EXPERIMENTAL STUDY ON AXIAL AND DIAGONAL COMPRESSIVE BEHAVIOR OF BRICK MASONRY WALLS

Panuwat Joyklad[1] and Qudeer Hussain[2]

[1]Department of Civil and Environmental Engineering, Srinakharinwirot University Ongkharak Campus, Nakhonnayok 26120, Thailand, panuwatj@g.swu.ac.th

[2]Research Faculty, CONTEC, School of Civil Engineering, Sirindhorn International Institute of Technology, Thammasat University, Thailand, qudeer@kbu.ac.th

ABSTRACT

Masonry is one of the oldest building materials known to the man and is believed to have been in use for over 6000 years. Construction using masonry remains relatively popular in many parts of the world and is practiced widely even today. This study present an experimental investigation on the axial and diagonal compressive response of hollow cement clay interlocking brick masonry walls. Hollow interlocking bricks were collected from the Nakhonnayok Province of Thailand. A total under both pure axial and diagonal compression. Different types of cement-sand grouts (such as ordinary Portland cement and high performance non-shrink cement) with and without steel bars were used to construct the masonry walls. It was evidenced from the experimental results that cement grout impact ultimate load carrying capacity of hollow cement clay interlocking brick masonry walls under axial and diagonal compression. It was also noticed that the reinforced brick masonry walls showed very ductile failure mechanism as compared with unreinforced brick masonry walls along with an increase in the ultimate load carrying capacity of the hollow cement clay interlocking brick masonry walls.

KEYWORDS: Cement, Interlocking Bricks, Masonry Walls, Axial Compression, Diagonal Compression, Compressive Strength, Shear Strength

1. Introduction

Masonry is one of the oldest building materials known to the man and is believed to have been in use for over 6000 years. Construction using masonry remains relatively popular in many parts of the world and is practiced widely even today. Masonry is composed of two different materials namely: the masonry units and the mortar phase. Masonry units may be either solid or hollow and may be made of a wide variety of materials. Clay bricks, blocks of stone, concrete blocks, pressed earth bricks, calcium silicate bricks, soft mud bricks etc. are some examples of masonry units used in masonry construction [1]. The behavior and strength of masonry prisms under compressive loading has been a fundamental research topic [2 -24]. Sarangapani et al. 2005 conducted a series of tests on masonry prisms constructed with very soft solid bricks (modulus of elasticity 500 MPa) and a combination of different mortar grades. It was observed that for the soft brick-stiff mortar masonry, the compressive strength of masonry increases with the increase in bond strength, which increases with the mortar strength along with other factors [25]. Kaushik et al. 2007 investigate the stress-strain characteristics of clay brick masonry and its constituents i.e., solid clay bricks and mortar under uniaxial compression. It was observed that for the strong and stiff bricks and mortar of lesser but the comparable strength and stiffness, the stress-strain curves of masonry do not necessarily fall in between those of bricks and mortar [26]. Similar to the axial compression, several experimental studies have been carried out on the diagonal compression behavior of masonry walls [27, 28]. Sathiparan et al. 2006 conducted diagonal compression tests on non-reinforced and polypropylene mesh reinforced adobe masonry wall specimens. Authors reported that the mesh effect was not observed before the wall cracked. After cracking, the mesh presence positively influenced the wall behavior [27]. San Bartolomé et al. 2009 tested four small walls 800 x 800 x 180 mm under diagonal compression to evaluate the shear resistance. Tests were not effective as detachment occurred during the handling prior to the test, resulting in very low values for shear resistance, which are not cited in the publication [28].

In Thailand, hollow cement clay interlocking bricks made of locally available clay, sand and aggregates along with cement are widely used to construct low rise residential buildings throughout the country. These interlocking bricks are manufactured locally in small factories located in the different regions of Thailand. The manufacturing process of these bricks is essentially comprised of three steps. In the first step, the large size clay boulders are broken into fine pieces by using mechanical grinding machine. In the second step, the fine-grained clay is mixed with cement and water using mechanical concrete mixer. In the final step, the cement-clay mix is placed into the aluminum molds and pressed either by hydraulically or manually operated machines. The pressed bricks are placed in the room temperature for 7-10 days (Figure 1).

Figure 1 Manufacturing process of interlocking hollow bricks

The CCI hollow bricks are usually used for the construction of load bearing and partition walls in different ways such as without using any cement binder, using cement sand grout with and without steel bars. Mechanical properties of these hollow cement clay interlocking brick units have been investigated by many researchers [29-30]. Joyklad et al. 2018 investigated the mechanical properties of local cement-clay interlocking bricks in the central part of Thailand. The interlocking bricks were collected from different regions of Thailand. Results show that each region is following different mix design ratio based on availability of local materials and knowledge [29, 30]. As per author's information there are limited study on the axial and diagonal compressive response of hollow cement clay interlocking hollow brick masonry walls. Therefore, the primary objective of this research is to investigate the axial and diagonal compressive response and deformability of hollow cement clay interlocking brick masonry walls representing existing construction practices in Thailand.

2. Experimental program

2.1 Test matrix

In this study a total number of ten masonry walls were constructed and tested. Whole experimental program is divided into two groups i.e., group A and group B as shown in table

1. Both groups comprised of five hollow cement clay interlocking brick masonry walls. In group A, masonry walls were tested under pure axial compression whereas masonry walls of group B were tested under diagonal compression. In each group, first wall was constructed without using any cement binder, second and third walls were constructed using ordinary Portland cement sand grout and non-shrink cement sand grout without steel bars, whereas, fourth and fifth walls were constructed using ordinary Portland cement sand grout and non-shrink cement sand grout with steel bars. The length and height of the tested masonry walls were 1000 mm x 1000 mm. Wall names are assigned to represent each research parameter. For example in wall specimen 1-A-N-R, first digit is representing wall number, second digit is representing loading type i.e., axial compression, third letter is representing use of cement sand grout and last letter is indicating the presence of steel bars.

2.2 Material properties

In this study, the hollow cement clay interlocking bricks were used to construct the masonry walls. The masonry bricks were collected from the local plant located in the Nakhonnayok province of Thailand. A typical hollow masonry brick sample is shown in the figure 2. The typical dimensions of the bricks used in the experimental program were 250 mm x 125 mm x 100 mm (length x thickness x height). The brick average gross area and net area were 375 cm^2 and 348 cm^2, respectively. According to the Thai community product standards, the lowest compressive strength of clay units is 7.00 MPa [31]. In this experimental program, the average compressive strength of the CCI hollow bricks was recorded as 6.74 MPa, which is considered close to the standard values. Ordinary Portland cement and Non-Shrink cement were manufactured by Siam Cement Public Company Limited, Thailand and General Engineering Company Limited Thailand, respectively. The cement to sand proportion of 1:2 was used for both types of cement grouts. The average compressive strength of Ordinary Portland cement sand grout and Non-Shrink cement sand grout was 25.0 MPa and 50.0 MPa, respectively. The average yield and ultimate tensile strength of steel bars (RB9) was 340 MPa and 440 MPa.

Table 1 Test matrix

Group	Wall	Binding Material	Reinforcement
A	1-A	-	-
	2-A-P	Portland	-
	3-A-N	Non-Shrink	-
	4-A-P-R	Portland	3RB9
	5-A-N-R	Non-Shrink	3RB9
B	1-D	-	-
	2-D-P	Portland	-
	3-D-N	Non-Shrink	-
	4-D-P-R	Portland	3RB9
	5-D-N-R	Non-Shrink	3RB9

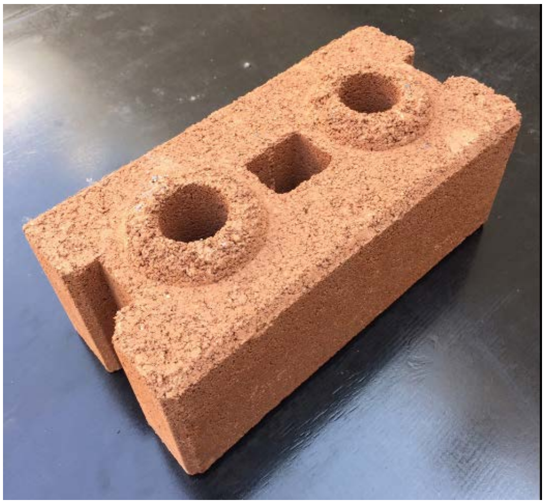

Figure 2 Typical hollow brick sample

2.3 Construction of masonry walls

All masonry walls were constructed in the running bond pattern as shown in the figures 3 and 4. Two masonry walls (1-A and 1-D) were constructed in such a way that hollow cement clay interlocking bricks were placed over each other in the running bond pattern without using any mortar or grout to bind bricks to each other as shown in figure 5. The construction of the cement grouted un-reinforced (2-A-P, 3-A-N, 2-D-P and 3-D-N) masonry walls were similar to the first wall, however, after the construction, the circular and square holes in the bricks were filled using ordinary Portland cement sand grout and non-shrink cement sand grouts, respectively (Figure 6). The remaining walls (4-A-P-R, 5-A-N-R, 4-D-P-R and 5-D-N-R) were also grouted with Portland cement sand and non-shrink cement sand mortar, respectively, however, prior to the grout filling, steel bars (RB9) were also inserted into the holes at different locations to reinforce the masonry walls. A schematic diagram of the different construction techniques is shown in the figure 7 and walls are shown in figure 8.

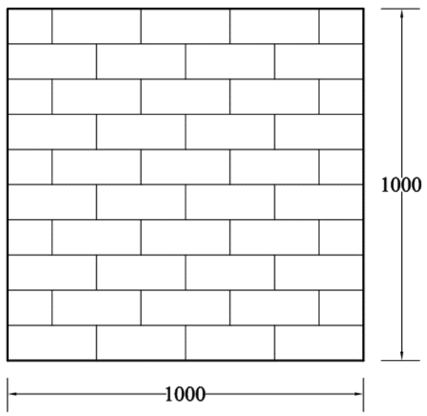

Figure 3 Details of axial wall (units in mm)

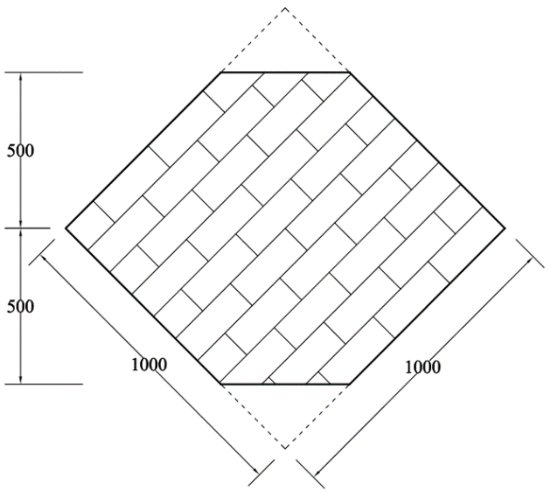

Figure 4 Details of diagonal wall (units in mm)

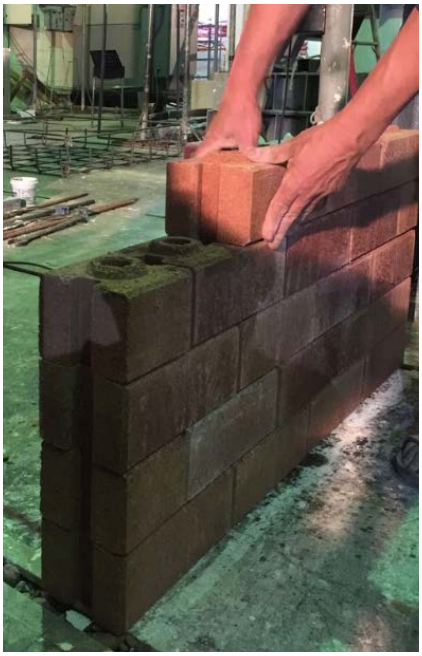

Figure 5 Typical construction of masonry walls

Figure 6 Typical grouting technique

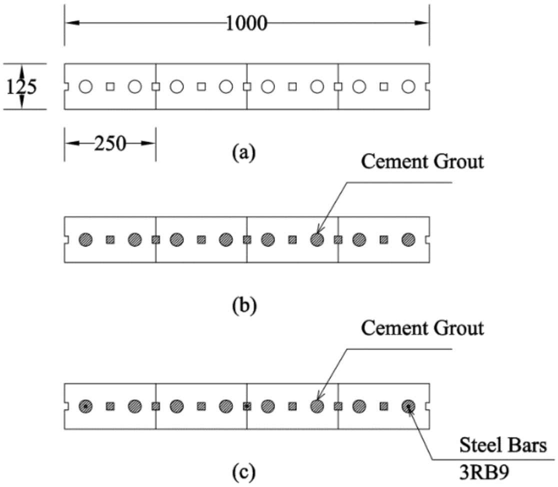

Figure 7 **Construction techniques; (a) un-grouted masonry walls, (b) grouted and un-reinforced masonry walls, (c) grouted and reinforced masonry walls**

Figure 8 **Typical brick walls**

2.4 Instrumentation and loading setup

In this research, the hollow cement clay interlocking brick masonry walls were tested under the pure axial and diagonal compression in the reaction frame having a capacity of 2000 kN. The axial load was applied using a hydraulic jack and load intensity was recorded through a calibrated load cell placed under the loading piston of the hydraulic jack as shown in figures 9 and 10. The hollow cement clay interlocking bricks walls were instrumented with two (L1 and L2) linear variable differential transducers (LVDTs) to measure the axial and diagonal deformation of the masonry walls. During the test, the initiation and propagation of cracks were visually inspected and recorded by photographs.

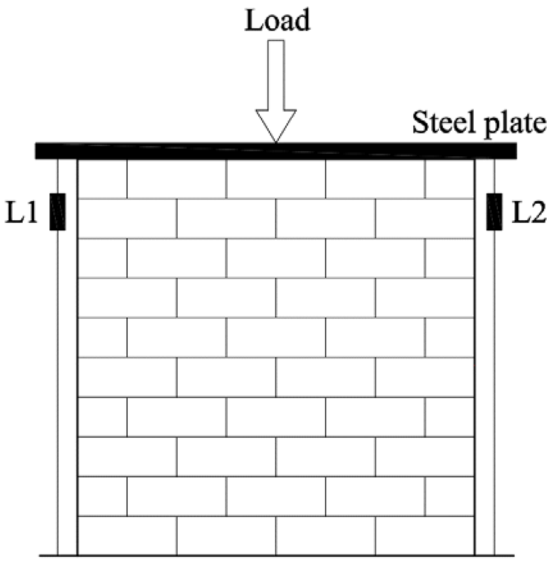

Figure 9 Axial compression loading setup

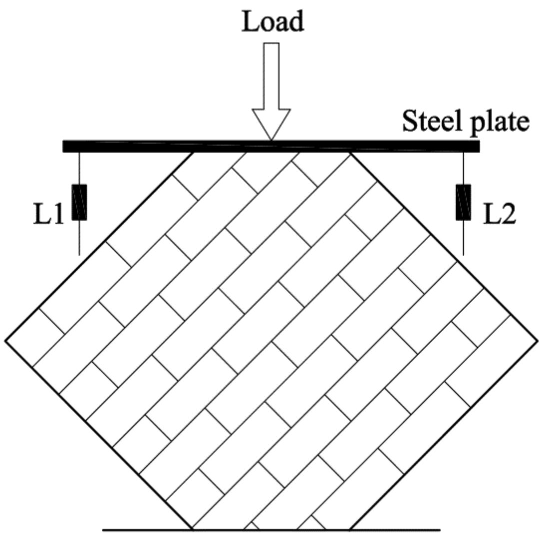

Figure 10 Diagonal compression loading setup

3. Experimental Results

3.1 Test matrix

The axial load versus axial deformation responses of the hollow cement clay interlocking brick masonry walls are displayed graphically in the figure 11. The experimental results in the term of ultimate load carrying capacity, % increase in the ultimate load carrying capacity and the axial deformation of the masonry walls against the ultimate load carrying capacity are summarized in the table 2.

Table 2 Experimental results (group A)

Wall	Ultimate load (kN)	% increase in ultimate load as compared with wall 1-A	Axial deformation against ultimate load (mm)
1-A	310.0	-	3.80
2-A-P	635.0	105.0	2.90
3-A-N	850.0	174.0	2.70
4-A-P-R	700.0	126.0	2.60
5-A-N-R	880.0	184.0	2.50

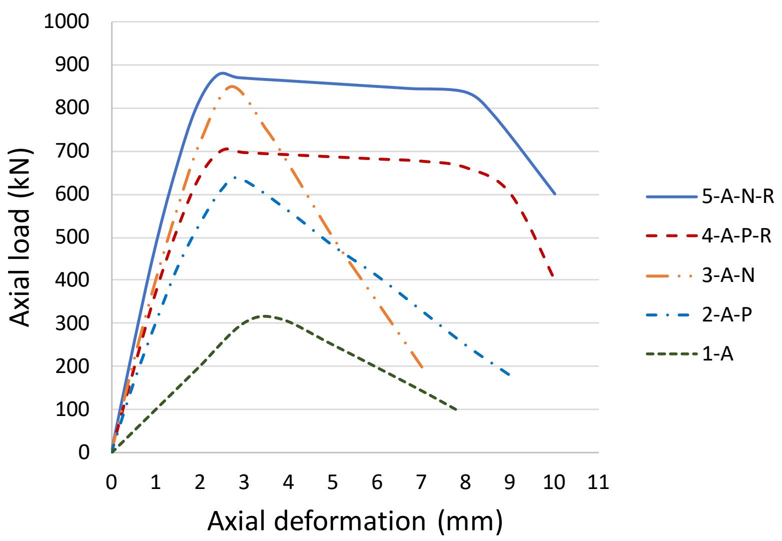

Figure 11 Experimental results (group A)

The un-grouted masonry wall specimen (i.e., 1-A) was failed at the ultimate load of 310.0 kN and axial deformation against the ultimate load was 3.80 mm. Further, it can be seen (Table 2 and Figure 11) that use of both kinds of cement grouts (i.e., Portland cement and non-shrink cement) is very useful to enhance the ultimate load carrying capacity of the both reinforced and un-reinforced masonry walls. The masonry wall specimen (2-A-P) was reached an ultimate load of 635.0 kN which was 105% higher as compared with the hollow brick masonry wall 1-A. The load carrying capacity of the wall specimen 3-A-N was recorded 174% and 69% higher than the wall specimens 1-A and 2-A-P. The peak load of the wall specimen 4-A-P-R was increased by 126% and 21% as compared with wall specimen 1-A and 2-A-P, respectively. Increases of 184% and 58% in the ultimate load carrying capacity of wall specimen 5-A-N-R were observed as compared with wall specimens 1-A and 3-A-N-R, respectively. It is evident from the experimental results that cement sand grouts and use of steel bars is every effective to enhance the ultimate load carrying capacity of masonry walls under pure axial compression. Further, it can also be noticed that the performance of non-shrink cement sand grout is superior as compared with ordinary Portland cement sand grout. This is mainly because of higher compressive strength of the non-shrink cement sand grout as compared with the ordinary Portland cement sand grout.

3.2 Masonry walls of group B

The diagonal load versus diagonal deformation responses of the hollow cement clay interlocking brick masonry walls are displayed graphically in the figure 12. The experimental results in the term of ultimate load carrying capacity, % increase in the ultimate load carrying capacity and the diagonal deformation of the masonry walls are summarized in the table 3. The un-grouted masonry wall specimen (i.e., 1-D) was failed at the ultimate load of 27.50 kN and average diagonal deformation against the ultimate load was 12.5 mm. Similar to the axial compression, it can be seen (Table 3 and Figure 12) that use of both kinds of grouts (i.e., ordinary Portland cement sand and non-shrink cement sand grout) is very useful to enhance the diagonal load carrying capacity of the both reinforced and un-reinforced masonry walls. The masonry wall specimen (2-D-P), in which square and circular holes were filled using ordinary Portland cement sand grout was reached ultimate load of 110.0 kN which was 300% higher as compared with the un-grouted hollow brick masonry wall i.e, 1-

D. The load carrying capacity of the wall specimen 3-D-N was recorded 500% and 200% higher than the wall specimen 1-D and 2-D-P, respectively.

Table 3 Experimental results (group B)

Wall	Ultimate load (kN)	% increase in ultimate load as compared with wall 1-D	Diagonal deformation against ultimate load (mm)
1-D	27.5	-	12.5
2-D-P	110.0	300.0	1.55
3-D-N	165.0	500.0	2.70
4-D-P-R	140.0	409.0	1.70
5-D-N-R	180.0	555.0	3.00

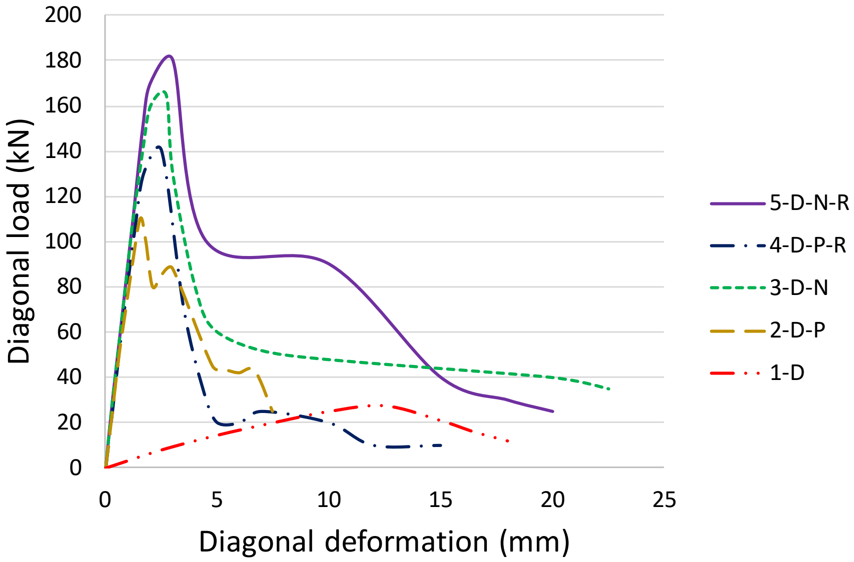

Figure 12 Experimental results (group B)

The peak diagonal compressive load of wall specimen 4-D-P-R was increased by 409% and 109% as compared with wall specimen 1-D and 2-D-P, respectively. Increases of 555% and 145% in the ultimate diagonal load carrying capacity of wall specimen 5-D-N-R were observed as compared with wall specimen 1-D and 3-D-N, respectively. The ultimate load carrying capacity of reinforced masonry walls is found higher than the unreinforced masonry walls which is mainly due to the presence of steel bars. It is evident from the experimental results that the use of steel bars is very effective to alter both ultimate load carrying capacity and ultimate failure mechanism of the CCI brick masonry walls. In case of reinforced masonry walls, it can be seen that right after peak load, there is a sudden drop in the load carrying capacity up to the 50% level of the total loading carrying capacity and after that masonry walls are still capable to carry load. This phenomenon is in contrast to the pure axial compression response as shown in figure 11. This can be associated with the crushing and tensile behavior of the bricks and steel bars. The drop in the peak load is mainly due to the crushing of the bricks and after that there is force stress transformation from the bricks to the steel bars thus resulting into the further stability in the ultimate load carrying capacity at 50% level of drop in the load carrying capacity.

3.3 Failure modes of masonry walls

The typical failure modes of hollow cement clay interlocking brick masonry walls tested in axial and diagonal compression are shown in the figures 13-15. In general, the final failure of the brick masonry walls under axial compression was mainly due to the splitting and crushing of the interlocking bricks under the loading region as shown in figures 13-15. Whereas in case of diagonal compression, the final failure of the masonry walls was mainly due to along the compressed diagonal, sliding of the hollow cement clay interlocking bricks along the bed joint (at bottom region) and crushing of the hollow bricks under loading region as shown in figures 16-18. The ultimate failure of the un-reinforced cement grouted masonry walls was observed brittle and sudden. In contrast to the unreinforced masonry walls, the overall response of the steel reinforced masonry walls were found significantly ductile as compared with unreinforced masonry walls. The term ductile is used to indicate a stable and gradual post peak response (such as in case of wall specimens 4-A-P-R and 5-A-N-R) as compared with sudden post peak responses of walls specimens 2-A-P and 3-A-N.

Figure 13 Failure mode of wall specimen 1-A

Figure 14 Typical failure mode of cement grouted un-reinforced walls (Axial compression)

Figure 15 Typical failure mode of cement grouted reinforced walls (Axial compression)

Figure 16 Failure mode of wall specimen 1-D

Figure 17 Typical failure mode of cement grouted un-reinforced walls (Diagonal compression)

Figure 18 Typical failure mode of cement grouted reinforced walls (Diagonal compression)

4. Conclusions

A series of tests has been conducted to study the axial and diagonal compressive response of hollow cement clay interlocking brick masonry walls. Different construction methods and techniques were adopted to investigate their influence on the ultimate load carrying capacity and axial deformation behavior of the hollow brick masonry walls. From the experimental results, it can be concluded that the hollow brick masonry wall built without using cement-sand grout shows large deformation under axial and diagonal loading. The cement sand grouted masonry walls (unreinforced masonry walls) resulted in higher ultimate load carrying capacity and less deformation as compared with un-grouted masonry wall. The overall response of the steel reinforced masonry walls were found significantly improving in terms of ultimate load carrying capacity and final failure modes.

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Author's Profile

Panuwat Joyklad (Ph.D), Assistant Professor, Srinakharinwirot University, Thailand. E mail: panuwatj@g.swu.ac.th

Qudeer Hussain (Ph.D), Research Faculty, CONTEC, School of Civil Engineering, Sirindhorn International Institute of Technology, Thammasat University, Thailand. Email: qudeer@kbu.ac.th