Increasing the Lateral Capacity of Timber Wall Panels using Inexpensive FRP Retrofitting Techniques

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Dedication

I dedicate this Research to my parents, siblings and loved ones.

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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 open for me and he guided me towards the right path and went out of his to help me out whenever I was stuck in any phase of the research.

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Last but not the least; I would also like to thank my parents as this research work would not have been completed without their persistent support and prayers.

ABSTRACT

Dhajji Dewari is a traditional non-engineered open construction technique. These traditional timber structures are mostly found in Northern mountainous parts of Pakistan and in places where availability of conventional building construction materials is limited or restricted, so people have to make use of the locally available materials like timber, stone and mud etc. for building construction as well. From the past research work done on Dhajji Dewari construction type it was found out that the construction type has adequate earthquake resistance qualities. Also, it has other prominent features like affordability, ability to tolerate lateral forces and it can be utilized using cheap relatively untrained labour.

This thesis presents experimental work conducted on typical Dhajji Dewari wall samples in two phases and their in-plane lateral load response was evaluated. Five reduced scale wall samples were constructed, two of the five walls were used as reference walls in the 1st phase of testing, the walls were bolted to the floor first without any joint strengthening applied and tested under in-plane monotonic loading, from the tests it was found that main vertical and horizontal joints governed major wall properties like its load carrying capacity, its ductility, energy dissipation and the wall’s mode of failure. So, to strengthen these critical vertical and horizontal joints, in the 1st phase of testing, conventional strengthening techniques were used (bamboo, metal strips and gusset plates) and their response was evaluated. For the 2nd phase of testing since there was limited research done on the subject of retrofitting aspect of Dhajji Dewari Walls, Fiber Reinforced Polymers were used in two forms (wraps and strips) to retrofit and strengthened the wall samples which were damaged from the initial testing. CFRP was used without and in conjunction with the strengthening techniques used in the 1st phase of testing and the walls were tested and evaluated under in-plane monotonic loading again.

From the test results it was noted that use of CFRP in conjunction with 1st phase strengthening techniques caused a sort of over-strengthening of the wall, the wall sample started to show bending due to torsion without significant increase in the load carrying capacity of the wall as compared to the cost of construction increase, this torsion effect was significantly lessened in the wall sample where both CFRP wraps and strips were used in conjunction with initial strengthening but causing further increase in construction cost. On the other hand, walls retrofitted and strengthened with only CFRP on critical joints showed significant increase load carrying capacity, energy dissipation and ductility as compared to previously tested samples.

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CHAPTER 1

1 INTRODUCTION

1.1 General

Wood has been used in construction of structures since man learned how to use an axe. After timber the main construction material used was masonry, but people soon found out that unreinforced masonry only provided good vertical load resistance due to its adequate compressive strength [12], but it didn't provide adequate seismic resistance because it didn't have any resistance to the forces such as tensile and flexure forces that are produced by the horizontal motion during an earthquake, so timber was used in construction in conjunction with masonry, that construction type was called "half-timber wall" [37]. These half-timbered constructions were found in the archaeological sites of the ancient Roman Empire so they probably go back to that time or even beyond so these types of constructions have been around for thousands of years but they were really popularized a couple of centuries ago when after the great earthquake of 1755 in Lisbon Portugal, which decimated half of the city. Pombalino buildings, which used the half-timbered walls in its construction as well, were introduced because of their superior seismic characteristics. This was done by introducing a bracing system, this inclusion increased the lateral load carrying capacity of the structure [9]. After their popularization in Portugal they spread out throughout Europe. Different regions gave the walls different names for example it was called "Casa Baraccata" in Italy, In Germany it was called "Fachwerk", in France it was called "Colombages", in UK it was called "half-timber", in Spain it was called "Entramados", in Turkey it was called "Himis and Baghdadi" it also spread as far as USA and South Asia where it is called "Balloon frame and Gingerbread house" and "Dhajji Dewari" respectively [26]. All these regions adopted the timber construction technique and they also brought small changes without invalidating the main idea that this type of construction was used to resist the tension forces which masonry failed to handle hence providing better seismic resistance compared to other construction means available at that time. This good seismic behaviour of this construction type was also validated during some of the recent earthquakes in Greece '03 and Pakistan and Indian occupied Kashmir '05 [30].

Dhajji Dewari, which is timber construction type used in South Asia, is a simple and non-engineered building construction type. It has been in use for 200 plus years in mountainous regions in the Northern areas of Pakistan and Indian occupied Kashmir for housing purposes, in those areas conventional building construction materials aren’t readily available, so people have to make do with what’s available in abundance in that region. it can be easy constructed using locally available materials such as timber, stone and mud and with the help of locally available labour [31]. The word Dhajji Dewari originates from the Persian language meaning “patch quilt wall”. Dhajji Dewai consists of a timber braced frame, the bracing types vary from their usefulness to their aesthetic qualities but the mostly used bracing technique used throughout the region is the cross-bracing system. The spaces left in the timber bracings are usually filled stone and mud mix, crushed brick masonry in combination with mud mortar are also used in some areas. Dhajji dewari is generally used for single story buildings, but several examples of multi-storeyed Dhajji Dewari buildings are found in Northeren Pakistan and Indian Occupied Kashmir [2]. This has been done by using Dhajji Dewari in conjunction with timber laced masonry bearing walls, these walls are called taq. The floors of the Dhajji building are made out combination of timber beams and floor boards, the floor boards go on top the beams and are usually overlain by a layer of clay or mud the walls of the timber framing structure are anchored to the floor with the help of bolts, they are filled after they are erect. A typical Dhajji Dewari house has been shown shown in the Figure 1.1 below.

Figure 1.1 Typical Dhajji Dewari House

The earthquake resistance of this structure comes from the fact that during a seismic activity the infill of the walls is easily cracked therefore a share of energy is absorbed during that action, and the remaining share of the energy is carried over to the frame which handles it through friction in the timber frame and its joints. Dhajji structures has closely spaced bracing and since the timber frame is also elastic in nature it helps prevent large cracks from propagating further forward. As compared to conventional structures having high mass hence dealing with higher inertial forces, the low mass and soft behaviour of the whole Dhajji structure helps mitigate inertial forces and high energy content of a seismic excitation [20]. These are the exact reasons that, during the 2005 earthquake of magnitude 7.5 on the richter scale in Northern Pakistan and India which decimated more than 5000 schools, close to 0.4million houses, 800 health and medical facilities and countless villages, leaving close to 3.5million people displaced and shelter-less resulting in 1% loss of annual GDP of Pakistan [11], it was mostly Dhajji structures due to its superior seismic resistance qualities that survived this destruction and performed better than conventional unreinforced and reinforced structures.

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

1.2 Problem Statement

The focus of the research carried out was to investigate the behaviour of Dhajji panels. That is when the panels were first strengthened by conventional methods, those panels were then tested to failure, after failure of the initial testing investigation was done into the fact that after re-nailing and re-gluing them and bringing them almost brought back to their original form, if they were retrofitted and strengthened by FRP Wraps and Strips or their combination, what will be their lateral load carrying capacity. Other important seismic parameters were also measured and comparison was done between the conventional strengthening and FRP based strengthening and retrofitting.

1.3 Research Objectives

The main objectives of this research are:

- Examine the previously damaged wall panels and Identify the damaged joints that need retrofitting by observing their cracking and failure pattern.

- Study the behavior of Dhajji Dewari wall panel joints retrofitted with CFRP wraps and strips and analyze the structural parameters of the wall under in-plane monotonic loading.
- Suggest the most effective and efficient joint retrofitting technique based on performance and cost comparison.

1.4 Research Significance

A pre-requisite of Dhajji Dewari's good seismic behaviour is the use of good timber and a wood craftsman that knows how to use that good timber to construct a stable and sturdy timber frame. Good quality timber also ensures that the frame isn't affected by rot or decay. FRP has been in use to counter the effects of ageing and adverse conditions and to reduce the vulnerability of old or damaged structures for ages now [13], so to prevent the timber frame joints from being affected by moisture (which causes rot and decay) and heat, preventive measures can be done like using FRP to wrap the critical joints and timber areas. Recently a lot of research has been done on the subject of using FRP in place of most traditional techniques to strengthened and restore timber structures [32]. Along with strengthening, some research has also shown the benefits of FRP in regards to its ability in regions of moisture and against heat or fire resistance, and how people should move towards this instead of conventional means of preservation due to its cost effectiveness [42]. FRP along with being beneficial in the moisture and heat department is also very flexible hence it can also be used in preservation as well as keeping the aesthetic of the original building intact [4]. While there has been research on previous mentioned things, minimal work has been done on the subject of retrofitting of previously damaged Dhajji structures instead of letting entire structures go to waste due to some seismic damage. Previous research and studies done on Dhajji structures showed that there are some critical joints on the timber frame. The critical joints are where the main horizontal and vertical timber posts meet, the joints which are directly in-line with direction of in-plane force are affected the most, while some of the intermediate connections are affected as well. While research has been done on Dhajji walls or structures as a whole, little is known about the in-plane lateral behaviour of the walls or structures if the wall has a door or window opening.

1.5 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

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 [29]. 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 [24]. 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 [17].

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 [40]

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 [18]

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 [17]. 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 [40]

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. [22]. 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.[16]. 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 [36]

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 19^{th} century and the first two decades of the 20^{th} century Casa Baraccata due to manifested applications for the seismic resistance it became the basis of instructions for construction practices in Italy [5]. 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.

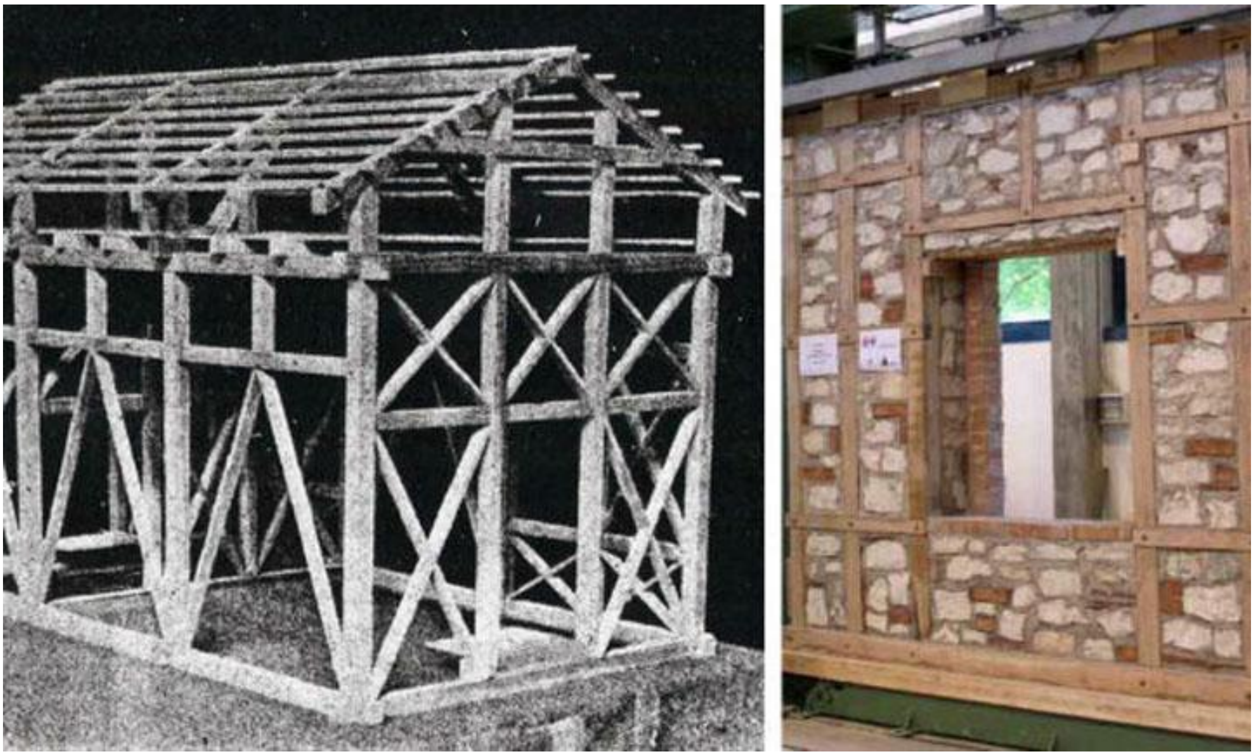

Fig 2.5: Casa Baraccata Buildings [40]

2.1.4 Himis Construction

Himis is another type of commonly used traditional buildings that is found in different parts of the world [21]. 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 [41]. 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 [15].

Fig 2.6: Himis House (Turkey) [16]

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 [16]. 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 [23]. Half-timbered structures consists of timber and masonry materials. Mostly timber wall is used in construction with masonry wall. According to Tampone [34] 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. [35, 39].

Fig 2.7: Bagdadi Construction [16]

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 2.8: Fachwerk House (Germany) [40]

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 [29]. 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 [33] . 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 [25].

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 2.9: A Dhajji House After 2005 Earthquake [40]

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 [15].

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 2.10: An Example of (1999) Turkey Earthquake [16]

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 shows 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 [8].

Fig 2.81: 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 [3].

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 [19].

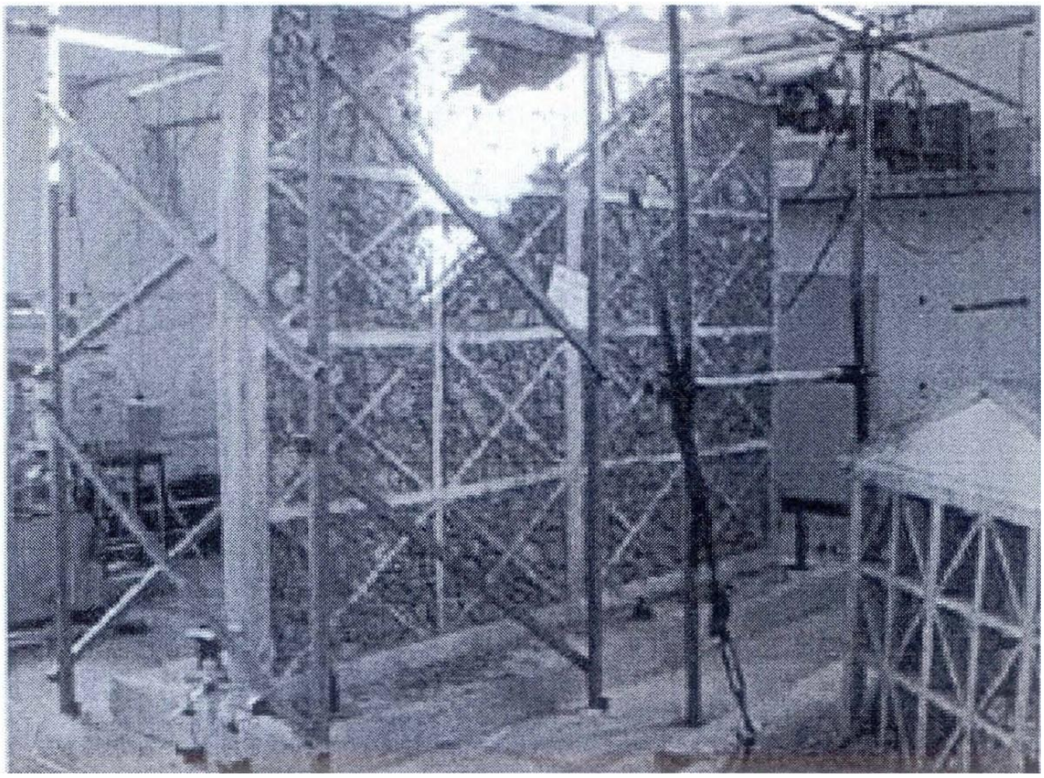

Fig 2.92: Full Scale Dhajji Wall Panel Test at University of Peshawar [19]

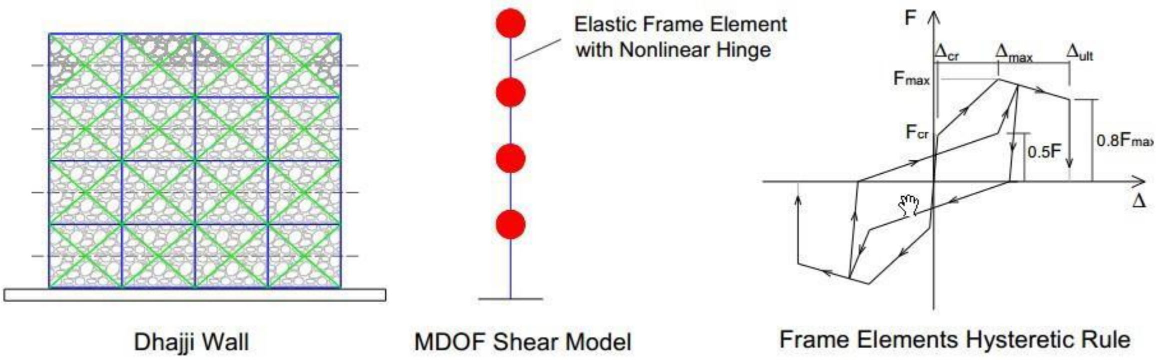

Fig 2.13: Numerical Model of Dhajji Wall [19]

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 [18].

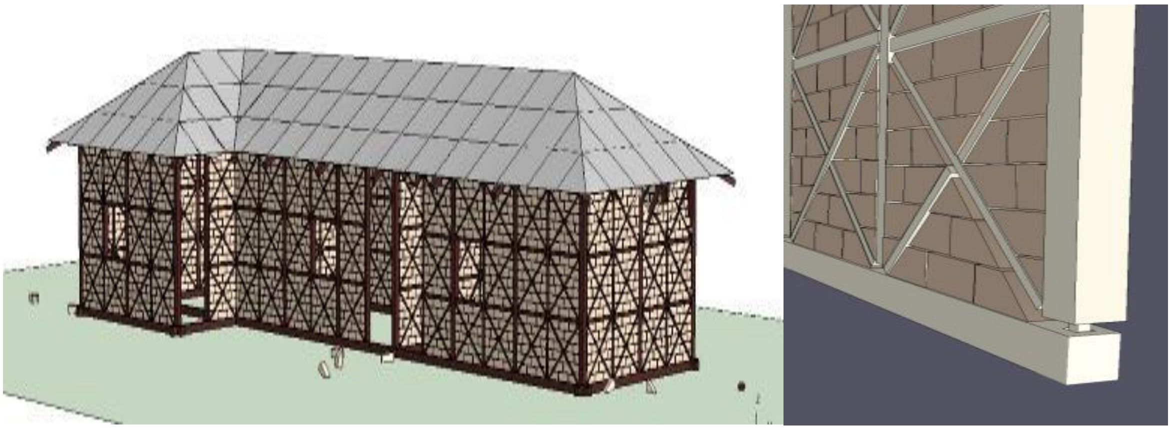

Fig 2.104: 3D House Model in LS-DYNA [18]

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 [10].

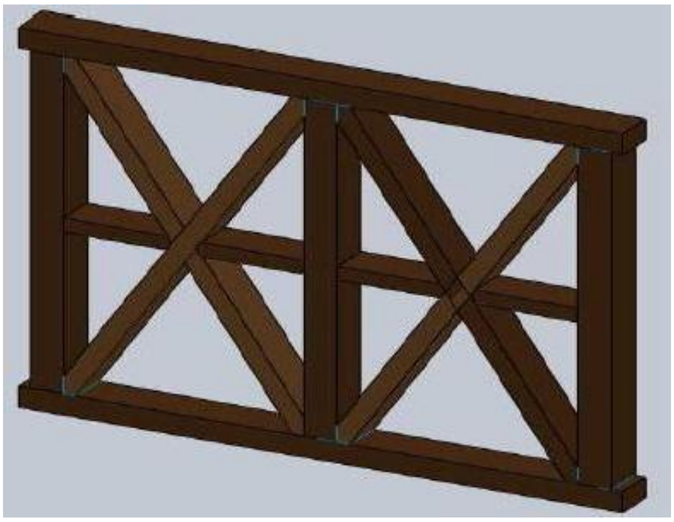

Fig 2.115: Best Bracing Type by Shah [10]

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 [38].

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 [19].

Fig 2.126: Traditional wall tested by Vieux [38]

CHAPTER 3

3 EXPERIMENTAL PROGRAM

This chapter deals with the methodology used to carry out experimental work i.e. the experimental work on the construction of Dhajji walls, materials used for its construction, configuration of the wall samples and the test setup. Dhajii Dewari is constructed integrates several different distinctive features like various different bracing techniques, different size and configuration of walls can be constructed, locally available soil and stones can be used as an infill material and the all this can be done and the structures can be constructed easily using local personnel. Five different Dhajji Dewari walls (DDWs) were constructed. For the 1st phase of testing, the walls were first strengthened using 3 different strengthening techniques, i.e. by using Bamboo culms, Metal Strips and Metal gusset plates (on specific wall panels). After applying the initial strengthening the walls were tested to failure. The failed wall samples were re-nailed and retrofitted with FRP wrap and FRP strips and by a combination of the two for the 2nd phase of testing.

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 essential materials needed in the construction of DDWs were timber, nails and glue. While the material used for infill are stone and mud. Standard test methods were used for the determination of material properties. Dhajji Dewari panels are made using several different timber types, the type of timber used usually depends upon cost and local availability. For the sample panels used in this experimental research was, Partal (Himalayan Spruce) wood, which is locally available and isn’t that expensive. This type of wood is usually used for furniture and doors etc. British Standard Methods (BS 373:1957) were used to determine the mechanical properties of the timber used in the construction of wall samples using small specimens. The properties are shown in Table 1 [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/m^3)
1	33.45	3.45	8.50	460
2	38.95	2.10	7.09	545
3	35.90	2.89	8.10	460
Avg.	35.90	2.82	7.90	490

The stones used in the infill were Marghallah Stones (local term "Water Bound"). Sieve analysis was done to determine the properties & size profile of the stones used. The results are shown in Figure 3.1.

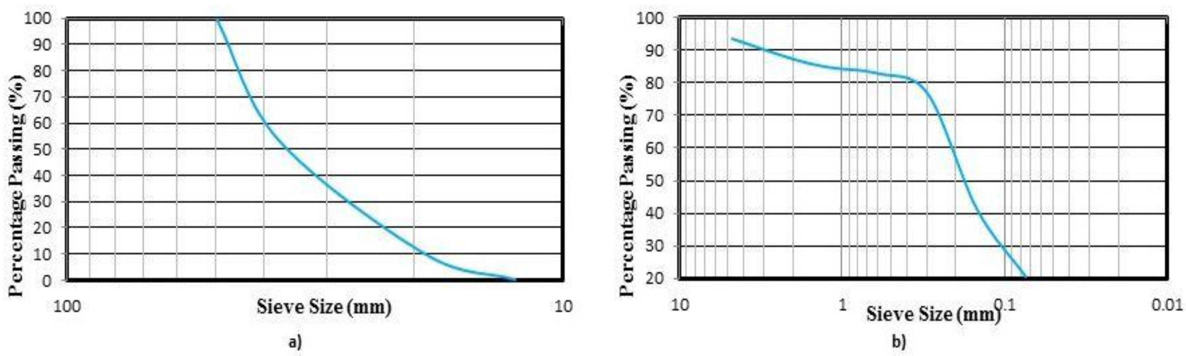

Figure 3.1. PSD of a) Stones and b) Soil used in the experimental research.

The test results indicated that the stones contained 90% particles in the range between 19-50mm. The remaining 10% lie in the 19mm or below size range. The soil used for the infill was taken from a local excavation site. Sieve analysis was done to determine the properties and size profile of the soil used. The test result indicated that 11% of the particles lie in the size range between 0.60-5mm, 63% of the particles lie in the size range between 0.075-0.60mm and the remaining 26% lie in the 0.075mm or below size range. Water to soil ratio used was according to the consistency of mud required as there was no direct method to calculate it.

Fiber Reinforced Polymers (FRP) materials are composites comprising of fibers that provide, when applied around the subject, the required load carrying capacity, stiffness, ductility or other required characteristics. The load is transferred via the polymeric resin in which the FRP is embedded, it also provides the FRP the required protection as well. For this research's retrofitting purposes FRP used was Carbon Reinforced Polymer or CFRP. The CFRP used was of two types, one was fabric type i.e. CFRP Wrap CFW-600, Woven Carbon Fiber Fabric and the other type used in the experimental program was CFRP Strips, Heavy-duty Carbon Fiber Reinforced Polymer. CFRP Wraps and Strips and their properties are shown in the Figure 3.2 and Table 2 [7] [6] below.

a) b)

Table 3.2. Properties of FRP.

CFRP Wrap CFW-600	CFRP Strips
Description	
Unidirectional woven carbon fiber fabric.	Heavy-duty carbon fiber reinforced polymer

Technical Properties (Dry state)	
• Tensile Strength = 4900 N/mm (nominal) • Mean Tensile Strength at break = ~5500 N/mm • Elongation at break = 1.5% (nominal) • Density = 1.79 g/cm Elastic Modulus (Tensile) = 230,000 N/mm	• Tensile Strength = 2800 N/mm • Mean Tensile Strength at break = 3050 N/mm • Elongation at break = 1.7% approximately • Density = 1.5 g/cm Elastic Modulus (mean value) = 165,000 N/mm

The reinforcement or retrofitting of timber with FRP is done using adhesive bonding. Different types of adhesives are available for example: polyesters, polyurethanes, phenolics, and epoxies. Taking into consideration the previous research work done on this subject and expect opinion, for this research the adhesive selected for application of FRP was Epoxy resin. And the method used for epoxy application was wet lay-up method, whereby the epoxy is first applied to the timber substrate and then the FRP is impregnated with adhesive and then it is applied to the timber under adequate pressure, either by hand or by mechanical means.

Since, there are two types of CFRPs used in this experimental research (Wraps and Strips), two different types of epoxies are used for the different type of FRP material. For CFRP Wraps the epoxy used was Chemdur-300, this specific epoxy was selected due to its compatibility with fiber based FRP and with wooden surfaces and also due to its resin-based nature for easy application. On the hand, for CFRP Strips the epoxy used was Chemdur-30, this epoxy was selected for its significantly more strength and compatibility with CFRP Strips as well as with wooden surfaces. The properties of the adhesives used are mentioned in the Table 3 below. Fiber Reinforced Polymer. CFRP Wraps and Strips and their properties are shown in the Figure 3.2

Table 3.3. Properties of Adhesives.

Chemdur-300	Chemdur-30
Description	
Solvent free, thixotropic, 2 component Epoxy based resin	Solvent free, thixotropic, epoxy based two component adhesive mortar
Physical Properties	

• Comp A colour = White resin • Comp B colour = Grey resin • Pot Life = 90mins at 15C • = 30mins at 35C • Open time = 35mins at 35C • Packaging = 5/10kg Units	• Comp A colour = White paste • Comp B colour = Dark Grey paste • Comp A+B mixed = Light grey paste • Pot Life = 120mins at 15C • = 40mins at 35C • Open time = 30mins at 35C • Packaging = 6/15kg Units
Technical Properties	
• Mix Ratio = 4:1 by weight (Comp A: Comp B) • Viscosity = Pasty, non-flowing • Density = 1.31 kg/lit (Comp A+B mixed) Adhesive Tensile strength (after 7 day curing period) = 30N/mm	• Mix Ratio = 3:1 by weight (Comp A: Comp B) • Consistency = Creamy paste/mortar • Density = 1.77 kg/lit (Comp A+B mixed) • Adhesive strength = 4N/mm Adhesive Shear strength = 15N/mm

3.4 Test Panel Properties

Dhajji Dewari are usually made using many different types of bracing arrangements but for this specific research purpose the bracing technique used was the cross-bracing technique, that was done because cross bracing is the most commonly used technique in practice. DDW was constructed using the cross-bracing technique. The wall was constructed on half scale that is 1500x1200mm and the panel consisted of three type of main timber members, the members had dimensions of 50x50, 25x50 and 12.5x50, all the lengths are in mm. The main vertical and horizontal posts of the whole frame are of 50x50mm dimension, and the intermediate horizontal and cross bracing posts were of 25x50mm and 12.5x50mm dimensions. Half scaled dimensions of a typical Dhajji wall as shown in Figure 3.3

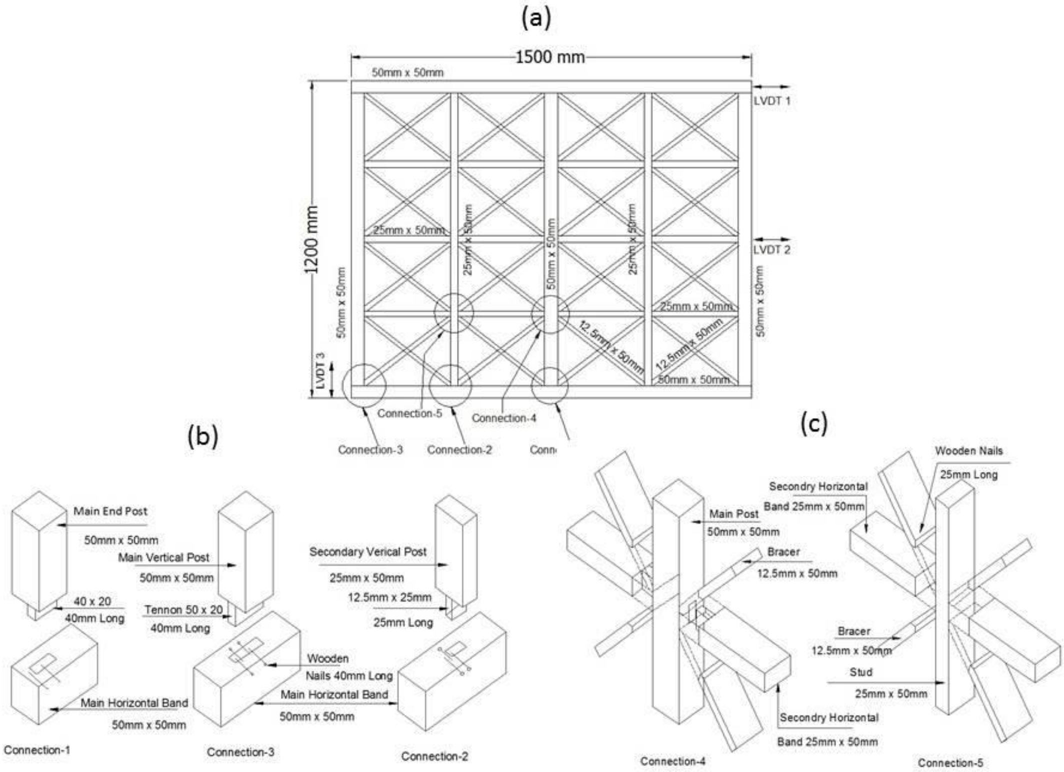

Figure 3.3. Detail of Members and LVDT.

There were 5 different types of connections types used in the construction process. For connecting the main vertical member posts to the horizontal member posts by using connection 1-3 types. While the intermediate member posts were connected to the main posts by using connection 4 and 5 type. The connections were held together by using wooden and steel nails having yield strength of upto 250MPa. The roof load was mimicked by applying vertical load of 1kN. The vertical load was applied on the sample by using aggregate filled in containers, the containers were placed in the specially designed circular iron moulds of 18" diameter. The iron moulds were fixed of the first, middle and last main posts.

To meet the field conditions, the walls were bolted to the floor, this was done to the maintain vertical standing of the wall, to measuring storey drift and also to restrain horizontal movement. The walls were filled with the stone and mud infill on the floor (except the bottom 3 panels where the bolts were to be inserted) and left to dry. After drying the walls were fixed vertically to the floor using the aforementioned bolts.

3.4.1 Panel Description

As mentioned before, a total of five DDWs were constructed for the experimental program, of the constructed walls, two walls were used as reference, that is, two were standard walls. Both walls which were used as reference were similar albeit having one small difference, the difference being that one wall was a standard wall with cross bracing all over without having any opening and the other one wall had cross bracing everywhere except where there was an opening, the opening in the 2nd wall replicated a door or a window. The summary and details of all the individual wall panels for both 1st phase (Pre-FRP retrofit strengthening) and 2nd phase (Post FRP retrofit strengthening) in given in Table 4 below.

Table 3.4. Summary of all test wall samples.

Wall Nomenclature.	Wall Type.	1st Phase testing: Pre FRP-Retrofit Strengthening Technique Used.	2nd phase testing: Post FRP-Retrofit Strengthening Technique Used.
DDW1	Fully cross braced wall.	No strengthening technique used.	Damaged 1st and 2nd critical horizontal and vertical joints retrofitted with a Single layer of FRP wrap.
DDW2	Cross braced wall with an opening for door.	No strengthening technique used.	Damaged 1st, 2nd and 3rd critical horizontal and vertical joints retrofitted with Double layer of FRP wraps.
DDW3	Fully cross braced wall.	Cross bamboo bracing used along the compression and tension struts.	Previous bamboo strengthening removed & damaged 1st, 2nd and 3rd critical horizontal and vertical joints along with middle and left-side intermediate joints

			retrofitted with Double layer of FRP wraps.
DDW4	Fully cross braced wall.	1st and 3rd critical horizontal and vertical joint strengthened with metal strips.	Previous iron strip strengthening kept and Double layer FRP wraps applied on damaged 2nd critical joint and on the middle intermediate joints and right-side intermediate joints.
DDW5	Fully cross braced wall.	1st, 2nd and 3rd critical horizontal and vertical joints strengthened with metal gusset plates.	Previous metal gusset plate strengthening kept and Double FRP wraps applied on right, middle and left side intermediate joints.

In the 1st phase of testing the two reference walls were tested without any conventional reinforcement technique used while the other three walls were strengthened using three different strengthening techniques. The panels were tested twice, in the 1st phase with the aforementioned strengthening techniques and later re-nailed and retrofitted with FRP and tested again for the 2nd phase of their testing.

3.4.2 1st Phase testing: Pre FRP-Retrofit

DDW1 was a standard wall and used as a reference and no strengthening technique was applied as shown in Figure 3.4(a). DDW2 was also a standard wall but it had an opening replicating a door or a window, it also had no strengthening technique used, detail is shown in Figure 3.4(b). These two walls were used to observe the behaviour of standard cross braced walls with stone and mud infill. DDW3 was strengthened using bamboo trunks/culms on the cross periphery of the wall, along the tension and compression struts. This was done to observe if it enhances the lateral load carrying capacity of the wall sample. The bamboo culms were nailed on the on the cross periphery of the walls as shown in Figure 3.4(c). DDW4 was strengthened at the critical joints, that is joints of the main horizontal and vertical posts of the wall with metal strips. The strips were bolted on. The critical joints were identified by the tests performed on the previous three wall samples. The shape of the strips was L and T-shaped depending on the location and shape of the joints, as shown in Figure 3.4(d). The thickness of the strip was kept at 2mm. The length and width of the strip was selected according to the timber characteristics, that the length was kept according to the spacing of bolts and the strength of timber while the width was 50mm i.e. as the width of the panel's post dimensions. DDW5 was strengthened at the critical joints with metal gusset plates. The joints strengthened in this case were all of the first 3 vertical and horizontal post connections. The strips were bolted on. Like the previous sample tested the shape of the strip was selected according to the location of the joint, i.e. L and triangular shaped plates. The thickness of the strip was kept at 2mm. The length and width of the strips was kept according to the properties of the sample timber properties as shown in Figure 3.4(e).

Figure 3.4. (a) DDW1 (b) DDW2 (c) DDW3 (d) DDW4 (e) DDW5.

3.4.3 1st Phase testing: Pre FRP-Retrofit

DDW1 was a standard wall and used as a reference and no strengthening technique was applied. After initial testing to failure it was re-nailed and was retrofitted by applying Single layer FRP wraps on the damaged 2 critical joints and retested. DDW2 was also a standard wall but it had an opening replicating a door or a window, it also had no strengthening technique used. This wall was tested to failure and later retrofitted by applying Double layer FRP wrapping on joint 1 and Single layer FRP wrapping on the other 2 damaged critical joints, joints 2 and joint 3, and retested. Details are shown in Figure 3.5(a). DDW3 was strengthened using bamboo culms nailed on the cross periphery of the wall, along the tension and compression struts. After initial testing to failure, Double layer FRP wrapping was applied on all the 3 vertical and horizontal critical joints and also on the intermediate damaged joints, the later testing was done without the initial bamboo strengthening, details are as shown in Figure 3.5(b). DDW4 was strengthened at the critical joints with L and T-Shaped Strips. After initial testing to failure the wall was re-nailed and retrofitted with Double layer FRP wraps but this wall was retested with the initial strengthening technique applied as well. Details are shown in Figure 3.5(c). DDW5 was strengthened at the critical joints with metal gusset plates. After initial testing to failure the wall was re-nailed and retrofitted with a combination of FRP wraps and FRP Strip. The FRP Wraps were applied on the intermediate damaged joints and the FRP strip was applied on the cross periphery of the wall panel on both sides as shown in Figure 3.5(d).

Figure 3.5. (a) DDW2 (b) DDW3 (c) DDW4 (d) DDW5.

3.5 Test Setup

The walls were bolted to the floor. A Hydraulic Jack of 500kN capacity was used to apply the in-plane lateral load on left top edge of the wall sample. The load was measured using a load cell and by also looking at the hydraulic jack dial while the displacements of the test were measured by placing linear variable displacement transducers (LVDTs) at strategic and important positions. 3 LVDTs were used during testing, 2 were placed opposite of the hydraulic jack's position, on at the top and one near the bottom while the third one was used vertically to measure base lift and rocking.

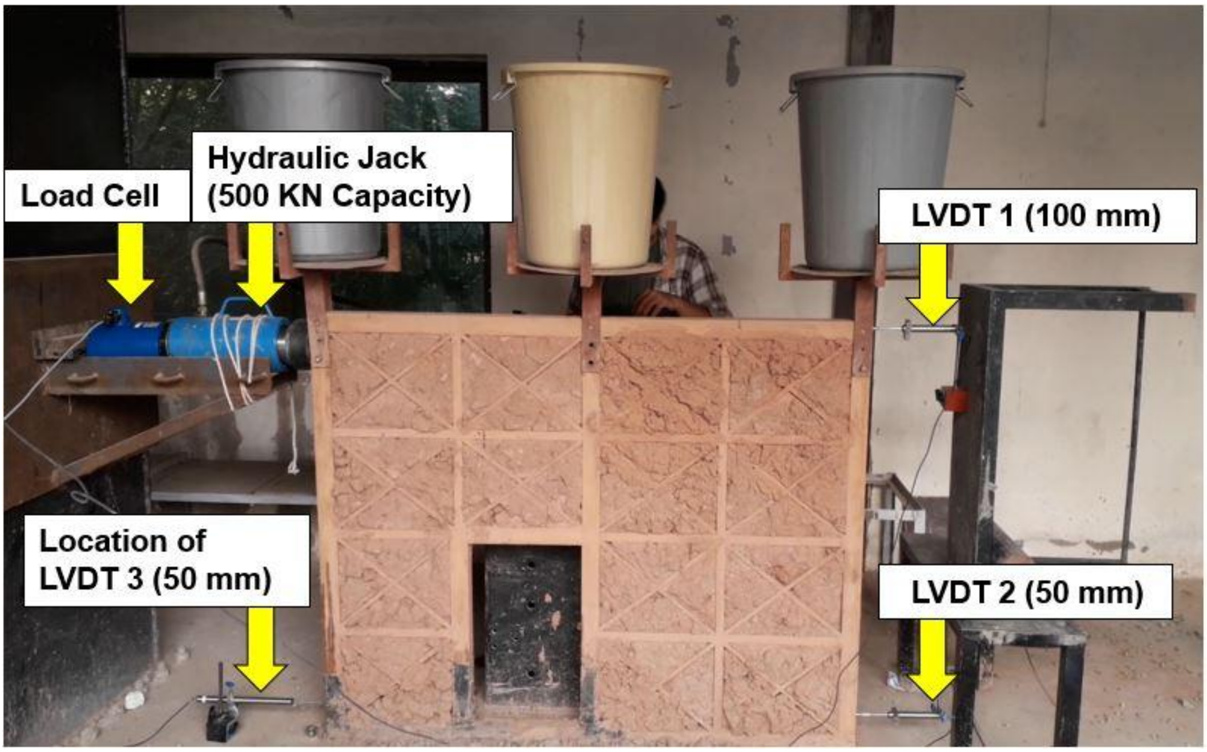

Figure 3. 6. Test Setup.

CHAPTER 4

4 RESULTS AND DISCUSSION

The In-plane monotonic testing done on the test sample walls tell us about the mechanical properties of the test samples. The mechanical properties about the wall are in the form of load and displacement sustained by the wall samples, the load displacement curves in return give us further information i.e. in the form of stress-strain, yield/ultimate displacement, Stiffness of the wall, Energy dissipation and Ductility of the wall. These results are further discussed below individually.

4.1 Load Displacement Behavior

A load–displacement curve measures the extrinsic properties of the test sample, e.g. the sample wall. The main parameters assessed through a load-displacement curve are stiffness, fatigue, and ultimate load and displacement. The stress–strain curve is similar but it measures the intrinsic properties of the test sample that it because it is normalized for the sample dimensions. These are the elastic or Young's modulus (E), the yield stress and strain, the ultimate stress and strain, and the energies to yield and failure. The load displacement curves for pre and post retrofit are presented in Figure 4.1. They represent the lateral force/load applied at the top of the sample wall vs the horizontal displacement of the walls measured by LVDTs, the absolute values are shown in Figure 4.2.

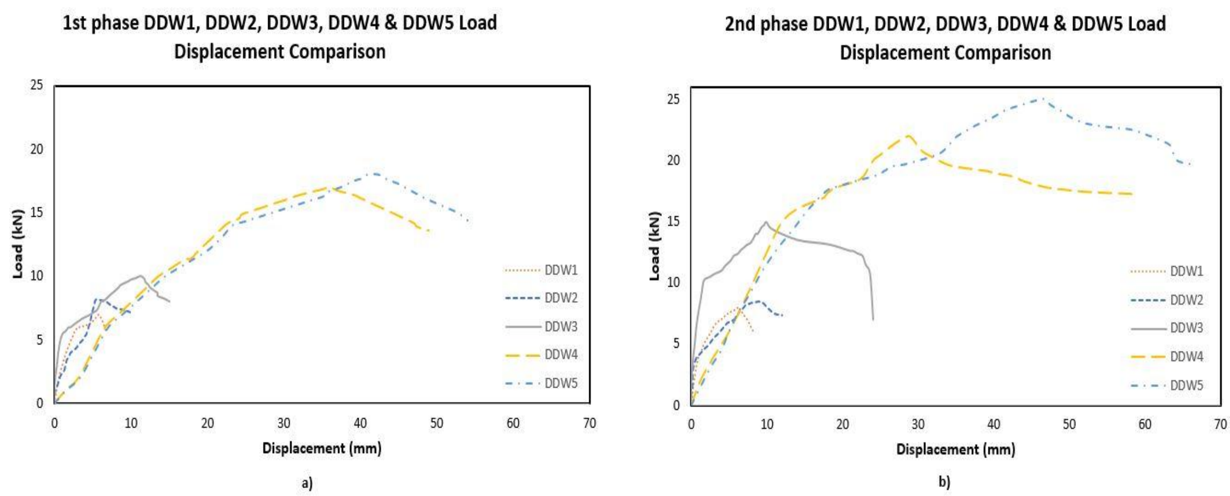

Figure 4.1. Load Displacement curves of all panels a) 1st phase b) 2nd phase.

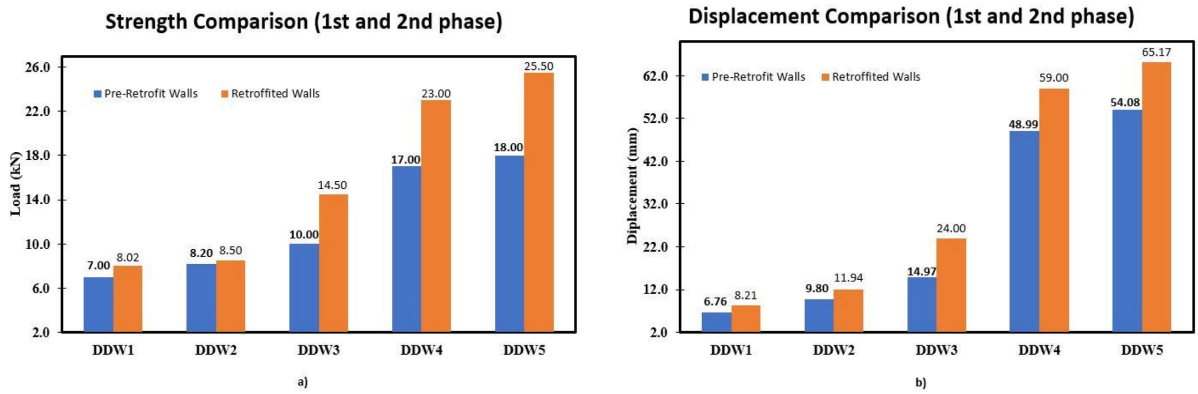

Figure 4.2. a) Strength b) Displacement absolute values comparison of all panels after tests.

For the 1st phase test wall samples from the load displacement curve it can be clearly seen that by strengthening the critical joints by Bamboo, Iron strips and Gusset plates improve the wall's load and displacement sustaining capabilities as they should. In DDW1, 2, and 3 the failure was due to wood rupture and tearing of main horizontal and vertical joints also known as the critical joints. While in the case of DDW4, 5 the failure is due to rocking and intermediate joint failure.

For the 2nd phase test wall samples from the load displacement curve it can be observed that even if the wall samples were damaged before (not completely destroyed), if they were re-nailed and properly glued back together with a heavy dose of epoxy and brought back to their almost new condition and were also strengthened at the critical joints and other damaged joints, which were found by analyzing the previous wall test results, with FRP wraps and strips they perform significantly better than wall samples which were strengthened with conventional strengthening techniques, showing better load carrying and displacement enduring capacities.

4.2 Energy Dissipation

The energy dissipated by the sample walls is an intrinsic property of the walls so it is also calculated from the load-displacement or stress-strain curves. Energy dissipation of a structure depends upon several factors, some of the factors involved are (1) the friction along joints, (2) crack propagation, (3) formation of new cracks, (4) crushing of wood, (5) base-lift and rocking. The failure mode of the sample walls also affects the energy dissipated. Higher the value of energy dissipated represent ductile failure, on the other hand higher values of energy dissipated by the specimens can also be due to the strengthening techniques used and their effectiveness. Figure 4.3 shows the energy dissipation value of all samples in both test phases.

$$Area\ Under\ Curve = (\frac{a+b}{2}) * (d-c) \tag{1}$$

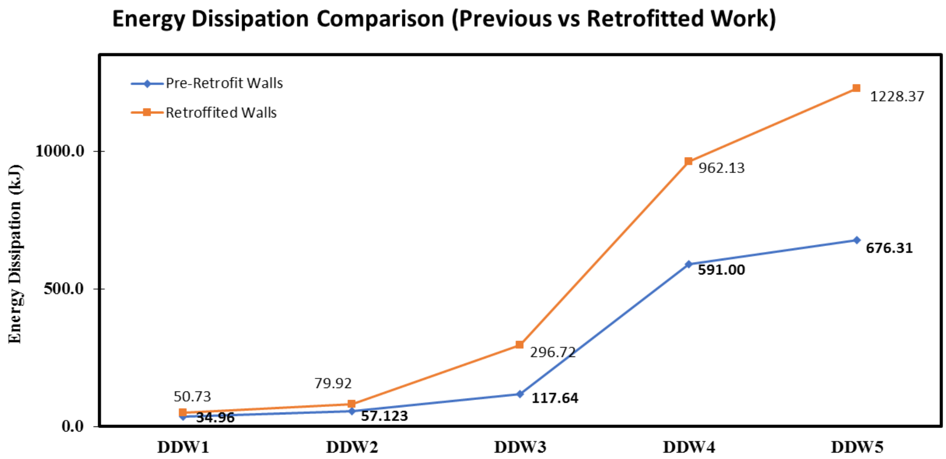

Figure 4.3. Energy Dissipation of all 1st and 2nd phase test samples

4.3 Ductility and Response Factor

One of the main factors taken into consideration while designing a structure in seismically active zones are Ductility and Response factor. Ductility of a structure is the property of a structure which lets the structure deform and bend beyond its yield strength without toppling and collapsing the whole structure. The relationship used to calculate was given by Muguruma [27] given in Equation 2. The response factor represents the seismic capability of a structure. Seismic forces are dealt with more effectively in ductile structures. The response factor of the test samples in both cases was calculated using the relationship given by Paulay and Priestley [28] given in Equation 3. Value of both of the factors are shown in Figure 4.4. Higher values of Ductility and Response factor indicated better ductile behaviour for that wall specimen.

$$\mu_d = \frac{\Delta u}{\Delta y} \tag{2}$$

$$R_f = \sqrt{(2\mu_d - 1)} \tag{3}$$

Where, μ_d displacement ductility, Δu is the ultimate displacement and Δy is the yield displacement. And R_f is the response factor of the structure.

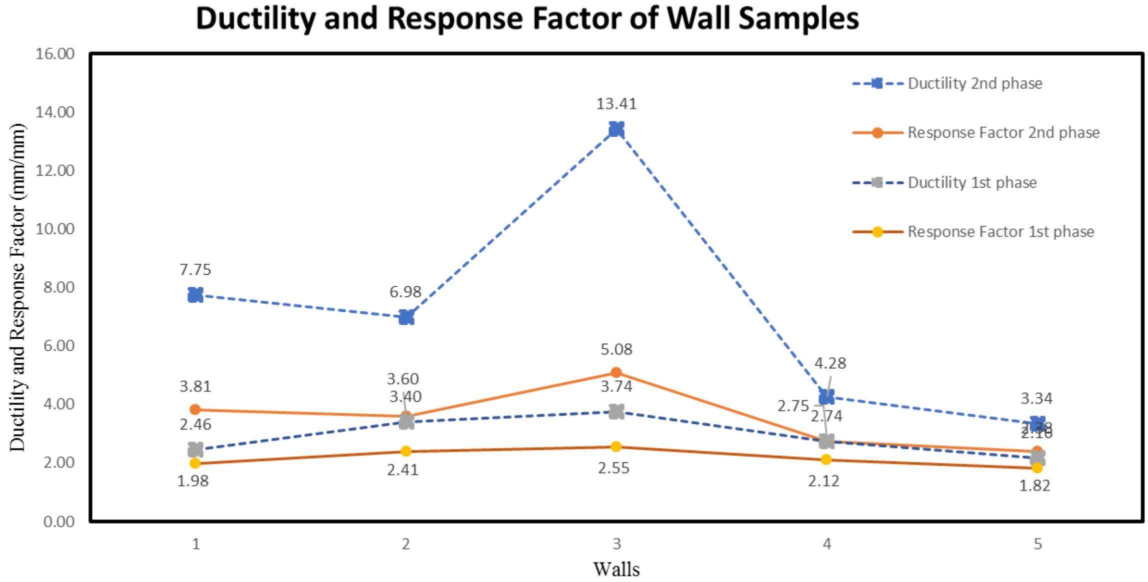

Figure 4.4. Ductility and Response Factor of all 1st and 2nd phase test samples

In 1st phase test wall samples, the wall with the opening the 1st 3 walls i.e. DDW2 and DDW3 represent similar and the best ductile behavior. Since both DDW2 was a standard wall with an opening, the better ductile behavior can be due to fact that in DDW1 the load distribution stopped at joint 2 due to rupture and failure of joint 1 and 2 respectively, while in DDW2 further load distribution and crack propagation occurred, i.e. till main joint 3 and intermediate joints. In the case of DDW3 bamboos were on the cross periphery of walls thus adding further elasticity to the structure. From further wall tests it can be deduced that if crack propagate further along wall sample instead of concentrating on 1 or 2 joints, the better was the ductile behavior of the wall.

In 2nd phase test wall samples, the wall with Double layer FRP wrapping on the 3 main horizontal and vertical critical joints represent the best ductile behavior i.e. DDW3. In the case of DDW3 double layer FRP was used and the second half of walls intermediate joints were left without any FRP wrapping thus allowing better crack propogation. And the results also show that if FRP wrapping and FRP strip (in the case of DDW5) show significant reduction in the ductility of the sample walls. That reduction in the ductility of DDW4 and DDW5 as compared can also be due to the fact that all the joints were over-strengthened and over-strengthening can lead to brittle type failure in case of Dhajji Dewari structures.

Response Factor showed similar trends that is DDW1 to DDW3 showed better behavior while DDW4 and DDW5 showed brittle behavior due to the use of both strengthening technique hence resisting the propagation of cracks and making the joints rigid.

4.4 Stiffness Degradation

In Dhajji Dewari structures the damage accumulated at the joints is the stiffness degradation. This damage to the joints is measured using empirical formulas and it is related to the bending and pull out of the nails which hold the joints together and with the deformation of the joints. Stiffness degradation represents the rate of stiffness reduction after yielding. Stiffness degradation ratio (Ck) is the rate of stiffness reduction beyond yield. Ck is the ratio of secant modulus at specified displacement (K) to the secant modulus at yield (Ko) as shown in Equation 4 [14]. Lower value of stiffness degradation indicates better seismic capability of the wall sample. Stiffness degradation percentages for all the specimen is shown in Figure 4.5. The overall stiffness values are shown in Table 5.

$$C_k = \frac{K_p}{K_o} \tag{4}$$

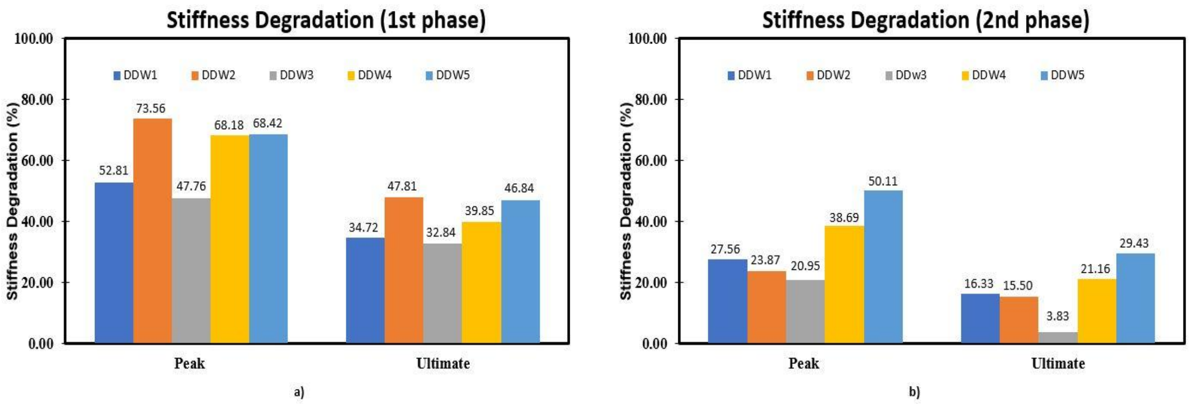

Figure 4.5. Stiffness Degradation Ratio of all panels after testing.

Table 4.1. Stiffness Values of all specimens

Stiffness	DDW1		DDW2		DDW3		DDW4		DDW5	
Effective Stiffness	2.49	3.92	2.69	3.54	4.75	**5.23**	0.84	1.19	0.68	1.13
Stiffness at	2.05	3.92	1.71	3.54	1.34	**5.05**	0.66	1.84	0.57	0.93

Yield										
Stiffness at Peak Load	1.08	1.08	**1.26**	0.85	0.64	1.10	0.45	0.71	0.39	0.47
Stiffness at Ultimate Load	0.71	0.64	**0.82**	0.55	0.44	0.20	0.26	0.39	0.27	0.27
Stiffness Degradation	0.35	0 .16	0.48	0.15	0.33	**0.04**	0.40	0.21	0.47	0.29

As was mentioned before, lower the value of the Stiffness degradation, better the seismic capability of the wall. Even though the stiffness degradation value for the 2nd phase test DDW4, DDW5 have lower stiffness degradation value than their 1st phase test counterparts, their ultimate values are still higher than that of DDW1 and DDW2 and significantly higher than that of DDW3 further showing that FRP reinforcing with conventional reinforcing techniques should be avoided.

4.5 Overall Comparison

Percentage increase or decrease in all the above calculated parameters have been complied in Figure 4.6 to get a better picture about which test wall sample improved as compared to other.

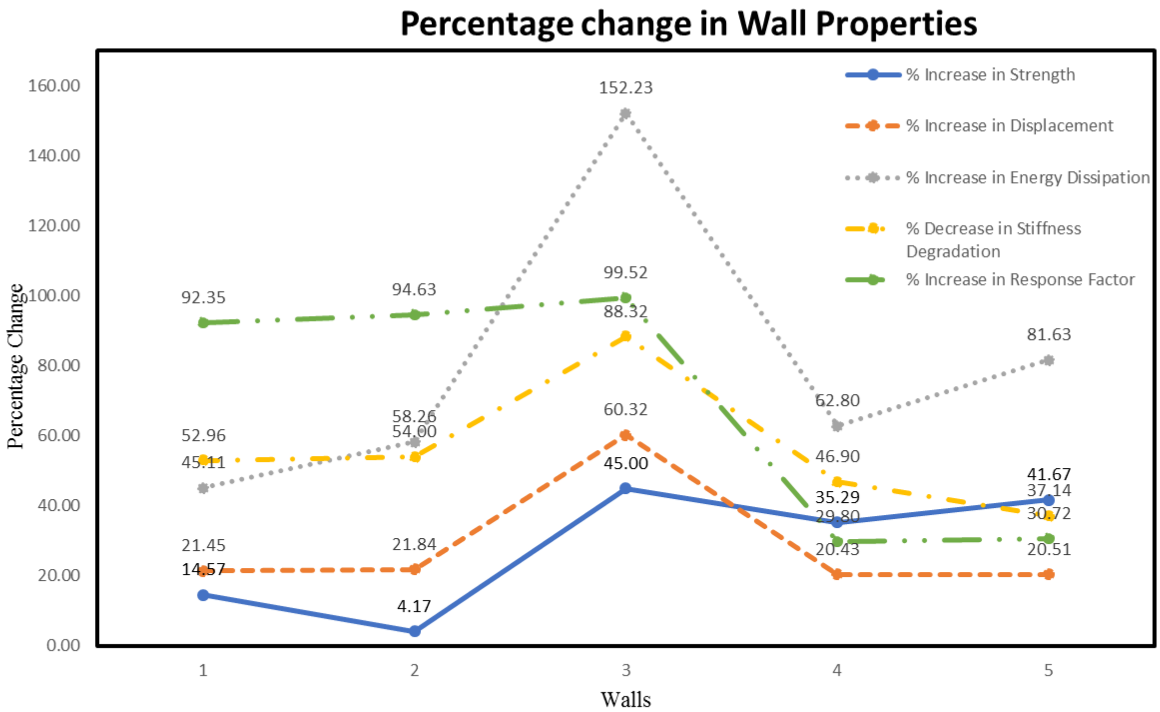

Figure 4.6. Percentage change in Wall Properties after both 1st and 2nd phase testing.

Since strength and displacement are our two most important and relevant properties in terms of a structure's capability, it was important to do their comparison with the percentage increase in price for the construction and repair work of the test wall samples.

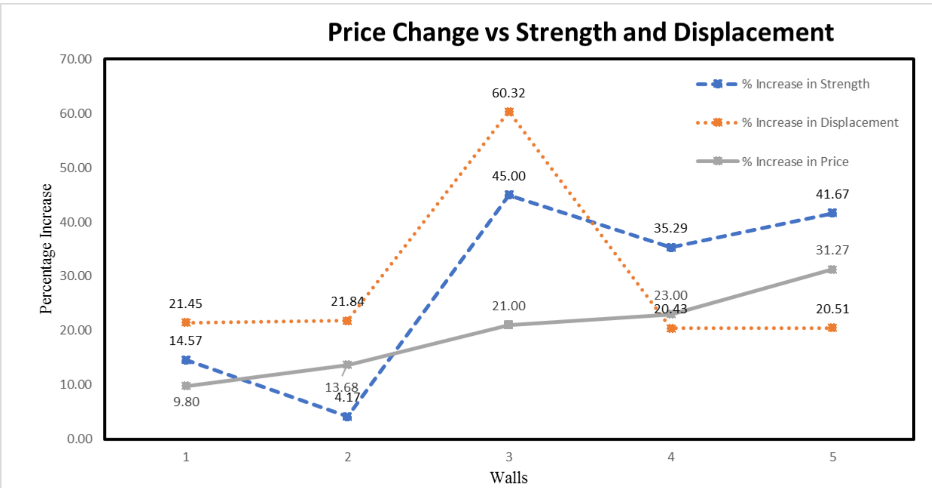

Figure 4.7. Price vs Strength and Displacement

4.6 Behavior of Walls at Failure

Failure patterns of all 5 walls of both 1st and 2nd phase test wall samples are shown below.

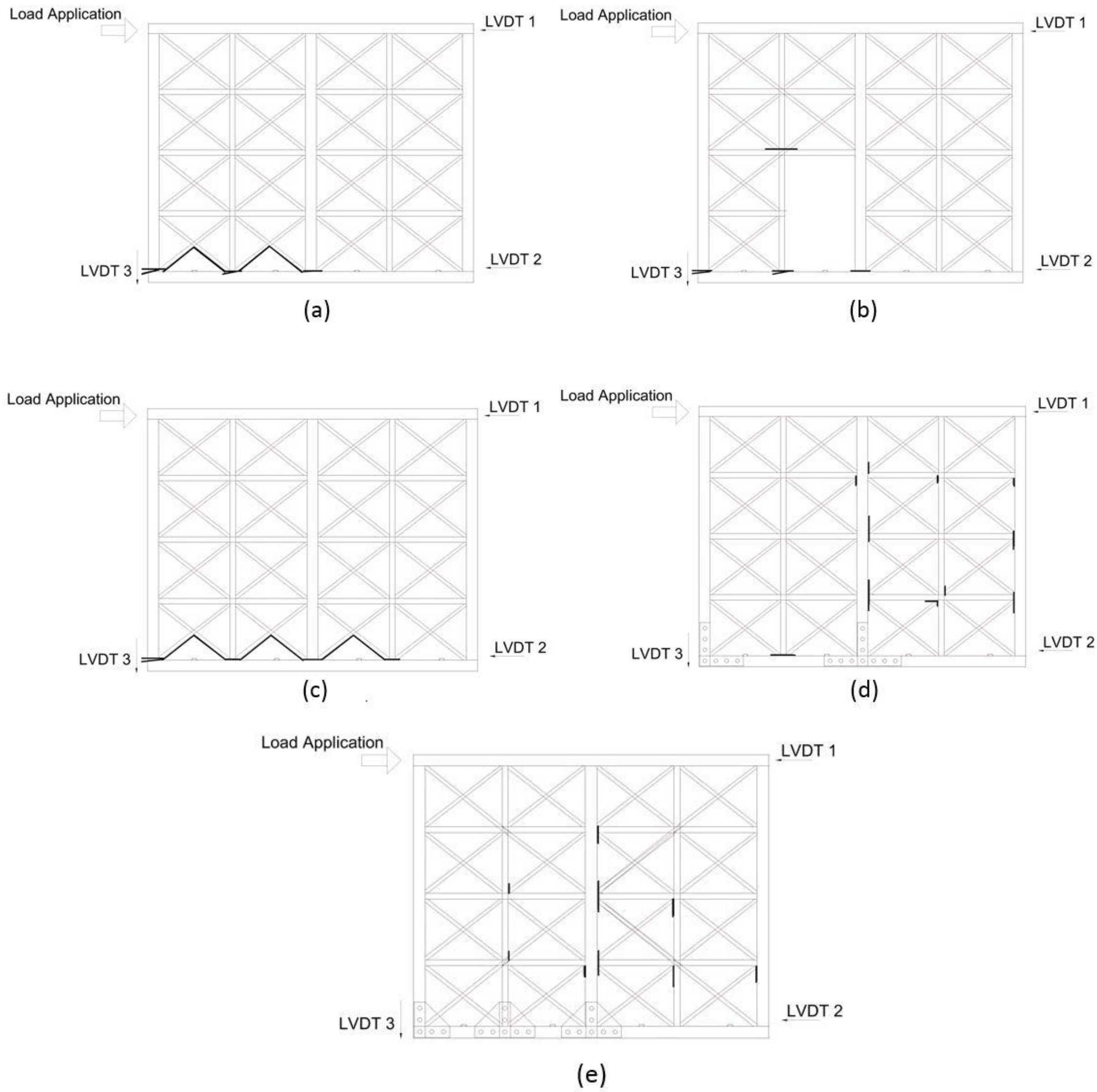

Figure 4.8. Line Schematic of all samples' failure pattern (1st phase)

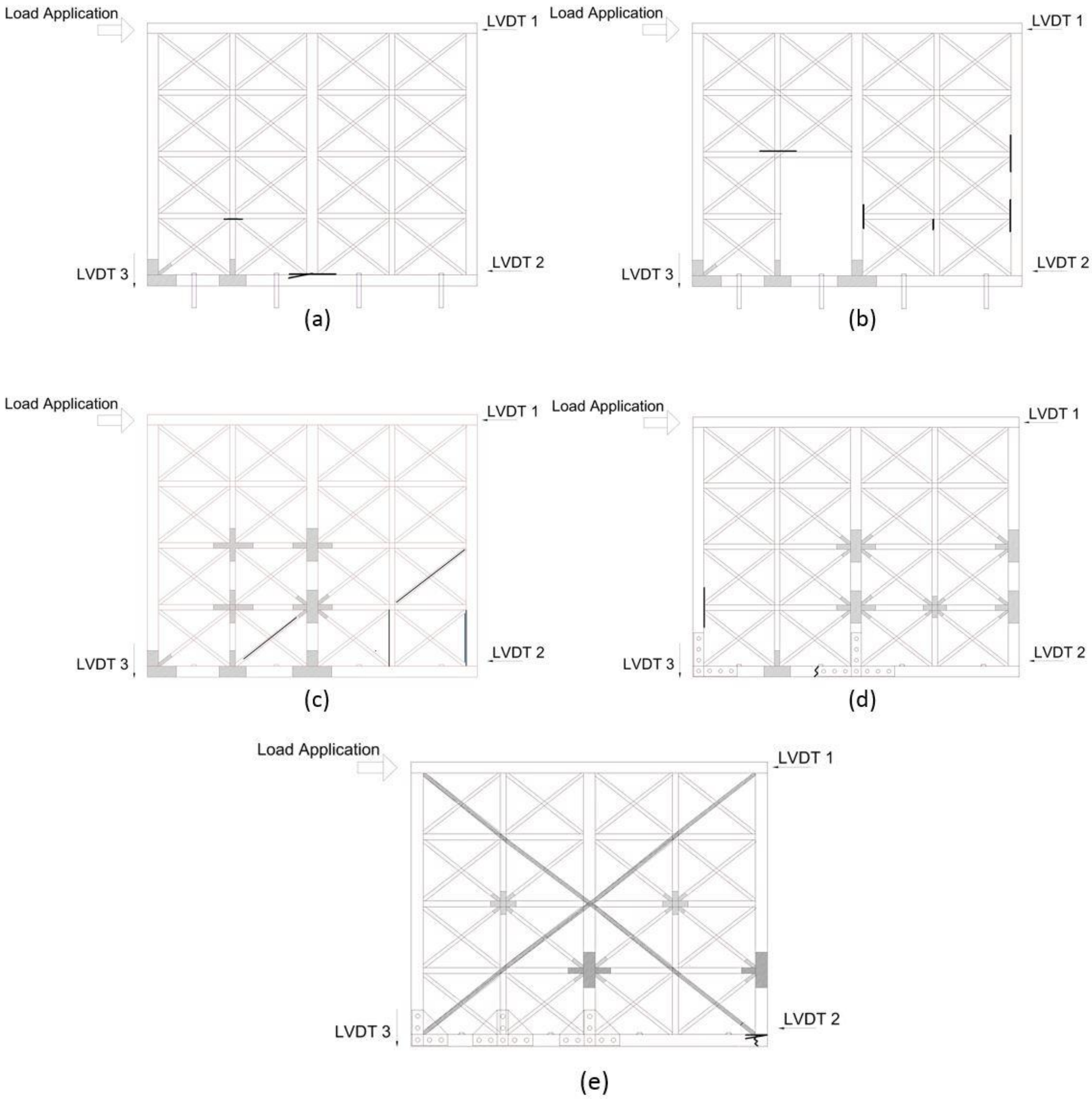

Figure 4.9. Line Schematic of all samples' failure pattern (2^{nd} phase)

The failure pattern of 1st phase DDW1 shows that the failure of the wall occurred due to pull-out failure in the main joints 1 and 2 without any intermediate joint damage, while in the case of DDW2 with opening as discussed before the opening helped propagate the cracks and that crack propagation advanced from the joint 1 and 2 pull-out to joint 3 as well with little damage to the joint 3 intermediate joint as well. In the case of DDW3 the inclusion of bamboos not only provided better crack propagation but the failure still occurred due to the main joint rupture instead of pull-out. In the case of DDW4 and DDW5 by providing rigid strengthening on the main joints the cracks propagated from the lower portion to intermediate joints.

Like discussed before by applying a wrapping of FRP on the damaged joints it not improved the key seismic parameters of wall samples but it also removed the scenarios where the critical joints of the wall samples pulled out or ruptured. In 2nd phase DDW1 the cracks propagated till the 3rd main joint before failure. In DDW2 the cracks propagated intermediate joints, same was the case in DDW3. DDW4 and DDW5 started showing signs of over-strengthening by exhibiting bending in the Z-direction hence showing signs of torsional failure by, torsional forces were somewhat mitigated in DDW5 by the inclusion of CFRP strips on the cross periphery of the wall sample. All the actual damaged wall panels are shown in the following figures.

Pre-Retrofit:

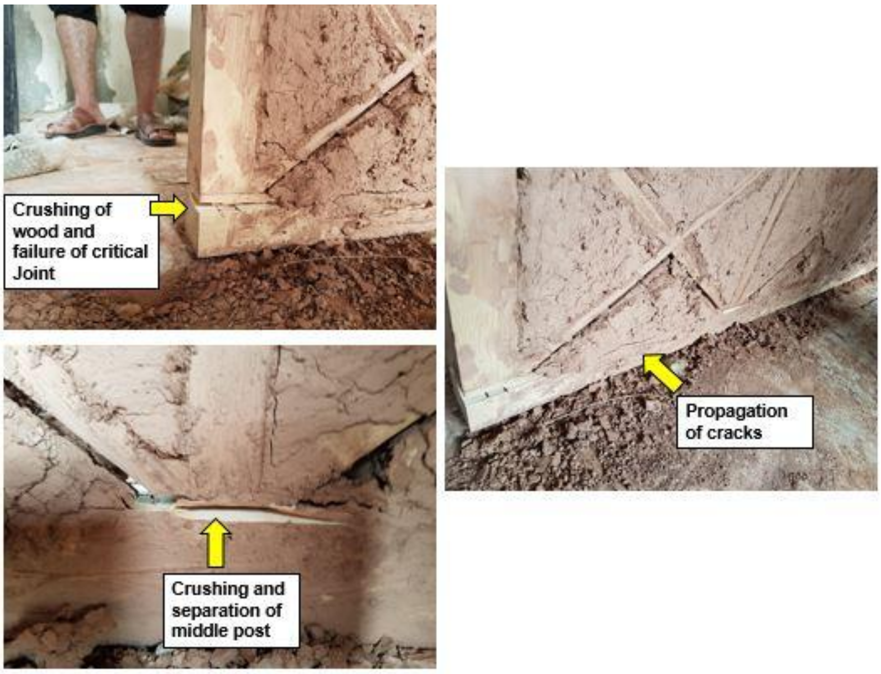

Figure 4.10. DDW1 Pre-Retrofit

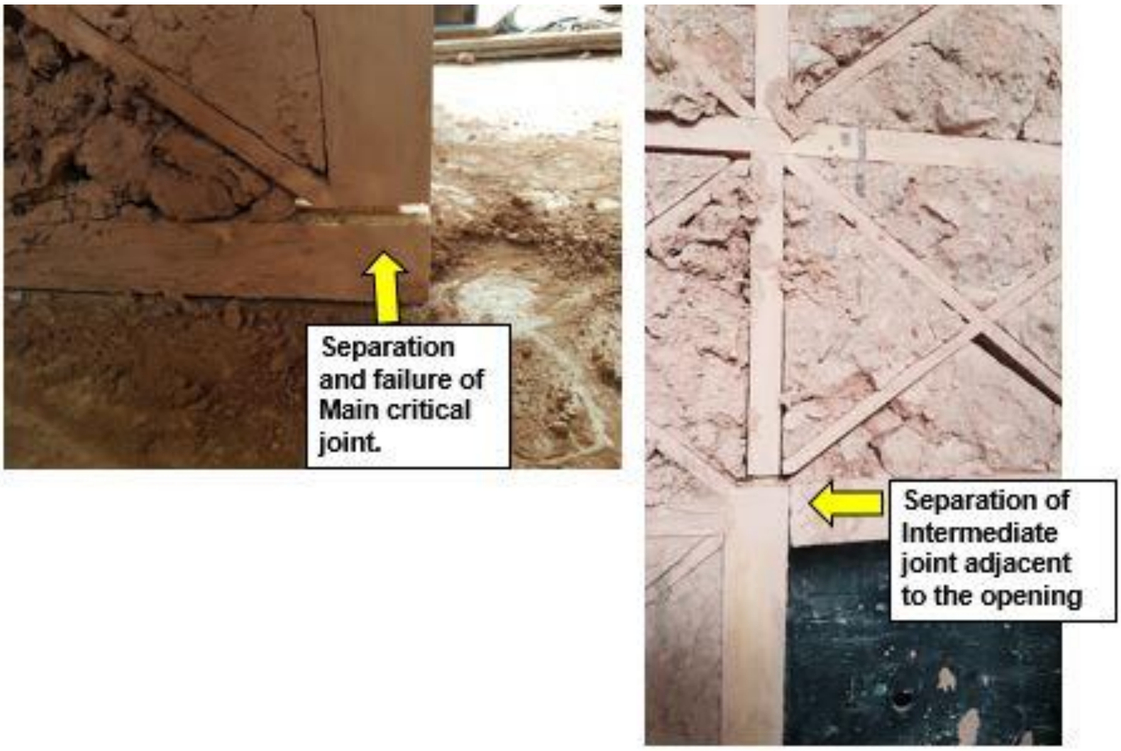

Figure 4.11. DDW2 Pre-Retrofit

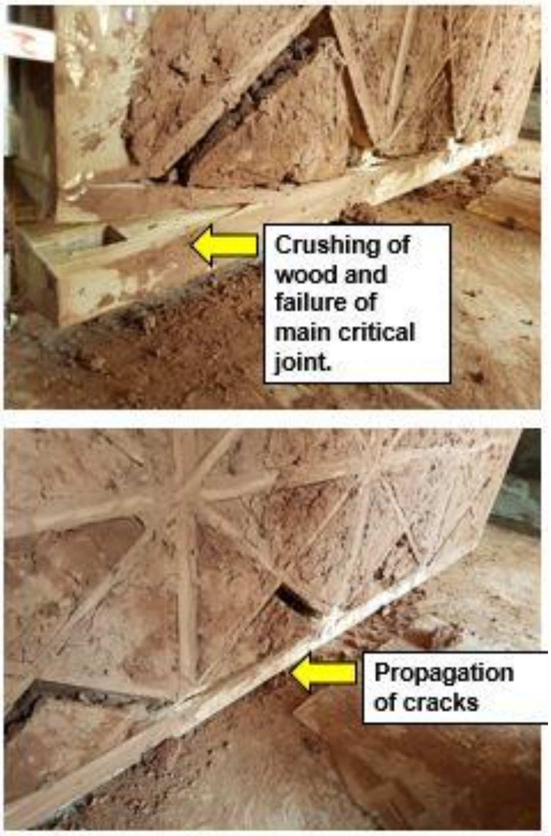

Figure 4.12. DDW3 Pre-Retrofit

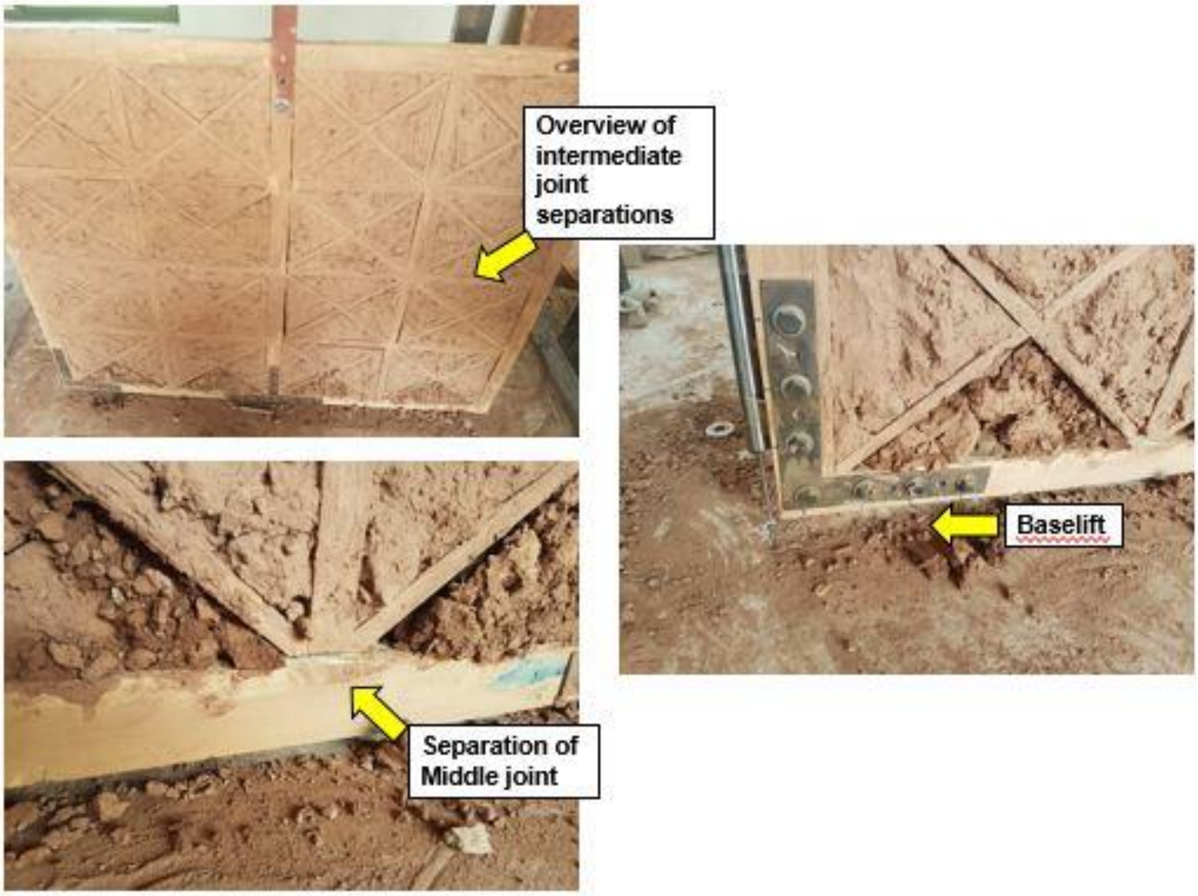

Figure 4.13. DDW4 Pre-Retrofit

Figure 4.14. DDW5 Pre-Retrofit

Post-Retrofit Panels:

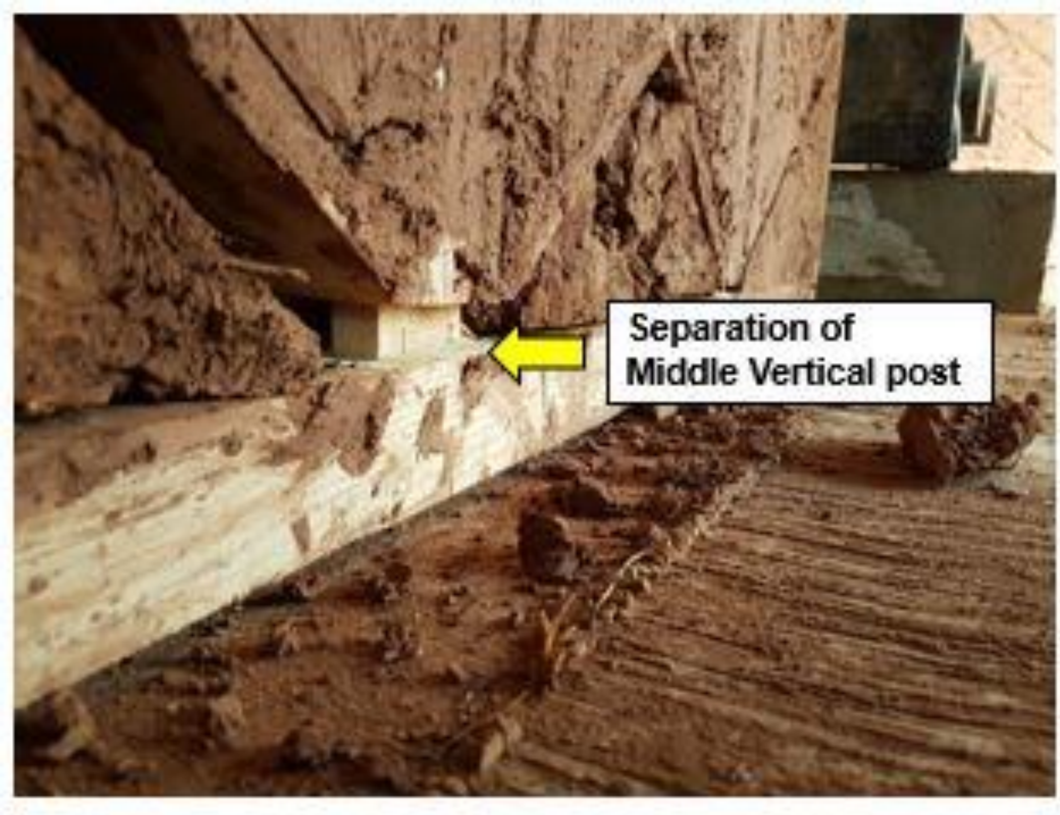

Figure 4.15. DDW1 Post-Retrofit

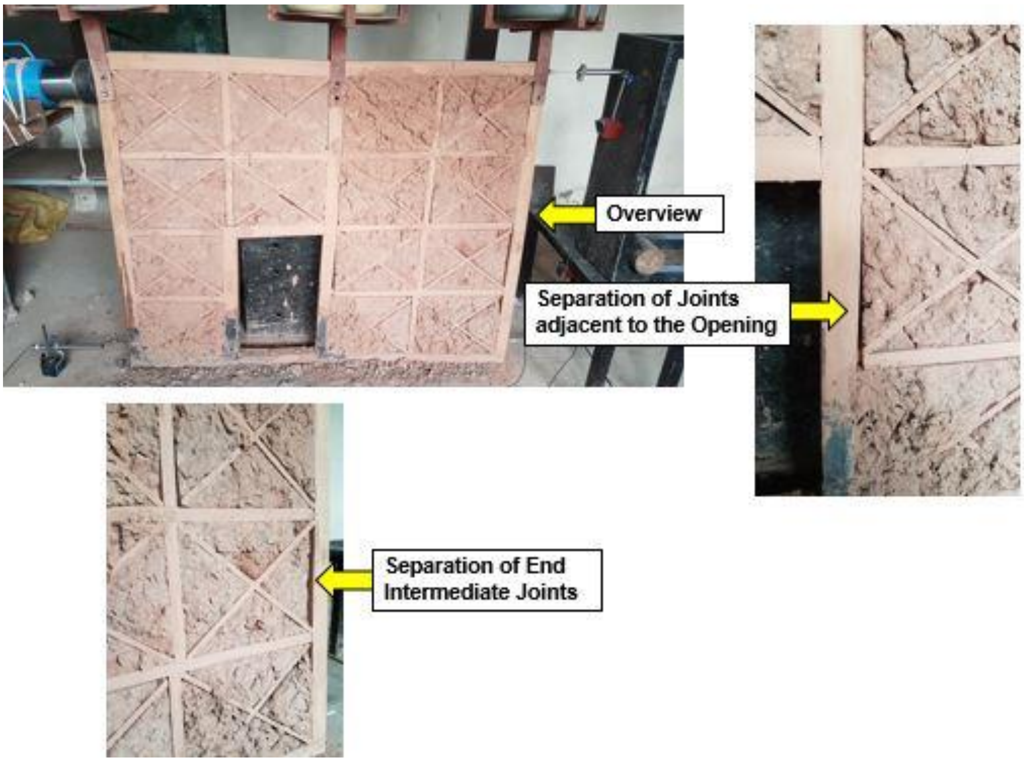

Figure 4.16. DDW2 Post-Retrofit

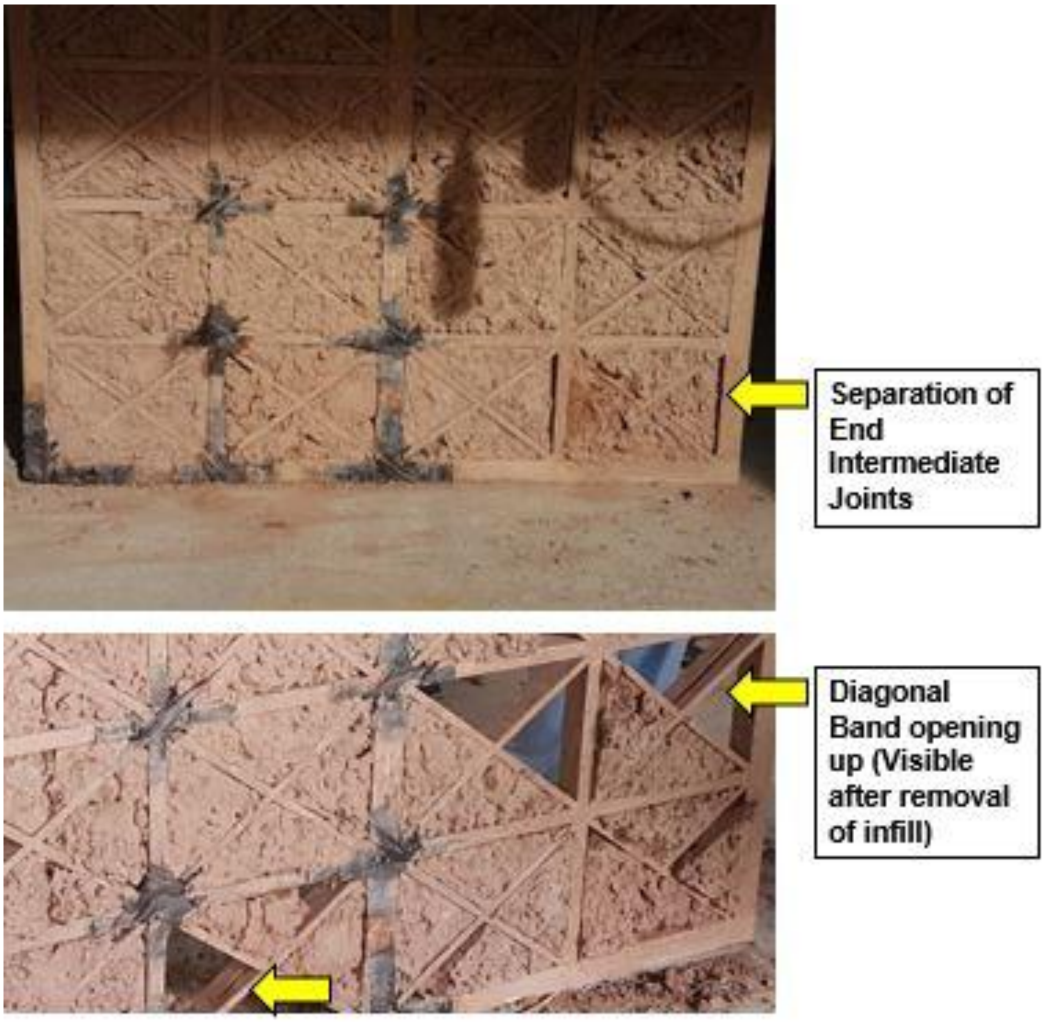

Figure 4.17. DDW3 Post-Retrofit

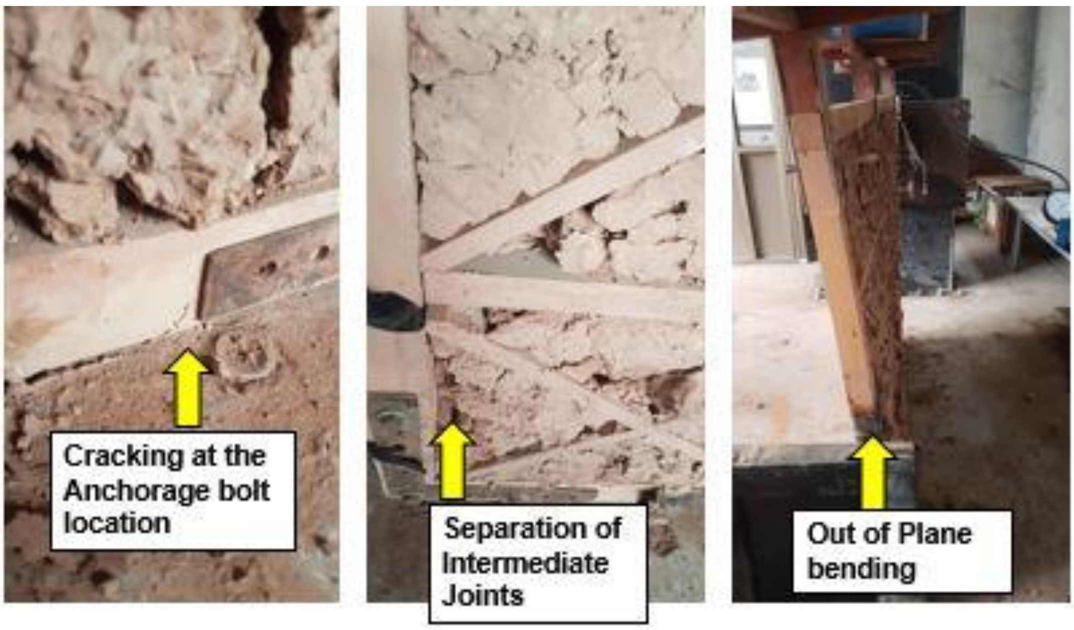

Figure 4.18. DDW4 Post-Retrofit

Figure 4.19. DDW5 Post-Retrofit

CFRP Wrap Area:

Table 4.2: CFRP Area

WALLS	**WALL POST RETROFIT (ft^2)**
DDW1	**1.8**
DDW2	**2.8**
DDW3	**6.5**
DDW4	**6.1**
DDW5	**4.1**

Base-Lift:

Table 4.3: Base-Lift

Walls	**WALL PRE RETROFIT**	**WALL POST RETROFIT**
DDW1	3.21	2.22
DDW2	2.73	2.01
DDW3	6.72	6.23
DDW4	11.95	10.25
DDW5	12.12	11.14

CHAPTER 5

5 CONCLUSIONS

The work done in this paper intended to provide useful information on the behavior of traditional timber wall Dhajji Dewari under lateral loads after strengthening and retrofitting of critical joints. Experimental analysis carried out of the DDW samples validated its structural and seismic capabilities after the application of conventional strengthening and CFRP strengthening techniques. After the 1st phase testing both the load and displacement carrying capacity of the wall samples increased significantly as compared to the reference wall samples along with other parameters like ductility, stiffness, energy dissipation and response factor. Of the three strengthening techniques used, DDW3 which was strengthened with bamboos on its cross periphery, showed better results in the seismic parameters. It can be concluded that that was due to the nature of the bamboo culms attached to the Dhajji frame providing it with extra elasticity to cater for the forces. In the 2nd phase of testing all the retrofitted wall samples performed better than their 1st phase counterparts, with the exception of DDW1 which performed on par with the 1st phase test sample in the load carrying aspect of the wall, that was most probably due to the application of only single layer of CFRP on the ruptured joints as compared to multiple layers in other test samples. DDW3 which was retrofitted only by multiple layers on main as well as intermediate joints showed better results in the seismic parameters as well as showing a 45% and 60% increase in load and displacement carrying capacity as compared to the 1st phase wall sample. It was noted that if the walls are over-retrofitted and strengthened as it seemed was the case in DDW4 and DDW5 which had both conventional rigid iron and gusset plate reinforcements and CFRP strengthening, there was no room for the cracks to propagate so the wall started to bend and torsional forces started to emerge. That is why even though the ductility, response factor and energy dissipation values increase, the percentage increase isn't significant enough when compared to the increase in cost of construction/retrofitting of the walls. So, it can be concluded that CFRP provides the retrofitted walls samples with the extra elasticity and ductility it requires and by providing adequate strengthening (like in case of DDW3) and not over strengthening the wall (like in DDW4 and DDW5's case) it allows the cracks to propagate to an allowable limit and also allows the joints to come into effect and absorb the forces through friction and in-plan cracking of the infill, hence de-tuning the building from energy rich content of seismic excitations.

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