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EXPERIMENTAL IN-PLANE COMPRESSION TEST OF BRICK MASONRY WALLS WITH REINFORCEMENT RATIO

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ABSTRACT

Perforated clay brick masonry is a popular and widely used construction, offering both structural and aesthetic benefits. The structural behavior of perforated clay brick masonry walls is a significant topic in the field of civil engineering. However, understanding the compressive and tensile strength of these walls are influenced by various factors such as the quality of mortar joints, the distribution of mortar, and the presence of reinforcement. The purpose of this study is to investigate the compressive behavior of four perforated clay brick masonry walls, using cement-sand mortar, with two different systems under in-plane compression load. The first masonry system is unreinforced with filling joints, and the other system is reinforced by steel bars embedded in the mortar as a low reinforcement ratio. The study provided valuable arguments about how mortar distribution affects wall performance, which is significantly impacted by poor quality of head joints and the fully or partially distributed mortar in the masonry joints. Also, the role of low reinforcement ratio within the construction industry has important effect. The mentioned parameters are investigated through practical case studies demonstrating their effects in the context of ductility and ultimate load capacity. It was found that the compressive strength of the unreinforced masonry system is highly increased to the distribution of the mortar by 35 % and 133% for filling all holes in brick units and the head joints, respectively, due to increasing the bonding between brick units in the masonry wall specimen. In the reinforced masonry system, the utilization of a low reinforcement ratio is increased the ultimate load capacity by 60% and decreased the ultimate displacement by 54%., but it is no longer provided significant changes to the ductility.

KEYWORDS

Masonry structure, Brick wall, Reinforced masonry, Head joint, Reinforcement ratio.

1. INTRODUCTION

Brick masonry is the most traditional and extensively utilized type of construction. It is preferred due to its affordability, good soundproofing, strong compressive strength, heat absorption, and availability (Ullah et al., 2022). Brick masonry is a non-homogeneous material with two constitutive elements: bricks and mortar, which is usually called unreinforced brick masonry and sometimes shortened to URM. The spaces between bricks that are filled with mortar are called masonry joints, which are usually named bed and head joints (Wakita and Linde, 2003). The mortar has different functions inside the masonry; that is, it forms a layer to assemble the bricks and permits a uniform transmission of the internal forces (Christy et al., 2013). In contrast, reinforced brick masonry, sometimes shortened to RM, is a construction system where steel reinforcement is embedded in the mortar or placed in the holes and filled with grout (Rai, 2005). Steel reinforcement used in masonry structures involves reinforcement bars, joint reinforcement, steel mesh, and deformed reinforcing wire (Narendra, 2010). Reinforcement has important advantages for masonry structures as it gives extra rigidity, permitting better utilization of brickwork's unassailable compressive quality (Vishal et al., 2019). Generally, it is important that the mechanical properties of the brick masonry, which involve compressive behavior and other characteristics such as diagonal shear and tensile tests, depend on the mechanical properties of the constitutive materials as well as the arrangement of the bricks inside the masonry (Christy et al., 2013).

A significant amount of research on the behavior of reinforced and unreinforced brick masonry under compression currently exists. The research studied many factors affecting the behavior of masonry, including the type and strength of brick and mortar, joint thickness, and type of reinforcement. (Da Porto et al., 2011) designed a reinforced masonry system for seismic areas using two forms of steel reinforcing and brick units with horizontal perforation: common steel bars or prefabricated trusses. At the wall edges or crossings of the masonry system, vertically perforated units are utilized in the construction of confining columns for vertical reinforcement. The behavior of the reinforced masonry system under compression was evaluated both on masonry specimens with and without confining columns. Tests showed 44% increase in compressive strength; The first crack was found at the intersection of the masonry panels and confining columns. As well, the two types of horizontal reinforcement had no significant impact on strength or deformability. Also, (Christy et al., 2013) investigated the design strength of short brick masonry prisms, which have been tested under axial compressive load. Two types of masonry units were used: clay brick and fly ash brick with using 1:6 cement-sand mortar with 0, 10 and 20% replacement ratio of fine aggregate with fly ash. The brick masonry is reinforced with woven wire mesh at the alternate bed joint and tested for the axial strength and elastic modulus of the prism specimens. The authors concluded that adding wire mesh to clay brick masonry increased its load-bearing capacity by 25%. However, adding wire mesh to fly ash brick masonry increased its load-bearing capacity by 10%. Also, the replacement ratio of 20% fine aggregate with fly ash had higher compressive strength. As well, (Basha and Kaushik, 2015) studied the non-linear stress-strain properties of clay brick masonry with weak bricks and strong mortar. Bricks made of fly ash were chosen because their compressive strength was lower than the mortar. To investigate the non-linear behavior of weak brick-strong mortar and the impact of mortar strength on masonry, prisms were built using three distinct grades of cement-sand mortar: strong (1:3), intermediate (1:4) and weak (1:6). The findings showed that, in comparison to strong brick-weak mortar masonry, weak brick-strong mortar masonry had a lower strength. Additionally, compared to strong brick-weak mortar masonry, the failure strain seen in the weak brick-strong mortar masonry example was noticeably higher. On the other hand, (Vishal et al., 2019) implemented a comparative analysis of reinforced and unreinforced brick masonry walls. The compressive behavior and other characteristics of the brick masonry, such as diagonal shear, water absorption, and tensile tests, were being carried out. Moreover, the crack patterns for reinforced and unreinforced masonry walls were compared with each other. Reinforced wall specimens constructed using plane or ladder-type reinforcement placed horizontally. Through this analysis, the test results of compression and diagonal shear of reinforced masonry were higher than the unreinforced specimens. Moreover, the ladder reinforcement gives a higher load-bearing capacity.

Furthermore, (Zengin et al., 2020) investigated the effect of joint thickness and material factors on the performance of clay brick masonry walls. The study analyzed the mechanical properties of materials used in historical and conventional masonry wall structures, such as solid and perforated clay brick. In the production of mortars, two different types of binders were used cement and natural hydraulic lime with a constant binder-aggregate ratio of 1:3. Twelve distinct combinations were created using three different joint thicknesses. The bed joint thicknesses were set at 10, 20, and 30 mm, and the head joint thicknesses were set at half that of the horizontal joint. It was found that joint thickness significantly affected the occurrence of wall damage and wall balance. The results exhibited that a 20 mm bed joint thickness is preferred for wall production due to its convenience and higher strength. Also, the strength of walls produced from cement mortar was found to be higher than lime mortar. Moreover, (Khalifa and Al-Wazni , 2021) investigated the mechanical properties of the brick masonry walls in the Imam Ali Holy Shrine structure, assessing the compressive strength of brick units and mortar samples.

They adopted two types of gypsum mortars and clay brick units, historical and traditional. The historical brick unit and mortar used experimentally in this study were taken from the Imam Ali holy shrine structure during the rehabilitation. The typical mortar is Iraqi gypsum, which can be found in the local market, and the traditional brick is Iranian yellow brick, which was utilized to repair two minarets. They concluded that the traditional brick units and mortar samples exhibited weaker mechanical properties than the historical samples, which were 19% and 14% in brick unit and mortar compressive strength, respectively. Further, (Dehghan et al. ,2022) introduced an experimental study utilizing two common varieties of solid and hollow burnt clay bricks in masonry building to ascertain and compare the mechanical characteristics of masonry prisms. Also, they used two types of cement-sand mortars strong (1:3) and weak (1:5). The findings demonstrated that mortar type has a greater effect on brick prism compressive strength, brick panel diagonal-tensile strength, and brick prism direct shear strength than brick shape. Additionally, the authors concluded that masonry examples with hollow bricks and sturdy mortar performed better than all other cases they examined.

In the present study, indications are generally investigated to characterize the structural response of unreinforced and reinforced perforated clay brick masonry wall in cases of fully or partially distribution of cement-sand mortar in head joints (poor quality of head joints), as well as in the holes of the perforated masonry units under compression loads. Also, the effect of reinforcement ratio on the compressive strength capacity of the brick masonry wall is considered. These aspects are particularly important for the behavior of masonry wall because it is consequently affecting its strength and ductility properties. The literature is limited to experimental studies on the effect of brick material, brick type (solid or hollow), mortar strength, and joint thickness on the behavior of brick masonry (Christy et al., 2013; Basha and Kaushik, 2015; Zengin et al., 2020; Khalifa and Al-Wazni, 2021; Dehghan et al., 2022), as well as some studies on the type of reinforcement (bars, mesh, fabricated truss, or ladder reinforcement) used in masonry construction (Da Porto et al., 2011; Christy et al., 2013; Vishal et al., 2019). Therefore, it is necessary to carry out further experimental investigation on this response due to a lack of information in this field.

2. EXPERIMENTAL PROGRAM

In this research, the experimental program includes three steps: material properties, specimen preparation, and test setup.

2.1. Material properties

Masonry is made up of brick unit and mortar, and in order to comprehend how a masonry wall will behave under compression, each component's characteristics must be assessed individually (Basha and Kaushik, 2015). The properties of the assemblage materials (brick units, mortar, and reinforcement) were considered. In this study, vertically perforated clay brick as a masonry unit and cement-sand mortar were used in the erection of wall specimens since they have been commonly preferred in the production of conventional masonry structures. The clay bricks have dimensions of (230×110×70) mm in length, width, and height, respectively. Six brick units are tested, the test is conducted in two manners: the first is applying the load to the lateral face of area (230×70) mm^2, while the second is normal to top face, standard manner, of area (230×110) mm2. This type of testing was to extract the difference in compressive stresses between the two methods. The results of compressive testing for the brick units in both ways are listed in Table1.

Table 1. Test results of brick units

No.	Direction	Load (kN)	Compressive Stress (MPa)	Average Value (MPa)	Mass (kg)
1	Lateral	75.30	4.677		2.820
2	Lateral	73.10	4.540	5.455	2.794
3	Lateral	115.10	7.149		2.790
4	Normal	395.60	15.636		2.648
5	Normal	466.80	18.451	16.250	2.788
6	Normal	371.00	14.664		2.782
Average					2.770

Ordinary Portland cement (Type I) manufactured in the Kufa cement plant and conforming to ASTM C150-07 is used in this work. Natural sand with characteristics conforming to ASTM C33/C33M-18 is also used. The testing results of natural sand are shown in Table 2 and Table3, respectively. The cement mortar is used in masonry walls and with mixing of 1:3 (cement: sand) weighting ratio. Six cubic samples with dimensions of (50×50×50) mm are tested in the lab according to ASTM C109-12 to extract the compressive stress of cement mortar, as shown in Fig 1. The results of compressive testing for two groups of the cement mortar cubic samples are listed in Table 4. The groups are classified according to the water/cement ratio used; the first group has a 0.45 ratio, and the second has a 0.50 ratio. The reason of using two water/cement ratios is to recognize the effect of increasing water on the mortar strength of brick masonry wall. It is clear from Table 4 that the low water/cement ratio has effect on mortar strength by increasing cubic strength of 8.8%. In this study, the water/cement ratio of 45% is adopted for erecting the masonry wall specimens.

Table 2. Sieve analysis of natural sand

Sieve Size	Passing %	ASTM C33/C33M-18
9.5 mm	100	100
4.75 mm	99	95-100
2.36 mm	92	80-100
1.18 mm	83	50-85
600 µm	55	25-60
300 µm	28	5-30
150 µm	7	0-10

Table 3. Physical properties of natural sand

Property	Test result	ASTM C33/C33M-18
Fines Modulus	2.36	–
Materials finer than sieve 75 µm %	3.9	≤ 5

Fig. 1. Casting and testing of cement mortar cubic sample

Table 4. Test results of mortar cubic samples

Group	water/cement	Load (kN)	Compressive Stress (MPa)	Average Value (MPa)
A-1	0.45	58.70	23.48	24.13
A-2	0.45	61.40	24.56	
A-3	0.45	60.90	24.36	
B-1	0.50	53.30	21.32	22.17
B-2	0.50	57.60	23.04	
B-3	0.50	55.40	22.16	

For the reinforced masonry wall (RM), horizontal reinforcement made of 8 mm deformed steel bars is used. The reinforcement had a yield stress of 425 N/mm^2 and an ultimate stress of 623 N/mm^2 that conform to ASTM A615-18 Grade 60.

2.2. Specimen preparation

The principal purpose of this research is to analyze the behavior of unreinforced and reinforced masonry walls with a low reinforcement ratio. For this purpose, four brick wall specimens were built in the structural laboratory at the Faculty of Engineering, University of Kufa, according to British Standard BS EN1052-1:1999. The specimens have dimensions of 470 mm in length, 410 mm in height, and 230 mm in width, as shown in Fig. 2.

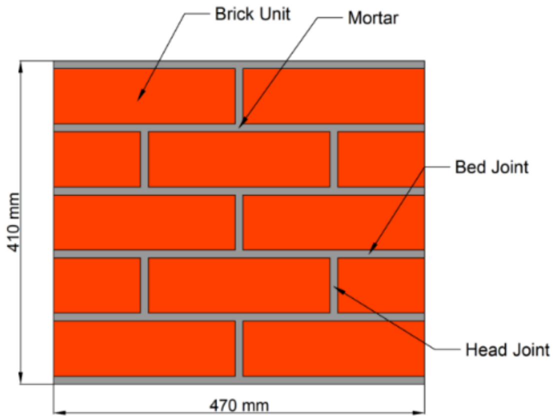

Fig .2. Geometry of masonry brick wall specimen

Three walls were constructed to study the response of unreinforced masonry in cases of fill-head joints with mortar as well as in the holes of the perforated masonry units under compression loads. On the other hand, reinforced wall with steel reinforcement bars was provided. Three deformed 8 mm steel bars embedded horizontally within the cement-sand mortar of the bed joint between the second and third courses of the wall, which is regarded as a low reinforcement ratio. The following are specimens' identification with variations in mortar distribution in the masonry and the reinforcing availability: Filling Head and Bed joints with mortar (FHB), Filling Bed joints only with mortar and one course Rotated 90o (FBR90), Filling Head and Bed joints with Filling all HOles (FHBFHO) and Filling Head and Bed joints with adding Steel Reinforcement bars (FHBSR) in the mortar.

The curing process of brick masonry wall specimens was carried out using water with an average temperature of 25^{o} C in the lab of Faculty of Engineering at university of Kufa and completed in 28 days according to test standard.

2.3. Test setup

All specimens were tested using a framed hydraulic structural universal testing machine (UTM) with a capacity of 2000 kN in the structural lab. Before that, the machine was prepared, and two of the thick rubber plates with dimensions of (250×500) mm were placed, which would be at the bottom and top of the model. They were added to make sure that the applied load was equally distributed on the surface of the specimen. Then, the tested specimen was gently picked up and placed in the test position using the fixing straps that were over-connected from the bottom. It is lifted using a mechanical winch and placed on the bottom rubber plate provided in the middle of the plate; likewise, the upper plate is placed on top of the model. The sample is equipped with an LVDT (Linear Variable Differential Transformer) device installed in a parallel direction to the load to measure the vertical displacement. Then a dial gauge was installed to monitor the vertical displacements. All data was recorded, such as the first crack load, crack deflection, the ultimate load, and displacement.

A rigid steel beam was placed on top of the specimen to ensure uniform distribution of the load and to avoid stress concentration. The concentric uniaxial in-plane compression load at a loading rate of 5 kN/min was gradually applied by a hydraulic jack. The test started as the results were manually written by recording the displacement per 5 kN and taking a photo of all sides of the specimen. After each sample test was completed, the debris was cleaned up. The same procedures were implemented for all specimen tests. Measurements of loads, matching displacements, and cracks up to the failure load were tracked and documented throughout the test run. When the applied stress significantly decreased or when a portion of the wall started to come loose, the tests were stopped.

3. RESULTS AND DISCUSSION

Compressive strength tests of specimens were carried out in the lab using a Universal Standard Testing Machine (UTM) in accordance with British standards. The test was carried out on the wall specimen on the 7th day after finishing the curing process.

3.1. Compression behavior of masonry wall specimen

One of the objectives of this research is to inspect the effect of mortar distribution in the bed and head joints of URM specimens under in-plane compression load. A repeatable and objective methodology to measure and characterize the load displacement curves of the specimens is adopted. Then, an indication about the load at which the initial crack will appear in each specimen is made. Also, the compressive strength capacity is considered. For satisfactory performance, a masonry structure must have strength as well as ductility. Ductility can be identified as the energy absorbed by the material unit until a complete failure occurs (Hussain et al., 1995). In the present work, the experimental ductility ratios (μ) are calculated according to the displacement at the ultimate load divided by the displacement at the service load (Russel, 2003). Three specimens were tested to study the effect of filling joints with mortar and have been subjected to compression tests under BS EN1052-1:1999.

The first masonry wall specimen of FHB is shown in Fig. 3. The primary cracks first appeared in diagonal order at 155 kN and spread to the specimen's center, as shown in Fig. 3, with displacement of 6.123 mm. The formation of these cracks represented 37% of the ultimate load, which shows the high ductility index of 1.93. The compressive load capacity of the specimen is 420 kN, corresponding to a record displacement of 11.825 mm at failure, as shown in Fig. 4.

Fig. 3. The first wall specimen FHB

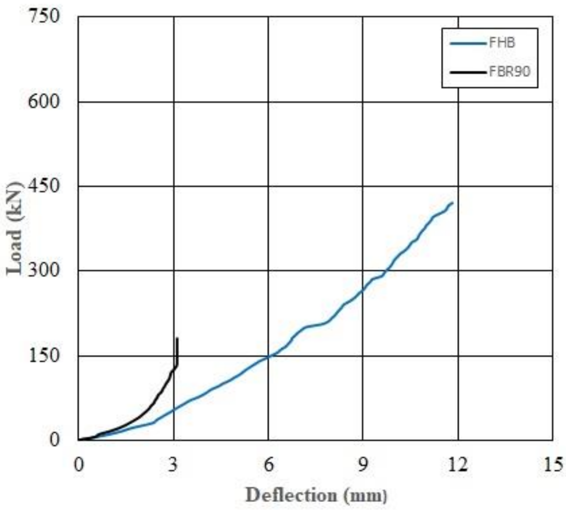

Fig. 4. Load-displacement curve of FHB compared with FBR90 wall

The second masonry wall specimen FBR90 is shown in Fig. 5. The typical disparities with the FHB specimen are the poor quality of the head joints and the rotation of the brick units in one course with an angle of 90°. In the case of leveling the wall base, some less experienced formers rotate the brick unit toward the thickness during the erection of the first course of the wall. Thereby, the strength of the masonry wall is decreased, and knowledge of the reduction value in the wall bearing capacity is needed. The initial crack started at load 120 kN with displacement of 2.935, which approximately appeared in the middle of the specimen as shown in Fig. 5. The result of the load-displacement curve of this specimen test is compared with the results of the FHB specimen. The load-displacement curves of the FHB and FBR90 walls are shown in Fig.4. The ultimate load capacity is 180 kN with ultimate displacement of 3.125 mm. From the figure, it was observed that due to partially distributed mortar in the head joints and rotation of the brick units in one course at a 900, the FBR90 wall's capacity and ductility index (180 kN, 1.06) were found to be lower than those of the FHB wall (420 kN, 1.93), which demonstrated a 57% and 45% reduction in load-carrying capacity and ductility index, respectively.

Fig. 5. The second wall specimen FBR90

The third masonry wall specimen FHBFHO is shown in Fig. 6. During the test of the specimen, it was found that the cracks propagated gradually with short segments, as shown in Fig. 6. An early crack formed at a load of 310 kN with displacement of 2.85 mm. As opposed to the previous specimens, the same location crack was observed at low load levels of less than 310 kN. The presence of mortar in the head and bed joints, as well as in the holes of the brick units, controlled the cracks, which ultimately resulted in a larger cracking load.

Fig. 6. The third wall specimen FHBFHO

Failure of the specimen occurred at a load of 565 kN with ultimate displacement of 4.15 mm. Because of the mortar was distributed throughout the brick masonry's holes and joints, the failure stress could be increased by 35% and 214%, respectively, compared to specimens FHB and FBR90. The load-displacement curve of this specimen test is shown in Fig. 7. It is clear from figure that FHBFHO wall has higher stiffness with decreasing in ductility index of 1.45 than FHB wall.

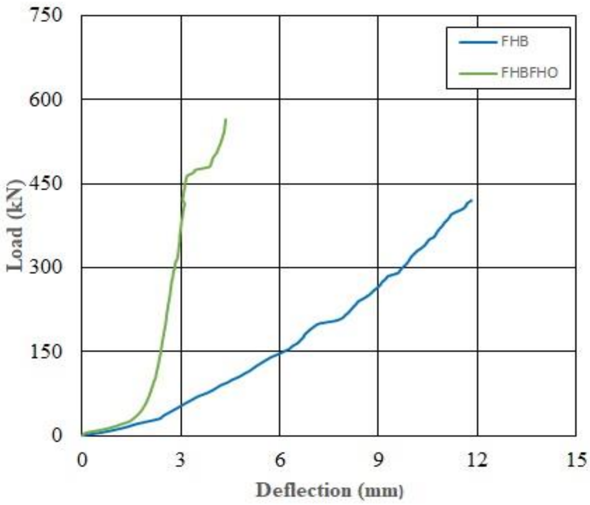

Fig. 7. Load-displacement curve of FHBFHO compared with FHB wall

The second aim of this research is to inspect the influence of reinforcement ratio on the compressive behavior of the brick wall. The fourth masonry wall specimen FHBSR is shown in Fig. 8 and it was similar to the specimen FHB in all details, except for the presence of the steel reinforcement.

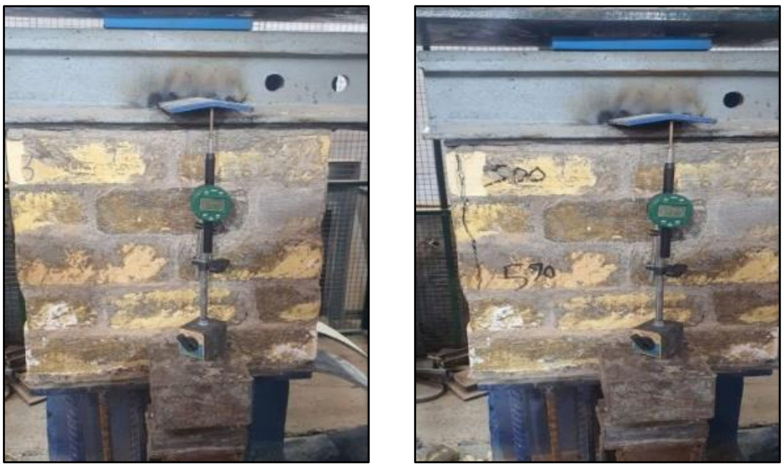

Fig. 8. The fourth wall specimen FHBSR

The steel reinforcement bar used in this case was deformed type of 8 mm diameter. Three steel bars were embedded within cement mortar in the middle height between the second and third courses of the specimen, as shown in Fig. 9.

Fig. 9. Utilization of steel reinforcement bar during erecting the fourth wall

The reinforcement ratio used is 6.55% of the area section of cement mortar, which is regarded as a low reinforcement ratio. Generally, the first noticeable crack appeared at a load of 500 kN with displacement of 4.95 mm. With the increase in the applied load, several cracks were observed in the specimen until failure happened at a load of 670 kN with ultimate displacement of 5.41 mm. It is obvious that due to the low reinforcement ratio, the FHBSR wall has a higher load-carrying capacity but less ductility compared to the FHB wall by 60% and 44%, respectively. In addition, the initial crack formation at the service load of the specimen FHBSR is higher than that of the specimen FHB by 233%. However, the application of low reinforcement in one course increases the strength of the FHBSR wall rather than its ductility. In this case, the reinforcement exists in a small area within the bed joint and no wall confinement is available. The load-displacement curve of this specimen test is shown in Fig.10.

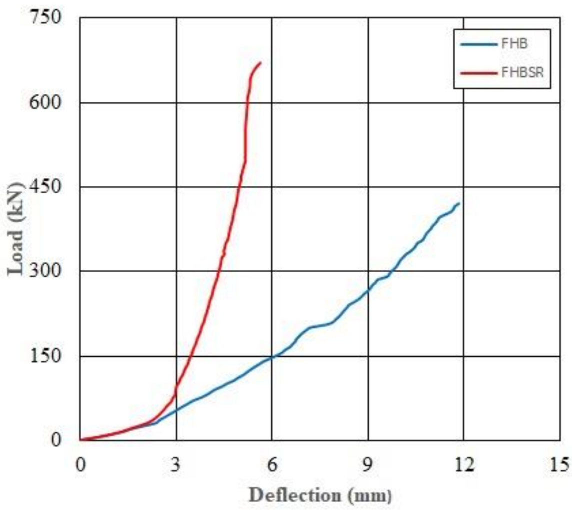

Fig. 10. Load-displacement curve of FHBSR compared with FHB wall

3.2. Comparison between RM and URM walls

This section was performed to evaluate the reinforcement ratio's contribution and compare it with the specimens of nonreinforced walls. The evaluation includes the first cracking load, ultimate load capacity, initial cracking displacement, ultimate displacement, and ductility. Test results for reinforced and unreinforced system specimens are reported in Table 5. In the comparison, the wall FHBSR is regarded as a control specimen.

Table 5. Test results of reinforced and unreinforced system specimens

Specimen Type	Cracking load (kN)	Ultimate Load (kN)	Initial Cracking Displacement (mm)	Ultimate Displacement (mm)	Ductility Index (μ)
FHBSR	500	670	4.950	5.410	1.09
FHBFHO	310	565	2.850	4.150	1.45
FHB	155	420	6.123	11.825	1.93
FBR90	120	180	2.935	3.125	1.06

The comparison showed that the cracking and ultimate loads of a brick masonry wall are highly influenced by the presence of reinforcement ratio as well as the distribution of mortar in masonry joints and in the holes of the brick units. The FHBSR wall demonstrated an increase in ultimate compressive load of 272% and 60% in comparison to the FBR90 and FHB specimens, respectively. While a compressive strength improvement of just 19% in comparison to the FHBFHO wall could be attained, the reinforced masonry showed a noticeable improvement over the corresponding unreinforced masonry in increasing the cracking load by 233%. Even though the addition of embedded reinforcement within the mortar joint in the FHBSR wall increased the ultimate compressive strength, it no longer provided significant changes to the ductility. In this case, the reinforcement increased the wall's strength to the horizontal tensile stress resulting from the uniaxial in-plane compression load. This helps control the tensile cracks and decrease the vertical displacement in the wall. Consequently, the ultimate load capacity of the wall is raised until it reaches a stress point at which the reinforcement deboned with the mortar and the specimen fails. Conversely, the full distribution of mortar in the bed and head joints of the unreinforced brick wall FHB produces a load-displacement curve with a large horizontal portion. This illustrates a high ductility behavior. In terms of displacement, reinforced masonry decreases the initial crack and ultimate displacements by 19% and 54%, respectively, compared with the corresponding unreinforced masonry. In general, the low reinforcement ratio in brick masonry increases the compressive strength and decreases the displacement, which could be used for masonry structures exposed to high compression loads with minimum displacement.

4. CONCLUSIONS

In this work, an experimental test was conducted on four brick masonry walls with two different systems; the first system is unreinforced, and the other system is reinforced by steel bars. A uniaxial in-plane compression load was applied to wall specimens until the failure occurred. The influence of filling joints and reinforcement on the performance of the wall specimens was investigated and discussed in terms of ultimate load capacity and displacement. From this study, it is concluded that:

1. The full distribution of mortar in the bed and head joints and without course rotated of unreinforced masonry wall specimen increases the cracking load and ultimate load capacity by 25% and 133%, respectively.
2. The filling of all holes in brick units with mortar of unreinforced masonry specimen increases the cracking load and ultimate load capacity by 107% and 35%, respectively.
3. The reinforced masonry showed a significant improvement than the corresponding unreinforced by increasing the cracking load and ultimate load capacity by 233% and 60%, respectively.
4. In terms of displacement, the filling of all holes in brick units with mortar of unreinforced masonry specimen decreases the initial crack and ultimate displacements by 53% and 65%, respectively.
5. Also, the reinforced masonry decreases the initial crack and ultimate displacements by 19% and 54%, respectively compared with the corresponding unreinforced masonry.
6. The ductility is improved for full distribution of mortar in bed and head joints of brick masonry wall specimen.
7. In brick masonry walls, the low reinforcement ratio increases the compressive strength and decreases the displacement, which could be used for masonry structures exposed to high compression loads with minimum displacement.

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