CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Effect of Slenderness on the Behavior of Interlocking Plastic-Block Structural Elements Under Compression

by

Muhammad Adnan

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

in the

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I want to dedicate this work to my family, who has helped me throughout my education. This is also a homage to our finest professors who have inspired us to face the challenges of presence with creativity, and courage and who have made us what we are today.

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List of Publications

It is certified that following publication(s) have been made out of the research work that has been carried out for this thesis:-

Journal Article

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Abstract

Earthquake is one of the most harmful and potentially fatal natural disasters. Different harmful effects are caused by earthquakes on the areas they affect. This includes damage to buildings and, in the worst case, human life loss. Particularly, masonry structures in seismic zones of urban and rural areas around the world pose a threat to human life. Because of the fact that earthquakes induce severe ground vibrations that seriously harm masonry structures. Housing that is both affordable and earthquake-resistant in earthquake-prone areas is currently in demand in developing countries. For affordable earthquake-resistant structures in earthquake-prone areas, numerous researchers have studied mortar-free interlocking structures. However, buildings made of interlocking plastic blocks are still unexplored.

To start with, prototype interlocking plastic block single and double width block columns, single and double block width solid walls, and single and double block width walls with opening are considered for making the mortar-free structure. The previous studies on these interlocking plastic blocks have shown favorable results against lateral loading. Therefore, there is a need to study the compressive behavior of these interlocking plastic blocks. Making a contribution to this requirement, the effect of slenderness on the behavior of interlocking plastic single and double block width width columns, single and double block width solid walls, and single and double block width walls with door opening, are investigated against compressive loading under the servo-hydraulic testing machine in the laboratory.

The effect of slenderness on the behavior of single and double-block width structural elements is investigated in terms of the stress-strain curve, energy absorption, and toughness index under compressive loadings. Correlations between the compressive strength of interlocking plastic block structural elements with varying thicknesses are developed. The total compressive toughness of the single block width column is less than that the of double block width column and the total compressive toughness of single block width walls is greater than double block width solid wall. Scaled-down prototypes of interlocking plastic block structural elements having double block width depicted more resistant to compressive load than single block width structural elements.The correlations among the peak load carrying capacities of single and double block width interlocking plastic block columns, single and double block width solid walls, and single and double block width walls with opening found in this analysis are PC(d) = 2.2PC(s), PSW(d) = 2.9PSW(s) and PWO(d) = 3.5PWO(s). This study can be applied in the future to better understand the detailed behavior of interlocking plastic blocks.

Contents

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Abbreviations and Symbols

3D	Three Dimensional
CFRC	Coconut Fibre Reinforced Concrete
$\mathbf{C}_s$	Single Block Width Column
$\mathbf{C}_d$	Double Block Width Column
EMS	European Macro Seismic Scale
$\mathbf{E}_1$	Energy absorbed upto peak load
$\mathbf{E}_2$	Energy absorbed after peak load
ET	Total Energy
GHz	Gega Hertz
GPa	Gega Pascal
kg	Kilo-Gram
kN	Kilo-Newton
mm	Mili-Meter
MPa	Mega Pascal
Mw	Moment Magnitude
ML	Richter Magnitude
Nm	Newton Meter
P	Peak Load
PC(s)	Peak load carrying capacity of single block width interlocking plastic blocks column
PC(d)	Peak load carrying capacity of double block width interlocking plastic blocks column
PSW(s)	Peak load carrying capacity of single block width interlocking plastic blocks solid wall

PSW(d)	Peak load carrying capacity of double block width interlocking plastic blocks solid wall
PWO(s)	Peak load carrying capacity of single block width interlocking plastic blocks wall with door opening
PWO(d)	Peak load carrying capacity of double block width interlocking plastic blocks wall with door opening
$\mathbf{SW}_s$	Single Block Width Solid Wall
$\mathbf{SW}_d$	Double Block Width Solid Wall
sec	Second
TI	Toughness Index
URM	Un Reinforced Masonry
$\mathbf{WO}_s$	Single Block Width Wall with Opening
$\mathbf{WO}_d$	Double Block Width Wall with Opening
W/mK	Watts per meter Kelvin
ε	Strain
σ	Stress

Chapter 1

Introduction

1.1 Background

An earthquake is a natural disaster that produces strong ground motion. The primary effects of earthquakes cause server damage, such as collapsing of buildings, roads, and bridges, which may kill many people. An earthquake can also cause floods and landslides. The building can literally sink when soil content is high water because soil having a high percentage of water content behaves like a fluid and lose its mechanical strength when soil shakes violently [1]. An earthquake that happens beneath the ocean floor, can lead to a tsunami. The structure is often affected during intense earthquakes and collapse. Most Structures are often affected during intense earthquakes and collapses. Earthquakes badly affect masonry structures due to strong ground motion.

The seismic swarm that hit Central Italy in August October 2016 affected a rather large area, spread over four Italian regions and including 140 municipalities and 2100 urban sites [2]. A Mw 6.4 earthquake hit the NW region of Albania on November 26, 2019, resulting in extensive damage to the civil structures in the broader area of Durres city and its surroundings. According to the official statistics, it caused 51 death toll and 1.2 billion US dollars in economic losses [3]. Earthquakes are a natural disaster that had caused significant damage to the masonry structural system. Annually, it kills many people. Most of the masonry structure had collapsed in the past earthquake due to design deficiencies and implementation in construction. Many studies had conducted in the past, and are also being carried out in the present to establish strategies to mitigate the adverse effects of the earthquakes [4].

Due to the increased demand for housing caused by the growing world population, more affordable and ecologically friendly construction methods are being investigated globally. To overcome the drawback of conventional masonry, mortar-free interlocking masonry systems were developed using a variety of technologies [5]. More affordable, secure, and long-lasting housing might be introduced worldwide through interlocked masonry building. It decreases the demand for highly trained workers, shortens the construction process, and lowers labour costs. The material characteristics of interlocking blocks have been improved by many investigations conducted throughout the years [6]. These have enhanced the interlocking masonry system's material performance, but further research is still needed to fully understand the system's structural performance before it can be widely used.

Mohammad [7] tested wall panels made of gypsum cement and coconut fibre. Ali [8] tested compressive strength of CFRC interlocking blocks using compressive testing machine in the laboratory. Simple compressive testing machine can be used to understand the compressive strength behavior of interlocking blocks made up of plastic. Qamar et al. investigated structural behavior of mortar less interlocking masonry wall [9]. Fakih et al. did experimental study on axial compressive behavior of rubberized interlocking masonry walls [10]. Masonry walls' capacity to sustain loads is significantly influenced by their slenderness (defined as having a height to thickness ratio of h=t) and the effective eccentricity of the loads placed on them. It also depends on the characteristics of the constituent parts, such as the mortar's and units' compressive strength and the tensile strength at the interface [24]. With increasing slenderness, the impact of brickwork compressive strength decreases. Only the overall stiffness, which is defined by the elastic moduli of the expanded units in the wall, is crucial in the scenario of high slenderness, with the majority of the walls showing stability failure [50]. Studies done in the past on these interlocking plastic blocks have shown favorable results when tested against lateral loading.

Therefore, it is necessary to investigate how these interlocking plastic blocks behave under compression. In order to meet this requirement, it was determined using standard techniques how slenderness affects the compressive strength of single block width column (C_s), double block width column (C_d), single block width solid wall (SW_s), double block width solid wall (SW_d), single block width wall with door openings (WO_s), and double block width wall with door openings (WO_d). All interlocking plastic blocks structural elements were tested in a compression testing machine to determine the peak load, stress, corresponding strain ε, total energy absorbed, and compressive toughness. To the best of the author's knowledge, no study has been conducted to investigate the effect of slenderness on the behavior of interlocking plastic-block structural elements under compression using the locally compressive testing machine.

1.2 Research Motivation and Problem Statement

A major earthquake may result in numerous fatalities by causing buildings, roads, and bridges to collapse. Such losses can be reduced if precise behavior of structures is studied which can help in its proper design. Developed countries have such facilities but developing countries are lacking these facilities. To start with, static behavior of structure may be studied with compressive testing machine. On other hand, confined brick masonry structures are expensive. An economical solution is needed. Ali [11] proposed an economical solution but the mass of block still needs to be reduced. The interlocking plastic-block structure can be one option with consideration of fire-resistant paint. For economical and environmental aspects, plastic waste can be recycled for this purpose (note: for time beings, it is outside the scope of this work). Thus, the problem statement is as follow:

In earthquake, most of the masonry structures collapsed due to design deficiencies [41]. Ali [11] developed a mortar free structure (a new construction technique) for earthquake-resistant housing. A mortar-free interlocking plastic-block structure has the ability to dissipate energy of earthquake. Lighter the mass of structure, lower *the inertia force generated. For this, light weight interlocking plastic-block is one solution along with fire-resistant paint. For economical and environmental aspects, plastic waste can be recycled for this purposes. For such kind of structure (i.e mortar-free interlocking plastic-block structure), effect of slenderness on the compressive behavior should be studied. This can be done with a simple compressive testing machine. Therefore, the effect of slenderness on the behavior of the interlocking plastic-block structure is needed to be investigated under static loading by using the locally compressive testing machine.*

1.2.1 Research Questions

- How much variation in maximum stress of single and double block width structural elements could be observed?
- How much variation in energy absorption of single and double block width structural elements can be there?
- How much reduction in load carrying capacity of single block width structural element could be as compared to double block width structural element?
- How much reduction in load carrying capacity of wall with door opening as compared to solid wall can be there?

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

The overall objective of the research program is to precisely investigate the behavior of scaled-down and full-scale mortar free interlocking plastic blocks structure in the laboratory and field respectively.

The specific aim of this MS research work is to investigate the effect of slenderness on the compressive behavior of scaled-down prototype interlocking plastic-block *structural elements i.e column, solid wall and wall with door opening using the servo-hydraulic (compressive) testing machine in the laboratory.*

1.4 Scope of Work and Study Limitations

The prototype interlocking plastic-block structure consists of one column having thirteen blocks i.e single block width, another column having fifty two blocks with double block width. Also, there will be four walls, two solid walls, and two walls with the door opening. It is important to note that two columns and four walls have the same height but their thickness will be different i.e single block width and double block width. These prototypes will be placed in a compressive testing machine. Loading at the rate of 0.02 kN/sec will be applied. Response in terms of load carrying capacity, elasticity, and deformation will be recorded. Correlation between the effect of slenderness on the compressive capacity for these interlocking plastic block structural elements are developed.

Study limitation include the use of servo hydraulic testing machine. Wooden planks are used as a lieu of cap beam. It is assumed that the wooden plank is going to transfer all the load from STM to the specimen uniformly. Scaled-down techniques are applied only on the elevation dimensions and not on the width. In case of opening wall, opening in the form of door in the middle is considered. The proposed earthquake resistant house is limited to only single storey with a maximum height of 10'-0". There will be no significant effect of wind on this height. The effect of wind and fire are out of scope of this study.

1.4.1 Rationale Behind Variable Selection

The justification behind specified selections are:

- Only the elevation measurements are scaled down by 10/4 due to (i) time period dependency as per method A of UBC 97 which depends upon height of the structure and (ii) the limitation of servo hydraulic testing machine.

- Simple boundary condition is known to study the effect of slenderness on the behavior of structural elements i.e columns solid walls and walls with door opening under compressive loading.
- Plastic blocks are used due to their lighter weight. The inertial forces produced decreases as the structure's load decreases.
- Because of their regular usage in homes, column, solid wall and wall with door opening are chosen.

1.5 Novelty of Work, Research Significance and Practical Implementations

To evaluate the effect of slenderness on the compressive strength of masonry structures corresponding to column, solid wall and wall with door opening several analytical models were required. A new construction technique of interlocking plastic block structure for earthquake-resistant houses has been investigated to empower the efficient and cost-effective solution for earthquake resistant houses. Previous studies on these recently developed interlocking plastic blocks have produced outstanding results regarding lateral loading. In order to recommend these interlocking plastic blocks structural elements the compressive behavior of these structural components composed of interlocking plastic blocks must therefore be explored. In this study, the effect of slenderness on the behavior of interlocking plastic blocks columns, solid wall and wall with door opening under compression has been investigated by using servo-hydraulic testing machine. There are, therefore, no codes of conduct to refer to.

Furthermore, there is no specification or code available to equate the compressive strength of the interlocking plastic block solid wall with interlocking plastic block wall with door opening compressive strength. To the best knowledge of author, no study has been conducted to explore the effect of slenderness on the behavior of interlocking plastic block column, solid wall and wall with door opening under compressive loading by using servo-hydraulic testing machine.

The data obtained in the present study will therefore, provide a guide to the design the interlocking plastic block column, solid wall and wall with door opening. The comparison between the compressive strengths of interlocking plastic block structural elements with varying widths is being explored. On the other hand, burning or dumping of plastic wastes is also causing environmental pollution. The mortar free structure made of interlocking plastic block structural units have shown better dynamic properties as compared to brick masonry.

The previous work of Aslam (2021) has shown favorable results. This work is a step forward in developing interlocking plastic-block structure. The proposed housing technology has the ability to provide underprivileged people with a decent standard of living.

1.6 Brief Methodology

Uniaxial compression test is performed on C_s, C_d, SW_s, SW_d, WO_s, and WO_d made of interlocking plastic blocks. C_s consisting of thirteen interlocking plastic block units, $C_d$having fifty-two blocks and wall systems, namely solid wall and wall with door opening are constructed. The compressive strength of interlocking plastic block structural elements is obtained by using the servo-hydraulic testing machine and the requirements of ASTM D695-02a are fulfilled to conduct the tests.

In order to prevent any local failure of interlocking plastic blocks and to distribute the applied load uniformly, samples are centrally put in the servo-hydraulic testing machine and capped at the top and bottom of the face shells by wooden plates. The speed of servo-hydraulic testing machine to compress sample is 0.02 kN/sec until failure. Based on the bearing area, the compressive capacity, energy absorption and toughness index of the interlocking plastic blocks structural elements are then calculated. Interlocking plastic block columns, solid walls and walls with door opening systems are tested against compressive loading in servo-hydraulic testing machine. The tested column with single block width was consisted of thirteen interlocking plastic block and its total height was 762 mm.

The flow chart present in **Figure 1.1** shows the brief description of current study.

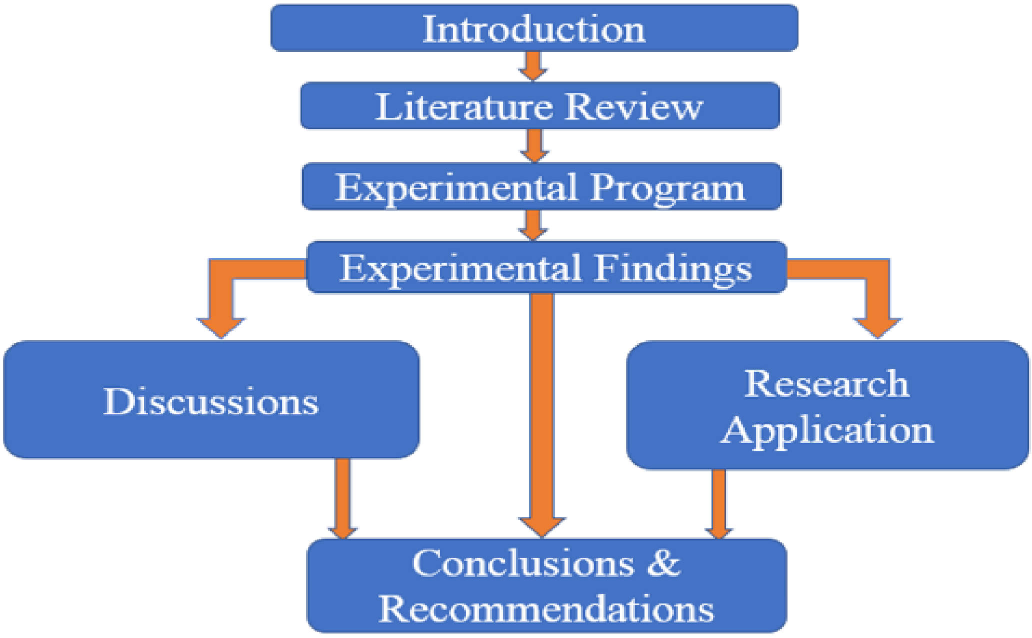


FIGURE 1.1: Flow Chat of Current Research

The tested SW_s consists of one hundred and fifty six interlocking blocks, SW_d consists of three hundred and twelve blocks, WO_s consists of one hundred and twenty blocks and WO_d consists of two hundred and forty inter-locking plastic blocks making a total height (H) of 762 mm. The wall with opening is having an opening in the form of door in the middle. The dimensions of opening are 248 mm x 495 mm. Wooden lintel was provided above the opening for support mechanism. In addition, rubber band are tied up from bottom to top through mid of blocks to provide vertical stiffness in interlocking plastic block columns and walls.

Load-deformation curves are recorded during experiments, which are then transformed into average stress-strain curves to comparison the properties of interlocking plastic blocks structural elements with different thicknesses. Energy absorption before and after cracking are than calculated using area under curves by Simpson's rule. Toughness index for each interlocking plastic blocks structural elements are then determined. Correlation between the peak load carrying capacities of single and double block width structural elements and also between solid walls and walls with door opening were then developed. The failure mechanism of these interlocking blocks structural elements were also reported.

1.7 Thesis Outline

There are six chapters in this thesis which are stated as:

Chapter 1: This chapter serves as the thesis introduction and covers the background, research motivation and problem statement, The overall objective and specific aim of the research work, scope of work and its limitations, novelty of current study with research significance and practical implementations, brief methodology and thesis outline.

Chapter 2: This chapter contains the literature review section. It consists of background, impacts of earthquakes on conventional masonry structures, new approaches for earthquake-resistant structures, mortar free interlocking structures, compressive behavior of masonry building structures, effect of slenderness on walls, compressive behaviour of mortar free walls and summary.

Chapter 3: This chapter consists of an experimental program. It contains background, continuation of research program, technique Introduction to constructing scaled-down interlocking plastic blocks column, solid wall, and wall with door opening, test setup of the servo-hydraulic testing machine with instrumentation, application of compressive loading, analyzed parameters, strength properties, and summary.

Chapter 4: This chapter consists of an experimental evaluation. It contains background, compressive behavior, stress-strain curves, the response of interlocking plastic block column, solid wall and wall with door opening, calculation of compressive strength, energy absorption, toughness index and summary.

Chapter 5: This chapter comprises of discussion. It contains background, correlation between peak load carrying capacity of single and double block width interlocking plastic blocks structural elements, correlation between load carrying capacity of solid walls and walls with door opening, and a summary.

Chapter 6: This chapter includes a conclusion and recommendations. References are presented right after chapter 6.

Chapter 2

Literature Review

2.1 Background

Earthquakes produce various damaging effects on the zones in which they occur. Masonry buildings, in particular, are a hazard to human life in seismic zones of rural and urban regions throughout the world. Ground acceleration is transferred from the ground to the foundation of the structure which causes inertia to damage the masonry walls. The current demand for earthquake-prone areas in developing countries is for affordable, earthquake-resistant housing. The absence of earthquake-resistant development practices causes catastrophic structural damage and societal loss during earthquakes in developing countries. However, research indicates that several earthquake-resistant development strategies and approaches have been used for the stated goal. For instance, masonry constructions with plinth beams, lintel beams, and vertical stiffeners. The literature indicates that various building techniques have been adopted in the form of structural components to build earthquake-resistant masonry buildings.

One new earthquake-resistant technique is the construction with interlocking blocks. But the bigger inertial forces due to the greater mass of these conventional building blocks are a problem. This chapter includes the literature review on the impacts of conventional masonry structures during earthquakes, a new approach for structures resistant to earthquakes.

The effect of slenderness on the compressive performance of interlocking plastic blocks structural elements i.e walls and columns.

2.2 Impacts of Earthquakes on Masonry Building Structures

A change in a system's material and/or geometric properties that has a negative impact on its present or potential performance is referred to as damage [13]. Data-driven techniques for earthquake-induced damage detection have been developed and evaluated in the literature as part of vibration-based long-term Structural Health Monitoring (SHM), using modal parameters as damage sensitive features and geared toward preventative conservation of historic masonry buildings [12]. A Mw = 6.3 earthquake that hit Lesvos Island on June 12th, 2017 resulted in one fatality and significant damage to the built environment. The traditional community of Vrissa, which primarily consisted of masonry buildings, was the most devastated area [14]. Corner towers may be one of the most vulnerable structural components, as evidenced by recent earthquakes, which have shown that old defended masonry constructions may sustain substantial damage, even under low-to-moderate seismic activity. One of the most efficient techniques for understanding deeply and identifying the primary structural flaws of such a building typology is a precise assessment of the structural seismic performance [15].

Through fragility analysis, which determines the likelihood of the demand surpassing the capacity at a given level of intensity, buildings' seismic performance can be evaluated. Although it is commonly known that earthquake uncertainties predominate the features of fragility, little is known about how the characteristics of the earthquake affect the fragility analysis [16]. The findings indicate that the Tarlay Earthquake's noteworthy length was 24 seconds. Within this time frame, resonance in the 1.82 to 2.1 GHz region seemed likely. The crucial duration was between 0.4 and 0.6 seconds, indicating that low- to medium-rise structures were most at risk. The findings also demonstrate that during the earthquake, horizontal

(a)

(b)

FIGURE 2.1: Failure of masonry building having vertical and horizontal stiffners: (a) cracks below band beam, and (b) collapse of wall between opening [60].

ground motion had a comparatively prominent role in the devastation of structural structures [17]. Jagadish et al. [60] investigated the behavior of unreinforced-masonry structures during the Bhuj earthquake in India in 2001. It has been shown that the majority of masonry buildings made of mud mortar experienced severe damage as a result of weak bonds. Future recommendations made in the study included the use of lintel bands and the provision of steel reinforcing in corners and connections of masonry structures. **Figure 2.1a** shows the behaviour of an unique two-story structure with earthquake-resistant measures.With a continuous lintel band and corner RC columns, cement blocks were used to construct this building. Although this structure didn't fall apart, there were significant cracks that extended below the lintel band.

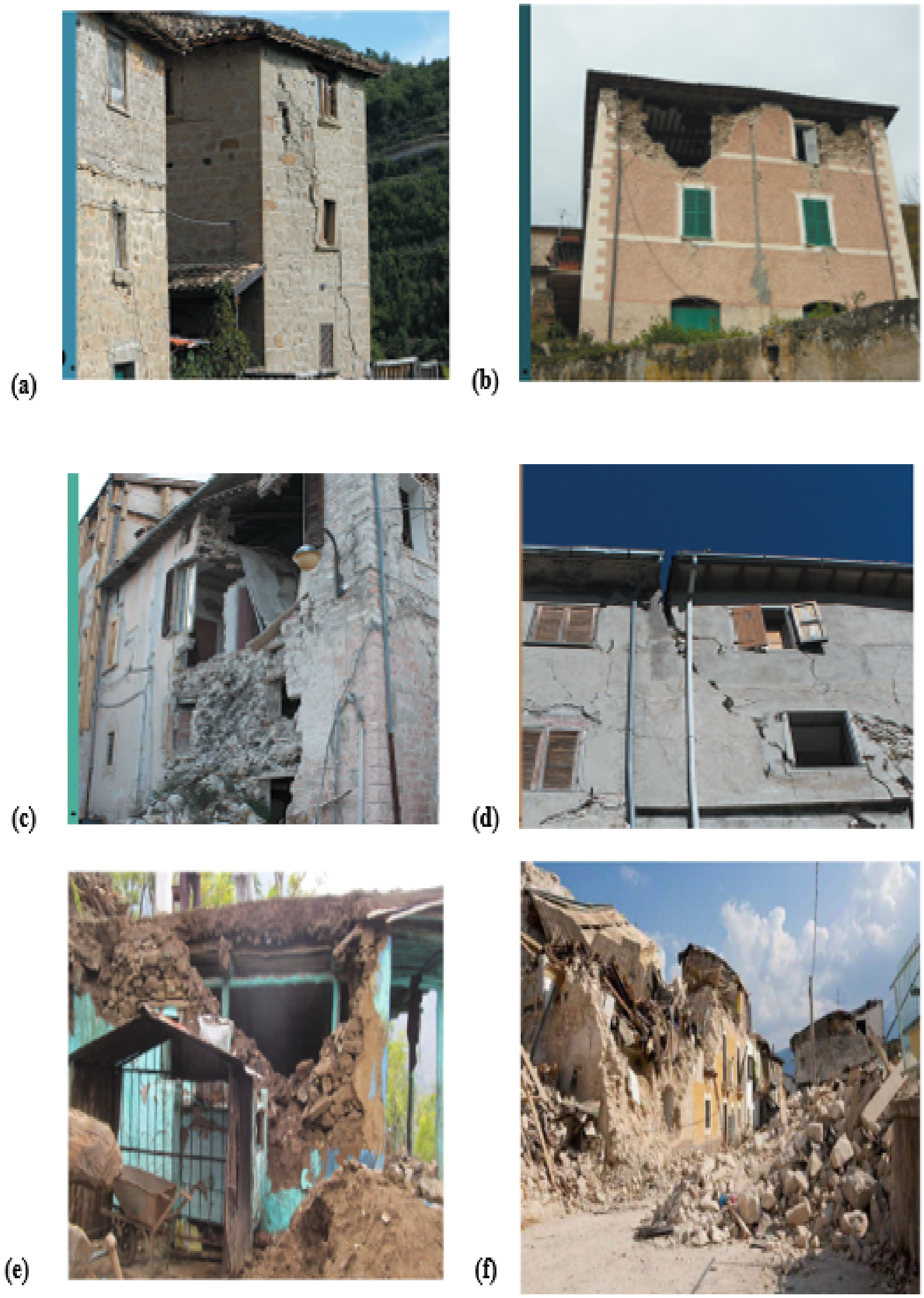


FIGURE 2.2: Conventional masonry failures: (a) corner overturning, (b) horizontal bending provoking out-of-plane leaves separation, (c) masonry crumbling, (d) pounding [2], (e) Out of plan failure of unreinforced masonry wall and (f) collapse of masonry building [20].

Although this structure didn't fall apart, there were significant cracks that extended below the lintel band. A school building is shown in **Figure 2.1b** with typical out-of-plane wall failure between two windows. On April 28, 2021, a moderate earthquake with a local magnitude of 6.4 struck Sonitpur, Assam, India. Despite the fact that the earthquake happened in India, Bhutan had significant structural and infrastructure damage, particularly in the eastern provinces. Various brick masonry failures in the form of corner overturning, horizontal bending provoking out-of-plane leaves separation, masonry crumbling and pounding, out of plan failure of unreinforced masonry wall and collapse of building were reported as shown in the **Figure 2.2**.

Although the shaking was very moderate, substantial damages were reported in many regions because to the inherent vulnerabilities of Bhutanese residential buildings, encased in rural stone masonry and rammed earth construction [18]. According to the EMS-98 scale, an earthquake with an epicentre at ML = 5.5 and a medium intensity of VII struck the Zagreb Metropolitan Area on March 22, 2020. The majority of the Lower Town's structures, including brick masonry buildings, colleges, schools, kindergartens, hospitals, and public buildings, were devastated by the main earthquake. The vast majority of structures constructed in the former Yugoslavia after the country's first earthquake laws went into effect (1964) were either unharmed or only moderately damaged [19]. All these damages can be minimized by providing earthquake resistant features such as confinement columns, band beams etc.

Recent earthquakes that have happened across the globe have demonstrated that unreinforced masonry (URM) buildings built to outdated codes may be a significant source of risk. It is well recognised that the volumetric relationship between the wall texture and the components, as well as the compressive and shear strengths of the bricks, all affect how mechanically responsive masonry constructions are. Therefore, in order to evaluate the risk brought on by the induced seismicity, the seismic susceptibility of various types of red clay brick and calcium silicate brick masonry structures must be determined. Since a minor earthquake struck the area lately (November 26, Durres), the usual construction methods revealed a lack of earthquake proof details [22]. Wenchuan and Ludian earthquakes in China caused 87,476 and 731 fatalities, 459,76,596 and 11,20,513 injuries,

Table 2.1: Earthquakes and their Damages

Sr. No.	Location	Year	Magnitude	Deaths	Comments
1	Northern Areas, Pakistan [21]	2015	7.5	280	Earthquake caused more than 68000 injuries, more than 450000 buildings damages and the losses to a total cost of US $5.2 billion.
2	NW Regions, Albania [3]	2019	6.4	51	Economic losses of 1.2 billion US dollars.
3	Sumarta, Indonesia [23]	2004	9.1	131000	seismic damage was occurred due to poor seismic designs, many mosques had survived the disaster and also suffered to masonry walls
4	Christchurch, New Zealand [46]	2011	6.3	185	The damage caused to the buildings was much devastating due to higher ground shaking levels in the city. Among all building types, unreinforced masonry buildings performed the worst and suffered the highest damages.

and economic losses of 852.309 and 19.849 billion dollars, respectively.

2.3 New Approaches for Earthquake Resistant Structures

In the seismic active regions, economical earthquake resistance housing is desirable in rural areas of developing counties. During strong ground motion, these regions often suffer a significant loss of life because of the lack of seismic resistance houses. Research indicates that several earthquake resistant development strategies and approaches have been used for the stated goal. For instance, in masonry constructions, provision of plinth beams, lintel band beams, and vertical stiffeners. Stiffeners were introduced by French structural engineer and builder Paul Cottancin to strengthen the masonry structures [25].

Many scholars have already investigated the seismic behaviour of masonry structures in laboratories. Under time-scaled Nahnni earthquake conditions, extreme non-linear behaviour of unreinforced masonry was seen in laboratory tests [26]. On the other hand, using reinforced brick masonry concrete stiffeners improved the strength and rigidity of the masonry structures [27]. These phenomena have been verified by laboratory testing as well as actual earthquake loading. During the laboratory testing, the failure modes transitioned from shear slip or diagonal tension to diagonal tension and toe-crushing. Reinforcing materials were incorporated into mortar joints to protect the structure from cracking [28]. When tested in a lab with lateral loads, confined masonry walls with horizontal stiffeners outperformed non-confined walls. When compared to unreinforced walls, masonry walls with vertical steel links stiffeners demonstrated a considerable increase in seismic capability [29].

To enable an efficient and cost-effective solution, new construction techniques were investigated utilizing structures consisting of interlocking plastic- blocks. Interlocking plastic- blocks used in structure play an important role during strong ground motion, these interlocking plastic- blocks dissipate more energy during a seismic event, because of the relative movement at the block interfaces. It was reported that proposed interlocking block shown in **Figure 2.3** is capable of regaining its original position afterwards the induced ground excitation due to provision of inclined key shape in blocks.

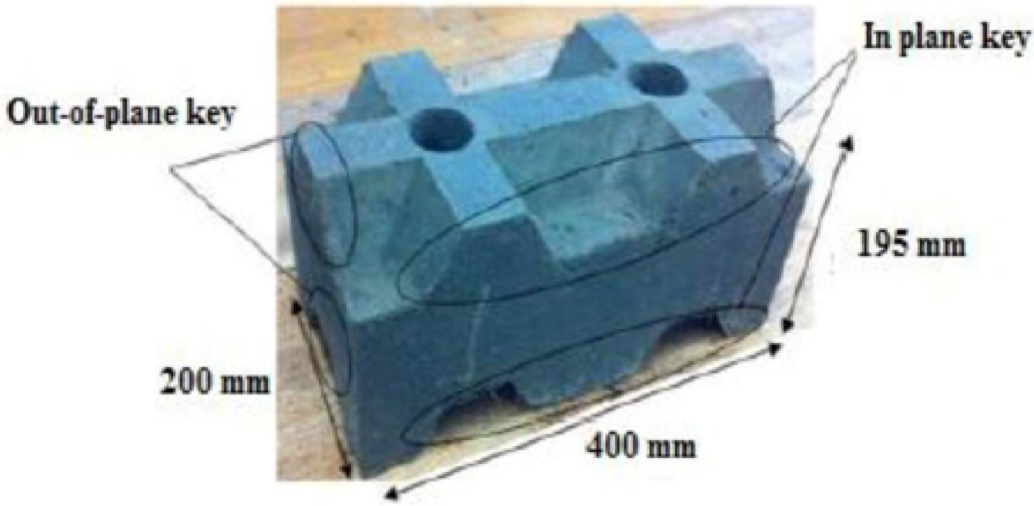


FIGURE 2.3: Coconut Fibre Reinforced Concrete (CFRC) Interlocking Block [52].

2.3.1 Mortar Free Interlocking Structures

Non-engineered structures in rural regions throughout the world had been severely damaged by the earthquake. For residents in such locations, it is necessary to build affordable but safe homes. One of the conceivable possibilities is an interconnecting framework [36]. A mortar-free interlocking block structure can dissipate energy of earthquake. Because of the slanted key between the blocks, interlocking blocks can return to their former locations after a ground motion. During applied earthquake loadings, the vertical relative movement had been seen at the interface of interlocking blocks in the mortar-free column [37, 38]. In the seismic occasion, interlocking blocks had absorbed more energy because of the interlocking key of interlocking blocks [39]. A mortarless or interlocking masonry wall system is a masonry wall that is built without the use of mortar.

Due to its advantages in enhancing field productivity and building efficiency with potentially less skilled labor and hence cheaper costs, the interlocking masonry system has recently become well known in the construction industry as either load or non-load bearing [42]. There are also interlocking blocks that can resist horizontal motion due to interlocking keys at sides. Because it has been an affordable, flexible, and practicable alternative for social interest houses, structural brick masonry construction has been among the most predominant construction systems. Masonry has been a complicated material made up of several units and mortar that gives the composite an anisotropic behavior. As a result, when structural masonry has been subjected to vertical loading, designers must ensure that the stress-strain relationship achieves the ultimate compressive strength and elastic modulus in order to predict load capacity and masonry in-plane displacement [53].

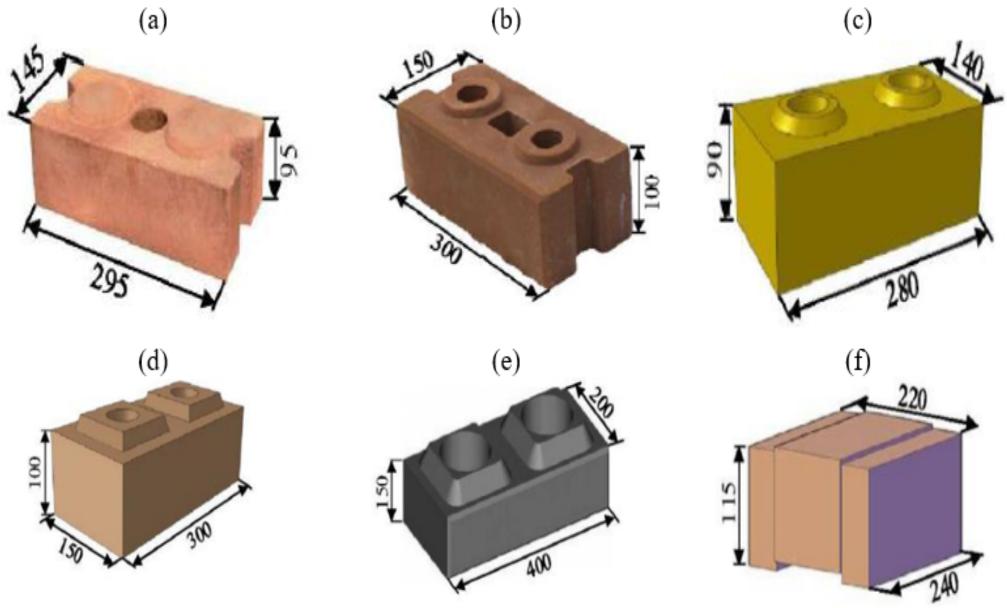


FIGURE 2.4: Various interlocking earth blocks; (a) Auram interlocking block [36], (b) Thai Rhino interlocking block [37], (c) HiLoTec interlocking block [56], (d) Tanzanian interlocking block [57], (e) Hollow interlocking block [58], (f) Hydraform interlocking block [59].

As shown in the **Figure 2.4**, numerous researchers have suggested various forms for interlocking compressed earth blocks. These blocks offer resistance to motion that is both horizontal and transverse to the surface of the wall. Although the shapes, sizes, and forms of these interlocking blocks vary, the protrusions and depressions, also known as the male and female features that make up their interlocking mechanism are relatively similar. The soil properties and curing circumstances made it challenging to maintain the correct shape and size of these interconnecting blocks due to the complicated arrangement of the blocks. A likely technique requires specialized equipment, superior mud selection, mix design, and favorable curative conditions. However, using such equipment is not practical or available in undeveloped countries. By making the interlocking block structure simpler while yet maintaining control over the geometry throughout the manufacturing process, the research offers another helpful approach. Effective locking of these blocks that can withstand the controlling pressures is the determining factor to create a straight and stable block wall [30].

Limited experimental testing showed that raising brick masonry thickness with varied numbers of bonded bricks did not improve compressive strength, despite a drop in slenderness ratio, leading to a reduction in slenderness ratio. Appropriate correction factors should be included to account for the reduction in slenderness ratio with an increase in the thickness when determining the compressive strength of connected brickwork [33]. The cyclic behaviour of interlocking and non-interlocking mortar-less brick was investigated by Liu et al. [34]. The effects of various interlocking forms, loading compression stress levels, and loading cycles were taken into consideration during the investigation of cyclic behaviour. Careful observation revealed a rise in the loading cycle and a fall in the friction coefficients at every joint. A substantial increase in the degradation of the friction has been seen with the loss of the flatness of the interlocking surface.

Figure 2.5 illustrates the size and cross-section profiles for both interlocking and non-interlocking bricks. Emami conducted diagonal compression and shear triplet tests to investigate different types of brick masonry to determine their shear capacity. Both tests revealed that shear capacity was entirely dependent on the strength of the mortar utilized. The interaction between mortar and brick was thought to be a key aspect of masonry construction's long-term strength. Mortar strength, brick strength, and joint thickness were all variables that could influence this interaction [35]. The benefits of these interlocking blocks for masonry construction are now being recognised by the construction industries of developed countries.

Table 2.2: Summarized Details of Various Interlocking Compressed Earth Blocks Proposed in Previous Researches to be used in Earthquake Resistant Masonry Structures

Reference	**Interlocking block shape**	**Surface area of holes %**	**Cement content**	**Main findings**
Maini et al.[54]	Auramblock	9.5	5	Dry compression, shear and bending compressive strength; absorption of water.
Qu et al.[55]	Thai Rhino block	12.7	6.2	Stress strain curves of prisms; seismic performance of flexure-dominated interlocking compressed earth block walls; the structural performance of interlocking compressed earth block walls under cyclic in-plane loading.
Sturm et al.[56]	HiLoTec block	10	9	Compressive and flexural strength of the units; compressive and shear behavior of masonry prisms.
Bland et al.[57]	Tanzanian block	8.7	7.1	The relationship between alignment and block geometric imperfection and the effect of block irregularity on wall quality.
Fay et al.[58]	Hollow block	28	9	Size, water absorption, and compression resistance of interlocking compacted earth blocks.
Uzeogbo et al.[59]	Hydraform block	0	5-20	Masonry unit compressive strength and dry stack wall compressive strength.

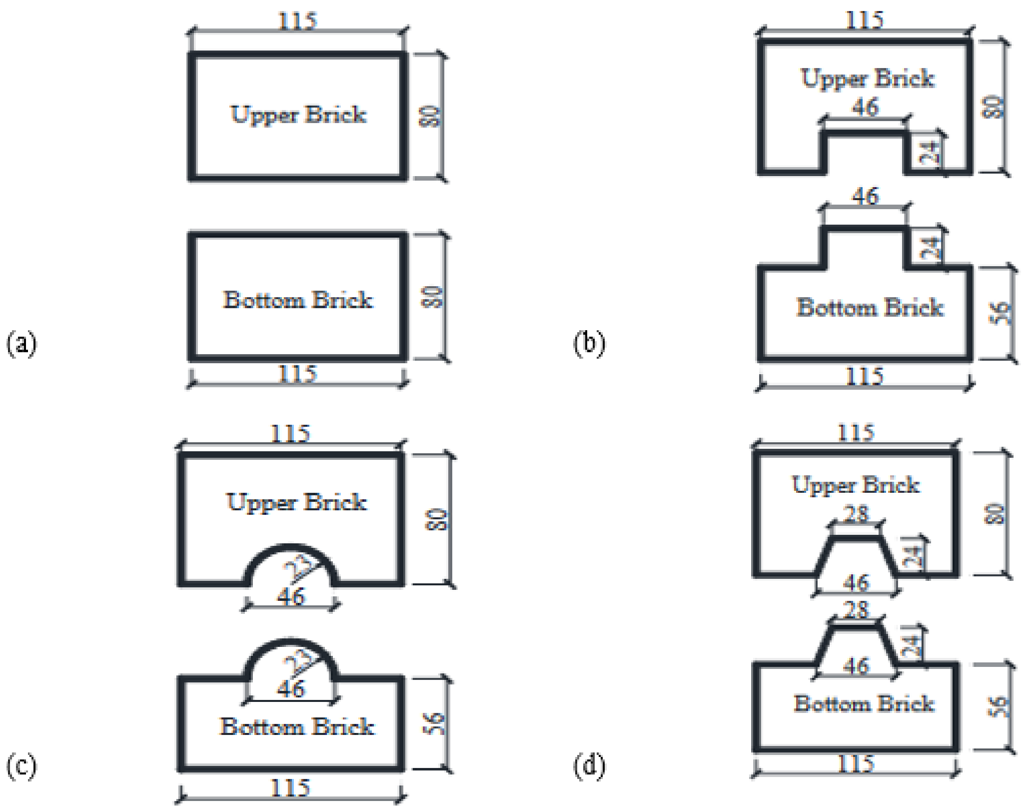


FIGURE 2.5: Dimensions and profiles of the cross-section for specimens of bricks with various interlocking shapes: (a) non-interlocking; (b) rectangular interlocking; (c) circular interlocking; (d) trapezoidal interlocking. (Units: mm) [34].

This innovative interlocking method speeds up building because it requires less work and doesn't use mortar pasting. The shapes, sizes, and materials used in the industry's interlocking blocks vary across these countries. These blocks have been classified as ones that either form complete or partial vertical interlocking on the vertical axis.

2.4 Compressive Behaviour of Masonry Building Structures

One of the crucial factors to understand when designing masonry walls for different loading effects, such as compression, in-plane shear, and out-of-plane flexure, is the compressive strength of the material. Masonry's compressive strength has been a crucial characteristic to understand when designing masonry walls that will be subjected to different loading patterns like compression, shear, and flexure [31]. Furthermore, the common concept that increasing the thickness of a masonry wall (i.e. reducing its slenderness ratio) will enhance its compression strength is well recognized in masonry compression design guidelines. As a result, this notion applies when only one brick or block masonry wall is designed with varying brick/block thicknesses under axial compression [32].

In numerous clay brick masonry buildings all around the world, the bonded brickwork walls are another typical component. These structures are frequently regarded as significant components of heritage, thus figuring out how they actually support loads is crucial to preserving them. Therefore, it is crucial to accurately anticipate the compressive strength of masonry in order to properly design new components and assess the strength of existing masonry buildings. Masonry strength values that can be used to measure the wall's strength have been recorded by a number of specifications and construction codes.The standard brick unit strength largely controls the compressive capacity of masonry, which is regarded as a crucial element in the construction of brick work structures.

In order to determine the compressive strength of masonry codes, specifications, and standards, two approaches have been developed, namely the unit prism strength method. However, the geometry and their interfaces determine the cracking pattern and the ultimate load-bearing capacity of the masonry wall panel Sarhosis et al [61]. Ahmad et al [62] evaluated the masonry wall's compressive strength that used concrete interlocking bricks constructed without mortar. According to studies, a mortar-free wall's inherent tension makes it suitable for usage in residential structures.

2.4.1 Effect of Slenderness on the Walls

Zahra et al. [31] discovered that large-thickness bonded brickwork walls constructed with prisms of double and triple bricks are frequent in load-bearing historical brick masonry buildings in various countries, necessitating interventions and compression capacity testing. The bonded brickwork's slenderness ratios ranged from 1.4 to 10.9. The strength under compression of bonded brickwork decreases as the slenderness ratio increases for all bonded thicknesses, according to the findings. The constructed bonded brickwork samples compression testing configuration is shown in **Figure 2.6**. Front and side view of single, double and triple widths bricks has been shown.

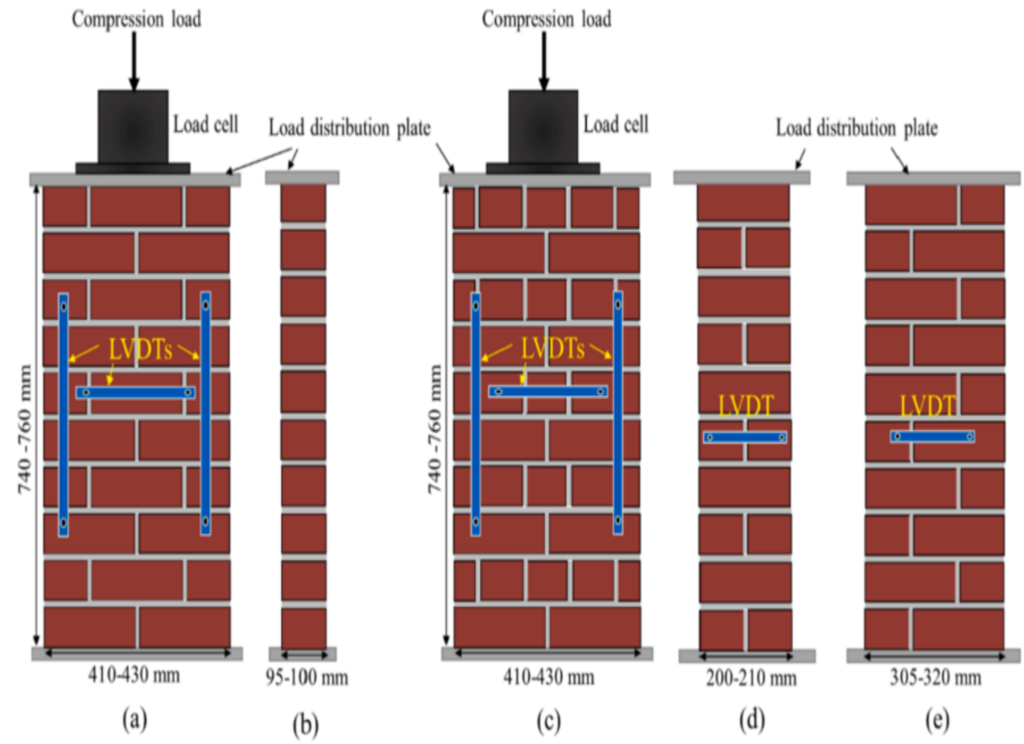


FIGURE 2.6: Compressive testing set-up (a) View of a single brick specimen from the front (b) View of a single brick specimen from the side (c) View of a single and double brick specimen from the front (d) View of a double brick specimen from the side (e) View of a triple brick specimen from the side [31].

Fu et al. proposed that optimum flange thickness ratio and slenderness can optimize the ultimate load-bearing capacity of unequal-walled columns. The parametric investigation shows that the slenderness ratio has an impact on the compression properties of bonded brickwork specimens. As a result, correction factors for compressive strengths computed using various slenderness ratios of brickwork specimens are given. A curve is plotted in between masonry wall compressive stress and slenderness ration. As shown in **Figure 2.7** as the slenderness ratio increases, masonry wall compressive stress is decreases [24].

Inherently, slenderness ratio play a large part in out of plan behaviour due to compressive arching action phenomena; nevertheless, slenderness ratio may reduce or

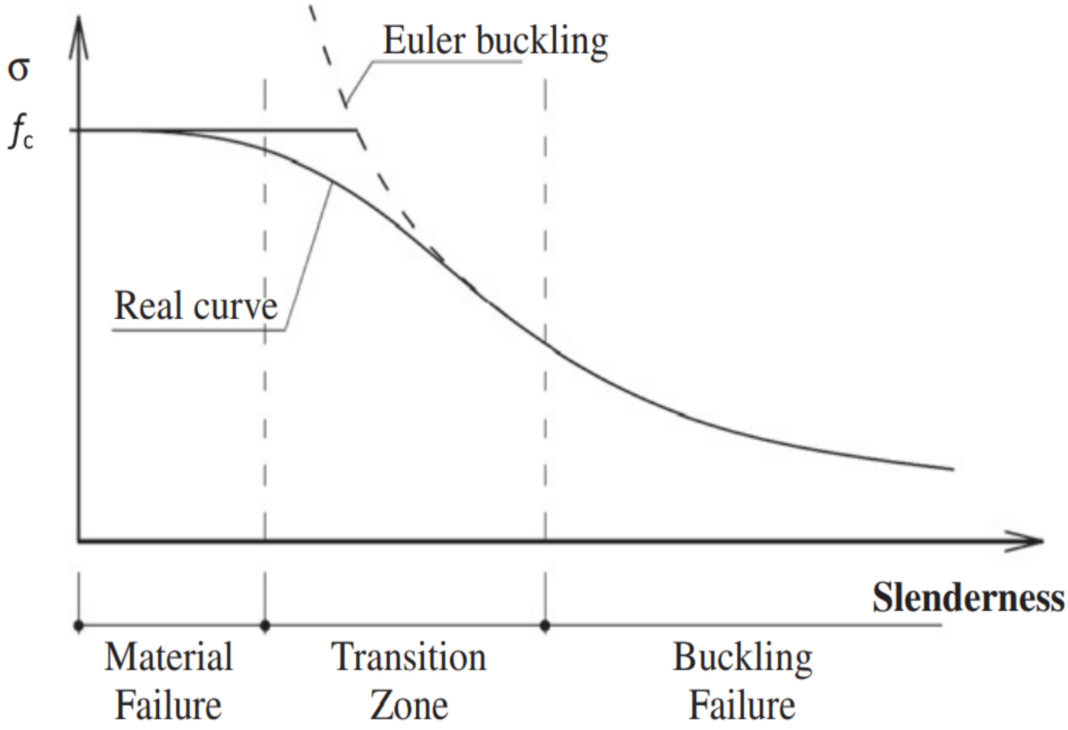


FIGURE 2.7: Relation between compressive stress and slenderness ratio

eliminate the arching action [43]. After the 2010 Maule earthquake, unexpected breakdowns were reported in slender structural RC walls of new residential structures. The ultimate displacement capacity, ductility, and energy dissipation ability of the wall were all lowered by 25%, when the wall thickness was reduced by 25% [40]. Apart from the preceding investigations on the performance of specific designs by various experts, thorough studies on the mechanical properties of interlocking brick are still needed.

2.4.2 Compressive Behaviour of Mortar Free Walls

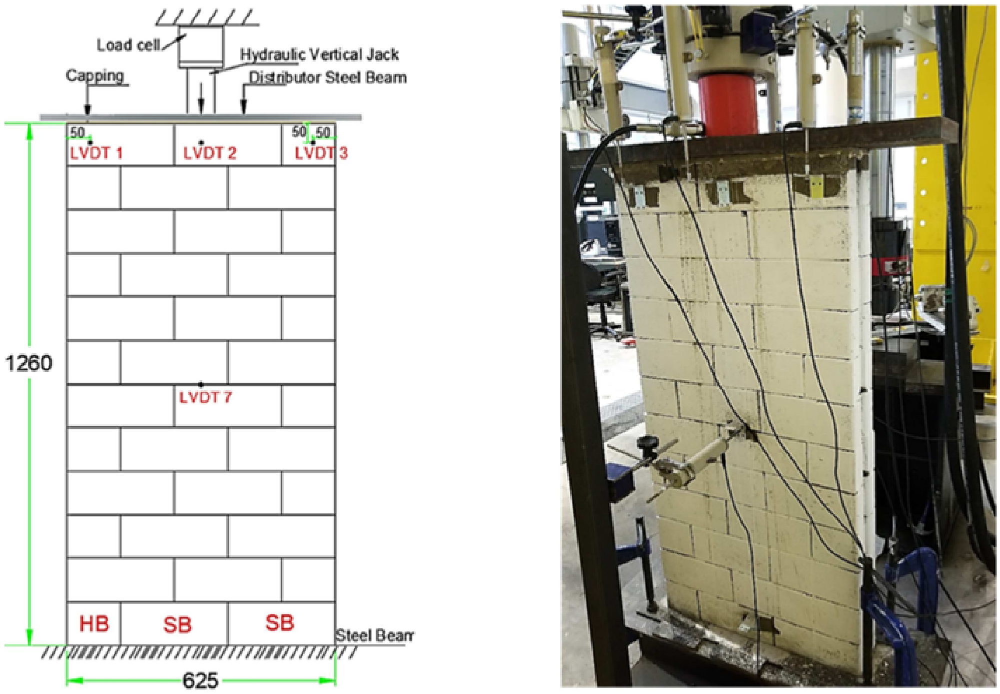
In last few decades, many studies have looked into the quality of mortarless brickwork that has been subjected to compressive loading. The compressive strength of a masonry wall composed of mortar-free concrete interlocking bricks was evaluated by a number of researchers [5]. Because stone masonry constructions have lengthy unsupported spans perpendicular to their plane and no slabs to ensure a diaphragm effect, collapse under large ground motions frequently manifests itself as out-of-plane overturning of the walls before they achieve their in-plane strength

[42]. This special fragility of the old masonry walls is shown by post-earthquake damage observations. The necessity for experimental measurement of these walls' out-of-plane damage limitations develops, particularly during numerical analyses.

It is vital to estimate the in-plane lateral load transfer capacity (Vn) of URM walls with reliability for seismic safety assessments of buildings in the design stage, as well as to decide on seismic retrofitting of existing structures [44]. The coupling relationship of flexural cracking and diagonal shear cracking processes was used to compute the Vn of URM walls. The diagonal cracking shear strength was calculated in their design model by iteratively determining the neutral axis depth and compressive stresses generated by flexure. Shi et al. researched interlocking blocks with natural fibres.

Previous design equations mainly assured only diagonal shear fractures as the prevailing failure mode of URM walls. These equations were designed based on the failure mechanism seen in wall samples strengthened using horizontal and/or vertical rebars. Furthermore, the preceding formulae did not take into account the influence of a disrupted loading path caused by apertures on the failure mechanism and Vn. Instead of being governed by a single mechanism, URM walls commonly exhibit a variety of failure modes such as diagonal cracking, rocking rotation, sliding and toe crushing [45].

The failure mechanism and cracking behaviour of rubberized concrete interlocking hollow and grouted prisms have been investigated. The sides of the bricks had severe fractures, which were detected. For both hollow and grouted prisms, the failure mode was characterized by face spalling and web splitting at the center along the longitudinal direction. The interlocking mechanism caused the web to fracture, putting it under a lot of strain. **Figure 2.8** illustrates the Interlocking Masonry wall test setup and instrumentations. Furthermore, because to the Poisson effect of crumb rubber, which causes the specimen to expand in directions perpendicular to the compression direction, the specimen split. The compressive strength of the grouted rubberized concrete interconnecting prism and wall was higher than that of the void rubberized concrete interlocking systems due to the presence of grout, increasing the masonry systems' stability and strength [47].



(a) (b)

FIGURE 2.8: Interlocking Masonry wall test setup and instrumentations (Unit: mm) a) elevation view and b) instrumentation and test set up [10].

Furthermore, a failure mechanism was discovered in the investigation to be a mix of shear and compression cracks with bed and head joint failure [10].

2.5 Summary

Conventional brick masonry buildings are vulnerable to earthquakes. Modern countries have included confined masonry into their building methods. However, these are also quite susceptible to seismic shocks. It is imperative that developing countries embrace contemporary methods for building earthquake-resistant homes. However, from an economic and dynamic standpoint, current techniques are highly constrained in underdeveloped countries. For developing nations, an affordable new contemporary technology for building earthquake-resistant structures is required. Researchers are focussing on interlocking blocks free of mortar as a substitute for brick masonry. For these blocks a lot of sizes, shapes and interlocking techniques have been featured in the available literature. Examining the effect of slenderness on the behavior of interlocking block prototype structures under compression using the compression testing machine in the laboratory gives output to a higher level of precision.

By conducting small scale testing, it is possible to better predict the effect of slenderness on the behavior of these interlocking block prototypes against compressive loading. Their analytical validation can be used for the development of empirical relationships to perform simplified testing with percentage identification of error. Many researches support and validate the results obtained from the testing of these prototype structures. Most researchers have till now focused on studies of concrete blocks or blocks of masonry. However, the use of any other lightweight material can play a crucial role in reducing the inertial forces. Use of plastic-blocks for prototype solid wall, wall with door opening and column interlocking is such an example of lightweight materials in this research.

Chapter 3

Experimental Program

3.1 Background

Damages caused by earthquakes, a building's reaction to an actual earthquake, and innovative earthquake-resistant technology are all covered in chapter two. Earthquakes produce various damaging effects on the zones in which they occur. Masonry buildings, in particular, are a hazard to human life in seismic zones of rural and urban regions throughout the world. Ground acceleration is transferred from the ground to the foundation of the structure which causes inertia to damage the masonry walls. The literature indicates that various building techniques have been adopted in the form of structural components to build earthquake-resistant masonry buildings. A lot of techniques are being studied to reduce the effect of earthquakes on structures. One new earthquake-resistant technique is the construction with interlocking blocks.

But the bigger inertial forces due to the greater mass of these conventional building blocks are a problem. Therefore, in this study light weight plastic interlocking blocks are being used. This chapter includes many topics such as the continuation of the research programe, proposed scaled-down structural elements, compression testing of the interlocking plastic block structural elements, test setup, compressive loading, analyzed parameters, compressive behavior and stress-strain curve of the interlocking plastic blocks structural elements, and summary.

3.2 Continuation of the Research Program

The response and reaction of structures during an earthquake must be anticipated or calculated when discussing the earthquake-resistant design of buildings. Different methods had been used all around the world for this specific assessment. The method of assembling the interlocking plastic block columns, solid walls, and wall with door opening, test setup and instrumentation, analyzed parameters, and correlation between the effect of slenderness on the behaviour of the interlocking structural elements of the plastic blocks, i.e. column, solid wall, and wall with door opening under compression, are all defined in this study. The interlocking plastic block earthquake resistant house was proposed by Khan [48]. A typical 5 marlas (approximately) house Plan and 3D view of proposed house is shown in **Figure 3.1** In order for a structure to be earthquake-resistant, the weight of the material and the consequent inertial forces are particularly important. Due to their light weight, interlocking plastic blocks will have little inertial force.

Inertial forces are typically thought of as a system's capacity to resist changes brought on by some kind of outside influence (acceleration). The idea is grounded on Newton's Laws of Motion, particularly the Law of Inertia and the Law of Action and Reaction. Due to their greater weight compared to lighter systems (materials), heavy systems (materials) respond more strongly to such external forces, resulting in stronger inertial forces. Compressive strength, which depends mostly on individual unit compressive strength, is the most important characteristic in the construction of structures. **Table 3.1** shows the summarized detail of previous researches on interlocking plastic blocks with scaled-down prototype sizes and their scales. Basically, current research work is the continuation of the research program. Almost 8 thesis have already been done. Out of which 7 thesis was conducted on lateral/dynamic loading with different aspects/structural elements. And these studies have shown favorable results. Before these interlocking plastic blocks structural elements would be going to recommended for practical use, there was a highly demand to investigate the static behavior of these interlocking plastic blocks structural elements.

Table 3.1: Summarized detail of previous researches on interlocking plastic blocks structural elements

Sr.No	Researcher Name	Area of Research	Structural Elements Sizes	Scale
1	Fayyaz Khan	Inter-locking plastic blocks column.	Column 62 mm X 330 mm	1/10
2	Mehran Sudheer	Out-of-plane behavior of wall with window opening.	Wall 375 mm X 330 mm	1/10
3	Sohail Afzal	Out-of-plane behavior of solid wall.	Wall 375 mm X 330 mm	1/10
4	Junaid Asad	Consequence of block return on in-plane of walls.	Wall 375 mm X 330 mm (With Block Return)	1/10
5	Khurram Shahzad	Effect of block return on out-of-plane of walls.	Wall 375 mm X 330 mm, (With Block Return)	1/10
6	Shaukat Anwar	Effect of Diaphragm on Dynamic Behavior of Interlocking Plastic-Block Structure with Different Elements Pattern	Wall 375 mm X 330 mm (Having Diaphragm with and without Block Return)	1/10
7	Hammad Bashir	Dynamic Response of Interlocking Plastic-Block Walls with Diaphragm using Numerical Approach	Wall 375 mm X 330 mm, (Numerical Analysis With Diaphragm)	1/10

Continued Table 3.1 Summarized detail of previous researches on interlocking plastic blocks structural element

Sr.No	Researcher Name	Area of Research	Structural Elements Sizes	Scale
8	Sajid Aslam	Compressive behavior of plastic block structural elements.	Wall 375 mm X 330 mm, Column 62 mm X 330 mm	1/10
9	Current Research	Effect of slenderness on the behavior of interlocking plastic block structural elements under compression.	Wall 762 mm X 762 mm, Column 62 mm X 762 mm	4/10

As far as testing against lateral loading is concerned almost all the aspects has been covered by using locally available 1 dimensional shake table. All experiments had shown favorable results.

Table 3.2: The comparison of Current Research with Compressive Behavior of Interlocking Plastic unit block and its Structural Elements conducted by Aslam. S [49]

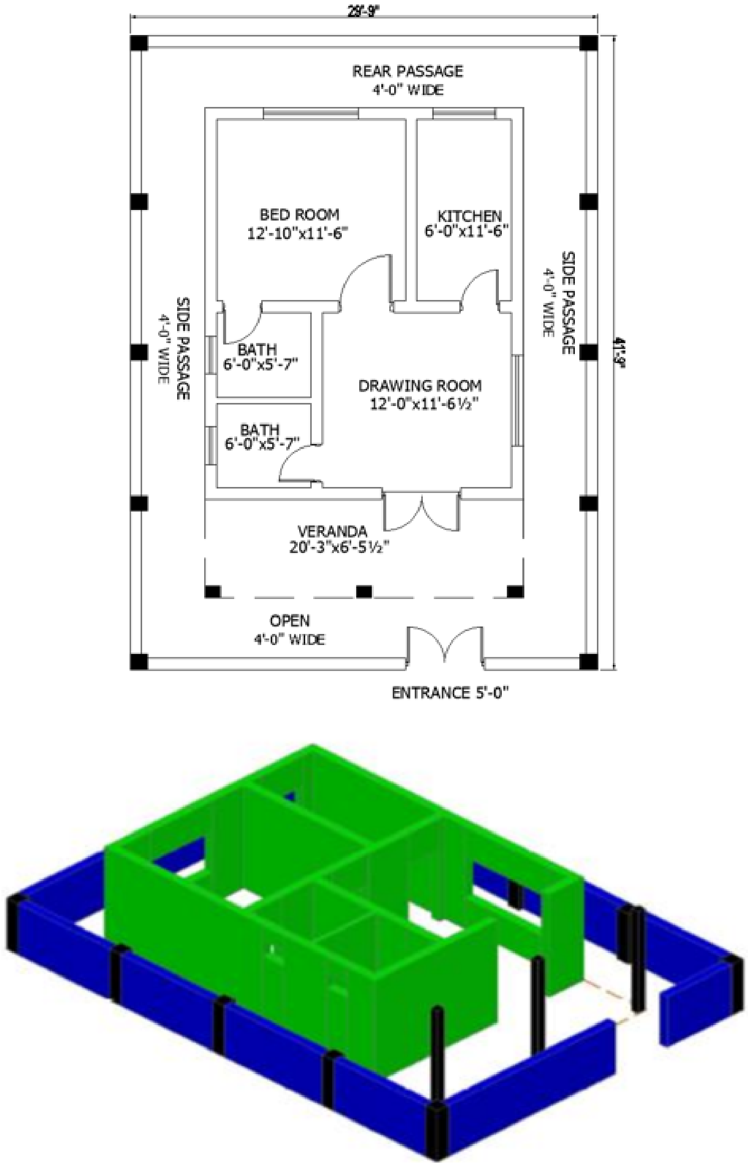
Sajid Aslam (1/10th scale)				Muhammad Adnan (4/10th scale)			
Unit Block, Prism of Two and Three Blocks	Column	Solid Wall	Wall with Window Opening	Single Block Width	Column	Solid Wall	Wall with Door Opening
				Double Block Width	Column	Solid Wall	Wall with Door Opening

Aslam. S [49] concluded that Interlocking unit blocks have a lower peak load carrying capacity than multiple blocks (prisms). Prisms (having two and three unit blocks) have a higher maximum load carrying capacity than columns with eight block units, this is due to high slenderness ratio of column. The peak load carrying capacity of column is less than peak load carrying capacity of solid wall and wall with opening. Peak load carrying capacity of a wall with opening is lower than that of a solid wall, this was due to fact that solid wall has more stiffness than wall with opening.

It may be noted that during a seismic event the structure has to withstand the combination of lateral as well as gravity forces, and more than 95% of its design life the structure has to withstand gravity forces only. But seismic event cannot be ignored. To start with, compressive behavior is needed to explore. Making a contribution to this requirement, current research was aimed to study the effect of slenderness on the behavior of interlocking plastic block structural elements under compression by using locally available servo hydraulic testing machine in the laboratory.

For construction of earthquake resistant housing, the proposed interlocking plastic blocks have base dimension of 150 mm x 150 mm and having four keys at the top. Total height of block is 140 mm including the 30mm height of interlocking key as shown in **Figure 3.2(a)**. Similarly, for prototype construction, the used dimensions in the study are 62 mm x 62mm with a height of 67 mm including the 12 mm height of interlocking key as shown in **Figure 3.2(b)**. Current research work is continuation of Aslam. S [49] research work. In this research work, prototype interlocking plastic block structural elements (column, solid wall, wall with door opening) are considered for finding the effect of slenderness on the behaviour of structural elements under compression testing. A comparison of current research with compressive behavior of interlocking plastic block unit and its structural elements conducted by Aslam. S [49] presented in **Table 3.2**. Prototype testing [31, 50] serve to provide specifications for a real or proposed working system rather than a theoretical one. Prototype walls scaling and construction technique adopted in this research work is purely based on research practices mentioned in literature Keivan et al. [51]. Outcome of such studies help to understand the behavior of full-scale mortar free interlocking structures.

It may be noted that the height of all prototypes (i.e., scaled down column and walls samples) is same, the thickness is varying i.e single block width and double block width. However, the elevation dimensions in both prototypes i.e solid wall and wall with door opening are approximately the same. **Figure 3.3(a)** shows schematic diagram of proposed real interlocking plastic block wall panels. It will have some grooved block mechanism for foundation and roof diaphragm. **Figure 3.3(b)** shows scaled downed schematic diagram of prototype interlocking plastic block solid wall, using 4/10 scale factor. Only the elevation measurements are scaled down by 10/4 due to time period dependency as per method A of UBC 97 which depends upon height of the structure and the limitation of testing machine. The primary purpose of this research is to study the correlation between the effect of slenderness on the compression strength of column, solid wall and wall with door opening. For this, slenderness ratio is an important parameter, which depends on the structure height and thickness. That is why, scale down technique is applied only on elevation dimension of structural elements.



(a)

(b)

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

3.3 Construction of Scaled-Down Structural Elements Prototypes

Prototype interlocking plastic block single width column having thirteen interlocking plastic blocks making a total height of 762 mm, another column with double block width having fifty two interlocking blocks making a total height of 762 mm as shown in **Figure 3.4**. Single block width solid wall with height of 762 mm consisting of one hundred and fifty six interlocking blocks, similarly solid wall with

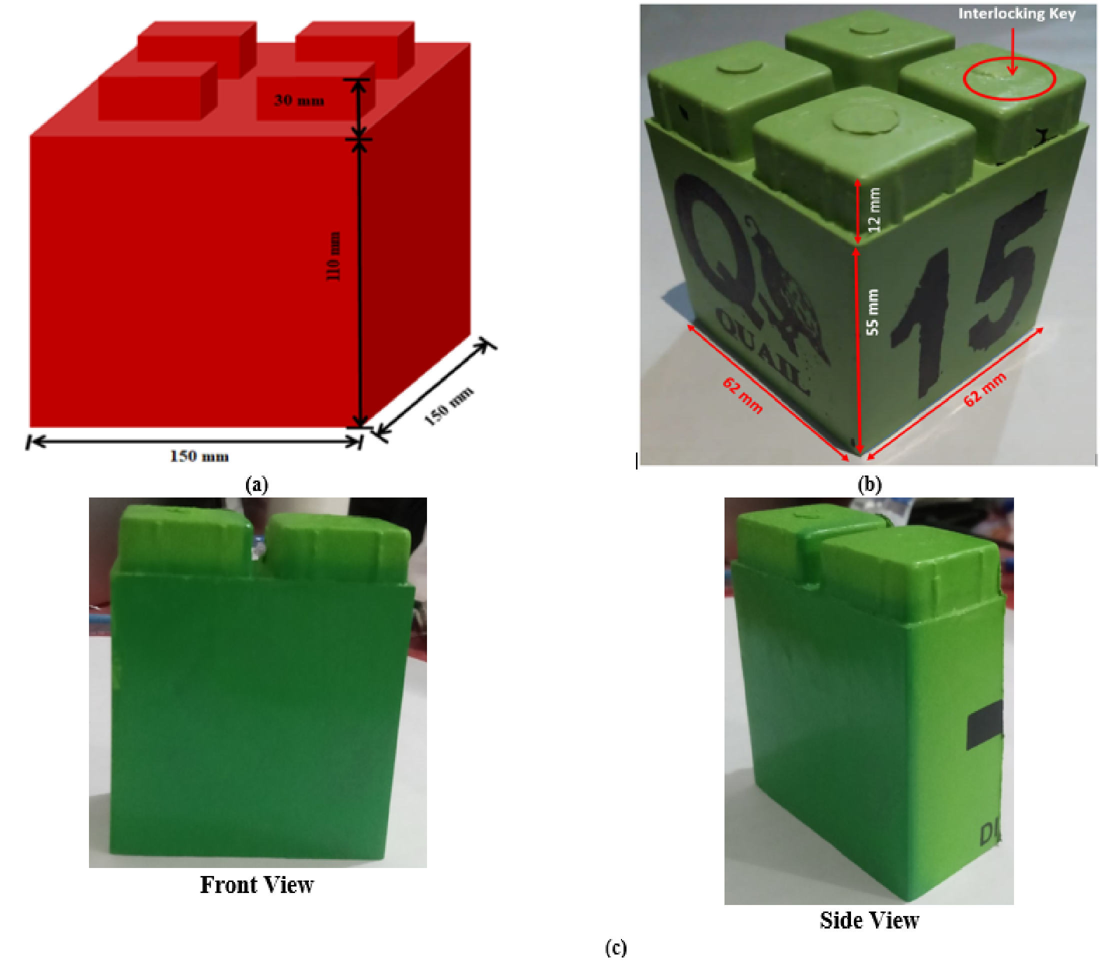
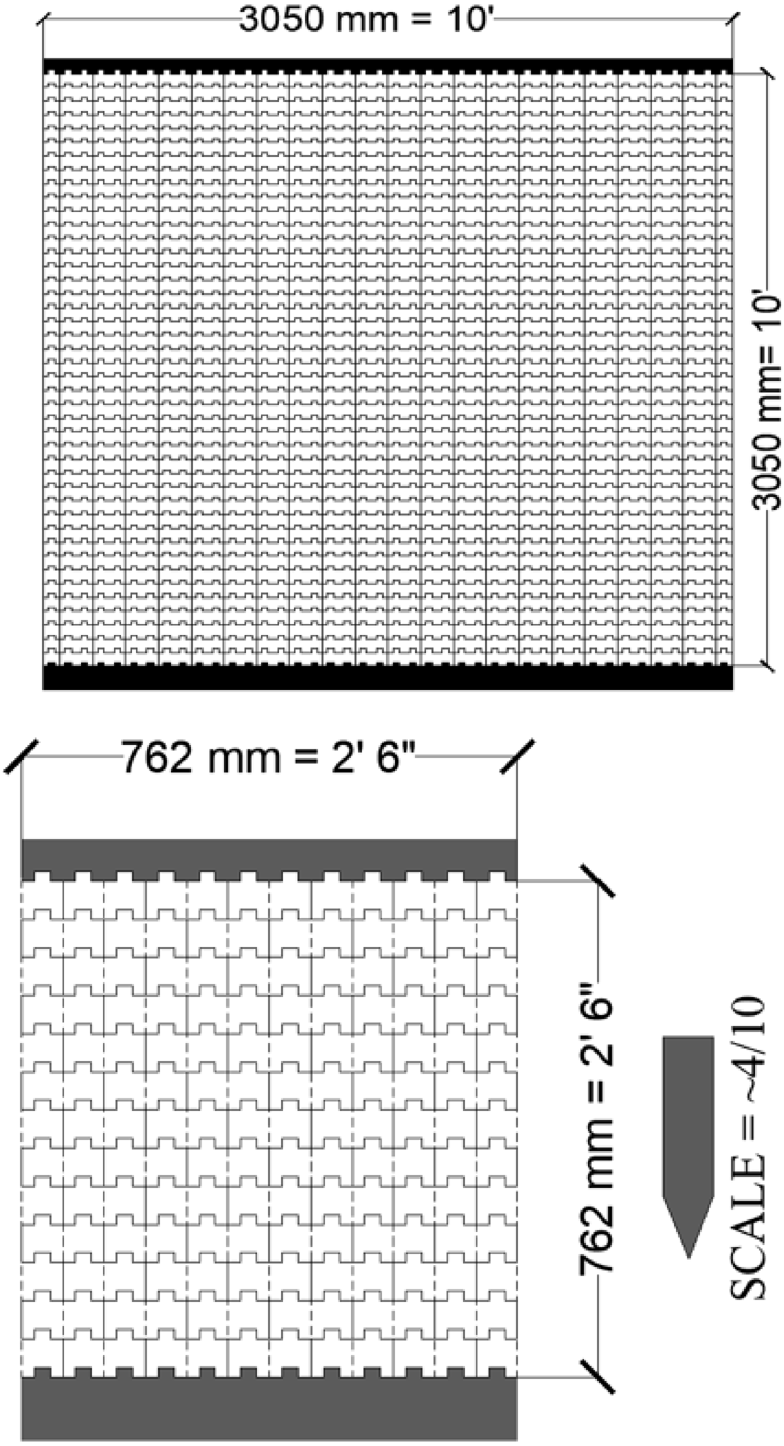


FIGURE 3.2: Proposed interlocking plastic-block: a) for construction, b) stretcher block for prototype construction, and c) half block (current research)

double block width consisting of three hundred and twelve interlocking plastic blocks as shown in **Figure 3.5**. Single block width wall with door opening having one hundred and twenty interlocking plastic block units and double block width opening wall having two hundred and forty interlocking plastic blocks as shown in **Figure 3.6**. The wall with opening is having an opening in form of door in the middle.

The dimensions of opening are 248 mm x 495 mm. Wooden lintel is provided above the opening for support mechanism. In addition, rubber band are tied up from bottom to top through mid of blocks to provide vertical stiffness in interlocking plastic blocks structural elements. Rubber band provides integrity of prototype interlocking plastic block structural elements and it also avoids sudden failure of structural elements in terms of buckling. Due to rubber band plastic deformation will increase which ultimately results in greater post-crack energy dissipation and toughness index.



(a)

(b)

FIGURE 3.3: a) Proposed actual wall, and b) scaled downed prototype wall for current work

The elastic modulus, tensile strength and thermal conductivity of the common plastic materials are 2.55 GPa, 65 MPa and 0.15 W/mK respectively [64]. No mass is provided at top of the structural element. The weight of single interlocking plastic block is 24g. However, the total mass of C_s is 0.920 kg, the total mass of C_d is 1.850 kg, the total mass of SW_s (M) is 4.29 kg, SW_d having mass of (M) 9.095 kg, similarly the mass of single and double block width opening walls are 3.35 kg and 7.425 kg respectively.

3.4 Test Setups and Instrumentation

Uniaxial compression test is performed on interlocking plastic block single width column, column having double width, single block width solid wall, solid wall with double width, wall with door opening having single block width and wall with door opening with double block width made of interlocking plastic block units. The height of all these structural elements is same i.e 762 mm. All the interlocking plastic block structural elements are tested in servo-hydraulic testing machine to determine the compressive capacity (σ), corresponding strain (ε), modulus of elasticity (E), total compressive toughness Tc.

To prevent any local failure of interlocking plastic blocks and to distribute the applied load uniformly, samples were centrally mounted in the servo-hydraulic testing machine and capped at the top and bottom of the face shells by wooden planks. For the wall samples, wooden planks were placed at the top and bottom to ensure the uniformity of applied load. The compressive capacity of interlocking plastic block structural elements was obtained by using the servo hydraulic testing machine and the test was performed in compliance with the requirement of ASTM D695-02a. The speed of servo-hydraulic testing machine to compress sample was 0.02 kN/sec until failure. **Figure 3.7 (a)** shows the instrumentation of compression test for single block width column, made of interlocking plastic stretcher blocks as shown in **Figure 3.2 (b)**, **Figure 3.7 (b)** shows the instrumentation of compression test for double block width column, made of interlocking plastic stretcher and half blocks as shown in **Figure 3.2 (b,c)**. At top load is being applied from STM, and the displacement is being recorded at the top.

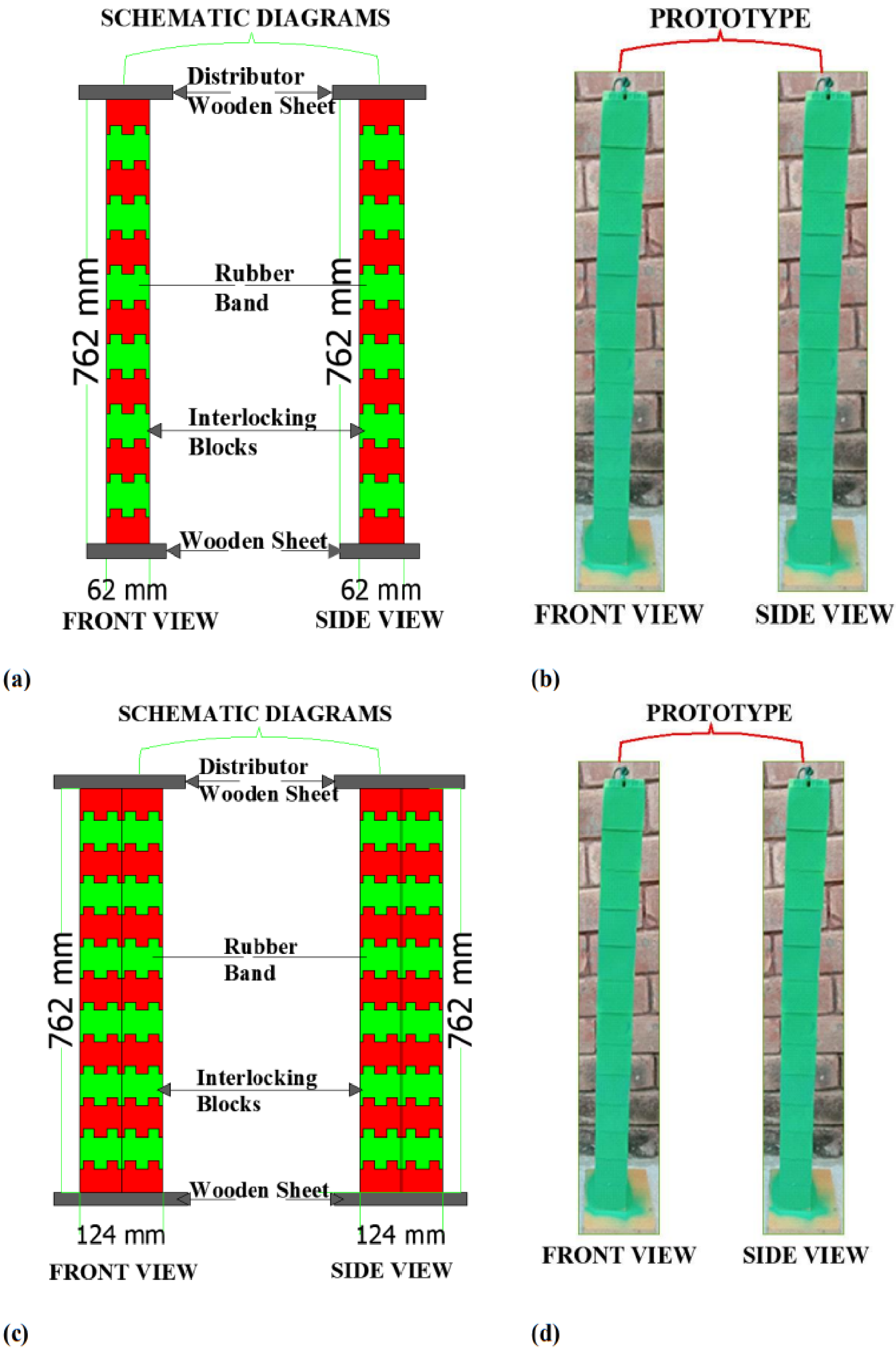


FIGURE 3.4: Considered columns) Schematic diagram of C_s, b) prototype of C_s, c) Schematic diagram of C_d, and d) prototype of C_d

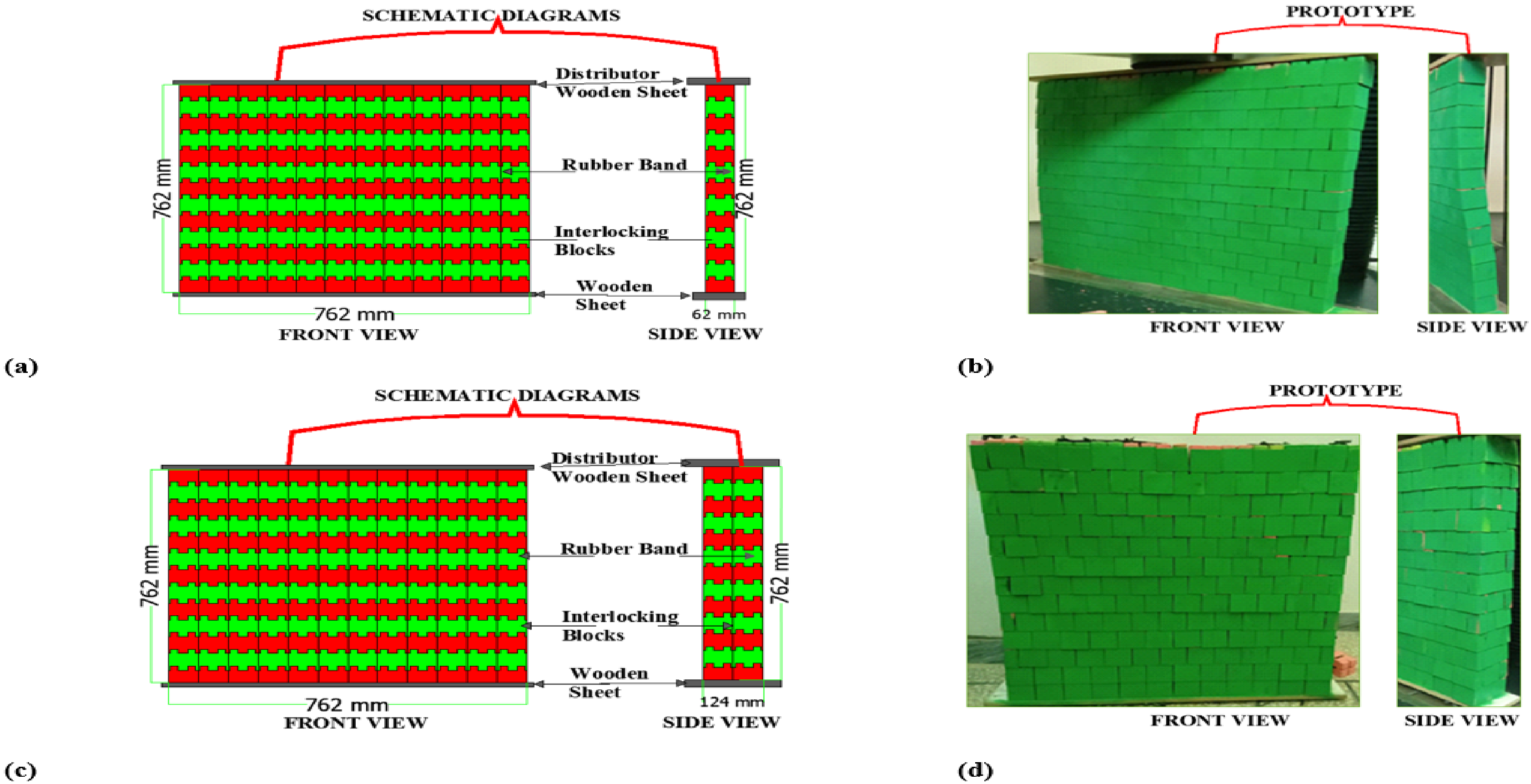


FIGURE 3.5: Considered solid walls a) Schematic diagram of SW_s, b) prototype of SW_s, c) Schematic diagram of SW_d, and d) prototype of SW_d

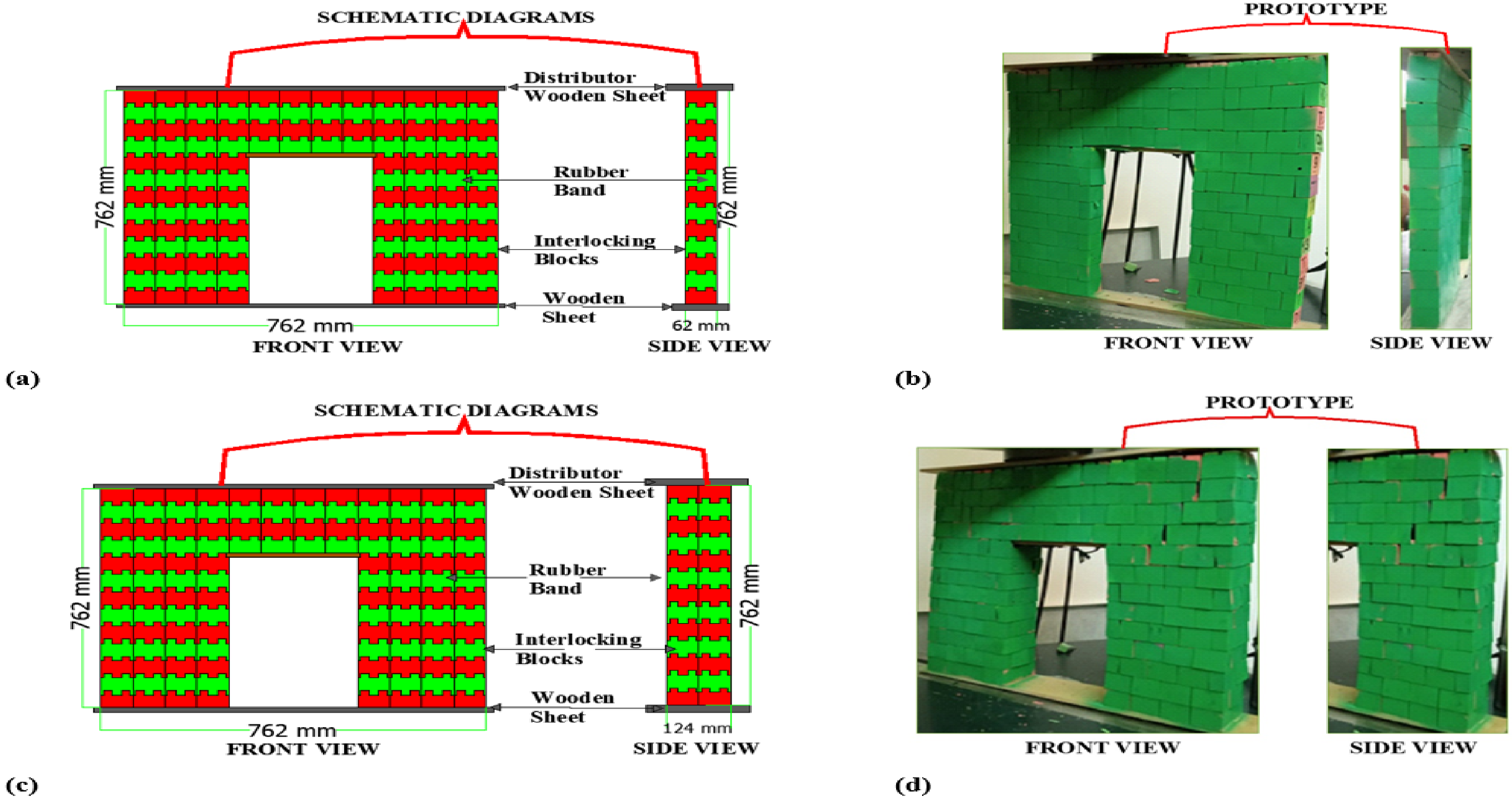


FIGURE 3.6: Considered walls with opening a) Schematic diagram of WO_s, b) prototype of WO_s, c) Schematic diagram of WO_d, and d) prototype of WO_d

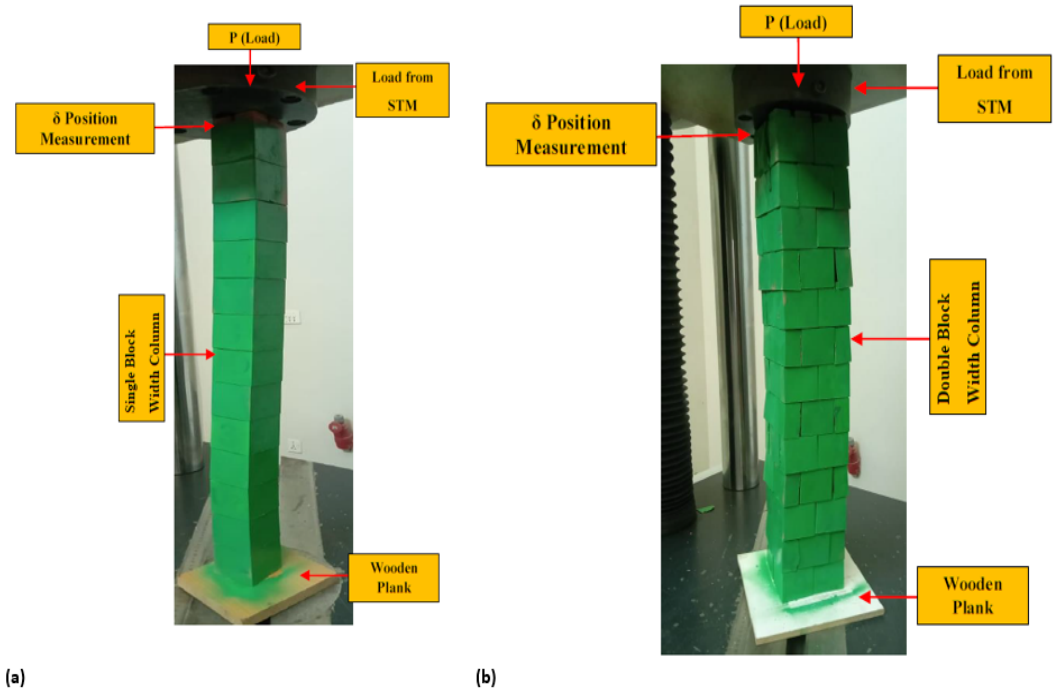


FIGURE 3.7: Experimental test setups; a) C_s and b) C_d

The column of interlocking plastic blocks was made and tested under compressive load, as per the method prescribed in ASTM D695-02a, using servo hydraulic testing machine. The height of both columns i.e single block width column and double block width column was 762 mm. The thickness for single block width column was 62 mm, while for double block width column the thickness is 124 mm. The interlocking plastic blocks columns are put centrally in the servo-hydraulic testing machine to ensure uniform distribution of applied loads and to prevent any local block failure as shown in **Figure 3.7**. The both solid walls i.e single and double block widths and both door opening walls (one with single block width and other with double block width) have dimensions of 762 mm length, 762 mm height. The thickness of single block width column, solid wall and wall with door opening was 62 mm, on the other hand the thickness was double for all these structural elements i.e column, solid wall and wall with door opening was 124 mm.

The solid walls and walls with opening in the form of door have been made using interlocking plastic blocks in stretcher bond. The stretcher block was the main unit of the wall panel, while the half interlocking plastic block was used to construct the wall course.

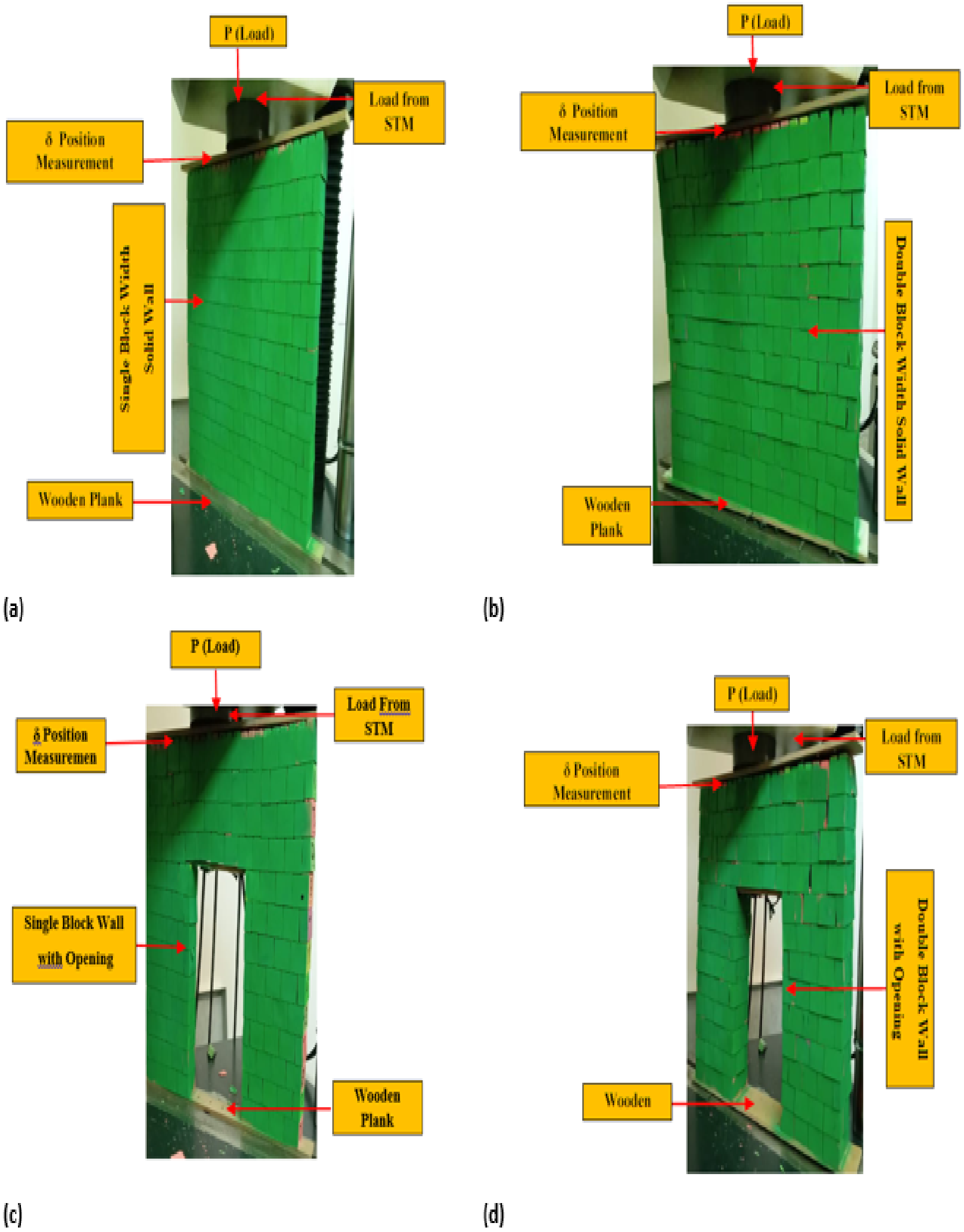


FIGURE 3.8: Experimental test setups; a) SW$_s$,b) SW$_s$,c) WO$_s$, and d) WO$_d$

A single block-width solid wall was made of 13 courses, the first course at the bottom contains thirteen stretcher interlocking plastic blocks (SB) as shown in **Figure 3.2(b)**, the second course contains twelve stretcher interlocking plastic blocks (SB), and two half interlocking plastic blocks (HB). On a wooden plank, the first course of the interlocking blocks was laid out tightly in a straight line. The four interlocking keys on the top shell-face surface are positioned closely into the cavity part on the bottom shell-face surface of the block. These interlocking keys and cavities allow the blocks to interlock with other blocks placed above and below. By adopting the same procedure, the whole wall has been constructed. For double-block width solid wall, two rows of interlocking plastic blocks were staggered on a wooden plank parallel to each other horizontally. In the second course twelve interlocking plastic blocks were used at mid to seal the joint between both first rows with half interlocking plastic blocks on both edges along the length of the wall. Both edges along the width of the double-block solid wall, a series of half interlocking plastic blocks were staggered in second row. This staggering technique were repeated for thirteen rows vertically. Wooden lintel is provided above the opening in wall with door opening for support mechanism. Interlocking plastic block solid walls and walls with door opening are capped with wooden planks on the bottom and top of the specimen to ensure vertical load distribution uniformly as shown in **Figure 3.8**. The test is performed in compliance with the ASTM D695-02a specifications. Interlocking plastic block structural elements labeling and their top and bottom contact areas are shown in **Table 3.3**.

3.5 Compression Testing

3.5.1 Procedure for Compressive Behaviour and Stress-Strain Curves

The maximum peak load carrying capacity, compressive capacity, strain, elastic modulus, total energy absorbed, and toughness index of an interlocking plastic block single block width column with thirteen blocks, a double block width column with fifty-two interlocking plastic blocks, a single block width solid wall, a single block width wall with door opening, a double block width solid wall and a double block width solid wall with door opening are tested in a servo-hydraulic testing machine. In order to examine interlocking plastic block properties including elastic modulus, energy absorption, and toughness index, test load-deformation curves are recorded and then transformed into average stress-strain curves. From these stress-strain curves energy absorption, toughness index and modulus of elasticity were then calculated. Energy absorption values were calculated by Simpson's Rule.

Table 3.3: Interlocking Plastic Blocks Structural Elements Labelling and their contact areas i.e top and bottom

Sr. No.	**Interlocking Plastic Block Structural Element**	**Label**	**Top Contact Area** (mm^2)	**Bottom Contact Area** (mm^2)
1	single block width column	C_s	2304	178
2	Double block width column	C_d	9216	711
3	Single block width solid wall	SW_s	29952	2311
4	Double block width solid wall	SW_d	59904	4622
5	Single block width wall with Door Opening	Wo_s	29952	2311
6	Double block width wall with Door Opening	WO_d	59904	4622

The top and bottom contact areas are different because of the fact that these blocks are hollow and also having four keys at the top. For the calculation of stress the similar approach was also used by Ali et al. [38].

3.5.2 Strength Properties

The compressive strength of the wall must be calculated for the construction of the interlocking plastic block wall. There is no code or specification available that compares the compression ability of the interlocking wall of plastic blocks with the compressive ability of the block single block. In this study correlations were developed between the effect of slenderness on the compressive capacity of C_s, C_d, SW_s, SW_d, WO_s, and WO_d in an effort to develop a design code for the interlocking plastic blocks. Furthermore, the output of the interlocking mechanism was evaluated and the failure mode were tested. All measures of strength used in this analysis were based on the net area. As required by some procedures, depending on the gross area, this can be readily converted into capacity. The capacity relationship results found in this study, however, will not be affected.

3.6 Summary

The detailed experimental program has been covered in this chapter. The prototype interlocking plastic block structure is selected for research work. Interlocking plastic blocks are purchased from local market. To evaluate the impact of slenderness on the behaviour of structural elements under compressive loading in material testing laboratories, a prototype interlocking plastic block structure was chosen. Rubber band can be used to maintain the prototype interlocking plastic block structure's integrity. Stress-strain curve for interlocking plastic-block structure were then calculated from load-deformation curves.

Chapter 4

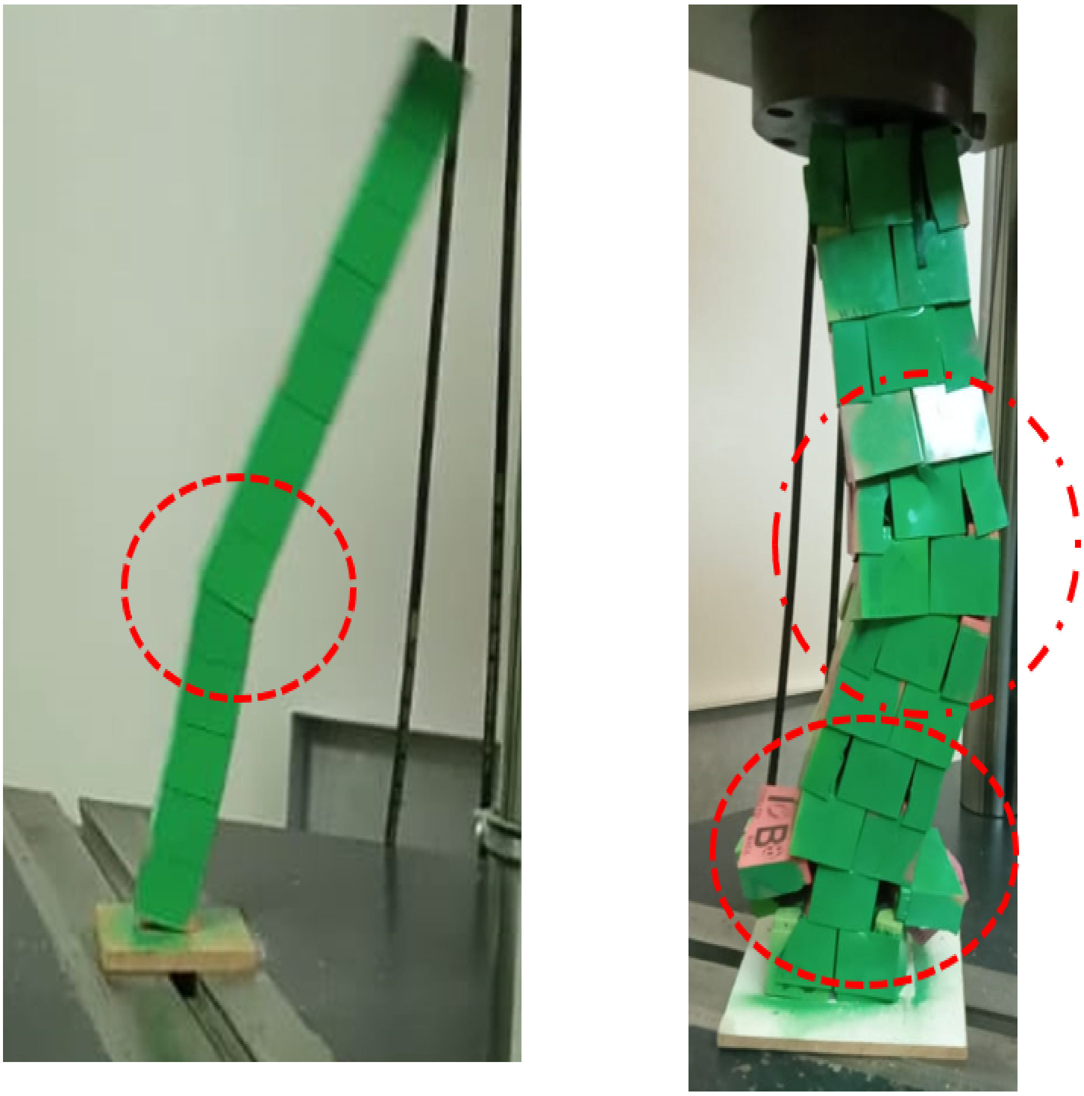
Experimental Findings

4.1 Background

The experimental procedure is thoroughly detailed in the preceding chapter. The experimental assessment of the collected data is the topic of this chapter. This chapter includes a detailed discussion about stress-strain curves, energy absorption and toughness index of the single and double block width solid wall panels, single and double block width wall panels with door openings, and interlocking plastic block columns with single and double block width.

4.2 Compressive Behavior

It was observed that single block width column (C_s) buckle from the middle with sudden impact and cracks were observed at the bottom corners of middle block. Also, the blocks at the lowest part of the above mentioned specimen were intruded into each other and one of their corners was also broken as shown in **Figure 4.1(a)**. Due to the presence of rubber band (C_s) was not split into individual blocks, however it was collapse. Out of plan behavior was observed in case of double block width column (C_d). Initially buckling starts from middle height of the column but it was not with sudden impact and then at the bottom side some of the half blocks have shown slippage which means a more stable foundation is required. Some cracks were also developed at the top most blocks. The (C_d) was giving some warning before buckling failure as observed in case of (C_s) i.e sudden failure. Maximum deviation from center line was observed at mid length of column as shown in **Figure 4.1(b)**.



(a) (b)

FIGURE 4.1: Cracking and failure modes of interlocking plastic blocks column a) C_s and b) C_d

Wooden planks were transferring all the load uniformly from STM to specimen uniformly except in case of double block width solid wall where wooden plank was bent down slightly from the middle due to high stiffness of double block width solid wall. In the case of single block width solid wall (SW_s) the bucking was detected in minor but when it started gaining load, its physical behavior changed and it was erected.

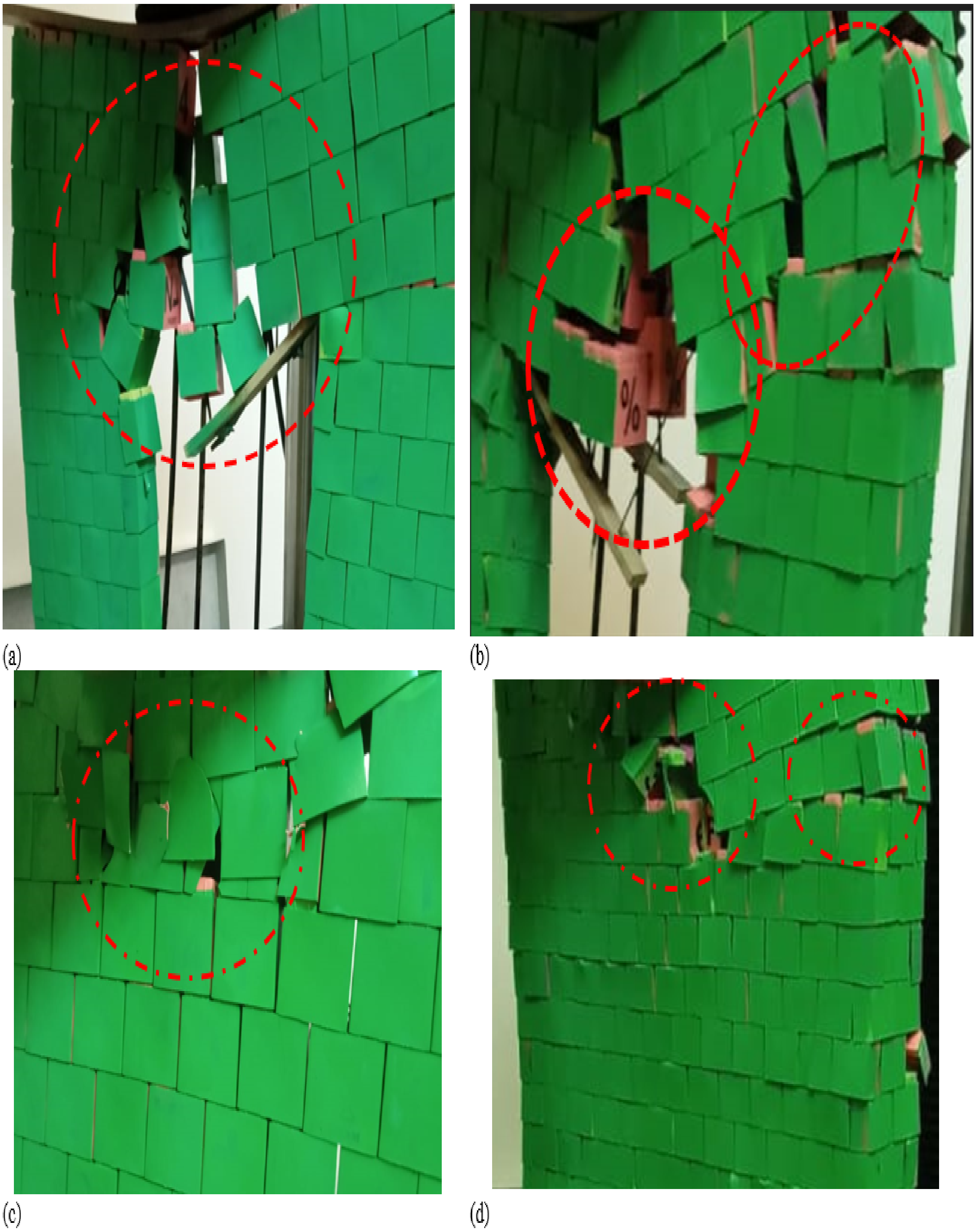


FIGURE 4.2: Cracking and failure modes of interlocking plastic blocks wall panels a) WO_s, b) WO_d, c) SW_s and d) SW_d

The reason here is due to interlock force applied by some internal flexible rubber, it holds each other and the whole block wall establish some brittle behavior. At maximum load the upper most layer of blocks starts cracking as shown in **Figure 4.2(a)** and the SW_s fail to get more load. In the case of double block width solid wall (SW_d), it takes maximum load as compared to the other structural elements. The internal stresses gain the load and give the warning sign before starting to collapse as shown in **Figure 4.2(b)**. The load was inserted uniformly, therefore, it gain maximum load and take maximum time to fully collapse. In addition, the blocks at the upper portion also gain the load but cannot collapses. Although the stiffness of the SW_d is too much as compared to SW_s, but the increment in capacity is marginal this is because of the fact that, in the case of the SW_d in order to make a proper bond a lot of half blocks has been used. Due to the presence of half blocks, there was not a significant increase in load-carrying capacity of SW_d as compared to the SW_s.

In the case of single block width wall with door opening (WO_s) the cracks were observed in one of the corner blocks around the top of door opening and also in the blocks on which the lintel is resting. It indicates that the load was transferred to the wooden support which act as beam. One of the side of opening was showing failure of shells of blocks on which lintel is resting as shown in **Figure 4.2(c)**. Diagonal cracks was observed at one of the side around opening. In the case of double block width wall with door opening (WO_d) the cracks were observed in one of the corner blocks around the top of door opening and also in the blocks on which the lintel is resting. It indicates that the load was transferred to the wooden support which act as beam. One of the side of opening was showing failure of shells of blocks on which lintel is resting. Diagonal cracks was observed at one of the side around opening as shown in **Figure 4.2(d)**.

4.3 Stress Strain Curves

Load-deformation curves are recorded during experiments, which are then transformed into average stress-strain curves to comparison the properties of interlocking plastic blocks structural elements with different thicknesses. For C_s, the maximum load was 1.3 kN and the corresponding deformation was 1.068 mm. For

C_d the peak load was 2.8 kN while 4.718 mm was the corresponding deformation. The peak load for C_d is more than C_s. This is due to high slenderness ratio in case of C_s.

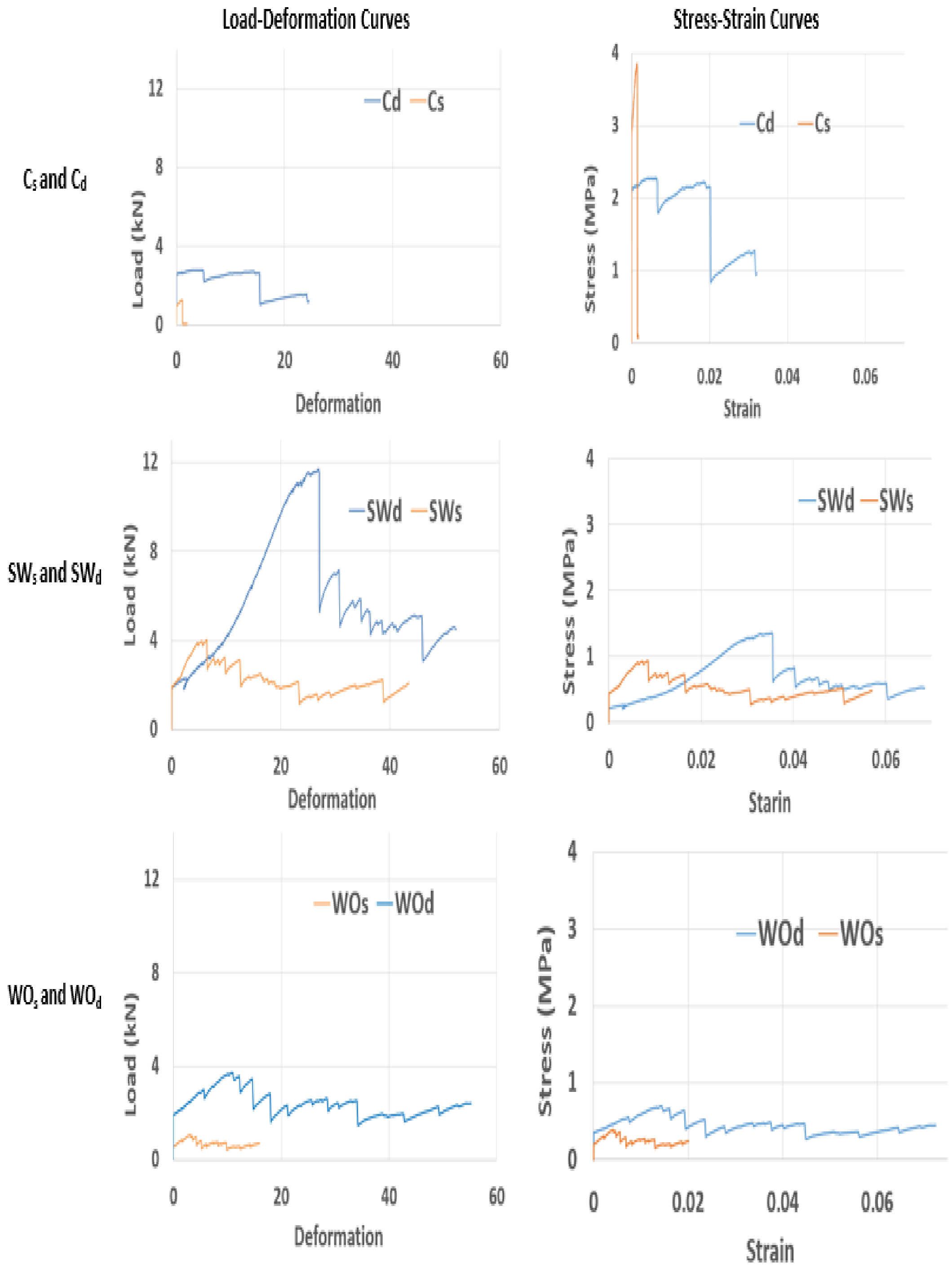


FIGURE 4.3: Load-deformation and stress-strain curves of all tested structural elements

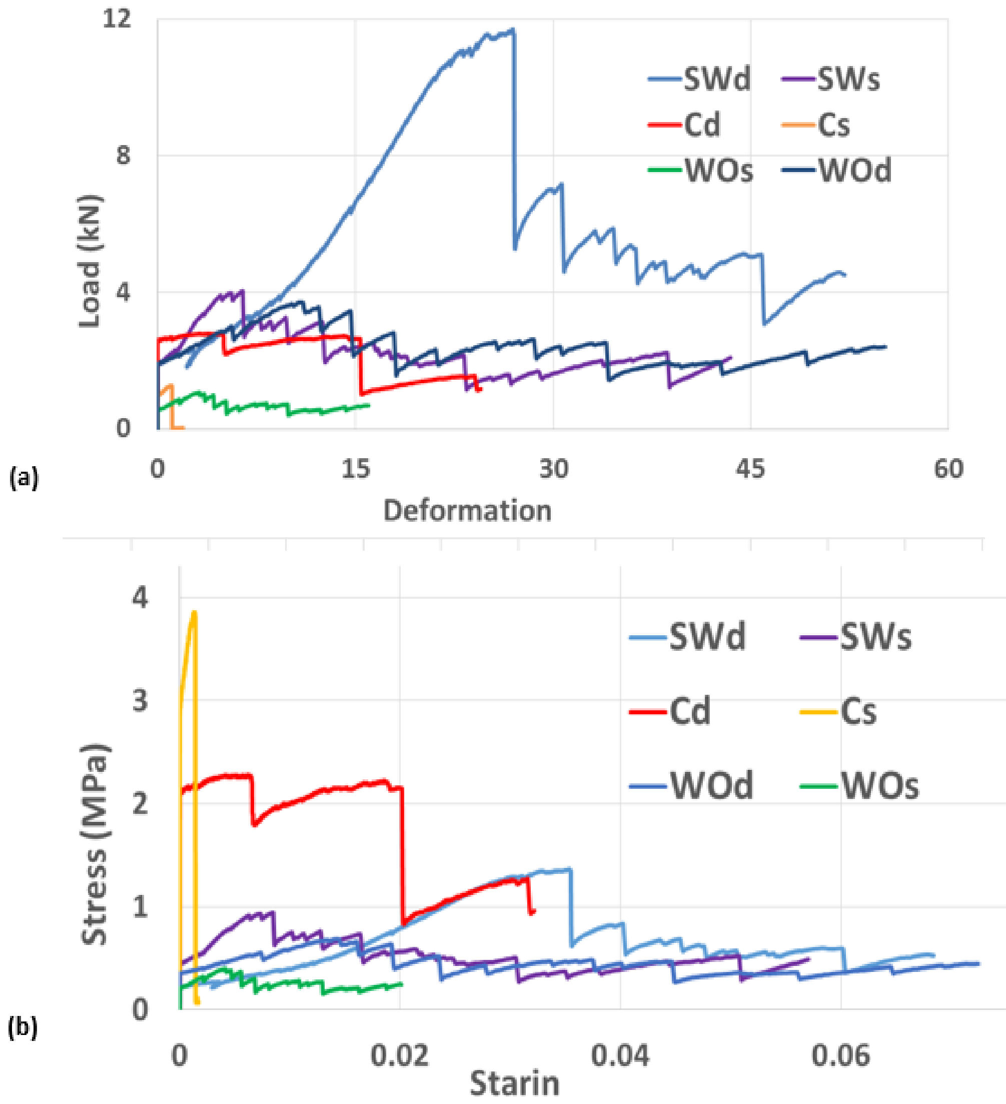


FIGURE 4.4: Comparison of all tested structural elements; a) load-deformation curves and b) stress-strain curves

For the single and double block width interlocking plastic block solid walls, the peak load is 4.1 kN and 11.7 kN respectively while the corresponding deformation is 6.42 mm and 26.95 mm respectively. For the single and double block width interlocking plastic block walls with door opening the maximum load is 1.1 kN and 3.7 kN respectively while the corresponding deformation is 3.11 mm and 10.72 mm respectively. The average stress of C_s was obtained by dividing the peak load of single block width column with its cross-sectional area (load-bearing area i.e, top and bottom) and its corresponding global strain was obtained by dividing deformation by original height of the interlocking plastic block structural element. By adopting same procedure stress-strain values for other structural elements were also obtained. For single and double block width column the average stresses were 3.85 MPa and 2.28 MPa respectively and their corresponding global strain were 1.7 x 10^{-3} and 32.1 x 10^{-3} respectively.

The stress of double block width column is less than single block width column because of the fact that double block width column have almost four times the cross sectional area as compared to single block width column. And the maximum load in case of C_d is not more than four times the peak load of C_s. For single and double block width solid wall the average stresses were 0.94 MPa and 1.36 MPa respectively and their corresponding global strain were 57 x 10^{-3} and 68.3 x 10^{-3} respectively. For single and double block width walls with door opening the average stress were 0.39 MPa and 0.68 MPa respectively and their corresponding global strain were 20.1 x 10^{-3} and 72.4 x 10^{-3} respectively. From the above values it is clear that (in case of walls) as the slenderness ratio increases their stresses decreases. In current study as the height is constant so by increasing thickness stress values are also increases. But in case of column this assumption is not fulfilled.

4.4 Energy Absorption and Toughness Index

The amount of energy absorbed per sample unit area during a specific deformation is referred to as the capacity of energy absorption. The ratio of the total area to the area before the peak load under the stress-strain curve is known as the toughness index. The peak load and strain for C_s were 1.3 kN and 1.7 x 10^{-3} respectively. The compressive capacity of a C_s is 3.85 MPa. At peak load cracking initiates and area under stress-strain curve upto this point is known as energy absorption upto peak load, similarly area under curve after peak load is known as energy absorption after peak load. And the algebraic sum of both these values is known as total energy absorption by that particular interlocking plastic block structural element. Its energy absorption and compressive toughness is 5.06 x 10^{-3} Nm and 1.05 respectively. The peak load for C_d is 2.8 kN. The peak load for C_s is less than the peak load for C_d is due to higher slenderness ratio.

Table 4.1: Experimental values of energy absorption and toughness index of interlocking plastic blocks structural elements

Sr.No	**Structural Element**	**Peak Load kN**	**Stress** σ **MPa**	**Strain** ϵ (10^{-3})	**Energy Absorbed Upto Peak Load** (E_1) ($10^{-3}Nm$)	**Energy Absorbed After Peak Load** (E_2) ($10^{-3}Nm$)	**Total Energy Absorbed** (E_T) ($10^{-3}Nm$)	**Toughness Index (TI)** (E_T/E_1)
1	Single Block Width Column	1.3	3.85	1.7	4.81	0.24	5.06	1.05
2	Double Block Width Column	2.8	2.28	32.1	13.71	42.35	56.07	4.09
3	Single Block Width Solid Wall	4.1	0.94	57	6.18	23.42	29.61	4.79
4	Double Block Width Solid Wall	11.7	1.36	68.3	26.32	19.22	45.55	1.73
5	Single Block Width Wall with Door Opening	1.1	0.39	20.1	1.26	3.83	5.11	4.02
6	Double Block Width Wall with Door Opening	3.7	0.68	72.4	7.54	24.12	31.67	4.20

The stress values are of average stress due to different top and bottom contact areas and that of strain values are of global strain.

The compressive capacity of C_d is 2.28 MPa. The energy absorption and compressive toughness for the above mentioned specimen were 56.06 x 10^{-3} Nm and 4.09 respectively. The energy absorption and compressive toughness for SW_s is 29.61 x 10^{-3} Nm and 4.79 respectively. The compressive strength (compressive capacity) of SW_d is 1.36 MPa. Its energy absorption and compressive toughness were 45.55 x 10^{-3} Nm and 1.73 repectively. The energy absorption of SW_d is more as compared to the energy absorbed by SW_s. The compressive capacity of single and double block width walls with door opening were 0.39 MPa and 0.68 MPa respectively. The energy absorption and compressive toughness for the double block width wall with door opening is 31.67 x 10^{-3} Nm and 4.20 respectively. The energy absorption and compressive toughness for the WO_s were 5.11 x 10^{-3} Nm and 4.02 respectively. A material is said to be ductile if it can resist plastic deformation without rupturing. Therefore, materials with greater ductility will have a higher toughness index. According to the findings, interlocking plastic block samples have a smaller area under the curve after cracking, which is a sign of their brittle behavior.

4.5 Summary

In this chapter, experimental evaluation of recorded data is presented. Stress strain curves are evaluated to find energy absorption and compressive toughness of interlocking plastic structural elements. It is concluded that the peak load for double block width column is greater than single block width column, peak load for double block width solid wall is more than single block width solid wall and also peak load for double block width wall with door opening is greater than the peak load of single block width wall with door opening.

Chapter 5

Discussion

5.1 Background

Compressive strength (compressive capacity), energy absorption, compressive toughness, and experimental interpretation of recorded data are all covered in the previous chapter. There is a developed relationship between how slenderness affects the compressive strength of certain structural elements. This chapter will cover the correlation between load carrying capacities, stress, energy absorption and toughness index of single and double block width interlocking plastic blocks structural elements and also a correlation between compressive capacities of solid wall panels and wall panels with door opening.

5.2 Correlation Between Compressive Capacities of Single and Double Block Width Structural Element

As observed during experimentation the peak load carrying capacity for single block width column (C_s) is 1.3 kN which is less than peak load of double block width column (C_d) i.e 2.8 kN. This is due to fact that C_s has more slenderness ratio than C_d. The stress of C_s is 3.85 MPa which is greater than stress of C_d which is 2.28 MPa. This is due to the fact that cross sectional area in case of C_d is almost four times as compared to C_s and the maximum load of C_d is very marginal as compared to C_s, therefore stress of C_d is less than that of C_s. During the construction of scaled down prototype for testing it was needed to use half blocks as shown in **Figure 3.2c** for proper bonding. Due to the presence of a lot of half blocks in case of all double block width structural elements the peak load carrying capacity was very marginal as compared to single block width structural elements. The energy absorption and toughness index of C_s were 5.06×10^{-3} Nm and 1.05 respectively. These values were also less as compared to C_d i.e 56.07×10^{-3} Nm and 4.09.

In case of solid walls, the peak load of single block width solid wall (SW_s) is 4.1 kN which is less than the peak load of double block width solid wall (SW_d) i.e 11.7 kN. This is also due to slenderness ratio as well as due to more bearing area in case of SW_d. As far as the stress is concern the behavior is same as that for bonded brick work case. By increasing slenderness ratio load carrying capacity decreases [24]. The stress of SW_d (slenderness ratio is less) is more than stress of SW_s (slenderness ratio is high). The energy absorption of SW_s was 29.61×10^{-3} Nm. This value was also less as compared to SW_d i.e 45.55×10^{-3} Nm. In case of wall with door opening for single and double block width the peak load carrying capacity is 1.1 kN and 3.7 kN respectively. Peak load carrying capacity for double block width wall with door opening (WO_d) is greater than single block width opening wall (WO_s). Here is also the same reason the slenderness ratio is grater in case of single block width opening wall. The energy absorption and toughness index of WO_s were 5.11×10^{-3} Nm and 4.02 respectively. These values were also less as compared to WO_d i.e 31.67×10^{-3} Nm and 4.20.

The peak load for C_d is equal to 2.2 of the peak load for the C_s. The peak load for the SW_d is equal to 2.9 of the peak load for the SW_s. The peak load for the WO_d is equal to 3.5 of the peak load for the WO_s. The similar results were also observed by Jaafar et al. [63] for their developed interlocking hollow concrete blocks compressive strength of a wall panel is more than compressive strength of

TABLE 5.1: Correlation between the peak load carrying capacity of single block width and double block width interlocking plastic blocks structural elements

Sr.No	**Structural Element**	**In Term of**	**Correlation**
1	Double Block Width Column	Single Block Width Column	PC(d)=2.2PC(s)
2	Double Block Width Solid Wall	Single Block Width Solid Wall	PSW(d)=2.9PSW(s)
3	Double Block Width Wall with Door Opening	Single Block Width Wall with Door Opening	PWO(d)=3.5PWO(s)

Where PC(s), PC(d), PSW(s), PWO(s), PSW(d), and PWO(d) are the peak load carrying capacities of C_s, C_d, SW_s, WO_s, SW_d, and WO_d respectively. The trend of correlation is same as observed in case of bonded brick work i.e the peak load carrying capacity of double block/brick width structural element is more as compared to single block width structural element. The maximum difference in peak load carrying capacity of single and double block width structural element is in wall with opening.

prism with three blocks and unit block. To sum up the similarity between the C_s, C_d, SW_s, SW_d, WO_s and WO_d, the following similarity is obtained as shown in **Table 5.1**: where, PC(s) is the peak load for C_s, PC(d) is the peak load for C_d, PSW(s) is the peak load for SW_s, PSW(d) is the peak load for SW_d, PWO(s) is the peak load for WO_s and PWO(d) is the peak load for SW_d.

5.3 Correlation Between Compressive Capacities of Solid Walls and Walls with Opening

The peak load carrying capacity of SW_s is 4.1 kN which is more than peak load carrying capacity of WO_s i.e 1.1 kN. Similarly, peak load carrying capacity of SW_d is 11.7 kN which is greater than peak load carrying capacity of WO_d i.e 3.7 kN. Door opening in the wall causes more plastic deformation in wall with opening as compared to solid wall. The stress of SW_s was 0.94 MPa which is more as compared to WO_s i.e 0.39 MPa. Similarly the stress of SW_d was 1.36 MPa which is more as compared to WO_d i.e 0.68 MPa. The energy absorption and toughness index of SW_s were 29.61x10^{-3} Nm and 4.79 respectively. These values were more as compared to WO_s i.e 5.11x10^{-3} Nm and 4.02. Similarly the energy absorption of SW_d was 45.55x10^{-3} Nm. This values was more as compared to WO_d i.e 31.67x10^{-3} Nm.

The similar results were also observed by Aslam. S [49] for their developed interlocking plastic blocks that maximum load carrying capacity of solid wall panel is more than maximum load carrying capacity of wall with opening. It was observed that, the solid wall specimens continued to gain strength with reduced stiffness until the final strength was reached. Unlike solid walls, a sudden failure was observed in case of walls with door opening. The total area of opening is 24% and a decrease in peak load carrying capacity of single and double block width opening walls is 73% and 68% respectively. The overall compressive properties of solid wall are better than walls with opening as in case of bonded brick work.

TABLE 5.2: Correlation between the peak load carrying capacities of solid walls and walls with opening

Sr.No	Structural Element	In Term of	Correlation
1	Single Block Width Solid Wall	Single Block Width Wall with Opening	PSW(s)=3.8PWO(s)
2	Double Block Width Solid Wall	Double Block Width Wall with Opening	PSW(d)=3.2PWO(d)

Where PSW(s), PWO(s), PSW(d), and PWO(d) are the peak load carrying capacities of SW_s, WO_s, SW_d, and WO_d respectively.

5.4 Summary

In this chapter correlations have been developed between compressive strength of interlocking plastic block structural elements for varying thicknesses. It is concluded that the peak load for C_d is greater than C_s, peak load for SW_d is more than SW_s and also peak load for WO_d is greater than the peak load of WO_s. Correlation has also been developed between solid wall panels and wall panels with door opening. It is concluded that the peak load for SW_s is greater than WO_s and peak load for SW_d is more than WO_d.

Chapter 6

Conclusion and Future Work

6.1 Conclusions

Many earthquake resistant construction techniques are available in literature for earthquake prone areas such as provision of vertical and horizontal stiffeners in the form of confinement columns and band beams. But these are uneconomical. Developed societies can afford such types of techniques to lessen the earthquake damages. But people living in rural areas cannot afford such type of approaches. Therefore interlocking structure is one option for such kind of peoples. In order to reduce the mass of structure interlocking plastic blocks can be used. Previous research on these interlocking plastic blocks has yielded excellent findings in terms of lateral loading. Therefore, it is necessary to investigate the compressive behaviour of these structural components made of interlocking plastic blocks. In this pilot study, effect of slenderness on the compressive behavior of interlocking plastic block structural elements is compared. Scaled-down prototypes are tested under compressive loading. Correlations have been developed between interlocking plastic block structural elements. Following conclusions have been drawn from this research work:

- The relationship between the load carrying capacities of single and double block width structural elements had been established.

- The maximum stress of double block width structural elements i.e solid wall and wall with opening are more than single block width structural elements 30% and 50% respectively. But in the case of columns, this phenomenon was not fulfilled.
- The energy absorption of double block width structural elements i.e column, solid wall, and wall with opening are more as compared to single block width structural elements 74%, 35%, and 84% respectively.
- Due to the slenderness effect peak load-carrying capacities of double block-width structural elements i.e column, solid wall, and wall with door opening are more than the peak load-carrying capacities of double block-width structural elements 53%, 65%, and 70% respectively.
- Peak load-carrying capacities of single and double block width solid walls are more than the peak load-carrying capacities of single and double block width walls with opening 73% and 68% respectively.

On overall basis, the compressive properties of double block width interlocking plastic blocks structural elements are better as compared to single block width interlocking plastic blocks structural elements.

6.2 Future Recommendation

Following may be considered to further explore the behavior of interlocking plastic block structure.

- The effect of length of wall on the compressive capacity of interlocking plastic block solid wall and wall with opening.
- The behavior of interlocking plastic block structural elements with eccentric and lateral loads.

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