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Research Paper

Influence of Opening and Boundary Conditions on the Behavior of Concrete Hollow Block Walls: Experimental Results

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Abstract

The assembled pattern of concrete hollow building blocks contributes to the wall structure's durability. This paper presents experimental research on the behavior of concrete hollow block walls. The experimental work included testing of four concrete hollow block wall panels with different opening sizes and positions. Constant vertical axial load was applied on top of the wall panels until failure, characterized by boundary conditions. The results showed that the presence of openings reduced the strength of the wall panels; it was possible to observe these differences since the opening area was between 20 and 40% of the gross wall panel area. It was also observed that while the opening percentage had a significant impact on the strength of the wall, the boundary conditions had a less substantial impact on the overall wall response. A high localized concentration of stress was observed at the top corners of the wall panels and a high stress concentration was also observed along the vertical sides of the openings. Variation in the number and the shape of the openings often changed the failure mechanism in the wall panels, even when the percentage area of the opening remained constant. The wall panels A1-B2 reached peak stress levels at 0.019 MPa, 0.036 MPa, 0.056 MPa, and 0.030 MPa. The equivalent peak strains were 0.018, 0.011, 0.012, and 0.010 respectively. This research established significant data and is expected to help in the design and analysis of axially loaded unreinforced masonry walls with openings.

Keywords: *axial compression; boundary conditions; concrete hollow block compressive strength; experiment; openings.*

Introduction

Masonry is a non-homogeneous anisotropic material [1] and is among the oldest building materials in use today in the construction sector [2-4]. One of the key characteristics designs of the masonry walls under various loading scenarios is compressive strength. The compressive behavior of masonry members is one of the most essential issues in designing and evaluating the safety of buildings because these structures are under compressive forces [5]. Previously, several studies have been conducted to examine the compressive behavior of concrete hollow block walls [6-9]. In addition, masonry design guidelines specify the number of provisions to forecast the strength of concrete hollow block walls under axial compression [10, 9]. The standards differ in their ability to estimate the compressive strength of a concrete hollow block wall, nevertheless, when compared to an equivalent solid wall, a wall's maximum load capacity is significantly decreased by openings [11]. Due to the complicated failure mechanisms of such components, there is relatively little information in the research literature regarding the design equations that can be used to assess the axial strength of a block wall with an opening. There are several guidelines for example as in [11, 12]. These claim that the effects of an opening on the axial strength can be disregarded if the walls are restricted on all sides and contain an opening with an area smaller than one-tenth of the total wall area, the opening's impacts on the axial strength can be disregarded. Additionally, the opening's height should be less than one-third of the height of the wall. If these requirements are not met, it is necessary to treat the area between the opening and the restraining member as being supported on three sides and the area between the opening (if there are many openings) as being supported on two sides. Special reinforcement bars need to be inserted around the openings to prevent early failure; this system is only effective if the openings are designed early. No recommendations are offered if the openings are created [11].

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A possible tendency toward stress concentration at the opening's corners has been discovered. The area around the opening (door or window) is axially loaded; the structural wall panel is the location of high-stress concentration [13]. Concrete hollow block wall openings can alter the distribution of stress within the wall, influencing its behavior. The impact of a small opening is frequently overlooked, whereas the presence of a large opening typically results in significant structural system changes [11]. The influence of the opening's size and position, the aspect ratio of the panel, the loading arrangement, and the boundary conditions have not been validated, therefore, to identify the impact of openings on CHB wall panels via parametric studies, appropriate experimental work needs to be carried out on full-scale on CHB wall panels to investigate the following parameters that may influence the behavior and failure pattern of axially loaded CHB wall panels based on failure mode [14-16]:

1. Position of the opening
2. Support condition assigned to the base and edge of the wall panel
3. Size of the opening(s)
4. Aspect ratio (height to length) of the wall panel
5. Loading arrangement applied on the wall panel.

Materials and Methods

A concrete hollow block (CHB) with a size of 390 mm x 140 mm x 190 mm, as shown in Figure 1a, was used in this study. A bond beam block, as shown in Figure 1b, was used to span the opening in the CHB wall panel. The wall above the beam block forms a natural arch, which can transfer the load to the abutment of the opening. Bond beam blocks are concrete units with narrowed-down or knocked-out webs. Bond beam blocks have the same dimensions and specifications as standard CHB, 190 mm in height, 140 mm in width, and 390 mm in length. Webs or removable sections are removed before inserting the unit into the bond beam to make it easier to install a horizontal bond beam reinforcement. A 12-mm size reinforced concrete was cast into the web's hole after the bond beam block had been placed into a wall with 100 mm on either side. The reinforcement was according to CP 110: Part 1 [17]. The bond beam block's load bearing capacity was evaluated according to BS: 5977: Part 1 [18].

(a) (b)

Figure 1 (a) Hollow concrete block and (b) bond beam block.

Compressive strength tests were performed on the CHB units to ensure that they met the minimum strength requirements of the applicable unit specification [19]. The block units were subjected to an axial compressive load at a loading rate of 0.25 $N/mm^2/s$ until failure using a UTM with a maximum capacity of 1000 kN. The water absorption for the CHB used was 7.362%, and the density was 1,203 kg/m^3.

A dropping ball test was used for the mortar type II with the designation 1:3, it had a consistency of about 10 ± 1 mm. The mortar and grout were cast in 50 mm × 50 mm × 50 mm cubic molds as per the recommendations in ASTM C-109/ C109M [20] and were tested on the same day as the walls. For the first 24 hours, the cubes were stored and covered with a polythene sheet before being removed and cured for 28 days in water at 20 °C. The cubes were weighed in both air and water to determine the relative density of the mortar. They were then loaded at a rate of $0.1N/mm^2/sec$ to determine the mortar's compressive strength. The results of the workability,

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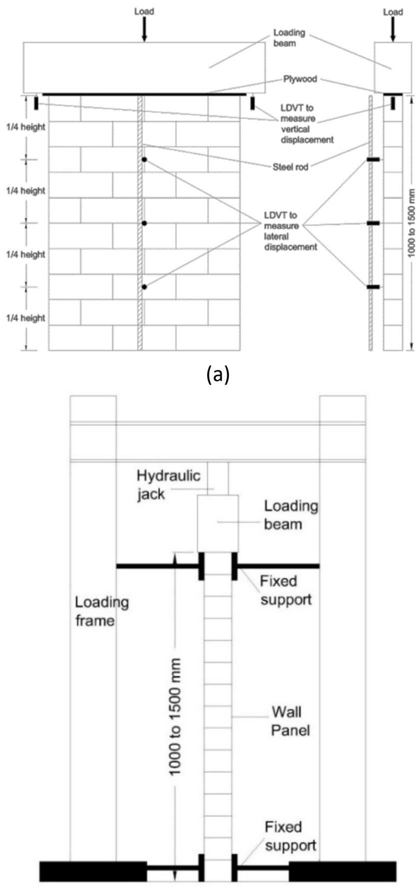
water absorption, and density tests of the concrete hollow block as well as strength properties (concrete hollow block, and mortar) are shown in Table 1.

Table 1 Engineering properties of concrete hollow block masonry

Engineering Properties	Values (Unit)
Workability (dropping ball apparatus)	10 ± 1 (mm)
Water absorption	7.362 (%)
Density	1,203 (kg/m^3)
Compressive strength (hollow concrete block unit)	8.39 (N/mm^2)
Compressive strength (mortar)	21.34 (MPa)
Flexural strength (hollow concrete block unit)	3.91 (N/mm^2)

The present study applied localized stress and axial load on top of the wall panels until failure. A loading frame with a load capacity of 1800 kN was fixed to the floor of the laboratory as shown in Figure 2(a) and (b). It was installed with a loading system and boundary conditions when testing the concrete hollow block wall panels. The maximum height of the specimen used in the loading frame was 1600 mm. Transducers were attached to the wall panels to measure the lateral deflection and the readings were measured from a data logger. The readings obtained were used to illustrate the height against lateral deflection along the vertical centerline of the concrete hollow block wall panels. End support was also applied to the CHB wall panels to idealize those in practice. Point load (concentrated) was applied to the panels and for safety reasons, the load was concluded at a load of 900 kN.



(b)

Figure 2 Loading frame for testing wall panels.

Point Load (Concentrated Load)

The concrete hollow block wall consists of four wall panels (A1-B2) with different opening sizes. A1 and A2 (810 × 1200), B1 (410 × 1200), and B2 (610 × 1200), the boundary conditions assigned to these panels were fully restrained at the base (fixed-fixed) and the top end left fixed. All wall panels were constructed using CHB with a mortar ratio of 1:3. The aspect ratio (height/length) of these panels was 1 (1590 × 1590) and the slenderness ratio (height/thickness) was 1:11. Table 2 shows the test results for wall panels A1-B2 and Table 3 summaries the test results and maximum axial displacement and lateral deflection of the wall panels, respectively.

Table 2 Test results for wall panels A1-B2

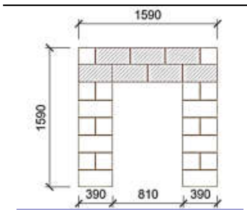
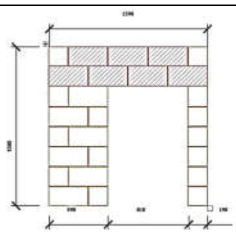
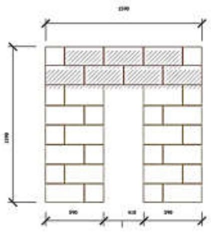
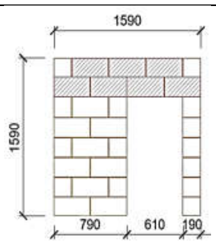
Panel configuration	Panels ref.	Boundary conditions		Loading arrangement	Failure load (KN)	Cracking load (kN)
		Bottom	Top			
	A1	Fixed	Fixed	Point Load	151	46
	A2	Fixed	Fixed	Point Load	172	50
	B1	Fixed	Fixed	Point Load	204	100
	B2	Fixed	Fixed	Point Load	182	75

Table 3 Maximum axial displacement and lateral deflection for wall panels A1-B2

Wall	Maximum axial displacement (mm)	Maximum axial displacement at the top (mm)	Maximum axial displacement at the middle (mm)
A1	27.98	0.0183	14.735
A2	17.81	0.0183	11.750
B1	18.39	0.0183	10.326
B2	16.44	0.0183	10.329

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Results and Discussion

The experimental work to determine the influence of openings and boundary conditions on the behavior of concrete hollow block walls was conducted at the structural laboratory of University Sains Malaysia. The development of cracks was determined by the initial compressive stress values in the wall under compressive load; cracks first appeared at the corners of the wall panels A1-B2 on top of the opening at 46, 50, 100, and 75 kN, respectively. The cracking patterns from wall panels A1-B2 are shown in Figure 3. The cracks overlapped the diagonal section of the wall panel running to the other side of the panel. With the damage concentrated in the wall segments on both sides of the opening, the strength of the wall deteriorated, and the crack width increased as the diagonal cracks approached the openings. There were also diagonal cracks in the mortar joint at the center of the wall panel. All cracks in wall panels A1-B2 began at the top layer of the wall (a vertical mortar joint) and progressed downwards as loading increased until failure at 151, 172, 204, and 182 kN, respectively. Due to the smaller size of the opening, wall panel B1 had the highest compressive strength, while wall panel A1 had the lowest compressive strength due to the larger size of the opening and the positioning of the opening (at the center of the wall panel). Cracking started at the door opening's corner and spread to the bond beam, with cracks visible in each load direction. At the end of the test, the stair-stepped cracks had widened.

A1 A2 B1 B2

Figure 3 The cracking patterns of wall panels A1-B2.

The opening location and aspect ratio were found to have a significant effect on wall behavior, with short walls having the highest tensile stresses and long walls having the highest shear stresses. Lizarraga [21] reported a study on the behavior of CHB walls supported by flexible elements using experimental and numerical methods. According to the study, there was a very serious case of vertical loading due to the concentration factor of normal stresses on the wall base, where the largest stresses were observed to be on the beam support, i.e. the tie-columns and masonry panel borders, because masonry has a significantly higher stress-to-strength ratio than concrete. CHB wall failure occurs when the mortar approaches its confining strength limit, and the crushing of mortar joints causes the masonry to break. Tensile strength in a block can also cause masonry to fail. Therefore, it is essential that the proportions of the mortar mix and the block are comparable to prevent failure due to tensile stress in the block. The mortar has a significant impact on the behavior of the masonry when joint crushing failure occurs, without lowering the failure load. Nicola *et al.* [22] revealed that a panel with low-strength mortar failed due to the loss of bonding between the block and the mortar. Parsekian *et al.* [23] state that when a grouted panel fails due to tension in the block shells, the grout core remains intact and the components act non-homogeneously and when shear failure occurs and the grout cores remain intact, the components act uniformly.

Lateral Deflection

Lateral deflection gives a structural deformation response of CHB walls under loading. Figure 4 shows the lateral deflection curves of wall panels A1-B2. These curves indicate that the CHB wall specimens exhibited ductile behavior with the continuous increase of lateral deflection and increasing load. The curves show linear behavior in the initial loading region, followed by a nonlinear curve up to the ultimate failure load. The curves show that only slight deflection was produced with increasing load in the linear region. In the nonlinear region, the lateral deflection increased rapidly as the load was increased.

The highest maximum lateral deflection occurred at the middle of wall panel A1, followed by A2, B2, and B1. The structural deformation response of CHB walls under loading is described by the lateral deflection. The total lateral deflection of all wall panels was calculated, and graphs were drawn. All plotting revealed that lateral deflection was greater in wall panel A1 due to the larger size of its opening and its positioning. This is due to the increased stiffness of the wall panels with an opening. The abrupt changes in the curve's slope were caused by irregular stiffness. The presence of an opening in wall panels A1 to B2 caused the axially loaded CHB units to deflect laterally. This behavior indicates that the presence of an opening in an axially loaded CHB unit's wall panel could impair the wall panel's strength.

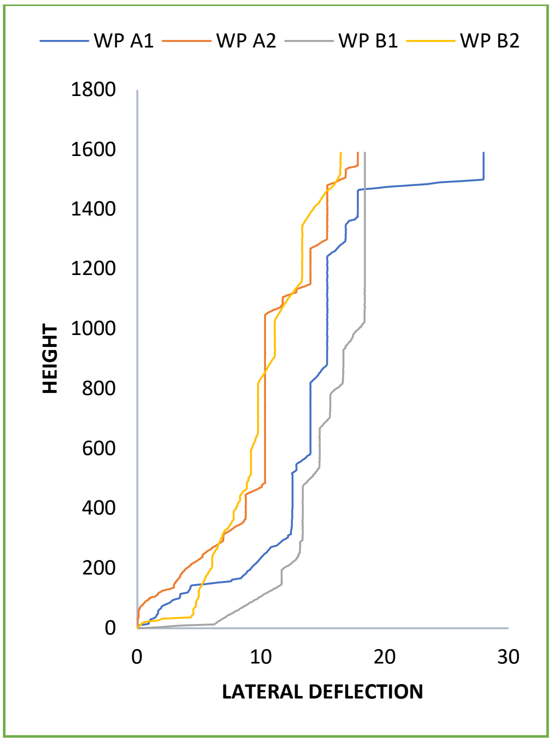

Figure 4 Lateral deflection response of wall panels A1 to B2.

Stress-strain

The stress-strain engineering measures, denoted as σe and εe respectively, were determined from the measured load and deflection using the original specimen cross-sectional area A_0 and length L_0 as $\sigma e = P/A_0$, $\epsilon e = \delta/L_0$. Figure 5 shows that the curves initially were found to be slight and linear due to the negative stress-strain results. Most strain gridlines show that high stress occurred near the opening's top corner. The initial slight curves show the large strain at low stress applied due to an offset occurring before the rig of the machine stably compressed the specimens. The stress-strain relationships of the constituent materials are considered the most important mathematical relationships that guide the prediction of the strength and deformation of any structure.

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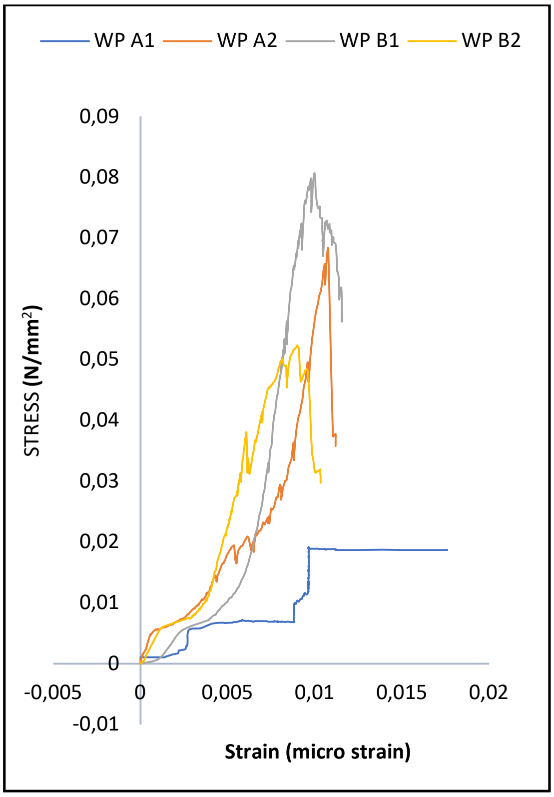

Figure 5 Stress-strain of wall panels A1 to B2.

Conclusion

Due to their nonhomogeneous structure and different material properties, concrete hollow blocks are among the most complex building materials in terms of determining their behavior within structural systems. The main conclusions drawn from this study can be summarized as follows:

1. The research successfully introduced an experimental methodology for examining the behavior of CHB wall panels with openings and as expected, the current opening reduced the strength of the wall panels; it was possible to observe these differences because the opening area was approximately 20 to 40% of the total panel area, so it could be concluded that the opening has a significant impact on panel response.
2. The study found a high localized concentration of stress at the top corners of the wall panels, as well as a high-stress concentration along the vertical sides of the opening. When the opening position moves from the edge of the wall panel to the center, the stress increases slightly and the concentration of stress in wall panels increases significantly as the opening size increases.
3. The boundary conditions assigned to the wall panels at the base and the top edge has no significant effect on the final amount of axial displacement.
4. The capacity of a complete wall can significantly be impacted by the size and location of openings in wall panels. Variation in the number and shape of the openings often changes the failure mechanism in the wall panels (even when the percentage area of the opening remains constant) and may lead to failure, significantly reducing the wall strength.

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