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Effect of Diaphragm on Dynamic Behavior of Interlocking Plastic-Block Structure with Different Elements Pattern

by

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Dedicated this work to my parents, for always supporting and helping me throughout my education. Specially to my teachers who guided me to face the troubles with boldness.

CERTIFICATE OF APPROVAL

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Abstract

Economical earthquake-resistant housing is prudent in seismic active regions for developing countries. Because of lack of earthquake-resistant housing, there is significant loss of life in seismic regions. Rural areas often suffer loss of lives due to strong ground motions of earthquakes. Conventional masonry structures collapse is a result of large displacement and strong horizontal ground motions. Many of the methods are used to minimize the effects of the earthquakes. Earthquake- resistant housing needs to be built in developing countries. Interlocking block structure is among one of the possible alternative for earthquake-resistant structures.

The dynamic behavior of interlocking block structures are well-known by many researchers. But the interlocking plastic-block structures are still not completely explored. In this research work, the experimental results of interlocking plastic block structural components have been studied by locally manufactured shake table. The specific goal of current research is to determine the dynamic response of prototype interlocking plastic-block structural elements with diaphragm using locally developed 1D shake table in laboratory. The structure consists of two plastic-block walls, wooden diaphragm and rubber band connections. The effect of diaphragm on dynamic behavior of interlocking plastic-block structure with different elements pattern is studied by using locally built shake table.

Dynamic response in terms of acceleration-time and displacement-time histories of wooden diaphragm and interlocking plastic-block walls are observed. Base shear-displacement curves, energy dissipation, and damping have also been calculated. Effect of diaphragm on walls and effect of wall with opening has been determined in this research. It is determind from previous studies, that the results obtained from the analysis of graphs by using wooden diaphragms produce less relative displacement at top of interlocking plastic-block walls and also dissipate more energy.

Keywords: Mortar-free interlocking, plastic-block, shake table, dynamic response, solid wall

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Abbreviations

1 D	One Dimensional
3 D	Three Dimensional
E	Energy Absorption
IDW	Solid Wall Wall with Window-In-Plan
IDW_{BR}	Wall- Wall with Window-In Plan (With Block Return)
IPBW	Interlocking Plastic-Block Wall
IPBWW	Interlocking Plastic-Block Wall with Window
ISW	Solid Wall- Wall with Window-In Plan
ISD	Solid Wall- Wall with Door-In Plan
ISW_{BR}	Wall- Wall with Window-In Plan (With Block Return)
ISD_{BR}	Wall- Wall with Door-In Plan (With Block Return)
ODW	Solid Wall- Door with Door-Out of Plan
ODW_{BR}	Wall- Door with Window-Out of Plan (With Block Return)
OSW	Solid Wall- Wall with Window-Out of Plan
OSD	Solid Wall- Wall with Door-Out of Plan
OSD_{BR}	Wall- Wall with Door-Out of Plan- (With Block Return)
OSW_{BR}	Wall- Wall with Window-Out of Plan (With Block Return)
RB	Rubber Band
SDOF	Single Degree of Freedom

Symbols

ξ	Damping ratio
f_n	Fundamental frequency
g	Gravitational acceleration
Q	Base shear
$\ddot{u}_{t-IPBSW}$	Average acceleration at top of solid wall
$\ddot{u}_{t-IPBWW}$	Average acceleration at top of wall with window opening
$\dot{u}_{t-E}$	Average experimental velocity
CFRC	Coconut fiber reinforced concrete
$\ddot{u}_g$	Average acceleration at base
$\ddot{u}_{t-E}$	Average experimental acceleration
$\ddot{u}_t$	Average acceleration at top of Interlocking plastic-block structure
u_{t-E}	Average experimental displacement
$u_{t-IPBSW}$	Average displacement at top of solid wall
$u_{t-IPBWW}$	Average displacement at top of wall with window opening

Chapter 1

Introduction

1.1 Background

The shaking of earths surface that create an unpredicted force and seismic wave is called earthquake. Ground motions are the consequences of earthquake that could be produced anytime and anywhere. Earthquake can cause swear destruction to buildings and infrastructures and also results in human injuries as well as loss of lives. Building can overturn in case of moist soil because in such soil plastic behavior starts and soil loses its mechanical strength and ultimately the phenomenon of liquefaction starts during ground motion. A tsunami is a series of waves that are migrated to inland after being triggered by earthquakes or undersea volcanic eruptions. As the depth of the ocean decreases, the waves build up to greater and greater heights. The speed of tsunami waves is determined by the depth of the ocean rather than the distance from the wave's source. In the poor and fast expending countries, there is a need of the construction of economical houses which should be not only in reach of every one but should be constructed very fast and resist strong ground motions. In this regard, many efforts have been made to minimize the damages of earthquake such as the introduction of vertical stiffeners, band/beams at plinth, lintel and roof level of houses with load bearing masonry walls. Countries that are prone to earthquake, the economic and safe housing construction have shown many challenges especially in hilly areas where the construction cost is much high because of the transportation of heavy material to the top.

In case of any earthquake, it is observed that such regions face major human losses and destruction of properties because lake of knowledge of earthquake resisting construction houses. To achieve the goals of economic, fast construction, and seismic resistance houses, a technique of the construction of plastic inter-locking block has been investigated. For this purpose Ali [13] proposed a cheap and inexpensive solution by introducing mortar free interlocking plastic-block structure solution to construct earthquake resistance structures. Such plastic inter-locked blocks dissolve more seismic shock due to their relative movement. It was investigated that by the introduction of diaphragm the dynamic performance of interlocking block wall systems has been improved and it was proved that it has provided better performance than mortar brick masonry.

Many researchers have worked on interlocking block masonry system. Interlocking blocks are used to reduce the construction cost and save the time of construction. Ali [25] proposed a cheap mortar free interlocking structure by using coconut-fiber ropes and coconut-fiber-reinforced-concrete interlocking blocks (a new construction technique for earthquake-resistant housing). It was suggested that the interlocked walling system is a probable solution for traditional brick mortar masonry because under axial and eccentric loading it shows stronger or comparable structural performance.

Interlocking plastic block walls with wooden diaphragm model are to be used with rubber reinforcement for earthquake shaking. To produce real earthquake motion data, an electro-hydraulic shake-table with six degrees of freedom is desired. Hydraulic shaking table of six degree of freedom cannot be used because it is not worthwhile and need more functioning and repair cost. To overcome such type of issues, 1D (One Dimensional) shake table can be used in earthquake engineering laboratory. It is a very challenging to develop shake-table for the earthquake engineering laboratory at low cost. To study the dynamic performance of structures single translation degree of freedom shake-table is used because it is cost-effective. From this point, un-axial shaking tables were designed at short cost.

By using local economical shake-table, the earthquake simulation can be found in laboratory. To produce earthquake simulation shake-table is used to test prototype structure.

No research was carried out to the best of the authors knowledge to investigate the behavior of interlocking plastic-block with diaphragm structure with different elements pattern under harmonic loading using locally developed low-cost 1D shake table.

1.2 Research Motivation and Problem Statement

Earthquake causes severe damage, such as building collapse, roads and bridges that can kill many people. Such sufferers can be abridged if specific behavior of structures during earthquake is considered which can help in its appropriate design. Developed countries have all facilities and provide relevant services for researchers and designers to design earthquake resistance structures but on the other hand developing countries are requiring these facilities. The performance of structure may be studied with locally developed shake table (operating in one direction which is one of the solutions). The confined brick structures are the second but could cost a bit. A cheap solution is needed for which Ali [13] proposed an economical solution but the mass of block still needs to be reduced. Interlocking plastic-block structure can be one solution but there was a concern that the plastic block are prone to catch quick fire, the issue could be reduced by the use of fire resistance paint to the plastic blocks. For financial and environmental aspects, plastic waste can be recycled for this cause (note: for time beings, it is outside the scope of this work). Thus, the problem statement is as follows:-

In earthquake, most of the masonry structures collapsed due to design deficiencies [20]. Ali [24] developed a mortar free structure (a new construction technique) for earthquake-resistant houses. A mortar-free interlock- ing plastic-block structure has the capability to dissipate energy of earthquake but the use of coconut fiber reinforced concrete blocks in bulk is still a point of concern. Lighter the mass of structure, lower is the inertia force produced. For this, light weight interlocking plastic-block is one option towards the solution together with fire-resistant paint. For such kind of structure (i.e mortar-free interlocking plastic-block structure), dynamic behavior should be considered. This can be done with simple shake-table. So, the behavior of interlocking plastic-block with diaphragm structure is required to be examined under dynamic loading by using locally developed 1D shake-table.

1.2.1 Research Questions

– How much energy absorption is increased after the installation of wooden Diaphragm?

– How much percentage deflection has been reduced after the installation of diaphragm on different walls of interlocking Plastic-Block Structure of different elements pattern.

– How much increase in dynamic response such as displacement is reduced after the installation of wooden Diaphragm compared with In-plane and out-of-plane structure behavior?

1.3 Overall Objective and Specific Aim

The overall objective of the research program is to analyze the 3D seismic response accurately of full-scale structure in laboratory and field. The specific aim of this MS research work is to investigate the dynamic response of a different prototype interlocking plastic-block structural elements with diaphragm using locally developed 1D shake table in laboratory.

1.4 Scope of Work and Study Limitations

Different prototype interlocking plastic-block structure with different elements pattern are tested under dynamic loading's of 90 rpm, 120 rpm and 150 rpm. Response in respect of acceleration-time, velocity-time, and displacement-time histories will be documented. Study limitations include the use of simple 1D shake table, only two accelerometers (one at base plate of shake table and other at the top), and three loading's (90 rpm, 120 rpm and 150 rpm) will be applied.

1.4.1 Rationale Behind Variable Selection

Out-of-Plane response of structure with diaphragm will be examined by using interlocking Plastic-Block structural elements and 1D shake table. Shake table test in laboratory is a cheap process to investigate the fundamental frequency and maximum failure acceleration on small-scale prototype structure. Reason of the selection of interlocking Plastic-Block structural elements for this research study is because the Plastic-Blocks are light weight and absorb more energy as compared to masonry walls [14].

1.5 Novelty of Research, Research Significance and Practical Implementation

To the best of authors knowledge, no work has been done to investigate the dynamic response of diaphragm on interlocking plastic-block structure with different elements pattern by using a low cost shake table. Further the in-plan, out-of-plan behavior of complete structure with diaphragm will be produced. The behavior such as in-plan, out-of-plan of the complete structure will come to know by elaborating the results of Single-Degree- of-Freedom.

1.6 Methodology

Twelve different types of prototype walls (interlocking plastic block walls) and a wooden Diaphragm with fixed base are proposed to check the dynamic properties in respect of acceleration-time, velocity-time displacement-time histories, frequency and damping. For the analysis, an individual test is conducted once by fixing an accelerometer on shake table and one on top of diaphragm and then fixing both accelerometers on the top of the walls by setting the frequencies of 1.5 Hz, 2 Hz and 2.5 Hz. The same three structural frequencies of previous works (e.g. Sudheer, Afzal etc) are used in current study because this is continuation of their research in which similar prototype construction (i.e. prototype blocks, house dimensions, scaling factor etc) has been used. It is assumed that the employed frequencies would encompass the fundamental frequency of the complete structure. Frequency and damping will be determined. Thus, it might help to understand the global as well as local behaviors at these frequencies. It may be noted that the effect of material frequencies and shear keys contributions is outside the scope of this MS thesis (only structural frequencies are being employed). From material (plastic) to product (interlocking block including shear keys design) to structural elements (mortar-free interlocking column or wall including shear key contribution at interface for energy dissipation, wall stiffness etc), it is being parallely studied at doctoral level. All twelve types of element patterns will be tested by performing of 72 tests. Response of all walls in out-of-plane direction in terms of acceleration-time will be recorded. Then the processed acceleration-time and displacement time histories are obtained using seismo-signal software. With the assistance of displacement vs time-history, acceleration vs time-history data and base shear (Q) will be calculated. The averaged energy absorption in one cycle will also be calculated which called total energy is observed.

1.7 Thesis Outline

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

Chapter 1 comprises of introduction section. It includes background, research motivation and problem statement, overall objective and specific aims, scope of work and study limitations, methodology adopted for conducting the research and description of the thesis.

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

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

Chapter 4 comprises of experimental evaluation. It contains background, results of snap back test, behavior of walls against harmonic loading's, calculation of base shear, damping ratio and energy absorption and summary.

Chapter 5 comprise of dialogue. It contains background, relationship of empirical equations, outcome of study with reference to practical requirements and summary.

Chapter 6 comprises of conclusions and recommendations. References are present right after chapter 6.

Annexure A is provided after references.

Chapter 2

Literature Review

2.1 Background

The shaking of earths surface that create an unpredicted force and seismic wave is called earthquake. Ground motions are the results of which could be produced anytime and anywhere. Earthquake can cause swear destruction from buildings to infrastructures resulting human injuries and loss of lives. Building can overturn in case of moist soil because in such soil plastic behavior start and loses its mechanical strength and ultimately the phenomenon of liquefaction start during ground motion.

The Primary effect of the earthquake is to attack houses and causes the damages of highways therefore directly effecting human beings [15]. As there is no trend of constructing the earthquake resistant houses in most of the developed countries if compared to their population resulting the human losses. The earthquakes severely damages of the traditional construction of masonry structures and the same was happened in 2005 Kashmir-Pakistan earthquake and causes the destruction of more of less of 450,000 structures including schools, colleges, universities and government buildings [16]. The Sichuan, Chinas earthquake in 2008 of recorded with one of the utmost scale not only targeted the buildings by collapsing about 216,000 in numbers but human population was badly affected by killing 70,000 people [17].

A notable earthquake with scale of 7.6 magnitude recorded near the western coastal areas of Sumatra in 2009 with a destructive effect on a vast number of traditional masonry structures. This earthquake has badly affected the infrastructures as well as the society [18]. The Haiti earthquake in 2010 with recorded magnitude 7 on rector scale causes the human loss of 316,000 and severe casualty of more than 300,000 in numbers. The authorities of Haiti claimed that 80-90 percent bricks constructed structures were primarily damaged [19]. In 2010 in Maule seismic incident of some 80,000 citizens were badly offended with death toll of 524 were recorded [20]. The Lombok Earthquake was happened in June 2018 damaging Indonesia badly where 154,000 people were killed [21]. To minimize the human casualties and suffering from the devastating effect of earthquake, it is required to construct earthquake resistant houses. A realistic way out is to present the inexpensive seismic-resistant structures in far-flung rural areas for in severe seismically effected areas [22]. In region of seismic affected areas with strong ground movements, these high earthquake zones results massive loss of human-being in absence of earthquake resistant structures.

2.2 Damages of Masonry Structure During Earthquake

During the earthquakes, numerous researchers from all over the world reported damage to traditional unreinforced masonry structures. Owing to their un-containment and weak diaphragm anchorage, much of the damage to masonry structures occurred. Sharma et al. [40] Lead survey research after the 2015 Gorkha earthquake in Nepal. Approximately 80000 partially or completely damaged buildings have been recorded. Jagadish et al. [22] During the 2001 Bhuj earthquake in India, conducted a report on the action of unreinforced-masonry structures. The study concludes that most of the mud mortar or lime mortar masonry buildings were badly damaged due to the poor strength of the bond. Due to the heavy bonding, masonry buildings with cement mortar are more resistant than others, according to the report.

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

2.3 New Approach for Earthquake Resistant Structure

Majority of the traditional masonry houses generally collapse due to ignorance of adopting proper designs and engineering practices as well as following contemptible construction procedure [23]. To achieve the goal of producing safe houses by resisting ground motion an alternative and cheap solution is to produce interlocking blocks which could not only resist earthquake but could be a fast and low cost construction solution [24]. To get creative and economic solution, new techniques have been developed by using the mortar-free interlocking blocks to construct earthquakes resistance structure [25]. Many researchers have contributed in this regard and have presented many ways and solutions to make safe and earthquake-resistant houses and medium tall buildings by using interlocking blocks [26]. The weight of interlocking blocks is a point of concern, to do so an effort was made by introducing CFRC (Coconut fiber reinforced concrete) interlocking block. Where coconut fibers were added to reduce the weight of interlocking block, but ultimately the mass of CFRC block was observed to increase instead of decreasing [2].

In this research work, interlocking plastic blocks are investigated because of the lower weight of interlocking plastic blocks. Due to the interlocking key of interlocking plastic blocks, these interlocking plastic blocks dissipated more energy in seismic situations. Fayyaz and Ali conducted in their previous research to determine the dynamic response of interlocking plastic blocks using columns composed of made up of interlocking plastic blocks [13]. However, the complex behavior of various elements of the interlocking plastic block structure needs to be studied. In addition, the incorporation of waste marble powder (WMP) into the interlocking of burnt clay bricks can lead to economic and sustainable construction of masonry [18]. In this research, for dynamic response, interlocking plastic block walls with wooden diaphragm are examined. In such houses the roofs are provided to cover it from the top, protecting it from rain, sun and many other catastrophes. The response of seismic or dynamic of diaphragm structures depends upon the supports and connections [27]. Wooden diaphragms are used because of their strong efficiency during seismic activity in rural areas. [28].

Elvin et al. [65] investigated the full scale structural behaviour under harmonic loading in lab where complex study of a prototype structure was performed. It was also confirmed that earthquake-related structural damage can overcome if the structure is adequately built to withstand earthquake loading. No work was done to establish the impact of the diaphragm to the best of the authors knowledge on dynamic behavior of interlocking Plastic-Block structure with different elements pattern. This research therefore helps to explain the complex behavior of the interlocking structure of plastic blocks for practical use in design and building. A research to enhance lateral resistance in mortar- free interlocking walls with plaster using natural fibers was conducted by [47]. The out-of-plane lateral resistance is the key explanation for the mortar-free interlocking wall device failure. This study shows an improvement in lateral peak load and a further increase in the reinforced plastered wall system of rice straw and sisal fiber. Liu et al. [49] examined non-interlocking mortar-less brick and interlocking mortar-less brick cyclic behavior. During the analysis of cyclic behaviour the impacts of different interlocking modes, loading compression stress levels and loading cycles were considered. A mechanical sample has been developed with the aid of the hysteresis loop technique. By using the mohr-coulomb failure technique, the shear failure modes of all the tested joints were well-defined. It was carefully observed to increase the loading duration, decrease the friction coefficients of all the joints. A major raise in the degradation of friction has been seen with the decrease of the flatness of the interlocking surface.

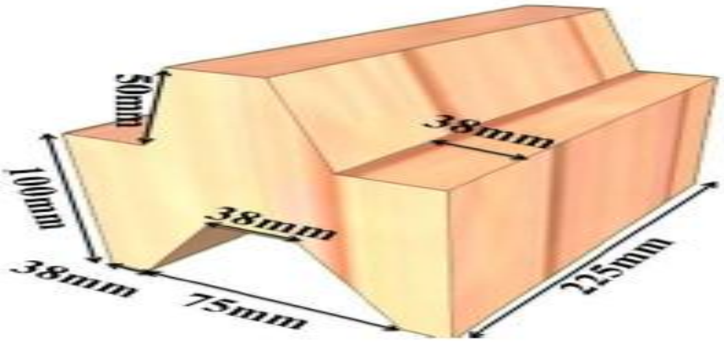


Figure 2.1: Interlocking Burnt Clay Brick [18].

Out-of-plane conduct is more important than in-plane conduct. Several researchers stated that due to the failure of out-of-plane behavior, most of the damage and collapse in unconfined masonry structures occurred. However, the prototype structure appear to underestimate the real OOP ultimate displacement potential until significant damage occurs [48]. Various studies have been per- formed on the implications of out-of-plane actions. Kallioras et al. [52] given a single data collection that captures the in-plane and out-of-plane efficiency of un-reinforced masonry walling at full-scale. And given a complex global reaction of an earthquake building to load. Saifee et al. [19] concluded that the action of the wall was largely controlled by broad horizontal displacement and dry joint opening at the mid-height of the wall (location of extreme moment). Fig. 4 demonstrates less wall exposure of the interlocking mortar to out-of-plane loading. Martinez and Atamturktur [46] understand the wall results in order to understand the less masonry wall was experienced under out-of-plane loading. Due to the increase in block compressive strength and impact of the wholly or partially grouted wall, improvement in critical lateral load ability was evaluated.

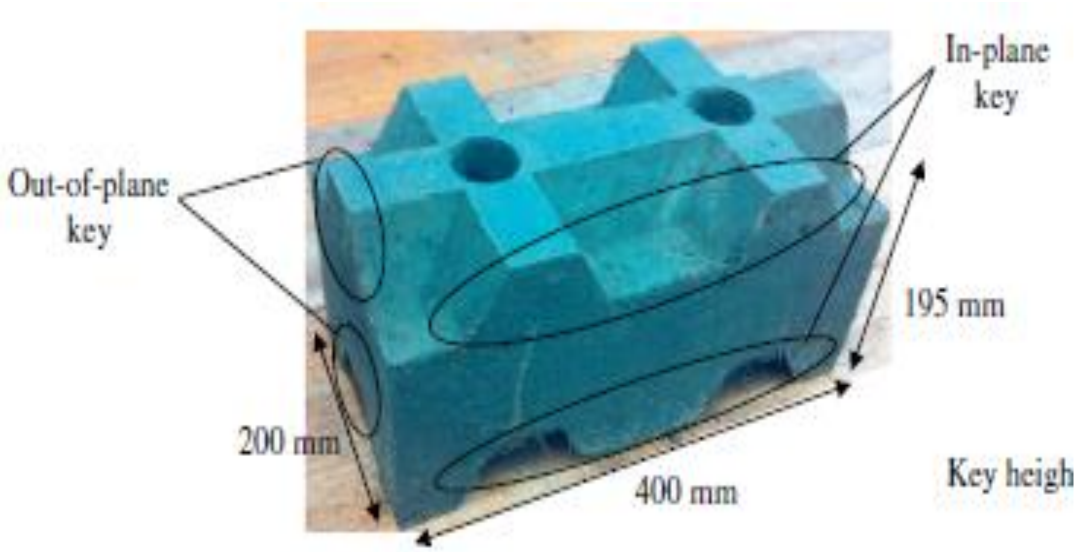


FIGURE 2.2: Interlocking Block of Coconut Fiber Reinforced Concrete (CFRC) [16].

In Table 2.1, the out-of-plane behavior of mortar-free walls is shown by different researchers in different studies. No research was conducted to investigate the action of effect dynamic response of diaphragm on interlocking plastic-block structure with different elements pattern by using locally built low cost 1D shake table to as per the information of an author.

2.4 Effect of Walls having Block-return and Stiffeners Along with Diaphragm

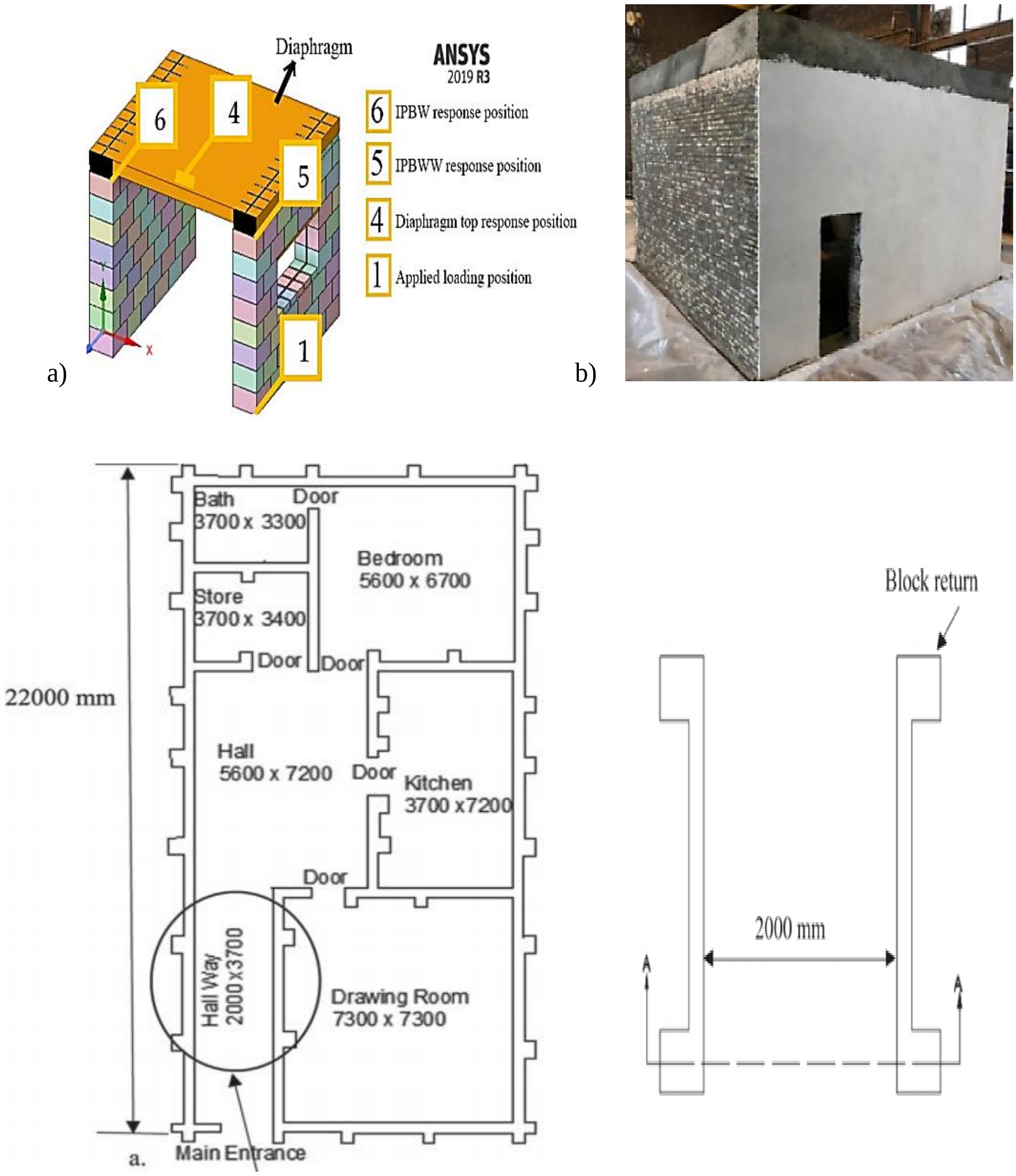
Brick masonry is one of the ancient and widely implemented construction practice. The supply of brick masonry structural members in ancient buildings is additionally abundant. Throughout the earth, unreinforced brick masonry buildings are continuous threat to mankind, because of their high vulnerability to seismicity [22]. The biggest contribution to the economic loss caused by an earthquake is the damage to structural components. These structures were constructed with conventional materials and by considering the gravity loading only [3]. These materials in majority of the cases are bricks, stones and wood, which arent earthquake resistant [5]. In October 2005 earthquake of Pakistan, most of the traditional unreinforced buildings including concrete block brickwork, conventional brickwork and stone masonry were fully or partially damaged [23]. Similarly, separation between the roof diaphragms and therefore the masonry walls (in the out-of-plane direction) and damage to masonry pillars at upper levels of unreinforced masonry buildings were observed within the 2010 Darfield (Christchurch, Nz) Earthquake [13]. Seismic performance of masonry buildings were studied in laboratory by many researchers within the past. Immense non-linear behavior of unreinforced masonry was observed within the laboratory testing under time-scaled Nahnni earthquake 1985 [24].

Reyes et al. [45] performed a study on earthen wall with the opening having horizontal and vertical wooden stiffeners to discover the seismic behavior. On contrary, reinforced brick masonry within the sort of concrete stiffeners usage enhanced strength and stiffness of the masonry buildings [25]. Not only by laboratory research, but even in the case of actual earthquake loading, these phenomena were confirmed. The failure modes during the laboratory testing changed from diagonal tension or shear slip into a mixture of diagonal tension and toe-crushing. Incorporation of reinforcing elements in mortar joints prevented the structure from cracking [26]. When subjected to lateral laboratory loading, confined masonry walls with horizontal stiffeners performed well compared to non- confined walls. Masonry walls with vertical stiffeners had a large improvement in seismic ability relative to unreinforced walls in terms of steel links [27]. Reyes et al. [45] conducted the study on seismic behavior of earthen wall with opening having horizontal and vertical wooden stiffeners. Mexico country features a long record of using confined masonry technique in their housing construction. Graziotti et al. [49]) examined the out-of-plane behaviour of a full-scale wall with a outer leaf (block-return). Samples consist of an OOP panel and two window opening and non-opening block-return walls. A research was conducted to enhance the lateral resistance in mortar-free interlocking block-return walls with plaster by using natural fibres [47].

- Out-of-plane lateral resistance is the main factors for the failure of the mortar-free interlocking wall framework.
- In this analysis, regular increase in lateral peak load was noted for the reinforced plastered wall system of rice straw and sisal fibre.

Its the foremost common construction practice within the country, and is extensively utilized in the country. Confined masonry is typically practiced within the sort of engineered and non-engineered construction everywhere the country. During the 2003 earthquake of Tecomn having magnitude 7.6, designed masonry structures performed significantly well than un-designed brick masonry buildings; majority sizable amount of designed masonry buildings were unharmed or grieved only slight damage [28]. Qamar et al. (2020) [47] carried out a study for the improvement of lateral resistance in mortar-free interlocking block-return walls with plaster by using natural fibers.

The major reason of the failure of mortar-free interlocking wall system is the out-of-plane lateral resistance. Increase in lateral peak load was noted in this study and further increase also noted for rice straw and sisal fiber reinforced plastered wall system. They studied the out of plane behavior of wall with an outer leaf constructed (block-return). They deliberate the four single leaf and one cavity U.R.M full-scale walls by separately examined full-scale samples comprising of OOP panel and two return-block walls, fluctuating in terms of boundary conditions usually encountered and overburden added or the absence/presence of an opening. The samples were subjected to incremental input motion arrangements before the failures were completed, and these findings were illustrated in terms of deformed profiles, failure mechanisms and hysteretic displacement-force curves. Best in class logical procedures dependent on the technique for virtual work was applied to assess their dependability as disentangled apparatuses for evaluating the conduct of all walls exposed to OOP two-way twisting excitation. The harmonic tests were found to be more successful in identifying the fundamental frequencies of the structure compared to the snap-back test. Fig 2.3 below shows the previous works done on plastic block walls with diaphragm to show the dynamic behavior of interlocking plastic-block structure.



a)

b)

FIGURE 2.3: Previous works done by other researchers on different Patterns of walls having diaphragm, a) Bashir (2020), b) Ghezelbash et al. (2020)

2.5 Dynamic Performance of Prototype Structure in Laboratory

In the past, major experiments have been carried out to review the behavior of real-life structures with the aid of scaled-down laboratory prototypes. In developed countries, the 3-D shake table with six degrees of freedom is used to investigate the dynamic structure response in order to obtain real earthquake data. Emerging countries, on the other hand, lack such a refined and costly 3-D shake table for multiple pieces. These countries, however, use a simple 1-D shake table to understand the dynamic response of laboratory prototype structures. The goal behind the development of laboratory prototype structures is to carry out such studies. Several researchers have performed dynamic laboratory testing of small and large-scale designs using the shake table. In these experiments, simplified boundary conditions have been applied for small-scale research. Second, well-designed secondary structure parameter distributions result in a multi-mode tuning between the primary and secondary structures and thus a multi-mode control effect [49]. These studies confirm the conduct of prototype research using the shake table inside the laboratory. Time history analysis can be a useful technique for the determination of the seismic behavior of certain prototypes under dynamic loading [31]. The action of full-scale structure under harmonic loading has been studied [32], [33] and [34]. The results of the study revealed that the responses of the top and bottom relations are very different. The top connection appears to have typical Coulomb friction behavior, while the bottom connection's response is best defined by visco-elastic behavior.

Some researchers have performed small to large-scale dynamic testing. Shake table was used to prototype structures in the lab. In these studies, simpler boundary conditions were used for small scale monitoring. Stareini et al. [38] The most critical finding is that the floor diaphragm's bending stiffness has very little effect on the collected results for these particular studies. The stiffness of the wall-to-floor diaphragm connections, on the other hand, has a substantial effect. Tamagnone et all. [55] Despite the large number of nonlinear cycles imposed by successive documents, the structural response was not significantly affected by the alternative constitutive relations considered. Sousa et al. [46] Walls collapsing and dropping objects pose a serious threat to life safety that must be assessed. In an ideal world, new laboratory data and bench-marking samples will be merged in an effort to reduce the ambiguity in current risk management methodologies and fatality with outcomes [58]. Multiple dynamic studies were conducted to determine the primary failure mechanism and to examine the effect of various seismic input motions on the structure's response [58-61]. As the hysteretic portion increased, there was a lower participation of energy dissipation due to impacts. The overall drift of rocking walls as well as the number of wide drift excursions after the first peak of response were both reduced as hysteretic damping was increased. Using the force-displacement hysteresis response's enclosed area. Nazari et al. [60] Energy is consumed due to the hysteretic behaviour, the connections also respond inelastically during the dynamic response which also consumed more energy in each cycle. Ioannis N. et al. [55] Compared with the un-controlled traditional suspended buildings, average reductions of 50 percent in the top displacements of the primary structure and 45 percent in the accelerations of the suspended modules are seen. Time-history curves show lower peaks of the passively controlled structures and faster decay [35]. The dynamic study of the prototype structure was studied and carried out in a laboratory.

Table 2.1: Detail of different studies conducted in laboratory to determine the dynamic performance of prototype structure by using Shake Table.

Prototype	**Structure Findings**
Plastic block column for interlocking with and without rubber band [6]	Compared to columns without rubber band, the column with rubber band performed well against harmonic loading.
Comparing Interlocking plastic block wall with masonry wall [39]	The window of the interlocking plastic-block wall withstands harmonic loading when the masonry wall has collapsed during testing.
Rate independent linear damping performance of inter-story isolated structure [40]	To research a 14-story inter-story isolated structure, real-time hybrid simulation on shake table is used. By limiting isolation layer displacements without amplifying accelerations, RILD provides an appealing control alternative.
Full-scale corner wall retrofitted with timber elements, out-of-plane shake table test [42]	Propose a retrofitting technique for both in plane and out of plane directions that increases the wall power. In order to form a confining wood frame, this technique consists of symmetrically stalled vertical and horizontal timber elements on each face of the wall, complemented by vertical tensors that recompress the wall.

Laboratory shake table testing was performed to evaluate the out-of- plane output of partially grouted, reinforced concrete masonry walls subjected to simulated seismic loading [46]. A research on the dynamic analysis of the burnt clay brick wall structure in the laboratory was performed by [47]. The use of a shake table in the laboratory for dynamic analysis is well known. Complex 3D shake tables are used in developed countries, while 1D shake tables are used in developing countries due to their low cost. Many researchers have used the shake table to investigate the dynamic behavior of prototype structures. Chen et al. [66] used a shake table to perform tests on a quarter-scale frame structure to determine the prototype structure's strategy for suppressing storey drift and accelerating the structure's floors. Similarly, several studies have been carried out in the past, using small-scale experiments to investigate the real complex activity in the laboratory.

2.6 Summary

Conventional masonry structures are vulnerable to earthquakes. The restricted masonry technique has been introduced by contemporary countries in their building methods. Nevertheless, up to a certain range, they are also vulnerable to earthquake vibration. As brickwork replacement, scholars are focusing on interlocking mortar-free bricks. For these bricks, current literature has implemented several interlocking methods, sizes and shapes. In this respect, a possible solution for earthquake tolerant housing is interlocking block buildings. As always, because of the resultant higher inertial forces during the earthquake, the greater mass of interlocking blocks is a point of concern. Therefore, there is a need to reduce the mass of the interlocking blocks.

The lighter the block mass, the smaller the inertial forces produced during the earthquake. From material (plastic) to product (interlocking block including shear keys design) to structural elements (mortar-free interlocking column or wall including shear key contribution at interface for energy dissipation, wall stiffness etc), it is being parallelly studied at doctoral level. All twelve types of element patterns will be tested by performing of 72 tests Dynamic conduct of plastic inter-locking block-return walls is considered for that type of construction (i.e. mortar-free interlocking plastic-block structure). This can be achieved with a simple table for shaking. The behavior of plastic inter-locking block-return walls is therefore investigated by using the low-cost 1D shake table locally built under dynamic loading.

No research has been performed to the best of the authors knowledge to investigate the action of plastic interlocking block-return walls under harmonic loading using a locally built low-cost 1D shake table. Therefore, current research would help to explain the behavior of interlocking plastic-block walls with rubber band block-return for future use in comparison to harmonic loadings.

Chapter 3

Experimental Program

3.1 Background

When talking about the earthquake resistant architecture of buildings, the response and reaction of structures during the earthquake is very important to expect or quantify. Different methods have been adopted all over the world for this particular determination. The method of assembling the plastic interlocking block-return walls, snap back test, harmonic loadings, analysis parameters, development of empirical equations, test setup and instrumentation using the low-cost 1D shake table locally developed is described in this study.

The interlocking plastic block for earthquake-resistant house (plan and 3D view of the proposed house is shown in Figure 3.1a and Figure 3.1b respectively) and prototype testing is proposed by [38] due to its lighter weight and lower inertial forces. In earthquake-resistant structures, the role of material weight and consequent inertial forces is very crucial. Inertial forces are usually taken as the ability of a system to withstand changes caused by any external force (acceleration). The theory is based on Newtons Laws of Motion, namely the 1^{st} and 2^{nd} Laws. Heavy systems (materials) react more in response to this external force because of their higher weight as compared to lighter systems (materials), thus creating higher inertial forces. The proposed interlocking plastic for construction of earthquake resistant housing are shown in the figures:

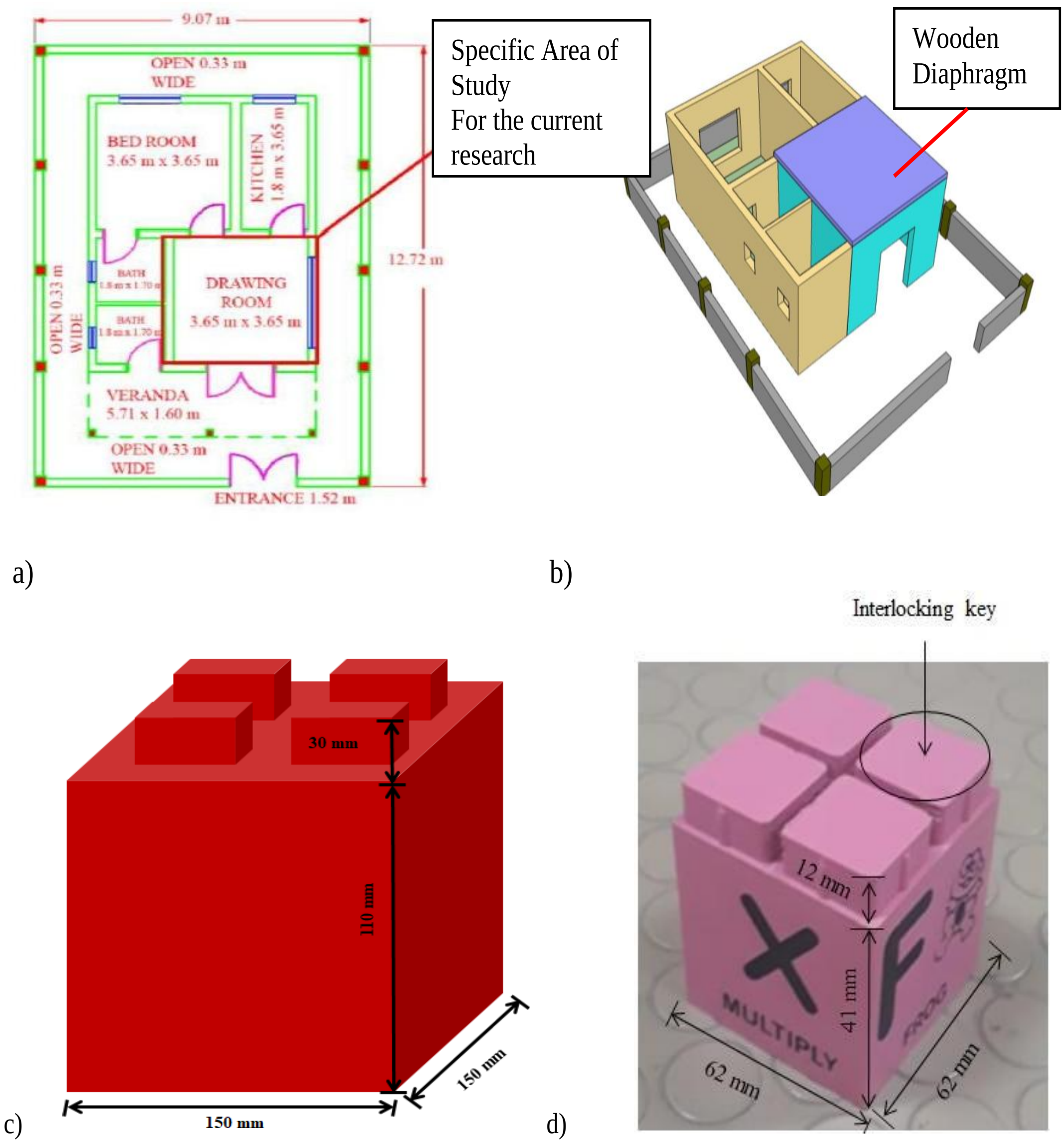


FIGURE 3.1: Proposed inter-locking plastic-block house: a) plan, Bashir (2020) b) 3D view and Inter-locking plastic-blocks c) proposed for construction and d) prototype for current study. [38], [39].

The blocks have base dimension of 150x150 mm and have four keys at the top. The total block height is 140 mm, including the 30 mm interlocking key height, as shown in Figure 3.1 (c). Similarly, the measurements used in the study for prototype construction are 62x62mm with a height of 53 mm, including the interlocking key height of 12 mm, as shown in Figure 3.1 (d). The strength of a said block is 0.1 MPA as determined by [13]. The latest research work is the continuation of research work of [38-39]. For dynamic research, prototype plastic interlocking block-return walls (solid wall, window opening wall and door opening wall) will be considered in this analysis. Prototype testing helps to include, rather than theoretical, criteria for a real or proposed working de- vice. The scaling and construction technique of prototype walls adopted in this research work is based solely on research practices referred to in the literature [40]; [41]; [42]; [43]. The outcomes of such studies help to comprehend the behavior of full-scale systems. The primary aim of current research is to study the dynamic behavior of block-return structural walls with diaphragm of different walls pattern. The structural time period is an important parameter for this, which depends on the height of the structure (UBC-97). For this purpose, the scale-down approach is primarily applied to the elevation dimension of structural walls. It should be noted that the dimensions of the units used in both designs are slightly different (i.e., scaled down wall samples with block return). The elevation measurements are, however, roughly the same in both prototypes. Figure 3.2 (a) shows schematic diagram of proposed real walls made up of interlocking plastic blocks. It will have some grooved block mechanism for foundation and roof diaphragm and prototype interlocking plastic block wall scaled down schematic diagram, using 1/10 scale factor. 1/10 scale is applied on elevation dimensions by considering the method A of UBC-97 regarding time period which depends only on the structure height. Figure 3.2 (b) demonstrates the analysis of the interlocking plastic block column prototype with and without a rubber band [38]. Figure 3.2 (c) shows the comparison of interlocking plastic block with brick masonry wall by [39].

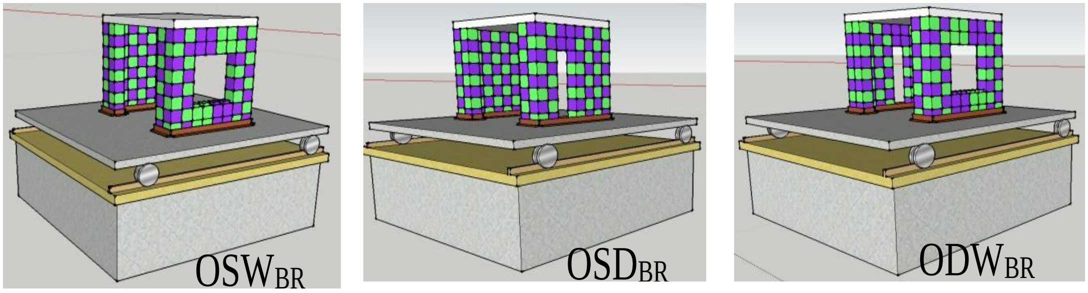
3.2 Construction of Prototype Walls with Diaphragm of Different Elements Pattern

Prototype solid wall interlocking plastic block with block-return and standard first three layers consists of sixty-four (64) plastic interlocking blocks, allowing a total height (H) of 330 mm as shown in Figure 3.3 (c). It is a firm wall with no opening i-e no window or no door. To provide vertical stiffness in the wall, rubber bands are connected from bottom to top through mid-blocks. With the help of base plates and nut bolts, a fixed base was given. A diaphragm is provided on the top of the walls made of ply wood with dimensions equal to 375 mm x 496 mm and 25 mm thick. The mass of the wooden diaphragm was about 0.35 Kg and it was fixed to the walls with the help of rubber. Therefore, the total wall (M) mass became equal to 2.225 Kg, including the mass of the walls which was 1.875 kg. The load capacity of the wall The plastic interlocking block-return wall prototype with window opening consists of 58 plastic interlocking blocks (58), allowing a total height (H) of 330 mm as shown in Figure 3.3 (e). In the center, it has an opening in the form of a window. The opening scale is 125x125 mm. A wooden lintel is provided as a supporting tool over the window opening. Moreover, to provide vertical stiffness in the wall, rubber bands are tied-up from bottom to top by mid-blocks. With the help of base plates and nut bolts, a fixed base is given. Again at the wall top, the same wooden diaphragm is installed. Therefore, the total wall mass (M) became equal to 2.065 Kg including the mass of the wall which was 1.715 Kg. Similarly, the plastic interlocking block-return wall with door opening prototype consists of 55 plastic interlocking blocks, giving a total height (H) of 330 mm as shown in figure 3.3 (c). It has a door-shaped opening on the right side of the wall. The wooden lintel band is supplied above the support mechanism opening. Moreover, to provide vertical stiffness in the wall, rubber bands are tied-up from bottom to top by mid-blocks. Nuts and bolts are applied to fix the base plates with the base. The 3D prototype plastic wall samples with different patterns having diaphragm can be seen in the Fig. 3.2.

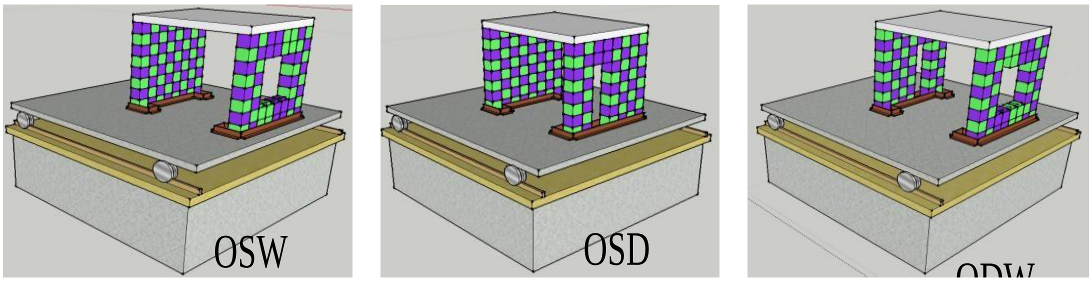
Table 3.1: Labeling Scheme of prototype

Wall Combinations	**Out-Plane**	**Out-Plane**	**In-Plane**	**In-Plane**
—	Without BR	With BR	Without BR	With BR
Solid Wall- Wall with Window	OSW	OSWBR	ISW	ISWBR
Solid Wall- Wall with Door	OSD	OSDBR	ISD	ISDBR
Wall With Door- Wall with Window	ODW	ODWBR	IDW	IDWBR

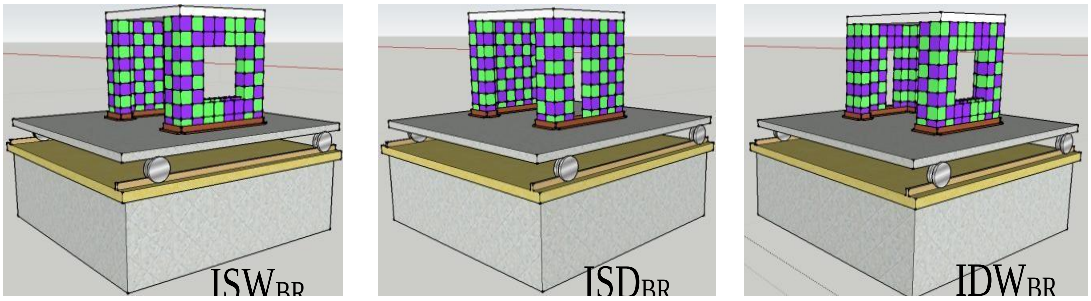
Various wall patterns are prepared for this research work. The Table 3.1 shows the Labeling Scheme of these prototype walls and Figure 3.2 show the Schematic diagram of prototype interlocking block walls with diaphragm on each pattern placed on Shake table.



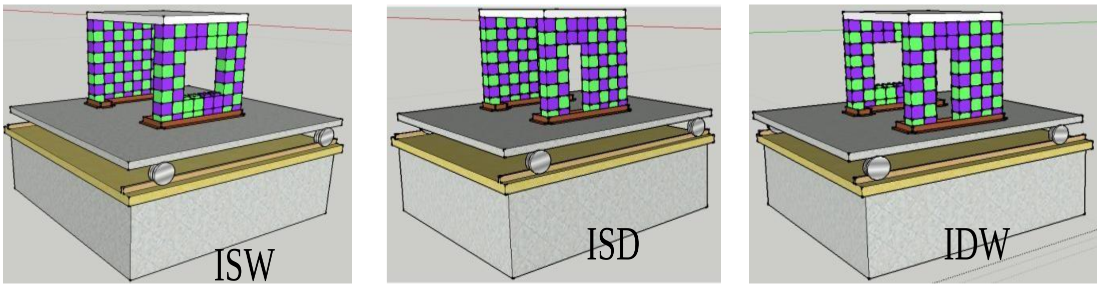
a) Out-of-Plan Pattern with Block Return



b) Out-of-Plan Pattern without Block Return



c) In-Plan Pattern with Block Return



d) In-Plan Pattern without Block Return

FIGURE 3.2: show the Schematic diagram of prototype interlocking block walls with diaphragm of different patterns on shake table.

3.3 Test Setup

3.3.1 Snapback Test and Instrumentations

Figure 3.3 shows the Schematic diagram of experimental test: a) Snap back test of different pattern of walls attached with diaphragm b) proposed harmonic loading. The test was performed in such a way that a wire having length of 400 mm is attached at the top of all interlocking plastic-block walls.

Free vibration of the interlocking plastic-block walls are observed by leaving the attached wire. Responses of the walls are recorded in terms of acceleration-time history using the accelerometer data. Log decrement method is used to calculate the damping ratio (ξ) and fundamental frequency (f_n) of the all interlocking plastic-block walls having block-return.

3.3.2 Shake Table Test and Instrumentations

The instrumentation of shake table research and proposed harmonic loading are shown in Figure 3.3 (a). On the shake table, all plastic interlocking block-return walls (solid wall, window opening wall and window opening wall) are placed one by one using base plates and nut bolts. Two accelerometers are used in total (one is attached to the top of the diaphragm and one is attached to the base of the shake table), repeating this procedure on all walls patterns.

In terms of acceleration-time history, responses from all walls are registered. As it is already described that 1/10 scale is applied on elevation dimensions by considering the method A of UBC-97 regarding time period which depends only on the structure height. However, as per Performance based design the half width wall (4.5” wall) behave better under seismic loading instead of full width wall (9 wall). Additionally the full width wall perform well against seismic load in Code based analysis. Then this information is translated using the seismo-signal program into velocity-time history and displacement-time history.

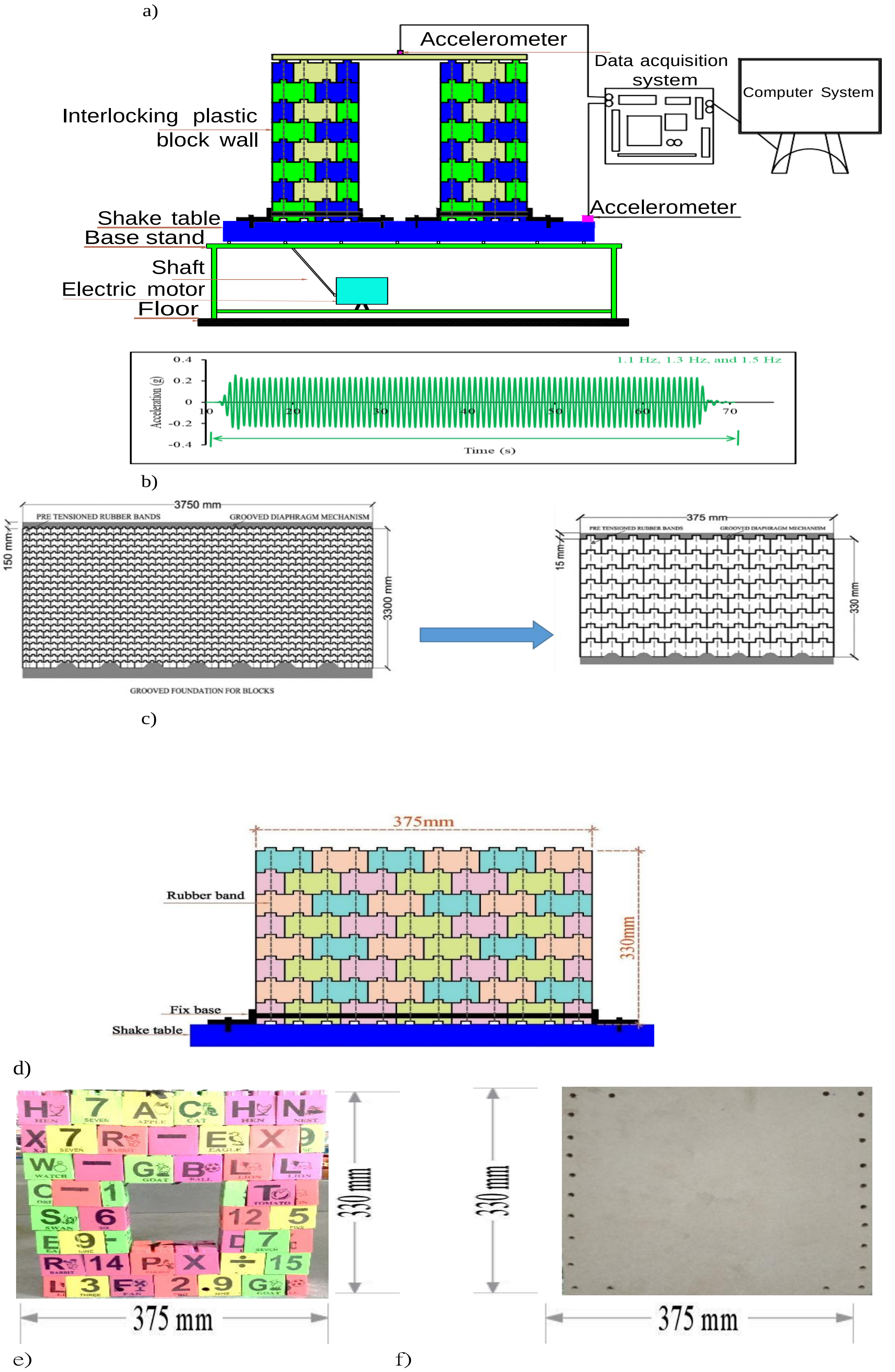


FIGURE 3.3: Schematic diagram of experimental test a) Snap back test of different pattern of walls attached with diaphragm b) proposed harmonic loading c) Schematic diagram of real wall d) Prototype wall with simplified boundary condition e) Wall with opening and f) wood diaphragm

3.4 Loadings

3.4.1 Snapback Test

The snapback test is performed in such a way that all the prototype walls with different patterns having diaphragm were displaced by 50 mm from the top with the help of attached wire one-by-one to perform a snap back examination. Then, to generate free vibration, the wire was abruptly released. With the aid of the accelerometer attached at the top of the wall, acceleration- time history data was collected for different interlocking plastic-block structure with different structural element patterns walls along with diaphragm. The damping ratio and fundamental frequency have been determined with the help of the log decrement process.

Table 3.2: Magnitude of loading considered for all prototypes

Test	**Amplitude**
Snap back	u_t=50 mm
Harmonic	u_g = 30 mm (f=1.5 Hz)
	u_g = 30 mm (f=2.0 Hz)
	u_g = 30 mm (f=2.5 Hz)

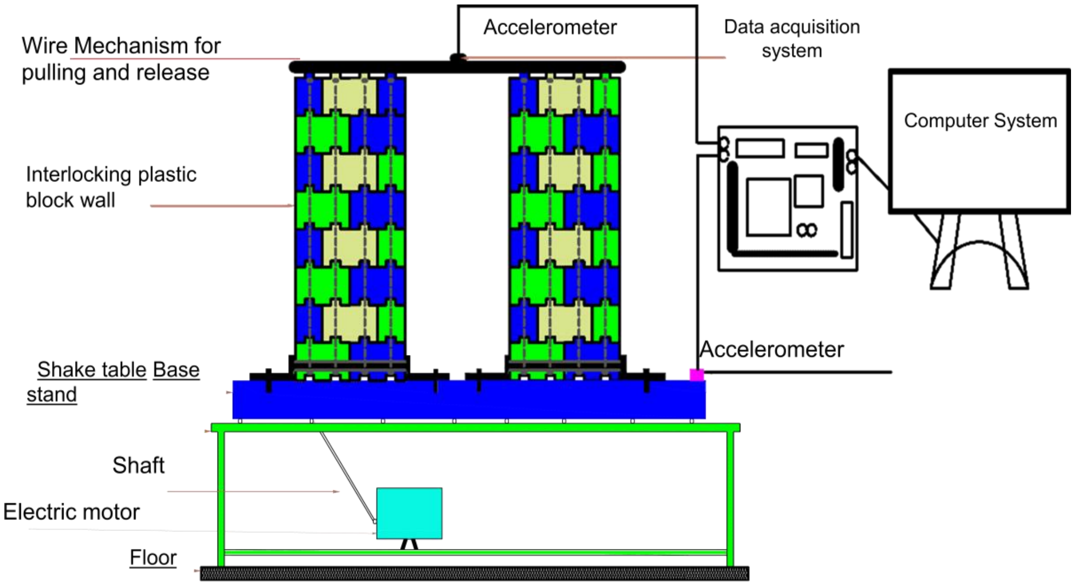


Figure 3.4: Snapback test

3.4.2 Harmonic Loading Test

For various plastic interlocking block-return walls, snap back tests are conducted. Frequencies of 1.5 Hz, 2 Hz, and 2.5 Hz are considered for harmonic loading. Reason for selection of frequencies of 1.5 Hz, 2 Hz, and 2.5 Hz... The amplitude of the interlocking plastic-block walls (solid wall, window opening wall, and door opening wall) is 30 mm for harmonic loading. In order to study dynamic response, harmonic loading (being simple dynamic loading) is selected. Due to the use of the simple 1D shake table, earthquake loadings are not picked. The acceleration time history and displacement time history at the top of all walls and the base of the shake table are compared in order to determine the dynamic response of walls under the influence of harmonic loading. For the case of plastic interlocking block-return walls with door opening, the acceleration-time history and displacement-time history are forecast to be greater.

3.5 Analyzed Parameter

3.5.1 Analyzed Parameter from Snapback Test

Raw data for all interlocking plastic-block structure with different structural element pattern walls along with diaphragm is recorded in terms of acceleration-time history (solid wall, wall with window opening and wall with door opening). Some noise was also recorded for the duration of the recording period in acceleration-time history data. Seismo-signal software was used to eliminate this noise from test results. The bandwidth filter of the Seismo-signal software was used to remove unnecessary data (see annexure A for detail). By using the acceleration-time history, the damping ratio and fundamental frequency (fn) of the plastic interlocking block-return walls structure are determined such as the damping ratio of the plastic interlocking block-return wall with the door opening is expected to be greater. Furthermore, the damping ratio and fundamental frequency (fn) of the plastic interlocking block-return walls were calculated using the acceleration-time history.

3.5.2 Analyzed Parameter from Shake Table

For all block-return walls, harmonic loading with frequencies of 1.5 H_z, 2 H_z and 2.5 H_z was applied for interlocking plastic-block structure with different structural element patterns walls along with diaphragm. The response of these walls was reported in terms of acceleration-time history. Using the seismo-signal program, velocity-time history and displacement-time history were measured. Similarly, base shear (Q) - displacement curves have also obtained for all prototype walls with different patterns having diaphragm with the aid of acceleration-time history data. Base shear is taken where the mass of the wall is M and the acceleration at the top of the wall is $\ddot{u}_t$.

3.6 Summary

The investigational methods of the research work are discussed in depth in this chapter. Different interlocking plastic-block structure with different structural element patterns walls along with diaphragm are checked under harmonic loading. Test setup, snapback and harmonic loading parameters evaluated at different frequencies are also explored in depth for all interlocking plastic-block structure with different structural element patterns walls along with diaphragm.

Chapter 4

Experimental Findings

4.1 Background

In the last chapter, the snapback and harmonic loading test investigation methods and parameters that were analyzed are discussed in detail. The current chapter illustrates the experimental effects of the data recorded during study. Fundamental frequency (fn) and damping ratio (ξ) are determined by using acceleration-time history for all walls having block-return. The data are gathered in raw form, the MATLAB software was initially used and then seismo-signal software was used to delete the additional noises to analyze the effect of diaphragm on dynamic behavior of interlocking plastic-block structure with different structural element patterns.

4.2 Damping Ratio and Fundamental Frequency

The results of the snap back test performed on various plastic interlocking block-return walls are shown in Figure 4.1. (Prototype Interlocking plastic-block structure with different structural element patterns with diaphragm). The damping ratio (ξ) and fundamental frequency (fn) was also determined for interlocking plastic block structure with different structural element Patterns with diaphragm as show in Table 4.1.

TABLE 4.1: ξ and fn of prototypes

Prototype	**fn (Hz)**	ξ **(%)**
—	ut=50	ut=50
OSWBR	2.65	2.8
OSW	2.8	2.7
OSDBR	2.4	2.6
OSD	2.6	2.4
ODWBR	2.9	2.5
ODW	3.1	2.3
ISWBR	1.8	3.5
ISW	1.95	3.4
ISDBR	2.0	3.0
ISD	2.2	2.9
IDWBR	2.5	2.8
IDW	2.6	2.7

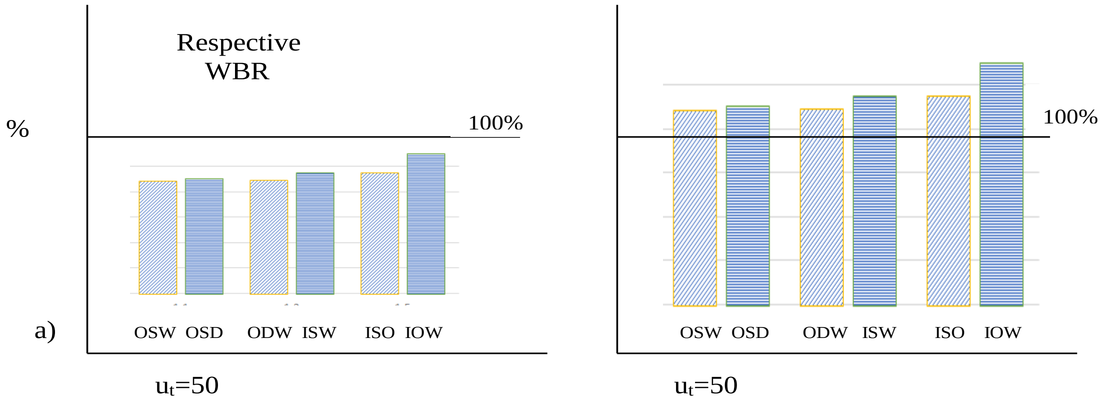
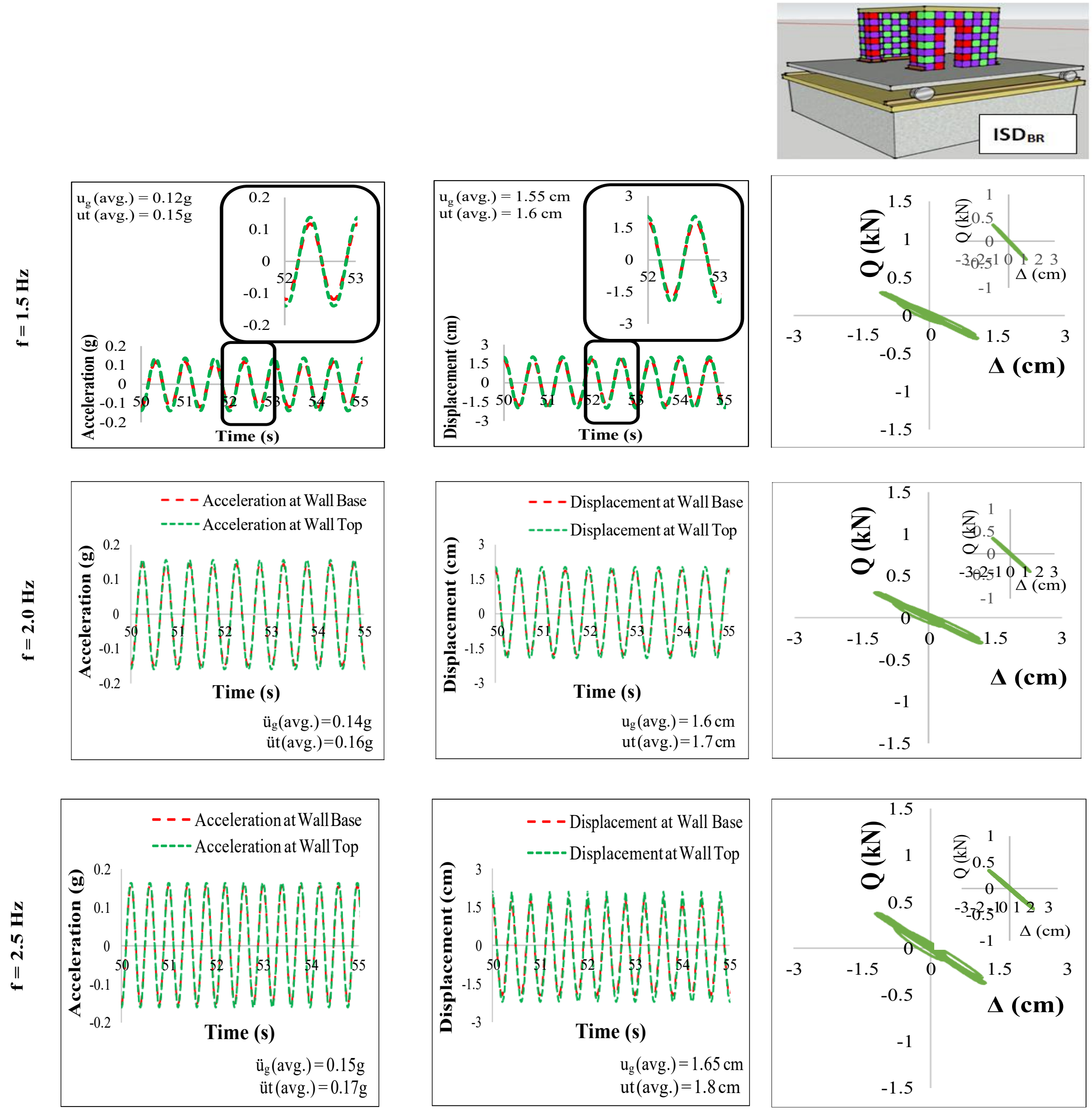


FIGURE 4.1: Comparison for amplitude and block return effects (a) fn & (b) ξ

Table 4.1 lists the snap back test result of different plastic interlocking block-return walls (solid wall, wall with window opening and wall with door opening). The table explains the frequency (fn in Hz) and damping ratio (ξ) of all the prototype structures displaced by 50 mm at top. It is observed that there is some difference between damping values. The damping ratio of solid wall having block-return displaced by 50 mm found more as compared to that of other block-return walls.

4.3 Response of Prototype Structures against Harmonic Loading for In-plane Behavior

In respect of acceleration-time history and displacement-time history and base shear during the 50s to 55s period, the response of interlocking plastic-block structure with different structural element patterns with diaphragm is reported as shown in Figure 4.2 and Figure 4.3.



Solid and window with block return (ISD$_{BR}$)

FIGURE 4.2: Structural behavior of prototypes at global level a) $\ddot{u}$-t of prototype Structures with diaphragm of different patterns. b) u-t of prototype Structures with diaphragm of different patterns c) Q-u of selected prototype Structures with diaphragm of different patterns.

The green dash line represents the acceleration at top of diaphragm and the orange colored dash line shows the acceleration as structures base or shake table or base excitation (applied loading), similarly the blue dotted dash line represents the displacement at base of the wall and orange blue dotted dash line shows the displacement at top of the wall for the displacement cure of various prototype wall structures.

The acceleration-time history and displacement-time history obtained from performance analysis are sufficient in order to investigate the dynamic response of all prototype Structures. Acceleration-time history is reported and then, as previously suggested by using seismo-signal software, the acceleration-time history is converted into displacement-time history.

4.4 Response of Prototype Structures against Harmonic Loading for Out-of-plane Behavior

The locally shake table is sufficient to precisely apply harmonic loading, i.e. the constant amplitude of various cycles, now the average acceleration and change of base excitation (i.e. $\dot{u}_g$ and u$_g$ respectively) is considered to be applied loading. The dynamic response for all prototype plastic walls structure with different elements patterns with diaphragm is considered to be the average acceleration and displacement at the top of diaphragm of the plastic interlocking with and without block-return structures (for all structures patterns) i.e. u and ut, respectively. Figures 4.2 and Figure 4.3 shows the acceleration time histories of all plastic interlocking with and without block-return structures (for all structures patterns) during harmonic loads of 1.5 Hz, 2 Hz and 2.5 Hz between 50s and 55s. The excitation of the structure can be divided into three phases: (A) As the structure began vibrating before the steady-state was reached, (B) The structures steady state response, and (C) Free structure vibration [25].

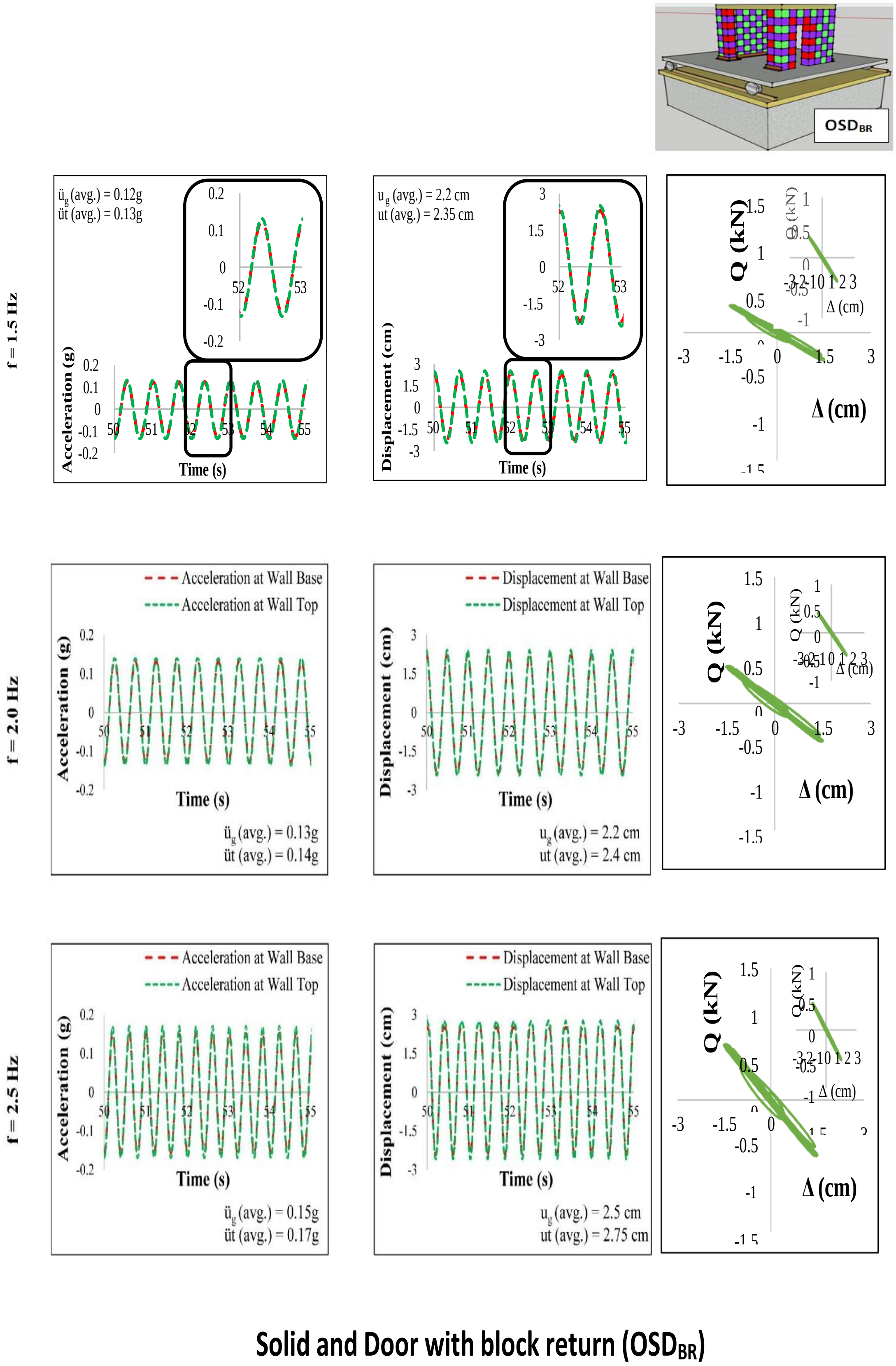


FIGURE 4.3: Structural behavior of prototypes at global level a) $\ddot{u}$-t of prototype Structures with diaphragm of different patterns. b) u-t of prototype Structures with diaphragm of different patterns c) Q-u of selected prototype Structures with diaphragm of different patterns.

Only the portion of the steady state results are shown for clarification in Fig 4.2 and Fig 4.3, It also addresses the average acceleration at the base and top of the diaphragm. It has been found that by increasing the shake table frequency, the acceleration of these bands also increases. During harmonic loads of 1.5 Hz, 2 Hz and 2.5 Hz between 50s and 55s. Average displacement is also reported on the ground and at the top of structures. It has been found that by increasing the shake table frequency, the displacement of structures increases but it was also noted that the structures did not collapse even at a higher frequency during harmonic loading due to the fact of the presence of the diaphragm. But ultimately at further greater frequency, the prototype plastic interlocking plastic-block structures with different structural element patterns will collapse.

4.5 Energy Absorption and Base Shear (Q) Displacement (Δ) Curve

The total mass (M) of plastic interlocking block-return walls (solid wall with window opening and wall with door opening) and additionally the diaphragm is presumed to be lumped at the top of the walls where the history of its response acceleration time (i.e., $\dot{u}$t-t) was registered. Base shear is calculated as (Q) which is shown as ut in Figure 4.2 and Figure 4.3 (c) as displacement curves of different block-return walls. This was previously calculated as per working of [25]. The Energy absorption of prototype structure for various walls pattern of OSW & OSW$_{BR}$, OSD & OSD$_{BR}$, ODW & ODW$_{BR}$, ISW & ISW$_{BR}$, ISD & ISD$_{BR}$ and IDW & IDW$_{BR}$ for all prototype plastic walls structure with different elements patterns with diaphragm corresponding to frequencies of 1.5 Hz, 2.0 Hz and 2.5 Hz are shown in different Figures. For discussion and clarification purpose only Figures 4.2 and 4.3 are shown here while rest of Figures are presented in the Annexture A of this thesis.

In Table 4.2, the average energy absorption (e) in one cycle and the total energy absorbed in one cycle are represented as “E”. The number of harmonic cycles is labeled "N" and the region inside the loop is taken as the absorption of energy (E). Plastic interlocking block with different walls pattern having diaphragm have been noted to dissipate more energy during harmonic loading at 1.5 Hz, 2 Hz and 2.5 Hz frequencies. In comparison with other walls having block-return, it is concluded that greater energy is dissipated in interlocking plastic-block walls with block-return having door opening at 2.5 Hz. In a seismic case because the relative movement at block interfaces is due to plastic interlocking block-return walls will absorb more energy. Experimentation has been conducted to find out that the dissipation of energy is due to relative block movement or uplift. For the plastic blocks walls system such observation will be examined in the future.

Table 4.2: Energy absorption of prototype structure

Prototype	**f (Hz)**	**e (W/OBR) (Nm)**	**e (WBR) (Nm)**	**N (number of cycles)**	**E (W/O) (Nm)**	**E (WBR) (Nm)**
OSW & OSW$_{BR}$	1.5	1.7	2.0	78	132.6	156
	2.0	3.2	3.8	80	256	256
	2.5	4.0	4.5	90	360	405
OSD & OSD$_{BR}$	1.5	1.5	1.8	90	135	140.4
	2.0	3.5	4.0	78	273	171.6
	2.5	4.5	5.2	80	360	320
ODW & ODW$_{BR}$	1.5	2.3	2.8	90	207	218.4
	2.0	4.8	5.6	78	374	448
	2.5	5.5	5.9	80	440	495
ISW & SW$_{BR}$	1.5	1.3	4.5	90	117	117
	2.0	1.7	1.8	78	132.6	144
	2.5	2.6	2.7	80	208	243
ISD & ISD$_{BR}$	1.5	1.6	1.8	90	144	140.4
	2.0	2.4	2.5	78	187	200
	2.5	3.0	2.7	80	240	243
IDW & IDW$_{BR}$	1.5	1.5	2.8	78	117	140.4
	2.0	2.6	3.4	80	308	224
	2.5	3.4	3.6	90	306	324

4.6 Summary

The experimental results from the data collected during research are explained in this chapter. The experiment was conducted twice to perform a rigorous analysis. Fundamental frequency (fn) and damping ratio (ξ) are determined by using acceleration-time history for all all prototype plastic walls structure with different elements patterns with diaphragm. To filter the data, MATLAB software was initially used and then seismo-signal software was used to remove the additional noises. Similarly, the displacement time and velocity time was also measured using a seismo-signal. This chapter demonstrates the graphical representation of acceleration-time, displacement-time histories and base shear curves. It was observed that the Interlocking plastic-block wall with door opening having block-return dissipated more energy as compared to other walls.

Chapter 5

Discussion on Practical Implementation

5.1 Background

The graphical representation of Fig 4.3 of Chapter No. 4 explained in detail the acceleration-time history, displacement time history, and base shear-displacement. It was noted that the energy dissipation was found to be greater in the in interlocking plastic-block wall with block-return door opening as compared to other block-return walls. Similarly, experimental findings are compared with observational results by testing the percentage difference for the purpose of comparing results. The relationship between experimental and empirical values is established in this chapter to predict the behavior of interlocking block-return plastic-block walls. In addition, a percentage difference is presented between the empirical and experimental values.

5.2 Comparison of the Study Results

The results of the dynamic behavior of interlocking plastic-block structure with different structural element patterns with diaphragm are compared between the block return verses without block return for the acceleration time and displacement time result. Out of many prototype interlocking plastic-block walls structure with different elements patterns attached with diaphragm. The considered prototype structures are OSW, OSD, ODW, ISW, ISD and IDW. The max percentage difference of -11.11% has been found for $\ddot{t}/\ddot{u}$g (Acceleration) and -18.8% for ut/ug again IDW at frequency of 1.5 Hz.

Table 5.1: Comparison of block-return versus without block-return prototype structures

Prototype	**f (Hz)**	**W/O BLOCK-RE-TURN**	**W/O BLOCK-RE-TURN**	**WITH BLOCK-RE-TURN**	**WITH BLOCK-RE-TURN**	**% DIFF.**	**% DIFF.**
—	—	$\ddot{u}t/\ddot{u}g$	ut/ug	$\ddot{u}t/\ddot{u}g$	ut/ug	$\ddot{u}t/\ddot{u}g$	ut/ug
OSW	1.5	1.11	1.13	1.05	1.1	5.4	2.65
	2	1.14	1.12	1.07	1.04	6.1	7.14
	2.5	1.15	1.14	1.06	1.05	3.6	7.9
OSD	1.5	1.08	1.06	1.02	1.16	5.5	-9.4
	2	1.07	1.09	1.11	1.03	-3.7	5.5
	2.5	1.13	1.1	1.02	1.12	9.7	-1.8
ODW	1.5	0.92	1.2	1.0	1.1	-8.7	8.3
	2	1.16	1.12	1.07	1.05	7.75	6.25
	2.5	1.15	1.24	1.2	1.13	4.3	8.8
ISW	1.5	0.8	1.03	0.75	1.06	6.25	-2.9
	2	1.1	1.04	1.12	1.07	1.8	-2.8
	2.5	1.07	1.08	1.2	1.06	-12.1	1.85
ISD	1.5	1.1	1.06	1.25	1.03	-13.6	2.83
	2	1.14	1.08	1.1	1.06	3.5	1.85
	2.5	1.2	1.1	1.13	1.08	5.8	1.82
IDW	1.5	0.9	1.055	1.0	1.07	-11.11	-18.8
	2	1.09	1.03	1.06	1.12	2.8	-8.7
	2.5	1.15	1.08	1.07	1.06	6.95	1.85

5.3 Comparison with Previous Study

Table 5.1 shows the comparison of the current study with previous study (Bashir 2020). Maximum percentage difference of üt/üg is 8.8%, 1.12% and 11.03% while

Table 5.2: Comparison of block-return versus without block-return prototype structures

Pattern	*üt/üg*	**ut/ug**	*üt/üg*	**ut/ug**	**% DIFF. of** *üt/üg*	**% DIFF. of ut/ug**
–	Bashir (2020)	–	Current Study	–		
OSW	1.02	1.11	1.11	1.13	8.8	1.8
–	1.03	1.08	1.14	1.12	10.6	3.7
–	1.02	1.01	1.15	1.14	11.03	12.8

ut/ug is 1.8%, 3.7%, and 12.8% at frequency of 1.5 Hz, 2.0 Hz and 2.5 Hz respectively. The percentage difference of the results is relatively large due to dynamic characteristics of interlocking assembly. As Ali [29] percentage difference was up to 35% in predicting the structure response which could be attributed towards the complex behavior of the structure versus the simple empirical approach. But still, this can help in understanding the behavior of mortar-free interlocking structure in a systematic manner.

5.4 Outcome of Research Work With-respect-to Practical Needs

The application of harmonic loading using the locally built 1D shake table is capable of generating a certain amount of accurate dynamic results. So, it is possible to determine the seismic response of the structure under observation. This is because the applied harmonic loading is taken as the base ground motion and the structural components action is analyzed in relation to it. Alternatively, the perceived reaction of various interlocking block-returning plastic-block walls is roughly the same as defined in the literature. The different block-return walls stud- ied showed positive potential in the form of structural stability and the absorption of energy. All prototype plastic walls structure with different elements patterns with diaphragm should therefore be studied in combination with other components. Moreover, by using interlocking plastic blocks for earthquake- resistant structures, the opposite effect of earthquakes can be minimized.

5.5 Summary

In this chapter, the findings of research work are clarified with respect to practical needs. The results generated by the locally built 1D shake table with fixed amplitude and variable frequencies are slightly in-accurate. It is, however, capable of producing harmonic loading precisely to some degree. From the study it was concluded that Interlocking plastic-block walls having block-return having diaphragm are more convenient for earthquake resistant construction compared to that of masonry wall in order to examine the seismic behaviour under the observation of structural elements. Compared to other block-return walls, the plastic-block wall with a block-return opening dissipates more energy. Owing to the limitations of the shake table and human errors, experimental values are less reliable, while empirical values are more accurate relative to experimental values in order to verify the percentage difference of values with respect to experimental values. Owing to the limitations of the shake table and human error, the experimental values are less reliable.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

Many earthquake-resistant building methods for earthquake-prone areas are available in literature. Those are, however, uneconomical. Developing nations cannot afford such approaches to reduce the harms caused by earthquakes. In this pilot study the dynamic behavior of prototype plastic walls structure with different elements patterns with diaphragm was studied. Prototypes of all walls are checked to determine the response and their dynamic characteristics under various harmonic loads. In order to study dynamic response, harmonic loading which is considered the simple dynamic loading, is selected. The mass of the diaphragm is considered to perform the earthquake loading's to achieve the results of harmonic loading but with some limitation of the use of the simple 1D shake table. The scope of the test is only to investigate the behavior of various interlocking plastic-block walls with simplified boundary conditions. The harmonic tests were found to be more successful in identifying the fundamental frequencies of the structure compared to the snap-back test. It is possible to draw the following conclusions from this research.

– During snapback test, it is observed that the damping ratio varied among different prototype walls structures. However, the damping ratio is noted to be more for solid walls with block-return.

– Response of displacement time histories and the acceleration time histories are found to be less for all prototype interlocking plastic-block walls structures such as OSW & OSW$_{BR}$, OSD & OSD$_{BR}$, ODW & ODW$_{BR}$, ISW & ISW$_{BR}$, ISD & ISD$_{BR}$ and IDW & IDW$_{BR}$ in case of in-plane behavior. Additionally, the energy absorption is also found to be less in the said case.

– Displacement time histories and the acceleration time histories against harmonic loading are observed to be more for all prototype interlocking plastic-block walls structures (OSW & OSW$_{BR}$, OSD & OSD$_{BR}$, ODW & ODW$_{BR}$, ISW & ISW$_{BR}$, ISD & ISD$_{BR}$ and IDW & IDW$_{BR}$) in case of out-of-plane behavior.

– Base shear (Q) and energy absorption of all prototype interlocking plastic-block walls structures are determined. However, more values of Base shear (Q) for the prototype plastic walls structures with block return and diaphragm are determined.

– Energy dissipation capacity of interlocking plastic-block walls having block-return is increased by using diaphragm and rubber band as a vertical reinforcement. This study revealed that Interlocking plastic-block walls having block-return and diaphragm are more convenient for earthquake resistant construction under seismic behavior.

– The comparison of this study with the previous study shows that the percentage differences of results are relatively large due to dynamic characteristics of interlocking assembly.

Overall, the plastic prototype interlocking block-return walls OSW & OSW$_{BR}$, OSD & OSD$_{BR}$, ODW & ODW$_{BR}$, ISW & ISW$_{BR}$, ISD & ISD$_{BR}$ and IDW & IDW$_{BR}$) made a remarkable sound contrary to harmonic loading. The proposed housing technology has the ability to provide underprivileged individuals with a decent standard of living

6.2 Recommendations

This research program was conducted to understand the effect of diaphragm on dynamic behavior of interlocking plastic-block structure with different elements pattern;

The next study in the research program should be in-plane and out-of-plane dynamic response of the diaphragm-attached block-return interlocking plastic-block wall for a complete prototype house.

The dynamic response of the structure without block-return and block-return interlocking plastic-block for L-shaped wall.

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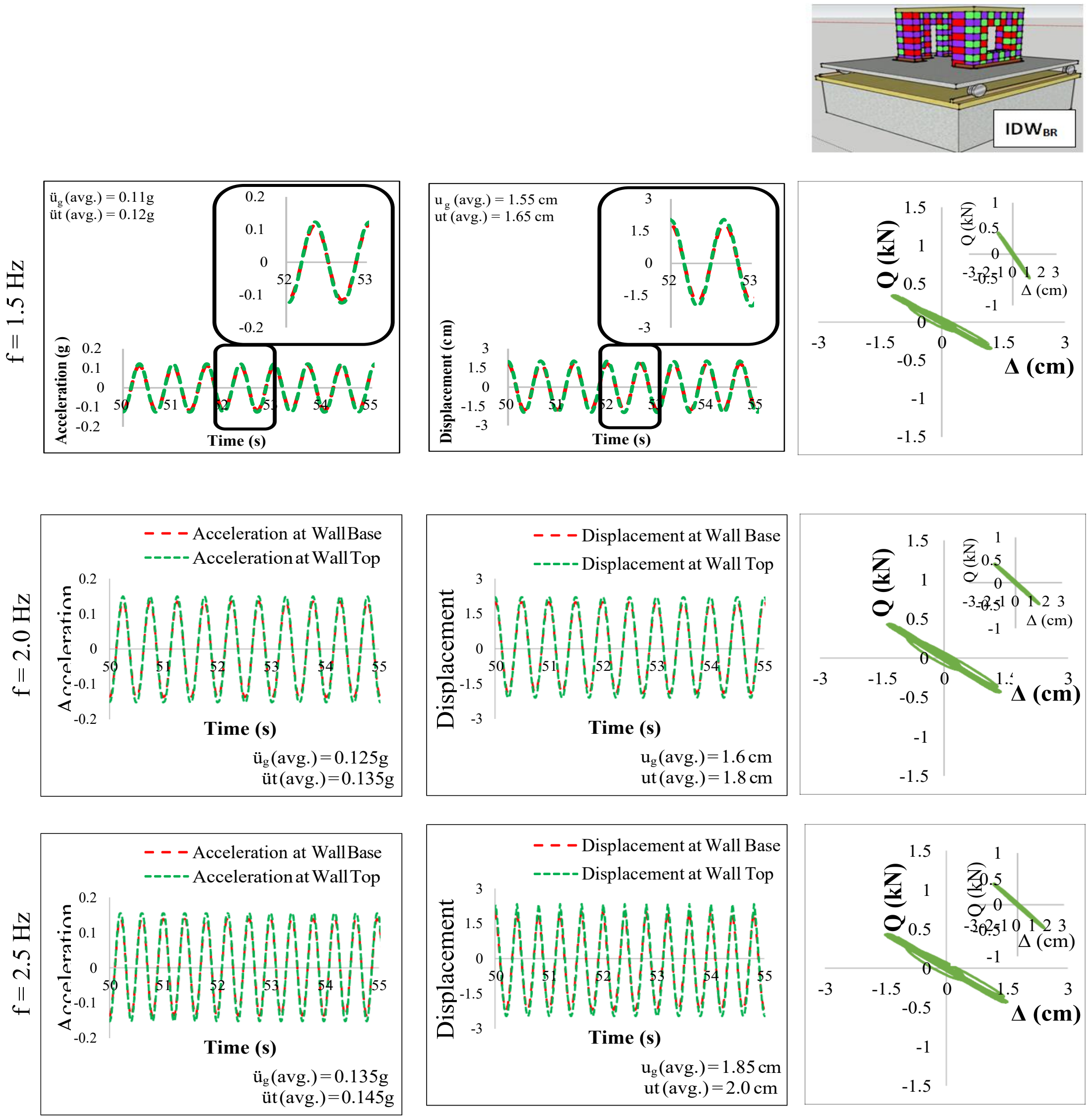
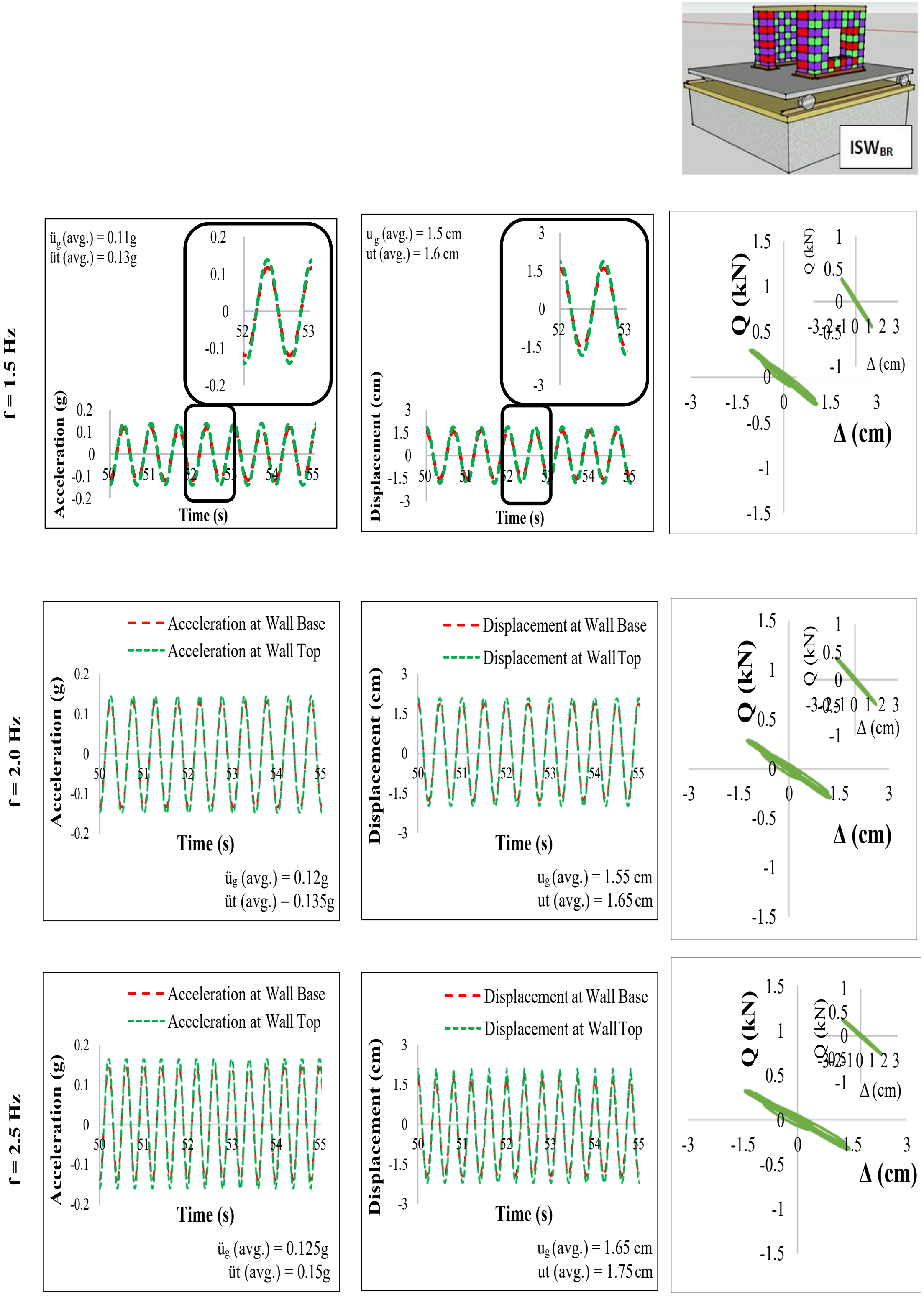
Annexure A



Door and window with block return (IDW$_{BR}$)

Figure A.1: Structural behavior of prototypes at global level a) ü-t of prototype walls with diaphragm of different patterns. b) u-t of prototype walls with diaphragm of different patterns c) Q-u of selected prototype walls with diaphragm of different patterns.



Solid and window with block return (ISW$_{BR}$)

FIGURE A.2: Structural behavior of prototypes at global level a) ü-t of prototype walls with diaphragm of different patterns. b) u-t of prototype walls with diaphragm of different patterns c) Q-u of selected prototype walls with diaphragm of different patterns.

WITHOUT BLOCK RETURN IN-PLANE

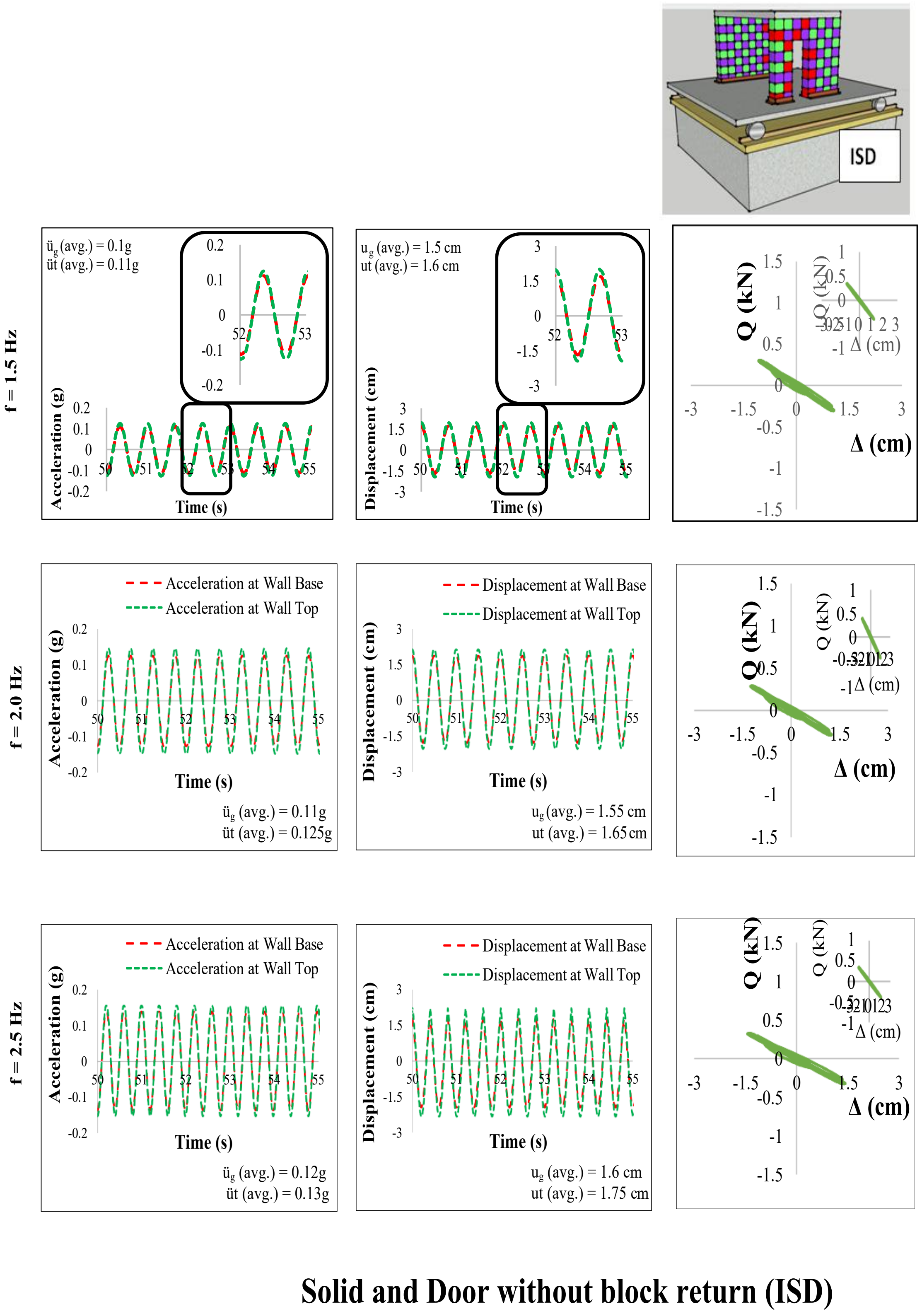
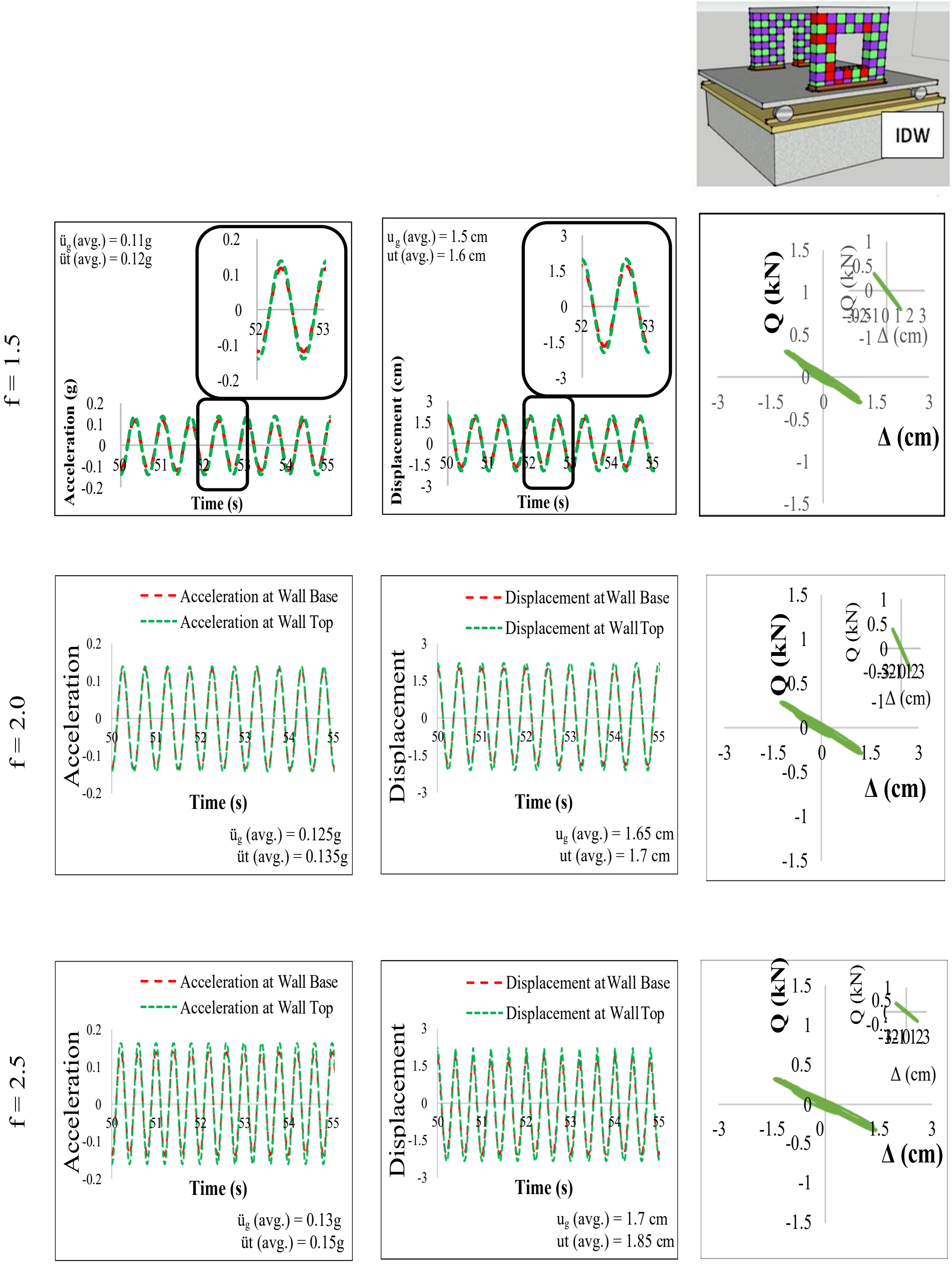
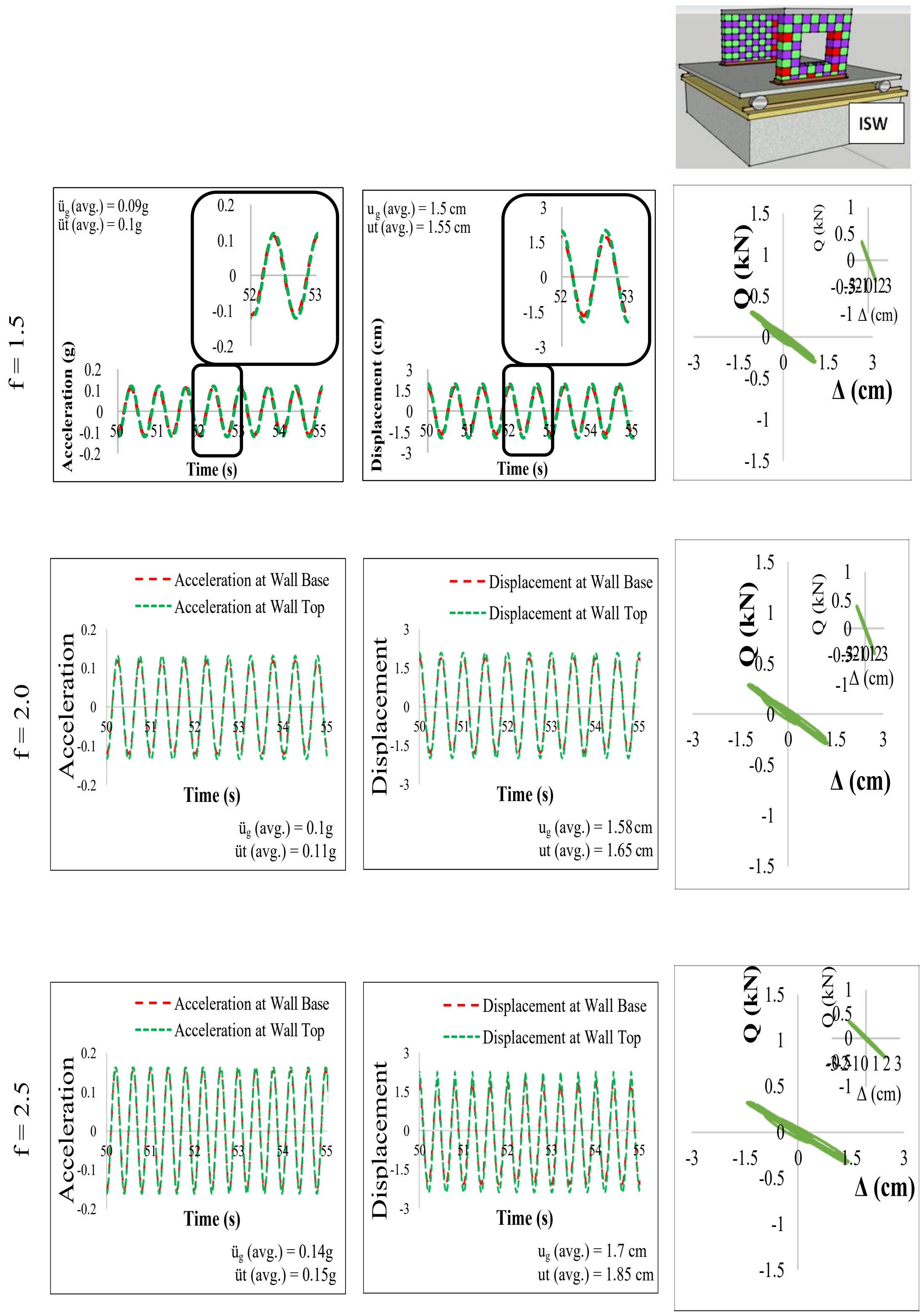


Figure A.3: Structural behavior of prototypes at global level a) ü-t of prototype walls with diaphragm of different patterns. b) u-t of prototype walls with diaphragm of different patterns c) Q-u of selected prototype walls with diaphragm of different patterns.



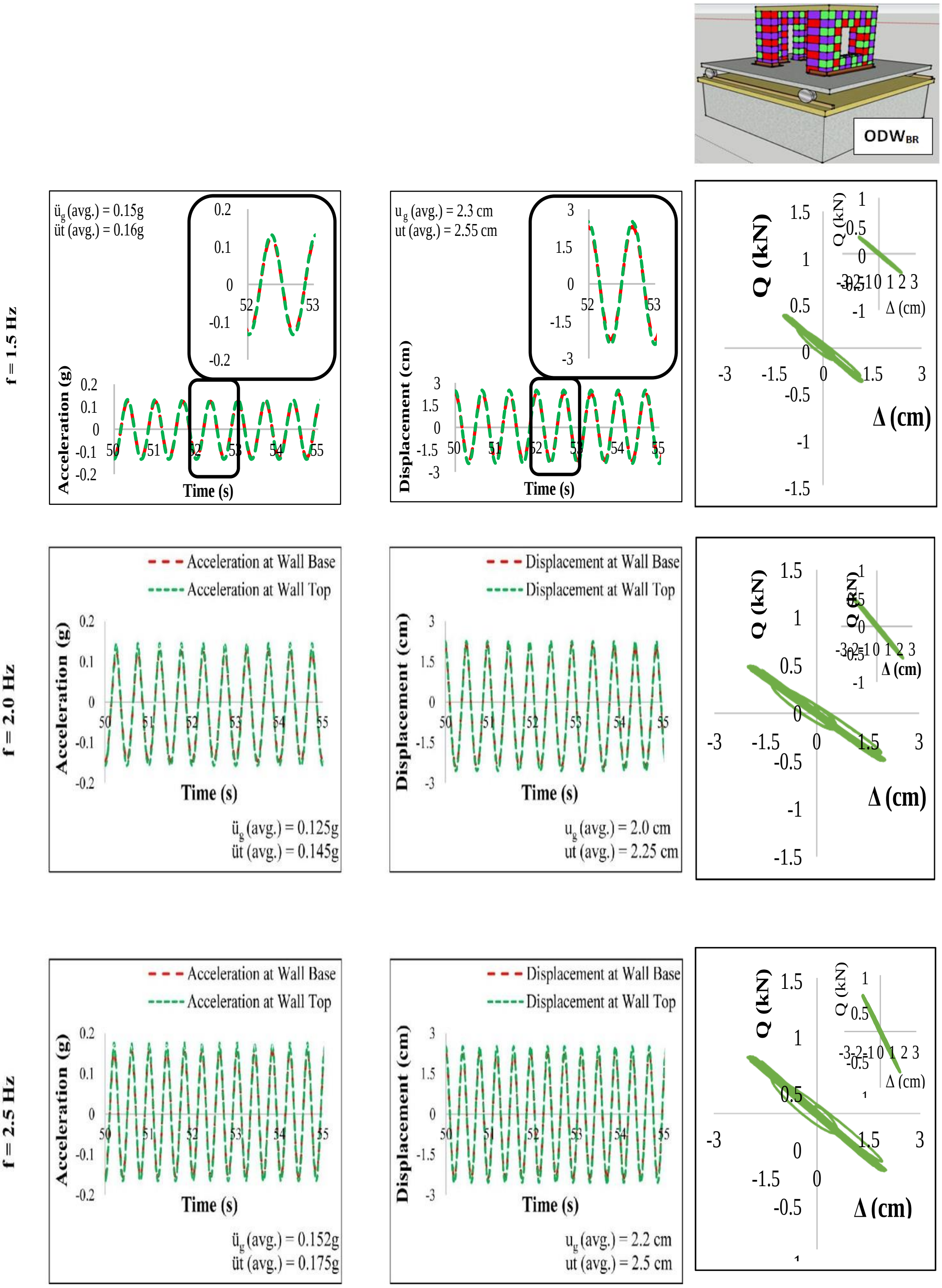
Window and Door without block return (IDW)

FIGURE A.4: Structural behavior of prototypes at global level a) $\ddot{u}$-t of prototype walls with diaphragm of different patterns. b) u-t of prototype walls with diaphragm of different patterns c) Q-u of selected prototype walls with diaphragm of different patterns.



Solid and window without block return (ISW)

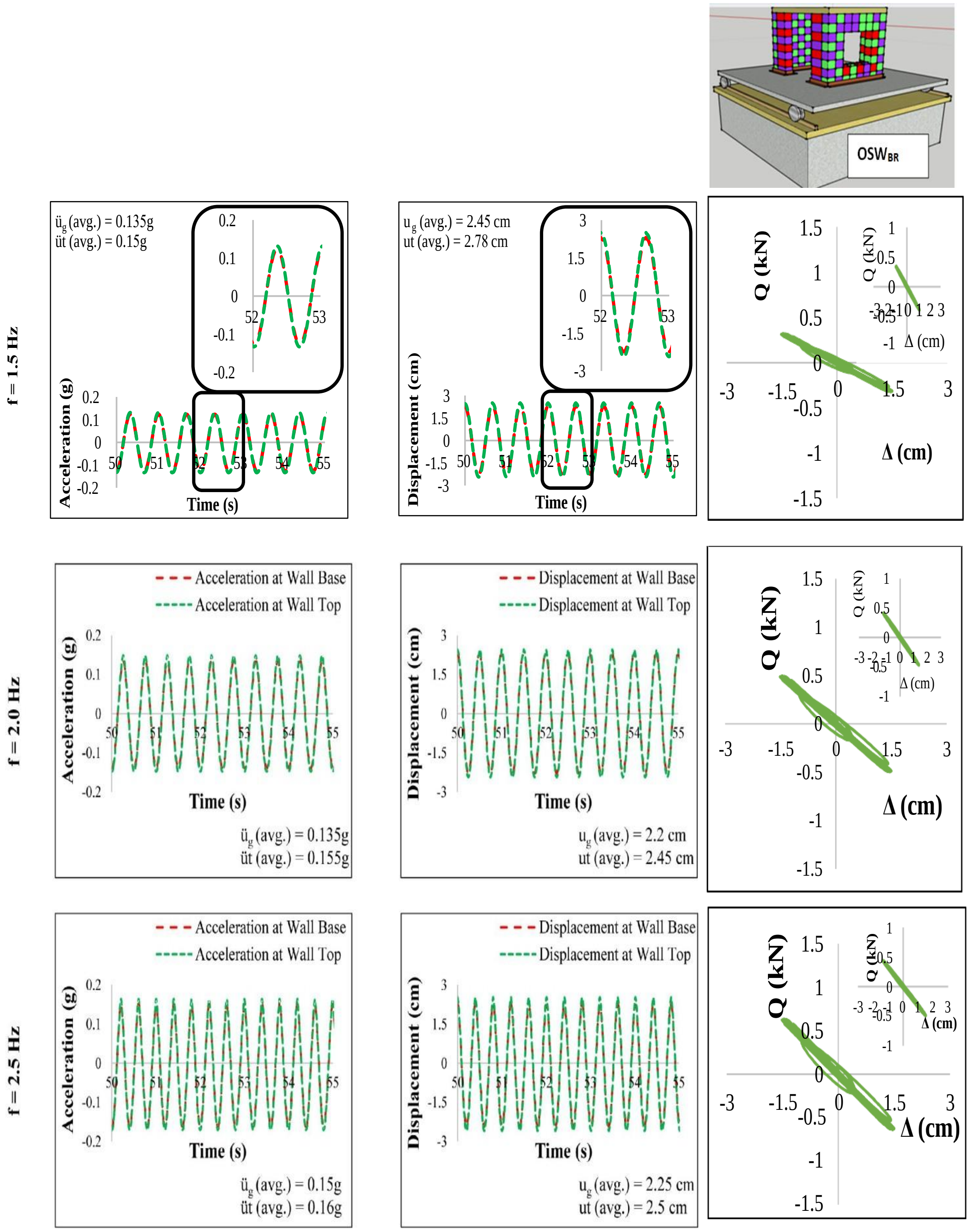
Figure A.5: Structural behavior of prototypes at global level a) ü-t of prototype walls with diaphragm of different patterns. b) u-t of prototype walls with diaphragm of different patterns c) Q-u of selected prototype walls with diaphragm of different patterns.



Door and Window with block return (ODW_{BR})

Figure A.6: Structural behavior of prototypes at global level a) $\ddot{u}$-t of prototype walls with diaphragm of different patterns. b) u-t of prototype walls with diaphragm of different patterns c) Q-u of selected prototype walls with diaphragm of different patterns.

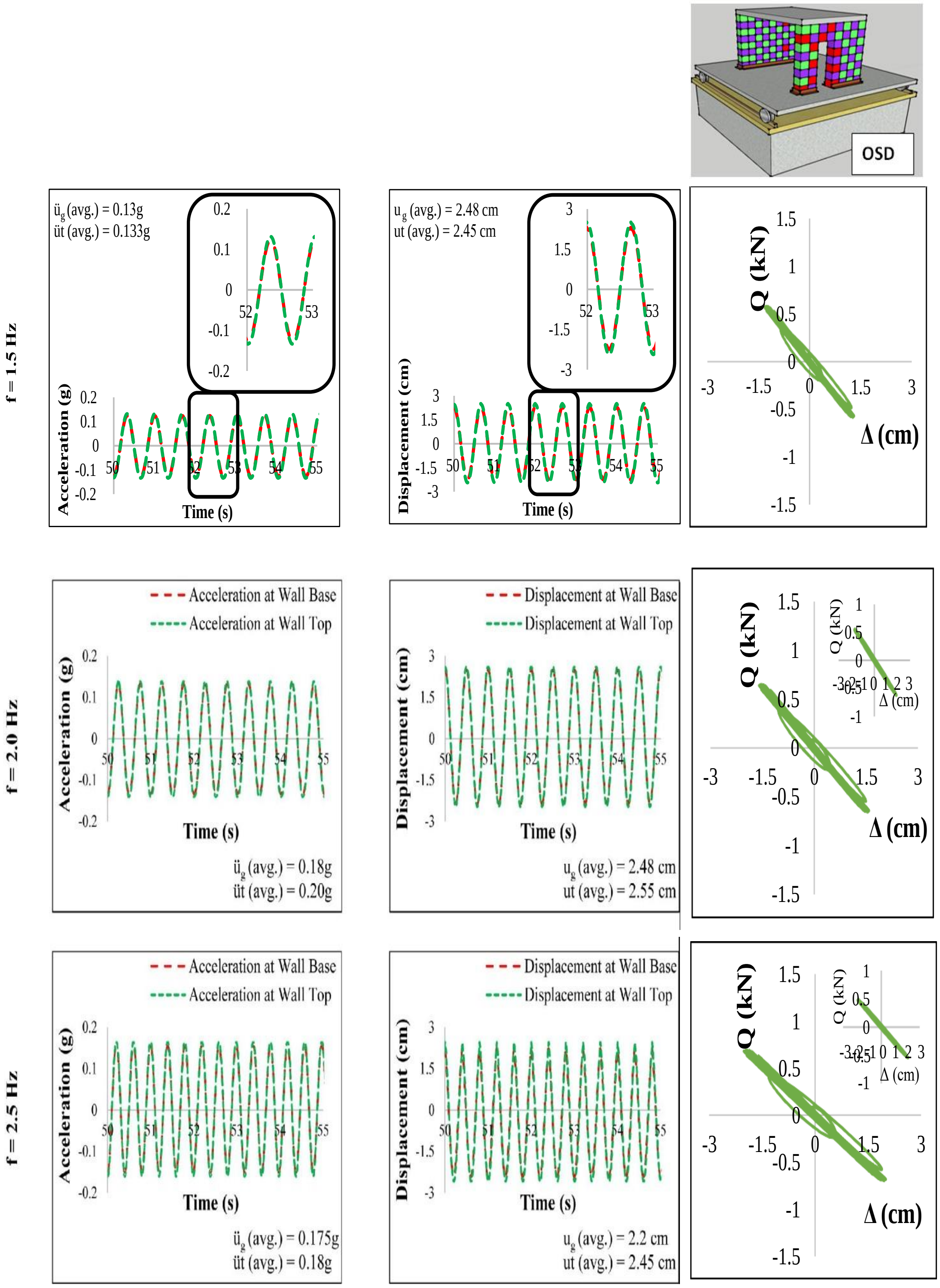
Window and solid with block return (Out-of Plane)



Solid and Window with block return (OSW$_{BR}$)

FIGURE A.7: Structural behavior of prototypes at global level a) $\ddot{u}$-t of prototype walls with diaphragm of different patterns. b) u-t of prototype walls with diaphragm of different patterns c) Q-u of selected prototype walls with diaphragm of different patterns.

WITHOUT BLOCK RETURN (OUT OF PLANE)



Solid and Door without block return (OSD)

Figure A.8: Structural behavior of prototypes at global level a) $\ddot{u}$-t of prototype walls with diaphragm of different patterns. b) u-t of prototype walls with diaphragm of different patterns c) Q-u of selected prototype walls with diaphragm of different patterns.

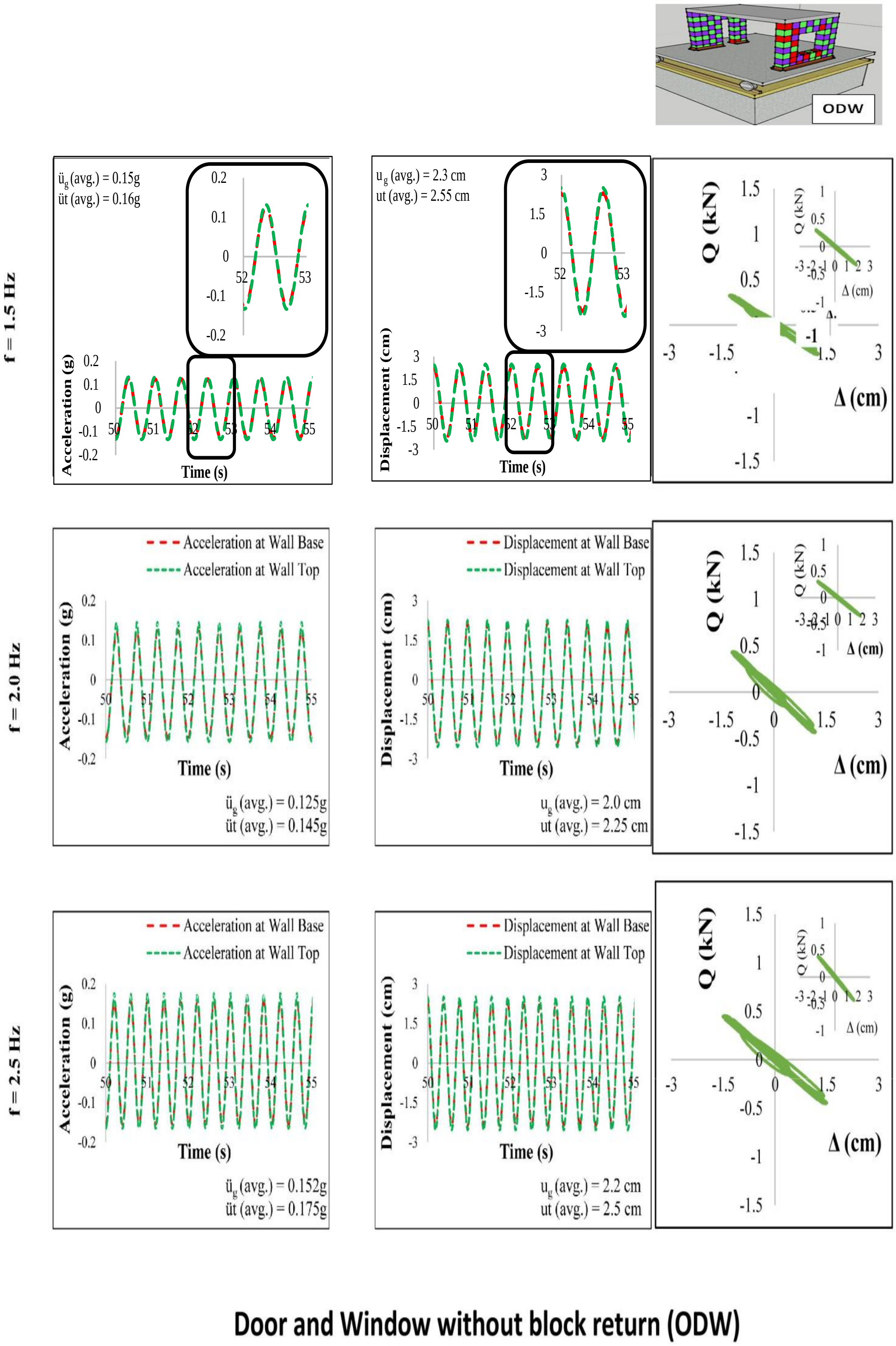


FIGURE A.9: Structural behavior of prototypes at global level a) ü-t of prototype walls with diaphragm of different patterns. b) u-t of prototype walls with diaphragm of different patterns c) Q-u of selected prototype walls with diaphragm of different patterns.

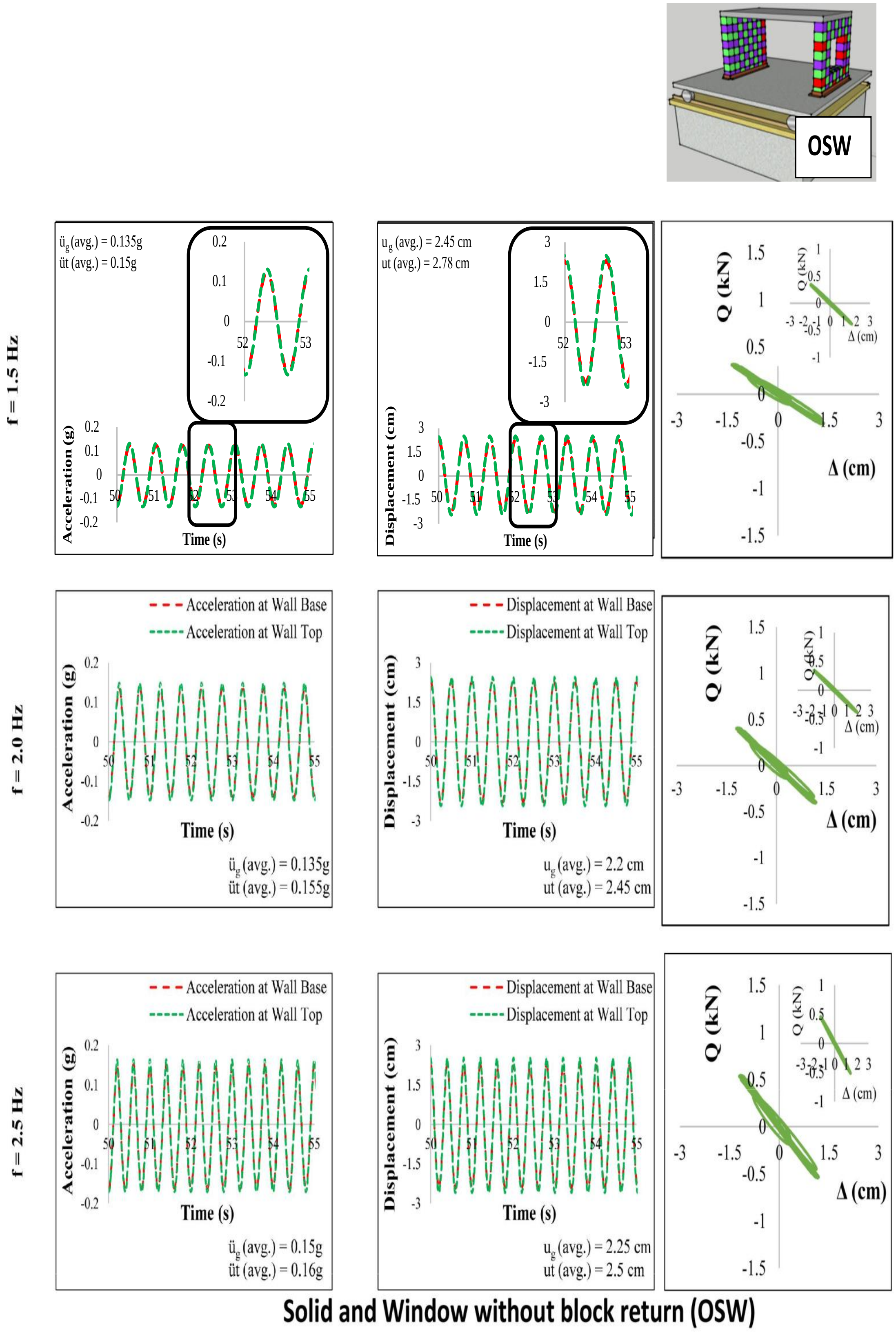


Figure A.10: Structural behavior of prototypes at global level a) ü-t of prototype walls with diaphragm of different patterns. b) u-t of prototype walls with diaphragm of different patterns c) Q-u of selected prototype walls with diaphragm of different patterns.