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Experimental Investigations of Cement Clay Interlocking Brick Masonry Structures Strengthened with CFRP and Cement-Sand Mortar

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Abstract: Many masonry structures are constructed with cement clay interlocking brick (CCIB) due to its added benefits. Recent research has demonstrated the vulnerability of brick masonry walls against seismic loading. Various strengthening materials and techniques are extensively used to improve the structural behavior of brick walls. Carbon fiber-reinforced polymer (CFRP) composites are the most popular strengthening material due to their advantages of easy application, lightweight qualities, and superior tensile strength. The current research work aimed to explore the cost-effective solutions and feasibility of CFRP composite-based strengthening techniques to improve the load-bearing capacity of CCIB walls. Various configurations and combinations of strengthening materials were investigated to customize the cost of repair and strengthening. The experimental results indicated that CFRP composites in combination with cement-sand (CS) mortar are an efficient strengthening material to enhance the strength and ultimate deflection of CCIB walls. The ultimate load-bearing capacity and axial deformation of the strengthened CCIB wall (using two layers of CFRP strips and CS mortar of 10 mm thickness) remained 171% and 190% larger than the unstrengthened CCIB wall. The conclusions of this study are expected to enhance the seismic performance of masonry buildings in developing countries. It should be noted that due to the reduced number of tested specimens, the results to be assumed as general considerations need a wider experimental campaign and a large numbers of tests for each strengthening typology.

Keywords: axial capacity; bricks; cement; clay; CFRP; masonry walls; mortar; strengthening

1. Introduction

Earthquakes pose serious threats to the safety of infrastructure and human life. Modern urban development has caused rapid infrastructural growth, especially masonry structures, which are commonly opted for across the world for construction [1–4]. This is due to its load-bearing characteristics, durability, sound and heat insulation, easy construction, and appealing architectural and aesthetic appearance, etc.

Recent earthquakes have demonstrated that the behavior of the masonry structures is questionable against lateral and diagonal loadings. Masonry structures are known to be an earthquake-prone class of buildings due to their brittle nature. The seismic response of existing masonry buildings has verified the extreme vulnerability of such types of structures. The masonry structures have suffered heavy damage in the recent earthquakes. The destruction has resulted in a huge number of displaced and injured people and high death tolls. The 6.3 magnitude earthquake in Christchurch caused extensive damage to the brick masonry buildings in the city and the masonry structures demonstrated worst performance compared to the reinforced construction [5,6]. Similarly, an earthquake followed by a tsunami in 2004 severely hit Thailand and other regional countries, causing massive destruction to infrastructure and taking precious human lives [7]. The Northern Thailand earthquake of 2011 and the Mae Lao province earthquake in 2014 are recent examples of seismic events of moderate intensity that saw serious destruction to infrastructure and buildings.

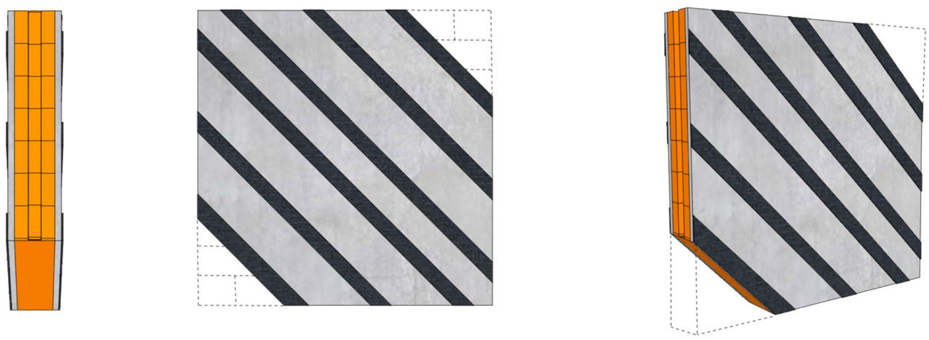
Most buildings in Thailand are constructed with brick masonry and are considered an essential feature of most construction works due to the several benefits of construction and ease in economic manufacturing [8,9]. Numerous researchers have investigated various modification techniques to enhance the performance of brick masonry [10–13]. Interlocking brick masonry is such an innovative example that has now been extensively adopted in Thailand as a replacement for conventional brick masonry. Locally manufactured cement–clay interlocking (CCI) bricks [14,15] are viewed as a feasible alternative to traditional bricks since the placement of CCI bricks requires less cement–sand mortar. The behavior of CCI bricks was investigated by many researchers and the improved performance of CCI bricks under compressive loading has been reported [16,17]. Nevertheless, the behavior of CCI bricks was not found effective under lateral, tensile, and diagonal compression loadings [18,19].

Several researchers have conducted many experimental studies on device-strengthening methods for concrete and brick masonry structures [20–22]. For instance, the effectiveness of using steel rods, mortar jacketing, fiber-reinforced polymer ropes, and fiber-reinforced polymer (CFRP) composites, etc. has been explored for the strengthening of structures [23–31]. Among these techniques, steel rods and mortar jacketing have many disadvantages such as an increase in dimension and weight along with corrosion issues. On the other hand, FRP ropes are low density and have high performance. However, their application to masonry structures could be complex and ineffective [32–35]. Though the improved load-carrying capacity of brick masonry could be realized by CFRP composites, the advantages of CFRP composites are offset by their inflated cost when compared to other, cheaper, techniques for masonry construction. For example, the total estimated strengthening cost of CFRP composites alone could surpass the cost of mortar or concrete jacketing by 100–130% [36–39]. Therefore, it is desirable to explore inexpensive strengthening substitutes for enhancing the overall capacity of CCI brick structures. Thus, this current study is focused on developing efficient and cost-effective retrofitting and strengthening techniques by combining traditional and newly developed strengthening materials for the enhancement of strength and ultimate deflection of the walls of CCI bricks.

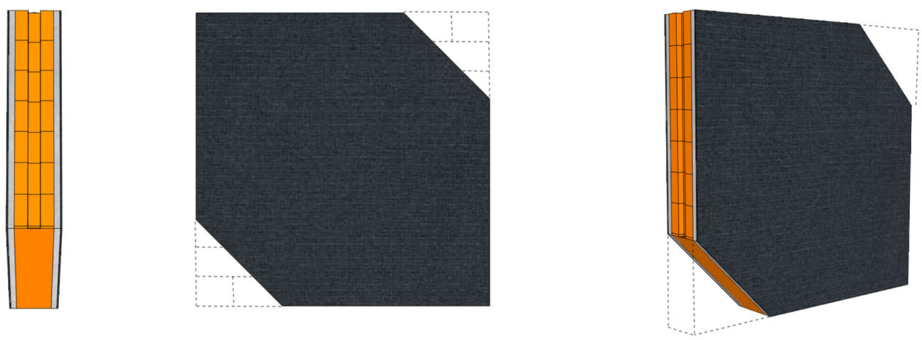
In the present feasibility assessment, the viability of CFRP composite, combined with cement–sand (CS) mortar, which is readily available, and cheaper than CFRP composites, was explored. Furthermore, the bond behavior of CFRP composite with CS mortar and CCI bricks was also investigated due to the lack of understanding of the failure mechanism. First, CFRP composite was directly applied to the CCI bricks using epoxy resin. Next, CS mortar was also finished on the surface of the CCI brick before the application of the CFRP composite. In this way, this work bridges the literature gap by investigating the behavior walls of CCI brick strengthened with the CFRP composite and the CS mortar combination. The outcomes of this study could be extended to regions where bricks are primarily opted for building construction like South Asia to offer efficient design of brick masonry structures. This paper is articulated as follows. Details of experimental programs for the preparation and testing of specimens are provided in Section 2. The key findings of the research are described in Section 3. The conclusions of this study are summarized in Section 4. Finally, recommendations are proposed for prospective research in design improvements of brick masonry construction.

2. Experimental Scheme

Six reinforced walls of CCI brick masonry were examined considering pure diagonal compression conditions to examine the maximum load-bearing capacity and failure modes of specimen walls. Among the six specimens, five were strengthened externally with a combination of CFRP and CS mortar. For reference or as a control, one wall was tested without any exterior strengthening (W-CON). To find out how the CFRP composites, the number of layers, and the use of CS mortar affected the strength and ultimate deflection of walls of CCI brick masonry, the CFRP composites were applied in two different configurations (A and B). In strengthening configuration A, the CFRP composites were applied to the CCI brick walls' whole surface (Figure 1a). On the other hand, the CFRP composite strips were applied in strengthening configuration B (Figure 1b). These configurations were also investigated in combination with 10 mm thick Type-I Portland cement (PC1) sand mortar. The experimental scheme's specifics are shown in Table 1. All wall specimens were designated with names that could systematically illustrate different parameters of research e.g., strengthening the material and its arrangements. For instance, the letter W in W-PC1-10-CFRP-2L indicates the masonry wall, PC1-10-CFRP represents the CFRP combined with 10 mm thick CS mortar, and 2L presents the number of layers of CFRP composites, respectively.



(**a**)



(**b**)

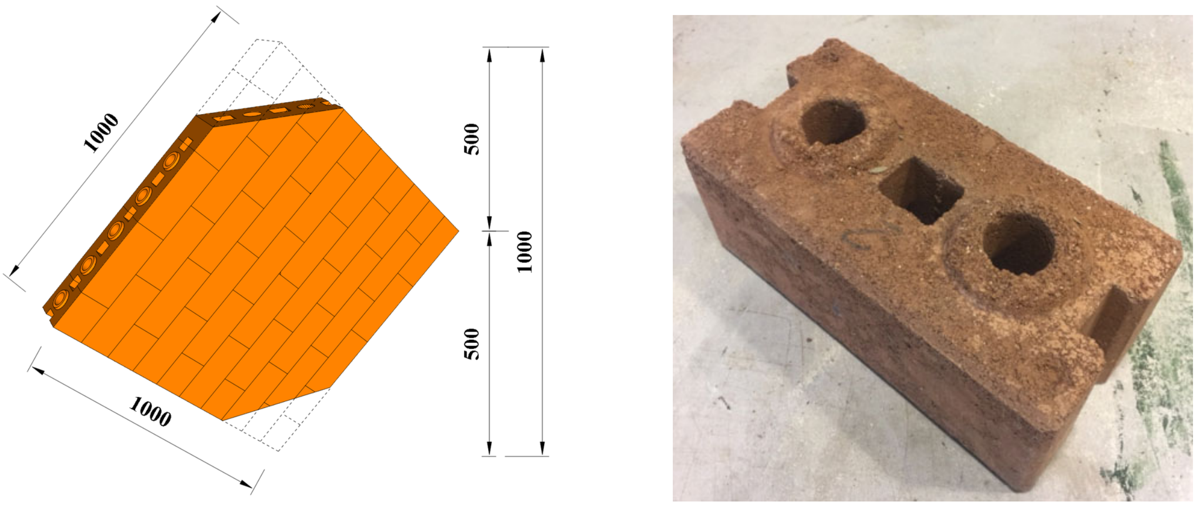
Figure 1. Typical strengthening details: (**a**) Configuration A; (**b**) Configuration B.

Table 1. Details of CFRP strengthening scheme.

CCIB Masonry Walls	Strengthening Material	Configuration	Layers of CFRP
W-CON	-	-	-
W-CFRP-1L	CFRP	A	1
W-CFRP-2L	CFRP	A	2
W-PC1-10-CFRP-1L	CFRP + CS Mortar	A	1
W-PC1-10-CFRP-2L	CFRP + CS Mortar	A	2
W-PC1-10-CFRP-2S	CFRP Strips + CS Mortar	B	2

2.1. Details of CCI Brick Masonry Walls

The wall specimen size was selected according to the conditions of lab facilities like the capability of the reaction frame, load cell, and hydraulic jack. The specimen of CCI brick masonry walls was 1000 × 1000 mm in size (Figure 2a) and the thickness of the wall was kept at 125 mm. The prevailing brick masonry construction practices of Thailand were adopted in the preparation of specimens and locally available CCI bricks were utilized to construct masonry walls with a running bond pattern (Figure 2b). The CCI brick walls were reinforced by inserting 6 mm diameter plain bars in the square holes of the bricks. The steel bars were approximately spaced at 150 mm center to center. Additionally, the CS grout was filled in the circular holes of the CCI brick walls [40].



(**a**) (**b**)

Figure 2. Typical details of the CCI brick masonry wall: (**a**) Wall details (units are in mm); (**b**) CCI brick.

2.2. Properties of Materials

The mechanical properties of locally manufactured CCI bricks were obtained from standard tests [41,42]. The CCI bricks' compressive and tensile strengths, density, and water absorption are summarized in Table 2. River sand and Type I Portland cement, both readily available in the area, were used to prepare the cement–sand (CS) mortar. The CS mortar was tested for compressive strength with standard cubes of 50 × 50 mm. The CS mortar had an average compression strength of 50 MPa. The round steel bars of 6 mm size (RSB6) were tested with the standard testing method to determine their tensile strength. The RSB6 had yield and ultimate tensile strength of 400 MPa and 550 MPa, respectively.

Table 2. Properties of CCI bricks.

Material Property	Test Result	Units
Compressive strength	6.70	MPa
Tensile strength	0.22	MPa
Water absorption	13.0	%
Density	1850	Kg/m3

2.3. Preparation of CCI Brick Wall Specimens

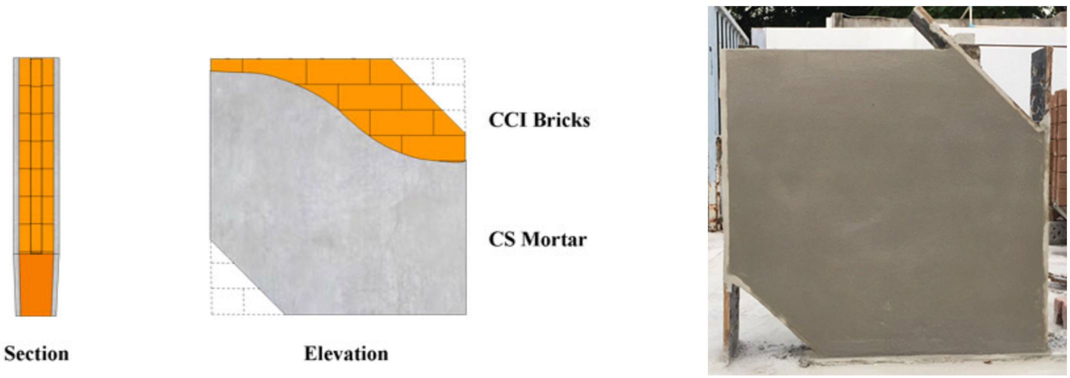
The test specimens of walls of CCI brick were prepared by stacking CCI bricks in a running bond pattern. The walls of CCI brick masonry were reinforced with RSB6. The CS grout was filled in circular holes of CCI bricks and was cured at ambient temperature for seven days.

Next, the unidirectional CFRP composites were applied using epoxy resin to the walls of CCI brick masonry, as shown in Figure 3. The CFRP composites were applied using the hand layup method. The CFRP composites were employed in two configurations, in the form of strips and over the full surface, as shown in Figure 1. In addition, similar configurations were also prepared in combination with the CS mortar.

(**a**) (**b**) (**c**)

Figure 3. Application of epoxy resin and CFRP: (**a**) Epoxy resin applied to the wall; (**b**) Hand layup method of CFRP application; (**c**) Unidirectional CFRP.

For CFRP + CS mortar strengthened walls, Portland cement Type 1 (PC1) was used to prepare the CS mortar. The CCI brick walls were plastered with CS mortar using the conventional hand labor method. Special attention was exerted to attain the required 10 mm thickness of CS mortar. The CFRP composites were then attached to the CCI bricks using Epoxy resin with the method described earlier in Figure 3. The typical details of the CS mortar application are exhibited in Figure 4.



(**a**) (**b**)

Figure 4. CS Mortar Strengthening: (**a**) Details of CS Mortar Strengthening; (**b**) CS mortar strengthened wall.

2.4. Loading Setup and Instrumentation Details

All CCI brick walls were tested using a reaction frame of 2000 kN capacity using the load control method. A hydraulic jack with a capacity of 600 kN was used to apply the diagonal compressive load. The load cell was first calibrated and then positioned under the hydraulic jack's loading piston and the intensity of the load was monitored. A 1000 × 200 × 20 mm size steel plate was used on the top surface of the wall specimen to uniformly apply the load. Total vertical diagonal deformations (L1 and L2), midregion vertical shortening (L3), and lateral dilatation or horizontal extension of the brick wall at the midregion (L4) were assessed with four linear variable differential transducers (LVDTs). The LVDTs were manufactured by Tokyo Measuring Instruments Laboratory Co., Ltd., Shinagawa-ku, Tokyo, Japan. The maximum deformation of these LVDTs was 50 mm. The walls were directly placed on the floor. Prior to their placement, high-performance white cement was used to maintain the level of CCI brick walls. Visual inspection and photographic data were used to track the beginning and growth of cracks during the test. Typical sketches of instrumentation details and loading setup are shown in Figures 5 and 6.

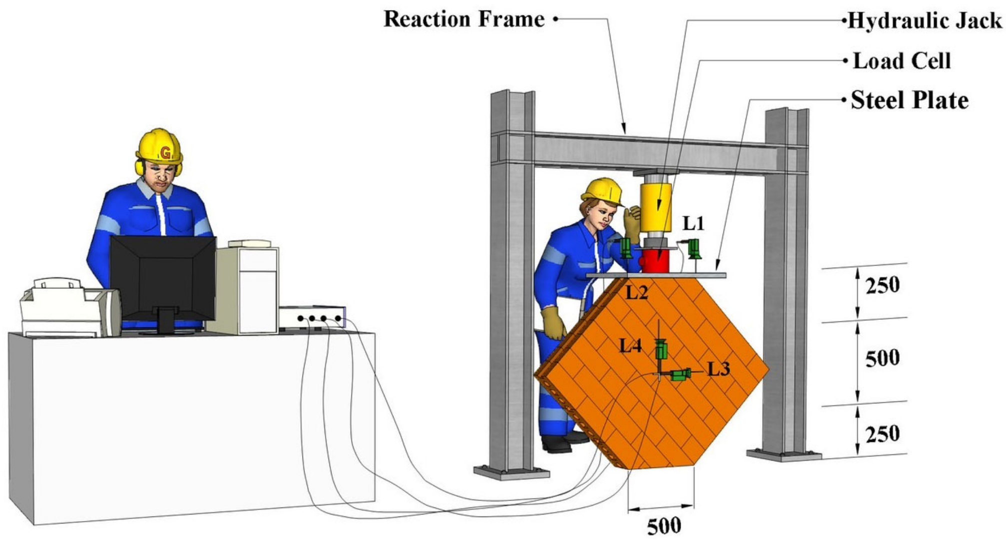


Figure 5. Sketch of loading setup (units are in mm).

Figure 6. Laboratory view of loading setup.

3. Experimental Results

A total of six specimens of walls of CCI brick were prepared to test in diagonal compression loading. Five specimens were externally strengthened using a combination of CS mortar and CFRP composites. The experimental results of strengthened walls were compared with the control wall. The axial load versus deformation, maximum load carrying capacity, maximum deformation, and failure modes of walls of CCI brick are discussed in the following sections.

3.1. Axial Load Versus Axial Deformation Response

The axial load versus the deformation response of the walls of CCI brick are shown in Figures 7–9. The axial deformation was plotted by using the average results of LVDTs L1 and L2. It was found that the stiffness, ultimate load-bearing capacity, and ultimate deflection of the CCI brick masonry walls could be very effectively enhanced by exploiting the combination of CS mortar and CFRP composites.

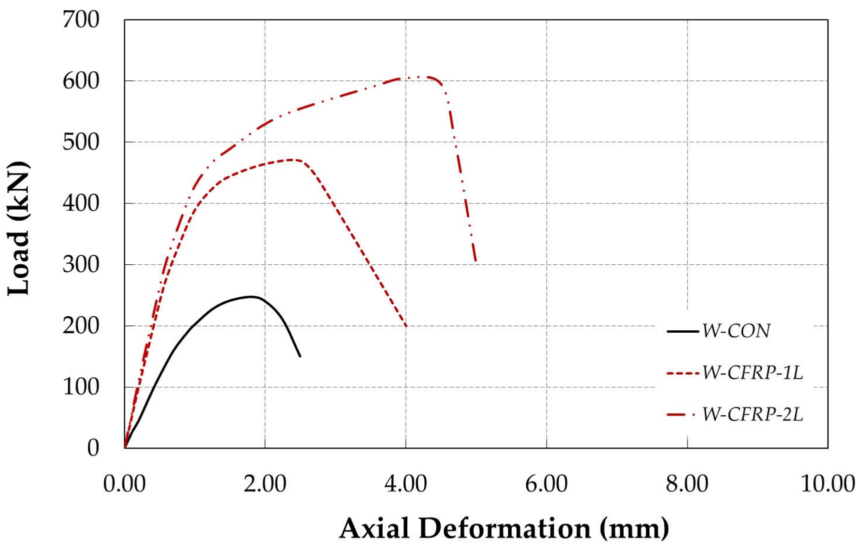


Figure 7. Axial Load versus axial deflection responses (control and CFRP walls).

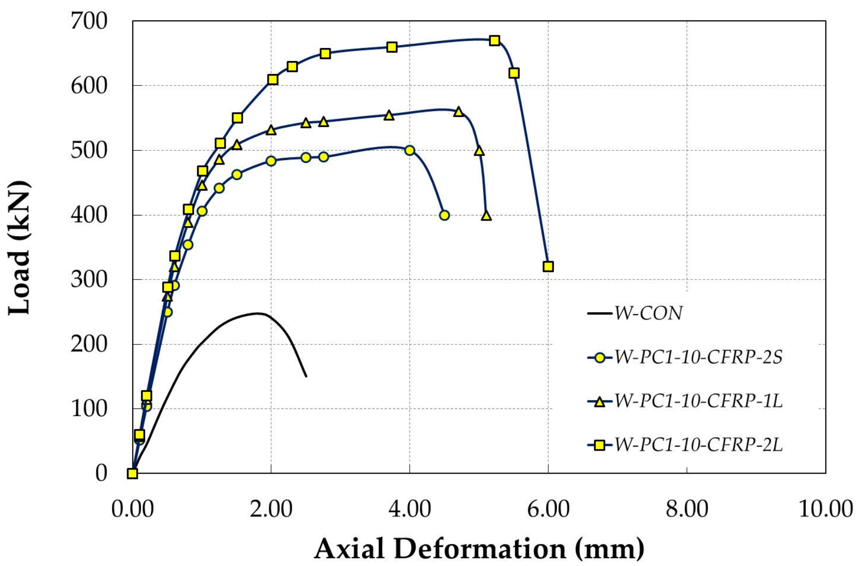


Figure 8. Axial Load versus axial deflection responses (control and CFRP with CS mortar walls).

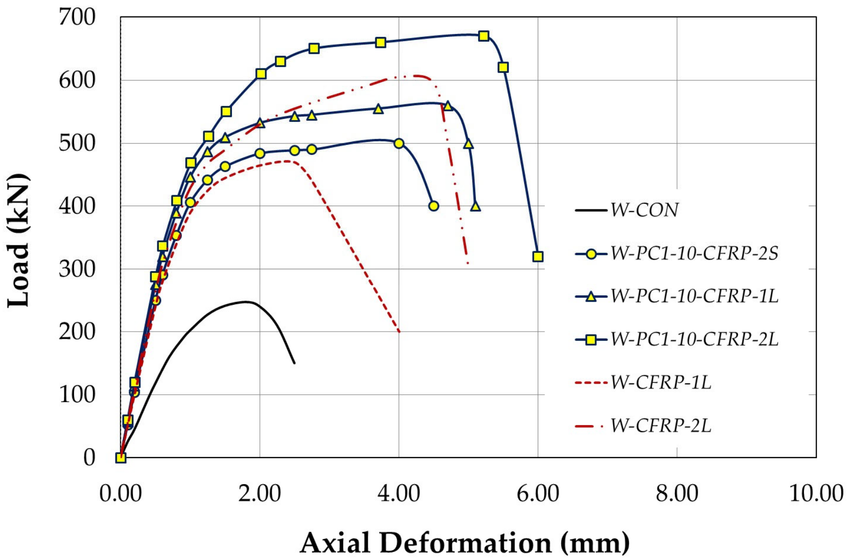


Figure 9. Axial Load versus axial deflection responses of all CCI brick masonry walls.

The control wall (W-CON) exhibited approximately linear axial load versus axial deformation response until the ultimate load. The CCI bricks were crushed at the peak load and the load carrying capacity suddenly decreased. On the other hand, the axial load against axial deformation responses of the strengthened walls were comprised of three parts. The first part of the response is described by a linear line similar to the response of the control wall. The second portion of the curve is a transitional part, where both the load and the deformation of the confined masonry were softened and exhibited a nonlinear behavior accompanied by a large increase in deformation. In the third phase, the load versus deformation responses of the wall again increased linearly until the sudden failure. However, a much lower elastic modulus was exhibited compared to the initial first segment of the curve of strengthened specimens.

3.2. Ultimate Load Bearing Capacity of Walls

The ultimate load-bearing capacity of CCI brick masonry walls was greatly influenced by different strengthening methods such as CFRP and its combination with CS sand mortar. The experimental results of ultimate load-carrying capacity are graphically compared in Figure 10. It can be viewed from the figure that, the CFRP composites alone or in combination with the CS mortar are very effective to improve the ultimate load-bearing capacity of the walls of CCI brick masonry.

The ultimate load bearing capacity of the CFRP composite-strengthened walls (W-CFRP-1L and W-CFRP-2L) was observed 90% and 145% larger than the control wall, respectively. Moreover, the combined use of CS mortar with the CFRP composite further enhanced the maximum load-bearing capacity of the walls of CCI brick. In comparison to the control wall, the ultimate load-bearing capacities of W-PC1–10-CFRP-1L and W-PC1-10-CFRP-2L were raised by 127% and 171%, respectively. Moreover, the performance of strengthening configuration B (CFRP composite strips) was also investigated with the purpose of reducing the cost of the strengthening material. The test results reveal that the use of CFRP composites in strips is also useful to enhance the maximum load-bearing capacity of the CCI brick walls. The maximum load-carrying capacity of the W-PC1-10-CFRP-2S wall was increased by 102% as compared to the control wall.

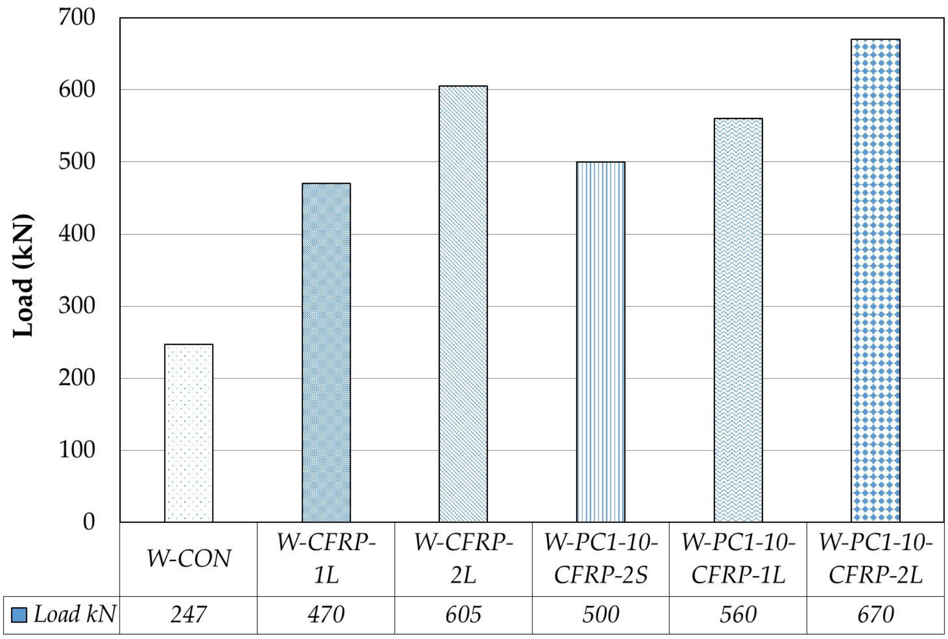


Figure 10. Comparison of ultimate load carrying capacities of CCI brick masonry walls.

3.3. *Ultimate Deflection of CCI Brick Walls*

The results of the experiment for ultimate axial deformation are graphically compared in Figure 11. A maximum of 1.80 mm axial deformation was observed in the control wall (W-CON). The maximum axial deformations of CFRP composites that strengthened the walls (W-CFRP-1L and W-CFRP-2L) were observed to be 39% and 122% larger than the reference wall, respectively. Further, the combined use of CS mortar and CFRP composite effectively enhanced the ultimate axial deformation of the walls of CCI bricks. The maximum axial deformations of the reinforced W-PC1-10-CFRP-1L and W-PC1-10-CFRP-2L walls, made of CFRP composites with CS mortar, were 161% and 190% higher than those of the reference wall, respectively. Further, in the case of the W-PC1-10-CFRP-2S wall (wall specimen of configuration B), the ultimate axial deformation of the CCI brick masonry wall was observed to be 122% larger than the reference wall. These results indicate that the use of CFRP composites in strips could also be useful to enhance the ultimate axial deformation of the walls of CCI brick masonry. The summary of experimental results is provided in Table 3 in terms of ultimate axial load, the percent increase in ultimate axial load, and ultimate axial deflection.

Table 3. Experimental results.

Nomenclature of Walls	Ultimate Load (kN)	% Increase in Ultimate Load	Ultimate Axial Deformation
W-CON	247	-	1.8
W-CFRP-1L	470	90	2.5
W-CFRP-2L	605	145	4.0
W-PC1-10-CFRP-1L	560	127	4.7
W-PC1-CFRP-2L	670	171	5.2
W-PC1-CFRP-2S	500	102	4.0

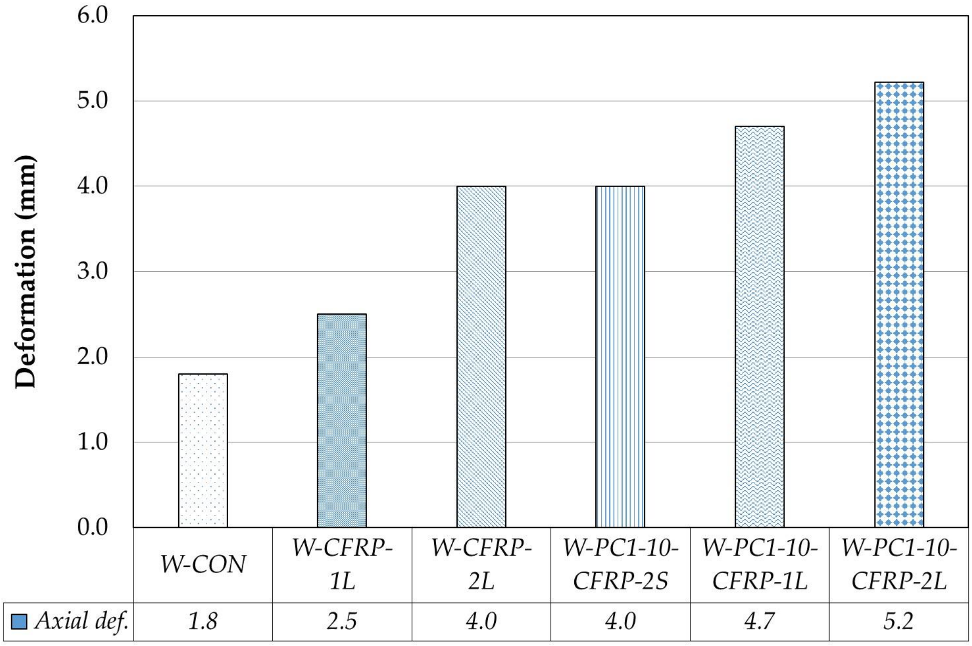


Figure 11. Comparison of ultimate axial deformation of CCI brick walls.

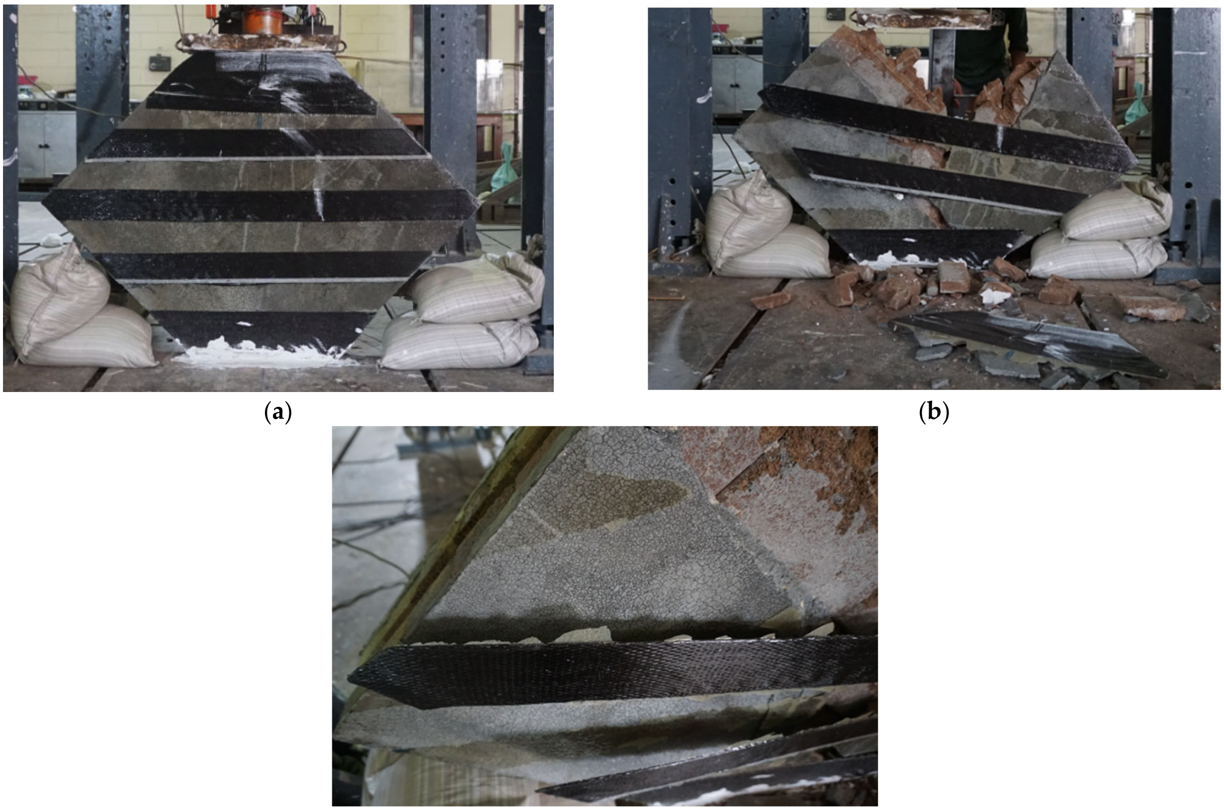
3.4. Modes of Failure of CCI Brick Masonry Walls

The modes of failure of the walls of CCI brick at the ultimate stage are displayed in Figures 12–15. As shown in Figure 12, the CCI brick splitting in the middle of the masonry wall was the primary cause of the control or unstrengthened masonry wall ultimate failure. At the base of the reference wall of CCI brick masonry, severe compression crushing of the CCI bricks was recorded before the ultimate failure, while minor splitting and cracking were also seen there. As illustrated in Figure 13, the final failure of CCI brick masonry walls strengthened with CFRP composites (without CS mortar) was mostly caused by the explosive splitting and crushing of the CCI bricks, together with a quick fall. As illustrated in Figure 14, the eventual failure in the case of walls of CCI brick masonry strengthened with a combination of CS mortar and CFRP composite was caused by the crushing of the CCI bricks and a slight debonding of the CFRP composite from the CS mortar. The CCI brick masonry wall (W-PC1-10-CFRP-2S) that had been reinforced with CFRP composite strips and CS mortar ultimately failed due to severe crushing and splitting of the CCI bricks in the area that was being loaded, as well as the complete debonding of the CFRP strips from the surface of the CS mortar, as shown in Figure 15.

Figure 12. Cracking of control wall at load 247 kN.

Figure 13. Failure of W-CFRP-1L and W-CFRP-2L walls at loads 470 and 605 kN, respectively.

Figure 14. Debonding of CFRP composites from CS mortar at load 450 kN.



(**a**) (**b**)

(**c**)

Figure 15. Ultimate failure modes of W-PC1-10-CFRP-2S wall: (**a**) Before damage at 470 kN; (**b**) Damage of CFRP composite strips wall at load 500 kN; (**c**) Debonding of CFRP composite strips at load 500 kN.

Debonding of the CFRP composites from the wall and compression crushing and splitting of the CCI bricks are two basic categories of the failure process of walls of CCI brick masonry. A splitting and compression crushing failure mode would be inherited by brick masonry. On the other hand, the application of CFRP and CS mortar would offer confinement to the brick masonry and the ultimate failure would be a combination of debonding of the CFRP composite and the crushing and splitting failure of the walls of CCI brick masonry. The failure modes of the walls of CCI brick masonry are summarized in Table 4.

Table 4. Ultimate failure modes of CCI brick masonry walls.

Nomenclature of Walls	Strengthening Material	Failure Modes
W-CON	-	Compression crushing and splitting of the CCI bricks
W-CFRP-1L	CFRP	Explosive splitting and crushing of the CCI bricks along with sudden fall
W-CFRP-2L	CFRP	
W-PC1-10-CFRP-1L	CFRP + CS Mortar	Crushing of the CCI bricks and slight debonding of the CFRP composites
W-PC1-10-CFRP-2L	CFRP + CS Mortar	
W-PC1-10-CFRP-2S	CFRP Strips + CS Mortar	Severe splitting and crushing of the CCI bricks and complete debonding of the CFRP composite strips

4. Conclusions

In order to enhance the performance of walls of CCI brick masonry, this study presents a detailed experimental program to test the efficacy of various strengthening procedures. Six brick masonry wall specimens were prepared, and they were tested under diagonal compression. Different strengthening methods such as CFRP composites and a combination of CS mortar with CFRP composites were employed to strengthen the walls of CCI brick masonry. It was disclosed that the use of CFRP composites in combination with CS mortar can effectively enhance the maximum load-bearing capacity, ultimate deflection, and toughness of walls of CCI brick masonry. Furthermore, the overall cost of the strengthening scheme could be decreased by introducing conventional materials into the strengthening scheme. The following conclusions are deduced based on experimental results.

- The ultimate load-bearing capacity and ultimate deflection of the CCI brick wall are greatly enhanced when CFRP composites are utilized with a CS mortar combination. The strengthening method of configuration A was shown to be more effective than the strengthening method of configuration B; however, strengthening configuration B can still provide practical ways to improve the structural performance of CCI brick walls;
- The increase in maximum axial load-bearing capacity and axial deformation were maximum in the W-PC1-CFRP-2L specimen. The axial capacity of this strengthening scheme was 171% and 26% larger than the W-CON and W-CFRP-2L wall specimens, respectively;
- The as-built or control CCI brick masonry walls exhibited very brittle failure and very low ultimate load-bearing capacity and ultimate deflection. Whereas strengthened walls of CCI brick masonry demonstrated a very ductile ultimate failure mode as compared to the reference wall. The proposed CFRP composites and CS mortar combination-based strengthening techniques were observed to be very promising to improve the ultimate load-bearing capacity and ultimate deflection of walls of CCI brick masonry;
- For future study, appropriate constitutive models need to be established to explore the failure mechanism employing an accurate finite element and analytical modeling techniques. Furthermore, the influence of external reinforcement on the behavior of CCI brick masonry walls needs to be investigated;
- Based on the results of the experiments, it can be inferred that the overall cost of the strengthening program could be substantially decreased by utilizing conventional, low cost, and locally available materials. The CFRP composites, combined with CS mortar, provided an economical solution for the strengthening of CCI brick masonry walls. Similarly, additional work is needed to evaluate the performance of the proposed strengthening scheme with a combination of other viable and economical methods;
- It should be noted that due to the reduced number of tested specimens, the results to be assumed as general considerations need a wider experimental campaign and a large number of tests for each strengthening typology;
- The proposed methods are efficient and applicable to old structures and buildings. However, the proposed strengthening methods were only used for CCI bricks. For wider applications, there is a need to further explore the efficiency of these methods for solid bricks and concrete blocks.

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References

1. Farzampour, A. Compressive Behavior of Concrete under Environmental Effects. In *Compressive Strength of Concret*; BoD–Books on Demand: Norderstedt, Germany, 2019.
2. Farzampour, A. Temperature and humidity effects on behavior of grouts. *Adv. Concr. Constr.* **2017**, *5*, 659.
3. Chalangaran, N.; Farzampour, A.; Paslar, N. Nano Silica and Metakaolin Effects on the Behavior of Concrete Containing Rubber Crumbs. *CivilEng* **2020**, *1*, 17. [CrossRef]
4. Chalangaran, N.; Farzampour, A.; Paslar, N.; Fatemi, H. *Experimental Investigation of Sound Transmission Loss in Concrete Containing Recycled Rubber Crumbs*; Virginia Tech, Virginia Polytechnic Institute and State University: Blacksburg, VA, USA, 2021.
5. Sorrentino, L.; Cattari, S.; Da Porto, F.; Magenes, G.; Penna, A. Seismic behaviour of ordinary masonry buildings during the 2016 central Italy earthquakes. *Bull. Earthq. Eng.* **2019**, *17*, 5583–5607. [CrossRef]
6. Moon, L.M.; Griffith, M.C.; Dizhur, D.; Ingham, J.M. Performance of unreinforced masonry structures in the 2010/2011 Canterbury earthquake sequence. In Proceedings of the 15th World Conference on Earthquake Engineering (15WCEE), Lisbon, Portugal, 11 March 2011.
7. Ruangrassamee, A.; Ornthammarath, T.; Lukkunaprasit, P. Damage Due to 24 March 2011 M6.8 Tarlay Earthquake in Northern Thailand. In Proceedings of the 15th World Conference on Earthquake Engineering (15WCEE), Lisbon, Portugal, 24–28 September 2012.
8. Hendry, A.; Khalaf, F.M. *Masonry Wall Construction*; CRC Press: Boca Raton, FL, USA, 2017.
9. Shakir, A.A.; Mohammed, A.A. Durability Property of Clay Ash, Quarry Dust and Billet Scale Bricks. *J. Eng. Sci. Technol.* **2015**, *10*, 591–605.
10. Lenczner, D. *Elements of Load Bearing Brickwork*; Pergamon Press: Oxford, UK, 1972.
11. Bakhteri, J. Sambasivam, Mechanical Behaviour of Structural Brick Masonry: An Experimental Evaluation. In Proceedings of the 5th Asia-Pacific Structural Engineering and Construction Conference, Johor Bahru, Malasia, 26–28 August 2003; pp. 305–317.
12. Ahmad, A.; Othman, S.Z.; Md Yunus, B.; Mohamed, A. Behaviour of Masonry Wall Constructed using Interlocking Soil Cement Bricks. *World Acad. Sci. Eng. Technol.* **2011**, *60*, 1263–1269.
13. Haach, V.G.; Vasconcelos, G.; Lourenço, P.B. Development of a New Test for Determination of Tensile Strength of Concrete Blocks. In Proceedings of the 12th Canadian Masonry Symposium, Mississauga, ON, Canada, 2–5 June 2013.
14. Cascardi, A.; Leone, M.; Aiello, M.A. Transversal joining of multi-leaf masonry through different types of connector: Experimental and theoreticals investigation. *Constr. Build. Mater.* **2020**, *265*, 120733. [CrossRef]
15. Joseph, S.; McGarry, B.; Sajjakulnukit, B.; Sopchokchai, O. A Study of Brick Production in Thailand. *TDRI Q. Rev.* **1990**, *5*, 11–15.
16. Shakir, A.A.; Naganathan, S.; Mustapha, K.N. Properties of bricks made using fly ash, quarry dust and billet scale. *Constr. Build. Mater.* **2013**, *41*, 131–138. [CrossRef]
17. Ravula, M.B.; Subramaniam, J.L. Experimental Investigation of Compressive Failure in Masonry Brick Assemblages Made with Soft Brick. *Mater. Struct.* **2017**, *50*, 19. [CrossRef]
18. Sandoval, C.; Calderon, S.; Almazán, J.L. Experimental cyclic response assessment of partially grouted reinforced clay brick masonry walls. *Bull. Earthq. Eng.* **2018**, *16*, 3127–3152. [CrossRef]
19. Joyklad, P.; Hussain, Q. axial compressive response of grouted cement–clay interlocking hollow brick walls. *Asian J. Civ. Eng.* **2019**, *20*, 733–744. [CrossRef]
20. Joyklad, P.; Hussain, Q. Performance of Cement Clay Interlocking Hollow Brick Masonry Walls Subjected to Diagonal Compression. *J. Eng. Sci. Technol.* **2019**, *14*, 2152–2170.
21. Joyklad, P.; Hussain, Q. Lateral response of cement clay interlocking brick masonry walls subjected to earthquake loads. *J. Eng. Sci. Technol.* **2020**, *15*, 4320–4338.
22. Sadek, D.M. Physico-mechanical Properties of Solid Cement Bricks Containing Recycled Aggregates. *J. Adv. Res.* **2012**, *3*, 253–260. [CrossRef]
23. Kadir, A.B.A.; Mohajerani, A. Physical and Mechanical Properties of Fired Clay Bricks Incorporated with Cigarette Butts: Comparison between Slow and Fast Heating Rates. *Appl. Mech. Mater.* **2013**, *421*, 201–204. [CrossRef]
24. Theint, P.S.; Ruangrassamee, A.; Hussain, Q. Strengthening of shear-critical RC columns by high-strength steel-rod collars. *Eng. J.* **2020**, *24*, 107–128. [CrossRef]
25. Valluzzi, M.; Tinazzi, D.; Modena, C. Shear behavior of masonry panels strengthened by FRP laminates. *Constr. Build. Mater.* **2002**, *16*, 409–416. [CrossRef]
26. Turco, V.; Secondin, S.; Morbin, A.; Valluzzi, M.R.; Modena, C. Flexural and shear strengthening of un-reinforced masonry with FRP bars. *Compos. Sci. Technol.* **2006**, *66*, 289–296. [CrossRef]
27. Alecci, V.; Barducci, S.; D'Ambrisi, A.; De Stefano, M.; Focacci, F.; Luciano, R.; Penna, R. Shear capacity of masonry panels repaired with composite materials: Experimental and analytical investigations. *Compos. Part B Eng.* **2019**, *171*, 61–69. [CrossRef]
28. Krevaikas, T.D. Experimental study on carbon fiber textile reinforced mortar system as a means for confinement of masonry columns. *Constr. Build. Mater.* **2019**, *208*, 723–733. [CrossRef]
29. Chalioris, C.E.; Kytinou, V.K.; Voutetaki, M.E.; Papadopoulos, N.A. Repair of heavily damaged RC beams failing in shear using U-shaped mortar jackets. *Buildings* **2019**, *9*, 146. [CrossRef]

30. Thomoglou, A.K.; Karabinis, A. Experimental investigation of the shear strength of hollow brick unreinforced masonry walls retrofitted with TRM system. *Earthq. Struct.* **2022**, *22*, 355–372.
31. Mazzuca, P.; Firmo, J.P.; Correia, J.R.; Castilho, E. Influence of elevated temperatures on the mechanical properties of glass fibre reinforced polymer laminates produced by vacuum infusion. *Constr. Build. Mater.* **2022**, *345*, 128340. [CrossRef]
32. Golias, E.; Zapris, A.G.; Kytinou, V.K.; Osman, M.; Koumtzis, M.; Siapera, D.; Chalioris, C.E.; Karayannis, C.G. Application of X-shaped CFRP ropes for structural upgrading of reinforced concrete beam–column joints under cyclic loading–experimental study. *Fibers* **2021**, *9*, 42. [CrossRef]
33. Hussain, Q.; Ruangrassamee, A.; Tangtermsirikul, S.; Joyklad, P.; Wijeyewickrema, A.C. Low-cost fiber rope reinforced polymer (FRRP) confinement of square columns with different corner radii. *Buildings* **2021**, *11*, 355. [CrossRef]
34. Hussain, Q.; Ruangrassamee, A.; Joyklad, P.; Wijeyewickrema, A.C. 2022. Shear enhancement of RC beams using low-cost natural fiber rope reinforced polymer composites. *Buildings* **2022**, *12*, 602. [CrossRef]
35. Golias, E.; Zapris, A.G.; Kytinou, V.K.; Kalogeropoulos, G.I.; Chalioris, C.E.; Karayannis, C.G. Effectiveness of the novel rehabilitation method of seismically damaged RC joints using C-FRP ropes and comparison with widely applied method using C-FRP sheets—Experimental investigation. *Sustainability* **2021**, *13*, 6454. [CrossRef]
36. Yardim, Y.; Lalaj, O. Shear strengthening of unreinforced masonry wall with different fiber reinforced mortar jacketing. *Constr. Build. Mater.* **2016**, *102*, 149–154. [CrossRef]
37. Wahab, N.; Srinophakun, P.; Hussain, Q.; Chaimahawan, P. Performance of concrete confined with a jute–polyester hybrid Fiber reinforced polymer composite: A novel strengthening technique. *Fibers* **2019**, *7*, 72. [CrossRef]
38. Joyklad, P.; Suparp, S.; Hussain, Q. Flexural response of JFRP and BFRP strengthened RC beams. *Int. J. Eng. Technol.* **2019**, *11*, 203–207. [CrossRef]
39. Chaiyasarn, K.; Hussain, Q.; Joyklad, P.; Rodsin, K. New hybrid basalt/E-glass FRP jacketing for enhanced confinement of recycled aggregate concrete with clay brick aggregate. *Case Stud. Constr. Mater.* **2021**, *14*, e00507. [CrossRef]
40. Joyklad, P.; Ali, N.; Verre, S.; Magbool, H.M.; Elnemr, A.; Qureshi, M.I.; Hussain, Q.; Chaiyasarn, K. Experimental Study on the Out-of-Plane Behavior of Brick Masonry Walls Strengthened with Mortar and Wire Mesh: A Pioneer Study. *Infrastructures* **2021**, *6*, 165. [CrossRef]
41. *ASTM C1314-1314*; Standard Test Method for Compressive Strength of Masonry Prisms. ASTM International: West Conshohocken, PA, USA, 2014.
42. *ASTM C1006-07*; Standard Test Method for Splitting Tensile Strength of Masonry Units. ASTM International: West Conshohocken, PA, USA, 2007.