ANKARA YILDIRIM BEYAZIT UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

OUT-OF- PLANE BEHAVIOUR OF MASONRY WALL STRENGTHENED WITH CARBON FIBER REINFORCED POLYMER (CFRP)

M.Sc. Thesis by

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May, 2023

ANKARA

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A Thesis Submitted to

The Graduate School of Natural and Applied Sciences of

Ankara Yıldırım Beyazıt University

In Partial Fulfillment of the Requirements for the Degree of Master of Science

in Interdisciplinary Master Program of Post-Disaster and Post-War Reconstruction and Rehabilitation

by

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May, 2023

ANKARA

M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"OUT-OF- PLANE BEHAVIOUR OF MASONRY WALL STRENGTHENED WITH CARBON FIBER REINFORCED POLYMER (CFRP)"** completed by **MUHAMMET MUDAR YASIN** under the supervision of **ASSIST. PROF. DR. MAHMUT CEM YILMAZ** and co-supervision of **ASSIST. PROF.DR. ÖMER MERCİMEK,** we certify that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ACKNOWLEDGMENTS

Firstly, I would like to express my sincere gratitude to my supervisor, **Assist.Prof.Dr. Mahmut Cem Yılmaz** for his tremendous support and motivation during my study. His immense knowledge and precious recommendations constituted the milestones of this study. His guidance assisted me all the time during my research and while writing this thesis.

I would also like to thank my co-advisor **Assist.Prof.Dr. Ömer Mercimek**, who helped me with the laboratory tests, and his kindly recommendations.

2023, 30 May **Muhammet Mudar YASIN**

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ABSTRACT

The masonry walls are widely used in all over the world, especially in historical buildings. Strengthening of the masonry walls is one of the important issues to investigate for the researchers. There are some methods to improve the masonry walls' in-plane or out-of-plane resistance capacities against static or dynamic loading. Fiber Reinforced Polymers (FRP) application is one of these methods used to increase the bearing capacity of masonry walls. The aim of this study was to examine the effectiveness of Carbon Fiber Reinforced Polymer (CFRP) for strengthening the masonry walls. In the study, the out-of-plane failure mechanism of masonry walls, which is frequently encountered during earthquakes, was discussed. Ten 100 mm x 410 mm x 1200 mm masonry walls were fabricated for experimental study. Solid brick that has the dimensions of 50 mm x 100 mm x 200 mm was used in the production of the masonry walls. For mortar, repair mortar was used for ease of production. Nine of the test specimens were strengthened with carbon fiber reinforced polymer (CFRP). Application form of the CFRP (as strip or full layer) and number of layers were adopted as test parameters. Masonry wall specimens were tested under the effect of bending, applying three-point loading. During the experiments the measurements of load and displacement were taken. The behavior of the masonry walls were assessed in terms of ultimate load, the displacement corresponding to the ultimate load, stiffness, and energy dissipation capacity. According to the results obtained, it is concluded that the strengthened masonry walls with CFRP are quite successful against the out-of-plane collapse mechanism. It is thought that the findings of this study can serve as a guide for engineers and architects that have an interest in strengthening masonry walls.

Keywords: masonry, out-of-plane, CFRP, reinforcement, historical buildings

KARBON FİBER POLİMERLERLE (CFRP) GÜÇLENDİRİLEN YIĞMA DUVARLARIN DÜZLEM DIŞI DAVRANIŞI

ÖZ

Yığma duvarlar tüm dünyada, özellikle tarihi yapılarda yaygın olarak kullanılmaktadır. Yığma duvarların güçlendirilmesi bilim insanlarınca araştırılan önemli konulardan birisidir. Yığma duvarların statik veya dinamik yüklemelere karşı düzlem içi veya düzlem dışı dayanım kapasitelerini iyileştirmeye yönelik bazı yöntemler bulunmaktadır. Elyaf Takviyeli Polimerler (FRP) uygulaması, yığma duvarların taşıma gücünü artırmak için kullanılan bu yöntemlerden birisidir. Bu çalışmanın amacı, yığma duvarların güçlendirilmesinde Karbon Elyaf Takviyeli Polimerin (CFRP) etkinliğini incelemektir. Çalışmada, depremlerde sıklıkla karşılaşılan yığma duvarların düzlem dışı göçme mekanizması ele alınmıştır. Deneysel çalışma için 10 adet 100 mm x 410 mm x 1200 mm yığma duvar imal edilmiştir. Yığma duvarların üretiminde 50 mm x 100 mm x 200 mm ebatlarında dolu tuğlalar kullanılmıştır. Harç olarak ise imalat kolaylığı açısından tamir harcı kullanılmıştır. Deney elemanlarından dokuzu karbon fiber takviyeli polimer (CFRP) ile güçlendirilmiştir. CFRP'nin uygulama şekli (şerit veya tam katman olarak) ve katman sayısı deney parametresi olarak seçilmiştir. Yığma duvar numuneleri, üç noktalı yükleme uygulanarak eğilme etkisi altında test edilmiştir. Deneyler sırasında yük ve yer değiştirme ölçümleri alınmıştır. Yığma duvarların davranışı, nihai yük, nihai yüke karşılık gelen yer değiştirme, rijitlik ve enerji sönümleme kapasitesi bakımından değerlendirilmiştir. Elde edilen sonuçlara göre, CFRP ile güçlendirilmiş yığma duvarların düzlem dışı göçme mekanizmasına karşı oldukça başarılı oldukları görülmüştür. Bu çalışmadan elde edilen bulguların, yığma duvarların güçlendirilmesi ile ilgilenen mühendis ve mimarlara yol gösterici olabileceği düşünülmektedir.

Anahtar Kelimeler: Yığma duvar, düzlem dışı davranış, CFRP, güçlendirme

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CHAPTER 1 INTRODUCTION

This chapter is a discussion about the research objectives and goals, as well as providing a clear explanation of the research problem and its limitations.

1.1 Motivation

The use of masonry in construction has many advantages, including its strength, durability, and aesthetic appeal (Augenti et al., 2013). However, masonry structures can be susceptible to damage from natural disasters, especially earthquakes (Kanit et al., 2005)In seismic areas, masonry walls may experience significant cracking or even collapse, leading to devastating consequences for both people and property. (Lagomarsino et al., 2019).

To address these challenges, researchers and engineers have been exploring various approaches to reinforce and strengthen masonry structures, with the aim of improving their performance and increasing their resistance to damage from earthquakes. One approach that has shown potentials is the application of carbon fibre reinforced polymer (CFRP) strips. CFRP strips are lightweight, high-strength materials that can be easily applied to masonry walls to enhance their resistance to external forces, including those caused by earthquakes (Kanit et al., 2005).

The motivation for using CFRP strips in the reinforcement of walls of masonry is clear. By reinforcing masonry walls with CFRP strips, it is feasible to significantly strengthen their load-carrying ability, resistance to bending and shear forces, and overall structural integrity, all of which are critical factors in seismic areas (Shafaei et al., 2017). This can help reduce collapse or collapse risks, and protect people and property in the event of earthquakes and other types of disasters.

It is necessary to reduce post-disasters reconstruction and rehabilitation strategies by enhancing the pre-disasters situation for all kind of buildings as well as the other facilities.

Another motivation for using CFRP strips in masonry wall reinforcement is their versatility and ease of use. Unlike many other reinforcement techniques, such as external steel bracing or grouted reinforcing bars, CFRP strips can be applied quickly and easily, often with minimal disruption to building occupants or operations (Li et al., 2019).This makes them an ideal solution for retrofitting existing masonry structures in seismic areas, which may not have been originally designed with reinforcement in mind.

In addition to their practical advantages, CFRP strips also offer significant potential benefits from a sustainability perspective. Unlike traditional reinforcement materials, such as steel or concrete, CFRP strips are lightweight and require minimal energy to manufacture, transport, and install (Obaidat et al., 2019). This can help to reduce the carbon footprint of construction projects and promote more environmentally friendly building practices.

Overall, CFRP strips have the potential to revolutionize the way we approach masonry construction and help to protect lives and property in the face of seismic hazards. With continued research and development, it is likely that we will see even more innovative applications of CFRP strips in the years to come, further advancing the field of masonry engineering and construction in seismic areas. Earthquakes are a major threat to masonry walls (Melinda & Juliafad, 2022). These natural disasters can cause significant damage to buildings, particularly those constructed with older or weaker materials. The shaking caused by earthquakes can cause masonry walls to crack, crumble, or collapse entirely, putting those inside the building at risk of injury or even death. This is particularly concerning in areas with a high risk of earthquakes, where buildings must be designed and constructed to withstand the forces of these natural disasters.

It is necessary to reduce post-disasters reconstruction and rehabilitation strategies by enhancing the pre-disasters situation for all kind of buildings especially the historical building with saving their historical identity as well as the other facilities.

1.2 Statement of Problem

Masonry is rarely used in western countries because the usual building type in those countries is usually reinforced concrete or steel structures (Santis, 2022). However, brick, adobe and stone masonry walls are commonly used in many historical buildings. Earthquakes cause collapse and loss of life in masonry buildings as well as strengthened concrete and hardened structures. That is the reason why, it is extremely necessary to comprehend the earthquake behaviour of masonry structures and to make such structures safe against earthquakes. Walls of masonry are widely used in building construction due to their durability and strength. However, they are highly susceptible to damage from natural hazards such as earthquakes, hurricanes, and floods. Earthquakes are one of the most common natural hazards that can cause significant damage to masonry walls. During an earthquake, the ground can move violently, causing the walls to shift and crack. This can result in structural damage to the building, such as collapsed walls or ceilings. The severity of the damage depends on the magnitude of the earthquake, the building's age and construction materials, and the quality of its design and construction (Kanit et al., 2005). In the Last earthquake many historical buildings have been damaged, some of these buildings have been completely destroyed as shown in **Error! Reference source not found.**& Figure 1.2& Figure 1.3. This earthquake caused widespread damage to buildings throughout the region. Historical buildings are particularly vulnerable to earthquake damage due to their age and construction methods. Additionally, historical buildings often have unique architectural features and structural elements that can be difficult to repair or replace in the event of earthquake damage. (Augenti et al., 2013).

Our study comes from the mitigation process which is main factor in disaster risk reduction cycle, mitigation and preparedness processes are mainly aims to analyse hazards, structural retrofit and develop plans and procedures that give us positive respond to disasters.

Figure 1.1 Habibi Neccar Mosque (https://indigodergisi.com)

Figure 1.2 Antakya Ulu Mosque (https://indigodergisi.com)

Figure 1.3 Ulu Antakya Rum Orthodox Church (https://indigodergisi.com)

1.3 Aim and objectives of this study.

In context of disasters recovering strategies, it is known that pre-disaster and post-disaster strategies are key components of disaster risk reduction and management. Pre-disaster strategies refer to measures taken before a disaster to mitigate potential damage and loss of life, while post-disaster strategies refer to measures taken after a disaster to facilitate recovery and reconstruction. Different methods of strengthening have been developed over the years. However, this study aims to minimize the damage and loss of life resulting from a disaster, which reduce the efforts in planning, management and implementing of post-disaster process. Moreover, in the context of strengthening building, this study focuses on masonry walls which is commonly used in the historical buildings. Accordingly, nine masonry walls were strengthened using (CFRP) sheets to improve their out of plane behaviour and tested under three-points bending load.

1.4 Methods

This study used both quantitative and qualitative methods.

The qualitative method starts with the selection of materials. The masonry wall is made of masonry bricks, while the CFRP sheets were made of unidirectional carbon fibres. The selection of these materials was based on their mechanical properties and compatibility. Also, the preparation of the masonry wall involved a qualitative application of the cleanliness of the wall to ensure proper adhesion of the CFRP sheets.

The quantitative method was followed in a bending load test conducted to determine the load-bearing capacity of masonry walls. The load was applied gradually, and the deflection of the wall was measured at regular intervals using a linear variable deformation transformer (LVDT). The load was increased until the wall failed, and the maximum load-bearing capacity was recorded.

CHAPTER 2 LITERATURE REVIEW

The using CFRP (Carbon Fiberglass-Reinforced polymer) material to strengthen masonry walls and enhance their ability to withstand threats such as earthquakes. This solution has been applied to structural components of buildings to make those two components work together to provide stronger structure and better-bearing components that benefit the building in many aspects, out-of-plane and in-plane loads can prove to require variable strengthening methods, which is why we will be focusing more on out-of-plane approach while mentioning the in-plane to get the results for both.

2.1 Experimental studies examined In-Plane behaviour.

Several studies were carried out by a number of other researchers, and they have demonstrated that FRP retrofits improve the lateral load-carrying ability of URM walls, albeit the outcomes for ductility have varied depending on the pattern of FRP application. (Mahmood et al., 2008). The studies discussed in this article had two walls one left as the source and the other retrofitted with unidirectional glass FRP (GFRP) sheets and their purpose was to examine the cyclic shear behaviour of URM walls constructed with New Zealand materials, with two layers of GFRP sheet applied horizontally, the retrofitted wall was strengthened in shear to allow for failure in a ductile/pseudo-ductile mode. Further testing using various FRP retrofit schemes and forms are planned as a result of the results, which demonstrated an increment in the lateral force ability and stiffness of the retrofitted URM wall. (Mahmood et al., 2008). The test walls were built using recycled bricks from demolished buildings that had been cleaned and prepared for use (Mahmood et al., 2008). According to another study, the reinforcement employed in this one involved applying a layer of carbon fabric-reinforced cementitious matrix (FRCM) overlay to one side of the wall for in-plane strengthening and deep carbon fibre reinforced polymer (CFRP) strips embedded in a viscous-elastic epoxy for out-of-plane reinforcement. Clay brick masonry wallets that had undergone diagonal compression testing were used in an experimental program to determine the impact of this strengthening mechanism on the in-plane behaviour. The findings showed that, in comparison to the unenhanced control specimens, the single-sided carbon FRCM overlay increased the wallets' shear capacity by 80%. A thicker matrix layer did not further increase the shear capacity of the wallets, but it did improve the ductility of the reinforced specimens, according to testing of two different FRCM overlay thicknesses. Intriguingly, the investigation discovered that the out-of-plane reinforcement had no effect on the wallets' in-plane strength under shear loading and, in contrast to the control specimens that had not been strengthened, had even prevented disintegration after achieving the failure load. (Türkmen et al., 2020). As a result, the failure load and the FRCM layer thickness exhibited only a weak correlation with each other, and the FRCM layer thickness had little effect on the shear modulus. The quantity and location of diagonal cracks seen on the as-built side of the reinforced samples were influenced by the FRCM layer's thickness. While the last stages of the diagonal compression testing, out-of-plane bending resulted from differences in stiffness between the as-built side and the FRCM enhanced side. The non-uniform shear stress distribution at the panel's centre is not taken into consideration by either strategy. The method proposed by Triantafllou (2016) produced more conservative results with a ratio of 1.94 compared to ACI 549-13 with a ratio of 1.31. Moreover With experimental to design value ratios ranging from 3.47 to 4.89, the design values obtained for the shear strength of FRCM reinforced masonry were cautious, especially when utilizing the design value for masonry contribution as derived using Eurocode 8-3.(Türkmen et al., 2020)

Another study looked at how well masonry walls reinforced with carbon fibre reinforced polymer (CFRP) and polyethylene terephthalate-reinforced polymer (PET-FRP) sheets performed when subjected to in-plane shear loads. After the FRP sheets were bonded to their surfaces in three distinct configurations Figure 2.1, twelve clay brick masonry walls were exposed to static lateral loading under continual compression. The deformation at peak load and ultimate shear strength were the researchers' two main points of interest. From the first uncracked state to the ultimately totally cracked state, they examined the methods by which the load was carried. In-plane shear capacity of the brickwork was found to be greatly boosted by bonding either CFRP or PET-FRP to the surface of the walls, while ductility was decreased when CFRP was employed, according to the study. The walls that had been cross-diagonally retrofitted with PET-FRP exhibited good ductile behaviour in both pre-peak and post-peak regimes. The efficiency of the strengthening offered by each form of FRP was evaluated using experimental data.(Rahman & Ueda, 2016)

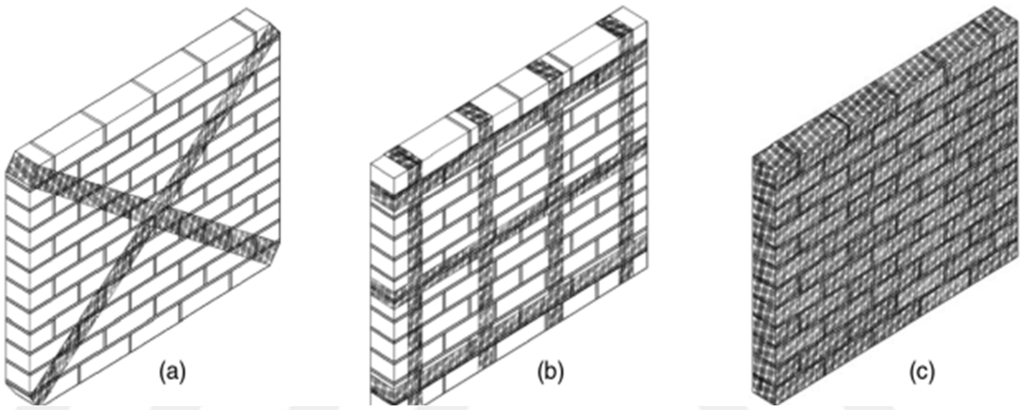


Figure 2.1 different applications of reinforcement stripes (Rahman & Ueda, 2016)

The failure modes of unreinforced and FRP-strengthened masonry walls were observed under static lateral loading. Unreinforced walls failed in shear sliding and toe crushing preceded by flexural cracking, while FRP-strengthened walls predominantly failed in diagonal tension and toe crushing preceded by flexural cracking, with debonding being the most common failure mode for FRP. While both CFRP and PET-FRP strengthened walls showed significant improvement in in-plane shear strength, the ductility was compromised when CFRP was used. PET-FRP exhibited better seismic performance than CFRP, particularly in the post-peak region where ductile behaviour is important for safety. Exceeding a certain range of stiffness did not increase the in-plane shear strength of masonry walls and only increased costs. Diagonal bracing with PET-FRP sheet can enhance capacity while also increasing ductility, making it a good option to prevent catastrophic failure. FRP strengthening has only marginal effects on structural performance at service load conditions but can significantly improve safety during accidental overloading like earthquakes. Cost is a major concern, with the cross-diagonal configuration requiring the least amount of PET-FRP materials and installation work, making it the most cost-effective option(Rahman & Ueda, 2016). A study was carried out to investigate the behaviour of masonry walls under in-plane loading, specifically those reinforced with unidirectional CFRP composites. The study focused on two groups of walls with varying percentages and orientations of CFRP composites. The wall specimens used were made of clay brick units with dimensions of 240X115X63mm and had an overall dimension of 1200X1200X115mm. The CFRP composites were applied to both the front and back sides of the walls (El Malyh et al., 2021). As a result, the reinforcement system increased strength, energy dissipation, and ductility, enhancing the safety of structures during earthquakes. The strongest increase in strength came from using three vertical CFRP strips. Walls reinforced using diagonal reinforcement configurations exhibited the greatest improvement in sheer and ultimate strength. The amount, placement, and direction of the CFRP reinforcement all had an impact on the reinforced wall's strength. The diagonal composite reinforcement scheme had significant promise as a strengthening alternative, and the investigation proved the ability of CFRP reinforcement to improve the mechanical behaviour of URM walls (El Malyh et al., 2021).

2.2 Application of CFRP reinforcement on an existing building

Several applications were applies on many existing building in different region on different structural elements, (Motavalli et al., 2010) had studied the behaviour of many types of CFRP retrofitting on many structural elements columns, slabs, beams and walls. The process involved in strengthening the walls using composite materials included the application of Glass Fibre Reinforced Polymer (GFRP) fabrics to the surface of the wall, followed by the application of Carbon Fibre Reinforced Polymer (CFRP) strips that were placed crosswise on top of the GFRP fabric layer. To anchor the strip ends securely in the Reinforced Concrete (RC) decks, steel plates were used as shown in Figure 2.2.

This methodology was employed to enhance the flexural and shear strength of the walls and to prevent cracking and ultimate failure of the structure.

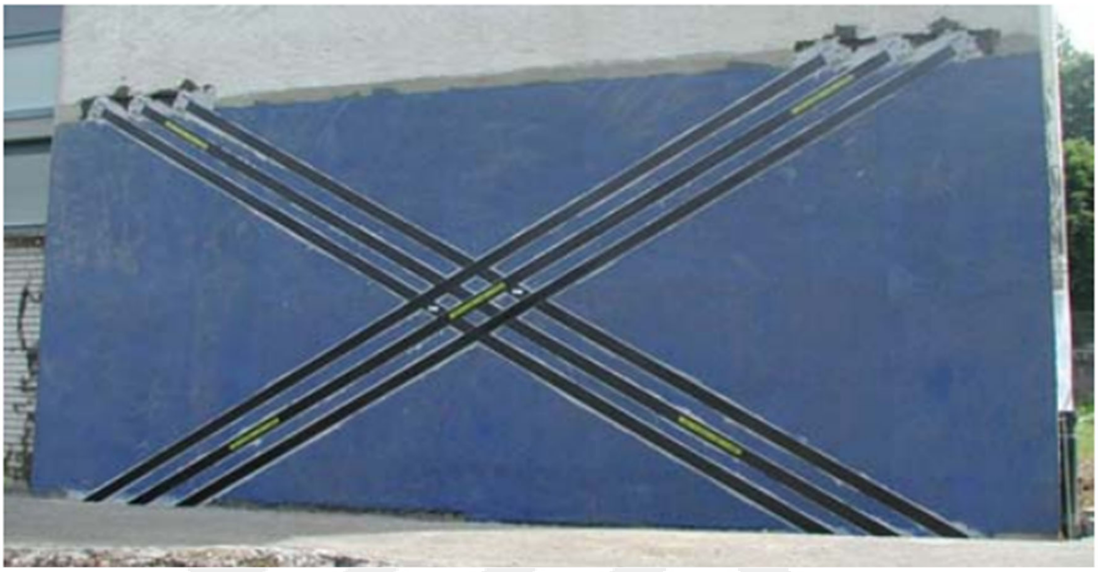


Figure 2.2 Seismic retrofitting of a masonry wall using GFRP fabric and CFRP strips , (Motavalli et al., 2010)

it is noted that the use of Fibre Reinforced Polymer (FRP) composites in strengthening structures has been primarily driven by two factors: the lowest tendered price or a lack of alternative viable solutions. While the material costs of FRP composites are generally several times more expensive than conventional materials like steel and concrete, the life-cycle cost, which includes fabrication, application, protection, and projected maintenance costs, is comparable and in some cases even less than that of conventional materials. It is important to consider both the short-term and long-term costs when evaluating the feasibility of using FRP composites in strengthening structures (Motavalli et al., 2010).

2.3 Experimental studies examined the Shear Loading

Three main shear failure modes-sliding, surpassing diagonal tensile stresses, and stepwise diagonal failure-are known to exist. The degree of vertical pressure, the kind of masonry, and the calibre of the materials employed all influence the kind of failure that takes place. Masonry can be strengthened using metallic or non-metallic techniques, each with advantages and downsides, to increase shear capacity. Prior to adopting strengthening measures, it is essential to identify probable failure modes, and the strengthening strategy should be adapted to the geometry of the masonry and the local building conditions. Masonry can have non-metallic reinforcement added to it using either mortar (TRM) or epoxy adhesive (FRP).(Kišiček et al., 2020).

Another study was published by (Bernat-Maso et al., 2016)obtaining to conduct an experiment on full-scale brick walls, where they strengthened 15 of the 17 walls with Carbon Fibre Reinforced Polymer (CFRP) laminates using five different configurations. The walls were subjected to eccentric compressive loads until failure, and the results were compared to those predicted by a numerical model and a novel analytical approach. The mortar used in the walls had a compressive strength of 3.7MPa and a flexural strength of 1.25MPa. The FRP used was consisted of an epoxy primer, an epoxy adhesive, and carbon fibre laminates that were 80mm wide and 1.2mm thick. The experiment used a pin-fixed configuration with equal constant eccentricity of the load at both ends of the walls (Bernat-Maso et al., 2016). During an experimental study, real-size brick masonry walls that were reinforced with Fibre Reinforced Polymer (FRP) were subjected to eccentric compressive loads until they failed. The results showed that thicker adhesive layers than those recommended by manufacturers were needed to install FRP on existing brick masonry, which could have economic implications and result in a stiffer lateral response. Additionally, all FRP-strengthened walls collapsed due to compressive/shear failure near the ends of the wall, and no debonding of the FRP laminates from the masonry was observed. This suggests that the structures may have been over-strengthened, as the masonry failed before the debonding process of FRP was activated. The study also indicated that the load-bearing capacity of the walls can be increased by over 200% with the use of FRP strengthening systems, and that vertical laminates are more effective in strengthening against second order bending effects than horizontal laminates. Furthermore, a numerical model was developed to forecast the observed failure mechanism and revealed a negligible impact of the strengthening pattern on the resistance of the examined cases, allowing for minimal computational cost prediction of the load-bearing capability of FRP-strengthened walls under eccentric compressive loads. However, the thick layer of epoxy adhesive's stiffening effect or a potential miscalculation of the masonry's Young's modulus could cause the projected lateral deformation to be bigger than the experimental measurements (Bernat-Maso et al., 2016). Further experimental study is advised to examine the behaviour of the interface between FRP and masonry and determine more accurate fracture energy values to enhance the numerical model. Additional information about the impact of interfaces on the structural response of FRP-strengthened masonry walls may also be found in parametric and 3D analyses. Additionally, a method for properly calculating the load-bearing capacity of FRP-strengthened walls under eccentric loads was established. This method may be applied for design reasons. Overall, this study offers important insights into the numerical and analytical calculations of such structures as well as FRP strengthening of brick masonry walls, particularly for eccentric compressive loads that induce second order bending effects. (Bernat-Maso et al., 2016)

2.4 Experimental studies examined the Flexural capacity.

Many researches had tested the Flexural capacity of Masonry walls and their performance against different loading types. (Al-Jaberi et al., 2016) had tested twelve reinforced masonry walls using Eternally bonded FRP laminate. Masonry units made of fully grouted concrete were used to build every wall, and different amounts of steel reinforcing were used. Four reference walls were also constructed without any additional reinforcement. The exteriors of the remaining six walls were strengthened using either one or two sheets of carbon fibre-reinforced polymer laminate (CFRP) or wet lay-up glass fibre sheet (GFRP). The FRP debonding strain was predicted using a straightforward model. The moment-curvature relation can be used to analyse nonlinearly the walls. In (Al-Jaberi et al., 2015) study, four-point bending tests on all reinforced masonry walls were performed using an MTS double-acting hydraulic jack with a push-pull capability of 965 MPa (140 kips) and simply supported bounds Figure 2.3. Continuous steel plates and bars were used to transfer the vertical load to the masonry examples over their whole width, resulting in two equal line loads. Additionally, each time a steel plate and a specimen came into contact, a thick rubber film was applied. (Jaberi et al., 2015)

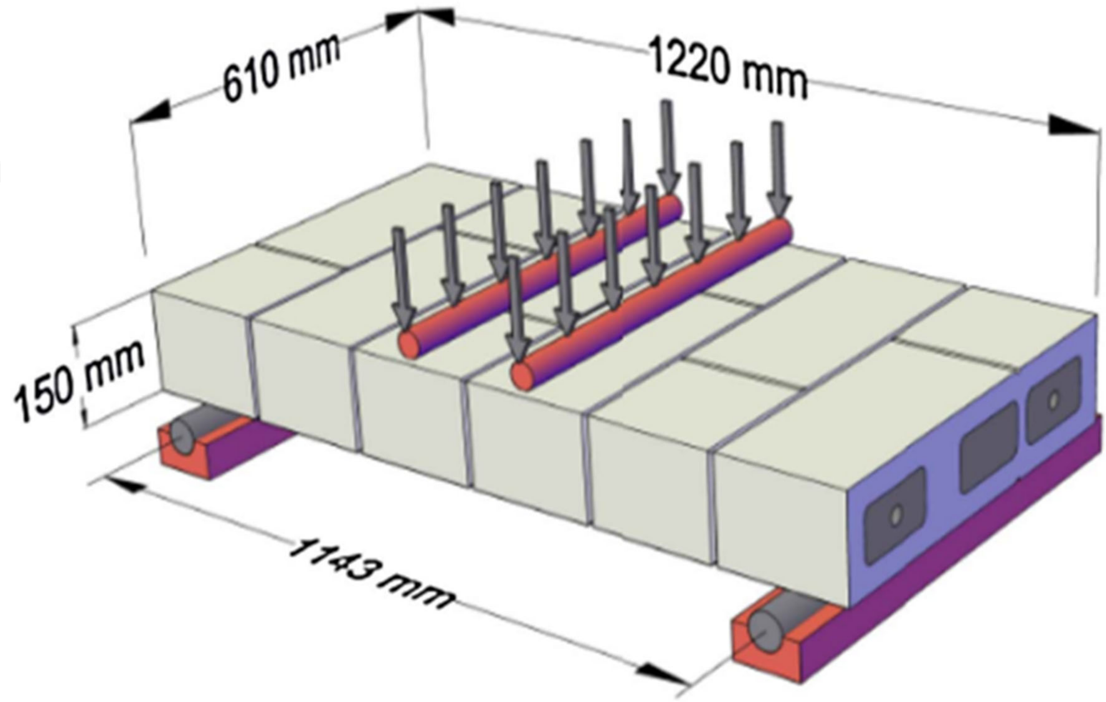
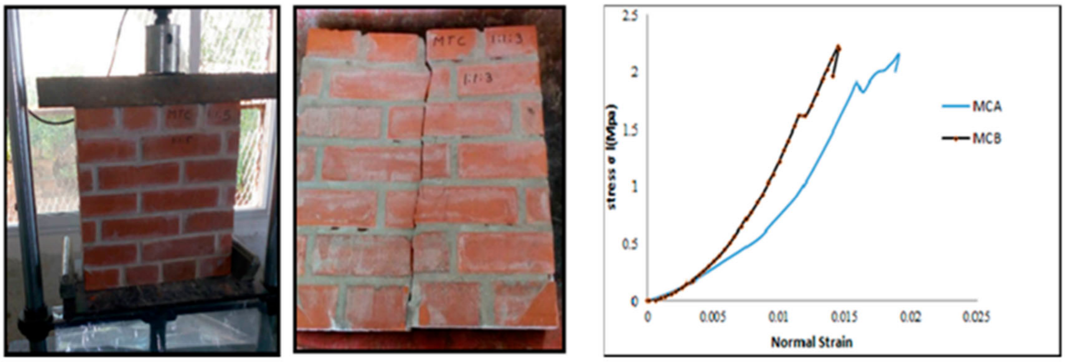


Figure 2.3 details of compression process (Al-Jaberi et al., 2016)

In comparison to un-strengthened walls, the study indicated that reinforced masonry walls enhanced with fibre-reinforced polymer (FRP) materials had a much higher flexural capacity and stiffness but a lower displacement ductility. Compared to carbon FRP (CFRP), the increase in flexural capacity was larger for walls reinforced with glass FRP (GFRP). The ratio of fibre to steel reinforcement, debonding strain, and masonry bond design all had an impact on pre-yield stiffness. The study suggested that, to increase ductility and overall performance, FRP reinforcement should be sufficiently anchored. The bond strength and flexural capacity were increased by surface preparation with a putty infill layer. The flexural strength capability of the stack bond brickwork increased even without reinforcing for continuous head or bed joints. The specimens displayed two failure modes, flexural and shear failure, with debonding accounting for the majority of failures.(Jaberi et al., 2015)

The investigation of reinforced masonry walls with NSM CFRP strips against combined loads was determined by another study (Hernoune et al., 2020). The paper's introduction presents an experimental examination that looked at the behaviour of brick masonry walls reinforced with NSM CFRP strips under combined shear-compression pressures, with varied bed joint orientations of 90 and 45 with respect to the loading direction, the walls were tested under vertical compression as shown in Figure 2.4. The wall's reinforcements were used in a variety of orientations, including vertical, horizontal, and a combination of both sides.2020 (Hernoune et al., 2020). Concrete Damaged Plasticity (CDP) constitutive principles were used in the analysis to mimic the non-linear behaviour of the brick and mortar. The findings demonstrated that adding NSM-CFRP strips to a masonry wall had a substantial impact on its strength, ductility, and post-peak behaviour. It also changed the failure modes. The study discovered that adding more sand to mortar boosted its ductility and shear strength, particularly when reinforced. Shear strength of masonry panels was correlated with compressive strength, and compressive and shear strength were both influenced by the unit/Emortar ratio (Hernoune et al., 2020), while vertical reinforcement increased ductility, horizontal reinforcement reduced sliding failures. The study also discovered that utilizing CFRP strips increased bond strength and ductility, with vertical reinforcement on both sides achieving the greatest improvement. Maximum strength and failure mode were correctly predicted by the Finite Element model (Hernoune et al., 2020).



(a) (b)

Figure 2.4 compression process & results (Hernoune et al., 2020)

2.5 Experimental studies examined Out of-Plane behaviour.

This group contains the most prevalent wall deformities, making it the primary subject of this study. Using a variety of techniques, including externally bonded (EB) glass FRP fabrics, EB pultruded carbon FRP (CFRP) plates, and near-surface mounted pultruded CFRP rectangular bars, a sturdy used total of seventeen unreinforced masonry (URM) wallets were retrofitted. Data was gathered for the applied force and accompanying wall drift before these wallets were tested by applying a diagonal compressive force. The outcomes were contrasted with five nominally equivalent un-retrofitted wallets. According to the study, the adoption of FRP systems significantly improved pseudo-ductility and toughness, two key objectives in any seismic retrofitting intervention, and significantly raised the shear strength of the wallets. (Mahmood & Ingham, 2011)

The experimental wallets that were utilized in the study were separated into three stages, with stages 1 and 2 measuring 1170 mm in length and 1170 mm in height, and stages 3 measuring 1170 mm in length and 1075 mm in height. All wallets had a same bond pattern of 4 out of 34 and were 225 mm thick. FRP components such rectangular NSM bars, pultruded CFRP plates, and uniaxial and biaxial GFRP textiles were employed to refit the wallets. (Mahmood & Ingham, 2011)

All wallets showed a linear connection between the applied force and the associated wall drift (or displacement) up to about 50% of the maximum force. The entire surface biaxial GFRP fabrics produced a shear strength improvement of up to 0.54 MPa. Due to a process known as dilatation, the shear strength significantly increased when only vertical FRP pieces were used, when compared to the wallette strength before the various retrofit treatments were used, the shear strength increased by 31–325% (0.1–0.54 MPa).(Mahmood & Ingham, 2011). A material's ductility refers to its capacity to deform and absorb energy without cracking or breaking. It is a crucial component of earthquake design. The ductility of wallets that failed due to diagonal shear cracking was dramatically improved by the FRP retrofit operations. The wallettes with a grid of GFRP fabric strips (WTG6), the wallette with CFRP diagonal plates (WTC4), and the two wallettes with simply horizontal retrofits (WTG1 and WTC1) all saw significant increases. The gains in ductility for the wallets with NSM retrofits were noticeably less significant (Mahmood & Ingham, 2011). The application of FRP improved the toughness of the wallettes, particularly for those that experienced diagonal shear cracking failure. According to the study, seismic behaviour can be improved by adopting FRP systems for seismic retrofit interventions of URM. One face might be retrofitted with FRP and yet get a significant increase in shear strength of up to 325%. Some wallettes, though, exhibited noticeable out-of-plane displacements in diagonal shear cracking. In instance, wallettes that failed by diagonal shear cracking exhibited enhanced pseudo-ductility and toughness because of the FRP application. Vertical or diagonal FRP retrofits were successful in boosting shear strength and preventing the wallettes from sliding, however horizontal FRP was ineffective in reducing the sliding deformation mode of URM. The debonding was more pronounced in wallettes with CFRP plates, and the investigation found that there was no discernible decrease in stiffness. A linear link between the increase in shear strength and the sum of the horizontal reinforcement ratio and the elasticity modulus of the FRP was also discovered by the investigation.

Another experiment had been determined, six different types of solid clay bricks with measurements of 230 x 110 x 75 mm and various mechanical characteristics were used in this experimental investigation. The Portland cement, hydrated lime, and sand used in the mortar mix had a volume ratio of 1:2:6 when used to build the masonry prisms. The effect of the mortar mixes on the test findings was anticipated to be minor given that the mortar joints only interacted with a tiny percentage of the bond area between the FRP strip and the clay bricks. The CFRP strips were thoroughly cleaned with acetone after being accurately cut to the desired dimensions. The groove and CFRP strip were both covered with a two-part epoxy-based glue.(Dizhur et al., 2014). As a result, all the prism failure mechanisms that were observed were explosive and abrupt, with the force-displacement response cracking and plateauing at the loaded end before to failure. The loading eccentricities used in the test arrangement were partially responsible for the trapezoidal failure plane seen in pull test prisms with the letters H and H+R. It is possible to prevent sliding failure mode by not employing large grooves and making sure that all bonded surfaces are properly prepared and cleaned. Sliding failure mode was seen in 8 prisms. (Dizhur et al., 2014). Existing analytical models were evaluated, and a modified version that matched the outcomes of the experiment was proposed. Using readily available mechanical properties of construction materials, this model offers structural engineers a straightforward method for assessing the pull-out resistance of NSM FRP strips.

2.6 Experimental studies using Alternatives Strengthening Materials

2.6.1 Experimental studies using geotextile material

Many researchers tried to make other experimental studies on Masonry walls aiming to find other materials that can be used in reinforcement process. for instance (M.T. Mansourikia & A. Hoback, 2014) tested ten Unreinforced masonry walls without using any transverse reinforcement. They assessed eight walls four with CFRP material and four walls using Geotextile material. they applied two widths of reinforcement for every reinforcing substance. Testing was performed on all walls using cyclical shear loading, and the number of cycles until collapse was recorded. Both materials reduced drift and increased the number of loading cycles before collapse. It was observed that with more cycles, CFRP demonstrated increased efficiency. Test specimens were built and examined as depicted in Figure 2.5. Unreinforced Masonry (URM), CFRP with 100- and 200-mm widths (CFRP-100, CFRP-200), and Geotextiles with the same widths were evaluated separately in five groups. (GT-100, GT-200) Corner to corner on the wall, the CFRP and the GT were arranged in a crossing pattern. (M.T. Mansourikia & A. Hoback, 2014)

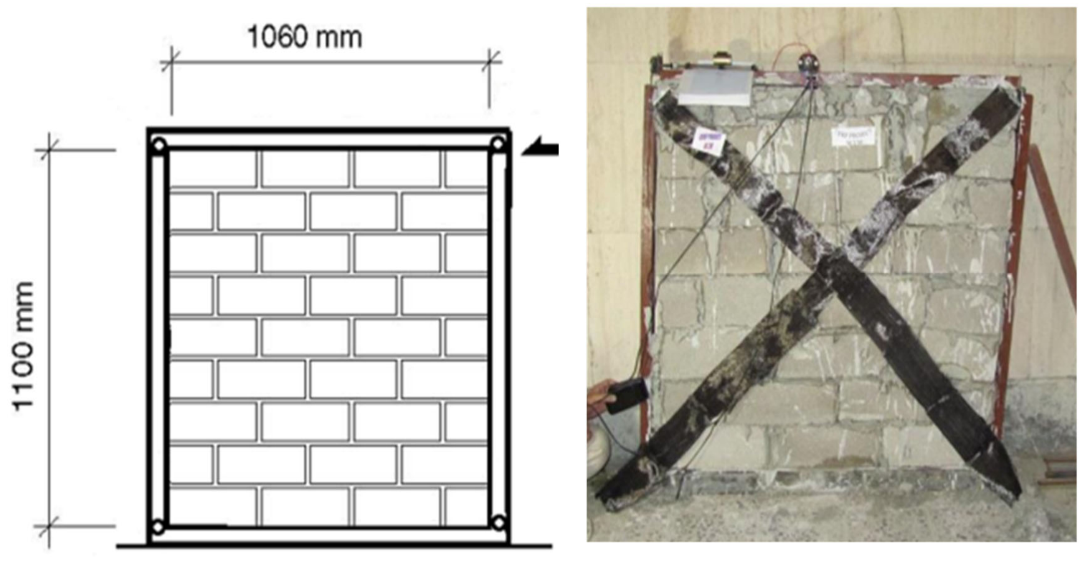


Figure 2.5 test apparatus with CFRP applying and construction method. (M.T. Mansourikia & A. Hoback, 2014)

The study's conclusion showed that using geotextile crossing strips is a workable replacement for CFRP. It has been demonstrated that both materials can decrease drift, increase the time to failure under cyclical load, and dampen vibrations. Geotextile is also a financially sensible option, reducing the cost by more than half and bringing down the materials cost to about one third of the whole cost. This greatly reduces the cost of seismic retrofitting not only in the study area but also in many other parts of the world. (M.T. Mansourikia & A. Hoback, 2014)

2.6.2 Using mortar and Wire Mesh

The goal of the study by .(Joyklad et al., 2021). was to determine whether it was feasible to use readily available and reasonably priced strengthening materials, such as wire mesh and cement-sand mortar, to increase the flexural strength of Cement-Clay Interlocking Brick (CCIB) masonry walls. This study sought to determine how well wire mesh and various shapes and thicknesses of cement-sand mortar (CS) might be used to reinforce cement-clay interlocking brick (CCIB) masonry walls. According to experimental findings, using wire mesh with CS mortar to increase the flexural strength of CCIB masonry walls showed potential. Particularly, it was discovered that a CCIB masonry wall fortified with 20 mm thick CS mortar and three layers of wire mesh had an 87% and 46% higher flexural capacity and energy absorption capacity, respectively, than a reference CCIB masonry wall (Joyklad et al., 2021). To investigate the out-of-plane behaviour of CCIB masonry walls, six reinforced cement-clay interlocking brick (CCIB) walls were built and tested under three-point bending conditions. Five of the six walls had their exteriors strengthened using wire mesh (WM) and cement-sand (CS) mortar. .(Joyklad et al., 2021). All the CCIBM walls were built utilizing the running bond technique. The details of CS mortar strengthening are displayed in the

.

CCIB Masonry Walls	Thickness of CS Mortar (mm)	Configuration	Layers of Wire Mesh
MW-CON	-	-	-
MW-CS10-A	10	A	-
MW-CS20-A	20	A	-
MW-CS10-A-WM-1L	10	A	1
MW-CS20-A-WM-3L	20	A	3
MW-CS20-B-WM-3L	20	B	3

Table 2.1 Details of Cement-Sand mortar (Joyklad et al., 2021)

The dimensions of the walls were 1000 mm in length and height, with a thickness equivalent to that of the CCIB, which was 125 mm as shown in **Error! Reference source not found.**.

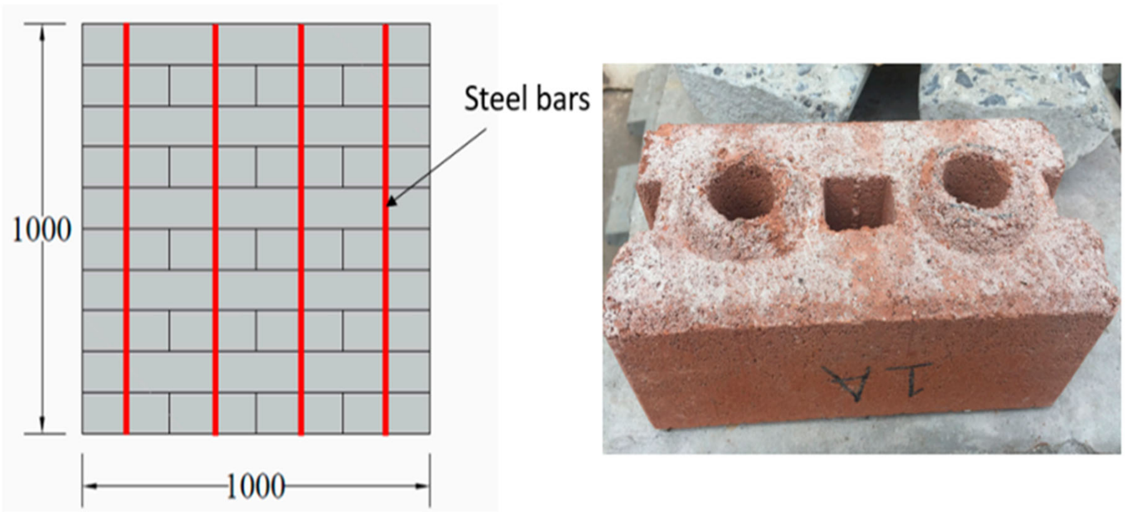


Figure 2.6 walls and bricks dimensions (Joyklad et al., 2021).

As a result of their research, to increase the ultimate load-carrying capacity, toughness, and energy absorption capacity of reinforced cement-clay interlocking brick (CCIB) masonry walls, cement-sand mortar and wire mesh have been shown to be an efficient solution. According to experimental findings, adding layers of wire mesh and cement-sand mortar can boost a structure's final load-carrying capability and energy absorption capacity. Furthermore, it was discovered that strengthening configuration A was more effective than strengthening configuration B. With a flexural capacity that is 87% and 15% larger than that of CCIB masonry walls MW-CON and MW-CS20-A, respectively, masonry wall WM-CS20-A-3L demonstrated the biggest gains in ultimate load-carrying capacity and energy absorption capacity.(Joyklad et al., 2021). In terms of the ultimate failure modes of CCIB masonry walls, it was discovered that walls strengthened with cement-sand mortar and wire mesh failed due to the tensile splitting and crushing of the CCIBs, whereas control or reference masonry walls failed primarily due to large deflections and joint openings at the mid-span. In general, there are three types of ultimate failure modes for CCIB masonry walls: flexure failure, shear failure, and a combination of both flexure and shear failures, or flexure-shear failure. Overall, the experimental findings imply that using wire mesh with CS mortar is a workable technique for improving the performance of CCIB masonry walls. However, additional analysis and comparison with other methods are required to identify the best strengthening strategy. (Joyklad et al., 2021).

2.6.3 Using textile Reinforced Mortar (TRM)

Another type of the non-metallic reinforcement techniques that have gained significant attention in recent years is the use of Textile Reinforced Mortar (TRM). TRM reinforcement is a composite system consisting of high-strength fibres embedded in a cement-based mortar matrix. The fibres are typically made of carbon, glass, or aramid materials and are arranged in a unidirectional or bidirectional pattern. The mortar matrix is composed of cement, sand, and water, and may include additives to improve the bond strength between the fibres and the matrix. (Bernat-Maso et al., 2016). TRM reinforcement has several advantages over other reinforcement techniques. It is lightweight, flexible, and easy to apply, making it an ideal solution for retrofitting existing masonry walls. TRM reinforcement also has excellent durability and resistance to environmental factors such as moisture and UV radiation. Furthermore, the use of TRM reinforcement does not require any special equipment or expertise, making it a cost-effective solution for enhancing the shear strength of masonry walls. (Maso et al, 2021). The effectiveness of TRM reinforcement on masonry walls have been examined in several researches. The behaviour of masonry walls reinforced with TRM reinforcement under diagonal compression was examined in a study by (Kišiček et al., 2020). The findings demonstrated that TRM reinforcement boosted the masonry walls' ability to carry loads and their ductility. Along with researching the behaviour of masonry walls reinforced with TRM under in-plane shear. According to the study, TRM reinforcement enhanced the masonry walls' shear strength and prevented early failure. Additionally, they investigated the behaviour of TRM-reinforced masonry walls under cyclic loads, the findings demonstrated that TRM reinforcement improved the masonry walls' ductility and capability for absorbing energy. The study also discovered that TRM reinforcement increased durability by reducing the width of existing cracks and preventing the development of new cracks.(Kišiček et al., 2020). (Joyklad et al., 2021)compared the effects of mixed bending/buckling phenomena on masonry walls reinforced with FRP and TRM. The study discovered that while the axial rigidity of the strengthening systems varied depending on each scenario, they reduced the system-dependent type of failure. Therefore, in most of the investigated walls, the collapse was primarily governed by the compressive/shear properties of the masonry. The study showed that the load bearing capacities of TRM and FRP strengthened walls were comparable when the observed failure mechanism was mostly determined by the masonry features. This is because the masonry properties, which are comparable for TRM and FRP enhanced situations, also affect the in-plane compressive response. However, depending on the strengthening technology used, the lateral bending reaction of the walls differed.

CHAPTER 3 METHODOLOGY

3.1 Test Specimens and Materials

Ten masonry walls were built and tested under three points bending load, nine of the ten walls were strengthened using CFRP sheets.

The properties of the test specimens used in the study have been outlined in detail in **Error! Reference source not found.**. It is worth mentioning that the nomenclature of the specimens has been derived based on certain conventions. In particular, the first letter "S" in the name of the specimens refers to "strengthened". The second letter "S" in the specimen's name refers to "strip" indicating that the reinforcement involved the use of sheets. The written number near the second letter "S" indicates the number of strips used in the reinforcement process. Moreover, the second letter "F" in the specimen's name refers to full coverage of specimen's surface. Furthermore, the letter "L" in the specimen's name refers to "layer". The written number near the letter "L" indicates the specific number of layers in each specimen. For example, the specimen named "S-S2-L1" was strengthened using two strips and had only one layer. By following this nomenclature convention, it is easy to determine the specific properties of each specimen and to compare them to each other. It is also worth mentioning that the dimensions of the bricks and wall specimens used in the study were provided in Figure 3.1. These dimensions can provide valuable insights into the nature of the specimens and can be used to contextualize the findings of the study.

Specimen	*Dimensions*	*Number of sheets*	*Number of layers*
Control	100 mm x 410 mm x 1200mm	without strengthening	
S-S1-L1		1	1
S-S1-L2			2
S-S1-L3			3
S-S2-L1		2	1

S-S2-L2			2
S-S2-L3			3
S-F-L1			1
S-F-L2		Full	2
S-F-L3			3

Table 3.1 Properties of Test Specimens

Masonry blocks of 50 mm x 100 mm x 200 mm were characterized by compression following (Rahman & Ueda, 2016). A cement-based mortar was used in the bed joints (10 mm wide). It is classified as M5 according to (Doran et al., 2022) and was fully characterized on bending and compression, and elastic modulus, according to (Doran et al., 2022).

Material	*Compressive strength (N/mm^2)*	*Flexural strength (N/mm^2)*	*Elastic Modulus (N/mm^2)*
Solid brick	3.15	-	-
Mortar	9.23	2.08	7.12

Table 3.2 Average mechanical properties of masonry materials and assemblages

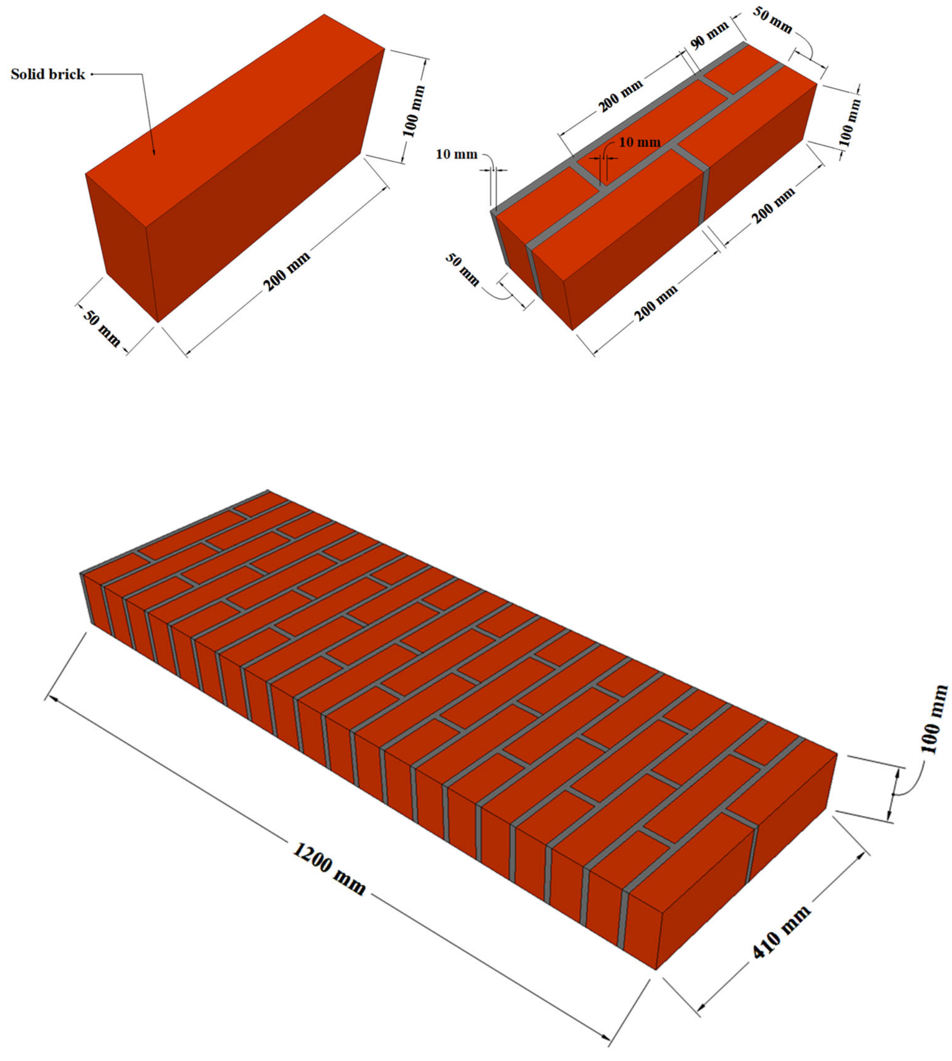


Figure 3.1 Geometric dimensions and some details of the test specimens

The strengthening details of the test specimens are an important aspect of the study, and these details have been presented in Figure 3.1 Geometric dimensions and some details of the test specimensFigure 3.1. It is worth mentioning that the strength of the specimens was improved using a combination of Carbon Fibre Reinforced Polymer (CFRP) and a two-component epoxy. The specific properties of the CFRP and the epoxy used in the study have been outlined in detail in **Error! Reference source not found.**.

Respectively, the steps of producing walls are shown in Figure 3.3. To ensure that the strengthening process was conducted accurately and efficiently, specific stages were followed. These stages have been illustrated in Figure 3.2, and they include preparing the surface, applying the epoxy, and placing the CFRP strip onto the surface. The first step in the strengthening process involved smoothing the surface on which the strip would be bonded. This was done using a sanding machine to remove protrusions and create a flat surface. Once the surface was smoothed compressed air was applied to remove any dust from the surface, and a wet cloth was used to ensure that the surface was completely clean. After the surface was prepared, the position of the strip was marked, and the two-component epoxy was applied to the wall surface. The CFRP strip was then placed onto the epoxy by hand pressing. Finally, another layer of epoxy was applied on top of the strip to ensure that it was firmly bonded to the wall surface as shown in Figure 3.4. By following these specific steps, the test specimens were strengthened effectively and efficiently, and this allowed for accurate comparisons to be made between the different specimens. Overall, the strengthening process played an important role in the study, and the details of the process have been presented clearly to ensure that they can be replicated in future research.

Properties of the CFRP	*Value*	*Picture*
Specific Weight (g/m²)	300 ± 10	
Thickness (mm)	0,12	
Tensile Strength (MPa)	4100	
Modulus of Elasticity (MPa)	231000	
Maximum Tensile Strain (%)	1,7 %	

Table 3.3 CFRP Sikawrap 300-C and Sikadur 330

Properties of the Epoxy	*Value*	*Picture*
Tensile Strength (MPa)	30	
Modulus of Elasticity (MPa) (Bending)	3800	
Modulus of Elasticity (MPa) (Tensile)	4500	
Maximum Tensile Strain (%)	0,9 %	

Table 3.4 Sikadur 330

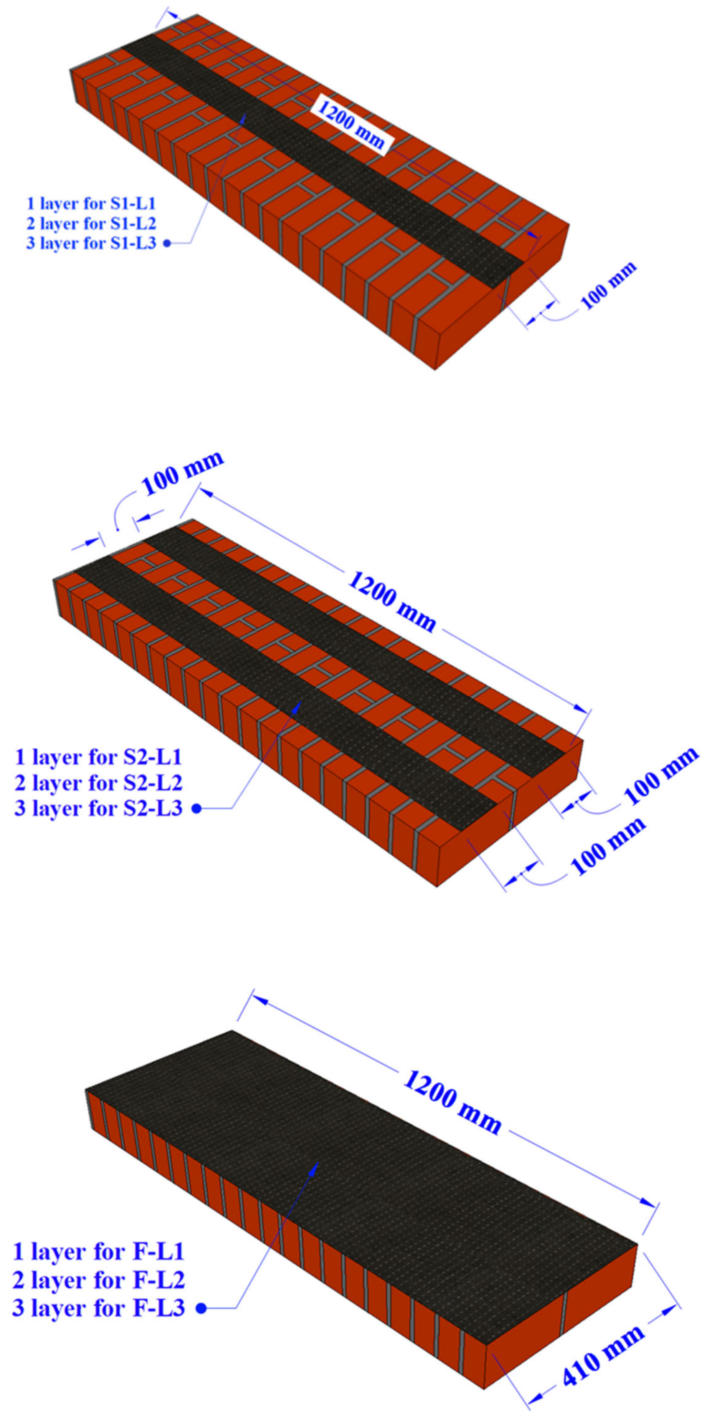


Figure 3.2 Strengthening details of specimens.

Figure 3.3 Production prosses of masonry panels

Figure 3.4 Strengthening prosses of masonry panels.

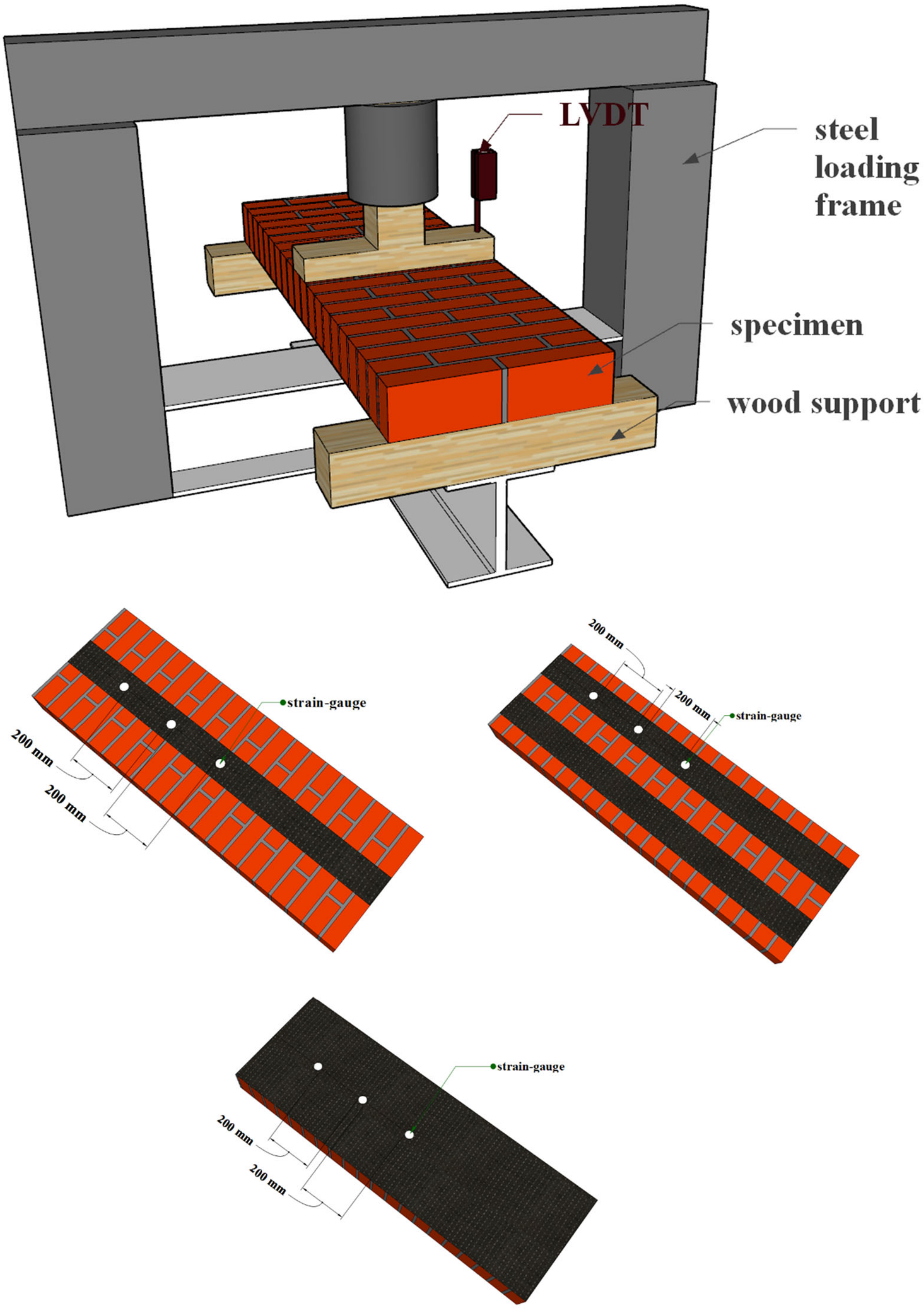


Figure 3.5 Test setup and instrumentations and strain-gauge location

3.2 Test Setup and Instrumentation

Figure 3.5 provides a detailed illustration of the test equipment and instruments used in the research, which were essential elements of the investigation. It is important to note that the test setup's 200 kN axial load capability allowed for the testing of several masonry wall specimens under varying loads. The test specimens were loaded until they collapsed, because of monotonically increasing loading, and the focused bending load was applied to the masonry walls specimens using a motor-controlled hydraulic system. Drawing load displacement curves in parallel with the tests during the testing procedure gave researchers important insights into how the specimens behaved under loads. The axial load and displacement values of the specimens were measured using a variety of instruments to guarantee the accuracy and dependability of the data gathered throughout the testing process. A load cell with a 200 kN capacity was used to measure the axial load placed on the masonry wall test specimens. A linear variable differential transformer (LVDT) with a capacity of 100 mm was included in the test setup in addition to the load cell to detect displacement values that occurred in the test specimens because of the applied load. This LVDT made it possible to measure displacement values precisely and accurately, which was crucial for comprehending how the specimens deformed. Finally, by uploading them to a computer equipped with a data gathering system, all data gathered throughout the testing process were reviewed. This technology made it possible to evaluate and interpret the data quickly, which gave us important new information about how the specimens behaved under various weights. Overall, the testing set-up and equipment employed in the investigation were essential in understanding how the masonry wall specimens responded to bending load and gave insightful information for further study.

CHAPTER 4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Test results

4.1.1 Control Specimen

According to the experiment's results, the control specimen achieved a load of 2.39 kN with a displacement of 0.95 mm and collapsed with a brittle manner. The collapse occurred at the mortar interface. There was no damage to the solid bricks forming the masonry panel walls. Load displacement curve of control specimen was shown in Figure 4.1. The photos of the control specimen testing and collapsing were shown in Figure 4.2.

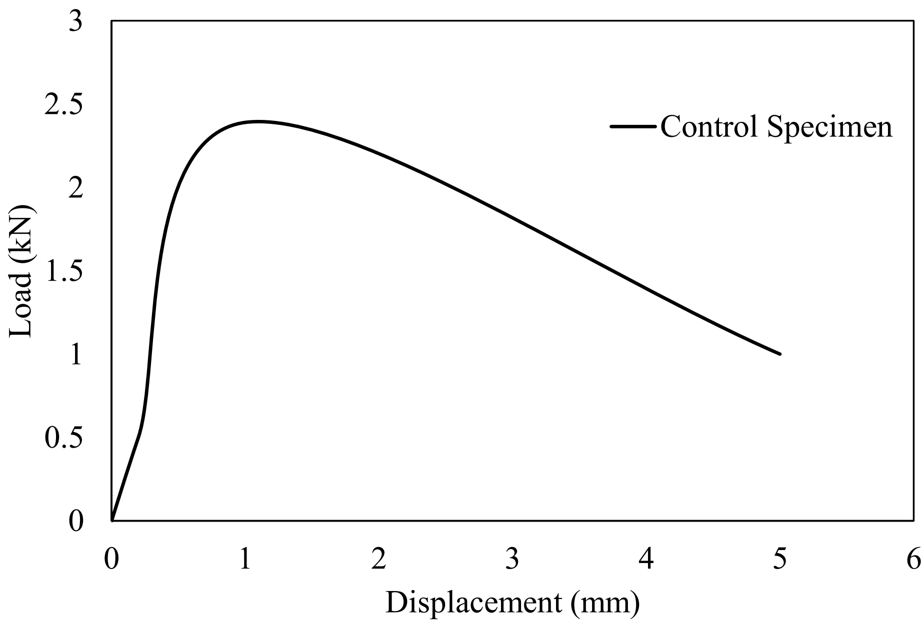


Figure 4.1 Control specimen Load-displacement graphs

Figure 4.2 Testing & Failure mode of control specimen

4.1.2 S-S1-L1 specimen

The results revealed that the S-S1-L1 specimen demonstrated a remarkable increase in load-bearing capacity in comparison to the control specimen. Specifically, the S-S1-L1 specimen was able to withstand a load of 20.09 kN, which is eight times greater than the load that the control specimen was able to withstand. The corresponding displacement of the S-S1-L1 specimen was 12.71 mm as seen in Figure 4.3, which was thirteen times greater than the displacement of the control specimen. However, despite this impressive performance, the S-S1-L1 specimen ultimately failed due to debonding of the CFRP strip from the masonry surface. As a result of this debonding, the specimen suddenly lost its bearing capacity and collapsed. It was observed that the solid bricks in the middle part of the masonry wall had been crushed due to compression (Figure 4.4).

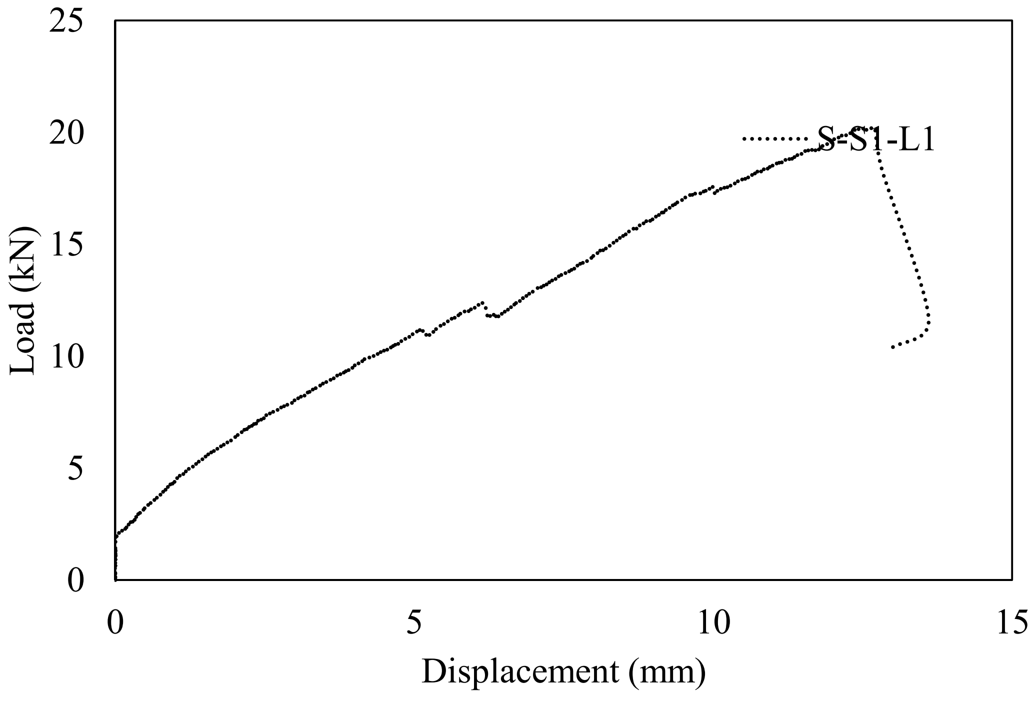


Figure 4.3 S-S1-L1 Load-displacement graphs

Figure 4.4 Testing & Failure mode of S-S1-L1

4.1.3 S-S1-L2 specimen

The results revealed that the S-S1-L2 specimen demonstrated a remarkable increase in load-bearing capacity in comparison to the control specimen. Specifically, the S-S1-L2 specimen was able to withstand a load of 21.05 kN, which is eight and a half times greater than the load that the control specimen was able to withstand. The corresponding displacement of the S-S1-L2 specimen was 12.71 mm, which was ten and a half times greater than the displacement of the control specimen (Figure 4.5). However, despite this impressive performance, the S-S1-L2 specimen ultimately failed due to debonding of the CFRP strip from the masonry surface. S-S1-L2 specimen had the same failure mode of S-S1-L1 (Figure 4.6).

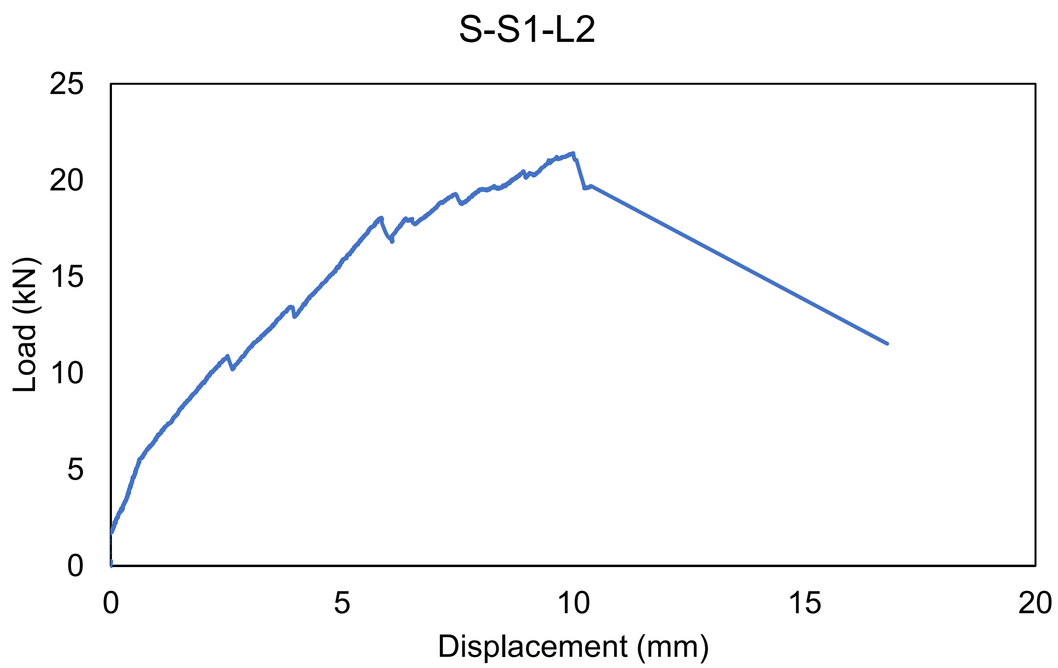


Figure 4.5 S-S1-L2 Load-displacement graphs

Figure 4.6 S-S1-L2 Testing & Failure mode.

4.1.4 S-S1-L3 specimen

The results revealed that the S-S1-L3 specimen demonstrated a remarkable increase in load-bearing capacity in comparison to the control specimen. Specifically, the S-S1-L3 specimen was able to withstand a load of 29.81 kN, which is Twelve and a half times greater than the load that the control specimen was able to withstand. The corresponding displacement of the S-S1-L3 specimen was 9.92 mm, which was ten and a half times greater than the displacement of the control specimen (Figure 4.7). However, the S-S1-L3 specimen ultimately failed due to debonding of the CFRP strip from the masonry surface. As a result of this debonding, the specimen suddenly lost its bearing capacity and collapsed. Upon closer examination, it was observed that the solid bricks in the middle part of the masonry wall had been crushed due to compression (Figure 4.8).

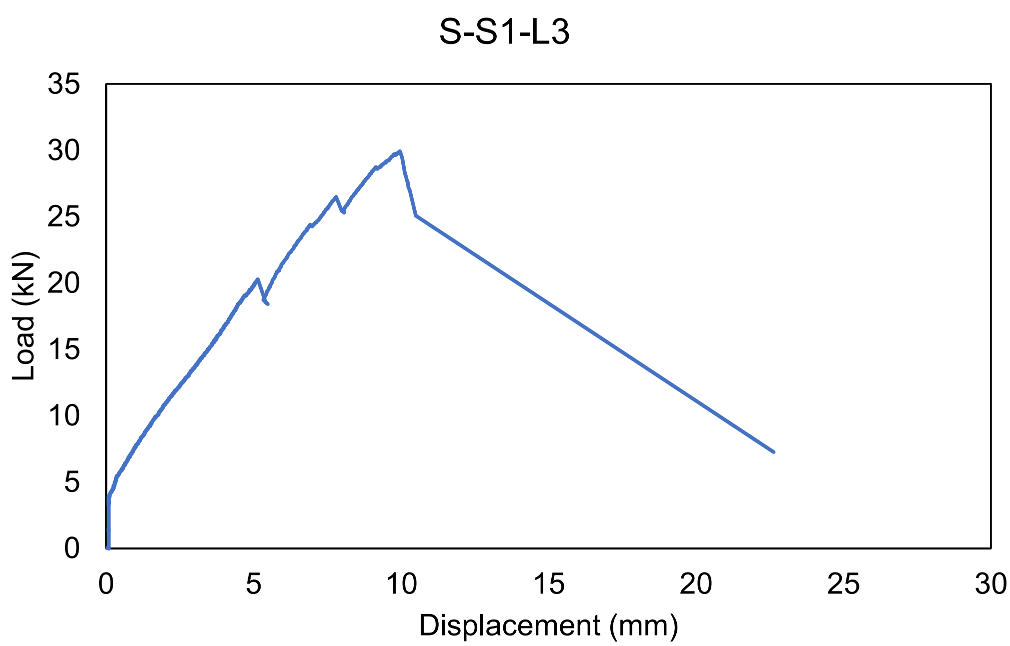


Figure 4.7 S-S1-L3 Load-displacement graphs

Figure 4.8 Testing & Failure mode of S-S1-L3

4.1.5 S-S2-L1 Specimen

In the experiment, the specimen S-S2-L1 was able to withstand a load of 22.81 kN which is nine and a half times greater than the load that the control specimen was able to withstand. The corresponding displacement of the S-S2-L1 specimen was 14.33 mm, which was fifteen times greater than the displacement of the control specimen (Figure 4.9). However, the specimen suddenly lost its bearing capacity and collapsed due to debonding of the CFRP strip from the masonry surface. It was observed that one of the strips deboned from the surface, while the other one continued to contribute to the bearing capacity despite locally debonding. It is thought that the reason why these two strips did not collapse at the same time was due to a workmanship fault. This is because the behavior of the strips was not identical even though there were identical loads on both strips (Figure 4.10).

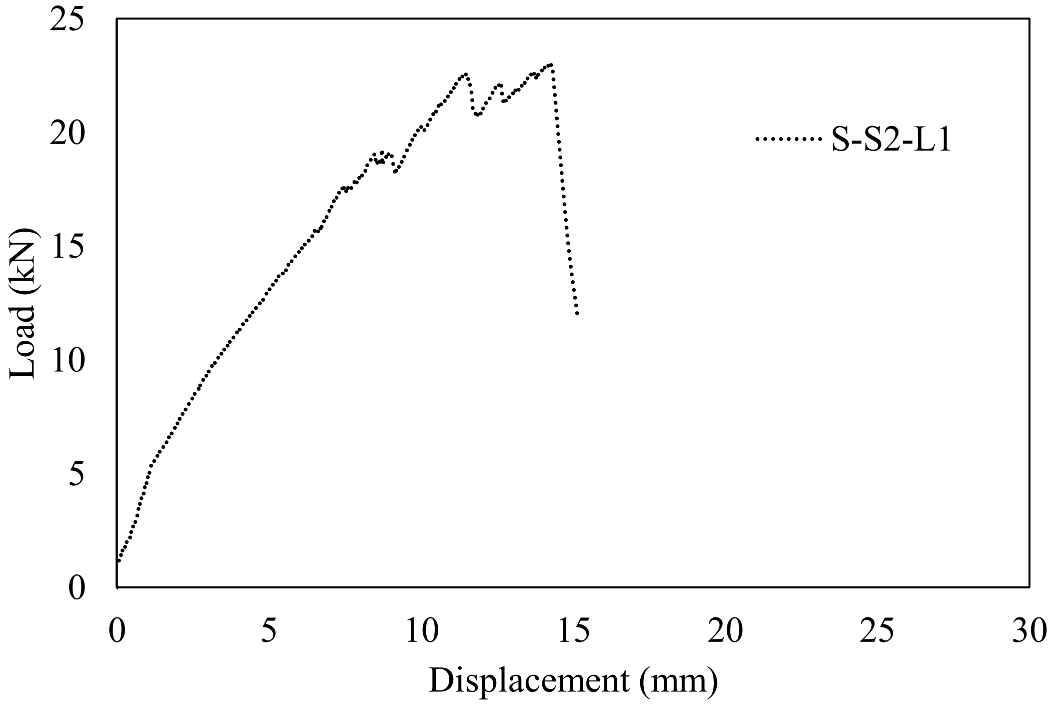


Figure 4.9 S-S2-L1 Load-displacement graphs

Figure 4.10 Testing & Failure mode of S-S2-L1

4.1.6 S-S2-L2 Specimen

The results revealed that the S-S2-L2 specimen demonstrated a remarkable increase in load-bearing capacity in comparison to the control specimen. Specifically, the S-S2-L2 specimen was able to withstand a load of 30.34 kN, which is more than twelve and a half times greater than the load that the control specimen was able to withstand. The corresponding displacement of the S-S2 L2 specimen was 8.90 mm, which was more than nine times greater than the displacement of the control specimen as shown in Figure 4.11. However, the S-S2-L2 specimen ultimately failed due to debonding of the CFRP strips from the masonry surface. As a result of this debonding, the specimen suddenly lost its bearing capacity and collapsed. Upon closer examination, it was observed that the solid bricks in the middle part of the masonry wall had been crushed due to compression (Figure 4.12).

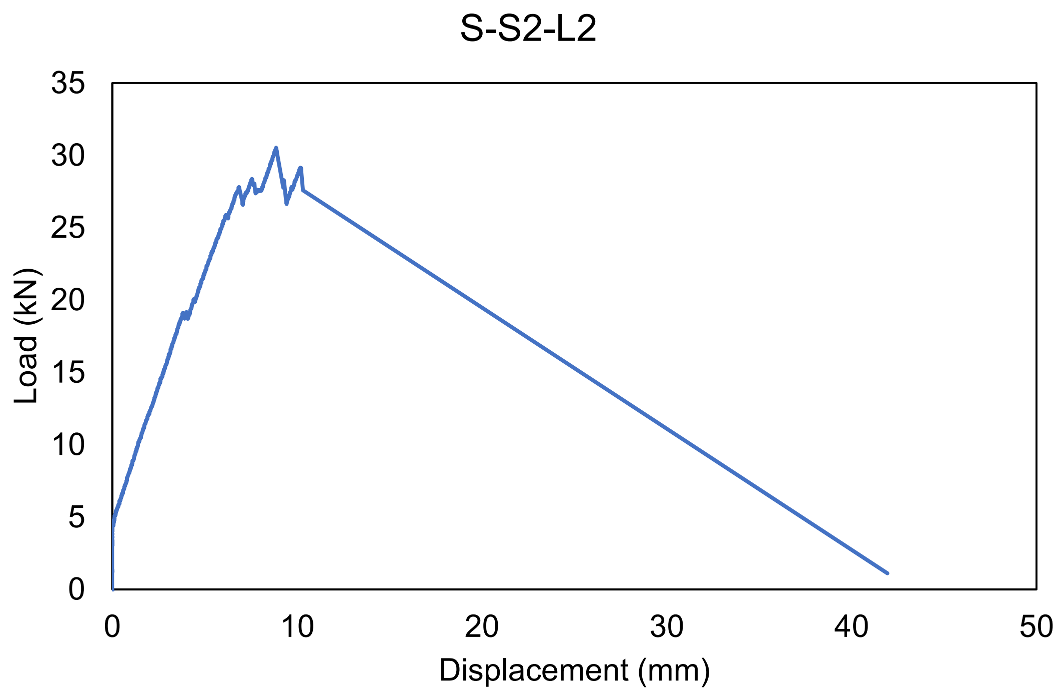


Figure 4.11 -S2-L2 Load-displacement graphs

Figure 4.12 Testing & Failure mode of S-S2-L2

4.1.7 S-S2-L3 Specimen

The results revealed that the S-S2-L3 specimen demonstrated a remarkable increase in load-bearing capacity in comparison to the control specimen. Specifically, the S-S2-L3 specimen was able to withstand a load of 34.61 kN, which is fourteen and a half times greater than the load that the control specimen was able to withstand. The corresponding displacement of the S-S2 L3 specimen was 6.99 mm, which was more than seven times greater than the displacement of the control specimen as shown in Figure 4.13. However, despite this impressive performance, the S-S2-L3 specimen ultimately failed due to debonding of the CFRP strips from the masonry surface. As a result of this debonding, the specimen suddenly lost its bearing capacity and collapsed. Upon closer examination, it was observed that there is no crushing in the solid bricks in the middle part of the masonry (Figure 4.14).

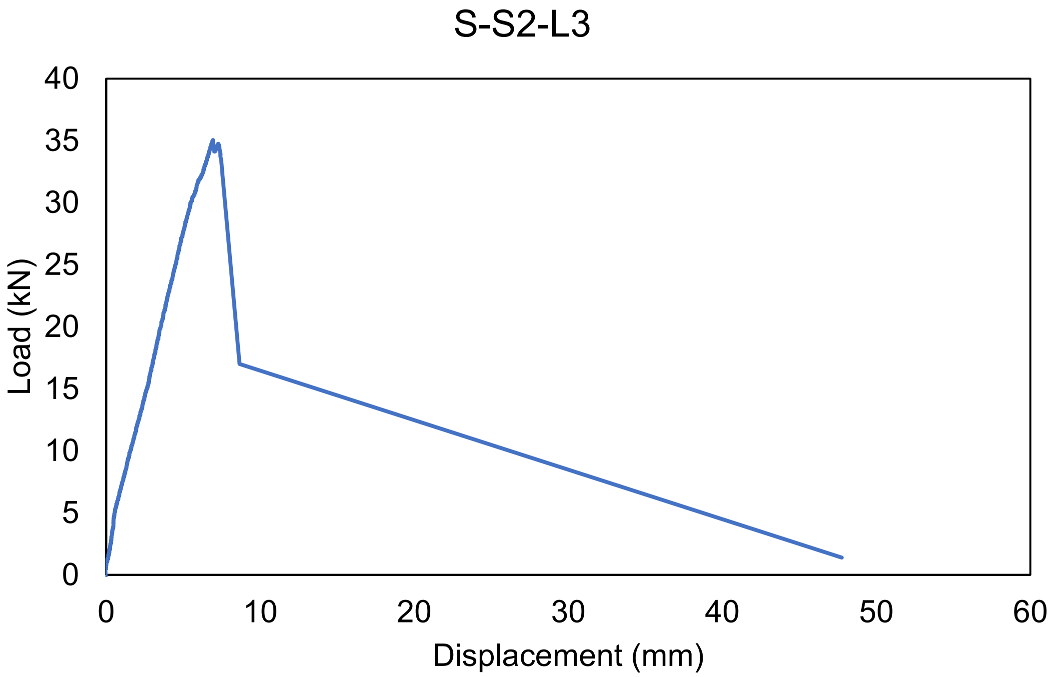


Figure 4.13 S-S2-L3 Load-displacement graphs

Figure 4.14 Testing & Failure mode of S-S2-L3

4.1.8 S-SF-L1 Specimen

The results revealed that the S-F-L1 specimen demonstrated a remarkable increase in load-bearing capacity in comparison to the control specimen. Specifically, the S-F-L1 specimen was able to withstand a load of 43.04 kN, which is eighteen times greater than the load that the control specimen was able to withstand. The corresponding displacement of the S-F-L1 specimen was 14.04 mm, which was thirteen times greater than the displacement of the control specimen (as shown in Figure 4.15), solid bricks had large cracks and damage unlike other specimens. In other words, the specimen did not collapse due to the damages at the mortar interface. It determined that the solid bricks that make up the specimen reached the bearing capacity and were failure to compression and shear (complex) collapse (Figure 4.16).

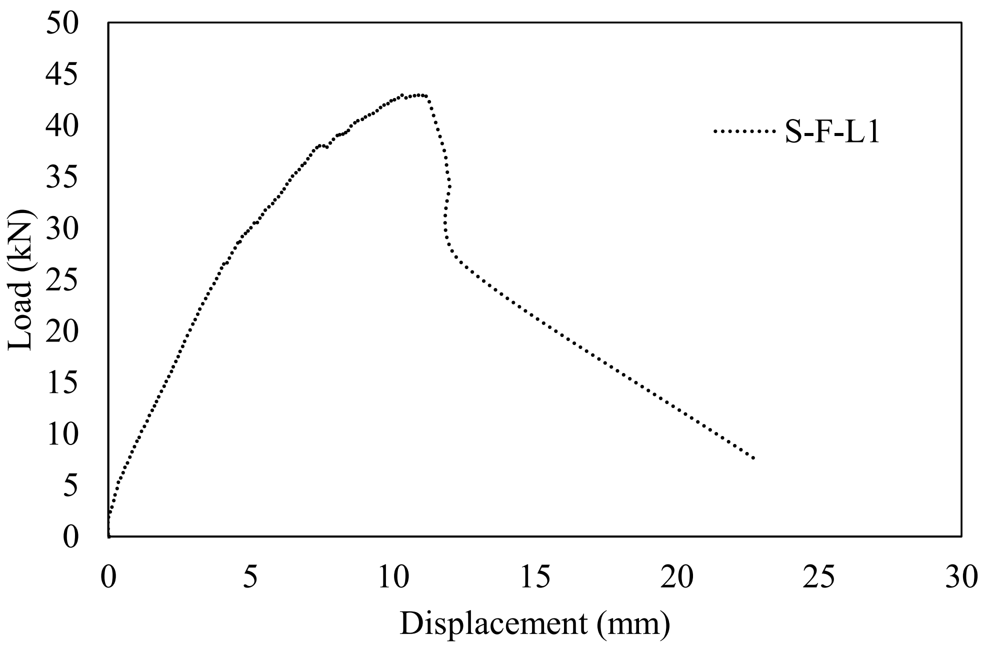


Figure 4.15 S-F-L1 Load-displacement graphs

Figure 4.16 Testing & Failure mode of S-F-L1

4.1.9 S-F-L2 Specimen

The results revealed that the S-F-L2 specimen demonstrated a remarkable increase in load-bearing capacity in comparison to the control specimen. Specifically, the S-F-L2 specimen was able to withstand a load of 48.47 kN, which is twenty times greater than the load that the control specimen was able to withstand. The corresponding displacement of the S-F-L2 specimen was 9.36 mm, which is around ten times greater than the displacement of the control specimen (Figure 4.17) solid bricks had the same large cracks and damage like S-F-L1 specimen. That's mean, the specimen did not collapse due to the damages at the mortar interface. The collapsing behaviour is identically with S-F-L1 specimen (Figure 4.18).

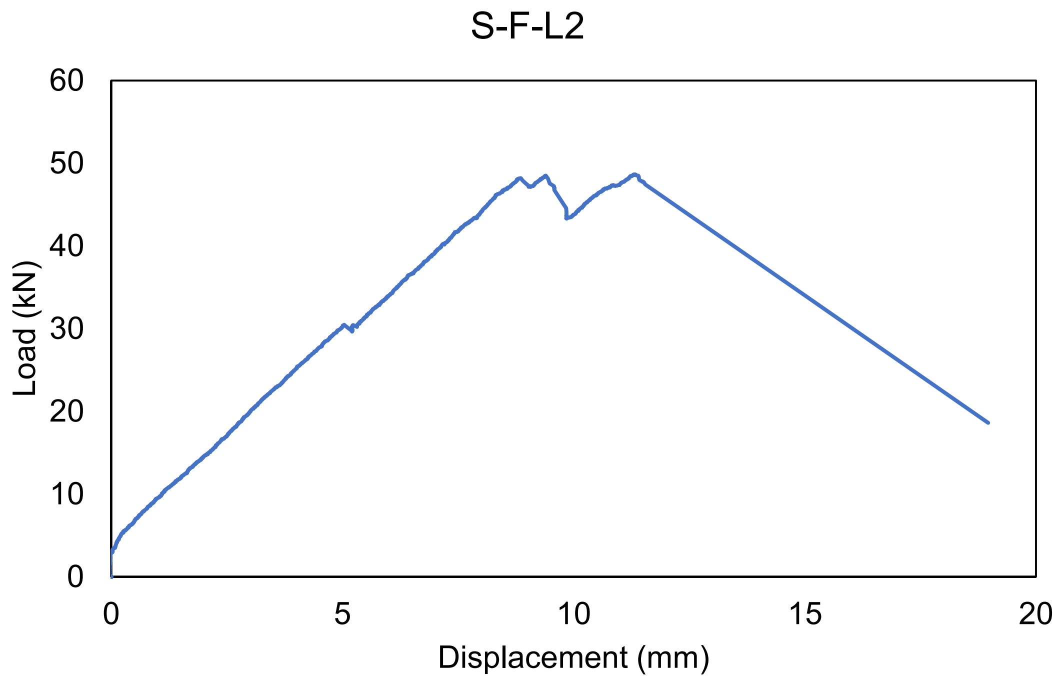


Figure 4.17 S-F-L2 Load-displacement graphs

Figure 4.18 Testing & Failure mode of S-F-L2

4.1.10 S-SF-L3 Specimen

The results revealed that the S-F-L3 specimen demonstrated a remarkable increase in load-bearing capacity in comparison to the control specimen. Specifically, the S-F-L3 specimen was able to withstand a load of 67.47 kN, which is twenty-eight times greater than the load that the control specimen was able to withstand. The corresponding displacement of the S-F-L3 specimen was 8.35 mm, which is around nine and a half times greater than the displacement of the control specimen (Figure 4.19). solid bricks had no large cracks and damage as shown in (Figure 4.20).

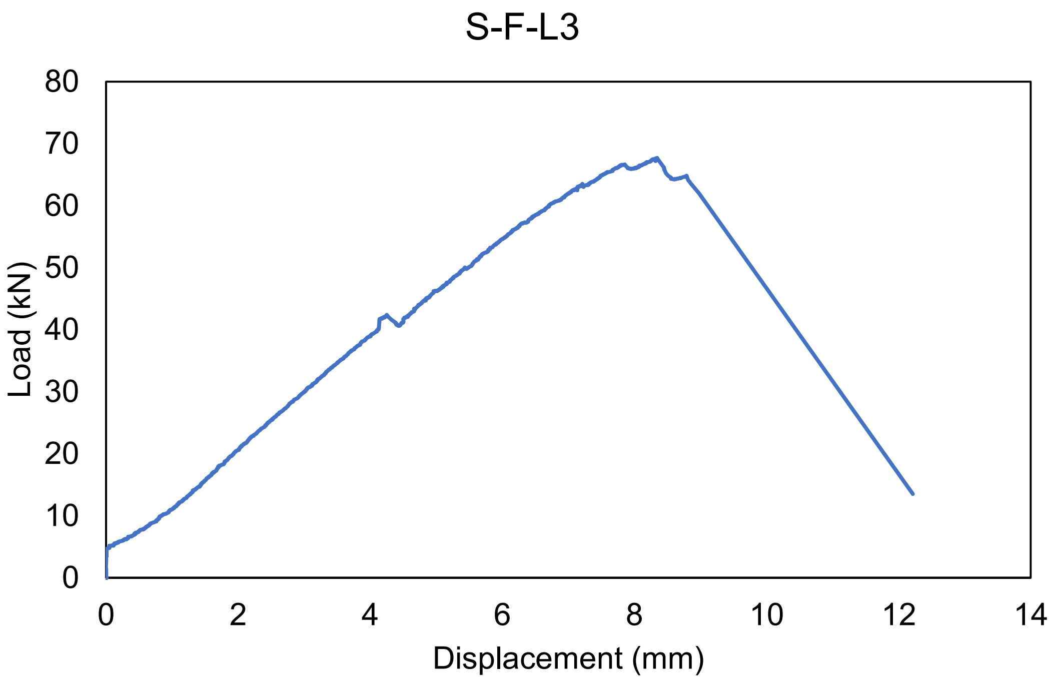


Figure 4.19 S-F-L3 Load-displacement graphs

Figure 4.20 Testing & Failure mode of S-F-L3

4.2 Discussion

The load-displacement curves that were obtained from the tests give important information on the performance and behavior of the test specimens. The load-displacement curves allow for the determination of parameters, such as maximum bearing capacity, stiffness, and energy dissipation capacity, which are essential for evaluating the performance of the test specimens. The performance of the specimens was compared using these parameters. The study's findings were gathered in **Error! Reference source not found.**, which gives a thorough summary of the individual test specimens' ultimate load, displacement corresponding to ultimate load, stiffness, and energy dissipation capacities. Reading the ultimate load value attained in the load-displacement curves allowed us to establish the ultimate load capacity of the masonry panel walls. By dividing the ultimate load by the corresponding deflection, the stiffness of the test specimens was computed. Additionally, by calculating the area under the load-displacement curves, specifically considering the portions of the curves up to the ultimate load, the energy dissipation capacities of the test specimens were determined.

All specimens, including the control specimen as shown in the previous figures have the same failure mode. Using CFRP had significantly increased the maximum load capacity of the strengthened elements. However, wall specimens couldn’t reach the expected maximum load because of debonding of CFRP. It is thought that debonding of CFRP can be prevented using anchorage, thus the ultimate load can be significantly bigger than the results achieved in this study.

Spec. #	Ultimate Load (kN)	Disp. At Ultimate Load (mm)	Stiffness (kN/mm)	Energy Dissipation Capacity (kN-mm)
Control	2.39	0.95	2.52	4.49
S-S1-L1	20.09	12.71	1.58	169.74
S-S1-L2	21.05	10.07	2.09	252.39
S-S1-L3	29.81	9.92	3.01	394.85
S-S2-L1	22.81	14.33	1.59	232.26
S-S2-L2	30.34	8.90	3.41	380.57
S-S2-L3	34.61	6.99	4.95	541.05
S-F-L1	43.04	14.04	3.07	545.10
S-F-L2	48.47	9.36	5.18	706.56
S-F-L3	67.47	8.35	8.08	485.21

Table 4.1 Experimental Results

4.2.1 Comparison of Control Specimen with One-strip Group Specimens

The load displacement curves of S-S1-L1, S-S1-L2, S-S1-L3 and control specimen are given in Figure 4.21. The bearing capacity of S-S1-L1, S-S1-L2 and S-S1-L3 is 8.41, 8.81 and 12.47 times greater than the reference specimen, respectively. The displacement capacities of the strengthened specimens have also increased, the displacement corresponding to maximum load of these specimens are 13.38, 10.6 and 10.44 times greater than the reference specimen, respectively. Significant improvements have been achieved in energy dissipation capacity of this group, it is 37.80, 56.21 and 87.75 times greater than the energy dissipation of control specimen.

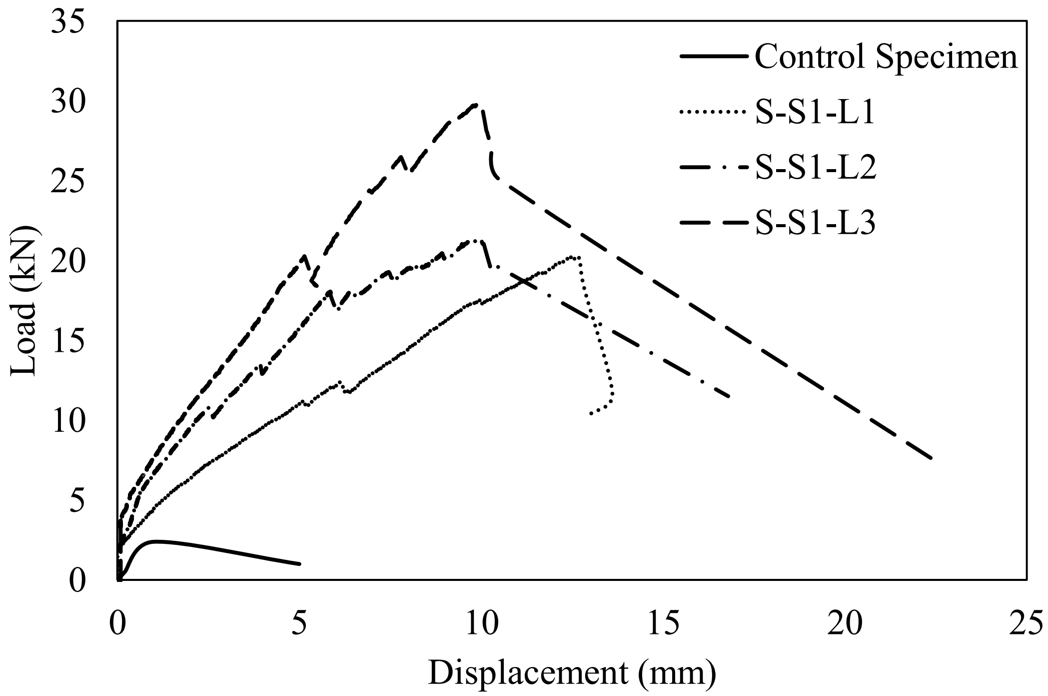


Figure 4.21 Loading displacement comparison Reference& S1 group.

4.2.2 Comparison of Control Specimen with Two-strip Group Specimens

The load displacement curves of S-S1-L1, S-S1-L2, S-S1-L3 and control specimen are given in Figure 4.22. The bearing capacity of S-S2-L1, S-S2-L2 and S-S2-L3 is 9.54, 12.70 and 14.48 times greater than the reference specimen, respectively. The displacement capacities of the strengthened specimens have also increased, the displacement corresponding to maximum load of these specimens are 15.10, 9.67 and 7.36 times greater than the reference specimen, respectively. Significant improvements have been achieved in energy dissipation capacity of this group, it is 51.73, 84.76 and 120.50 times greater than the energy dissipation of control specimen.

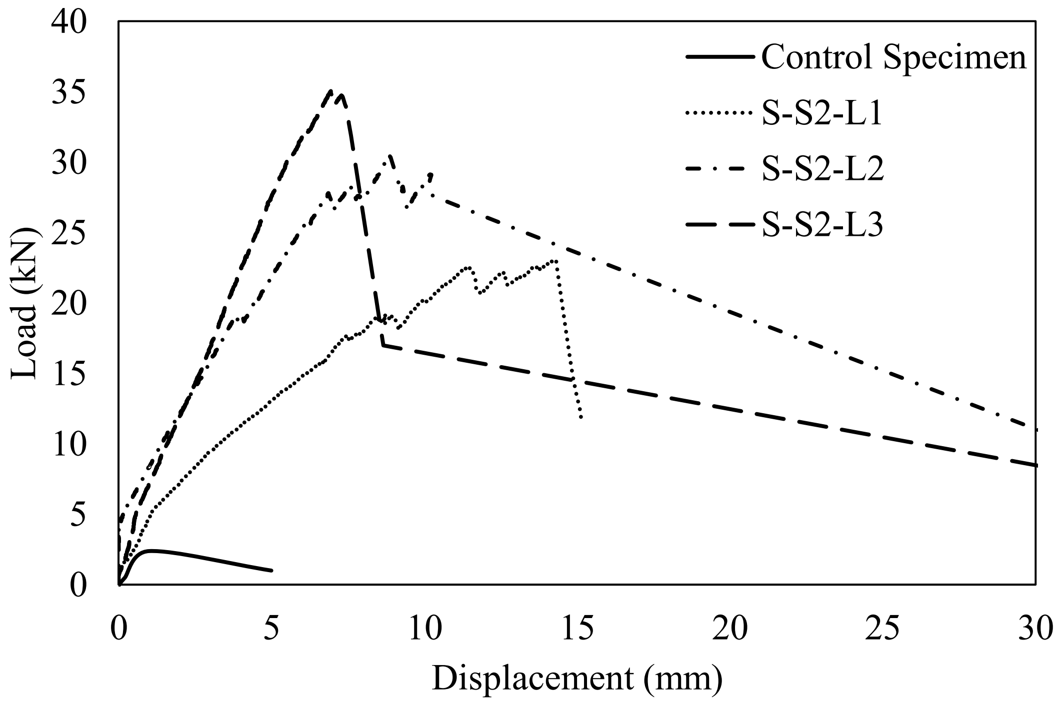


Figure 4.22 Loading displacement comparison Reference& S2 group.

4.2.3 Comparison of Control Specimen with Full covering Group Specimens

The load displacement curves of S-F-L1, S-F-L2, S-F-L3 and control specimen are given in Figure 4.23. The bearing capacity of S-F-L1, S-F-L2 and S-F-L3 is 18.00, 20.28 and 28.23 times greater than the reference specimen, respectively. The displacement capacities of the strengthened specimens have also increased, the displacement corresponding to maximum load of these specimens are 14.78, 9.86 and 8.79 times greater than the reference specimen, respectively. Significant improvements have been achieved in energy dissipation capacity of this group, it is 121.40, 157.36 and 108.10 times greater than the energy dissipation of control specimen.

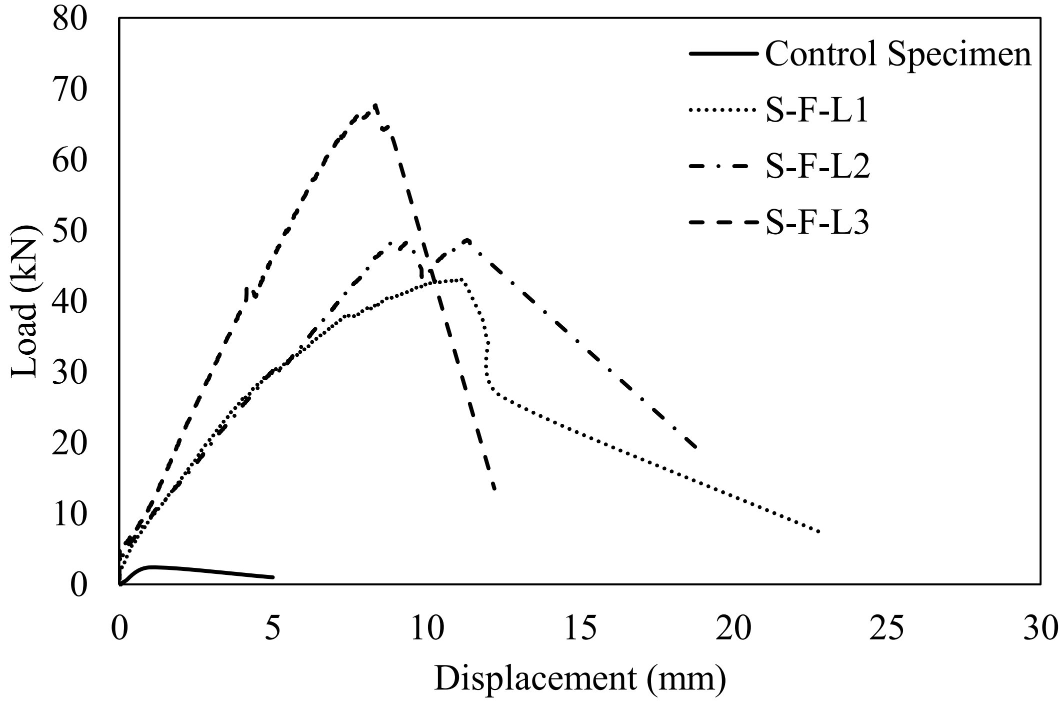


Figure 4.23 Loading displacement comparison Reference& F group.

CHAPTER 5 Conclusion and Recommendations

5.1 CONCLUSION

Within the scope of this study, it was aimed to improve the bearing capacity of the masonry walls in out-of-plane behaviour under bending loading using Carbon Fiber Reinforced Polymer (CFRP) sheets. Accordingly, ten masonry walls were constructed and nine of them were strengthened using CFRP sheets. Three types of strengthening form (with one strip, two strips and full covering) were applied to the masonry walls with different layer numbers (one layer, two layers and three layers). Masonry wall specimens were tested under three-point bending load. The following results were obtained:

- Masonry walls without strengthening are extremely weak in out-of-plane behaviour, it should be taken in consideration the need of strengthening masonry walls especially in the earthquake's regions.
- The reference specimen achieved a load of approximately 3 kN and had an extremely limited displacement (0.95 mm), with an extremely low energy dissipation (4.47 kN-mm).
- When the strengthened specimens are considered, the maximum load capacity was significantly increased by at least 8.41 at S-S1-L1 and at most 28.00 times at S-F-L3 specimen.
- Significant increases were also obtained in the displacement capacities corresponding to the ultimate load of the strengthened specimens. The increment was at least 7.36 times in S-S2-L3 specimen and at most 15.00 times at S-S2-L1 specimen.
- Considering the reference specimen in terms of energy dissipation, which is one of the most important parameters during an earthquake, an increase of up to 157 times was achieved in S-F-L2 specimen.

- Significant increases were also obtained in terms of stiffness corresponding to the ultimate load of the strengthened specimens. The maximum increment in S-F-L3 specimen was 3.20 times greater than the stiffness of the control specimen.
- By the comparison between using two strips with one layer and using of one strip with two layers, it is observed that the bearing capacity of two strips with one layer is 1.084 times greater than one strip with two layers specimens.
- It is thought that the findings of this study can also be useful for retrofitting and strengthening of masonry structures that were damaged by disasters, thus this study achieved the goal of mitigation and preparedness which are an important process in disaster risk reduction cycle.

5.2 Recommendations

Some recommendations that can be taken in consideration for future studies as follows:

- The usage of anchorage can be considered aiming to prevent the CFRP debonding.
- Comparative studies: One possible future study could be to compare the effectiveness of CFRP with other materials that are commonly used for masonry reinforcement, such as steel, wire mesh and TRM.
- Application CFRP strengthening with an Architectural point of view, future studies can define the ideal way that can reinforce historical buildings without effecting architectural values.
- Structural behavior under various loading conditions: It is important to understand how masonry structures reinforced with CFRP will behave under different loading conditions, such as lateral or seismic loads. Future studies could investigate the behavior of masonry walls under diverse loading scenarios, helping to inform the design of structures that can withstand different types of external loads.

- Testing in full-scale models: To validate the effectiveness of CFRP reinforcement of masonry walls, it may be beneficial to conduct full-scale testing of such structures.

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