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FLEXURAL BEHAVIOR OF CONFINED MASONRY WALLS USING INTERLOCKING CONCRETE BLOCKS SUBJECTED TO OUT-OF-PLANE LOADS

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ABSTRACT: This paper aims to determine the out-of-plane strength of confined masonry walls with different hooks' heights of concrete blocks. For this purpose, an experimental test of three full-scale confined masonry walls using interlocking concrete blocks was conducted. The wall specimen was installed horizontally and supported by four wall sides using the supporting steel frame, and the load was applied at the wall center perpendicular to the plane. The parametric studies on the material properties, hook performance on the wall, flexural behavior, and typical wall damage were conducted. Based on the experimental results, it was observed that the walls that were confined by reinforced concrete tie-beams and tie-columns provided sufficient contribution to the walls' strength. Likewise, a wall with interlocking concrete block material plastered on both sides produced adequate flexibility to withstand the out-of-plane loads. The ultimate applied load is reached, resulting in the maximum vertical deflection, which correlates the displacement ductility. A comprehensive discussion of the observed flexural behavior of confined walls, including failure of the wall panel and local failure of concrete confining elements, is explored intensively in this paper.

Keywords: Out-of-plane load, Interlocking concrete block, Confined masonry wall, Wall strength

1. INTRODUCTION

Reinforced Concrete (R.C.) frames infilled with masonry of non-structural masonry are composite systems in buildings and widely used in a standard building system [1]. Their behavior under earthquake loads is challenging to predict, such that most national codes ignore the contribution of infill to the structural response [2]. Post-1990, concrete blocks used as a masonry wall infill began to be used for new construction in earthquake-prone areas in Indonesia and other countries worldwide.

A confined masonry wall applied to earthquake-resistant buildings is a widely used solution in developing countries and has the potential for worldwide application since its economic and constructive advantages are relatively promising. It is observed that an earthquake force acts in all directions and starts at the supporting soil, and transmits to the building. The horizontal and vertical earthquake forces travel in different load paths, either in-plane or out-of-plane direction. The forces may result in tension, shear compression, bending, or torsion forces occurring not only to the building structures but also to non-structural elements such as masonry walls. Most buildings experience horizontal distortion when subjected to earthquake motion producing catastrophic damage [3, 4].

The experience of earthquake events in several regions in Indonesia shows that masonry's strength contribution and implications infill the R.C. frame structures are significant [4]. However, recent seismic events indicate that the masonry structure may need repair after an earthquake due to cracks. Construction defects subjected to earthquake loads are a significant cause of masonry cracking. These non-structural components often suffer severe damage during an earthquake because of their fragile nature on in-plane and out-of-plane, which can also be a significant threat to human life [5].

Learning from earthquake disasters in the past few years, walls as non-structural elements suffered severe damage after the earthquake. So far, designers have neglected the contribution of strength to masonry walls in buildings because the wall-forming material's brittle nature results in low strength. Some of the significant reasons to conduct this research are related to the damage pattern, hook system, and the loading mechanism on the masonry walls to withstand earthquake loads in the in-plane and out-of-plane directions. On another note, most interlocking blocks available in the industry differ in geometry, material composition, and dimensional characteristics producing different strengths. This study investigates the walls' flexural behavior with interlocking concrete block material plastered on both sides subjected to withstand the out-of-plane loads.

2. EXPERIMENTAL PROGRAM

2.1 Material Characterization

Four interlocking concrete block models were developed in the upcoming research with various height hooks, as shown in Fig. 1. Each model has three different height hooks, i.e., 15, 20, and 25 mm, where the unit is a standard concrete block with a dimension of 400×220×100 mm. The concrete block type-A was used in the confined masonry walls proposed in this research.

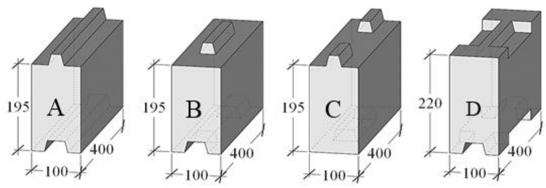


Fig. 1 Four models of interlocking concrete block

Four-cylinder samples were taken from each model by drilling to investigate the concrete block's compressive strength. Each sample had a diameter of 50 mm and a height of 100 mm. The test results of material properties for the interlocking concrete block and mortar are listed in Table 1. The mortar used for adhesive and plastering of all wall surfaces was the same material composition of concrete block with a water-cement ratio of 0.5 as shown in Table 1. The primary reinforcing steels with a diameter of 10 mm and the stirrup with a 6 mm diameter were used for the reinforced concrete tie-beam and tie-column. A concrete cylinder of 150 mm diameter and 300 mm in height was used to test the compressive strength of concrete. Table 2 presents the test results.

Table 1 Compressive strength and modulus of elasticity of the material

No.	Material	Unit type	Material composition (P.C.: sand)	Average density (kg/m^3)	Average compressive strength (MPa)	Average modulus of elasticity (MPa)
1	Concrete Brick (Core drill, 50 mm diameter and 100 mm high)	A	1 : 4	1971.94	6.39	805.41
		B	1 : 4	2033.06	7.13	844.86
		C	1 : 4	1992.82	6.34	820.52
		D	1 : 4	2025.35	5.73	826.74
2	Mortar (Cube 50x50x50 mm^3)		1 : 4	2088.83	13.66	-

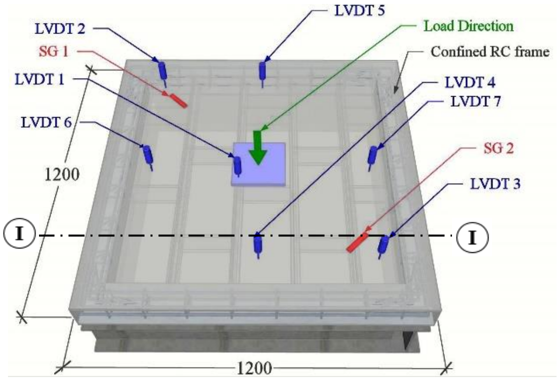
Table 2 Observed material for the confined R.C. frame

No.	Material	Average density (kg/m^3)	Average compressive strength (MPa)	Average tensile strength (MPa)	Average modulus of elasticity (MPa)
1	Concrete	2342.97	39.20	-	29985
2	Reinforcing steel, Ø6	-	-	313	193335
3	Reinforcing steel, Ø10	-	-	361	218961

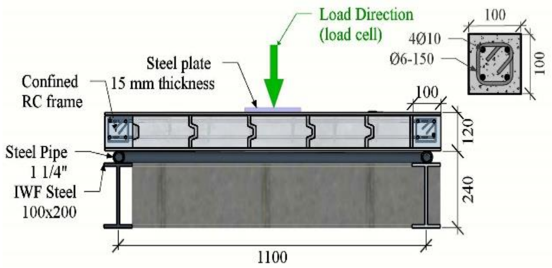
2.2 Confined Masonry Wall (CMW) Specimens

Three 1200 x 1200 mm confined masonry wall specimens were prepared to be tested experimentally with an out-of-plane load applied. In this research, concrete block type-A with variations hook height of 15, 20, and 25 mm was selected as the wall forming material restrained by the R.C. tie-beam and tie-column, forming a rigid portal. The three specimens are named A15, A20, and A25. Each sample was made of interlocking concrete block layers, which were neatly arranged, and the gaps or spacing between the hooks were filled with fine mortar to form a massive wall.

After the concrete blocks' installation is complete, restraint is carried out by attaching the R.C. tie-beam-tie and tie-column. Each wall specimen is plastered with a 10 mm thickness of the mortar on all sides of the surface to increase the walls' strength to withstand a bending load. The CMW sample was installed horizontally and supported by four wall edges using the supporting steel frame. The load was applied at the mid-center of the wall perpendicular to the plane, as shown in Fig.1.



(a) View of wall types: A-15, A-20, and A-25



(b) Section I-I

Fig. 2 Typical confined masonry walls

2.3 Out-of-plane Test Setups

Further research on the out-of-plane seismic response of masonry infill walls is adopted to increase knowledge of the behavior and develop effective strengthening strategies to prevent its collapse. However, such experimental tests are challenging to conduct this research due to test equipment's inherent complexities, loading approaches, and loading protocols [6-8].

This study proposes a simple out-of-plane experimental setup as depicted in Fig. 3. The wall specimen is positioned on a specially designed IWF 100x200 steel frame to support the wall's four sides. On top of the steel portal, a 1.25-inch diameter steel pipe is installed around the perimeter to become joint support. This specimen's clear span was measured from beam-tie and column-tie axles, as clearly shown in Fig. 1b.

Fig. 3 Experimental setup

Fig. 3 presents each sample with seven LVDT instrumentations and two strain gauges installed. Four LVDTs are fitted in the mid-length of the tie-beam and column-tie elements; two LVDTs are mounted at two wall corners. One LVDT is nestled right at the load center point, and two strain gauges are installed in the direction in line and perpendicular to the diagonal line of the wall. The out-of-plane load is incrementally applied at the center point of the wall.

3. RESULTS AND DISCUSSION

The lesson learned from the critical note of the post-large earthquake inspection results is that most of the more extensive damage to the infill wall did not occur at the top of the infilled frame. A more considerable out-of-plane seismic action is expected in these circumstances, but at the lower or intermediate level, where higher in-plane drift demand likely occurs [8-10]. This condition proves that the masonry panel decreases the stability outside its plane when subjected to in-plane action. The simultaneous effect of seismic action within the in-plane and out-of-plane produces a decrease in the in-plane deformation capacity due to out-of-plane action and vice versa. The following sections discuss the confined masonry wall's flexural behavior, where the out-of-plane load is applied at the wall's mid-center.

3.1 Behavior of Interlocking Concrete Block

As discussed above, a faster construction system has led to the change in masonry construction's conventional approach to the interlocking construction technique [11] as proposed in this research. Lessons learned from the most interlocking blocks available nowadays differ in geometry, material composition, dimensional characteristics, and compressive strength, including the proposed concrete blocks. In general, interlocking concrete blocks can be laid without mortar layers and require less labor. Referring to Ahmad et al. [12] and Maheri et al. [13], interlocking masonry units used in this research differ from traditional blocks that can be assembled with geometrical features built into blocks without the need for a mortar layer. This research, however, combined mortar and hook systems in constructing masonry walls using interlocking concrete blocks. Furthermore, portland cement and fine sand with a 1: 4 mixture composition were used for mortar and plaster. Mortal was used to attaching in between the hooks.

Several factors that affect the main parameters in masonry walls using interlocking concrete blocks have been considered in preparing for the specimens, for instance, the difficulty in ensuring a strong adhesion between the mortar and the brick-hooks, no air voids in the joints between the concrete block hooks, the uniform mortar strength, workability, and material quality. Fig. 4 shows how the concrete block interacts with each other to resist the out-of-plane load, demonstrating that the graphs of load and displacement responses measured from two different LVDT instrumentation points (4 and 5) have unsmoothly performed reached the maximum displacement at 19.12 mm. Furthermore, a similar trend of the load-displacement relationships measured from two other LVDT instruments at the wall corners serves lesser displacement responses because the measuring point is farthest from the load center. The displacements of the maximum loads recorded from the LVDT at points 2 and 3 vary from 3.89 to 8.86 mm, respectively.

At the early stage of loading up to approximately 50% of the maximum load, the specimen provided adequate strength to resist the out-of-plane load, where the vertical displacements were relatively small. It has been observed that the load increases until it reaches the ultimate load, displacement increases until it reaches the utmost condition. The load-displacement response trend for the three hook height types measured from different LVDTs shows similarities in the wall's bending performance.

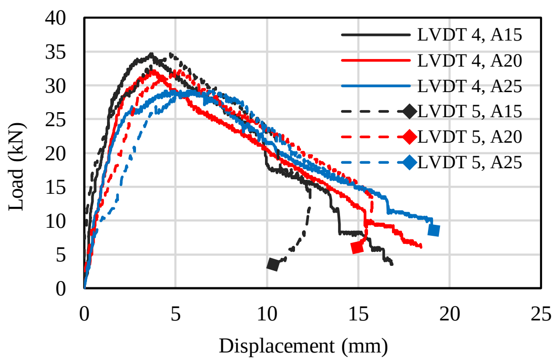


Fig. 4 Measured displacement at the LVDT-4 and LVDT-5

3.2 Out-of-plane Behavior of CMW

Building structures located in high seismicity zones are often subjected to lateral loads from seismic actions, meaning that structural systems are essentially designed to resist these loading types [5, 8]. In masonry buildings, the walls are the main structural elements that carry on these actions: in-plane and out-of-plane loads. In line with these actions' cyclic random nature, any building wall is most likely subjected to in-plane and out-of-plane loads [9].

Previous experimental investigations [8, 9, 13] focusing mainly on the in-plane seismic response on selected masonry typologies like clay bricks and concrete blocks were extended in this research. Limited tests have been conducted for investigating the out-of-plane response and even less in the mutual in-plane/out-of-plane interaction on the interlocking concrete blocks.

The out-of-plane or bending behavior of the CMW is considerably more complex than the in-plane behavior of walls. The walls can be subjected to bending in two directions. Consequently, it becomes a statically, indeterminate structure. The analysis of these walls is too complicated due to the tensile strength in horizontal flexure is likely several times greater than strength in vertical flexure. This difference may occur because the vertical flexure commonly depends on the bed joints' unit mortar interface's tensile bond strength, as proven in this research.

In contrast, the horizontal flexure depends on the bed joints' friction resistance and the tensile bond strength at the vertical joint interface [6]. Advanced finite element analysis by considering the interlocking system's complexity on the CMW in resisting the in-plane, out-of-plane, and diagonal-shear loads will be carried out after the entire research is completed. A technical paper on this subject will be published elsewhere in an international journal soon.

In this research, an experimental setup was developed using a different approach for applying the out-of-plane loading, as shown in Fig. 3. This paper provides an overview of the test setup adopted in the literature by other authors and discusses their implications in the CMW response. This research's point of interest lies in how the walls' optimal performance to withstand the load perpendicular to the plane as the bending structural behavior in general. Fig. 5 illustrates the flexural behavior of the CMW using the interlocking concrete block type-A as a masonry infill. The LVDT recorded the load-displacement response mounted at the wall center during the incremental out-of-plane load applied until the ultimate stage reached.

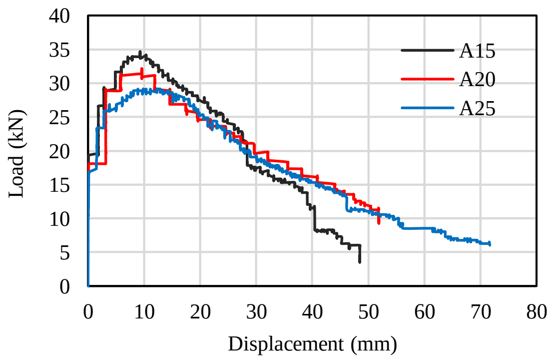


Fig. 5 Load-displacement responses

Three different types of CMW using the interlocking concrete blocks A-15, A-20, and A-25 models were experimentally conducted to investigate their flexural behavior in supporting the out-of-plane loads. As depicted in Fig. 5, the load-displacement relationships have similar trends in their strength in withstanding the out-of-plane loads. The results of specimen type A-15, A-20, and A-25 show that the ultimate loads of the three specimens have achieved the maximum loads of 34.4, 31.6, and 28.38 kN, respectively. The vertical deflections at the mid-point of the wall reached 48.47, 53.72, and 71.57 mm, correlated to the displacement ductilities of 5.22, 5.61, and 5.83, respectively. It can be concluded that specimen type A-15 is a more compact wall element than other specimens, i.e., type-20 and type-25, and relates to their height hokes. Furthermore, the unsmooth graphs were performed due to the interlocking interaction between concrete block hooks and mortar paste during the out-of-plane load applied gradually. Besides, specimens with shorter hooks can withstand more loads but produce less vertical deflection, and vice versa (Fig.6).

3.3 Wall Failures Propagation

As discussed earlier, the flexural wall behavior depends mainly on the masonry confined panel's boundary conditions. In the case of unreinforced masonry walls supported on four sides, the vertical bending moment at mid-height of the confined wall induces tensile stresses in the direction of out-of-plane bed joints. Since these stresses are higher than the tensile strength, a horizontal crack starts propagating around the load point (Fig. 6).

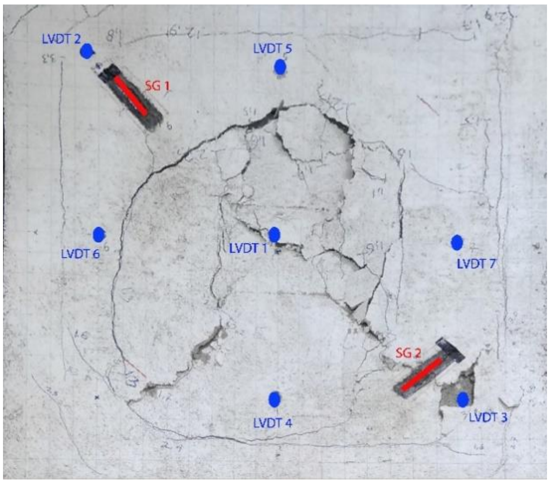


Fig. 6 Cracks propagation surrounding the point of load applied

Fig. 6 illustrates the wall failure propagation, showing that the cracked wall's behavior depends on the masonry's orthogonal flexural strength. Furthermore, the vertical flexure strength is the same as the horizontal flexure strength; and no additional strength occurred. When the load gradually increased, the crack propagates along the bed joint, and the damage mechanism immediately formes with only a little residual strength due to the self-weight. In line with previous research [10-12], the horizontal flexural strength's general case is more significant than its vertical strength, a crack propagates along the bed joint under constant load, and a stable state is reached. As load is further increased to achieve the ultimate loads, diagonal cracks immediately propagate to form a mechanism leading to the wall failure, as depicted in Fig. 6.

In this research, two strain gauges shown in Fig. 7 were installed at the corners of the walls following the diagonal line. The strain gauges SG-1 and SG-2 were mounted in parallel and perpendicular directions to the diagonal line. The installation of this strain gauge was intended to measure the strain that occurred in the plaster during the experimentation.

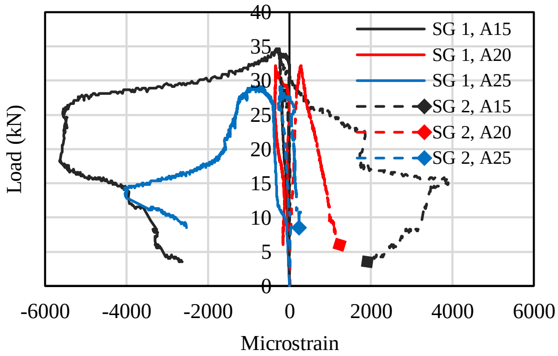


Fig. 7 Strain gauge instrumentations

In general, the plaster has reached over the maximum strain of 0.003 based on both strain gauge measurements; however, not all specimens achieve similar conditions. It should be noted that the strain gauge installed parallel can measure more strain than installed perpendicular to the diagonal line for measuring the actual flexural stresses due to the out-of-plane loads. The crack propagation in this experimental test meets the yield line theory where the diagonal crack starts propagating in line with the increasing the applied load.

4. CONCLUSION

In conclusion, the interlocking concrete block development presented in this study has confirmed that this system is potentially utilized in future masonry structures. Accordingly, the concept of the interlocking system is suitable for replacing the conventional method. It can be concluded that the shape of the interlocking concrete block varies with simplicity, which produces easy and fast production and assembly in the CMW systems. Moreover, all the interlocking concrete blocks' mechanism is sufficient to interlock the assembled concrete blocks in different directions. Based on the researches of the flexural behavior of interlocking concrete blocks in resisting the out-of-plane load, it can be summarized that the interlocking concrete blocks have met the minimum specifications and requirements as per SNI 03-0349-2989 Standards (Indonesian National Standard). It also verified that interlocking concrete blocks could be used either as a load-bearing wall or a non-load bearing system.

5. ACKNOWLEDGEMENTS

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