey configurations, where accumulated lateral drift and vertical load interaction significantly amplify interface demand at lower-level intersections. Research indicates that geometric keying mechanisms and contact optimization at these junctions can substantially improve load redistribution between intersecting walls, enabling more uniform stress transfer and reducing localized failure initiation [66]. Unlike conventional strengthening approaches used in masonry, interlocking plastic block systems achieve seismic performance enhancement through built-in geometric confinement rather than external reinforcement, where interface design governs stiffness, ductility, and energy dissipation capacity [67]. Cross-junction behavior in such systems is characterized by a combination of controlled sliding and rocking, which, when properly stabilized through interlocking geometry, allows the system to dissipate seismic energy without sudden brittle failure [13]. However, inadequate junction detailing leads to premature interface opening, loss of contact stability, and progressive stiffness degradation under cyclic loading, making junction design a critical factor in system reliability [68]. Therefore, in interlocking plastic block systems, cross-junctions function as the governing structural elements controlling seismic response, load transfer continuity, and failure progression under dynamic excitation.

2.4.1 Seismic Strengthening Approaches in Structural Construction

Masonry structures in seismic regions exhibit high vulnerability due to low tensile strength of mortar, brittle failure mechanisms, and inadequate detailing in older construction practices. Strengthening strategies have therefore evolved to improve lateral resistance, energy dissipation, ductility, and load transfer mechanisms within masonry assemblies [34]. Experimental, numerical, and analytical investigations consistently show that seismic performance depends not only on material properties but also on the configuration of strengthening systems and their interaction with existing structural components [50]. Modern approaches integrate reinforced concrete, fiber-based composites, timber-based systems, and prefabricated elements to improve global and local response under earthquake loading [69]. These interventions aim to control crack propagation, reduce displacement demand, and enhance overall stability under cyclic and dynamic excitation [65]. The effectiveness of strengthening is strongly influenced by connection behavior, interface integrity, and stiffness distribution across structural components [49]. As a result, seismic upgrading of masonry structures requires a system-level understanding of both vertical and horizontal load-resisting mechanisms under dynamic conditions. Seismic strengthening methods can broadly be categorized into systems that modify wall behavior, improve confinement action, enhance connection performance, and increase diaphragm effectiveness. Research shows that traditional strengthening techniques such as reinforced concrete additions coexist with modern composite-based systems including fiber-reinforced polymers, textile-reinforced mortars, and precast reinforcement elements [19]. Experimental studies indicate that these systems improve shear capacity, deformation ability, and energy dissipation while reducing sudden collapse risk [70]. Numerical simulations further confirm that strengthening interventions significantly modify stiffness degradation patterns and delay failure initiation under cyclic loading [40]. However, performance variation is observed depending on material compatibility, construction quality, and detailing accuracy [71]. In addition, strengthening effectiveness is closely linked to how loads are transferred between masonry walls,

diaphragms, and boundary elements [24]. Therefore, seismic strengthening strategies must be evaluated not only in terms of local element capacity but also in terms of overall structural interaction and global stability under earthquake excitation.

2.4.1.1 Interlocking Plastic Block Systems at Cross-Junctions

Interlocking plastic block systems represent an emerging class of mortar-free construction technologies in which seismic performance is governed primarily by geometric interlock, frictional resistance, and interface compatibility rather than mortar-based bonding (Figure 2.2). Under seismic loading, these systems exhibit distinct structural behavior compared to conventional masonry due to the discontinuous nature of load transfer across dry interfaces [24]. Experimental and numerical studies indicate that global stability is strongly influenced by local interaction mechanisms at block interfaces, particularly at geometric discontinuities such as cross-junctions where multiple load paths intersect [68]. In these regions, stress concentration develops under lateral excitation, leading to localized sliding, rocking, and partial separation between adjoining units [15]. Unlike traditional masonry, where failure is typically characterized by distributed cracking patterns, interlocking plastic block systems show concentrated deformation at junction nodes. Therefore, the seismic response of these systems is fundamentally controlled by interface behavior, concluding that cross-junctions act as primary regulators of structural stability under dynamic loading conditions. The behavior of cross-junctions in interlocking plastic block systems becomes even more critical in multi-storey configurations, where accumulated lateral drift and overturning moments amplify demand at lower-level interfaces. Experimental investigations using shake table and cyclic loading methods have shown that stiffness degradation and energy dissipation are strongly localized at junction regions, where repeated loading leads to progressive loss of frictional capacity [73]. As seismic excitation continues, micro-slips at the interface evolve into larger displacement discontinuities, significantly affecting global deformation patterns and load redistribution mechanisms [19]. The ability of cross-junctions to maintain stable contact conditions directly governs the overall performance of the structure, as failure at these

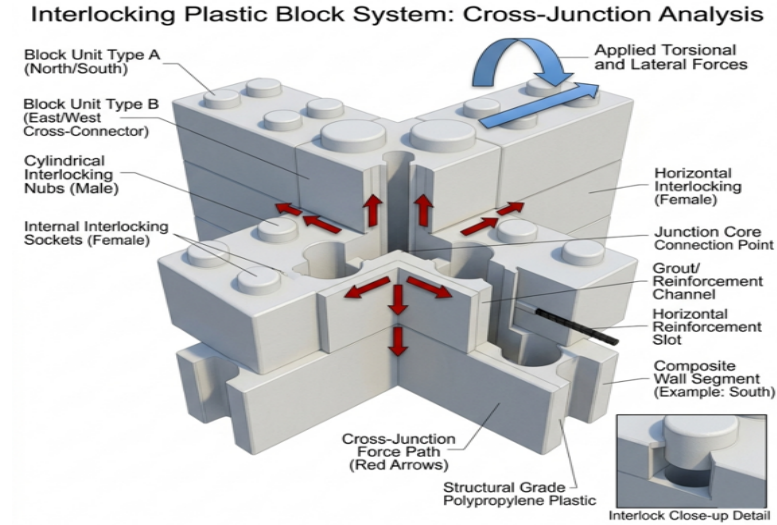


FIGURE 2.2: Conceptual Model of Interlocking Plastic Block [72].

nodes often triggers system-wide instability [74]. Numerical studies further confirm that improving junction geometry and contact conditions enhances energy dissipation and delays failure initiation [38]. Therefore, cross-junction behavior is the key determinant of seismic resilience in interlocking plastic block systems, concluding that junction-level performance governs both local damage evolution and global structural response under earthquake loading.

2.4.2 Experimental and Numerical Assessment of Structural Systems

Experimental and numerical investigations reported in the literature provide a comprehensive understanding of the structural response of masonry systems subjected to seismic and mechanical loading conditions [58]. Laboratory-based studies, including cyclic loading, shake-table testing, and vibration measurements, have consistently demonstrated that unreinforced masonry exhibits brittle behavior with limited ductility and rapid stiffness degradation, whereas strengthened systems show enhanced load-carrying capacity, deformation ability, and energy dissipation [32]. Observations from experimental programs indicate that failure mechanisms vary depending on material type and strengthening configuration, with common modes including diagonal shear cracking, sliding along joints, rocking behavior, and interface debonding [75]. Advanced measurement techniques

such as digital image correlation have enabled accurate tracking of strain localization and crack propagation, providing detailed insight into progressive damage evolution [15]. These experimental findings form the basis for understanding the influence of reinforcement techniques, material properties, and loading conditions on masonry performance under seismic actions.

Numerical approaches have been extensively employed to complement experimental observations and to simulate the complex nonlinear behavior of masonry systems [76].

TABLE 2.4: Case Studies on Experimental and Numerical Assessment of Masonry Systems [77, 78]

Masonry System	Methodology	Main Contribution
Mortar-free interlock-ing wall	Shake-table + Nu-merical	Improved seismic resistance through fric-tional rocking.
Interlocking masonry	Finite element analysis	Developed empirical load prediction mod-els.
Interlocking brick prisms	Compression + ABAQUS	Geometry controls strength and stiffness.
Dry-stack blocks	Experimental	Improved compressive strength and dura-bility.
ICEB walls	Compression test-ing	Slenderness significantly affects wall capac-ity.
Mortise-and-tenon masonry	Experimental + FE	Increased ductility using steel fibres.
Interlocking brick walls	Flexural testing	Reinforcement greatly improves flexural performance.
Meta-block systems	Dynamic testing	Significant vibration and displacement re-duction.
RC frames with ma-sonry infill	Cyclic testing	Infill enhances lateral stiffness and seismic response.
Self-locking block sys-tems	Literature review	Sustainable and efficient alternative to con-ventional masonry.

Finite element and applied element methods have been widely used to model stress distribution, deformation patterns, and failure progression under both static and dynamic loading [23]. The incorporation of constitutive relationships, bondslip

mechanisms, and interface interactions allows numerical models to reproduce experimentally observed responses with a high degree of accuracy [79]. Validation of numerical simulations against laboratory results has shown strong agreement in terms of load-displacement behavior and failure modes, confirming their reliability for predictive analysis (Table 2.4) [53]. Furthermore, numerical modeling enables parametric investigations of variables such as reinforcement ratio, material strength, and boundary conditions, which are difficult to explore experimentally. The integration of experimental data with computational modeling provides a robust framework for evaluating masonry behavior and improving seismic design strategies.

2.4.3 Structural Performance of Mortar-Free Masonry under Seismic Loading using Interlocking Plastic Blocks

The structural performance of mortar-free interlocking plastic block systems under seismic loading has emerged as a key research area in the development of lightweight, sustainable, and rapidly deployable construction systems in earthquake-prone regions [72]. Unlike conventional masonry, which relies on mortar-based bonding for continuity, interlocking plastic block systems depend entirely on geometric interlock, dry frictional contact, and interface compatibility between modular units [80]. This fundamental shift results in a distinctly different seismic response mechanism, where global stability is governed by interface behavior rather than material continuity [81]. Experimental and numerical studies indicate that these systems do not typically exhibit brittle diagonal shear failure as observed in traditional masonry; instead, they demonstrate controlled rocking, sliding, and localized separation at contact interfaces, particularly at discontinuity zones such as cross-junctions [30]. These characteristics allow for significant deformation capacity and energy dissipation through controlled interface movement, although they also introduce high sensitivity to joint behavior and contact conditions [52]. In double-storey configurations, these effects are amplified due to increased overturning moments, inter-storey drift accumulation, and progressive interface demand at lower junction levels [82]. Therefore, the seismic response of interlocking plastic

block systems is fundamentally governed by interface mechanics and junction stability, concluding that system performance is controlled by cross-junction behavior under dynamic loading conditions.

The seismic response of interlocking plastic block systems is further influenced by geometric configuration, vertical load interaction, and dynamic excitation characteristics, which collectively govern stiffness variation, load redistribution, and failure progression [83]. Experimental investigations using shake table testing and cyclic loading have shown that interlocking geometry plays a critical role in determining the balance between stability and deformability, where stronger geometric engagement enhances load transfer but may reduce energy dissipation capacity if excessively stiff [13]. The absence of mortar joints increases reliance on frictional resistance, making interface conditions highly sensitive to surface contact quality, manufacturing precision, and assembly alignment [84]. Under seismic excitation, the system exhibits nonlinear stick-slip behavior, where initial elastic response transitions into sliding once frictional limits are exceeded, resulting in hysteretic energy dissipation. Cross-junctions act as primary load redistribution nodes where multiple wall systems intersect, creating complex multi-directional stress states involving shear, compression, and torsion [43]. These junctions are therefore the most critical zones for stiffness degradation and damage initiation. In double-storey systems, vertical load effects initially enhance frictional resistance at interfaces; however, cyclic loading leads to progressive degradation, increased residual displacement, and reduced load transfer efficiency. The seismic behavior of interlocking plastic block systems is governed by coupled geometric and frictional mechanisms, concluding that interface stability at cross-junctions controls global structural performance.

2.4.3.1 Multi-storey Dynamic Behavior

The dynamic behavior of multi-storey interlocking plastic block systems is strongly influenced by their modular construction, interface-dependent load transfer mechanisms, and the interaction between interconnected structural components under seismic excitation [73]. Unlike conventional masonry systems, these mortar-free

assemblies do not rely on rigid bonding, and their seismic response is primarily governed by frictional contact, geometric interlock, and cross-junction stability [80]. Experimental and numerical studies indicate that such systems may exhibit relatively higher natural frequencies due to their lightweight and discrete unit configuration, which can reduce sensitivity to certain long-period ground motion effects [85]. However, their dynamic response remains highly sensitive to vertical accelerations and boundary conditions, as these factors directly modify interface contact forces and frictional resistance at block junctions [42]. In interlocking plastic block systems, sliding and rocking mechanisms act as primary deformation modes, enabling redistribution of seismic energy and reducing stress concentration compared to brittle masonry behavior [63]. These effects become particularly critical in multi-storey configurations where cumulative drift and overturning moments amplify demand at lower-level cross-junctions [30]. Therefore, the dynamic response is fundamentally governed by interface-controlled mechanisms, concluding that cross-junction stability is the primary factor defining multi-storey seismic behavior in interlocking plastic block systems.

The seismic performance of multi-storey interlocking plastic block systems is further controlled by structural configuration, connection detailing, and inter-storey load transfer mechanisms, which collectively influence deformation patterns and global stability [83]. Numerical and experimental analyses show that accurate representation of interlocking behavior and interface interaction is essential for reliable prediction of dynamic response, as neglecting these effects can lead to significant underestimation of displacement demand and failure risk [86]. In multi-storey systems, the interaction between successive story creates complex force redistribution patterns, where lower levels experience amplified demands due to cumulative lateral drift and inertia effects [72]. This behavior is further intensified at cross-junctions, which act as primary load transfer nodes and govern stiffness degradation, energy dissipation, and failure progression under cyclic loading [23]. While interlocking plastic block systems offer advantages in terms of flexibility, modularity, and controlled energy dissipation through sliding and rocking, their multi-storey performance requires careful evaluation to prevent instability under extreme seismic conditions [59]. Therefore, structural reliability in such systems depends

on accurate assessment of inter-storey interaction, concluding that cross-junction performance is the key determinant of multi-storey seismic safety in interlocking plastic block structures.

2.5 Damage Mechanisms in Mortar-Free Interlocking Plastic Block Systems

Mortar-free interlocking plastic block systems exhibit unique seismic damage mechanisms due to the absence of mortar and reliance on dry frictional interfaces, where structural stability is governed entirely by contact interaction, geometric interlock, and interface integrity under dynamic loading conditions [83]. The present research is primarily aimed at investigating the structural response of a double-storey residential building constructed using mortar-free interlocking plastic blocks through a controlled experimental investigation, where seismic loading conditions are simulated to evaluate stability, load transfer, junction behavior, stiffness variation, and energy dissipation characteristics [80]. Under such systems, the dominant failure modes include sliding, rocking, and localized separation at interfaces, which initiate early due to discontinuous load transfer mechanisms [59]. As seismic demand increases, these micro-slips evolve into larger displacement discontinuities, leading to nonlinear response behavior that governs global deformation [38]. In double-storey configurations, these effects are amplified due to increased overturning moments and inter-storey drift accumulation, which significantly intensifies demand at lower-level interfaces [87]. The study specifically focuses on how these mechanisms influence the suitability and reliability of mortar-free plastic block structures for residential applications, particularly under seismic excitation [23]. Cross-junctions, where multiple walls intersect, act as critical stress concentration zones where multi-directional forces interact, making them the primary locations for damage initiation [88]. These junctions experience combined shear, torsional, and rotational effects, which exceed local frictional capacity under cyclic loading [13]. Experimental investigations forming part of this research aim to capture

these failure patterns and establish a database on seismic performance of such systems [52]. Therefore, damage mechanisms are fundamentally governed by interface instability and junction behavior, concluding that cross-junction response controls the seismic reliability of double-storey interlocking plastic block structures.

In addition to primary sliding and rocking behavior, mortar-free interlocking systems also exhibit progressive degradation mechanisms that become more pronounced under cyclic seismic loading, where repeated opening and closing of interfaces leads to reduction in frictional resistance and accumulation of irreversible deformation [30]. The specific objective of this study is to critically assess the dynamic performance of cross-junctions in a double-storey residential structure made of interlocking plastic blocks under simulated seismic input using shake table and snap-back testing, where key parameters such as natural frequency variation, damping characteristics, stiffness degradation, slip behavior, and failure modes are evaluated [63]. Cross-junctions are particularly sensitive to these cyclic effects because they serve as multi-directional load transfer nodes, where intersecting walls experience complex stress interactions under seismic excitation [42]. As cyclic loading progresses, interface wear and micro-slip accumulation reduce stiffness and alter energy dissipation behavior, which directly affects global stability of the structure. The experimental framework of this research is designed to bridge the existing knowledge gap regarding the behavior of mortar-free interlocking plastic block systems in double-storey residential applications in seismic zones, with a focus on structural reliability and failure progression [89]. Numerical and experimental evidence consistently show that degradation is localized at junctions rather than distributed uniformly, confirming their governing role in structural response [90]. Progressive damage evolution is controlled by interface deterioration and junction instability, concluding that cross-junction degradation is the key indicator of seismic performance in the studied system.

2.5.1 Interface Behavior and Load Transfer Mechanisms

The structural response of mortar-free interlocking plastic block systems is fundamentally governed by interface mechanics, where load transfer occurs through

direct contact forces rather than bonded continuity, making frictional resistance and geometric interlocking the primary mechanisms controlling stiffness, stability, and energy dissipation [37]. In this research, the experimental investigation of a double-storey residential structure using shake table and snap-back testing is designed specifically to evaluate load transfer behavior, stiffness variation, and junction performance under seismic excitation (Figure 2.3), enabling assessment of structural reliability in real-time dynamic conditions [91]. Under lateral loading, shear forces are transmitted through discrete contact points, resulting in highly

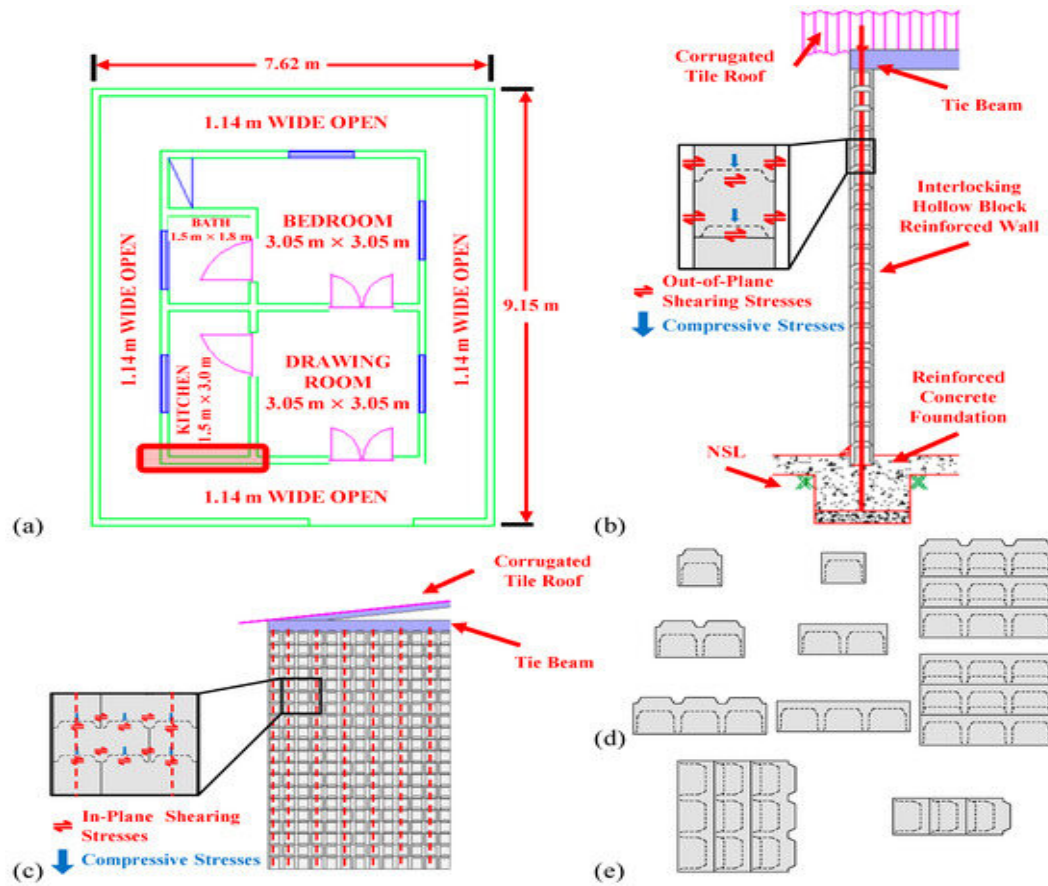


FIGURE 2.3: Schematic representation of the proposed mortar-free interlocking hollow block house, including the building layout, wall section, wall elevation, and the compression and shear test specimens [92].

non-uniform stress distribution across interfaces, particularly at geometric discontinuities such as corners and junctions [43]. The system exhibits a nonlinear stick-slip response, where initial elastic behavior transitions into sliding once frictional capacity is exceeded, producing hysteretic energy dissipation [44]. This behavior is critical in understanding the seismic performance of interlocking plastic block

structures intended for residential use, as it directly governs deformation capacity and energy absorption potential [80]. Cross-junctions act as primary load redistribution nodes where forces from multiple directions converge, creating complex stress states involving shear, compression, and torsion [59]. In the present study, these junctions are treated as key evaluation zones for assessing structural stability and failure mechanisms under simulated seismic loading conditions [25]. As cyclic loading progresses, interface wear leads to gradual reduction in stiffness and increased residual deformation, which is captured through experimental measurement of dynamic response parameters [93]. Therefore, interface behavior governs global load transfer efficiency, concluding that seismic stability of double-storey interlocking plastic block systems is controlled by frictional and geometric interface performance.

Cross-junctions play a dominant role in load transfer mechanisms because they represent the intersection of multiple structural load paths, where even minor changes in contact conditions can significantly alter global force redistribution patterns [73]. In double-storey systems, vertical and lateral load interactions further intensify stress concentration at these junctions, particularly under seismic excitation where cyclic loading leads to repeated opening and closing of interfaces [38]. The present research aims to create a comprehensive experimental database on stiffness variation, damping characteristics, slip behavior, and failure progression at these junctions, enabling evaluation of their reliability for residential construction in seismic regions [79]. Experimental and numerical observations show that junction stiffness directly governs global deformation patterns, as degradation at these locations leads to displacement concentration and reduced load transfer efficiency [30]. With increasing seismic demand, frictional resistance alone becomes insufficient to maintain stability, resulting in progressive interface instability and redistribution of stresses to adjacent elements [63]. This behavior highlights the importance of junction-level evaluation in understanding overall structural response [13]. Therefore, load transfer efficiency is fundamentally dependent on cross-junction integrity, concluding that junction performance is the controlling factor in maintaining seismic continuity in interlocking plastic block structures.

2.5.2 Cross-Junction Behavior and Seismic Vulnerability

Cross-junctions in mortar-free interlocking plastic block systems represent the most critical structural nodes due to their role as multi-directional load transfer points in the double-storey residential structure investigated under this study using shake table and snap-back testing under simulated seismic loading conditions [73]. These intersections are highly vulnerable because they rely entirely on frictional resistance and geometric interlock, both of which degrade under cyclic loading and repeated displacement reversals [80]. Under seismic excitation, cross-junctions experience combined shear, torsional, and rotational effects, which produce complex stress states that significantly exceed those in planar wall regions [59]. The specific objective of this research is to evaluate how these junctions govern natural frequency variation, stiffness reduction, damping evolution, slip behavior, and failure mechanisms, particularly under laboratory-simulated earthquake inputs [25]. As loading progresses, localized rocking and sliding occur at these intersections due to differential movement between intersecting walls, leading to partial loss of contact and stiffness degradation [79]. In double-storey configurations, this vulnerability is amplified due to increased lateral drift and accumulation of rotational effects at lower junction levels [38]. Experimental findings from similar systems indicate that failure at cross-junctions governs global collapse mechanisms, as localized instability triggers redistribution of stresses throughout the structure [93]. Therefore, cross-junction behavior directly governs seismic vulnerability, concluding that junction-level performance determines overall stability of interlocking plastic block residential systems under earthquake loading.

The seismic vulnerability of cross-junctions is further influenced by their inability to maintain stable contact conditions under repeated cyclic loading, where alternating tension-compression states lead to progressive degradation of interface integrity and frictional capacity [23]. The present study specifically addresses this behavior through controlled experimental testing of a double-storey interlocking plastic block structure to establish a performance database for seismic reliability assessment in residential applications [83]. As cyclic demand increases, micro-damage accumulates at junction interfaces, resulting in stiffness reduction

and increased displacement demand at critical nodes [13]. In double-storey systems, lower junctions experience amplified demand due to cumulative drift and inertia effects, making them primary locations for damage initiation and progression [63]. Snap-back testing further allows evaluation of residual deformation and post-damage stiffness loss, which are essential parameters for assessing structural safety. Shake table results are expected to provide detailed insight into dynamic instability development and failure progression mechanisms at these intersections [30]. Therefore, seismic vulnerability is governed by progressive junction degradation, concluding that cross-junction stability is the key determinant of structural reliability in mortar-free interlocking plastic block systems.

2.6 Summary

Mortar-free masonry systems, particularly interlocking plastic block assemblies, represent a significant advancement in sustainable seismic-resistant construction, where structural performance is fundamentally governed by interface mechanics rather than material continuity. Across experimental, numerical, and analytical studies, it is consistently observed that these systems exhibit distinctive seismic behavior characterized by sliding-dominated hysteresis, rocking mechanisms, and friction-based energy dissipation instead of brittle shear failure typical of conventional masonry. A major consensus in the literature is that load transfer in such systems is controlled by frictional resistance and geometric interlocking at block interfaces, making interface stiffness, surface conditions, and axial pre-compression critical parameters influencing global stability and seismic response. Furthermore, cross-junctions are repeatedly identified as the most vulnerable structural features due to multi-directional stress interaction, where shear, torsion, and rotational effects combine to initiate localized damage, stiffness degradation, and progressive failure under cyclic loading. Studies also highlight that axial pre-compression enhances interface stability by increasing normal contact forces, while bi-directional seismic excitation significantly amplifies demand at critical junctions, particularly in multi-storey configurations where drift accumulation intensifies lower-level damage. Although sliding and rocking mechanisms provide beneficial ductility

and energy dissipation, repeated cyclic loading leads to interface wear and gradual reduction in frictional capacity, which can compromise long-term structural performance if not adequately controlled through confinement or reinforcement strategies. Strengthening and mitigation approaches identified in literature emphasize the importance of junction-level confinement, improved connection detailing, and hybrid reinforcement techniques to enhance load transfer continuity and delay failure initiation. Experimental and numerical investigations further confirm that structural response is highly sensitive to modeling of interface behavior, and neglecting joint-level interactions leads to significant underestimation of seismic vulnerability. Overall, the literature indicates that the seismic reliability of interlocking plastic block systems is mainly controlled by cross-junction integrity, interface behavior, and frictional load transfer efficiency, highlighting the need for detailed experimental investigation of junction performance in multi-storey systems under seismic loading.

Chapter 3

Experimental Program

3.1 Background

Reliable prediction of structural response under seismic loading is accurately predicted to ensure safe design of structures located in earthquake-prone zones. Dynamic testing of scaled structural models under controlled laboratory conditions is commonly employed to measure vibration responses, stiffness deterioration, damping responses, and failure mechanisms. For mortar-free interlocking plastic block structures, where stability is ensured by geometric interlocking and frictional resistance, it is of immense importance to study the dynamic response of cross-junction sections of interlocking blocks. The methodology adopted for the study includes developing a scaled model of cross-junction sections of interlocking blocks, developing an experimental setup with necessary instrumentation for snap-back testing, and applying controlled harmonic loads using a shake table. Displacement-time and acceleration-time responses are measured and analyzed using MATLAB and SeismoSignal to identify dynamic responses and aid in developing empirical relationships for performance prediction of double-storey residential structures.

3.2 Continuation and Extension of the Research Program

Khan [94] previously proposed Interlocking Plastic Blocks (IPBs) as an efficient option for lightweight earthquake-resistant construction of residential structures,

as shown in the conceptual plan and 3D configuration of Figure 3.1 (a) and Figure 3.1 (b), respectively. From experimental observations, it was noted that the reduction in self-weight of the structure leads to a reduction in inertia forces. Since the inertia forces are directly proportional to the mass of the structure, it is natural that systems with low self-weight will exhibit low inertia forces, making the IPB-based housing structures more advantageous.

The proposed IPBs for practical application had dimensions of 150 mm x 150 mm, including four keys on the top surface for better stability. However, for the purpose of this research, 62 mm x 62 mm dimensioned IPBs with an overall height of 50 mm, including a 12 mm interlocking key, were used for prototype construction. These square-shaped plastic blocks are designed to include four keys, along with key-and-groove interlocking, for better interlocking. This research aims to enhance the previously proposed IPBs by incorporating the interlocking concept for the construction of the scaled cross junction prototype.

In this study, a scaled model of a cross-junction structure made of mortar-free interlocking plastic block walls was dynamically tested to derive guidelines for actual construction practices instead of strictly relying on predictions based on theories. The scaling approach and construction processes were adopted following conventional practices reported in existing literature to ensure that the results offer valuable insights into actual expected behaviors for full-scale structures.

The main emphasis of the present investigation is the dynamic behavior of the cross-junction region, where the structural period is of primary importance in the seismic behavior, as defined in the UBC-97 code. Accordingly, the elevation dimensions of the walls were scaled to maintain similarity in the dynamic response characteristics, making it feasible for laboratory testing. The proposed mortar-free interlocking plastic block residential arrangement is depicted in Figure 3.1, where (a) indicates the plan arrangement of the house, (c) indicates the geometry of the proposed plastic block, and (d) indicates the actual manufactured plastic block unit. In addition, the plan and elevation arrangement of the cross-junction region, as originally proposed, is depicted in Figure 3.4 (a), whereas Figure 3.2 (b) indicates the scaled boundary conditions for the controlled testing arrangement.

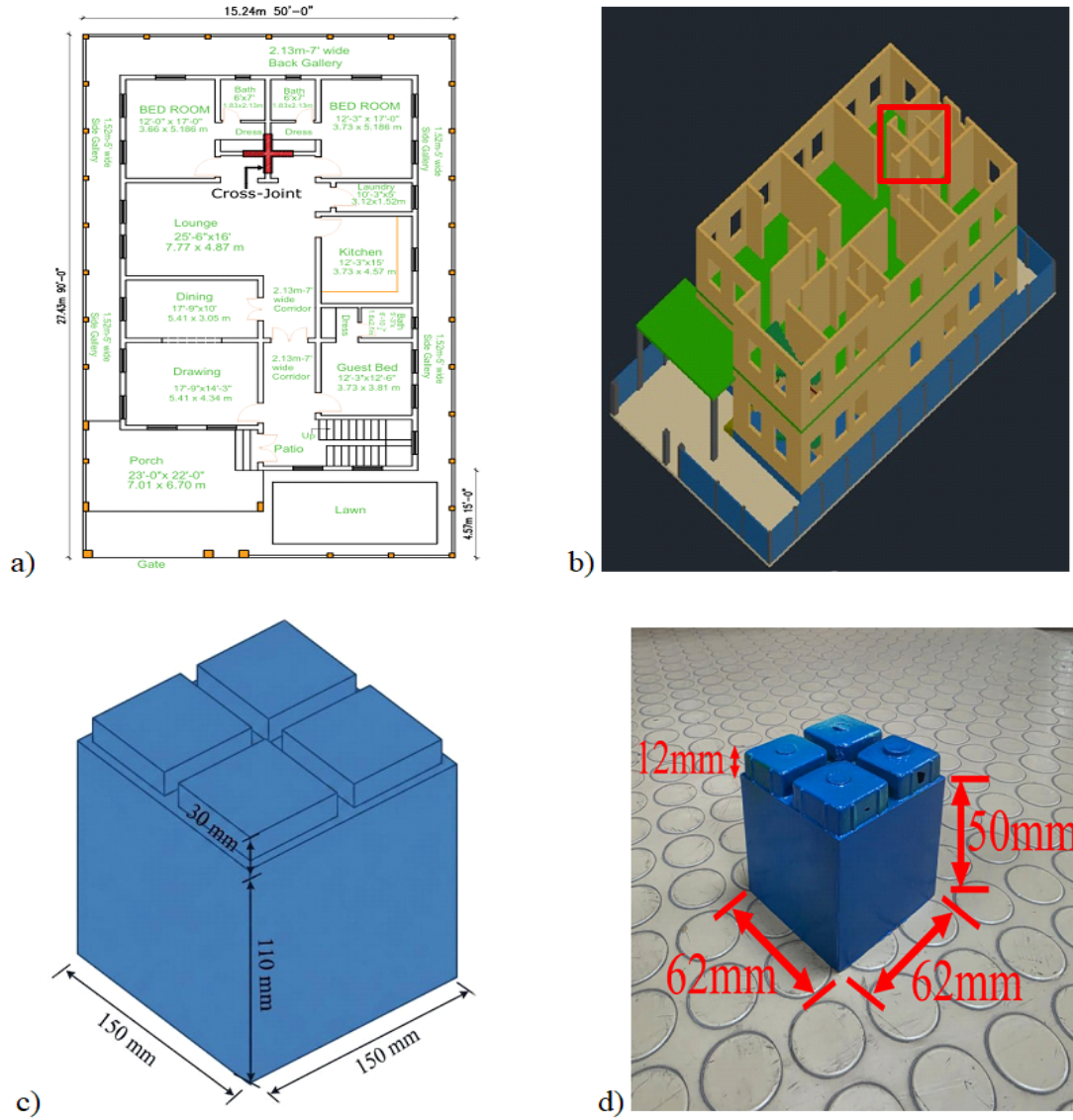


FIGURE 3.1: Proposed mortar free interlocking plastic block House (a) Plan, (b) 3D View, (c) Proposed Plastic Block (d) Real Plastic Block.

The cross-junction specimen was firmly anchored to a rigid base plate using steel angle sections to ensure adequate fixity during dynamic testing. For analytical comparison, full-scale wall dimensions of 2000 mm length and 3000 mm height were considered, while the laboratory prototype was constructed using scaled dimensions of 200 mm length and 300 mm height, maintaining geometric similarity in elevation. The fixed-base condition was implemented to simulate realistic boundary restraints typically present in residential structures. Dynamic evaluation was conducted primarily in the x-direction under unidirectional excitation, with the assumption that geometric symmetry of the cross-junction would provide

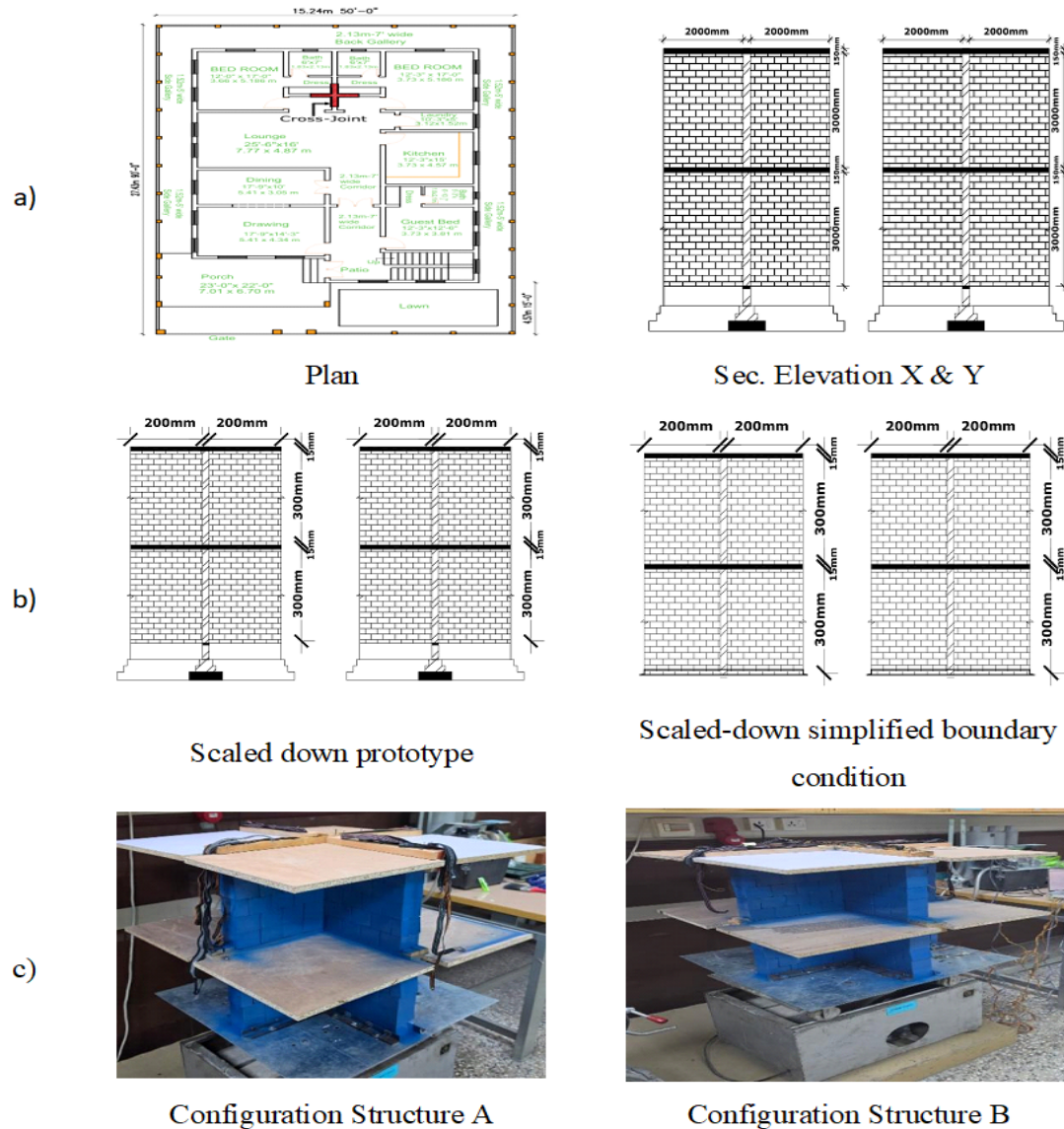


FIGURE 3.2: Consideration of Cross-joint; (a) plan of house with original Cross-joint consideration, (b) scaled-down and simplified boundary conditions, (c) Cross-joint with configuration structure A and B

comparable structural behavior in the y-direction.

3.3 Construction of Scaled Prototype Cross - Junction

The prototype of the cross junction of the mortar-free interlocking plastic block (IPB) wall system was designed using 170 plastic blocks across 10 layers, resulting in a total specimen height of 300 mm, with two distinct course configurations

(Structure A and Structure B) selected to establish different bonding patterns analogous to traditional masonry for controlling load paths and eliminating continuous vertical joint lines. This variation was implemented to evaluate how differing block arrangements at the four-way intersection influence out-of-plane response initiation.

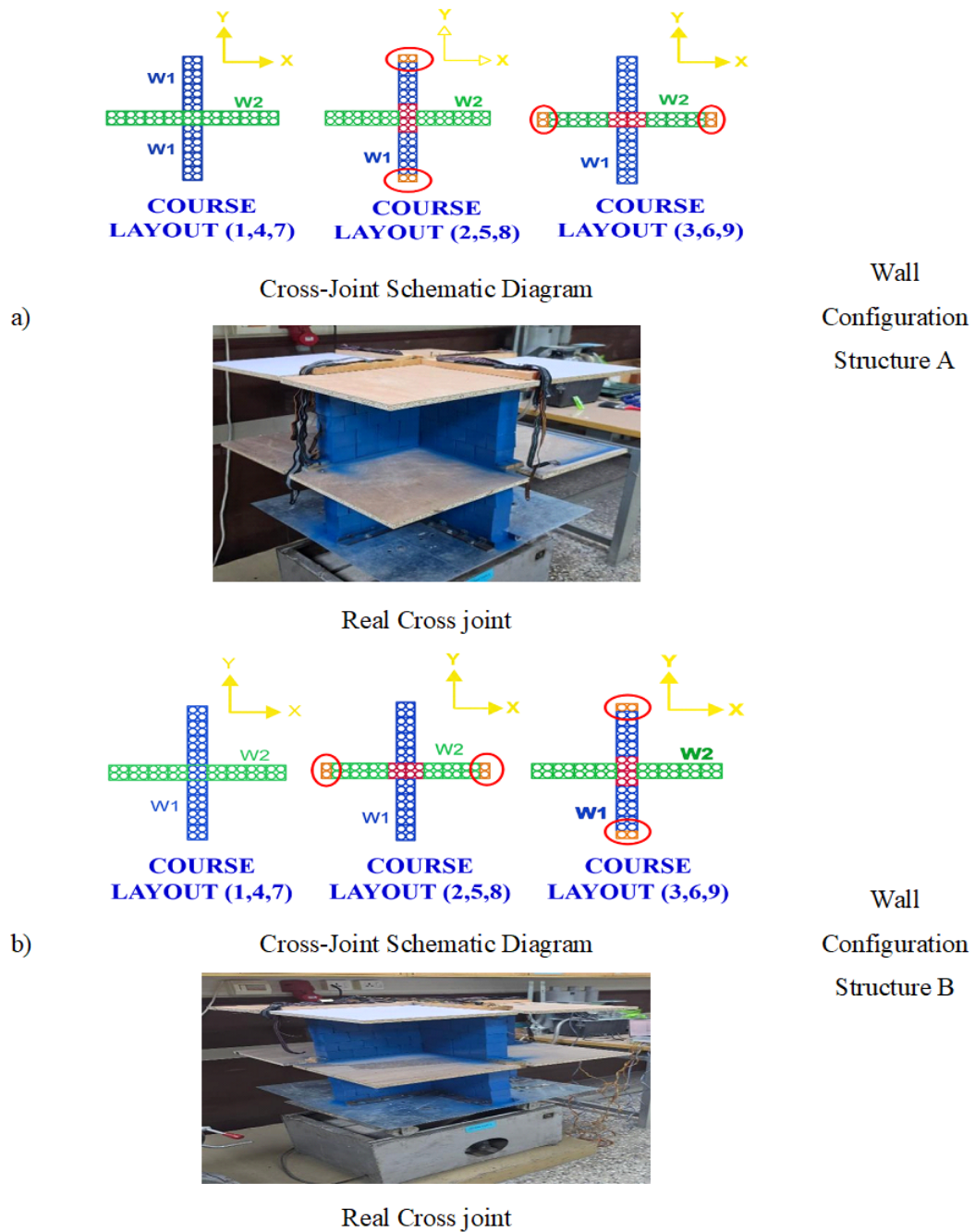


FIGURE 3.3: Cross-Joint construction details; a) wall configuration structure A and b) wall configuration structure B.

tion, joint continuity, and directional stiffness across orthogonal axes. In Structure A, the arrangement of the blocks facilitated the out-of-plane response of the X-axis

wall to initiate from the junction core, whereas in Structure B, the arrangement was configured such that the X-axis wall response initiated from the junction edges mirroring the orthogonal behavior where Structure A's Y-axis configuration aligned with Structure B's X-axis layout, and Structure A's X-axis configuration aligned with Structure B's Y-axis layout. To enhance the vertical stiffness of the structure, rubber bands were attached vertically from the base to the top of the structure through the central openings of the blocks. Five stiffeners, in the form of rubber bands, were incorporated into the structure: two in each of the orthogonal walls and one where the four walls intersected.

The specimen was rigidly fixed at the base of the shake table so that uniform excitation could be achieved without any unwanted base motion. No extra mass was applied at the top of the structure. The total self-weight of the assembled cross-junction structure was 11.8 kg. In order to further increase stability and avoid early collapse, five stiffeners made of rubber bands were placed strategically: one at the central junction point and two on each intersecting wall, simulating vertical reinforcement. For the dynamic testing, the cross-junction specimen was anchored to the shake table in the lateral direction by means of nut bolts and steel angle sections, thereby allowing the specimen to be excited in a realistic manner. The testing was performed primarily in the X-direction by means of unidirectional excitation, while the response in the Y-direction is considered to be similar due to symmetry in the geometry of the cross-section. The results obtained through the present investigation will prove to be useful in providing insight into the dynamic performance, stability, and seismic resilience of mortar-free interlocking plastic block systems used in double-storey residential constructions.

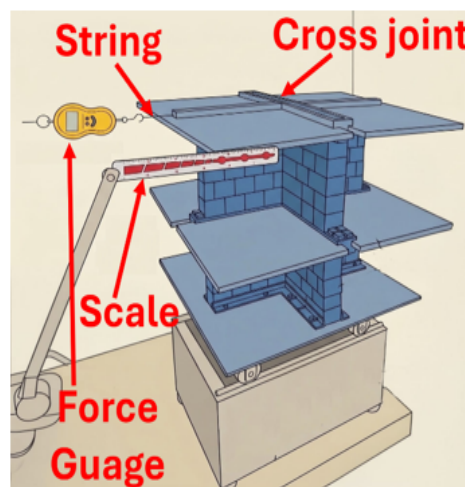
3.4 Test Setup

3.4.1 Static Stiffness Test Setup

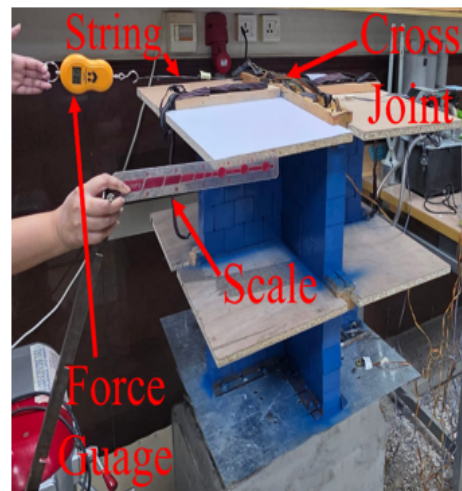
The static stiffness test was carried out to study the lateral strength and stiffness of the scaled Interlocking Plastic Block (IPB) cross-joint under static loading. Before testing, the specimen was firmly fixed to a strong steel base using steel

angle sections and bolts to prevent any movement during the test. The cross-joint specimen consisted of four connected wall sections, allowing its behavior to be studied under lateral loading similar to earthquake forces. A loading system was placed at the top of the wall to apply a horizontal force in the required direction. During the test, a calibrated spring balance was used to measure the applied load, while a measuring scale fixed near the top of the wall was used to record the horizontal displacement. The loading system was carefully aligned so that the force acted directly on the cross joint without causing any unwanted twisting or uneven loading.

Before the test started, all measuring instruments were checked and adjusted to ensure accurate readings. The specimen was also inspected to confirm that all interlocking blocks and rubber-band stiffeners were properly assembled before loading. During the test, the horizontal displacement and applied load were recorded at every loading stage. At the same time, the specimen was carefully observed to identify any movement between the interlocking blocks, opening of the joints, or deformation of the rubber-band stiffeners. These observations helped to understand the behavior of the cross-joint under increasing lateral load and to identify the beginning of any damage or instability.



Schematic Diagram of Static stiffness
Test Setup



Real Static stiffness Test Setup

FIGURE 3.4: Static stiffness instrumentation and testing: Schematic diagram and Real test setup

3.4.2 Snap Back Test Setup and Instrumentation

The snap-back test was carried out to study the free vibration behavior of the mortar-free Interlocking Plastic Block (IPB) cross-joint specimen. Before the test, the cross-joint was firmly fixed to the test platform to provide a stable support condition. A 600 mm long steel wire was attached to the top of the specimen to apply the required lateral displacement. An accelerometer was mounted at the top of the cross joint to record its vibration response. During the test, the specimen was pulled sideways to the required displacement and then the wire was released suddenly. This allowed the cross-joint to vibrate freely without any external force. Both Sequence A and Sequence B wall configurations were tested. Testing was carried out in both the X and Y directions for both Configuration Sequences A and B to fully evaluate the structural response of the cross-joint.

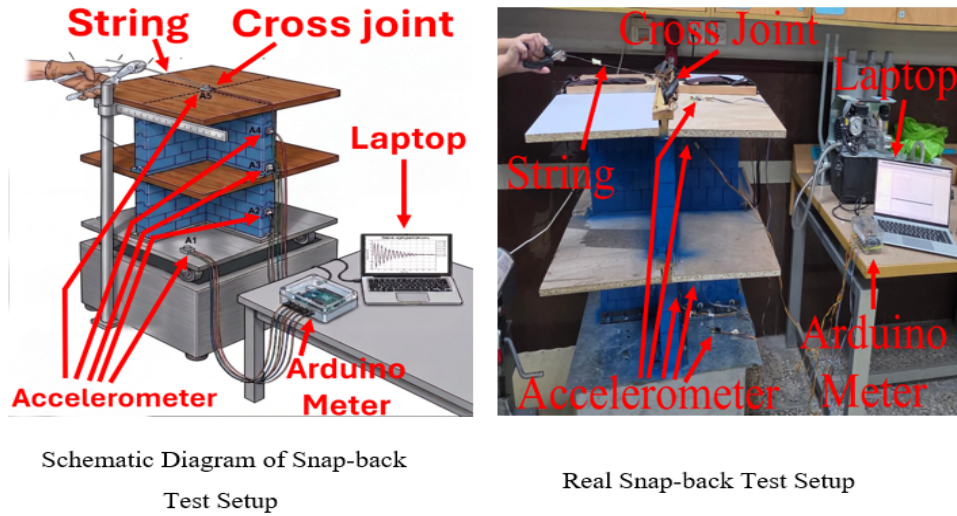


FIGURE 3.5: Snap-back instrumentation and testing: Schematic diagram and Real test setup.

The recorded acceleration-time histories were analyzed to determine the damping ratio (ζ) and the fundamental frequency (f_n) of the system using the logarithmic decrement method. The number of oscillation cycles and corresponding peak acceleration amplitudes were extracted from the measured data. The damping ratio was calculated using the following expression:

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

Where x_0 and x_1 represent the peak acceleration amplitudes of the first and last selected cycles, respectively, and N denotes the number of oscillation cycles considered. The fundamental frequency determined from the decay response is that of natural vibration of the cross-junction system. If it is close to that of the dominant frequency of seismic excitation, resonance may occur, which could lead to an increase in structural response and failure. Thus, it is crucial to understand the fundamental frequency with regard to assessing the seismic resilience of mortar-free IPB double-storey configurations.

3.4.3 Hammer Impact Test Setup

The hammer impact test was carried out to study the dynamic behavior of the mortar-free Interlocking Plastic Block (IPB) cross-joint specimen under impact loading. Before the test, the cross-joint specimen was firmly fixed to the testing platform using steel angle sections and bolts to provide a stable support condition. A pendulum-type hammer was used to apply a controlled impact to the specimen. The hammer was attached to a rigid arm of fixed length so that each impact was applied with the same amount of energy. To record the vibration response, five accelerometers were installed at different locations on the specimen. One accelerometer was fixed to the hammer to measure the input impact, while the remaining four accelerometers were placed at the free ends of the cross-joint walls, the center of the cross joint, and the base of the specimen. This arrangement allowed the vibration response to be measured at different locations of the cross-joint during the test.

All accelerometers were connected to the data acquisition system and checked to ensure accurate measurements. The hammer, supporting frame, and specimen were also inspected before each test to make sure that all parts were properly assembled and securely fixed. The sensors started recording immediately after each hammer strike and continued until the vibrations became very small. During the test, the specimen was visually monitored to observe any sliding between the interlocking blocks, separation at the cross-joint connection, or deformation of the rubber-band stiffeners. These observations were recorded along with the

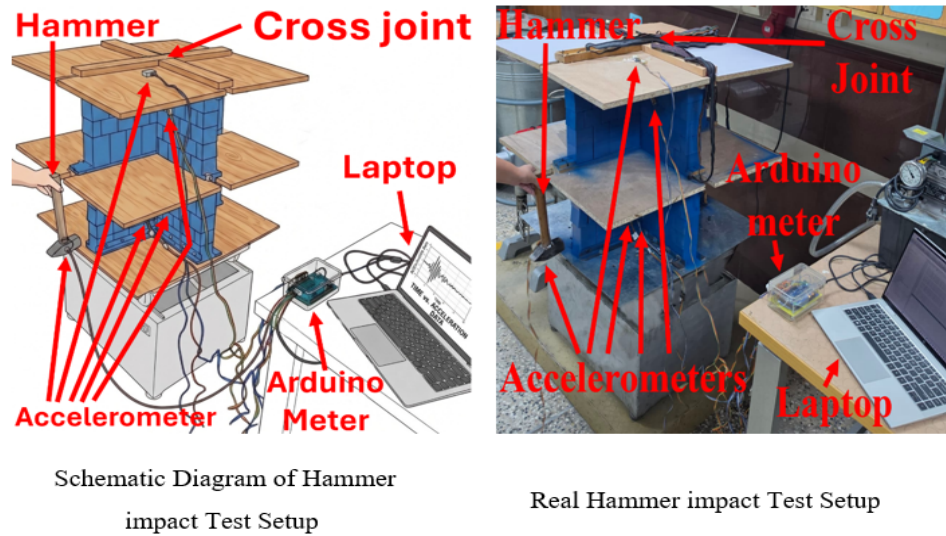


FIGURE 3.6: Hammer impact instrumentation and testing: Schematic diagram and Real test setup

acceleration data to provide a better understanding of the structural behavior under impact loading.

3.4.4 Shake Table Test Setup and Harmonic Test Instrumentation

For the shake table testing, the cross-junction made of mortar-free interlocking plastic block (IPB) walls was firmly fixed to the shake table platform by means of steel angle sections and nut-and-bolt connections to ensure rigid anchorage of the base. A total of five accelerometers were employed for comprehensive measurement of structural responses. One accelerometer was placed on the shake table to measure the input ground motion, while the other four accelerometers were fixed at different locations on the cross-joint specimen, including the free ends of the wall sections, the center of the cross joint, and the base of the specimen.

The dynamic performance of the cross-junction was assessed using recorded acceleration-time histories from the instrumentation system. The acceleration-time histories were further processed using SeismoSignal software, which produced corresponding velocity-time histories and displacement-time histories for further evaluation. The processed data helped evaluate amplification response, change in stiffness, and slip characteristics, thereby facilitating an evaluation of seismic resilience

under controlled harmonic excitation for the mortar-free IPB double-storey system.

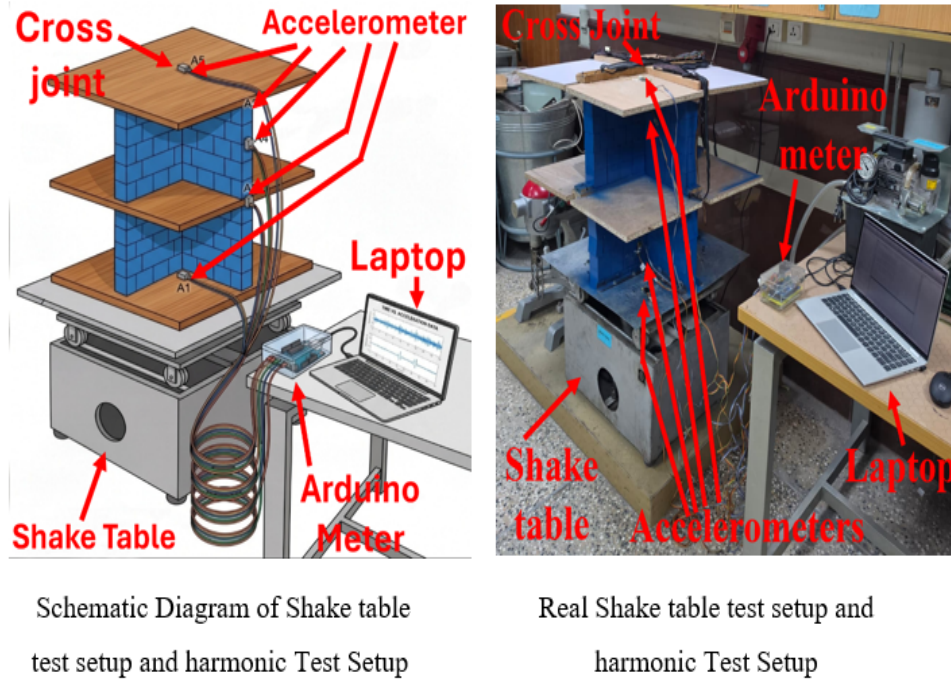


FIGURE 3.7: Shake table test setup and harmonic test instrumentation: Schematic diagram and Real test setup.

While real-world seismic events subject structural nodes to simultaneous multidirectional forces, the dynamic testing phase of this research was necessarily constrained by the use of a unidirectional (1-D) shake table. To overcome this methodological limitation and comprehensively investigate orthogonal load effects on the mortar-free interlocking plastic block (IPB) cross-junction, a systematic physical rotation protocol was implemented during the experimental setup. Both the Structure A and Structure B double-storey specimens were initially tested along their primary longitudinal axis, after which the entire base plate was manually rotated 90 degrees to repeat the dynamic loading sequence along the transverse axis. By independently evaluating the models in both orthogonal directions, this testing strategy successfully captured the distinct directional stiffness characteristics, localized load initiation paths, and energy dissipation mechanics of each block configuration, ensuring a rigorous assessment of the system's lateral performance despite the physical limitations of the testing apparatus.

3.5 Dynamic Loading

3.5.1 Dynamic Loading Parameters for Static Stiffness Test

The lateral load was applied gradually to determine the stiffness and load-carrying capacity of the cross-joint specimen. The load was increased step by step using a spring balance, and the test was paused after every 8.8 N increment to allow the specimen to stabilize before taking measurements. At each loading stage, the applied force and the corresponding horizontal displacement at the top of the wall were recorded. The loading continued until the specimen showed clear signs of failure, such as excessive sliding between the interlocking blocks, separation at the cross joint, loss of stability, or a significant reduction in its ability to resist lateral load.

TABLE 3.1: Applied loading magnitudes for the experimental specimen

Sr. No.	Specimen	Direction	Incremental Loading (N)
1	A	X	8.8
2	A	Y	8.8
3	B	X	8.8
4	B	Y	8.8

The recorded force and displacement values were then used to plot the lateral load-displacement (capacity) curve. The initial stiffness of the cross-joint was calculated from the slope of the straight-line portion of this curve before any permanent deformation occurred. This stiffness value shows how rigid the mortar-free cross-joint system is and how effectively it can resist lateral movement during the early stages of earthquake loading. The results obtained from this test were also used to compare the behavior of the different wall configurations and to evaluate the effectiveness of the interlocking mechanism and rubber-band stiffeners in improving the lateral stability of the cross-joint. The information obtained from the static stiffness test also served as a reference for interpreting the results of the dynamic tests performed later in the experimental program. Table 3.1 details the displacement magnitudes applied during the test.

3.5.2 Dynamic Loading Parameters for Snap Back Test

The snap-back test for the structure involved the lateral movement of the cross-junction in the mortar-free interlocking plastic block (IPB) wall system, which was displaced laterally by 25 mm and 50 mm at the top using a connected wire mechanism. Subsequently, the wire was released to initiate free vibration of the structure. The dynamic response of the structure was recorded in the form of acceleration-time history. An accelerometer was placed at the top of the structure to measure the response. The structure was tested under both Sequence A and Sequence B, with displacements applied in the X and Y directions.

Using the logarithmic decrement method, the damping ratio and fundamental frequency of the cross-junction in the mortar-free IPB wall system were determined based on the recorded acceleration-time history. Subsequently, the free vibration characteristics of the structure were determined. Snapback loading magnitude is given in Table 3.2.

TABLE 3.2: Snap-back loading magnitudes for the experimental specimen

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

3.5.3 Dynamic Loading Parameters - Hammer Impact Test

The hammer impact test will be carried out to assess the basic dynamic characteristics of the mortar-free interlocking plastic block (IPB) cross junction system before performing controlled excitation tests on the structure. The hammer was raised to a fixed angle of 90 and then released to strike the specimen under the action of gravity. This method ensured that each impact was applied with the same force during every test. The hammer had a mass of 0.81 kg and was attached to a 275 mm long rigid arm. The accelerometers were placed at different locations, including the free ends of the wall sections and the center of the cross joint,

to study how the impact location affected the vibration response. Each impact was repeated under the same loading conditions to maintain consistency and improve the reliability of the recorded data. During every impact, all accelerometers recorded the acceleration time-history of the specimen.

TABLE 3.3: Hammer Impact loading magnitudes

Sr. No.	Structure
1	A
2	B

3.5.4 Dynamic Loading Parameters for Harmonic Test

In harmonic testing, sinusoidal excitation signals with constant amplitudes were applied to the cross-junction specimen. The input signals had frequencies of 1.2 Hz, 1.4 Hz, and 1.6 Hz with a constant displacement amplitude of 25 mm applied in the X-direction. The input signal with a frequency of 1.4 Hz, as derived from the snap-back test, was taken as the fundamental frequency of the system. Therefore, it was taken as critical for determining any possibility of resonance. Additional input signals with 0.2 Hz lower and higher than 1.4 Hz were applied to test the structural response within a representative range of frequencies and observe any amplification effects due to resonance. Acceleration-time histories were measured at points on top of the specimen and at the base of the shake table. The input excitation and response acceleration histories were processed to derive corresponding velocity-time and displacement-time histories.

Two plastic block wall configurations were taken for this test. To keep the vertical cross joints from stacking directly on top of each other, we are throwing in half-blocks to stagger the seams, working just like a traditional stretcher bond in regular bricklaying. During the first round of testing (Structure A), Wall 1 takes force from the side an out-of-plane load in the X-direction while Wall 2 handles the in-plane pressure right along its length. The second round (Structure B) uses the

exact same loading setup, but the physical layout of Wall 1 was change starting right at the cross joint edge like it did in the first test, Wall 2 takes that edge position this time around.

TABLE 3.4: Harmonic loading

Sr. No.	Wall Configuration	Harmonic Loading Direction	Amplitude (mm)	Frequency (Hz)
1	Structure A	X	25	1.2, 1.4, 1.6
2	Structure B	X	25	1.2, 1.4, 1.6

3.6 Evaluation of Dynamic Response Parameters

3.6.1 Parameters to be Evaluated Under Static Stiffness Test

The static stiffness test will be carried out in order to assess the lateral load resisting capacity and deformation potential of the mortar-free interlocking plastic block cross-junction arrangement. During the test, the horizontal load on the prototype will be increased gradually, while the base is fixed. At the same time, the displacement response of the structure will be recorded in order to establish the load-displacement relation.

The base shear developed in the structure during the static stiffness test can be represented:

$$V = m.a \quad (3.2)$$

From the load-displacement curve, it is possible to identify essential structural characteristics, such as initial stiffness, lateral loading capacity, and deformation characteristics of the cross-junction system, as well as possible failure modes of the mortar-free system. Thus, it is possible to obtain information regarding the

structural capacity of the mortar-free system under increasing lateral loading, making it possible to assess its application for seismic residential construction.

3.6.2 Dynamic Response Parameters Under Snap-Back Loading

For the cross-junction of two interlocking plastic block (IPB) walls without mortar, which is formed by two intersecting IPB walls, the response data will be recorded in its raw format by acceleration-time histories during the snap-back test. Due to environmental noise and other possible disturbances that may occur during the experimental data collection, filtering will be applied to ensure that the data is of good quality. Initially, MATLAB will be employed to reduce excessive noise, followed by the application of a bandwidth filter using SeismoSignal software to remove unwanted frequency components from the data and condition the acceleration-time histories.

Based on the processed signals, the fundamental natural frequency (f_n) and damping ratio (ζ) of the cross-junction system would be determined through the application of standard analytical procedures. These values are significant in understanding the dynamic behavior of the structure since the damping ratio is a measure of the dissipation capacity of the structure, while the fundamental natural frequency is a measure of the susceptibility of the structure to resonance during seismic loading. The application of the filtering techniques would ensure the reliability of the values extracted from the signals since the values would represent the real behavior of the structure under free vibration conditions. In addition, the values of f_n and ζ would be used in the subsequent modeling of the proposed mortar-free IPB wall system.

3.6.3 Evaluation of Structural Response Under Hammer Impact Test

The hammer impact test is planned for determining the fundamental dynamic characteristics of the mortar-free interlocking plastic block (IPB) cross-junction

prototype. For this purpose, a short-duration impulse loading is planned to be applied to the prototype using an impact hammer. This would result in free vibration of the system, and acceleration-time history of the prototype would be recorded using accelerometers attached to it. These acceleration-time history records would be analyzed using MATLAB and SeismoSignal software for determining the frequency spectrum and vibration response of the prototype.

The major peak of the frequency spectrum would represent the fundamental natural frequency of the system. Natural frequency is related to stiffness and mass of the system and can be defined as:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (3.3)$$

Through the hammer impact test, modal parameters of the cross-junction system, including the natural frequency, can be determined. These parameters are essential in understanding the dynamic response of the mortar-free structure. These parameters can also be used to validate the results obtained from the subsequent snap-back and harmonic excitation tests.

3.6.4 Evaluation of Structural Response Under Harmonic Loading

Dynamic excitation will be applied to the cross-junction formed by two intersecting mortar-free interlocking plastic block walls at 0.8 Hz, 1.1 Hz, and 1.4 Hz, and the response will be measured in the form of acceleration-time histories. The dominant frequency identified during the snap-back test will be considered for the evaluation of resonance, while the additional two will be used to assess the variation in response about the critical value. SeismoSignal software will be employed to process the measured acceleration response by numerically integrating the response to obtain the corresponding velocity and displacement response in the form of time histories.

In addition, the acceleration-time data will be employed to create base shear versus displacement curves to examine the dynamic stiffness and response amplification.

Base shear will be calculated using the following equation:

$$Q = M \times \ddot{u}_t \quad (3.4)$$

Where M represents the effective mass of the specimen and $\ddot{u}_t$ with represents the measured top acceleration of the wall system. The resulting base shear-displacement curves will provide useful information about the stiffness properties, amplification of the response around resonance, and energy dissipation capacity of the cross-junction. These parameters will be used as a reference for comparison in assessing the performance of the structural system and identifying the critical values of the response in the mortar-free IPB double-storey system.

3.7 Development and Validation of Empirical Relationships

To better understand the dynamic behavior of the mortar-free Interlocking Plastic Block (IPB) cross-joint, empirical equations will be developed using the experimental results obtained from the static and dynamic tests. These equations will be formulated by considering the main parameters that influence the structural response, including the geometry of the cross-joint, block dimensions, interlocking arrangement, structural height, effective mass, and excitation frequency. The developed relationships will be used to predict important dynamic properties such as the fundamental frequency, damping ratio, lateral stiffness, displacement response, and vibration amplification of the cross-joint during snap-back, hammer impact, and harmonic loading tests. The objective is to establish simple mathematical expressions that can estimate the seismic performance of the mortar-free IPB cross-joint without requiring repeated experimental testing.

The proposed empirical equations will be validated by comparing the predicted values with the corresponding experimental results obtained during the laboratory investigation. The percentage difference between the calculated and measured values will be determined to evaluate the accuracy of each relationship. If any

noticeable variation is observed, a calibration factor ($K = 1.55$) will be introduced to improve the agreement between the predicted and experimental data. After validation, the empirical equations are expected to provide a reliable method for estimating the dynamic behavior of mortar-free IPB cross-joint systems under different loading conditions. These relationships may also serve as useful design tools for future studies and contribute to the development of safer and more earthquake-resistant two-storey mortar-free interlocking plastic block structures.

3.8 Summary

The experimental methodology and dynamic testing procedures used for the cross-junction formed by the intersection of two mortar-free interlocking plastic block (IPB) walls are explained in this section. The research focuses on the structural behavior of the scaled model under snap-back and harmonic loading conditions. The behavior of the cross-junction is examined and then compared with the predictions made using the empirical relationship developed. In addition, a detailed description of the experimental setup and instrumentation has been included in order to understand the procedures adopted during the experiment. The parameters of interest in this analysis are acceleration, velocity, displacement, damping characteristics, stiffness variation, and failure mechanisms. These parameters are identified and discussed in order to understand the structural behavior. This section of the dissertation has established a comprehensive framework for the experiment, ensuring the reliability of the results and providing a basis for the analysis of the performance of the mortar-free IPB double-storey system.

Chapter 4

Experimental Evaluation

4.1 Background

A comprehensive experimental investigation was carried out on the double-storey mortar-free masonry cross-junction prototype to characterize its structural response under static and dynamic loading conditions. The experimental programme comprised Snap-Back, Hammer Impact, Harmonic Loading, and Static Stiffness tests to evaluate the behavior of the cross-junction under free vibration, forced vibration, and monotonic lateral loading. The recorded acceleration responses were processed using MATLAB and SeismoSignal software to determine the fundamental dynamic properties of the prototype, including natural frequency, damping ratio, displacement response, vibration characteristics, and energy dissipation capacity. These experimentally determined parameters provide a quantitative characterization of the structural behavior of the mortar-free interlocking masonry system under the applied laboratory loading conditions.

The experimental results are organized according to the respective testing methods to provide a systematic evaluation of the lateral load-displacement response, lateral stiffness, natural frequency, damping characteristics, acceleration response, displacement response, base shear behavior, and energy dissipation capacity of the proposed cross-junction configuration. A comparative assessment of Construction Structure A and Construction Structure B is performed using the experimentally

measured parameters to examine the influence of block arrangement on the static and dynamic response of the mortar-free masonry system. The observed differences in stiffness, natural frequency, damping ratio, displacement response, load-carrying capacity, and hysteretic energy dissipation provide the basis for interpreting the structural behavior of the prototype under the applied loading conditions.

4.2 Lateral Load-Displacement Behavior - Static Stiffness

The lateral load-displacement behavior of the mortar-free Interlocking Plastic Block (IPB) cross-junction was evaluated through a static stiffness test. The objective was to determine the lateral load-carrying capacity, stiffness, and deformation characteristics under gradually increasing static loads. Both wall configurations, Structure A and Structure B, were subjected to lateral load increments of 8.8 N. During each loading stage, the applied force and the corresponding horizontal displacement at the top of the specimen were recorded until structural failure or a significant drop in load-carrying capacity occurred.

The results demonstrate that both wall configurations sustained a maximum lateral load of 96 N before exhibiting significant structural damage. However, the ultimate displacement response varied based on the block orientation relative to the loading axis. For Structure A, the maximum displacement at the peak load was 59 mm in the X-direction and 52 mm in the Y-direction. Because Structure B represents a 90-degree orthogonal shift in the block layout, its displacement behavior reflects this geometric rotation, reaching a maximum displacement of 61.2 mm in the X-direction and 53.6 mm in the Y-direction.

The differences in peak displacement between the loading directions are directly linked to the structural arrangement of the cross-junction. Although the joint provides multi-directional support, the frictional resistance and interlocking engagement vary depending on the axis of loading. The directions that exhibited slightly larger lateral displacements correspond to orientations where the specific block layout offered lower resistance to movement. Conversely, the stiffer loading

axes benefited from optimal block engagement and maximized friction along the contact surfaces, effectively restricting lateral deformation even as the structures approached their ultimate load-carrying capacity of 96 N.

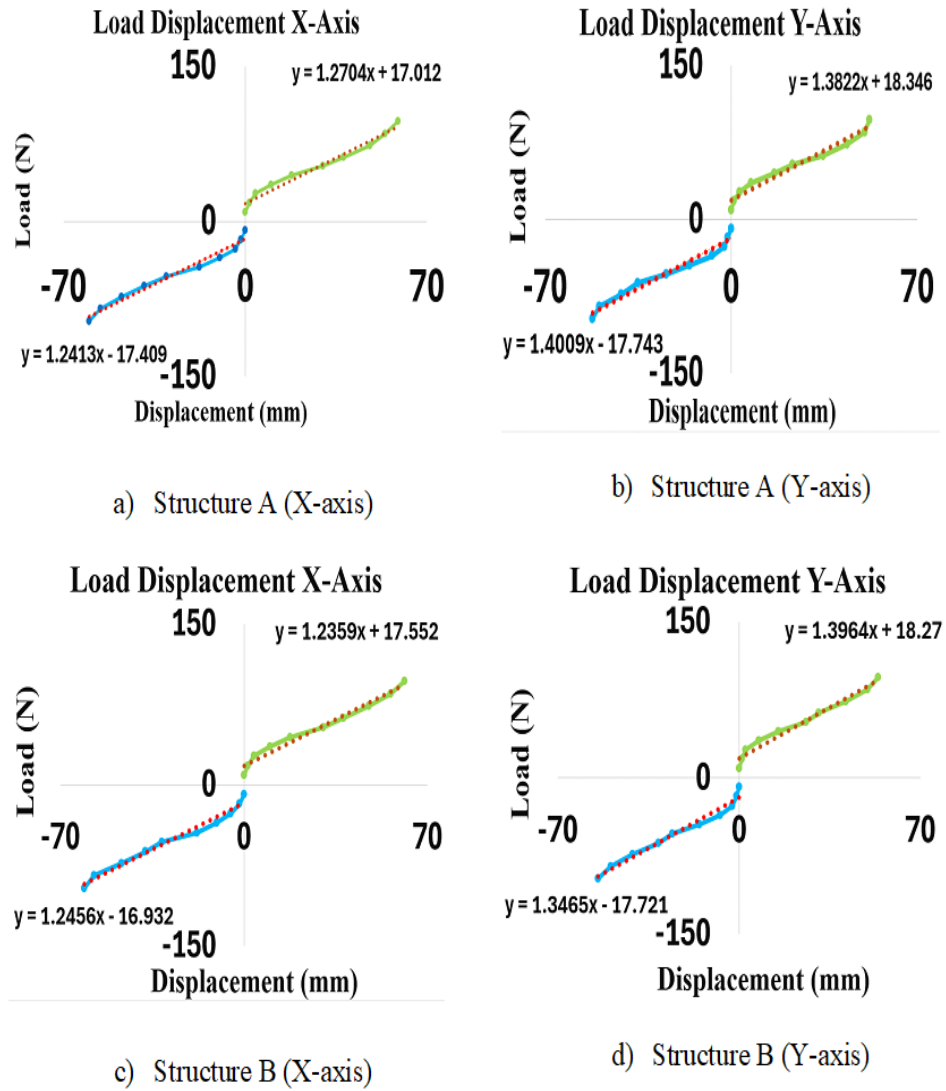


FIGURE 4.1: Static Stiffness load-displacement curve a) Structure A (X-axis), b) Structure A (Y-axis), c) Structure B (X-axis) and d) Structure B (Y-axis)

The initial stiffness of the structure was determined from the elastic portion of the Static Stiffness curve. The experimental arrangement used for the static stiffness test is shown in Fig. 4.1. The test specimen consisted of a scaled two-story Interlocking Plastic Block (IPB) cross-joint assembled without mortar. During the test, a horizontal force was applied at the top of the specimen using a cord connected to a calibrated spring balance. The lateral load was increased gradually in 8.8 N increments, and the corresponding horizontal displacement at the top of

the cross-joint was measured and recorded after each loading step. This procedure continued until the specimen reached its maximum load-carrying capacity or showed clear signs of structural failure.

The test results showed that the lateral stiffness of the cross-joint varied with the direction of loading. Although both loading directions were able to resist the applied load, the X-direction produced larger horizontal displacement than the Y-direction under the same loading conditions, indicating relatively lower stiffness in the X-direction. This difference can be attributed to the distribution of load through the interlocking blocks and the friction developed between the contact surfaces of the cross-joint. The recorded load and displacement data were further used to develop the load-displacement curves and evaluate the lateral behavior of the mortar-free IPB cross-joint.

TABLE 4.1: Static Stiffness Test Analysis

Sr. No.	Structure	Direction	Lateral stiffness “K” (N/mm)	Average “K” (N/mm)
1	A	X	2.17 ± 0.015	2.185
2	A	X	2.20 ± 0.015	
3	A	Y	1.92 ± 0.01	1.91
4	A	Y	1.90 ± 0.01	
5	B	X	1.90 ± 0.01	1.89
6	B	X	1.88 ± 0.01	
7	B	Y	2.22 ± 0.005	2.215
8	B	Y	2.21 ± 0.005	

The initial lateral stiffness (K) of the mortar-free Interlocking Plastic Block (IPB) cross-junction was determined from the linear elastic portion of the load-displacement curves to measure the maximum horizontal stiffness of the system prior to any potential collapse. The results obtained from the static stiffness test are presented in Table 4.1. In Structure A, the average lateral stiffness was 2.185 N/mm in the X-direction and 1.91 N/mm in the Y-direction. Because these are

cross-junctions, Structure B represents an orthogonal shift in the block arrangement. Consequently, Structure B exhibited an inverted response, with an average stiffness of 1.89 N/mm in the X-direction and 2.215 N/mm in the Y-direction.

These results highlight the inherent geometric symmetry of the cross-junction configurations. The structural layout that resists loading in the X-direction for Structure A is mechanically equivalent to the layout resisting loading in the Y-direction for Structure B. As a result, the stiffness of Structure A in the X-direction (2.185 N/mm) closely matches Structure B in the Y-direction (2.215 N/mm). Similarly, the stiffness of Structure A in the Y-direction (1.91 N/mm) mirrors Structure B in the X-direction (1.89 N/mm). This difference in directional stiffness is dictated by the specific orientation of the interlocking blocks and the resulting friction along the contact surfaces, meaning the primary resisting axis simply rotates by 90 degrees between the two wall configurations.

Despite these directional differences, the stiffness values obtained during the loading cycles were remarkably consistent. The recorded variations were minimal, with standard deviations ranging only from ± 0.005 N/mm to ± 0.015 N/mm, indicating excellent repeatability in the experimental results. This consistency confirms that the geometric interlocking mechanism remained completely stable during load application. Overall, the static stiffness test demonstrates that the IPB cross-junction provides reliable, predictable maximum lateral resistance and highly satisfactory structural performance under horizontal loading.

4.3 Natural Frequency and Damping Characteristics

The dynamic characteristics of the cross-junction prototype were evaluated using the snap-back test to determine its free vibration behavior. To evaluate the free vibration behavior and dynamic properties of the two-story mortar-free Interlocking Plastic Block (IPB) cross-joint, a snap-back test was performed under controlled laboratory conditions. During the test, a steel wire attached to the top of the

specimen was used to pull the cross-joint sideways to predetermined lateral displacements of 25 mm and 50 mm. After reaching the required displacement, the wire was released suddenly, allowing the specimen to vibrate freely without any external force. The accelerometer installed at the top of the cross-joint continuously recorded the acceleration response during the free vibration. The recorded acceleration-time history was then used to evaluate the dynamic behavior of the specimen and to study the reduction of vibration with time.

The acceleration-time history (acceleration vs. time) clearly showed that the vibration amplitude gradually decreased after the specimen was released. For both Structure A and Structure B, the response followed a smooth decay pattern, indicating stable vibration behavior throughout the test. In the 25 mm displacement test, the maximum acceleration reached approximately 0.05 g before gradually reducing with each vibration cycle until the motion almost disappeared. The specimen completed approximately five vibration cycles within about 4.5 seconds, which corresponds to the measured fundamental frequency of approximately 1.4 Hz. No sudden loss of vibration or irregular response was observed, suggesting that the cross-joint remained structurally stable during free vibration.

The dynamic characteristics and free-vibration response of the two-story mortar-free Interlocking Plastic Block (IPB) cross-joint were investigated using the snap-back test. During the experiment, the top of the cross-joint specimen was pulled sideways to predetermined lateral displacements of 25 mm and 50 mm using a steel wire. After the required displacement was reached, the wire was released suddenly, allowing the specimen to vibrate freely under its own restoring force. The acceleration response recorded during the test was used to generate acceleration-time history curves, which describe the vibration behavior of the cross-joint after release.

The recorded acceleration data were analyzed using the logarithmic decrement method to determine the fundamental frequency (f_n) and damping ratio (ζ) of the cross-joint system. The fundamental frequency represents the natural vibration frequency of the structure and is an important parameter for evaluating its

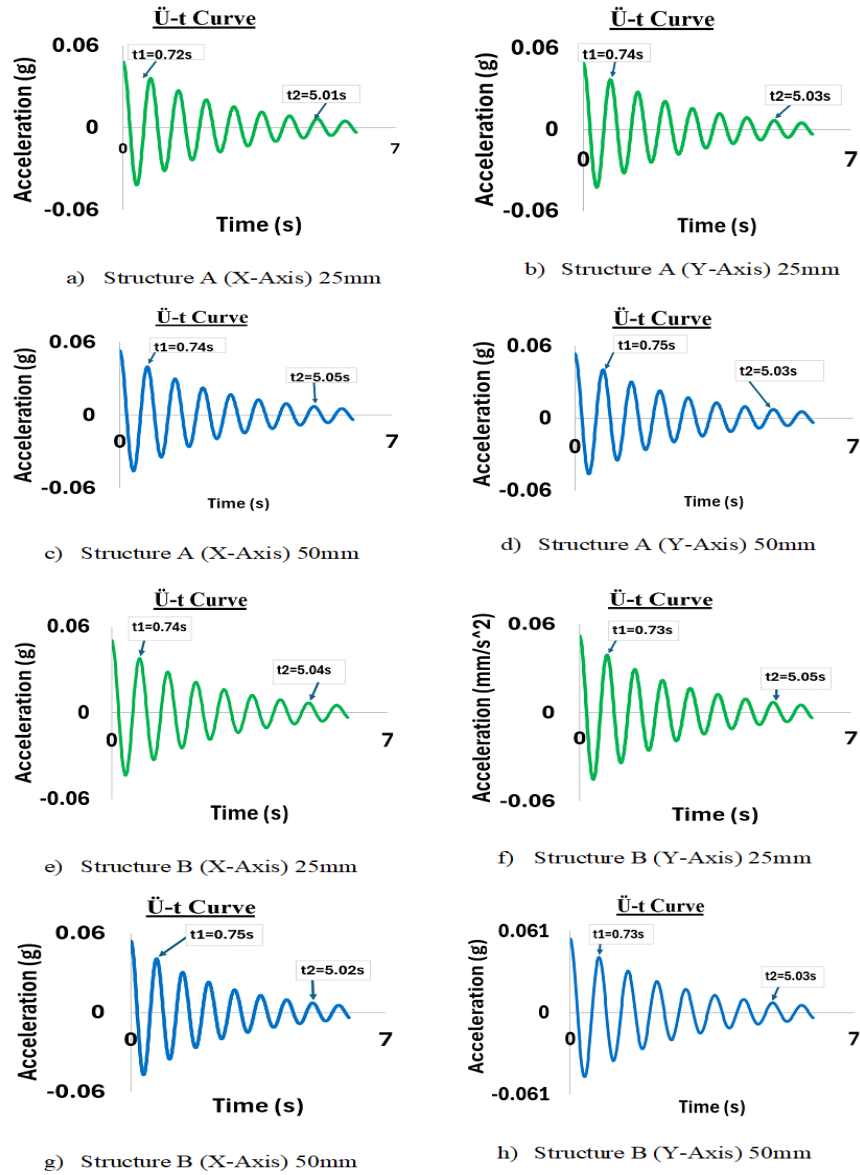


FIGURE 4.2: $\ddot{u}$ - t from Snap-back test; (a) Structure A-X (25 mm) (b) Structure A-Y (25 mm) (c) Structure A-X (50 mm) (d) Structure A-Y (50 mm) (e) Structure B-X (25 mm) (f) Structure B-Y (25 mm) (g) Structure B-X (50 mm) (h) Structure B-Y (50 mm)

seismic performance. If the natural frequency of a structure is close to the frequency of earthquake ground motion, resonance may occur, resulting in larger structural vibrations and increased damage. Therefore, determining the fundamental frequency and damping ratio is essential for assessing the dynamic behavior and earthquake resistance of the mortar-free IPB cross-joint. The results obtained from the snap-back test are presented in Table 4.2.

The results obtained from the snap-back test are presented in Table 4.2. The

TABLE 4.2: Modal damping ratio obtained from snap-back testing

Wall Configuration	Direction	Amplitude (mm)	Freq. (Hz)	Damping (%)
Structure A	X	25	1.40 ± 0.01	4.4 ± 0.18
	Y	25	1.40 ± 0.01	4.6 ± 0.21
Structure A	X	50	1.39 ± 0.02	4.8 ± 0.15
	Y	50	1.40 ± 0.01	4.6 ± 0.24
Structure B	X	25	1.38 ± 0.03	5.0 ± 0.19
	Y	25	1.40 ± 0.01	4.6 ± 0.12
Structure B	X	50	1.42 ± 0.02	4.5 ± 0.22
	Y	50	1.37 ± 0.04	5.0 ± 0.17

recorded data demonstrate that the fundamental frequency of the mortar-free Interlocking Plastic Block (IPB) cross-junction remained relatively constant across different testing conditions. For both Structure A and Structure B, the measured frequencies ranged from 1.37 ± 0.04 Hz to 1.42 ± 0.02 Hz, indicating that changes in wall configuration, loading direction, and displacement amplitude had minimal effect on the natural vibration frequency of the specimens. For example, in Structure A, the frequency was 1.40 ± 0.01 Hz in both the X- and Y-directions at a displacement amplitude of 25 mm, while at 50 mm, the recorded frequencies were 1.39 ± 0.02 Hz and 1.40 ± 0.01 Hz, respectively. Similar results were observed for Structure B, confirming the consistent dynamic response of the cross-junction layouts.

The damping ratios obtained from the free-vibration response varied between 4.4% and 5.0% across all test cases. The lowest damping ratio of $4.4 \pm 0.18\%$ was recorded for Structure A under a 25 mm displacement in the X-direction. Conversely, the highest base value of 5.0% was observed twice in Structure B: first under a 25 mm displacement in the X-direction ($5.0 \pm 0.19\%$) and again under a 50 mm displacement in the Y-direction ($5.0 \pm 0.17\%$). Although slight variations occurred under different loading conditions, the overall damping performance remained stable throughout the testing phase. These results indicate that the mortar-free cross-junction effectively dissipates vibration energy through friction

between the interlocking blocks and the action of the rubber-band stiffeners.

The small variation in both frequency and damping ratio shows that the dynamic properties of the cross-joint remained stable during free vibration. The specimen maintained nearly the same vibration characteristics regardless of wall configuration or displacement amplitude, indicating consistent structural performance. The measured damping ratios suggest that the interlocking mechanism and rubber-band stiffeners effectively reduced vibration by gradually dissipating energy during each oscillation cycle. This behavior demonstrates that the mortar-free IPB cross-joint has good vibration control characteristics and is capable of maintaining stable dynamic performance under repeated lateral excitation.

The Fast Fourier Transform (FFT) analysis was carried out to examine the frequency response of the mortar-free Interlocking Plastic Block (IPB) cross-joint using the acceleration data obtained from the snap-back test. The acceleration-time histories for Structure A and Structure B at displacement amplitudes of 25 mm and 50 mm were converted into the frequency domain to identify the dominant vibration frequency of the specimen. The resulting Fourier amplitude spectra for all test cases are presented in Figure 4.3.

The FFT results show a clear and distinct peak at approximately 1.40 Hz for all four testing conditions. This dominant peak remained almost unchanged for both wall configurations and for both displacement amplitudes, indicating that the natural frequency of the cross-joint was nearly constant throughout the experimental program. The similarity of the frequency spectra suggests that increasing the initial displacement from 25 mm to 50 mm did not significantly affect the dynamic characteristics of the specimen. Likewise, changing the wall configuration from Structure A to Structure B had only a minor influence on the measured frequency response.

The presence of a single dominant frequency peak indicates that the mortar-free IPB cross-joint vibrated mainly in its fundamental mode during the snap-back test. No additional large peaks were observed in the frequency spectrum, suggesting that the specimen maintained stable vibration behavior without significant

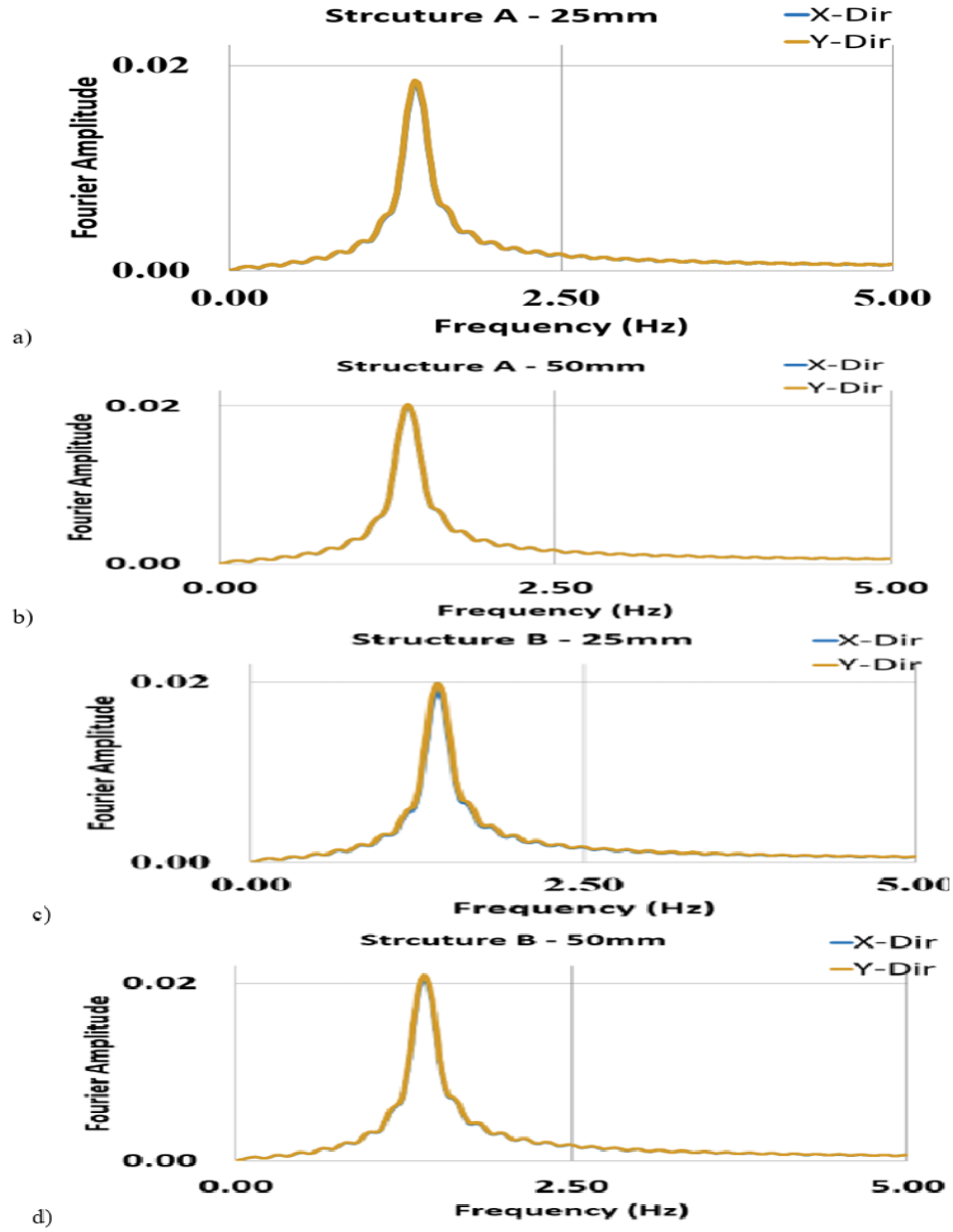


FIGURE 4.3: Fourier amplitude from snap back test: a) Wall structure A with 25 mm, b) Wall structure A with 50 mm, c) wall structure B with 25 mm and d) wall structure B with 50 mm.

higher-mode effects. The consistent frequency response also indicates that the interlocking block system remained structurally stable during free vibration. Energy generated during the snap-back excitation was gradually dissipated through friction between the interlocking blocks and the action of the rubber-band stiffeners, resulting in a smooth and stable vibration response. Overall, the FFT analysis confirms the results obtained from the snap-back test and verifies that the mortar-free IPB cross-joint possesses stable dynamic characteristics under different wall

configurations and displacement amplitudes.

4.4 Dynamic Characteristics from Hammer Impact Testing

The dynamic characteristics of the mortar-free Interlocking Plastic Block (IPB) cross-junctions, a hammer impact test was conducted to determine their modal properties under sudden loading. Both Structure A and Structure B were tested under identical conditions to guarantee a reliable comparison of their dynamic responses. To generate a consistent impact, the setup used a pendulum-style hammer consisting of a 0.89 kg mass attached to a 275 mm rigid arm. This hammer was raised to a 90-degree angle and allowed to swing freely under gravity. The recorded force-time history indicated a peak impact force of 5.12 ± 0.01 N for Structure A and 5.11 ± 0.01 N for Structure B, which served as the baseline input excitation for both structures. During the test, Structure A was rigidly fixed to the platform and evaluated first. The resulting acceleration-time histories were recorded at the wall base, first-floor level, and roof top to track how the acceleration response traveled through the structure. The exact same procedure was then repeated for Structure B. By maintaining identical impact and mounting conditions, any differences in the dynamic response could be directly attributed to the structural layout rather than variations in the testing method.

The corresponding force-time and acceleration-time histories for both structures are shown in Figure 4.4, and the dominant peaks in the frequency spectra were used to identify and compare their natural frequencies.

The acceleration-time histories indicate that the cross-joint responded immediately after the hammer strike and then gradually returned to its original position as the vibration amplitude decreased with time. Similar vibration patterns were observed at the base, first-floor, and roof top, showing that the impact energy was transferred through the entire specimen. The oscillations gradually became smaller because energy was dissipated through friction between the interlocking plastic blocks and the rubber-band stiffeners. No sudden increase in vibration,

Impact Testing

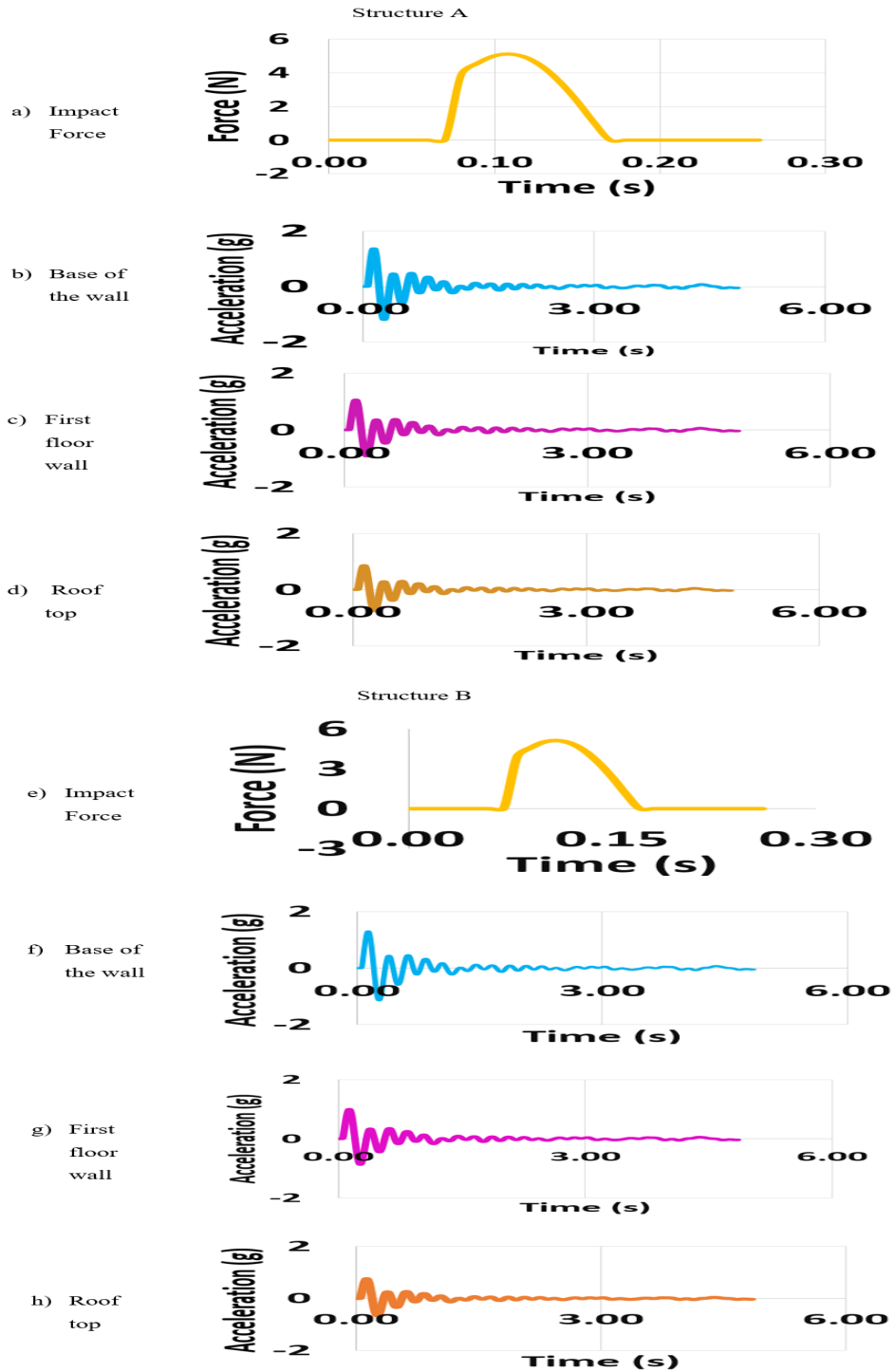
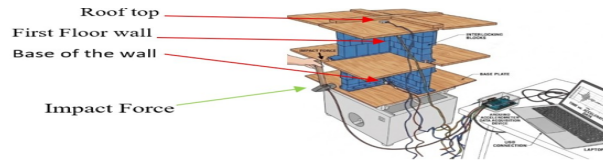


FIGURE 4.4: Impact Testing Graphs for Structure A and Structure B: a) Force-time, b) Acceleration-time history at the bottom of the wall, c) Acceleration-time history at the first floor of the wall, and d) Acceleration-time history at the roof top

block separation, or unstable behavior was observed during the test. When compared with Structure A, Structure B showed a similar overall vibration response, suggesting that changing the wall arrangement had only a small effect on the dynamic behavior of the mortar-free IPB cross-joint under impact loading. These results indicate that both wall configurations maintained good structural stability and were able to dissipate impact energy effectively.

TABLE 4.3: Natural frequencies obtained from hammer impact testing

Sr. No.	Description	Structure	Force (N)	Acceleration (g)	Frequency (Hz)	Damping (%)
1	Wall Bottom	A	5.12 ± 0.01	1.29 ± 0.03	5.43	7.73
2	First Floor	A	5.12 ± 0.01	0.994 ± 0.02	4.40	8.59
3	Roof Top	A	5.12 ± 0.01	0.857 ± 0.02	4.23	8.05
4	Wall Bottom	B	5.11 ± 0.01	1.3 ± 0.03	5.38	7.02
5	First Floor	B	5.11 ± 0.01	0.995 ± 0.02	4.30	8.80
6	Roof Top	B	5.11 ± 0.01	0.763 ± 0.02	4.17	7.44

The experimentally determined dynamic properties obtained from the hammer impact test are summarized in Table 4.3. For Structure A, the measured natural frequencies were 5.43 Hz, 4.40 Hz, and 4.23 Hz at the wall bottom, first floor, and roof top, respectively, with corresponding damping ratios of 7.73%, 8.59%, and 8.05%. Similarly, Structure B exhibited natural frequencies of 5.38 Hz, 4.30 Hz, and 4.17 Hz, with corresponding damping ratios of 7.02%, 8.80%, and 7.44% for the wall bottom, first floor, and roof top locations. The applied impact forces were recorded at 5.12 ± 0.01 N for Structure A and 5.11 ± 0.01 N for Structure B, while the resulting acceleration amplitudes varied by measurement location and included their respective standard deviations, as detailed in the table. Furthermore, it took 0.04 seconds for the acceleration response to travel from the wall bottom to the roof top. These experimentally obtained results characterize the dynamic response of the cross-junction prototypes under impulse loading.

4.5 Dynamic Response of the Cross Joint under Harmonic Loading

The displacement-time response of the mortar-free Interlocking Plastic Block (IPB) cross-junction was evaluated to study the structure's lateral movement during harmonic shake table testing. To obtain these displacement histories, the raw experimental acceleration data was processed using MATLAB. After applying necessary baseline corrections to filter out noise and errors, the acceleration-time records were double-integrated to calculate the corresponding horizontal displacements. This analytical process allowed the physical movement of the specimen to be accurately tracked at different elevations throughout the dynamic loading phase.

The selection of the specific harmonic excitation frequencies was directly driven by the earlier snap-back tests, which established the fundamental natural frequency of the structures at approximately 1.4 Hz. To comprehensively evaluate the dynamic behavior, the shake table tests were intentionally conducted at this resonant frequency (1.4 Hz), as well as at frequencies slightly below (1.2 Hz) and above (1.6 Hz) it. The resulting displacement-time graphs plot the movement of specific instrumented points using distinct colors to differentiate the locations: the shake table input is represented by a black curve, alongside individual curves for the sensors installed at the wall base, first-floor level, cross-junction center, and roof top. By comparing the displacement responses of Structure A and Structure B across 1.2 Hz, 1.4 Hz, and 1.6 Hz, the research effectively captures the lateral movement, vibration patterns, and overall structural performance as the cross-junction approaches, hits, and passes its fundamental resonance.

4.5.1 Acceleration-Time Histories

The acceleration-time response of the mortar-free Interlocking Plastic Block (IPB) cross-junction was investigated using a harmonic shake table test to evaluate its dynamic behavior under different loading frequencies. The cross-junction specimen was instrumented with five accelerometers placed at selected elevations to monitor

the transmission of vibration through the structure. One accelerometer was fixed to the shake table to record the input ground motion, while the remaining four were installed at the bottom of the wall, first-floor level, top of the wall, and roof top to measure the structural response. The signals recorded from all sensors were transferred through an Arduino-based data acquisition system and processed in MATLAB for data filtering and analysis. Harmonic excitation was applied in both the X-direction and Y-direction at frequencies of 1.2 Hz, 1.4 Hz, and 1.6 Hz. The resulting acceleration-time histories are presented in Figure 4.6.

To facilitate comparison, the acceleration histories for all sensor locations are shown using a consistent color scheme. The black line represents the input motion of the shake table, while the red, green, brown, and dark blue lines represent the responses at the bottom of the wall, first floor, top of the wall, and roof top, respectively. These graphs allow the vibration response of both Structure A and Structure B to be directly compared under different excitation frequencies and loading directions. By examining these responses, the variation in acceleration transmission from the base to the roof top of the cross-junction can be clearly observed.

TABLE 4.4: Acceleration Response under Harmonic Loading

Frequency (Hz)	Structure	Direction	Base (g)	Bottom of wall (g)	First Floor (g)	Top of Wall (g)	Roof Top (g)
1.2	A	X	0.144	0.135	0.096	0.064	0.048
		Y	0.144	0.120	0.107	0.072	0.058
1.4		X	0.168	0.145	0.128	0.120	0.096
		Y	0.168	0.137	0.120	0.096	0.064
1.6		X	0.200	0.170	0.142	0.129	0.107
		Y	0.200	0.172	0.143	0.130	0.107
1.2	B	X	0.144	0.119	0.085	0.057	0.043
		Y	0.144	0.125	0.103	0.070	0.056
1.4		X	0.168	0.152	0.135	0.114	0.101
		Y	0.168	0.142	0.125	0.100	0.067
1.6		X	0.200	0.175	0.146	0.133	0.111
		Y	0.200	0.177	0.148	0.134	0.112

At an excitation frequency of 1.2 Hz, the structural response remained stable, with acceleration amplitudes decreasing as the wave traveled upward through the

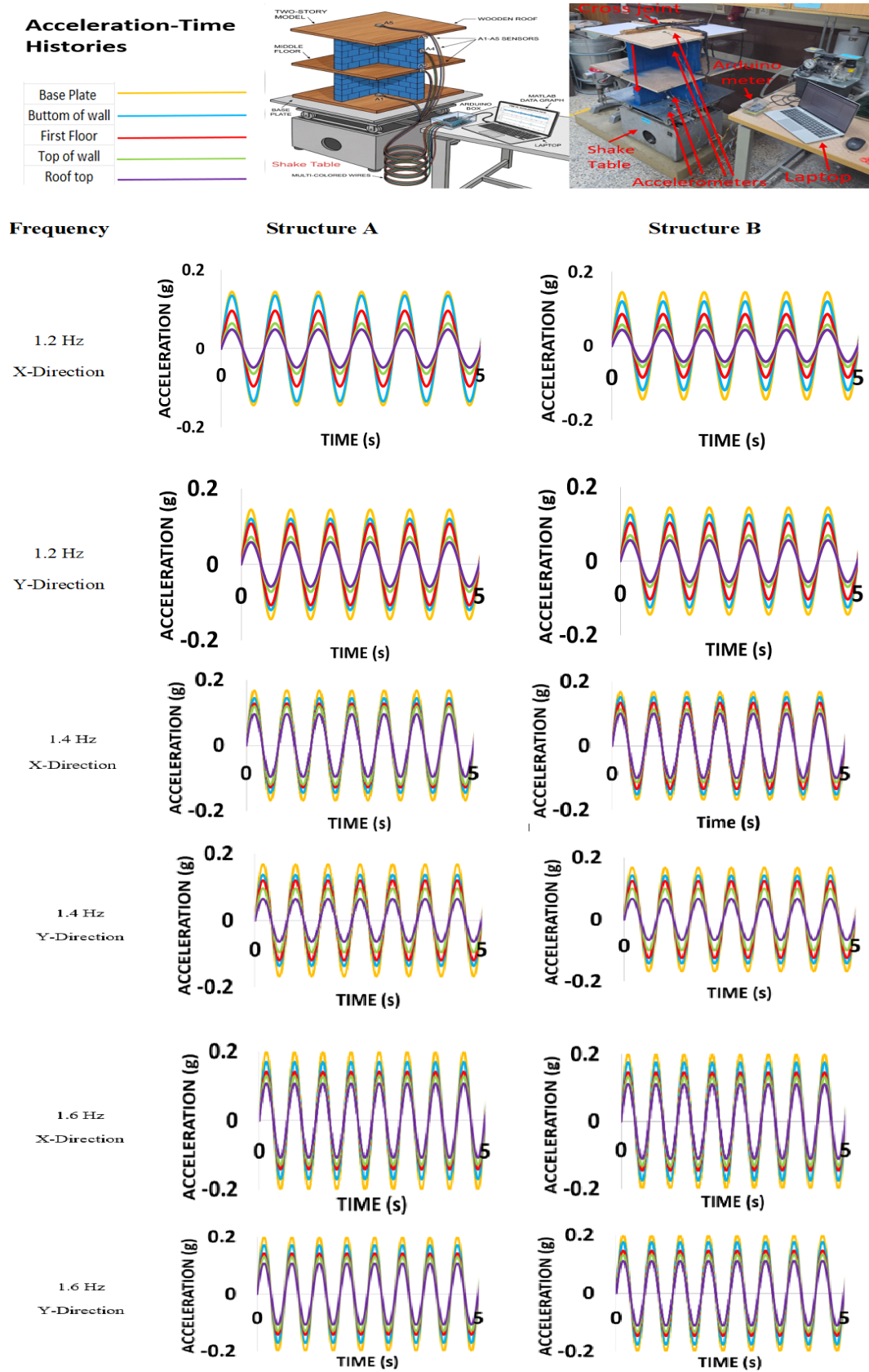


FIGURE 4.5: AccelerationTime Histories of the Cross Joint for Structures A and B under Harmonic Loading.

specimen. When the loading frequency increased to 1.4 Hz which aligns with the fundamental natural frequency of the cross-junction, the acceleration amplitudes recorded at the upper levels increased significantly, demonstrating that the specimen experienced its maximum dynamic response near resonance. When the excitation frequency was further increased to 1.6 Hz, moving beyond the resonant condition, the base input acceleration was highest, yet the upper levels still experienced notable acceleration transmission. Despite these dynamic shifts across frequencies, the cross-junction remained stable without any sudden loss of structural integrity, demonstrating that the mortar-free IPB system effectively dissipates energy through friction between the interlocking blocks and the rubber-band stiffeners.

The quantitative maximum acceleration values recorded during these harmonic tests are summarized in the corresponding tables 4.4. For Structure A, a base input acceleration of 0.144 g at 1.2 Hz in the X-direction resulted in a roof top response of 0.048 g. During resonance at 1.4 Hz, an increased base input of 0.168 g in the X-direction yielded a roof top acceleration of 0.096 g. At 1.6 Hz, a base input of 0.200 g produced a roof top response of 0.107 g. Structure B exhibited a similar trend: at 1.4 Hz in the X-direction, a base input of 0.168 g resulted in a roof top acceleration of 0.101 g, while the 1.6 Hz excitation with a 0.200 g base input yielded a 0.111 g response at the roof top. These recorded values confirm that while structural variations existed between the X and Y directions due to block orientation, both configurations successfully maintained stable dynamic performance over the complete range of harmonic loading.

4.5.2 Displacement-Time Histories

The displacement-time response of the mortar-free Interlocking Plastic Block (IPB) cross-joint was analyzed to evaluate the lateral movement and deformation of the structure during harmonic shake table testing. The displacement histories were obtained from the recorded acceleration data using MATLAB. Before calculating the displacement, the acceleration signals were filtered and corrected to remove baseline drift and unwanted noise. The corrected acceleration records were then

integrated twice to obtain the corresponding displacement-time histories. These displacement curves describe the movement of different parts of the cross-joint throughout the harmonic loading tests and provide a clear picture of its dynamic behavior.

The displacement-time graphs represent the response of the five instrumented locations on the shake table and the cross-joint specimen. For easy comparison, a consistent color scheme was used throughout the analysis. The black line represents the displacement of the shake table, while the red, green, brown, and dark blue lines represent the displacement measured at the base plate, wall base, first-floor level, top of the wall and roof top respectively. The displacement responses were compared for both Structure A and Structure B under harmonic excitation frequencies of 1.2 Hz, 1.4 Hz, and 1.6 Hz in both the X-direction and Y-direction. This comparison makes it possible to evaluate the lateral displacement, vibration pattern, and overall structural response of the mortar-free IPB cross-joint under different dynamic loading conditions.

The displacement-time histories show that the dynamic response of the mortar-free Interlocking Plastic Block (IPB) cross-joint changes with the applied excitation frequency. Under the 1.2 Hz harmonic loading, which is below the natural frequency of the specimen, the displacement recorded at all sensor locations remained close to the motion of the shake table. The displacement curves followed a similar pattern from the base to the top of the structure, indicating that the cross-joint behaved as a stable unit with only small relative movement between different levels. At this loading frequency, the interlocking mechanism and rubber-band stiffeners effectively resisted lateral movement, allowing the specimen to maintain good structural stability. The responses of both Structure A and Structure B were generally similar, with only small differences in the maximum displacement values.

As the excitation frequency increased to 1.4 Hz, which corresponds to the measured fundamental frequency of the cross-joint, the displacement response increased significantly. The largest displacement was observed at the upper levels of the structure, especially at the first-floor level and the top of the wall, while the displacement at the base remained comparatively smaller. This increase in displacement

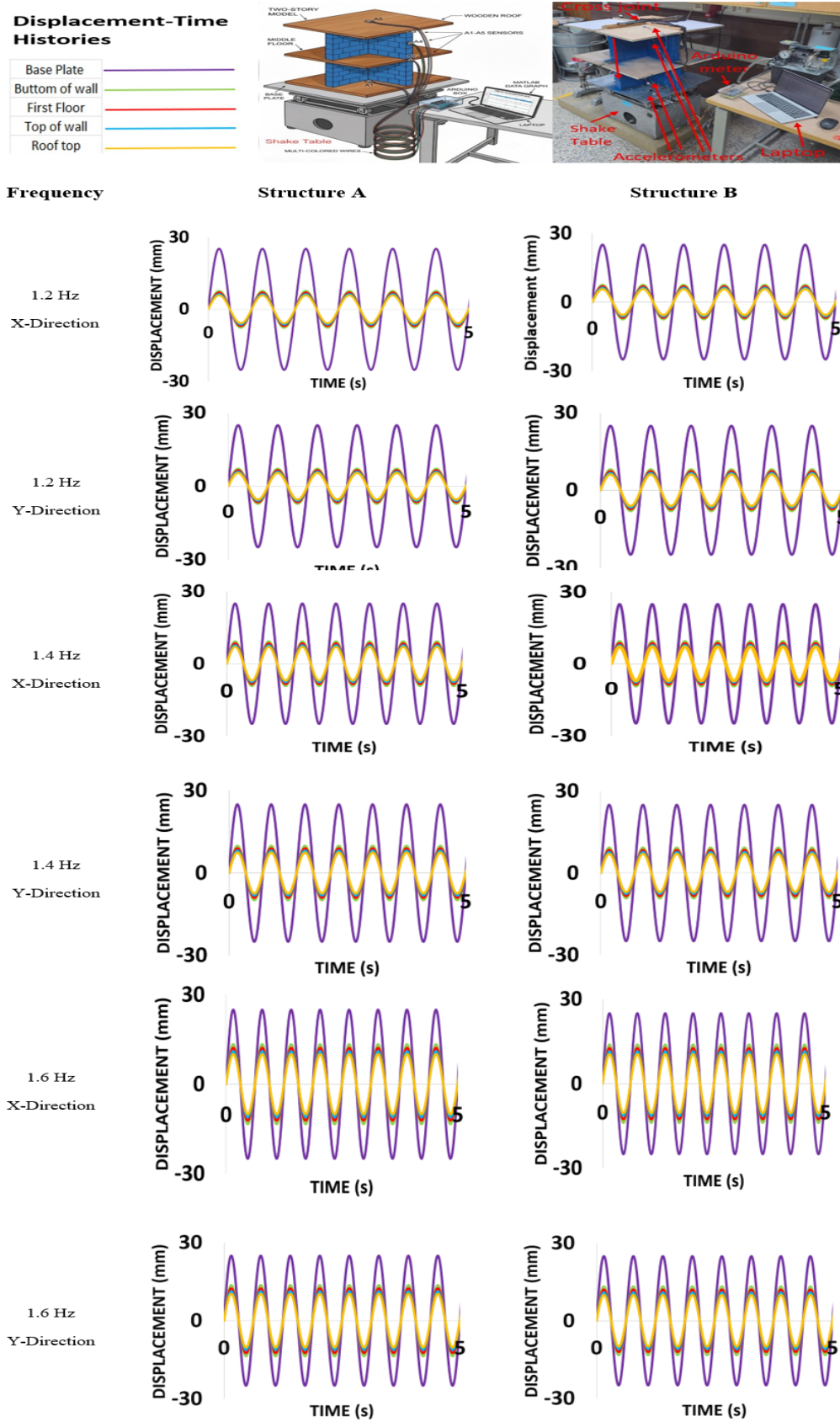


FIGURE 4.6: DisplacementTime Histories of the Cross Joint for Structures A and B under Harmonic Loadings.

indicates that the specimen experienced resonance, resulting in greater vibration amplitudes throughout the structure. The difference between the displacement of the shake table and the upper levels became more noticeable, demonstrating the amplification of structural motion near the natural frequency. Although both wall configurations showed increased displacement during resonance, the cross-joint remained stable throughout the test without sudden structural failure.

When the excitation frequency was further increased to 1.6 Hz, the specimen entered the post-resonant region and the displacement response decreased compared with that observed at 1.4 Hz. The vibration of the upper levels became less severe, although continuous cyclic movement of the interlocking blocks could still be observed. A slight phase difference between the base motion and the response of the upper levels indicated that part of the vibration energy was dissipated through friction between the interlocking blocks and the rubber-band stiffeners. The reduction in displacement after resonance shows that the mortar-free cross-joint was able to dissipate vibration energy effectively under higher-frequency loading.

A comparison of Structure A and Structure B shows that both wall configurations followed similar displacement trends throughout the harmonic loading tests. The displacement increased as the excitation frequency approached the natural frequency and decreased again when the loading frequency exceeded it. Overall, the displacement-time histories demonstrate that the mortar-free IPB cross-joint has stable dynamic behavior and good energy dissipation characteristics under harmonic loading. These results also confirm that the cross-joint can maintain its structural integrity while resisting repeated dynamic loading over a range of excitation frequencies.

Table 4.5 presents the maximum displacement response of the mortar-free Interlocking Plastic Block (IPB) cross-junction under harmonic loading for Structure A and Structure B at excitation frequencies of 1.2 Hz, 1.4 Hz, and 1.6 Hz. The results show that the displacement increased gradually with the increase in excitation frequency for both wall configurations. In Structure A, the maximum displacement increased from 7.71 mm (X-axis) and 7.20 mm (Y-axis) at 1.2 Hz to 13.40 mm (X-axis) and 13.70 mm (Y-axis) at 1.6 Hz. Similarly, Structure B

TABLE 4.5: Peak Displacement Response under Harmonic Loading

Sr. No.	Wall Configuration	Frequency (Hz)	X-Axis (mm)	Y-Axis (mm)	% Contribution
1	Structure A	1.2	7.71	7.20	7.02
2		1.4	9.30	9.90	6.45
3		1.6	13.40	13.70	2.24
4	Structure B	1.2	7.51	8.10	7.86
5		1.4	9.50	9.30	2.16
6		1.6	13.90	13.30	4.51

showed an increase in displacement from 7.51 mm (X-axis) and 8.10 mm (Y-axis) at 1.2 Hz to 13.90 mm (X-axis) and 13.30 mm (Y-axis) at 1.6 Hz. These results indicate that higher excitation frequencies produced larger lateral movements in the cross-junction specimen.

A comparison of the two wall configurations shows only small differences in displacement values, indicating that both Structure A and Structure B exhibited similar dynamic behavior under harmonic loading. At lower frequencies, the displacement remained relatively small, while larger displacements were observed as the excitation frequency increased. The percentage contribution values also varied with loading frequency, ranging from 2.16% to 7.86%, indicating slight differences in the response of the two wall configurations. Overall, the results suggest that the mortar-free IPB cross-junction maintained stable structural performance throughout the tests, while the increase in displacement with frequency reflects the expected dynamic response of the system under harmonic excitation.

4.5.3 Base Shear-Displacement Curves

The base shear-displacement relationships were developed to evaluate the response of the cross-junction prototype under harmonic excitation. To determine the energy absorbed by the mortar-free Interlocking Plastic Block (IPB) cross-joint during dynamic loading, the total mass (M) of the specimen was assumed to be concentrated at the top of the structure. The structural response was obtained from the recorded acceleration-time histories. The base shear force was calculated

by multiplying the total mass of the specimen by the measured acceleration (Base Shear = $M \times a$). The calculated base shear values were then plotted against the corresponding displacement values to generate the base shear-displacement curves, as presented in Figure 4.8.

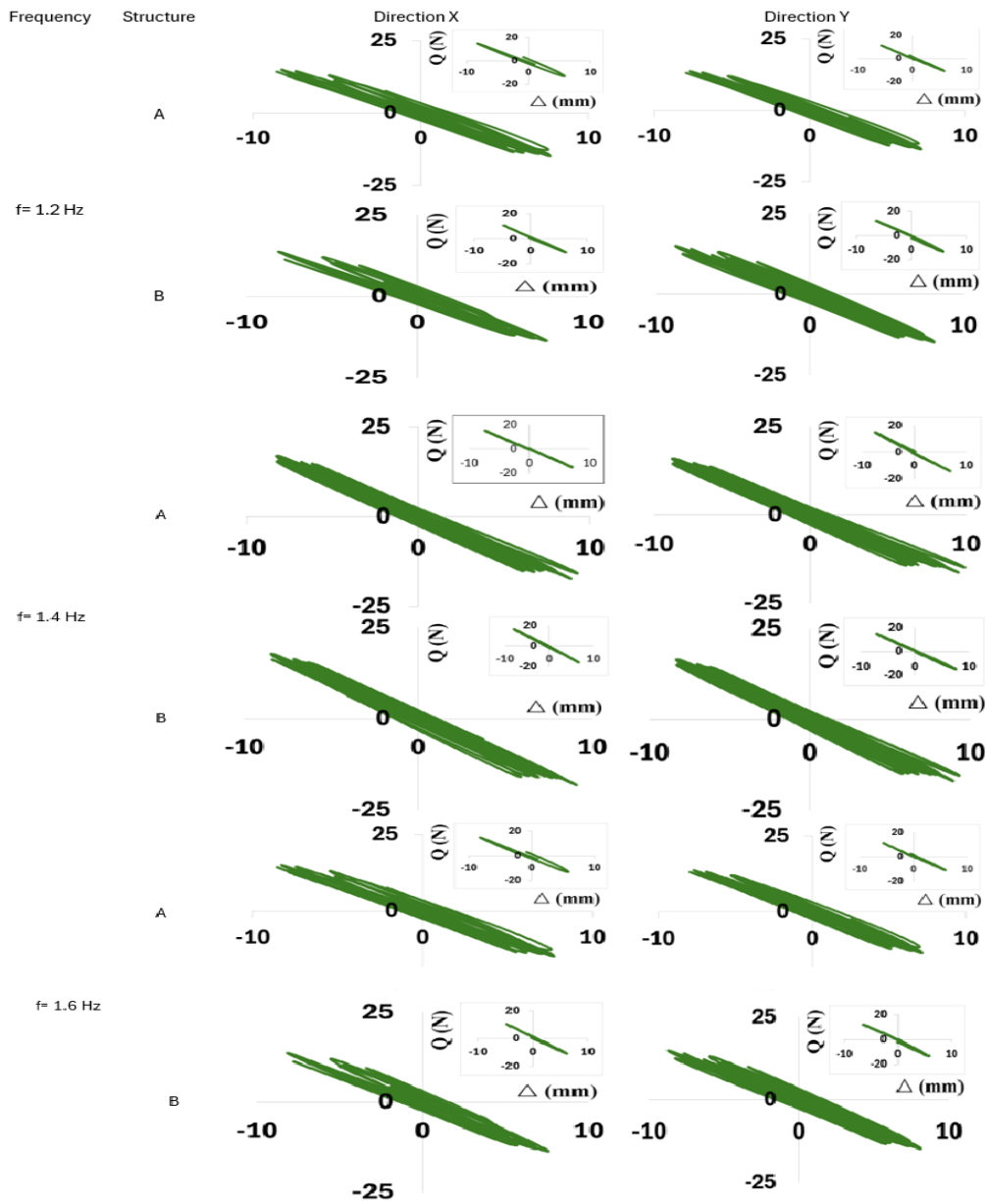


FIGURE 4.7: Base shear-displacement curves for Structure A and Structure B.

Following the experimental methodology outlined in, the relationship between base shear (plotted on the Y-axis) and lateral displacement (plotted on the X-axis) was used to evaluate the structural resistance and stiffness of the mortar-free cross-joint setup under continuous cyclic loading. The total area enclosed by these

hysteresis loops represents the amount of energy absorbed by the specimen. At a lower driving frequency of 1.2 Hz, initial static friction across the block interfaces mostly governed the dynamic behavior. Because a cross-joint design has symmetric geometry, both the X and Y loading directions showed very similar structural demands. In Direction X, Structure A reached a peak base shear of approximately 15 N at a displacement of 7.5 mm, whereas Structure B experienced a comparable peak shear of 13 N at roughly 7.5 mm of drift. Similarly, in Direction Y, Structure A showed a maximum base shear of 14 N at a displacement of 8.0 mm, while Structure B sustained a peak force of 15 N at a displacement of 8.5 mm. When the excitation frequency was increased to 1.4 Hz, the physical demands on the mortar-free structural node intensified. This higher frequency forced the interlocking blocks into active frictional sliding, which expanded the hysteresis loops. Along the X-axis, the lateral displacement for Structure A increased to 11.5 mm under a base shear of 17 N, while Structure B restricted its maximum lateral drift to 10.0 mm while drawing a slightly lower peak base shear of 16 N. A similar trend was observed under Y-axis loading, where Structure A reached a displacement of 12.5 mm at a peak force of 15 N, whereas Structure B limited its structural drift to 11.5 mm while sustaining a peak base shear of 16 N. These results prove that the block configuration in Structure B uses its internal mechanical interlocks more effectively under changing frequencies to control sliding and limit excessive physical drift. Subjecting the cross-joint assembly to a severe testing frequency of 1.6 Hz pushed the interlocking blocks to their maximum dynamic sliding limits, producing the widest load-deformation loops recorded across the entire testing program. In Direction X, Structure A reached its ultimate displacement at 14.0 mm while enduring a base shear of 18 N, whereas Structure B maintained better structural control by capping its ultimate drift at 13.5 mm despite sustaining a higher base shear of 20 N. Under Y-direction loading, Structure A experienced a maximum drift of 15.0 mm at a peak force of 18 N, while Structure B outperformed this by restricting its maximum lateral displacement to 13.5 mm against a peak base shear of 21 N. Throughout the tested frequency range, these hysteretic values show that the Structure B arrangement offers a more stable stiffness-to-damping balance for cross-joints. By safely accommodating a small increase in absorbed

TABLE 4.6: Maximum base shear developed during harmonic excitation

Sr. No.	Wall Configuration	Frequency (Hz)	Direction	Avg. Energy /Cycle (N.mm)	No of Cycles	Total Energy Absorption (N.mm)	Equi. Damping Ratio (%)
1	Structure A	1.2	X	135.5	91	12334.9	18.6
2		1.2	Y	112.6	90	10135.7	18.2
3		1.4	X	172.0	112	19267.0	17.5
4		1.4	Y	173.0	114	19717.9	17.5
5		1.6	X	316.4	121	38288.5	18.9
6		1.6	Y	324.5	123	39908.7	18.9
7	Structure B	1.2	X	107.1	93	9963.2	16.5
8		1.2	Y	132.7	94	12470.2	17.6
9		1.4	X	178.1	110	19588.9	17.6
10		1.4	Y	165.8	115	19066.0	17.2
11		1.6	X	335.9	124	41656.4	18.9
12		1.6	Y	324.1	127	41166.6	18.9

base shear, the Structure B layout achieves a crucial reduction in lateral movement, which successfully lowers the risk of joint separation and structural failure during high-frequency cyclic loading.

This equivalent damping is calculated using the standard mathematical formula, where E is the energy absorbed during a single loading cycle, while Q_{max} and Δ_{max} represent the maximum shear force and lateral displacement in a hysteretic loop, respectively. Figure 4.8 displays the energy absorption trends for the various loading frequencies, showing that energy dissipation consistently increases as the loading frequency gets higher. Table 4.6 provides a detailed summary of the energy dissipation capacities and equivalent viscous damping ratios for the unbonded cross-joint assembly across the designated harmonic testing spectrum of 1.2 Hz, 1.4 Hz, and 1.6 Hz. During the initial 1.2 Hz excitation phase, the system begins to overcome static friction, and energy absorption trends remain moderate. Within the X-direction, Structure A dissipates a total of 12,334.9 N.mm over 91 cycles, whereas Structure B absorbs 9,963.2 N.mm across 93 cycles. In the Y-direction, Structure A absorbs 10,135.7 N.mm over 90 cycles, while Structure B manages a higher value of 12,470.2 N.mm across 94 cycles. The calculated equivalent damping ratios during this initial interval stay fairly close, ranging between

16.5% and 18.6% across both axes. This baseline performance demonstrates that the physical interlocking of the blocks provides the main structural defense before widespread dynamic movement begins. When the excitation frequency is raised to 1.4 Hz, the system undergoes higher kinematic demands, causing the internal blocks to continuously slide against each other. This results in a clear increase in the total energy dissipated. Specifically, in the X-direction, Structure B exhibits strong dynamic performance by absorbing 19,588.9 N.mm over 110 cycles, which is highly comparable to the 19,267.0 N.mm recorded for Structure A across 112 cycles. In the Y-direction, Structure A absorbs 19,717.9 N.mm over 114 cycles, while Structure B dampens 19,066.0 N.mm across 115 cycles. Within this intermediate band, the equivalent damping ratios stay very stable, tracking tightly between 17.2% and 17.5% across both block setups and orientations. This consistent behavior shows that the dry-stacked joints are highly capable of continuously absorbing kinetic energy as the dynamic forces grow. Under rapid, severe loading conditions at 1.6 Hz, the cumulative energy absorption reaches its maximum absolute levels due to fast, continuous cyclic sliding and a much higher cycle count. In the X-direction, Structure B successfully dissipates a massive 41,656.4 N.mm over 124 cycles, outperforming the 38,288.5 N.mm absorbed by Structure A over 121 cycles. A similar high-energy trend occurs in the Y-direction, where Structure B absorbs an impressive 41,166.6 N.mm over 127 cycles compared to the 39,908.7 N.mm taken by Structure A across 123 cycles. Crucially, during this severe phase, the equivalent damping ratios rise uniformly to peak at exactly 18.9% for both configurations in both directions. This high-frequency assessment highlights the clear benefits of the Structure B layout; its specific joint distribution ensures aggressive, continuous frictional engagement, allowing the structure to safely absorb intense dynamic loads without cracking or breaking the materials. Ultimately, this excellent energy dissipation is controlled by the physical shape of the mortar-free system and macroscopic Coulomb dry friction. When moving dynamic forces become stronger than the static friction holding the blocks together, sliding starts along the unbonded horizontal joints. This action safely turns dangerous kinetic energy into heat through continuous rubbing. At the same time, major lateral shifting is actively stopped by the vertical mechanical interlocks and the pulling

forces of the pre-tensioned rubber stiffeners. This internal friction network is geometrically optimized by the alternating block layout of Structure B, forcing the touching surfaces to grip each other more tightly and absorb more cumulative energy before there is any danger of the joints decoupling or the global structure failing.

4.6 Summary

This chapter presented the experimental evaluation of the double-storey mortar-free Interlocking Plastic Block (IPB) cross-joint under both static and dynamic loading conditions. The static stiffness test was carried out specifically to determine the lateral load-carrying capacity and lateral stiffness of the cross-joint, and not for frequency evaluation. The results showed that the specimen provided stable resistance against lateral loading. The load-displacement response was used to calculate the initial stiffness and to evaluate the structural performance of the mortar-free system.

The overall structural behavior of the cross-joint was investigated using four tests: the static stiffness test, snap-back test, hammer impact test, and harmonic shake table test. The static stiffness test confirmed the stable lateral load-carrying capacity and initial stiffness of the system. To evaluate the dynamic properties, the snap-back test, analyzed using Fast Fourier Transform (FFT), showed that the specimen had a consistent fundamental frequency of approximately 1.4 Hz. The hammer impact test confirmed its vibration characteristics and energy dissipation capability. The harmonic loading tests, conducted at 1.2 Hz, 1.4 Hz, and 1.6 Hz, demonstrated that the maximum structural response occurred near the fundamental frequency and reduced at higher excitation frequencies. The acceleration, displacement, and base shear responses showed that the mortar-free cross-joint was able to dissipate vibration energy effectively through the interlocking mechanism and rubber-band stiffeners while maintaining overall structural stability.

Overall, Structure A and Structure B showed satisfactory performance throughout the testing program. The results indicate that the proposed mortar-free IPB

cross-joint possesses good stiffness, effective energy dissipation, and stable dynamic behavior under seismic loading. These findings demonstrate the potential of the proposed cross-joint system for improving the seismic performance of double-storey mortar-free interlocking plastic block structures and provide a useful foundation for future research and practical applications.

Chapter 5

Discussions

5.1 Background

This chapter discusses the experimental findings obtained from the double-storey mortar-free Interlocking Plastic Block (IPB) cross-joint and explains the structural behavior observed during both static and dynamic testing. The results from the static stiffness, snap-back, hammer impact, and harmonic shake table tests are compared to evaluate the overall performance of the cross-joint under different loading conditions. Special attention is given to the displacement-time, acceleration-time, and base shear-displacement responses to better understand the stiffness, vibration characteristics, energy dissipation, and seismic behavior of the proposed mortar-free system.

The discussion also examines the influence of the two wall configurations (Structure A and Structure B) on the structural response of the cross-joint. The experimental observations are compared with the developed empirical equations to evaluate the accuracy of the proposed predictive model. A calibration factor of $K = 1.55$ is incorporated into the empirical relationships to improve the agreement between the calculated and experimental results. The comparison between the predicted and measured values provides a better understanding of the dynamic behavior of the mortar-free IPB cross-joint and demonstrates the suitability of the proposed model

for predicting the seismic performance of double-storey mortar-free interlocking plastic block structures.

The cross-junction represents one of the most critical regions within a masonry structure because it serves as the primary intersection point for load transfer between orthogonal walls. During seismic excitation, this region experiences a combination of in-plane and out-of-plane actions that may lead to stress concentration and localized instability.

The experimental observations revealed that the cross-junction configuration significantly influenced the overall dynamic response of the structure. The interaction between intersecting walls improved structural continuity and contributed to a more uniform distribution of inertial forces throughout the specimen. Compared with isolated wall systems reported in previous studies, the cross-junction arrangement exhibited improved resistance against excessive displacement and rotational instability.

5.2 Development of Empirical Equations Based on Geometrical Parameters, Structural Response and Loading Conditions

To estimate the dynamic response of the mortar-free Interlocking Plastic Block (IPB) cross-joint system, empirical equations proposed by Khan [94] were adopted and modified according to the geometry of the present study. These equations establish a relationship between the input motion applied at the base and the resulting structural response at the top of the cross-joint specimen. The mathematical model considers important structural parameters, including the dimensions of the interlocking blocks, the overall height of the specimen, and the cross-joint configuration. Using these parameters, the equations were applied to predict the acceleration, velocity, and displacement responses of the cross-joint under dynamic loading.

The theoretical predictions obtained from the empirical equations were compared with the experimental results to evaluate their accuracy. Any differences between the predicted and measured values were assessed by calculating the percentage error. To improve the agreement between the theoretical and experimental results, a correction factor $K = 1.55$ was introduced in the empirical model. The modified equations provide a more reliable prediction of the dynamic behaviour of the mortar-free IPB cross-joint and can be used to estimate its seismic response under similar loading conditions. These equations also help explain the influence of block geometry, structural height, and joint configuration on the overall performance of the cross-joint system.

$$\ddot{u}_t = \frac{a}{h^2 n} \times S^3 m \times k^{(1+\frac{2n}{100})} \times \ddot{u}_g \quad (5.1)$$

$$\dot{u}_t = \frac{a}{h^2 n} \times S^3 m \times k^{(1+\frac{2n}{100})} \times \dot{u}_g \quad (5.2)$$

$$u_t = \frac{a}{h^2 n} \times S^3 m \times k^{(1+\frac{2n}{100})} \times u_g \quad (5.3)$$

Where K is the dimensionless structural coefficient, n represents the total number of Interlocking Plastic Blocks (IPBs) used in the cross-joint specimen, m is the number of blocks arranged along the length of one wall in a single horizontal layer, a is the base area of one IPB layer, h is the total height of the cross-joint assembly, and S is the number of stories, which is equal to 2. Similarly, $\ddot{u}_g$, $\dot{u}_g$, and u_g represent the average acceleration, velocity, and displacement measured at the base of the specimen, while $\ddot{u}_t$, $\dot{u}_t$, and u_t represent the corresponding predicted acceleration, velocity, and displacement at the top of the cross-joint. The accuracy of these empirical equations mainly depends on the proper selection of the dimensionless coefficient K , which accounts for the effects of boundary conditions, structural configuration, and the geometry of the mortar-free system.

Previous studies have reported different values of K for various types of mortar-free structures. Afzal [95] used a value of 0.45 for out-of-plane solid walls, Sudheer and Ali [96,97] recommended 0.50 for walls containing window openings, and Khan [94] proposed a value of 1.05 for basic column configurations. The empirical equation factor for this study, $K=1.55$, was derived through an iterative calibration process.

The derivation began by evaluating the system's initial static stiffness. From this starting point, the factor was systematically adjusted across multiple iterations, comparing the calculated outcomes against the experimental data until the optimal correlation was achieved. The final value of $K=1.55$ was selected because it yielded the most accurate representation of the observed structural response. Furthermore, this calculated K value is higher than those reported in previous studies because the present research specifically investigates a two-story mortar-free Interlocking Plastic Block (IPB) cross-joint. This complex configuration necessitates a higher calibration factor to accurately capture its unique geometry, load transfer mechanisms, and dynamic behavior under seismic loading.

The empirical results obtained using $K = 1.55$ were compared with the experimental measurements recorded at the top of the cross-joint specimen. The comparison showed good agreement between the predicted and measured responses, with only a small percentage difference. Such differences are expected because mortar-free systems exhibit complex behavior during dynamic loading, including sliding between interlocking blocks, local uplift, frictional resistance, and slight changes in contact conditions. Similar variations have also been reported in previous studies, where Nasery [98] observed prediction errors of up to 30%, while Ali [97] reported differences of approximately 35% between theoretical and experimental results. Therefore, the small variation observed in the present study indicates that the proposed empirical equations can reliably predict the dynamic response of the mortar-free IPB cross-joint and are suitable for evaluating its seismic performance.

Table 5.2 presents a comparison between the experimental and empirical values of cross-joint responses for Acceleration, Velocity, and Displacement measured along the X- and Y-axes at excitation frequencies of 1.2 Hz, 1.4 Hz, and 1.6 Hz for Structure A and Structure B. The percentage difference between the experimental and predicted empirical values ranges approximately from 5.7% to 7.6%, indicating a close agreement between the proposed empirical model and the experimental observations. The consistently low percentage differences across all test conditions demonstrate the reliability and accuracy of the modified empirical equation in predicting the dynamic response of the masonry cross-joint system.

TABLE 5.1: Comparison between experimental and empirical responses of the cross-junction under harmonic loading.

Frequency (Hz)	Cross-Joint sponse	Re- Axis	Experimental Value	Empirical Value	%age Difference	Differ-
Structure A						
1.2	Acceleration (g)	X	0.00043	0.0004	7.0%	
		Y	0.00037	0.00035	6.4%	
	Velocity (mm/sec)	X	0.1602	0.1494	6.7%	
		Y	0.1572	0.1476	6.1%	
	Displacement (mm)	X	0.0250	0.0233	6.8%	
		Y	0.0235	0.0219	6.9%	
1.4	Acceleration (g)	X	0.00048	0.00051	6.3%	
		Y	0.00046	0.000427	7.2%	
	Velocity (mm/sec)	X	0.1880	0.1761	6.3%	
		Y	0.2019	0.1872	7.3%	
	Displacement (mm)	X	0.0321	0.02993	6.9%	
		Y	0.0397	0.03712	6.4%	
1.6	Acceleration (g)	X	0.00063	0.00058	6.8%	
		Y	0.00068	0.00063	6.6%	
	Velocity (mm/sec)	X	0.2554	0.2375	7.0%	
		Y	0.22213	0.2071	6.8%	
	Displacement (mm)	X	0.0440	0.0415	5.7%	
		Y	0.0440	0.0412	6.4%	
Structure B						
1.2	Acceleration (g)	X	0.00035	0.00037	6.3%	
		Y	0.00037	0.00038	5.8%	
	Velocity (mm/sec)	X	0.1568	0.1589	6.6%	
		Y	0.1439	0.1584	6.3%	
	Displacement (mm)	X	0.0250	0.0237	6.7%	
		Y	0.0280	0.0261	6.8%	
1.4	Acceleration (g)	X	0.00054	0.0005	7.6%	
		Y	0.00047	0.0004	7.0%	
	Velocity (mm/sec)	X	0.1813	0.1702	6.1%	
		Y	0.1894	0.1767	6.7%	
	Displacement (mm)	X	0.0330	0.0319	6.2%	
		Y	0.0323	0.0301	6.8%	
1.6	Acceleration (g)	X	0.00056	0.00052	7.3%	
		Y	0.00058	0.00054	6.4%	
	Velocity (mm/sec)	X	0.2429	0.2284	5.9%	
		Y	0.2410	0.2232	7.4%	
	Displacement (mm)	X	0.0512	0.0478	6.6%	
		Y	0.0443	0.0413	6.7%	

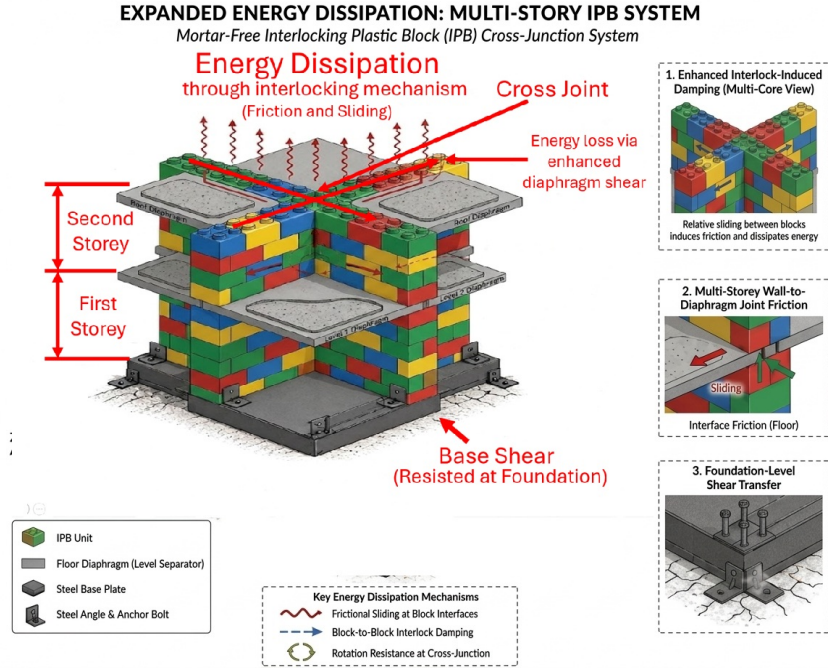


FIGURE 5.1: Schematic illustration of the energy dissipation mechanism in a double-storey mortar-free interlocking plastic block (IPB) cross-junction under lateral seismic loading

A comprehensive comparison of the percentage differences between the experimental results obtained in this study and the predictions of existing empirical models is presented in Table 5.2. Previous studies have reported considerable discrepancies when conventional empirical equations were used to predict structural responses. In particular, the study conducted by Akram [99] reported prediction errors ranging from 8% to 34% for certain structural configurations. To overcome these limitations, the current research introduces a story constant (S) into the empirical formulation together with a calibrated K -value of 1.55. This modification significantly improves the predictive capability of the model, reducing the deviation between experimental and empirical results to approximately 5.77.6%, thereby demonstrating a substantial enhancement in the accuracy and applicability of the proposed equation for double-story masonry structures. Refined empirical relationships are shown as:

$$\ddot{u}_t = \frac{a}{h^2 n} \times S^3 m \times k^{(1+\frac{2n}{100})} \times \ddot{u}_g \quad (5.4)$$

$$\dot{u}_t = \frac{a}{h^2 n} \times S^3 m \times k^{(1+\frac{2n}{100})} \times \dot{u}_g \quad (5.5)$$

$$u_t = \frac{a}{h^2 n} \times S^3 m \times k^{(1+\frac{2n}{100})} \times u_g \quad (5.6)$$

By including the story factor S , the proposed equation better represents the actual behavior of the structure. The results indicate that the prediction error is reduced to a narrow range of 5.7% to 7.6%. This improvement demonstrates that the modified equation provides a reliable and accurate analytical model for predicting the behavior of multi-story interlocking plastic block systems.

TABLE 5.2: Comparison of Empirical Equations, Structural Coefficient (K), and Percentage Variation Reported in Previous Studies

Author	Type of Structure	Empirical Equation	K-Value	% Variation
Fayyaz Khan	Block Column	$\ddot{u}_t = \frac{a/h^2}{n} K^{(1+\frac{2n}{100})} \ddot{u}_g$	1.05	3% - 12%
Khurram Shahzad	Block Wall	$\ddot{u}_t = \frac{(\frac{a}{h^2})}{n} R_b R_s K^{(1+\frac{2n}{100})} \ddot{u}_g$	0.45	18% - 19%
Sardar Junaid	Block-Return Wall		0.45	4% - 19%
Sohail Afzal	Solid Block Wall	$\ddot{u}_t = \frac{\frac{a}{h^2}}{n} R_s K^{(1+\frac{2n}{100})} \ddot{u}_g$	0.45	1% - 17%
Hammad Bashir	Wall with Diaphragm		0.45	12% - 23%
Mehran Sudheer	Block Wall		0.5	7%
Waseem Akram	Corner Joint	$\ddot{u}_t = \frac{a}{h^2 n} \times m \times k^{(1+\frac{2n}{100})} \times \ddot{u}_g$	1.14	8% - 34%
Arshad Ullah	T-Junction		0.98	7% - 14%
Jawad Nasar	In-Plane Block Walls		1.14	4.8% - 9.9%
Abu Bakar	Out-of-Plane Block Wall		1.20	17% - 25%

5.3 Practical Implications of the Experimental Findings for Structural Applications

The experimental testing carried out on the mortar-free Interlocking Plastic Block (IPB) cross-joint using a locally developed unidirectional shake table provided valuable information about its dynamic performance under harmonic loading. The controlled laboratory setup allowed the cross-joint specimen to be subjected to repeatable loading conditions, making it possible to evaluate its structural response with good accuracy. Through these tests, important characteristics such as vibration behavior, resonance, lateral movement, energy dissipation, and the interaction between interlocking blocks were successfully observed. The experimental program also demonstrated how the cross-joint responds to different loading frequencies and highlighted the contribution of friction and rubber-band stiffeners in controlling structural movement.

To understand the practical significance of these findings, the experimental results are compared with previously published studies on mortar-free interlocking wall systems. This comparison helps evaluate the performance of the proposed cross-joint configuration and shows how it differs from other mortar-free structural systems reported in the literature. The discussion also highlights the potential application of the developed cross-joint in earthquake-resistant construction, particularly for low-rise residential buildings, by relating the measured dynamic properties to established research findings and engineering practice.

5.4 Comparison of Experimental Findings with Previous Studies

The findings of this study are in good agreement with previous research on mortar-free interlocking block systems. Earlier studies have shown that interlocking blocks improve energy dissipation and reduce the risk of sudden structural failure during dynamic loading. The natural frequency and damping values obtained in this research also follow the general trends reported for similar mortar-free wall systems. However, this study specifically focuses on the cross-joint configuration, which has

been investigated less frequently in previous research. Overall, the results confirm that effective interlocking and structural continuity play an important role in improving the seismic performance and stability of mortar-free IPB structures.

TABLE 5.3: Comparison between Previous Research and Current Research

Previous Research	Current Research
Investigated single-storey isolated wall panels, solid walls, and corner-joints under simplified boundary conditions [95, 97, 100]	Evaluates the dynamic behavior of a scaled double-storey, four-way cross-junction constrained by fixed-base boundary conditions.
Structural coefficient K ranged from 0.45 (out-of-plane solid walls) [104] to 1.20 (double-storey pattern effects, 2026) [94, 97]	Derives a structural coefficient of $K = 1.55$, which reflects the higher mass, vertical scaling, and stiffness requirements specific to the two-storey cross joint.
Structural coefficient K ranged from 0.45 (out-of-plane solid walls) [94] to 1.20 (double-storey pattern effects, 2026) [101]	Structural coefficient calibrated at $K = 1.55$, reflecting increased mass, height, and stiffness demand of the two-storey cross-junction
Empirical prediction errors ranged widely, from 1% up to 34% in several studies [95, 99]	Empirical prediction errors reduced to 5.77.6% through inclusion of the story factor (S^3) in the modified formulation
Fundamental frequency and damping generally not reported together, or limited to single-wall geometries [97, 100]	Fundamental frequency consistently measured at 1.371.42~Hz (snap-back, FFT-confirmed); damping ratios of 4.45.0% (free vibration), 7.028.80% (impact), and 16.518.9% (hysteretic)
Lateral stiffness of cross-junction geometries not directly quantified in prior IPB literature [102]	Lateral stiffness quantified directionally: 1.891.91~N/mm (X-direction), 2.1852.215~N/mm (Y-direction)
Dominant response mechanisms reported as out-of-plane rocking and block-return effects in single-wall systems [95, 100]	Dominant response identified as interface stickslip sliding, rocking, and progressive frictional degradation localized at the four-way junction
Energy dissipation capacity not quantified for cross-junction geometries in earlier IPB studies [103]	Hysteretic energy dissipation quantified up to 39,908.7~N · mm (Structure A) and 41,656.4~N · mm (Structure B) at 1.6~Hz excitation
Established feasibility of IPB systems primarily at the single-wall/component scale [97, 100]	Quantitatively characterizes the dynamic behavior of a double-storey four-way IPB cross-junction using snap-back, hammer impact, and harmonic shake-table testing.

The harmonic loading tests carried out using the unidirectional shake table provided a clear understanding of the dynamic behavior of the mortar-free Interlocking Plastic Block (IPB) cross-joint under simulated earthquake loading. The experimental results showed that the two-story cross-joint maintained good structural stability while effectively dissipating vibration energy under different loading frequencies. The measured acceleration, displacement, damping, and natural frequency values indicate that the interlocking mechanism and rubber-band stiffeners work together to improve the seismic performance of the structure. These findings are consistent with previous studies on mortar-free interlocking systems and further demonstrate that cross-joints can perform efficiently under dynamic loading when properly designed.

Table 5.3 compares the results of the present study with those reported in earlier research on mortar-free interlocking structures. The comparison shows similar trends in terms of energy dissipation, vibration control, and structural stability. The use of lightweight plastic blocks also reduces the overall weight of the structure, which lowers earthquake-induced inertial forces and may reduce the need for heavy reinforcement. These characteristics make the mortar-free IPB cross-joint a practical and economical option for low-rise buildings, especially in earthquake-prone regions where affordable and sustainable construction techniques are required.

Another important advantage of the proposed system is its simple construction method. Since the blocks are assembled using a dry-stacking technique, no mortar or curing time is required, resulting in faster construction with lower labour and water requirements. The interlocking shape of the blocks helps maintain proper alignment during construction and reduces the dependence on highly skilled workers. In full-scale applications, the restoring action provided by the rubber-band stiffeners used in the laboratory model can be replaced with suitable internal plastic tendons or tie rods passing through the hollow cores of the blocks. This approach can improve the overall stability of the structure while maintaining the dynamic behavior observed during the laboratory tests. Therefore, the proposed mortar-free IPB cross-joint system has strong potential for practical application in affordable, earthquake-resistant housing and other low-rise structures.

5.5 Summary

The findings of this study demonstrate the dynamic performance and seismic behavior of the two-story mortar-free Interlocking Plastic Block (IPB) cross-joint through a combination of experimental testing and empirical analysis. The experimental results were supported by a modified empirical model developed for the cross-joint configuration, in which a structural coefficient of $K = 1.55$ was introduced to improve the prediction of acceleration, velocity, and displacement responses. Comparison between the experimental and empirical results showed acceptable agreement, although some differences were observed because of the complex behavior of the mortar-free system. These variations are mainly caused by block sliding, local uplift, friction between interlocking surfaces, and the action of the rubber-band stiffeners during dynamic loading.

The harmonic loading tests performed using the locally fabricated unidirectional shake table successfully evaluated the vibration characteristics of the cross-joint under different excitation frequencies. Although the testing equipment was not intended to produce complete structural failure, it effectively captured the important dynamic properties of the specimen, including its natural frequency, damping behavior, stiffness, and energy dissipation capacity. The overall results confirm that the mortar-free IPB cross-joint provides good structural stability, efficient energy dissipation, and reliable seismic performance. Therefore, the proposed cross-joint system can be considered a practical, lightweight, and economical construction solution for low-rise buildings in earthquake-prone areas.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The seismic performance of mortar-free structural connections is essential for developing safe and sustainable construction systems. This research experimentally investigated the dynamic behavior and energy dissipation characteristics of a two-story mortar-free Interlocking Plastic Block (IPB) cross-joint using a 1:10 scaled physical model. The specimen was constructed using dry-stacked interlocking plastic blocks and securely fixed to the testing platform using steel angle sections to provide stable boundary conditions throughout the experiments. Five accelerometers were installed at different locations of the cross-joint to continuously record the structural response under static and dynamic loading. Their arrangement enabled the measurement of acceleration at the shake table, wall base, first-floor level, and upper portions of the cross-joint, providing a detailed understanding of vibration transmission through the structure.

The experimental program consisted of static stiffness testing, snap-back testing, hammer impact testing, and harmonic shake table testing. Static loading was used to evaluate the lateral load-displacement behavior of the cross-joint, while snap-back testing determined the natural vibration characteristics and damping properties through the logarithmic decrement method. Hammer impact testing was performed to investigate the transient dynamic response and impact energy dissipation of the structure. Finally, harmonic loading was applied at excitation

frequencies of 1.2 Hz, 1.4 Hz, and 1.6 Hz to evaluate the seismic response of the cross-joint under continuous cyclic loading. MATLAB was used for data acquisition, whereas SeismoSignal software was employed to process the recorded signals by applying baseline correction and filtering. Based on the experimental investigation, the following conclusions are drawn:

- i. Static Stiffness testing demonstrated that lateral resistance is governed by block orientation, establishing complete mechanical cross-axis symmetry. Structure A exhibited higher lateral stiffness along the X-direction (2.185 N/mm) compared to the Y-direction (1.91 N/mm). This behavior perfectly inverted in the orthogonally rotated Structure B, where the primary stiffness shifted to the Y-direction (2.215 N/mm) over the X-direction (1.89 N/mm).
- ii. Snap-back testing identified the fundamental natural frequency of the structure between 1.37 and 1.42 Hz. The system yielded damping ratios ranging from 4.4% to 5.0%, confirming the stable free-vibration characteristics of the mortar-free cross-junction.
- iii. Hammer impact testing produced dominant modal frequencies between 4.17 and 5.43 Hz. Damping ratios increased significantly to a range of 7.02% to 8.80%, demonstrating the dry-stacked system's efficiency in dissipating transient impact energy.
 - a. The harmonic loading tests demonstrated that the mortar-free IPB cross-joint maintained stable structural behavior under repeated dynamic excitation across the investigated frequency range (1.21.6 Hz). The specimen exhibited increasing dynamic response near its fundamental frequency while preserving overall structural integrity throughout the testing program.
 - b. Acceleration amplification increased as the excitation frequency approached the fundamental frequency (1.4 Hz), indicating resonant behavior, whereas post-resonant loading at 1.6 Hz produced phase differences that reflected effective vibration energy dissipation through friction between the interlocking blocks.

- c. Maximum lateral displacement occurred at the resonant frequency of 1.4 Hz, while lower responses were recorded at 1.2 Hz and 1.6 Hz. The reduction in displacement beyond resonance confirms the ability of the mortar-free cross-joint to dissipate vibration energy and maintain structural stability under cyclic loading.
- iv. Hysteresis loops expanded progressively with increasing excitation frequencies, demonstrating enhanced energy dissipation through frictional sliding and reaching equivalent damping ratios of 18.9%. Structure B consistently exhibited lower lateral drift while sustaining comparable or higher base shear than Structure A, indicating more effective interlocking action, improved stiffness, and superior overall seismic performance.

The overall findings demonstrate that the two-story mortar-free Interlocking Plastic Block (IPB) cross-joint possesses satisfactory stiffness, stable dynamic characteristics, and considerable energy dissipation capacity under seismic loading. The combination of dry interlocking, lightweight construction, and friction-based damping provides economical and sustainable alternative for earthquake-resistant low-rise buildings. Furthermore, the empirical relationships developed in this study offer a practical tool for predicting the dynamic behavior of IPB cross-joints and may contribute to the future design and optimization of resilient mortar-free construction systems in seismic regions.

6.2 Future Recommendations

The following recommendations are proposed for future research to further improve the understanding of mortar-free Interlocking Plastic Block (IPB) cross-joint systems:

- i. To evaluate the coupled in-plane and out-of-plane dynamic behavior of IPB assemblies using block-return configurations to clarify orthogonal boundary confinement effects and improve multi-directional seismic performance.

- ii. Future research should investigate the axial load capacity and buckling stability of slender double-storey IPB walls to establish reliable structural design limits for mortar-free buildings.

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