ENHANCING LATERAL LOAD PERFORMANCE OF TRADITIONAL TIMBER WALL (DHAJJI-DEWARI) BY STRENGTHENING OF JOINTS

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Dedication

I dedicate this Research to

Asst. Prof. Dr. Muhammad Usman, my mentor

And

To my parents

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I am thankful to Allah Almighty, The Most Gracious and The Most Bountiful, who gave me the strength to complete this dissertation. After that, I would like to express sincere gratitude to my mentor and advisor Asst. Prof. Dr. Muhammad Usman for his continuous support, guidance and valuable discussions on the topic throughout the research phase. His doors were always remains open for me and he guided me towards the right path whenever I was stuck in any phase of the research.

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ABSTRACT

Dhajji Dewari is an open construction technique that can be easily built from local materials; timber and stone. Dhajji most commonly consists of a braced timber frame and the spaces left within the timber frame are filled with a thin wall of stones usually laid and plastered with mud mortar. Dhajji Dewari provides efficient use of material even with single layer of infill compared to modern construction techniques. The construction of houses after October, 2005 Kashmir earthquake was indecisive task. The donor agencies were not sure if the traditional structure would give better performance in case of similar magnitude Earthquake. Very limited research was available to validate the seismic performance of Dhajji Dewari construction. Later on it was experimentally proved that Dhajji construction is suitable for lateral resistance and additionally, it is suitable for remote areas, such as Kashmir where availability of skilled labor is limited due to ease of construction.

This thesis presents experimental work conducted on typical Dhajji Dewari walls found in northern areas of Pakistan and Kashmir, to evaluate their in plane lateral load response by using different joint strengthening techniques. The experimental work includes an in-plane monotonic test on four reduced scale walls. Out of four Dhajji walls, one wall was used without any strengthening and considered as reference wall. The remaining walls were strengthened with three different strengthening techniques. Cross bracing was used between closely spaced vertical posts and infill ratio of stone and mud was constant and it contains 70% stone and 30% mud.

Test results show that the connection functionality, controls the overall performance of the system, particularly at the joint of vertical posts and bottom plates. Strengthening of these joints not only enhances the lateral load capacity of the wall, but also significantly augments the energy dissipation capacity of the system. The performance of strengthening techniques has been experienced and based on cost benefit analysis it is concluded that wall strengthened with metal strips give the best reinforcement of Dhajji walls keeping in view the additional cost of strengthening and load deformation behavior.

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CHAPTER 1

INTRODUCTION

Dhajji Dewari is a non-engineered construction which can be easily constructed by locally available materials i.e. Wood, Stone and mud. This construction type is 200 years old and still in practice in those areas of Pakistan where wood is abundantly available [1].

Dhajji means "Patch work quilt" and Dewari means "Wall" in Kashmiri Language [2]. Dhajji Dewari is the construction type composed of traditional timber frame with stone infill, which is the prevailing construction for residential buildings in Northern areas of Pakistan and Kashmir. Dhajji most commonly consists of a braced timber frame, stone and mud. The spaces left within the timber frame are filled with a thin wall of stone traditionally laid and plastered with mud mortar [3]. Dhajji Dewari provides efficient use of material even with single layer of infill compared to modern construction techniques [4].

Dhajji buildings are rectangular in shape and mostly constructed as single story structure but multi storey structure also found in Indian occupied Kashmir [5]. Similar construction type with little modification is used around the World. For example, in France (Colombage), Germany (Fachwerk), Turkey (Bagdadi, Himis and Dizeme), Greece, Italy and Portugal (Gaiola) and in Britain as (Half Timbered) [3]. All these traditional structures are mainly differentiated based on the choice of infill material [6].

These traditional structures have performed well in Earthquake [2]. For construction of reinforced and combined masonry structure there are various codes, standards and guidelines are available globally that seeks to deliver minimum quality of design, material and workmanship. In some parts of Pakistan masonry and concrete structures are considered complex and costly. In contrast, Dhajji construction, which uses conventional methods of construction and locally available material, is easy to construct and has performed well in Earthquake, but often ignored by decision makers and donors as there were only empirical rather scientific evidence to justify its performance. Dhajji construction is non-ductile in nature and prone to extensive damage and collapse in moderate and severe Earthquake [1]. Therefore, it is necessary to study the vulnerability of Dhajji Dewari construction and to develop the cost effective strategies and technical guide line for its restoration with long term goal of stopping considerable loss of life in Earthquakes.

The magnitude of 2005 earthquake was Mw= 7.5, its epicenter found in Kashmir. This earthquake destroyed 5000 schools, 460000 homes, 800 health facilitation center, 4000 villages , leaving nearly 3.5 million people unsheltered. Most of the losses were endorsed to non-ductile reinforced concrete structures and unreinforced masonry structures resulting in overall economic loss of 0.9% of annual GDP of Pakistan [7]. The structures subsisted in this earthquake were traditional timber structures with moderate to reasonable damages. The performance of these traditional structures provides important information for historic conservation and lesson for the construction of affordable and earthquake resistant structures in high seismic zones where modern western construction techniques are unpractical. Buildings in remote and mountainous regions of Pakistan were badly damaged by such kind of swear earthquake. Reinforced concrete buildings have coped poorly because concrete and reinforcement detailing both were substandard. This form of construction requires engineering design and special construction techniques that are unavailable in remote areas. Dhajji houses had performed better than reinforced concrete structures that was a perilous point to think about it.

Inhabitants adopted traditional way for construction & rehabilitation after the experience of 2005 earthquake because:

- Dhajji Dewari construction performed well
- Easy and economical way of construction
- Materials were locally available i.e wood and stone
- Reinforced Concrete material was inaccessible

1.1 Problem Statement

Various studies on Dhajji walls indicates that connections especially those between vertical and horizontal posts of wall usually fail in rocking. So in this study our main focus will be to apply the different joint strengthening techniques to enhance the lateral load performance of Dhajji wall by directing the rocking.

1.2 Research Objectives

The main objectives of this research are:

- ❖ To study the effect of joint strengthening on performance of Dhajji Dewari walls under in-plane Monotonic loading.
- ❖ To suggest the most efficient joint strengthening technique based on cost benefit analysis.

1.3 Research Significance

After the October 2005 earthquake, there was need to understand the behavior of Dhajji buildings as many people live in these traditional houses. Very limited research has been done on Dhajji construction as it came in light after 2005 earthquake. Our main focus will be in providing the engineering basis for Dhajji construction that will enhance the performance of these low cost seismic houses in earthquake affected areas of Pakistan by using different strengthening techniques. Moreover, the understanding how this traditional construction resist earthquake can also help us to improve our modern construction techniques.

1.4 Thesis Overview

- **Chapter 1**

  This chapter include the introduction of Dhajji construction, its performance during swear earthquake like 2005 earthquake, problem statement, objectives of research and thesis overview.

- **Chapter 2**

  In this chapter brief literature review on Dhajji Dewari and other similar type of structures has been discussed.

- **Chapter 3**

  This Chapter include research methodology, scope of research, preparation of specimens, load application, test setup and overall testing of the thesis work.

- **Chapter 4**

  This chapter includes the discussion on test results of individual panels and their comparison with one another.

- **Chapter 5**

  This chapter contain conclusion of present research based on test results and also future recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Historic Perspective of Traditional Timber Construction

Traditional timber construction is found across the globe. For example, in France (Colombage), Germany (Fachwerk), Turkey (Bagdadi, Himis and Dizeme), Greece, Italy and Portugal (Gaiola) and in Britain as (Half-Timbered). All these traditional structures are mainly differentiated based on the choice of infill material. The type, nomenclature and seismic behavior of different traditional construction techniques exist in different parts of the world are discussed in detail as under;

2.1.1 Dhajji Dewari Construction

Dhajji Dewari is traditional construction found in the Northern areas of Pakistan and Kashmir [2]. The word Dhajji Dewari is a Persian word meaning "patchwork wall", consisting of timber, stone and mud. Dhajji most commonly consists of a braced timber frame, the spaces left between the bracing or frames is filled with a thin wall (single Layer) of stone traditionally laid and plastered with mud mortar [3]. The timber frame of Dhajji houses consists of vertical and horizontal posts of relatively bigger cross sections and frame further divided into secondary vertical and horizontal posts of smaller cross sections. And finally these secondary posts are provided with different types of bracing arrangements those later filled with stone or masonry. These houses are bolted with concrete or stone foundation to provide fixity with ground. Roofing system is quite simple in these houses; often wooden truss with corrugated sheets or simple corrugated sheets on flat wooden planks are used as roof [8].

These types of traditional houses consist of framework filled with burnt clay bricks. The composition of this type of structure is very different from that of a typical brick masonry structure and its superior performance has been proved to be earthquake resistant. In Dhajji Dewari houses the connected timber studs sub divides the infill which helps in detention of loss of masonry, and resists the destruction of wall.

Fig 2.1: A Typical Dhajji Dewari House [9]

The creation and further propagation of diagonal shear cracks and the possibility of out of plane failure of the masonry is halted by the closed spacing of the studs, even in higher stories and gable portions of the walls. In some structures usually the walls in lower portion are made of traditional brick or stone masonry and the upper stories are made as a Dhajji Dewari system. [2]

Fig 2.2: Kashmir Museum [10]

After October 2005 earthquake, focused has been made to construct the damaged houses in faster way by viewing the availability of materials and cost. In this regard Dhajji houses were the best solution and these were acknowledged by many peoples [8]. However, Dhajji Construction is not the natural type of construction when compared to modern construction methods namely as RCC which consist of column and beam frames with brick work as infill.

Fig 2.3: A Good Quality Dhajji House [9]

2.1.2 Pombalino Buildings

Lisbon earthquake 1755, had destroyed many areas including central region known as Baixa, the people of Baixa gathered the cluster of engineers to determine the best solution which retain their houses during earthquakes. The type of construction nominated by engineers was called as Pombalino wall, which was also called as gaiola or cage construction. [11]. The gaiola construction or Pombalino system consists of timber frame with horizontal and vertical square cross sections about 10-12 cm size and used in interior parts of buildings, with cross slope which act as internal bracing. The empty space between these walls was than filled with bricks and mixture of stones in different arrangements. The walls after filling with rubble stones were covered with plaster. The front side of Baixa buildings was rebuild with masonry wall having thickness about 60 cm and interior of wall had timber frame as well.[12]. The significance of these walls lies in the fact that they can resist the lateral loading of earthquake by enhancing the structural ductility.

Fig 2.4: Gaiola in Pombalino Buildings [13]

2.1.3 Casa Baraccata Buildings

Similar to Pombalino buildings another type of traditional timber frame structure was developed in Italian cities of Calabria and Sicily and was called as Casa Baraccata building systems. This type of structure was developed in response to the occurrence of earthquakes in the region. The origin of this type of structure coincides with the Gaiola in Portugal. During the 19th century and the first two decades of the 20th century Casa Baraccata due to manifested applications for the seismic resistance it became the basis of instructions for construction practices in Italy [14]. This traditional building construction type was the only alternative for inhabitants of Europe and other parts of the world against seismic actions. It was the first time that these traditional buildings were adopted as an earthquake resistant structures on government level.

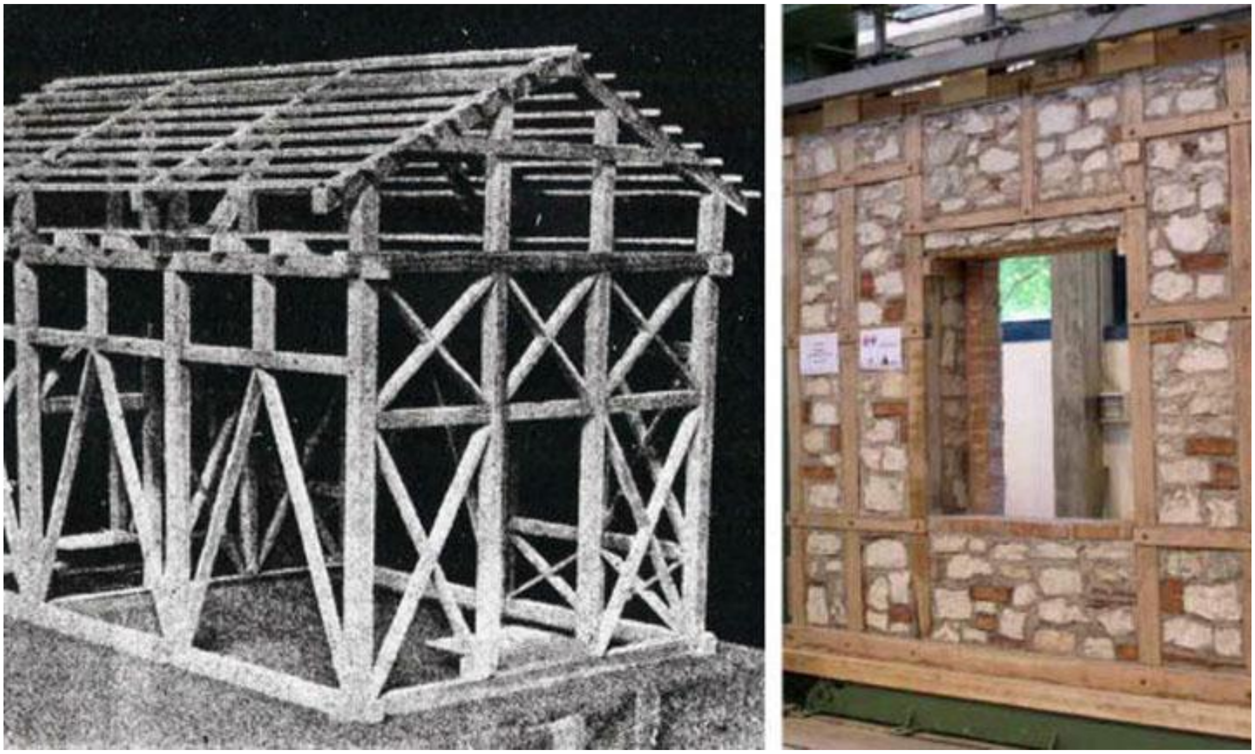

Fig 2.5: Casa Baraccata Buildings [9]

2.1.4 Himis Construction

Himis is another type of commonly used traditional buildings that is found in different parts of the world [4]. The masonry pattern in this type of building is different from the traditional bearing wall masonry. The timber frame is essential for providing the framework for the infill masonry. It consists of one layer of brick masonry, or a thin sheath of rubble stone mixed in mud of lime mortar. For decorative and aesthetic purpose bricks are placed at different angles on the front side. The thickness of the wall consisting of both timber and brick is 10 to 12 cm. Himis is in common use in Turkey but it was overtaken by the reinforced concrete rapidly in the beginning of the 20th century [12].

During the August 17th, 1999 earthquake in Turkey. The epicenter was east of Istanbul at just 100 kilometers away. More than one third of houses were destroyed by the earthquake and most of them RC structures [15]. While on the other hand most of the Himis buildings which were situated in the heart of the city were almost undamaged during earthquake, while some were critically damaged. Turkish researchers conducted surveys and also detailed statistical studies in the earthquake affected area of the district. It was found that there was a great difference in the number of RC buildings affected by the earthquake and the unaffected Himis buildings [16].

Fig 2.6: Himis House (Turkey) [12]

2.1.5 Bagdadi Construction

Bagdadi construction is another type of construction and fairly found in areas where Himis is common. This type of construction consists of short and rough pieces of timber for infill purpose which cover with plaster and form a solid wall. The significance of Bagdadi houses lie in the fact that they are light in weight, uses scrap wood, easy and economical to build. The main defect of these walls is the attack of insects which causes bigger rots to deteriorate [12]. A typical Bagdadi house is shown in figure 2.7.

2.1.6 Half-Timbered Structures

Half-Timbered structure traditionally found in Roman Empire, also referred to as Opus Craticium [17]. Half-timbered structures consists of timber and masonry materials. Mostly timber wall is used in construction with masonry wall. According to Tampone [18] timber elements was used in construction of Knossos and Crete located in Minoan forts were used to support the masonry work.

Different type of timber configuration was used in half-timbered construction but the mean and common method was that the timber members can resist tension, and masonry members resist compression thus making a perfect assembly to resist lateral. However using timber in conjunction with masonry not only provide confinement to structure but also improves mechanical properties against lateral loading. [19, 20].

Fig 2.7: Bagdadi Construction [12]

Fig 2.8: Half -Timber House (Britain) [9]

2.1.7 Fachwerk Construction

Fackwerk construction is very common in Germany. Different types of timber frames found and are classified by the number of stories and the geometric shapes. This type of construction was introduced in the 7th century but it took till 16th and 17th century to gain popularity. It has three main types (Alemannic, Lower Saxonian and Franconian), which are differed from each other due to dimensions, spacing of the elements and the nature of the framing [13].

Fig 2.9: Fachwerk House (Germany) [9]

2.2 Lateral Load Performance from Historic Perspective

The seismic performance of these traditional structures was found remarkable during earthquake; timber studs stop progressive destruction of wall by preventing propagation of diagonal shear cracks [2]. The diagonal bracing, closely spaced vertical and horizontal posts, and the inherent property of wood to be flexible without breaking during earthquake shaking contributes to the outstanding performance of the system. Dhajji Dewari construction is different from modern day construction techniques because; (1) mortar strength is negligible (2) no proper bond between infill wall and piers (3) weak bond between infill layer [21] . Timber frame of Dhajji Dewari add ductility to the system and ductility leads to energy dissipation capacity which helps traditional structures to sustain in earthquake [22].

The closely spaced vertical and horizontal posts, diagonal bracing, and the inherent property of wood to be flexible without breaking during an earthquake contribute to the due performance of the system. The performance of Dhajji Dewari in the 2005 Kashmir earthquake is another evidence of the steadily earthquake resilient behavior of this system. After Understanding of good performance of Dhajji Dewari, Earthquake Rehabilitation department of Government of Pakistan (ERRA), encouraged its use for construction of housing units in the far mountainous earthquake affected areas.

Fig 2.10: A Dhajji House After 2005 Earthquake [9]

Traditional timber buildings have performed better in different earthquakes around the world. Although they are called as non-engineered structures, history shows that these traditional structures have performed well in event of an earthquake. In 1999, Kocaeli earthquake, traditional timber structures remained safe but modern concrete structures were heavily damaged. This finding was set by Turkish researchers Gulhan and Guney after detailed statistical study on damaged areas of district [16].

The failure of reinforced concrete structures in an event of earthquake are mostly related to deprived design and poor construction practice. Contrary to this, the traditional buildings those lasted the earthquake were non-engineered, there were no design for them and they were made by local masons, with locally available materials.

Fig 2.11: An Example of (1999) Turkey Earthquake [12]

Thus, questionably the traditional buildings those survived naturally possess the type of construction scarcities generally the reasons why the modern buildings fell down. A latest example of good performance of Dhajji Dewari buildings was observed in October 2005 earthquake in Pakistan, while there were swear damages observed in RC frame structures.

2.3 Experimental Studies on Lateral Load Performance of Dhajji Dewari

The appropriate literature survey show that various research studies on the lateral load response of timber-braced frames have been conducted as under;

Graca Vasconcelos et al. [23] conducted experiments on typical Gaiola wall subjected to in-plane cyclic loading in order to perceive its mechanical behavior and to assess its performance under seismic actions. Cyclic test was performed and for this purpose three types of frames each having different typologies was analyzed. (1) Timber frame unreinforced and having no infill; (2) Glass Fiber Reinforced Polymer sheets (GFRP) used on connections of timber frame having no infill; (3) Brick masonry was used as infill in timber frames. Tests on typical “Gaoila wall” have shown that the walls in all cases were able to dissipate energy over many cycles without losing their structural integrity [23].

Fig 2.12: Gaiola Wall after Test

Ali et al. [24] conducted Quasistatic cyclic test on typical “Dhajji wall” in Earthquake Engineering Centre, UET Peshawar. It was among the first few full scale Dhajji walls which were tested and was consider very helpful in finding drift limits, hysteretic response, viscous damping and strength envelope of Dhajji Dewari walls. It was observed that Dhajji wall resist numerous load cycles before failure. Thus confirm that Dhajji Dewari retains remarkable resilience against lateral loading. Further it was proposed that this resistance is essentially offered by the timber frame with very less contribution from infill material and the most critical part of the system are the connections between the vertical and horizontal posts [24].

Ahmad used the experimental data of Ali [1] to formulate numerical model and to assess the seismic performance of Dhajji Dewari walls. He did time history analysis using equivalent frame approach to analyze the 2D Dhajji Dewari walls. He concluded that the Dhajji Dewari structures placed near to the epicenter of a high magnitude earthquake will need retrofitting while those houses positioned away from the epicenter will have a better performance and less damage. He added that more research is required to rectify the numerical model so that the results obtained are distinguished and more accurate. Also comparative study is required in the region to investigate the relative performance of different regional structural system [1].

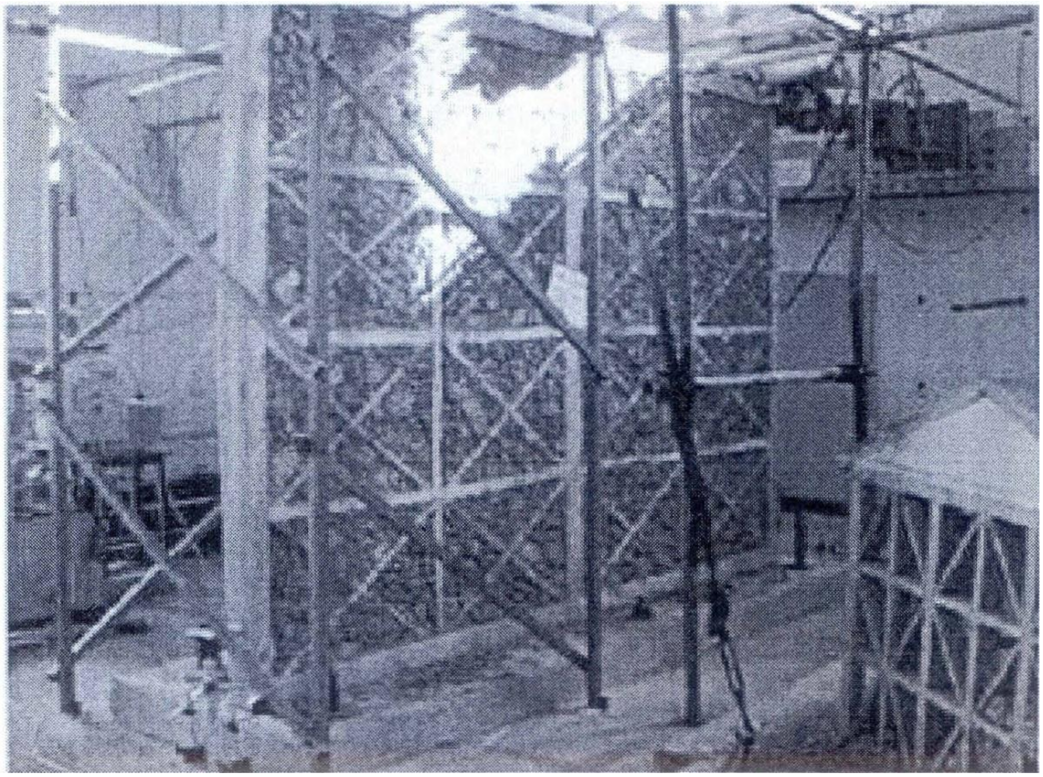

Fig 2.13: Full Scale Dhajji Wall Panel Test at University of Peshawar [1]

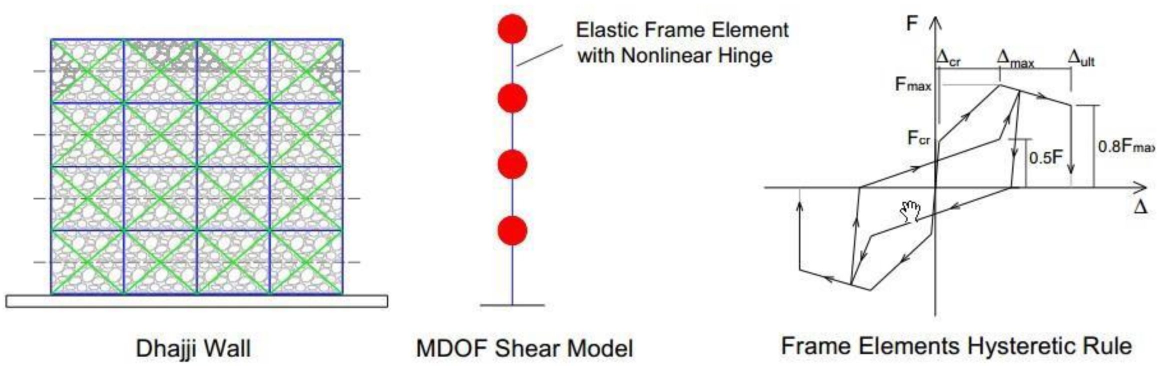

Fig 2.14: Numerical Model of Dhajji Wall [1]

Arup Gulf Ltd. [10] after observing the good performance of Dhajji Dewari houses, were keen on knowing the seismic performance of these structures on engineering root. The determination of their research project was to apply state of the art engineering analysis to a typical Dhajji Dewari house, similar to those built after the October 2005 earthquake. The project designed to know whether the building type could be accurately modeled and in doing so decide how it hypothetically performs when subjected to large earthquake. More precisely, such analysis allow us to understand the behavior of a system in response to ground shaking. Also, to know which critical engineering details guarantees the reliable seismic performance. The analysis was focused on finding the complete performance of the structure, then discovering the relative importance of specific aspects of the construction form. They made a detailed 3D model of Dhajji Dewari house in LS-DYNA similar to those constructed after the October 2005 Earthquake. Non-linear static pushover analysis and Non-linear response history analysis were performed. The building was analyzed twice, first, nails in their connections and then without nails.

After analyzing they determined that Dhajji Dewari can safely resist earthquake in high seismic zones if built properly. Connections are of critical importance to keep the bracing in place which has dynamic role in resisting the earthquake forces. Seismic energy is absorbed through friction between the infill and the timber frame. Overloaded masonry wall increases the energy dissipation capacity of the system which suggests that multi storey system will yield satisfactory results [10].

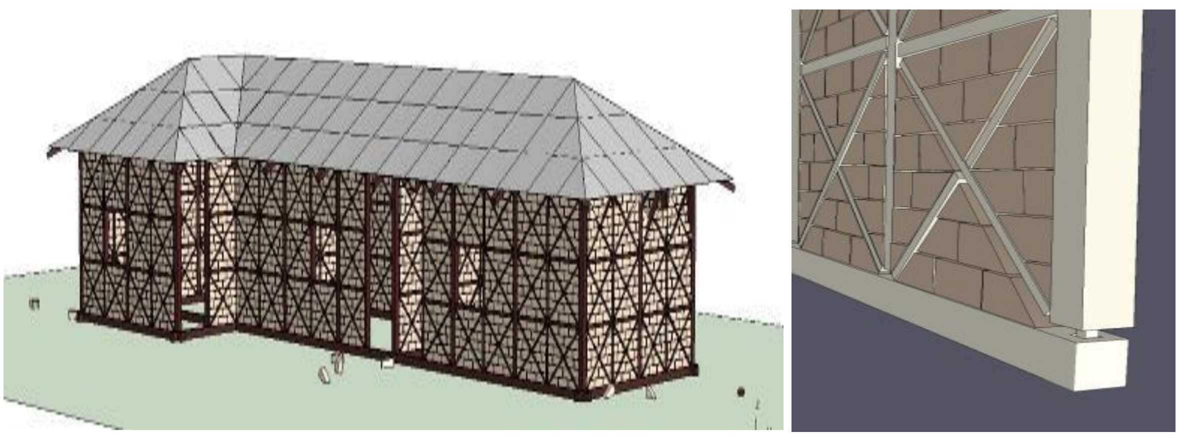

Fig 2.15: 3D House Model in LS-DYNA [10]

Shah et al [25] at NIT Srinagar also performed experiments on Dhajji Dewari frames to check their seismic resistance abilities. Further tests were performed to check that which bracing arrangement gives superior performance. Lateral load was applied to simulate the earthquake loading. It was decided that the joints are the most critical points also by increasing bracing by 1% increases the strength by 3%, while nailing and broad-shouldered the joints gave significant increase in load carrying capacity of the timber frame [25].

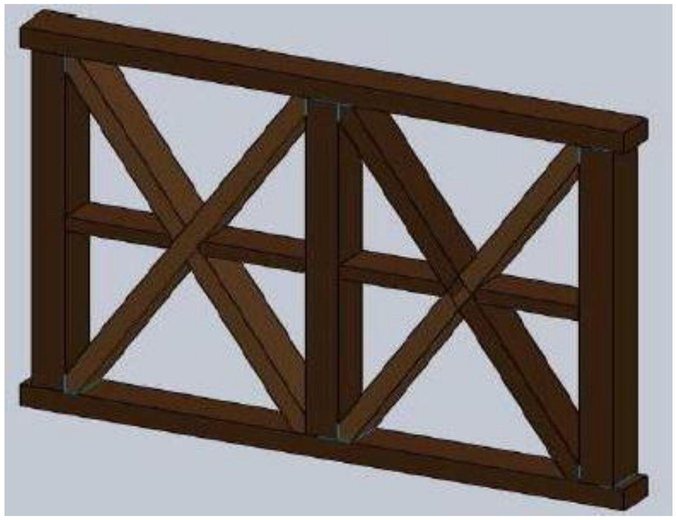

Fig 2.16: Best Bracing Type by Shah [25]

Vieux et al. [26] conducted various tests to study the seismic performance of timber framed structures filled with natural stones and earth mortar on three scales of experiments during which both cyclic and monotonic loadings were applied. For checking capacity of connection tests were performed in both normal and tangential directions to obtain the hysteretic behavior of nailed connections. Pushover and reversed cycle tests were performed to obtain the hysteretic behavior as a function of infill characteristics. Walls without any openings were considered. Through these tests the influence of the infill on stiffness, maximum load or equivalent viscous damping was analyzed. Based on experimental results they concluded that timbered masonry structures have appropriate seismic resistance [26].

In Earthquake exaggerated areas a survey was conducted to monitor the knocked houses by ERRA and UN. Ms. Stephenson gave details of survey carried out on different types of buildings in Earthquake affected areas 46% block, 30% Dhajji Dewari and 24% bricks and stone houses. She observed that Dhajji Dewari houses tend to have a more finished appearance than block/brick houses because in the Dhajji Dewari plaster was of mud and therefore low-cost and easy to apply. In the later cement was required which was costly and hence people were prone to delay plastering [1].

Fig 2.17: Traditional wall tested by Vieux [26]

CHAPTER 3

EXPERIMENTAL PROGRAM

This chapter deals with the methodology used to carry out experimental work. The experimental work will mainly focus on the construction of Dhajji wall, material used for this construction, test conducted to find the material properties and the behavior of wall. Four Dhajji Dewari walls (DDW1, DDW2, DDW3 and DDW4) were constructed (to check enhanced lateral load capacity after application of different strengthening techniques) with three sets of members having cross sectional dimensions 50 mm X 50 mm, 25 mm X 50 mm and 12.5 mm X 50 mm. The length of each specimen was kept 1500 mm, and height was 1200 mm, half scaled dimensions of a typical Dhajji wall.

For this purpose three different strengthening techniques like Bamboos, Metal Strips and Metal gusset plates were used on separate walls. The main objective of research was to investigate the lateral load capacity, ductility, energy dissipation, stiffness degradation and failure behavior of Dhajji walls before and after strengthening. A hydraulic jack was used to apply in-plane monotonic load on walls. LVDTs were used to measure the lateral response of wall.

3.1 Research Methodology

The methodology adopted to perform the in-plane Monotonic test on the Dhajji wall by application of different strengthening techniques is given below:

- ❖ Literature Review on the subject topic has been carried out to endorse the critical failure points of Dhajji walls
- ❖ Four reduced scale Dhajji walls were constructed to apply the different strengthening techniques
- ❖ Timber mechanical properties were determine using British Standard (BS 1957:373)
- ❖ Sieve analysis was used to determine the particle size distribution of the stones
- ❖ Sieve analysis was also used to determine the particle size distribution of the soil
- ❖ Pre-compression load was applied to cope the roof dead load
- ❖ Walls were anchor with the floor of testing lab to retrain the horizontal movement of wall

- ❖ Three strengthening techniques were applied to strengthen the critical locations of Dhajji walls like; Bamboos, Metal Strips, Metal gusset plates
- ❖ In-plane Monotonic test was performed to obtained the load displacement behavior of walls

3.2 Research Scope

Scope of research was limited to evaluate the response of Dhajji walls before and after strengthening. Four Dhajji Dewari wall panels on half scale resulting final sizes of 1500 mm x 1200 mm were tested under lateral loading. The infill ratio of stone and mud was 70:30 and it was constant for all panels. Cross bracing was used between closely spaced vertical posts of timber frame keeping in view the most common field practice. Out of all four Dhajji walls one wall was used as reference without strengthening and other three walls were tested after application of different joint strengthening techniques. A 500 KN capacity hydraulic jack was used for load application and displacement were recorded using LVDTs. Moreover, visual inspection was made to ascertain the failure points of Dhajji walls.

3.3 Material Characterization

The materials used for construction of Dhajji walls were timber, stone and mud. Material properties were determined using standard test methods and detail of each material type with their properties is discussed as under;

3.3.1 Timber

There are many different types of timber used in construction of Dhajji Dewari houses. The choice of timber mainly depends on the low price and local availability. For this experimental purpose Partal wood was used available in market also present on site abundantly. Mechanical properties of timber used in wall construction were determine according to British Standard Methods of testing small specimens of timber (BS 373:1957) and are shown in table 3.1.

Table 3.1: Mechanical Properties of Timber

Sample No.	Compressive strength parallel to grains (Mpa)	Tensile strength perpendicular to grains (Mpa)	Moisture Content (%)	Density (Kg/m3)
1	33.5	3.35	8.45	464
2	39.6	2.23	7.11	544
3	36.5	2.91	8.01	458
Average	36.5	2.83	7.86	488.6

3.3.2 Stone

Marghallah Crush (local term "Water Bound") was used for filling the panels and gradation curve of stones as shown in figure 3.2 indicate that 90% particles were having size ranges between 19 mm to 50 mm. Remaining 10% particle were less than 19 mm in size.

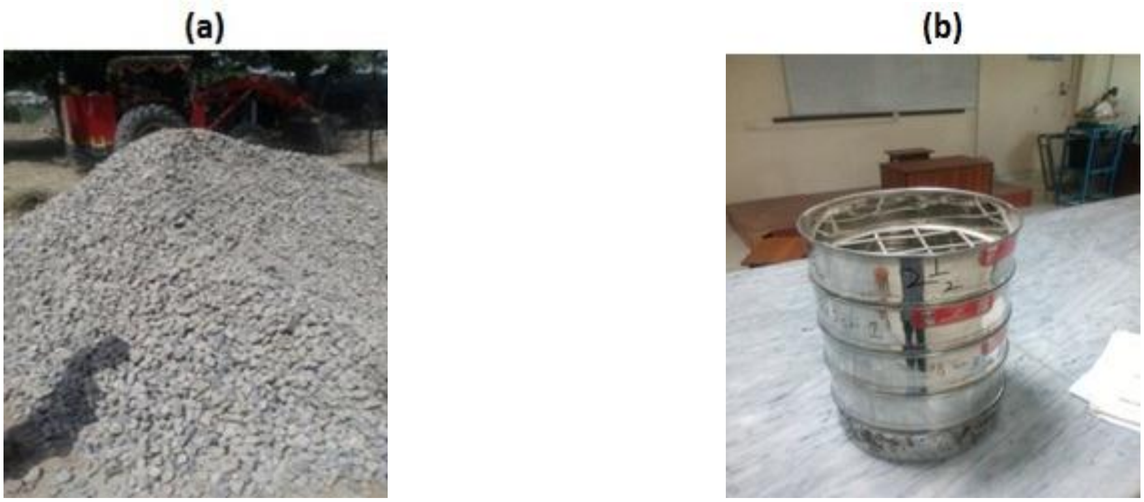

Fig 3.1: (a) Marghallah Stones (b) Set of Sieve

3.3.3 Mud

Soil engaged from local excavation site and gradation curve of soil as shown in figure 3.3 indicate that 11% particles were having size between 0.6 mm to 5 mm, 63% of particles were in range of 0.075 mm to 0.60 mm and remaining particles were having size less than 0.075 mm. There was no direct method to find the water soil ratio so quantity of water used was depending on the consistency of mud.

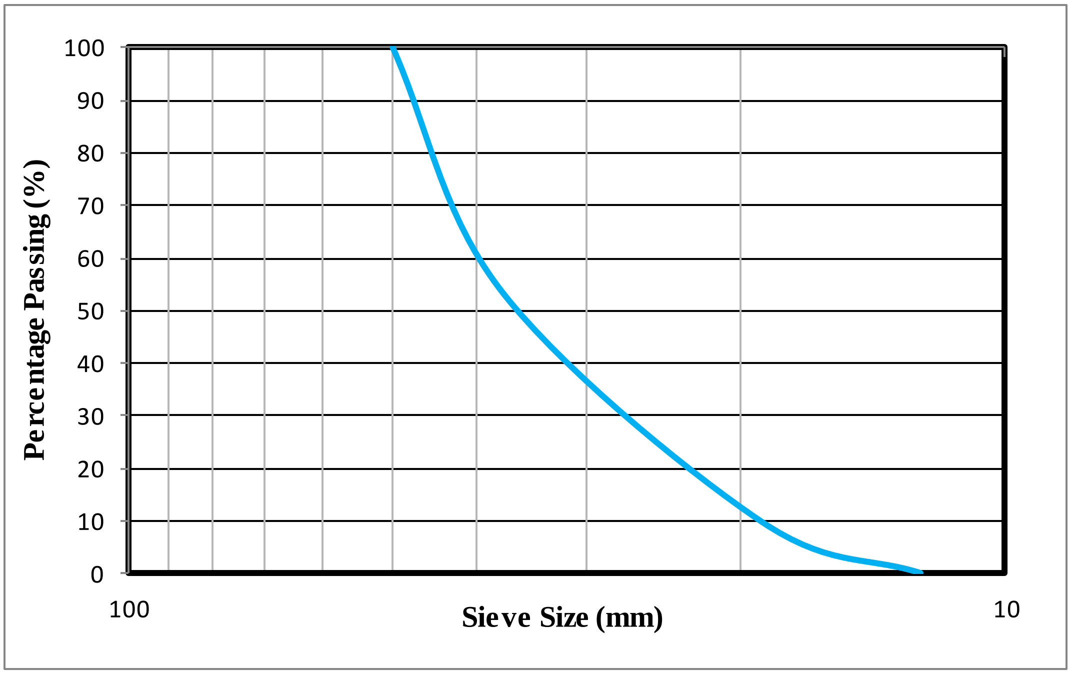

Fig 3.2: Gradation Curve of Stones

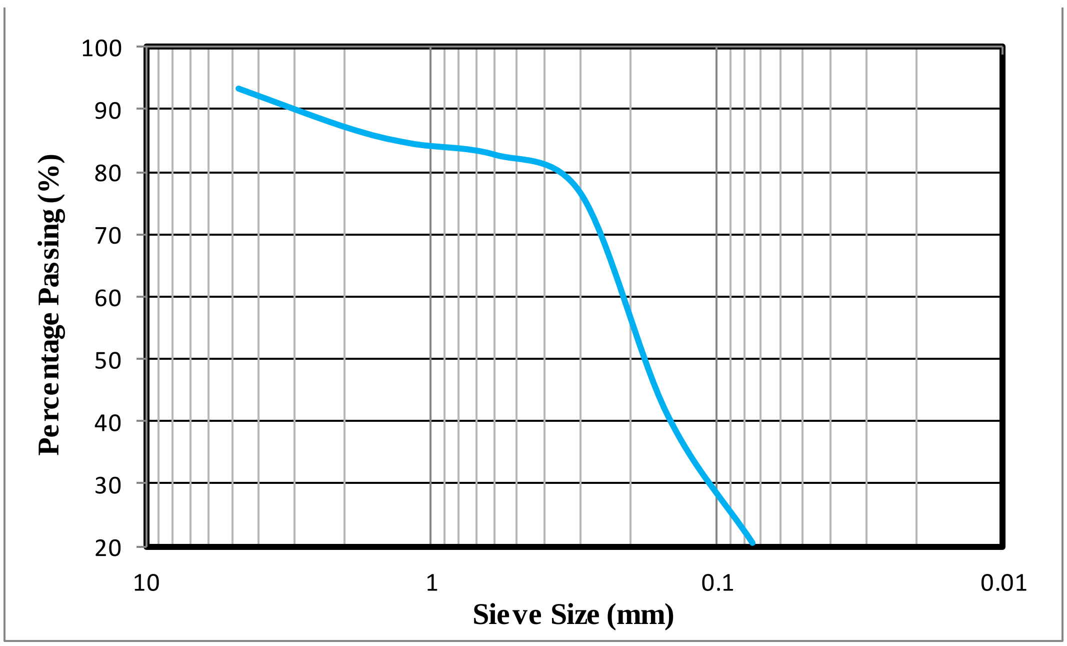

Fig 3.3: Gradation Curve of Soil

3.4 Test Panel Properties

3.4.1 Infill

Infill ratio of wall play a major role in the load carrying capacity. Higher ratio of stones lead to higher load capacity of traditional walls. But for our experimental work infill ratio was 70:30 and it was constant for all the specimens keeping in view the most common field practice.

3.4.2 Panel Description

There are many different types of bracings used in construction of Dhajji Dewari house as shown in figure 3.4. But for this experimental work cross bracing (Type A) was used to incorporate the most common field practice.

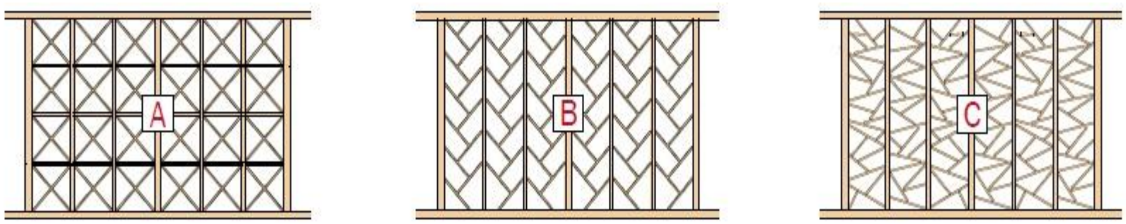

Fig 3.4: Different Bracing Arrangements

Dhajji Dewari walls were constructed with three sets of members having cross sectional dimensions 50 mm X 50 mm, 25 mm X 50 mm and 12.5 mm X 50 mm, half scale values of a typical Dhajji wall. The 50 mm X 50 mm members were used as main vertical posts and top and bottom horizontal bands. The 25 mm X 50 mm members were used as secondary horizontal bands and Studs (Intermediate vertical Posts). Similarly, 12.5 mm X 50 mm members were used as cross bracers. The length of each specimen was kept 1500 mm, and height was 1200 mm, half scaled dimensions of a typical Dhajji wall as shown in figure 3.5.

The main vertical posts and studs were connected to top and bottom main horizontal bands through type 1 to 3 connections. Similarly secondary horizontal bands were connected to main posts and studs through type 4 and 5 connections. Wooden nails made of steel having yield strength 250 Mpa were used to fix the connections.

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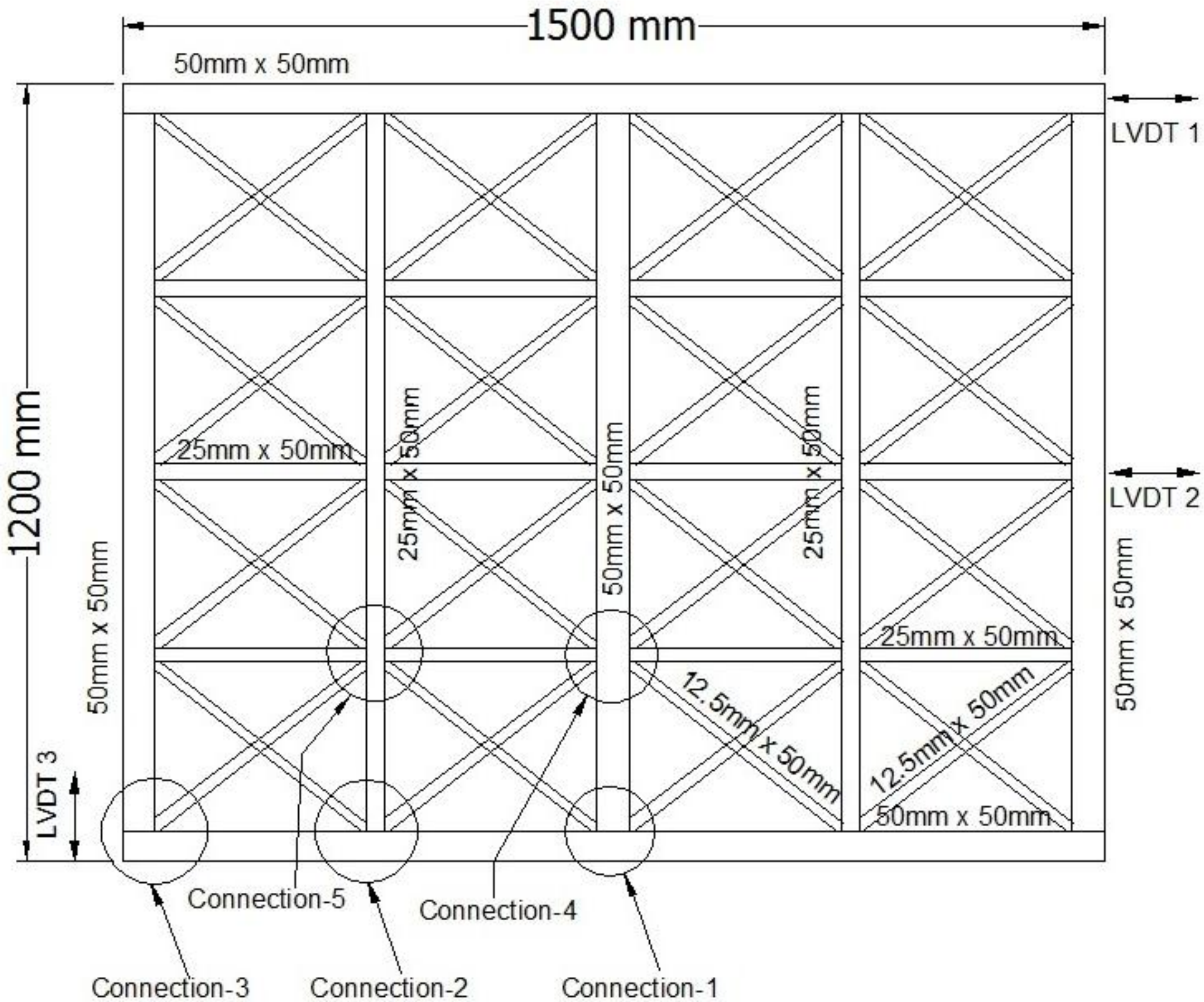

Fig 3.5: Detail of Members and LVDTs

3.4.3 Pre-Compression Load

Vertical load having magnitude 1 KN was applied to mimic roof dead load. Iron molds were designed for application of pre-compression point load on main vertical posts of wall, and using the magnitude of pre-compression load resulting in final sizes of 18" dia. circular moulds which were later bolted on top of main posts. Than load was applied with the help of aggregate filled with in containers. Application of load is shown in figure 3.6.

(a) (b)

Fig 3.6: (a) Iron Moulds (b) Application of Load

3.4.4 Anchorage of Wall with Floor

To meeting the field conditions and for measuring the storey drift, walls were bolted with floor to restrain horizontal movement. For this purpose bottom triangular portion of walls was left empty with holes in main bottom horizontal posts for purpose of bolting at four different locations. On drying of infill walls were fixed on the specified locations and then empty portion was filled with infill material. Detail is shown in figure 3.7.

(a) (b)

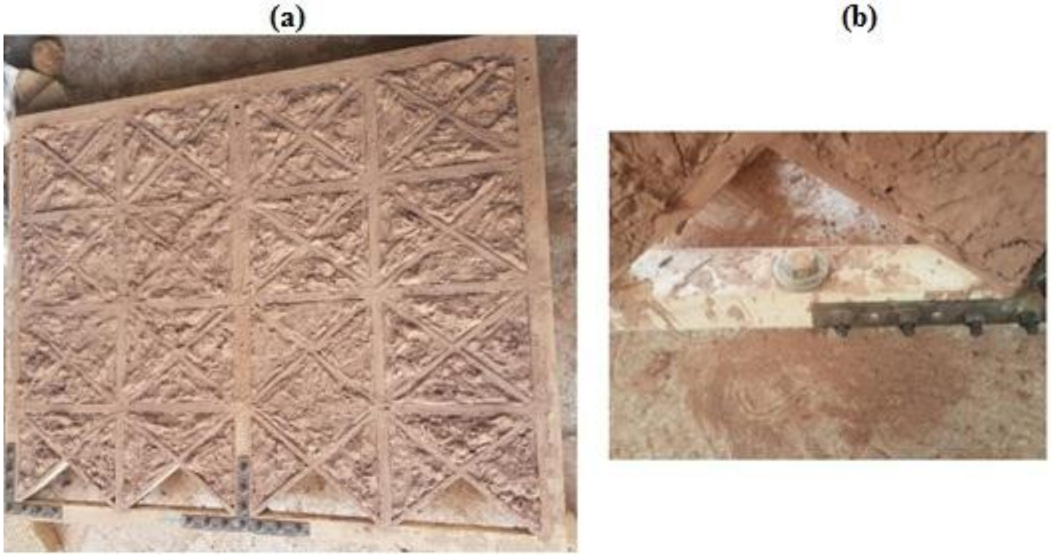

Fig 3.7: Dhajji Wall (a) Before Anchorage (b) After Anchorage

3.5 Test Panels Description

Four Dhajji walls were used for the experimentation and out of four walls, one wall was used without any strengthening and considered as reference wall. The rest three walls were strengthened with three different strengthening techniques. The detail of walls is as under:

3.5.1 Reference Wall: (DDW1)

This wall was used without any strengthening as shown in figure 3.8 and consider as reference wall to check the behavior of conventional wall and for comparison purposes with strengthened walls.

Fig 3.8: DDW1 (Reference Wall)

3.5.2 Wall Strengthened with Bamboos: (DDW2)

DDW2 was strengthened with Bamboos on periphery of wall and along tension and compression struts for purpose of enhancing lateral load performance by strengthening the joints. Detail is shown in figure 3.9.

Fig 3.9: DDW2 (Wall Strengthened With Bamboos)

3.5.3 Wall Strengthened with Metal Strips: (DDW3)

DDW3 was strengthened on the connection of main horizontal and vertical posts of wall with metal strips. Two types of strips were used and bolted on both sides of wall. The shape of strips used was depending on the location of connection i.e L-shaped strips were used on bottom corner joint and T-shaped strips were used on bottom middle joint as shown in figure 3.10. The size of strips was random, length was taken according to spacing of bolts and by keeping in mind the timber strength, thickness was 2 mm and width was selected according to width of post.

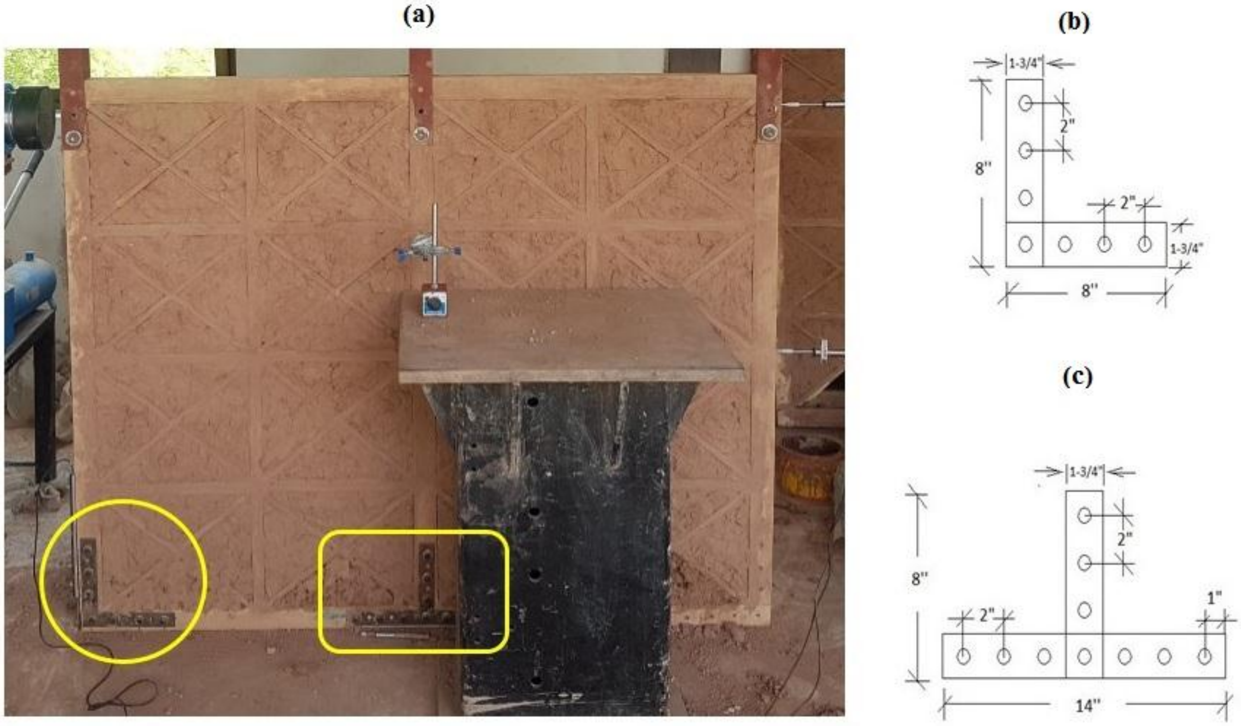

Fig 3.10: (a) DDW3 (b) L-Shape Strip (c) T- Shape Strip

3.5.4 Wall Strengthened with Metal Gusset Plates: (DDW4)

DDW4 was strengthened with metal gusset plates on connection of main horizontal and main vertical and secondary vertical posts. Two types of plates were used and bolted on both sides of wall. The shape of plates used was depending on the location of connection i.e L-shaped plates were used on bottom corner joint and triangular shaped plates were used on bottom intermediate joints as shown in figure 3.11. The size of strips was random, length was taken according to spacing of bolts and it was less than metal strips length reason behind was the large surface area of plates, thickness of strips was 2 mm and width was selected according to width of posts.

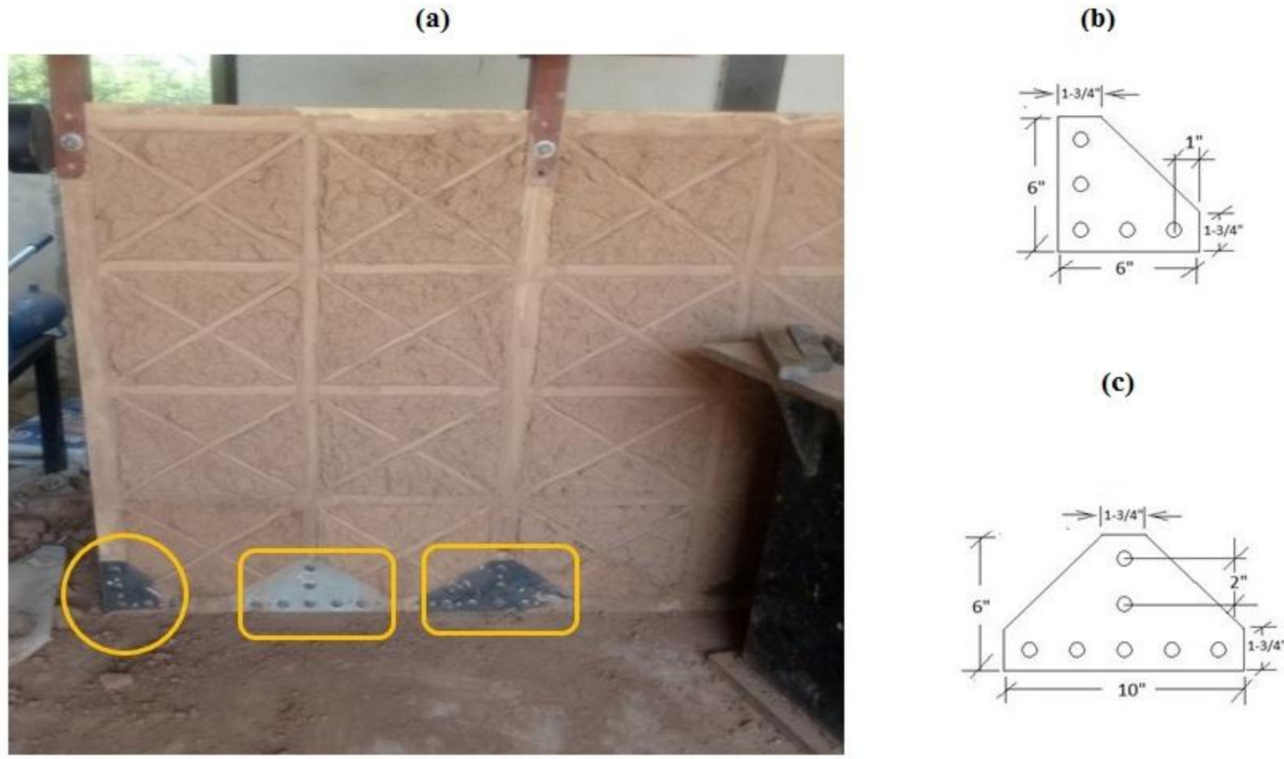

Fig 3.11: (a) DDW 4 (b) L-shape Plate (c) T-Shape Plate

3.6 Test Setup

An assembly was added to the vertical member of the reaction floor of dynamics lab to place the hydraulic jack for lateral load. Assembly contains two steel plates 42 in x 24 in size having 1/2 in thickness connected to the column with the help of ¾ in diameter high strength steel bolts and a W 8x64 section was welded with front plate using ¼ in fillet weld for purpose of placing hydraulic jack. Bolts enable the plates to move and to adjust the height of hydraulic jack.

Lateral load was applied using 500 KN capacity hydraulic Jack. Displacement was measured using three linear variable displacement transducer (LVDTs). The position of LVDTs is shown in figure 3.12. LVDT 1 and 2 were used to measure the displacement at top and mid height of the wall panel. LVDT 3 was attached at the bottom to measure rocking of panel during test.

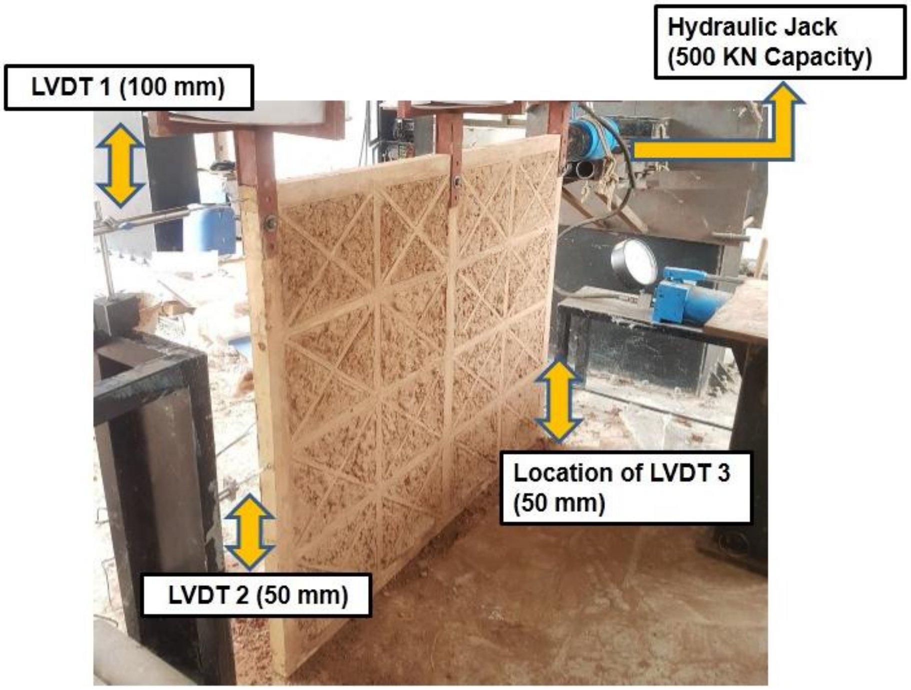

Fig 3.12: Test Setup

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

Analysis of results of Dhajji Dewari walls with different strengthening techniques is carried out in this chapter and for this purpose the experimental results of walls are divided into three main groups depending upon the different strengthening techniques. The comparison of Lateral load behavior of reference panel and panel strengthened with bamboos is discussed in detail in Group-1. The effectiveness of Dhajji wall strengthening using metal strips and metal gusset plates is discussed in Group-2. The comparison of all walls is discussed in Group-3. The different parameters studied are; 1) behavior of unstrengthen wall 2) strengthening effect of bamboos 3) efficiency of metal strips and metal gusset plates strengthening on Dhajji walls and 4) cost benefit analysis of different strengthening techniques used. The different performance parameters of Dhajji wall like load displacement behavior, energy dissipation, ductility, response factor and stiffness degradation are determined and discussed in detail.

4.2 General Failure Mechanism of Dhajji Wall

Dhajji walls are act as cantilever as they experience maximum deformation at top and deformation at bottom are almost zero because walls are fixed at bottom and allow to move free at top. The overall performance of walls is mainly controlled by the stresses produced due to formation of tension and compression struts leading to failure within them. In case of monotonic loading, when load applied on one side of wall the critical regions where maximum stresses are expected are the connection between horizontal and vertical posts and joint failure caused by the rocking of wall due to vertical tensile stresses. In case of in-plane cyclic loading the same phenomena of joint failure will occur for other joints as well and wall will experiences the biaxial compression and vertical tensile stresses from both the directions.

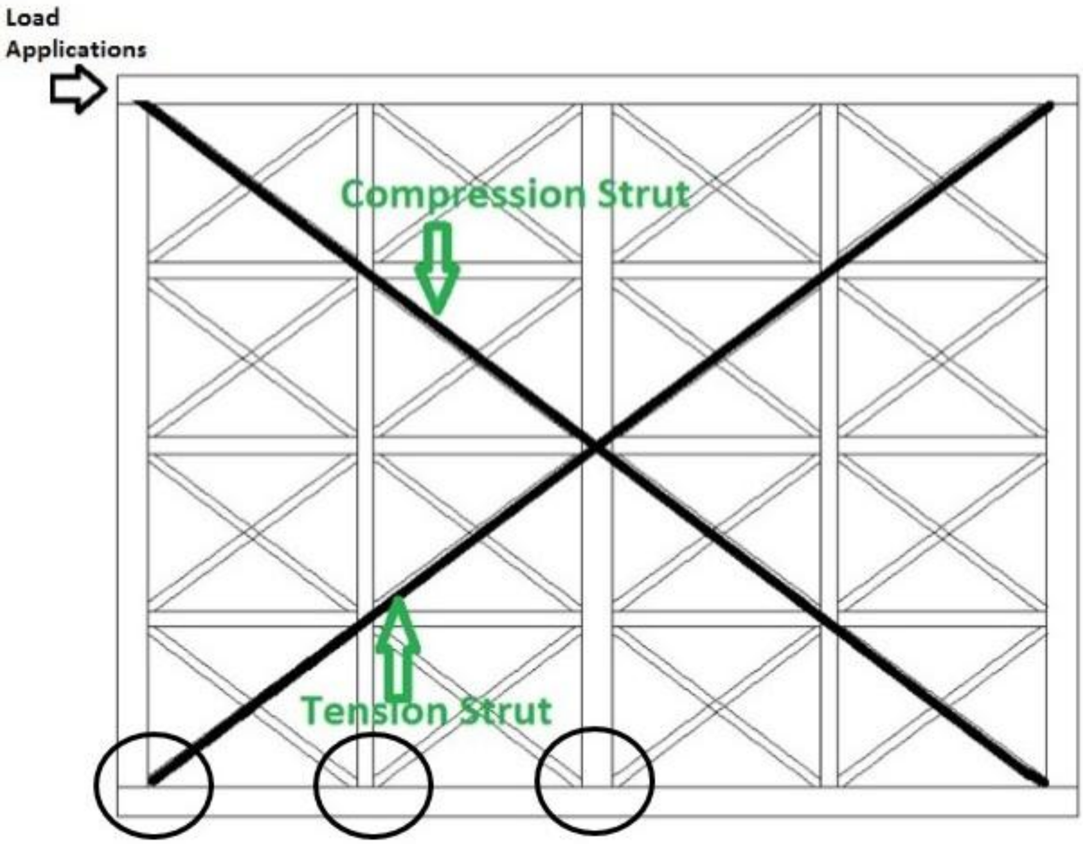

Fig 4.1: A typical Struts Diagram under Monotonic Test

4.3 Parameters of Lateral Load Behavior of Wall

The Lateral load behavior of Dhajji wall panels with different strengthening techniques is analyzed under the following headings:-

a. Load displacement behavior
b. Energy dissipation
c. Response factor
d. Stiffness degradation ratio
e. Base uplift of wall
f. Failure behavior of wall

For discussion on results panels are divided into three groups. The detail of each group is as under:-

a) **Group 1 – Unstrengthen Dhajji Wall and Wall strengthened with Bamboos**

This group comprised of two wall panels as under:-

1) Specimen DDW1 - Unstrengthen wall (reference wall)
2) Specimen DDW2 – Wall strengthened with Bamboos

b) **Group 2 – Dhajji wall panels strengthened with Metal Strips and Metal Gusset Plates**

This group was comprised of three wall panels as under:-

1) Specimen DDW1 - Unstrengthen wall (reference wall)
2) Specimen DDW2 – Wall strengthened with Metal strips
3) Specimen DDW3 – Wall strengthened with Metal Gusset plates

c) **Group 3 – Comparison of all wall panels**

This group was comprised of four wall panels as under:-

4) Specimen DDW1 - Unstrengthen wall (reference wall)
5) Specimen DDW2 – Wall strengthened with Bamboos
6) Specimen DDW2 – Wall strengthened with Metal strips
7) Specimen DDW3 – Wall strengthened with Metal Gusset plates

4.3.1 Typical Lateral Load Behavior

The typical lateral load behavior of Dhajji wall is shown in figure 4.2. The load displacement curve is divided into three segments to deliberate the Lateral load behavior of Dhajji wall during in-plane monotonic loading.

Segment AB- This segment represents the elastic portion of load displacement curve after which the joint detachment and cracking starts.

Segment BC- The post yield behavior is represented by segment BC. This behavior is mainly due to yielding of timber frame and propagation of shear and separation cracks.

Segment CD- This segment represent the ultimate behavior of wall during this stage displacement increase without significant increase in loads.

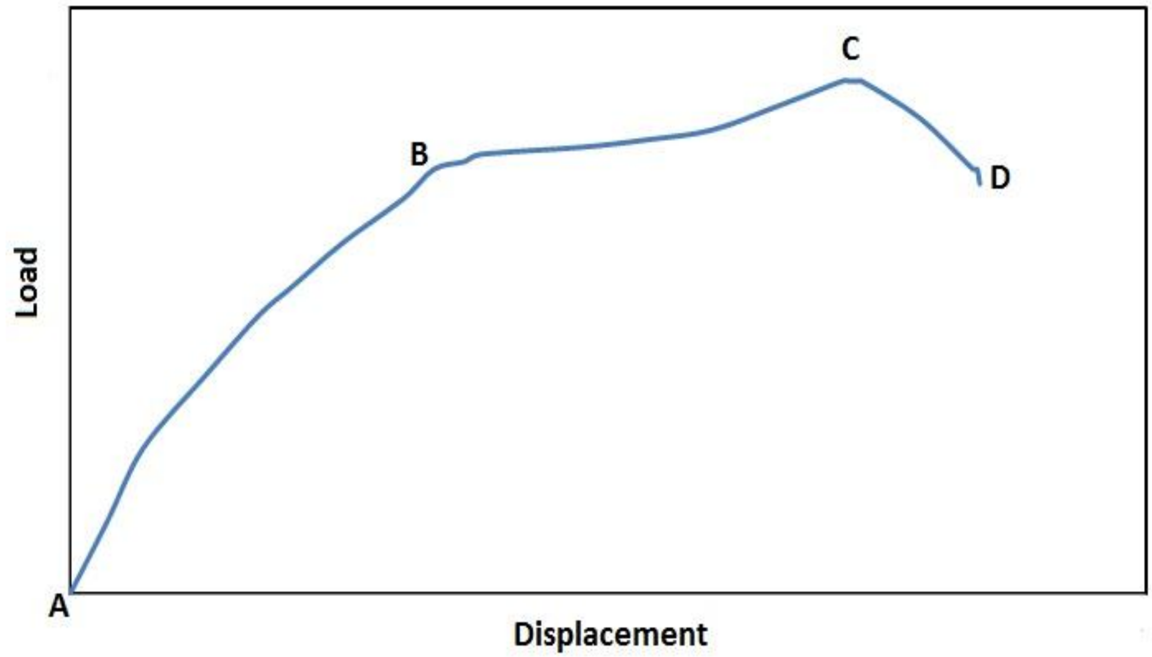

Fig 4.2: Failure Mechanism of Typical Dhajji wall under Monotonic Load

4.3.2 Determination of Energy Dissipation

Higher values of energy dissipation indicates good seismic behavior of structures. Energy dissipation is calculated as the area enclosed by the load displacement curve up to ultimate point. Whole area is divided into different segment and calculating sum of all the segment gives the energy dissipated by system. Area under the each segment is calculated using trapezoidal formula as given in equation 4.1. The detail is shown in figure 4.3.

$$\text{Area Under Curve} = \left(\frac{a+b}{2}\right) * (d - c) \qquad 4.1$$

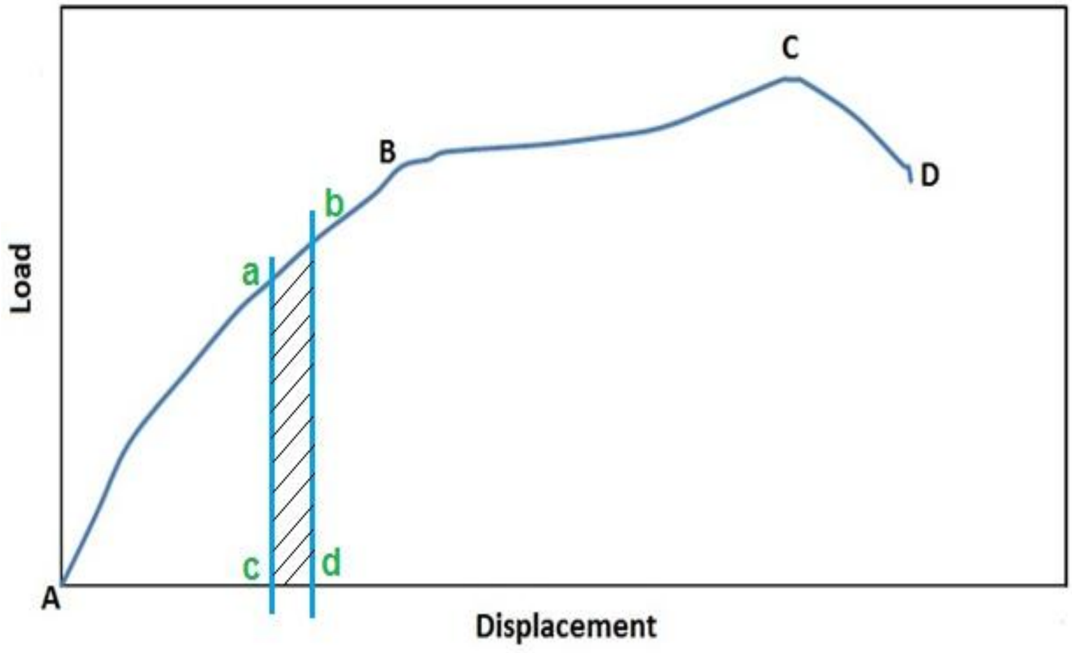

Fig 4.3: Area Enclosed by Segment abcd

4.3.3 Determination of Response and Ductility Factor

Ductility enable the structure to deform beyond yielding and it is the most important seismic parameter to check the performance of a structure. Ductility is calculated as the ratio of ultimate over yield displacement as given in equation 4.2. Structural properties and type of material control affect the ductility.

$$\mu d = \frac{\Delta u}{\Delta y} \qquad 4.2$$

Where, μd is ductility factor, Δu and Δy are ultimate and yield displacements respectively. Muguruma et al. [27] concept of equivalent elastic-perfectly plastic system was used to determine the yield and ultimate displacement on load displacement curve.

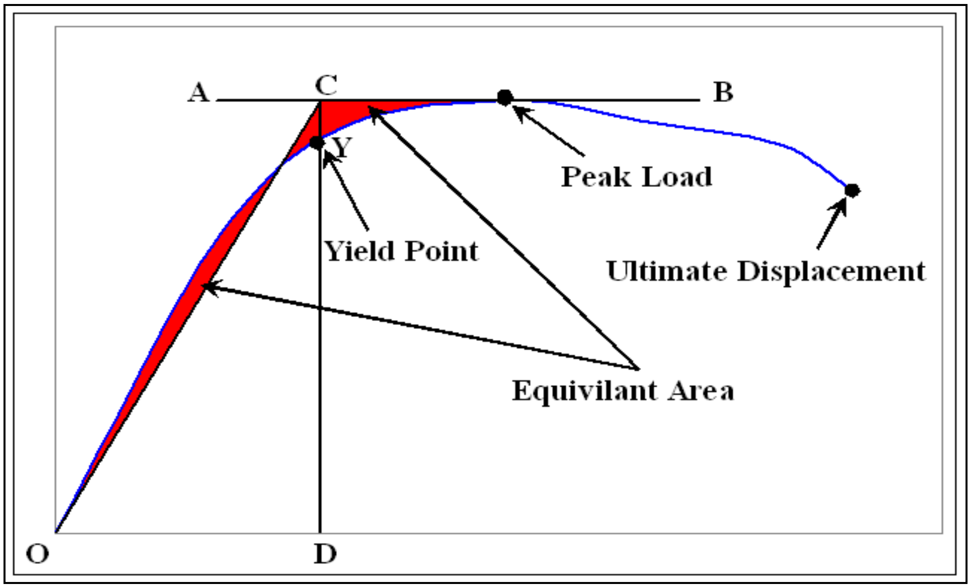

Fig 4.4: Muguruma Model of Yield and Ultimate Points

Response factor also known as force reduction factor is a number which represents the capability of the structure to dissipate energy through inelastic behavior. This factor is distinctive and different for different type of materials and structures. Hence, Response modification factor for various structural systems is extremely important in order to evaluate the capacity of structures based on their seismic demand. Paulay and Priestley [28] equation was used to determine the response factor.

$$Rf = \sqrt{(2\mu d - 1)} \qquad 4.3$$

Here "μd" is the ductility factor. The ductility factor is determined using the model of the equivalent elastic-perfectly plastic system proposed by Muguruma et al [27].

4.3.4 Determination of Stiffness Degradation Ratio

Stiffness degradation ratio is defined as the load applied to push the specimen from yield stage to ultimate stage with the assumption that stiffness till yielding remain unchanged. It tell the rate of stiffness reduction beyond yielding and measured as ratio of secant modulus at stated displacement "K" to the secant modulus at yield "Ko" as given in equation 4.4.

$$Ck = \frac{K}{Ko} \qquad 4.4$$

Where "Ck" is the stiffness degradation ratio "Kp" and "Ku" represents the slope of line joining the origin with peak and ultimate displacement respectively as shown in figure 4.5.

4.4 Discussion on Experimental Results

The group wise discussion on experimental results is as under:

4.4.1 Load Displacement Behavior

The load displacement curves presented in figure 4.6 refers to the horizontal displacement at top of wall vs. lateral load applied to the wall. The main results obtained from Monotonic test were in the form of load displacement curves which give further information in terms of ultimate displacement, energy dissipation, ductility and stiffness degradation. Load displacement curves are important to study the behavior of connections of timber frame walls. Curves represent that all the strengthened wall show good lateral load behavior and stiffness of walls gradually decreasing with the increase in load.

Group-1

The comparison of Dhajji wall strengthened with bamboos and wall without any strengthening is carried out in this group. The group contains two wall specimens abbreviated as DDW1 and DDW2. DDW1 was the reference panel whereas wall DDW2 was strengthened with bamboos fixed on periphery of wall. The importance of the discussion in this group is about the comparison of Dhajji wall strengthened with Bamboos and reference wall.

Figure 4.6 shows the comparison of load displacement curves. From load displacement curves it is clear that DDW2 show good elastic behavior and peak has also occurred at larger lateral displacement than the DDW1. After reaching the peak stage, DDW2 could not maintain peak load and degraded gradually. Quick stiffness degradation after yielding was due to rocking of the wall and propagation of separation crack. DDW1 show lower ultimate response due to brittle mode of failure. The cracking started at a lateral displacement of 2.75 mm. Peak stage occurred at a lateral displacement of 5.74 mm. The gain in lateral strength at peak was not very high and it degraded abruptly due to joints pullout.

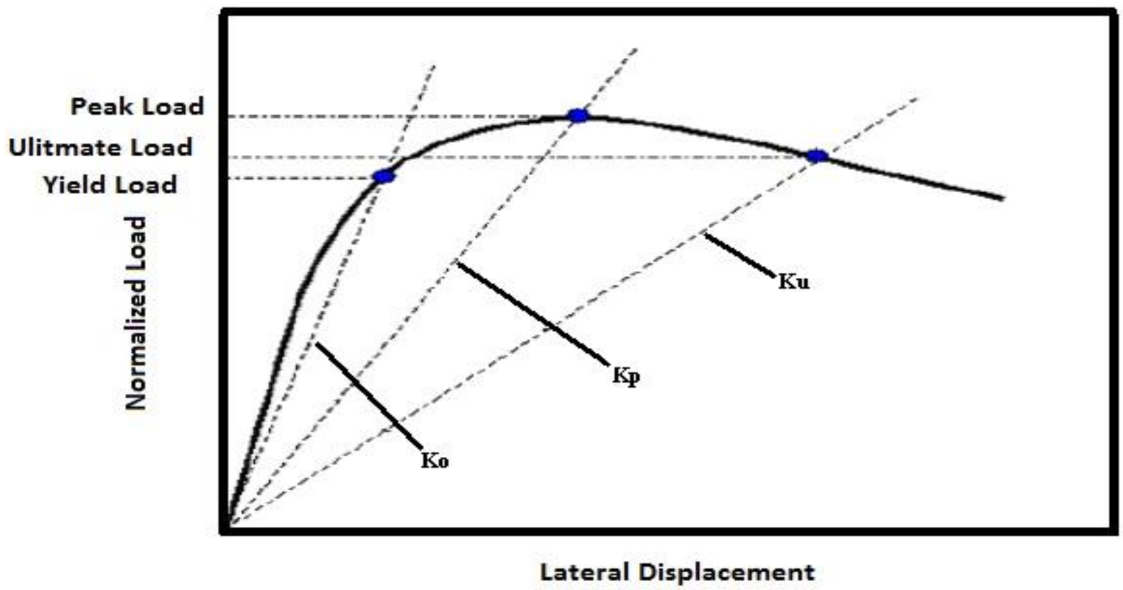

Fig 4.5: Stiffness Degradation Model

The lower lateral load response was due to tearing of timber, joint failure and propagation of separation crack due to which specimen DDW1 showed brittle failure.

The ultimate lateral displacement of reference specimen DDW1 was just 6.76 mm and its value for specimens DDW2 at ultimate stage was increased by 2.21 times the reference specimen as shown in figure 4.7 which indicates that yielding start at lower displacement values and DDW2 wall show good inelastic behavior.

Similarly displacement at yield for specimen DDW2 increased by 1.45 times the reference panels. The lesser ultimate displacement of DDW1 was due to unstrengthen wall and rocking failure was dominant in this wall specimen. However, for wall DDW2 the increment in displacement value at peak and ultimate stage was due to strengthening of wall with bamboos against tension and compression struts.

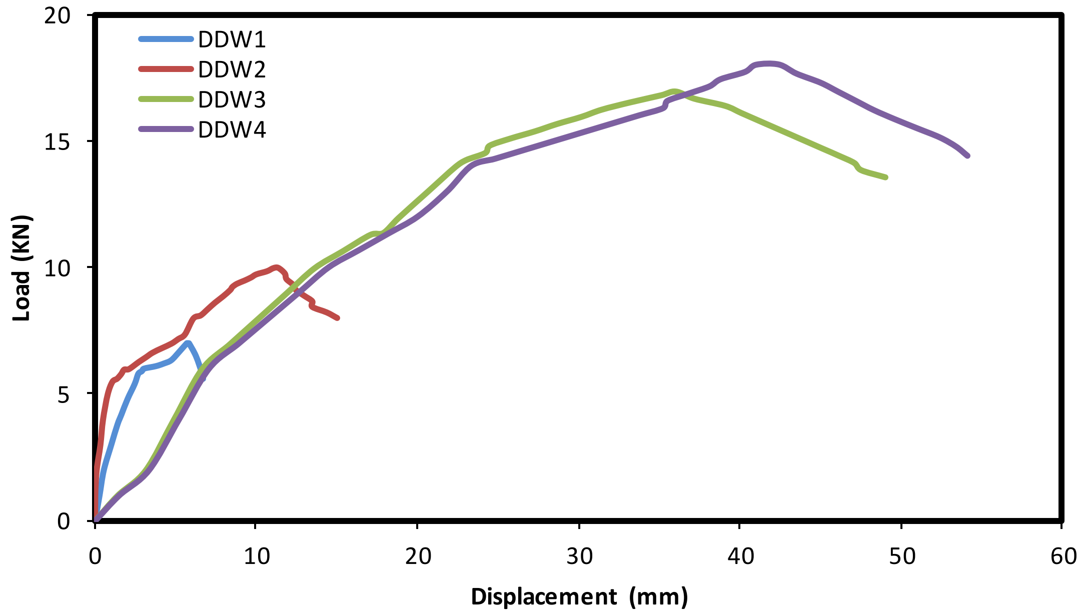

Fig 4.6: Load Displacement Curves of all panels

Strengthened wall DDW2 show good ductile behavior and inelastic response was also better than the reference specimen DDW1 as the lateral load was maintained for higher lateral displacement after yielding. Specimen DDW2 strengthened with Bamboos has showed load increment of 42.85% with reference to DDW1 at peak stage.

Higher lateral resistance of wall DDW2 was due to its ductile mode of failure because panel was strengthened with Bamboos along tension and compression struts. The ultimate displacement was not very high despite of delayed occurrence between yield and peak stages. The drift ratio of 1.25% was recorded for specimen DDW2 at ultimate stage as shown in figure 4.9, which was 2.23 times higher than reference specimen.

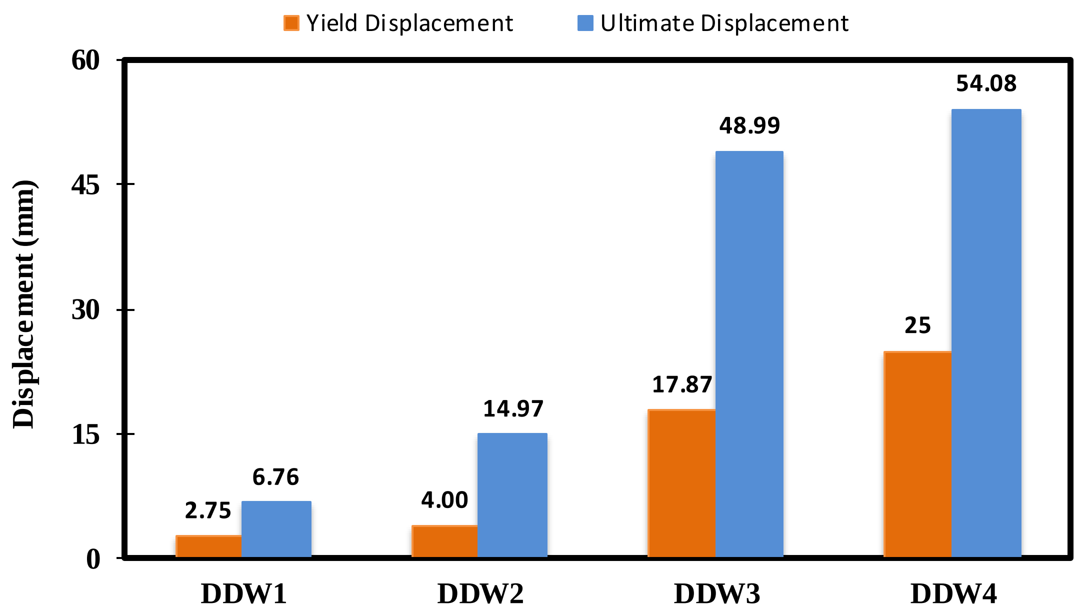

Fig 4.7: Comparison of Lateral Displacement at Different Stages

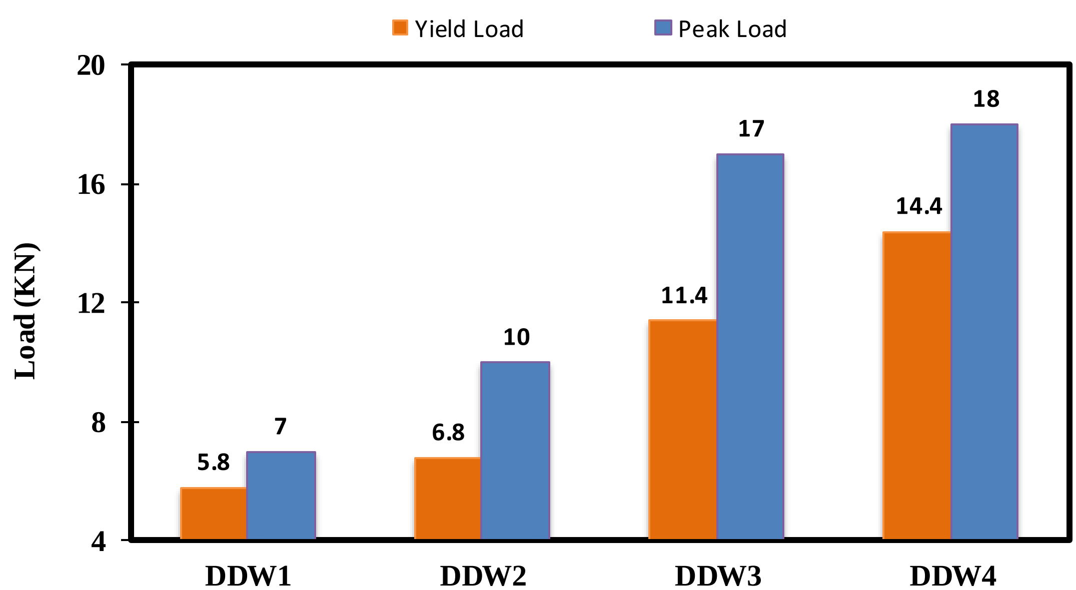

Fig 4.8: Comparison of Lateral Load at different Stages

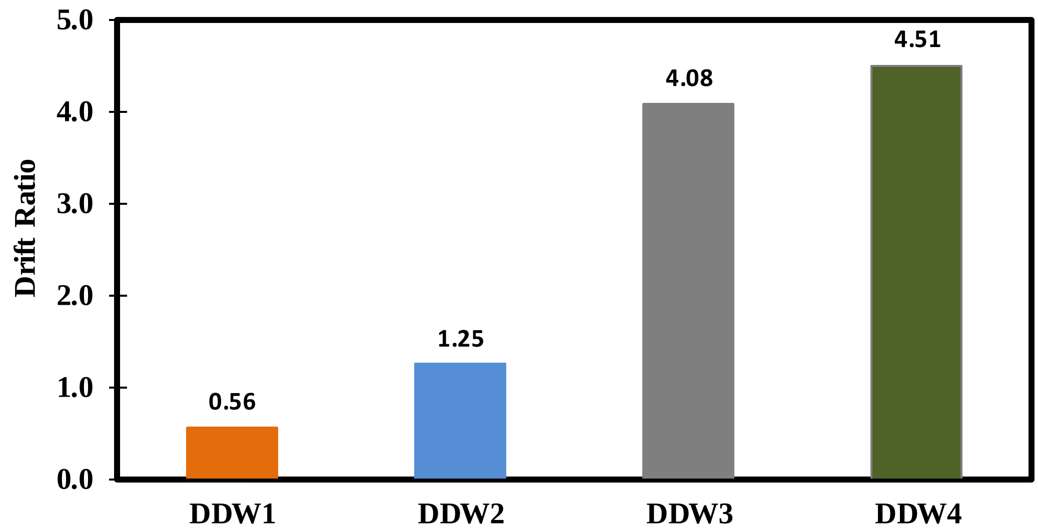

Fig 4.9: Comparison of Drift Ratio

Group-2

The comparison of Dhajji wall strengthened with Metal strips and Metal gusset plates with reference to wall without any strengthening is discussed in this group. The group contains three wall specimens abbreviated as DDW1, DDW3 and DDW4. DDW1 was the reference panel whereas specimen DDW3 was strengthened with metal strips and DDW4 was strengthened with metal gusset plates. The main discussion in this group is about the comparison of Dhajji wall strengthened with metal strips and metal gusset plates with reference wall.

It can be seen clearly in figure 4.6 that the specimen DDW4 showed higher lateral resistance before yielding and peak has also occurred at larger lateral displacement than the specimen DDW1 and DDW3. After peak stage, the lateral load of specimen DDW4 degraded gradually. Gradual stiffness degradation was due to ductile shear failure of the specimen and propagation of shear cracks at intermediate joints. The specimen DDW3 show lesser lateral load till yielding with lesser yielding displacement due to combination of rocking and shear mode of failure. The cracking started at a lateral displacement of 17.875 mm. And peak stage occurred at lateral displacement of 35.99 mm. The gain in lateral strength at peak was comparatively less compared with DDW4 and specimen failed due to joint pullout and shear crack formation at intermediate joints as shown in figure 4.19. The overall load displacement behavior of wall DDW3 and DDW4 was very effective compared with DDW1 because wall DDW1 was failing in rocking and showing brittle behavior and this mode of failure was controlled by application of metal strips and metal gusset plates at critical location of specimens in case of wall DDW3 and DDW4.

The ultimate lateral displacement of reference specimen DDW1 was just 6.76 mm and its value for specimens DDW3 and DDW4 at ultimate stage was increased by 7.24 and 8 times the reference specimen respectively as shown in Figure 4.7 which indicates that wall DDW3 and DDW4 showed good inelastic behavior.

Similarly displacement at yield for specimen DDW3 and DDW4 increased by 6.5 and 9.09 times the reference panels respectively. The lesser ultimate displacement of DDW1 was due to unstrengthen wall (reference wall) and rocking failure. However, for wall DDW3 the increment in displacement value at peak and ultimate stage was due to strengthening of wall with metal strips at two critical location of wall and for wall DDW4 this increment was due to strengthening of wall with metal gusset plates against rocking failure at three different locations of wall.

Strengthened specimens DDW3 and DDW4 show good ductile behavior and inelastic response was also much better than the reference specimen DDW1 as lateral load was maintained for higher lateral displacement after yielding. However, there was a slight difference in the loading values of wall DDW3 and DDW4 because DDW4 was strengthened at three critical location of wall compared with DDW3. Specimen DDW3 strengthened with metal strips and DDW4 strengthened with metal gusset plates have shown load increment of 142.85% and 157.14% with reference to DDW1 at peak stage.

The higher value of lateral resistance for specimen DDW3 and DDW4 was primarily due to its ductile mode of failure and due to strengthening of panel with metal strips and metal gusset plates respectively. The ultimate lateral displacement was very high due to delayed occurrence between yield and peak stages. The drift ratio of 4.08% and 4.51% was recorded for specimen DDW3 and DDW4 at ultimate stage as shown in figure 4.9, which was 7.28 and 8.05 times higher than reference specimen respectively.

Group-3

The comparison of all Dhajji walls unstrengthen and strengthened using different strengthening techniques is discussed in this group. The group contains four wall specimens abbreviated as

DDW1, DDW2, DDW3 and DDW4. DDW1 was the reference panel whereas specimen DDW2 was strengthened with bamboos, specimen DDW3 was strengthened with metal strips and DDW4 was strengthened with metal gusset plates. The discussion of results in this group is about the comparison of different strengthening techniques with reference wall.

The load displacement curves shown in figure 4.6 indicate that the lateral load of wall DDW2, DDW3 and DDW4 is significantly higher than DDW1. The peaks occur at larger loads against larger displacement values. The ultimate values of displacements are also much higher than Group-1 walls. However, the yield point of wall DDW2 occur at lower load values compared with all other walls and peaks occur after a significant delay in yield stage which indicates the good inelastic behavior of wall DDW2 compared with other walls. This behavior of wall DDW2 was due to strengthening of wall with bamboos along tension and compression struts which are the critical diagonals of Dhajji walls.

4.4.2 Energy Dissipation

Figure 4.10 represent the energy dissipation of all specimens during loading stage. Factors upon which energy dissipation of traditional wall depends are (1) the friction along joints, (2) crack propagation, (3) formation of new cracks, (4) crushing of wood, (5) rocking and joint detachment. Failure mode of traditional wall also affect the energy dissipation; for brittle failure its value will be less compared with ductile failure of wall.

Group-1

The ultimate displacement and energy dissipation increased significantly for DDW2. The improvement in behavior for strengthened specimens was recorded because the Dhajji wall was strengthened against rocking failure with Bamboos on tension and compression struts. The contribution of Bamboos confinement towards seismic performance can be seen from figure 4.6 which shows that after yielding Bamboos started to participate actively in resisting lateral load and improved significantly the energy dissipation compared with reference specimen DDW1.

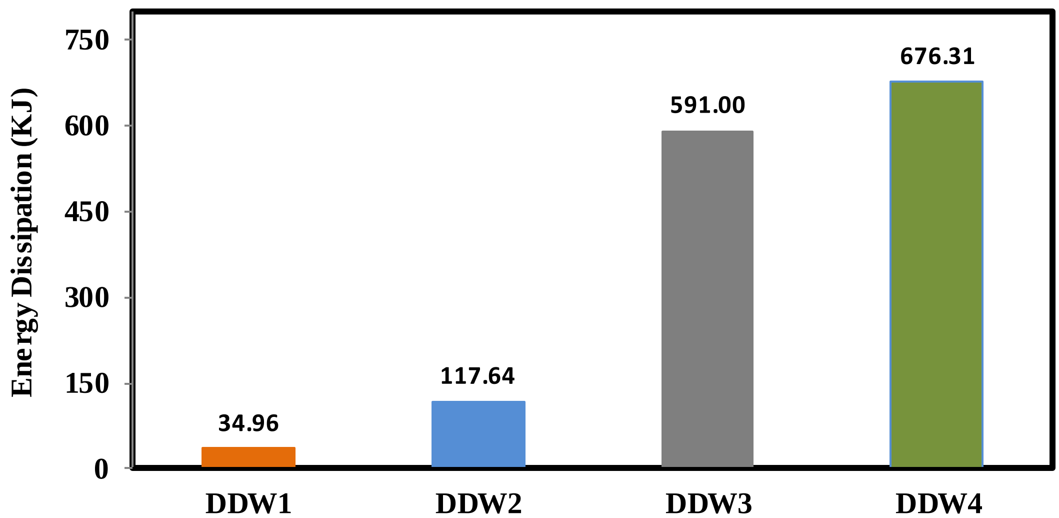

Fig 4.10: Comparison of Energy Dissipation

The specimen DDW1 experienced brittle shear failure and its energy dissipation was less due to abrupt decrease in loading values after peak stage and absence of significant inelastic portion. The specimen DDW1 dissipated maximum of 34.96 kJ energy and energy dissipated by DDW2 was 117.64 KJ which is 3.36 times the reference panel as shown in figure 4.10. The comparatively lesser values of energy dissipation for reference panel were primarily due to its brittle mode of failure in which displacement was less at ultimate stage. The higher values of energy dissipation in case of DDW2 were attributed to its ductile mode of failure. Greater portion of energy was absorbed by more widening of separation crack and tearing of timber compared with reference panel.

Group-2

The improvement in behavior of strengthened specimens DDW3 and DDW4 was recorded due to walls strengthened against rocking at critical locations with metal strips and metal gusset plates respectively. The contribution of metal strips and metal gusset plates against rocking failure of Dhajji wall can be seen in figure 4.6 which indicates increased lateral load behavior of walls which was specifically due to strengthening of joints. After yielding redistribution of stresses occur due to metal strips and metal gusset plates at critical locations of wall which helps in resisting the lateral loads and improved significantly the energy dissipation compared with reference specimen DDW1.

The specimen DDW1 dissipated maximum of 34.96 kJ energy and energy dissipated by DDW3 and DDW4 was 591 KJ and 676.23 KJ which are 16.91 and 19.34 times the reference panel as shown in Figure 4.10 respectively. The comparatively lesser values of energy dissipation for reference panel were primarily due to its brittle failure in which displacement was not much at ultimate stage. The higher values of energy dissipation in case of specimen DDW3 and DDW4 were attributed to its ductile mode of failure due to higher lateral displacements. Greater portion of energy was absorbed by metal gusset plates than metal strips might be due to more strengthened locations of DDW4 compared with DDW3.

Group-3

The significant increase in lateral load strength of strengthened walls can be seen in figure 4.6 which is an indication of enhanced energy dissipation of strengthened walls. Wall DDW2 showed the good inelastic behavior at start due to occurrence of yield at lower displacement values and delayed in yield and peak stages. But just after reaching the peak load values the rocking failure was dominated which stops the DDW2 taking further loads and ultimate stage reached at lower displacement values compared with specimens DDW3 and DDW4. Specimen DDW3 and DDW4 showed larger energy dissipation values due to strong confinement of joints against rocking failure. However, specimen DDW4 has higher values of energy dissipation than rest of panels which indicates that more strengthened locations of walls leads to higher energy dissipations and also the efficiency of metal gusset plates.

4.4.3 Response and Ductility Factor

Response factor is an important criterion for designing structures present in seismically active zones. The response factor represents the ductility of a structure. Ductile structures withstand the seismic forces more efficiently. The response factor of all the specimens determined by using the relationship given by Paulay and Priestley [28].

Group-1

Specimen DDW2 show higher value of response factor due to higher ductility. The response factor for specimen DDW2 was more than reference specimen and this enhancement in value was due to extended inelastic portion of load displacement curve as the yielding started earlier and delay occur in reaching the peak displacement of DDW2. An increase in response factor of 28.78% was calculated for specimen DDW2 as shown in figure 4.11. Failure mode also affects the ductility of structure like energy dissipation. In rocking failure peak stage delays because specimen tends to return to its origin after reaching peaks. So in group 1 both the panels were failing in rocking therefore response factor for these panels have significant values.

Group-2

Specimen DDW3 show higher value of response factor due to redistribution of stresses at strengthened joints. The response factor for specimen DDW3 was more than DDW1 and DDW4 and this enhancement in value was due to extended inelastic portion of load displacement curve as the yielding started earlier and delay occur in reaching the peak displacement of DDW3. Wall DDW1 has greater value of response factor than DDW4 this might be due to rocking behavior of DDW1 as well as delay in occurrence of yield point of DDW4 due to confinement of joints and redistribution of stresses.

Group-3

It can be seen in figure 4.11 that wall DDW2 show higher values of response factor which indicates the good ductile behavior of wall. And values of all strengthened walls are 1.28, 1.07 and 0.92 for DDW2, DDW3 and DDW4 with reference to unstrengthen wall respectively. Value of response factor for wall DDW4 is less than other panels which indicates that difference in yield and ultimate displacement is less which might be due to lower rate of stiffness degradation and delay in occurrence of yield point because of stresses redistribution.

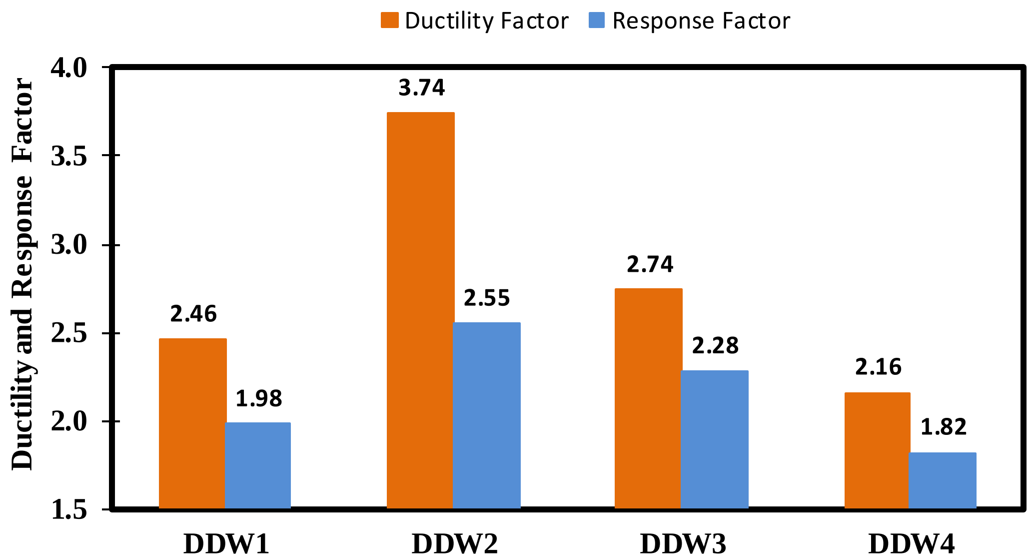

Fig 4.11: Ductility and Response Factor of all specimens

4.4.4 Stiffness Degradation

Stiffness degradation represents the damage accumulated at the connection of traditional timber wall, which is related with the deformation and nail pull out of wall. It tells the rate of stiffness reduction after yielding. Lower value of stiffness degradation indicates good seismic capabilities. Stiffness degradation ratio was determined for each specimen and is shown in figure 4.12. The overall stiffness behavior of walls is shown in table 4.1. The initial stiffness of DDW2 was almost doubled compared with DDW1.

Table 4.1: Stiffness Values of all specimens

Stiffness	DDW1	DDW2	DDW3	DDW4
Effective Stiffness	2.49	4.75	0.84	0.68
Stiffness at Yield	2.045	1.34	0.66	0.57
Stiffness at Peak load	1.08	0.64	0.45	0.39
Stiffness at Ultimate load	0.71	0.44	0.263	0.267
Stiffness Degradation	0.35	0.33	0.40	0.47

Figure 4.12 show that percentage stiffness degradation for all the specimens at both yield and ultimate stages is almost same and lower values as in case of DDW2 show good seismic

capabilities. Similarly higher values in case of DDW4 show stiff behavior of wall. Higher effective stiffness of DDW2 was due to bamboos but at yield load the stiffness of DDW2 decreases abruptly as shown in table 4.1 which indicate that deformation in DDW2 was due to rocking of joints and propagation of separation crack. The effective stiffness of panel DDW3 and DDW4 was less and stiffness degradation was also negligible compared with DDW1 and DDW2 which might be due to stiff behavior of walls after strengthening of joints with metal strips and metal gusset plates.

4.5 Behavior of Walls at Failure

The lateral drift and base uplift are the important parameters for describing the failure mode. The higher values of base uplift 6.72 mm and 11.95 mm for specimens DDW1 and DDW2 were due to rocking failure. Similarly for specimen DDW3 and DDW4 the base uplift values 2.73 mm and 3.21 mm were comparatively less and values of lateral drifts were higher which indicates that these panels have experienced ductile shear failure.

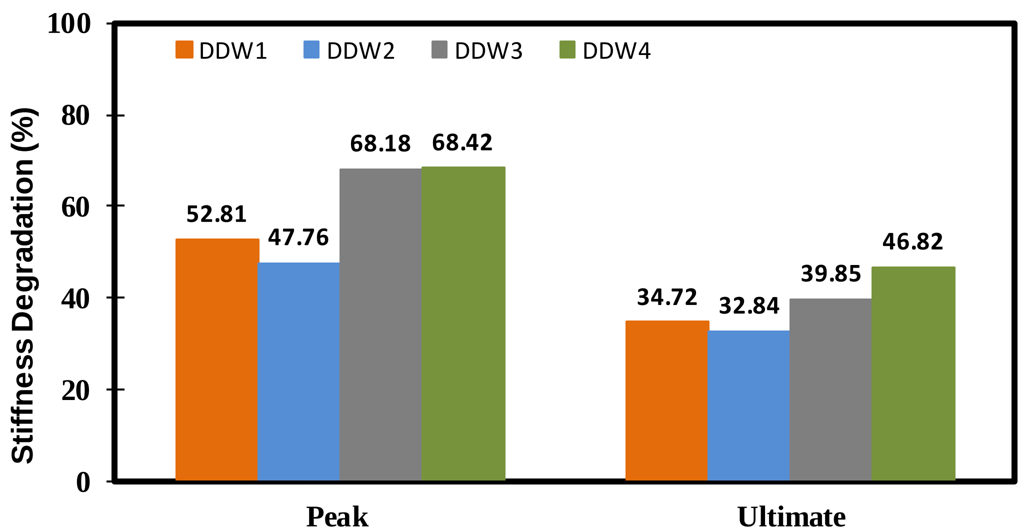

Fig 4.12: Stiffness Degradation Ratio of all specimens

4.5.1 Failure Pattern of Wall DDW1

The brittle shear failure occurs once there is no distribution of stresses on joints and stresses don't transfer to less stressed regions after the vertical post pulled out and initiation of shear cracks. The line diagram of failure of DDW1 is shown in figure 4.13 to understand the failure pattern. The typical damages included timber tearing, joint detachment and crack propagation. The major damage occurred at the connections when tensile stresses develop due to application of lateral load. The failure pattern is shown in figure 4.13 numerically. After the initiation of cracks, stress concentration occurs along the bracers and causing propagation of crack, which results in pulling out the next vertical member. Moreover, no damages observed in the infill material. Actual failure diagram of DDW1 is shown in figure 4.14.

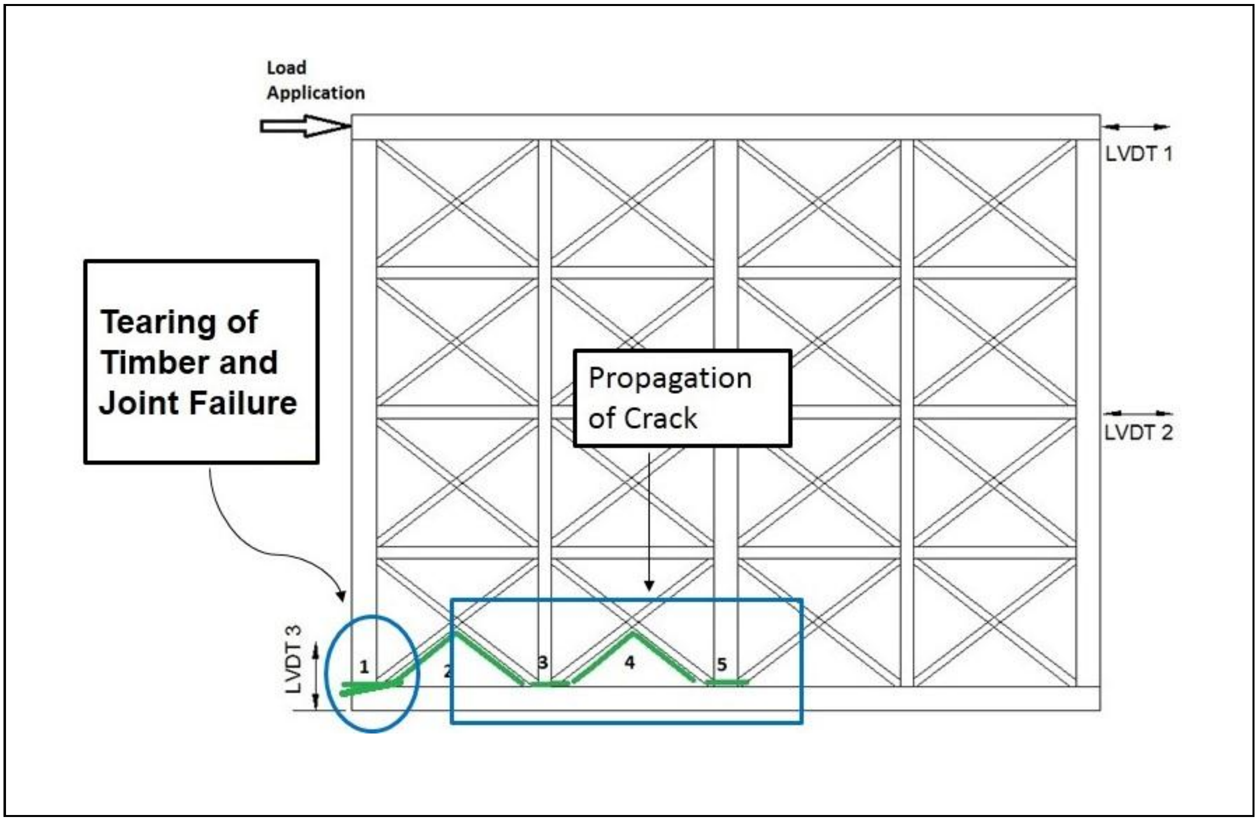

Fig 4.13: Line Diagram of DDW1 Failure

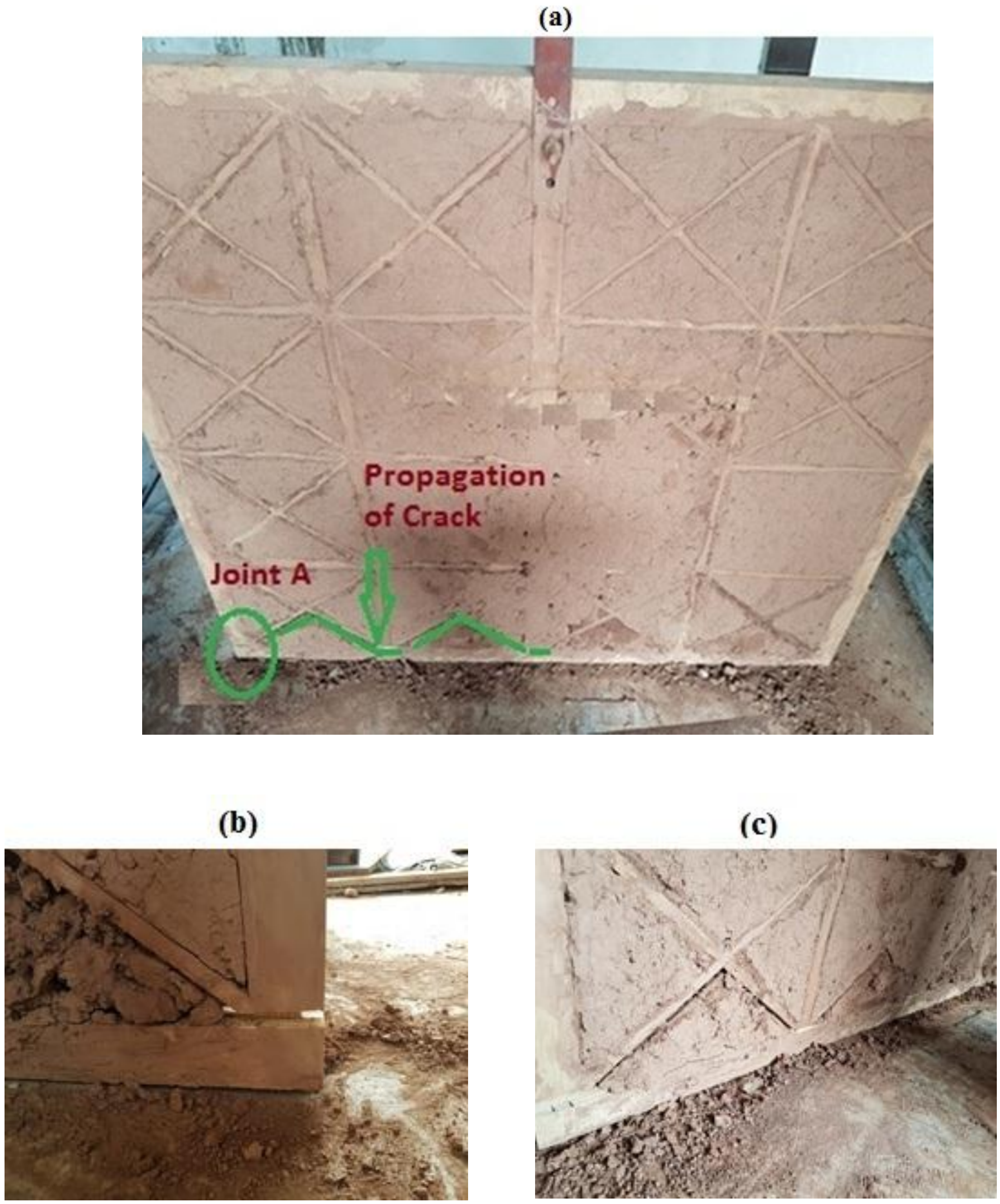

Fig 4.14: (a) Failure Locations of DDW1 (b) Joint A Pulled Out (c) Propagation of Crack

4.5.2 Failure Pattern of Wall DDW2

The typical damages of DDW2 includes timber tearing, joint detachment and crack propagation. Damages occurred at the connections due to rocking of wall when tensile stresses develop on the critical locations of wall. After the initiation of cracks, stress concentration occurs at the edges of bracers and causing extensive widening of crack, which results in pulling out the next vertical post and propagation of crack. The failure pattern of DDW2 was same as DDW1 but uplift of joint was more at bottom left corner and crack was also extended more than DDW1. Like DDW1 no damages were observed in the infill material. Line diagram and actual failure diagrams of DDW2 are shown in figure 4.15 and figure 4.16 respectively.

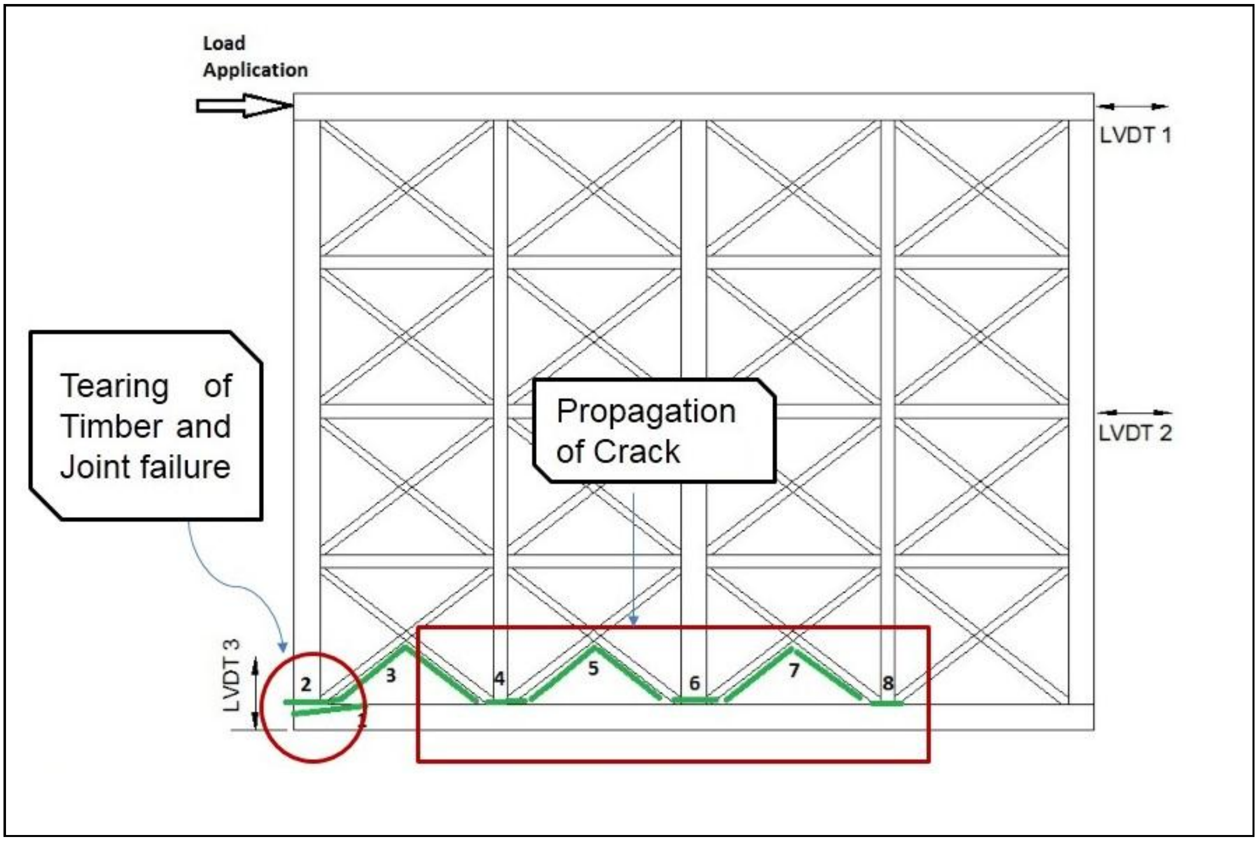

Fig 4.15: Line Diagram of DDW2 Failure

Fig 4.16: (a) Propagation of crack (b) Rocking of Stud

4.5.3 Failure Pattern of Wall DDW3

The failure pattern of wall DDW3 was different from DDW1 and DDW2 due to strengthening of joints with metal strips. There was no rocking observed at the corner joint due to metal strips. Tensile stresses were transfer to next unstrengthen joint and minor pull out of vertical member was observed. However shear crack start at location 2 of panel due to transfer of stresses from strengthened joints as shown in figure 4.17. Shear cracks were developed due to combination of tensile and compressive stresses and caused the detachment of intermediate joints at 12 different locations. Actual failure of DDW3 is shown in figure 4.18.

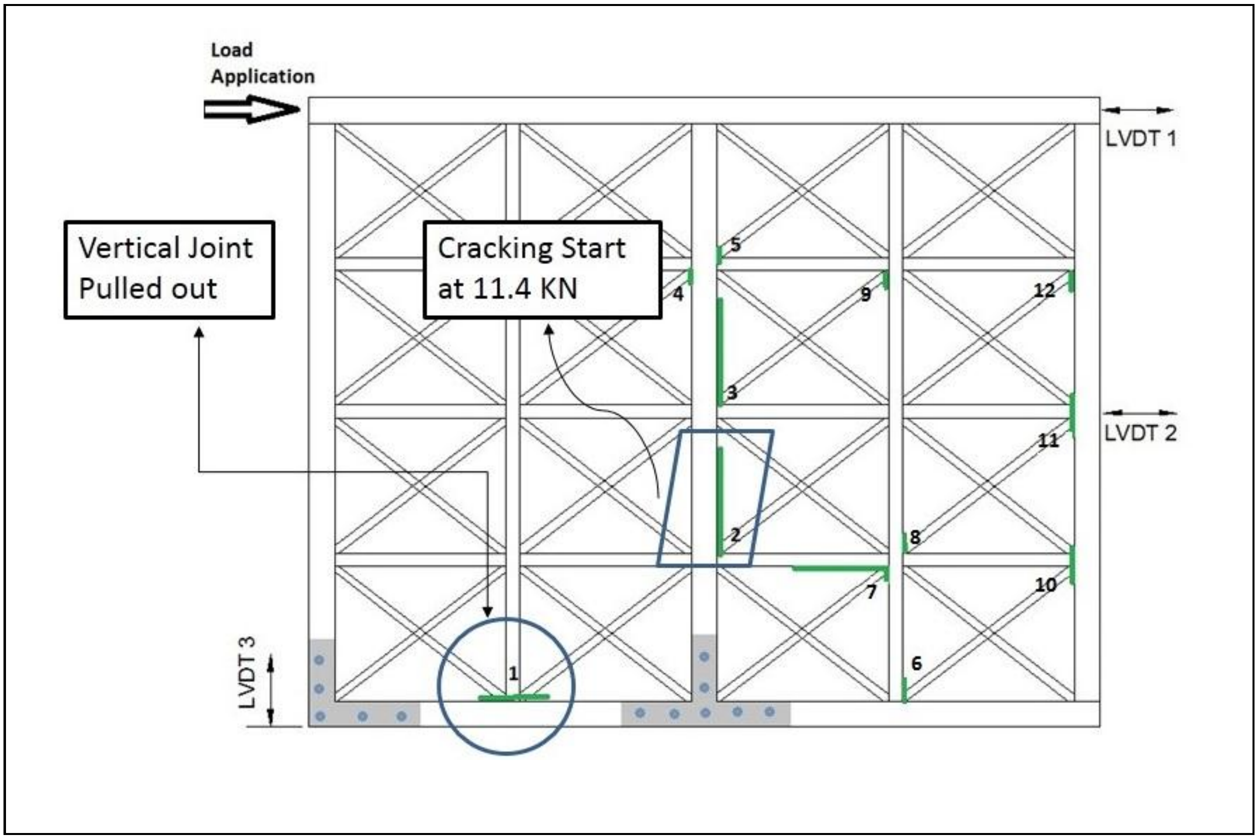

Fig 4.17: Line diagram of DDW3 failure

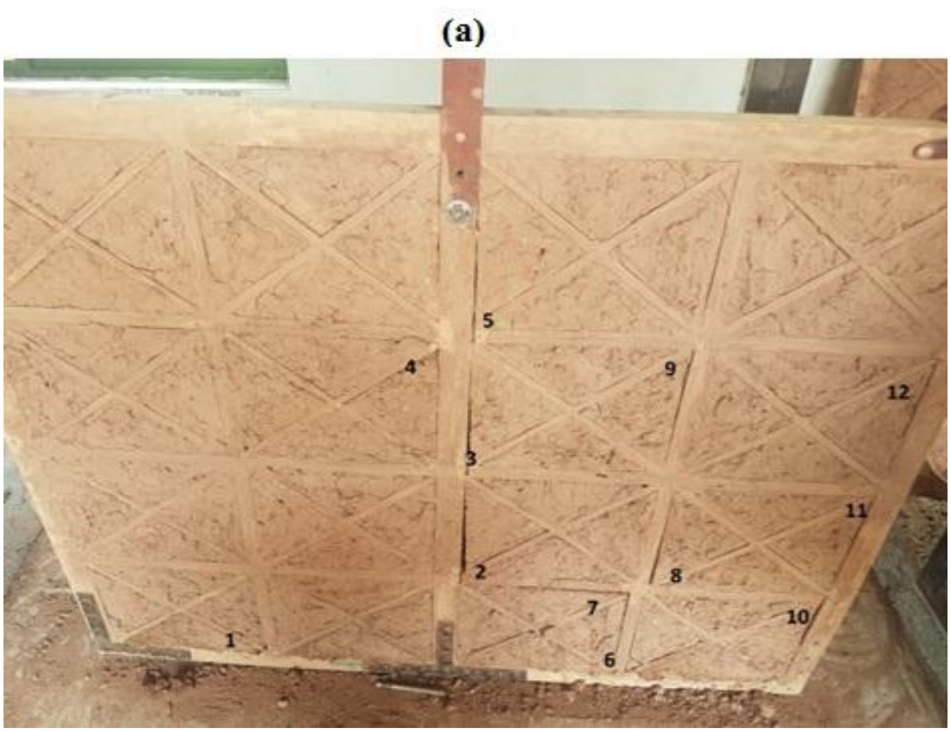

Fig 4.18: Results of DDW3 (a) 12 Different Locations of Failure (b) Close View of Joint 4 & 5 (c) Close View of Joint 10

4.5.4 Failure Pattern of Wall DDW4

The failure pattern of wall DDW4 was quite similar to DDW3 due to strengthening of joints with metal gusset plates. There was no rocking observed at the corner joint due to metal gusset plates. However shear crack start at location 1 of panel due to transfer of stresses through strengthened joints into less stressed region as shown in figure 4.19. The shear cracks were developed due to combination of tensile and compressive stresses and caused the detachment of intermediate joints at 9 different locations. Behavior of wall DDW4 was also ductile shear failure like DDW3, same phenomena happen in DDW4. But due to strengthening of joints at three consecutive locations with metal gusset plates no vertical member pulled out form the bottom posts only shear crack formed as a result of combination of tensile and compressive stresses. Initiation of cracks start at one third intermediate location due to redistribution of stresses on strengthened joints, next crack start at middle intermediate joint and then two third and so on. The location and sequence of crack formation is shown numerically in figure 4.19.

Shear crack width of panel DDW4 was observed more compared with DDW3 which means that stresses were more critical in case of DDW4. Width of cracks was wider but number of cracks were less compared with panel strengthened with metal strips.

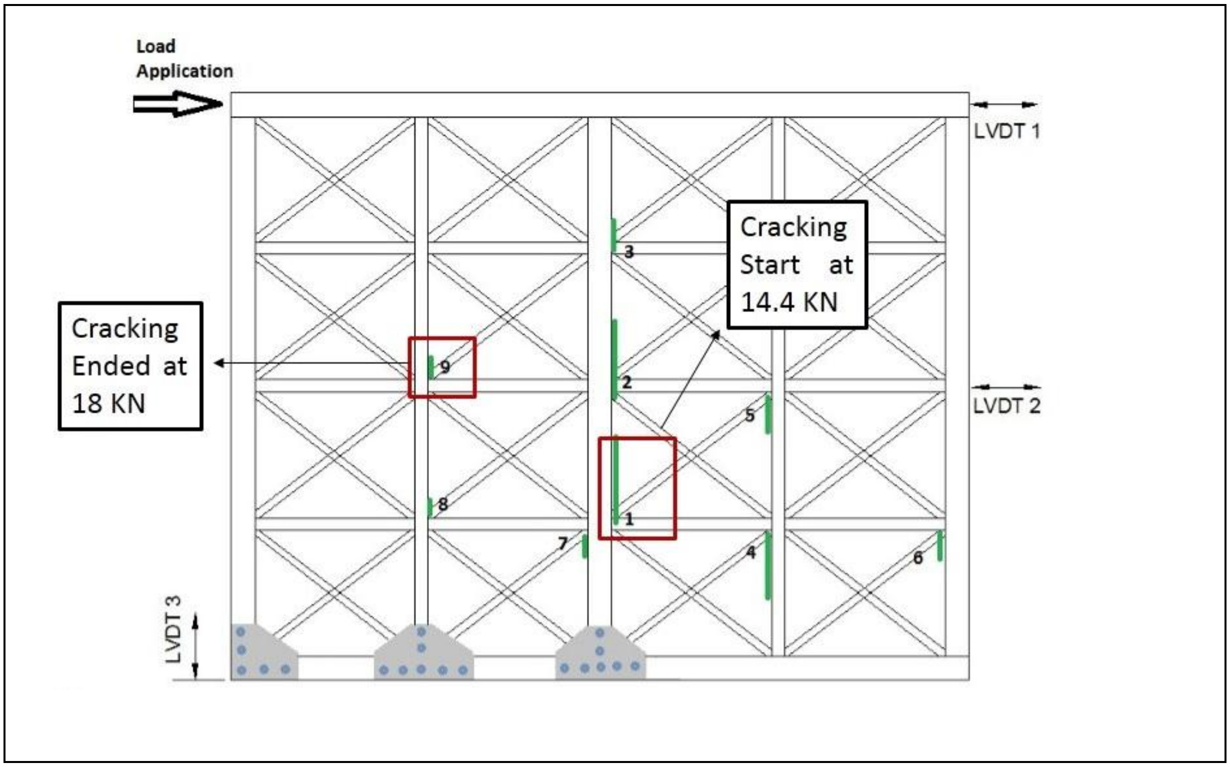

Fig 4.19: Line Diagram of DDW4 failure

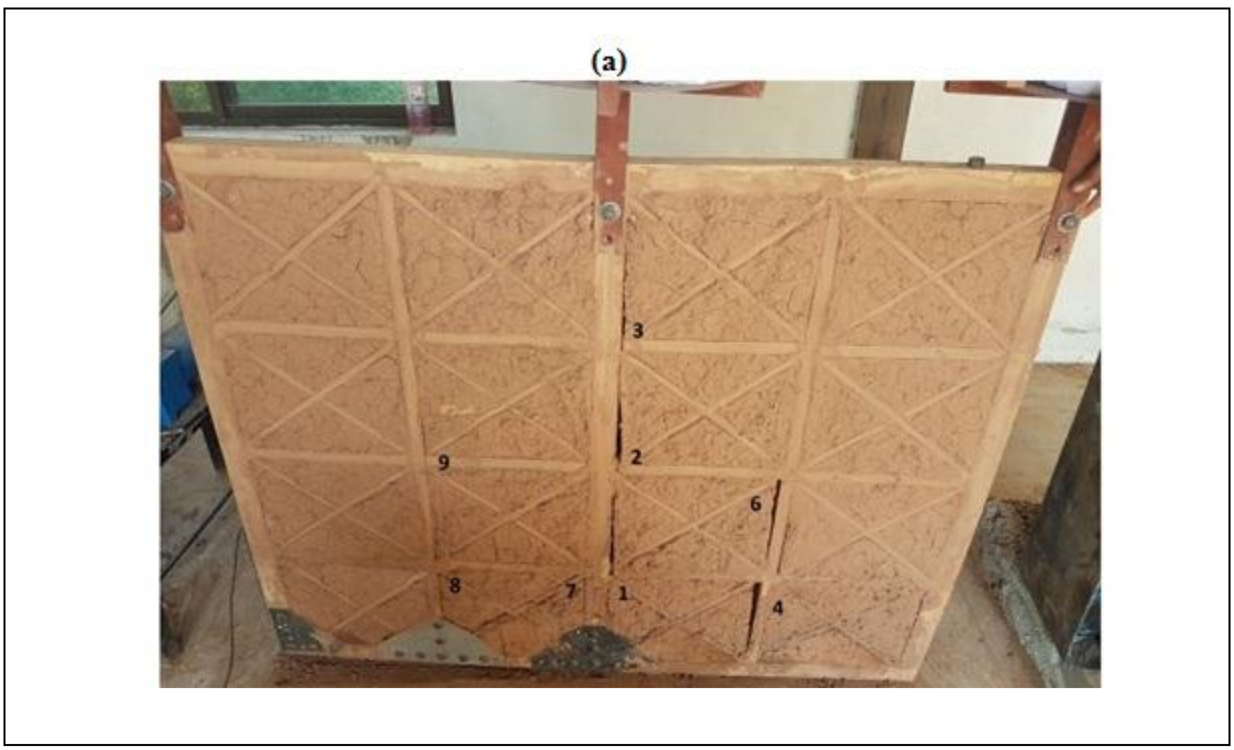

Fig 4.20: Test Results of DDW4 (a) 9 Different Locations of Failure (b) Close View of Intermediate joint 1 (c) close view intermediate joint 4

4.6 Cost Benefit Analysis

Cost benefit analysis of all the panels is made based on the results obtained from load displacement curves and additional cost of strengthening as shown in table 4.2. Wall DDW4 show good lateral behavior in terms of load, displacement and energy dissipation. Similarly, wall DDW2 show good ductility and energy dissipation and lesser cost of strengthening. However, wall DDW3 strengthened with metal strips show better lateral response, stiffness degradation and ductility and considered as the best panel of out of all.

Table 4.2: Cost benefit analysis

Parameters	**DDW1**	**DDW2**	**DDW3**	**DDW4**
Additional Cost	-	5.88 %	11.76 %	14.71 %
Lateral Load (KN)	7	10	17	18
Displacement (mm)	6.76	14.97	48.99	54.08
Energy Dissipation (KJ)	34.96	117.64	591	676.31
Ductility	2.46	3.74	2.74	2.18
Stiffness Degradation Ratio	0.35	0.33	0.40	0.47

4.7 Summary of Results

Following observations were made from the experimental results:

- Test results depicts that strengthening of joints enhanced the lateral load capacity of Dhajji walls and its enlarged values were 1.42, 2.42 and 2.57 time the reference wall for DDW2, DDW3 and DDW4 respectively.
- The substantial difference in values of yield and ultimate displacement of reference and strengthened walls indicates the ductile behavior of strengthened walls and it was significant for DDW2.
- The ultimate displacement values of strengthened walls were 14.97 mm, 48.99 mm and 54.08 mm for DDW2, DDW3 and DDW4 respectively those were 2.21, 7.24 and 8 times the reference wall indicating the enhanced lateral load behavior of strengthened walls.
- Drift ratio of strengthened walls increased up to 8.05 times the reference wall which indicates the remarkable resilience of Dhajji wall against lateral loads after strengthening the critical joints.
- Optimum energy dissipation capacity of strengthened wall was 19.34 times the reference wall which proves that strengthening of joints enhance the dissipation capacity of wall extraordinarily.
- The stiffness degradation ratio of wall DDW2 was more than other strengthened walls which indicates the good ductile behavior of wall. And it was less for wall DDW4 compared with all other walls which show stiff behavior of wall DDW4.
- The failure behavior of DDW1 was observed brittle and rocking started at small displacements. Rocking was also dominant in wall DDW2 and yielding starts at small displacements but because of strengthening of wall with bamboos against tension and compression struts the ultimate stage occur at larger displacement which indicate the ductile behavior of wall DDW2. The behavior of wall DDW3 and DDW4 was almost same and it was ductile shear failure.
- The ductility depends upon the inelastic behavior of Dhajji walls. Wall DDW2 show higher ductility due to early occurrence of yield point and redistribution of forces for higher ultimate displacements. Although wall DDW2 show lesser ultimate displacement compared with wall DDW3 and DDW4 but its ductility was more because ductility factor is a ratio of ultimate and

yield displacements and difference between yield and ultimate displacements was more for DDW2.

- Base uplift was more for DDW1 and DDW2 which indicates failure of these walls was due to rocking. But lesser values of top displacements for wall DDW1 show that behavior of wall was brittle but it was ductile for wall DDW2 due to higher values of top displacements. Similarly, values of base uplift were lesser for walls DDW3 and DDW4 due to strengthening of walls against rocking and higher top displacement of these walls indicates the ductile shear behavior.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This thesis intended to provide useful information on the behavior of traditional timber wall Dhajji Dewari under lateral loads after strengthening of critical joints. The experimental analysis was carried out on four reduced scale Dhajji walls to experience the joint strengthening techniques. The strengthening techniques were applied on three different walls using Bamboos, Metal strips and Metal gusset plates.

5.1 Concluding Remarks

- Joints strengthening enhanced the lateral load capacity of Dhajji walls by a factor 1.42-2.57 and energy dissipation from 117.64 kJ to 676.31 kJ by 3.36-19.34 times the reference wall.
- All the strengthened panel show good inelastic behavior and ultimate response increased by 2.21-8 times and ductility enhanced by 1.52 times the reference panel.
- Failure Patterns changed after joint strengthening and trend shift toward the ductile shear failure instead of brittle failure.
- Based on lateral load behavior and cost, DDW3 (Panel Strengthened with Metal strips) is better among the four panels tested and metal strips are suggested as the strengthening technique for Dhajji walls.

5.2 Recommendations

- ❖ Failure pattern of Dhajji walls can be observed under static cyclic and dynamic loading after applying the strengthening techniques on all connection between horizontal and vertical posts.
- ❖ Different types of joints can be analyzed in Dhajji Dewari panel to know which is better in resisting lateral load and provides more stability to the overall structure.

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