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Performance of masonry wall joint corner with perforated plate in non-engineering building

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Abstract

Indonesian houses are characterized as non-engineered and vernacular, constructed using local material, techniques, and architectural style. As a results, these houses are typically built without the involvement of experts. In Indonesia, most lower-class houses are unreinforced masonry (URM), masonry without moment resisting frame. The absence of those frame makes URM highly vulnerable to earthquakes and makes the masonry walls the main load bearers. This study analyses the performance of corner joint masonry walls with perforated plates to enhance the integrity between the perpendicular walls. This research was carried out experimentally. The results indicate that URM joint corner walls without perforated plates has the highest load capacity and ductility. Perforated plates in layers of masonry walls can decrease the lateral load capacity by 55%. The failure pattern that occurred are slip failure, with cracks appearing at the mortar-brick joint and mortar-perforated plate interfaces. From the tests that have been carried out, it was found that perforated plate could reduce the cohesiveness of the walls rather than enhance the integrity of the perpendicular walls.

Keywords

Masonry reinforcement, non-engineered building, perforated plate, unreinforced masonry (URM), infrastructure

INTRODUCTION

Indonesian houses are predominantly non-engineered and vernacular in nature. Non-engineered buildings are constructed without the involvement of architects, engineers, or other experts in the field [1]. As many as 79.67% of households in Indonesia build their own house rather than buying from a developer or non-developer [2]. Most of the houses are built without being designed by experts and are built based on the experience of the construction worker to reduce costs. In the other hand, in order to achieve proper building performance, reliable expertise is required [3]. Nonetheless, in Indonesia, cost-effectiveness is often more prioritized, leading to potential compromises in safety against natural hazards.

Non-engineered buildings in Indonesia generally use bricks as wall material [4] and 77.91% of houses in Indonesia use brick walls [5]. Two common types are confined masonry (CM) with reinforced walls and unreinforced masonry (URM) relying solely on masonry strength. Despite cultural significance, these houses pose risks to structural stability and safety.

In earthquake-prone area, for instances Indonesia, casualties primarily result from damaged or collapsed buildings, particularly vulnerable low-rise structures [6]. Many houses use CM or URM, but even CM structures often lack proper reinforcement, further compromising their stability during seismic events.

The absence of reinforcement weakens masonry buildings, making them susceptible to lateral forces and lacking shear strength. Failures result from inadequate lateral capacity, compromised wall integrity, weak mortar, and lack of structural cohesiveness [7] [8]. Internal friction between brick unit and mortar would not be able to rests the lateral force, resulting in the initiation of cracks, slippage, and separation between them [9]. The weaknesses compromise the stability of Indonesian houses earthquakes, with common failure modes including gable, out-of-plane (OOP), strip, and in-plane (IP) failures [10]. IP failure can manifest as flexural cracks, shear cracks along panels or brick patterns, or sliding near columns/frames [11]. OOP failure is the most likely to occur [10] [12] [13] due to inadequate connections between walls and between walls and roofs. Perpendicular walls tend to separate without integral-box action, leading to partial or complete collapse [1]. Inertia forces in the OOP direction overturn the wall. When a wall is subjected to IP load, the perpendicular walls receive OOP forces and prevent the collapse of other walls. As a result, cracks and separation can occur along these edges [14].

Several studies have explored masonry strengthening methods. Enhancing integrity of the wall and connecting perpendicular walls to make it one solid building is one method to strengthen URM. This connecting should be carried out using materials that possess strong tensile strength and good ductility, e.g. (i) wire mesh reinforcing, (ii) polypropylene bands, (iii) reinforced concrete corner stitches (L-stitch) [7]. [15] used timber-based panels to strengthen a masonry wall under out-of-plane load, demonstrating increased load and displacement capacity. [16] employed diagonally installed steel strips, resulting in

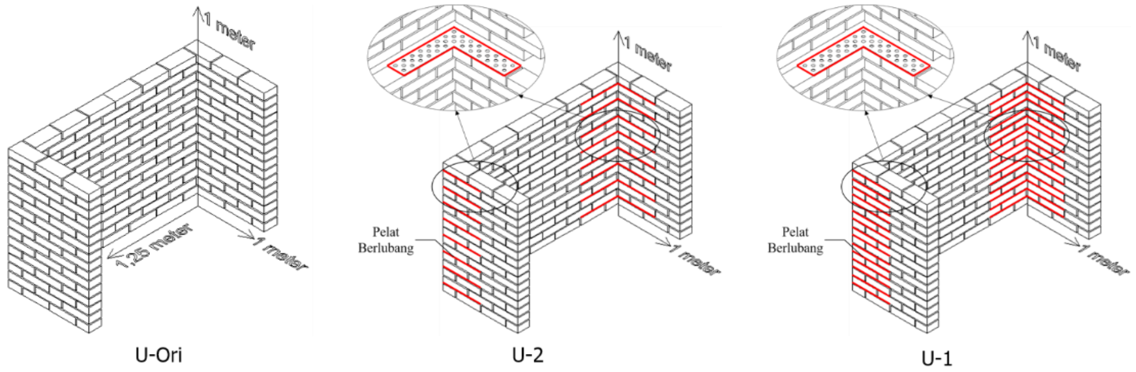


Figure 1 U Specimens

a strengthened masonry wall with improved ductility, stiffness, in-plane strength, and energy dissipation. [17] proposed a cable bracing system installed diagonally, significantly enhancing in-plane strength, ductility, and energy dissipation, with up to twice the lateral capacity of a plain masonry wall. [18] Proposed a bamboo strip mesh installed at the surface of the masonry wall. The bamboo strip in sufficient amount could increases strength, deformation and prevent brittle failure.

RESEARCH SIGNIFICANCE

One potential material for strengthening these structures is zinc alloyed steel. This material offers relatively high tensile strength, is cost-effective, and readily available. The proposed method involves inserting zinc alloyed steel into the masonry layers. Importantly, this process does not affect the outer appearance of the building, as the plates are concealed within the masonry and mortar layers. To ensure a cohesive bond between the steel plates and the masonry, the plates need to be perforated. This approach is expected to enhance the integrity of the perpendicular walls.

METHODOLOGY

The methodology of this research includes material tests and pushover test.

A. MATERIAL TESTS

The research methodology includes a comprehensive series of material tests, each designed to assess specific properties crucial to understanding the structural behaviour of the masonry system under investigation. These tests encompass the brick compressive test, mortar compressive test, mortar flexural test, and perforated zinc alloy steel tensile test.

The brick compressive test involved subjecting four sample bricks to compressive forces to determine their average compression strength (f_b). This parameter is essential for evaluating the load-bearing capacity of the bricks in masonry context.

For the mortar component, both compressive and flexural tests were conducted. The mortar compressive test utilized six cubes of 50 x 50 x 50 mm^3 mortar, following the guidelines outlined in SNI 6825-2002 [19]. Simultaneously, the mortar flexural test employed three samples of 40 x 40 x 160 mm^3 mortar, adhering to the specifications outlined in ASTM C348-08 [20]. These tests provided insights into the mortar's ability to withstand compressive and flexural stresses.

The tensile properties of perforated zinc alloy steel plate were evaluated through a tensile test involving five samples, following the standards established by SNI 8389-2017 [21]. This examination yielded critical data regarding the plate's capacity to resist tensile forces, an importer consideration in masonry systems subject to various loading conditions.

By systematically conducting these material tests in accordance with established standards, the research ensures a thorough understanding of the fundamental characteristics of each component, contributing to a holistic assessment of the masonry systems' structural integrity.

B. SPECIMEN

In this experimental setup, three distinct types of specimens, each representing a different configuration, were employed: U-Ori, U-2, and U-1, as illustrated in Figure 1. U-Ori denotes unreinforced specimens, meanwhile U-2 and U-1 incorporate perforated zinc alloy steel plate reinforcement, strategically placed every two layers and each layer, respectively. The purpose of the variations is to evaluate the impact of reinforcement on the structural performance of the masonry walls.

The test specimens are comprised of three single-layer masonry walls, arranged in a U-shaped plan, with dimensions of 125 cm length for the web wall and 100 cm length for the flange walls (Figure 2). The bricks are soaked/doused with water first before being assembled into a wall. To anchor the walls, a substantial 150 x 120 x 10 cm^3 concrete slab was employed. At the top of these walls, a 10 x 10 cm^2 concrete beam was installed to facilitate the transfer of loads and ensure stability during testing.

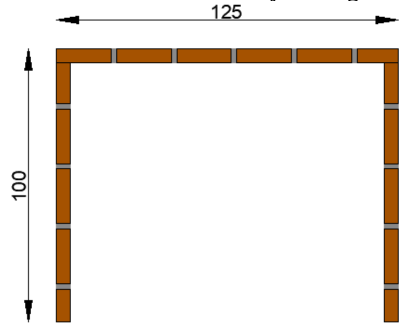
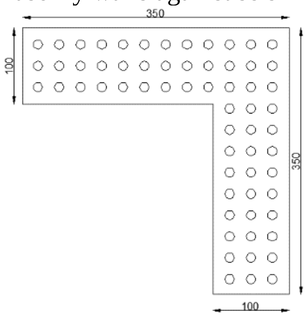


Figure 2 Specimen dimensions

Integral to this experimental configuration is the use of perforated zinc alloy steel plates, each exhibiting an L-shaped design with dimensions of 35 cm length, 10 cm width, 0.8 cm diameter holes (Figure 3(a)). The critical feature is the alternation of hole orientation, protruding alternatively upwards and downwards (Figure 3(b)). These perforated plates were strategically placed at the corners where the masonry walls intersect perpendicularly (Figure 5). Importantly, the mortar was meticulously ensured to pass through the holes in the perforated plates (Figure 5(b)), facilitating a seamless integration of the reinforcement within the masonry structure.

The testing of these specimens occurred at the 30-day age mark, allowing for a comprehensive assessment of their structural response and integrity. This meticulous experimental design, incorporating diverse reinforcement configurations and stringent construction details, aims to provide nuanced insights into the effectiveness of perforated zinc alloy steel plates in enhancing the seismic resilience of masonry structures. The distinct variations in reinforcement placement allow for a comparative analysis, resolving on the optimal strategies for strengthening masonry walls against seismic forces.



(a) Perforated plate dimensions

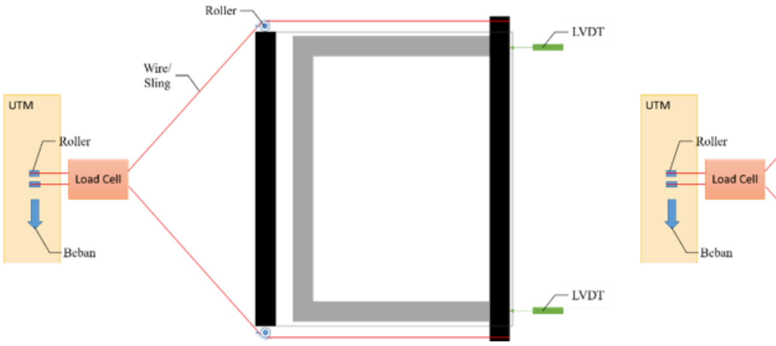
(b) Details of the plate

Figure 3 Perforated zinc alloy steel plate

C. LATERAL PUSHOVER TESTS

The investigation into the performance of masonry wall joint corners involved the implementation of lateral pushover tests conducted at the Laboratory of Structure of the Sepuluh Nopember Institute of Technology in Surabaya. These tests were meticulously executed using the pushover method, with a focus on scrutinizing the behaviour of the masonry walls under lateral forces. The experimental setup included sophisticated equipment such as the Universal Testing Machine (UTM) for applying load, LVDT for measuring displacement, and tensile load cells for precisely measuring the applied load.

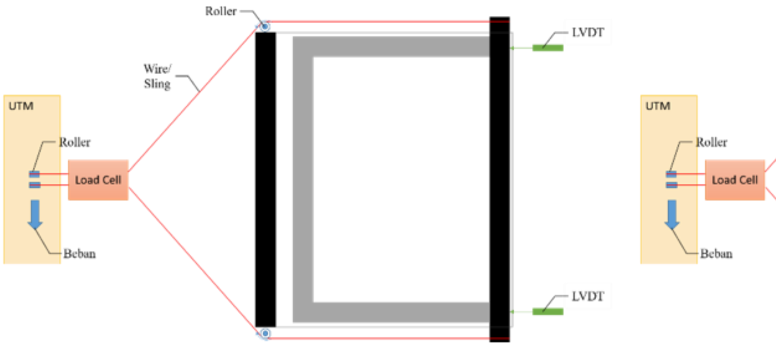
The testing procedure involved the gradual application of lateral loads to the structure until failure occurred. This process was facilitated by a wire connected to a transfer beam, load cell, and UTM, ensuring the controlled distribution of the applied load. The entire setup and configuration of the test are visually represented in



(a) scheme of set-up test for U-Ori and U-1

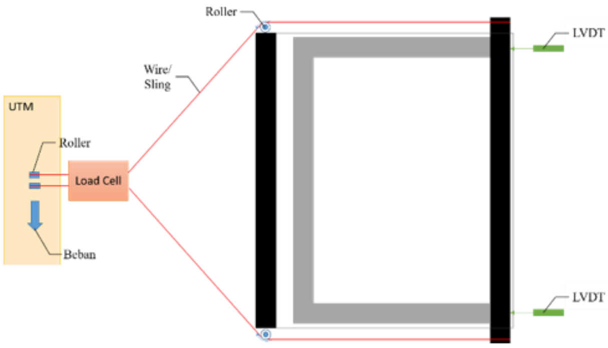
Figure 5, offering a comprehensive insight into the experimental arrangement.

It is noteworthy that, in the case on the U-2 specimen, a unique approach was taken. The orientation of the walls was intentionally reversed, resulting in the application of the load to the web wall instead of the top of the flange walls (

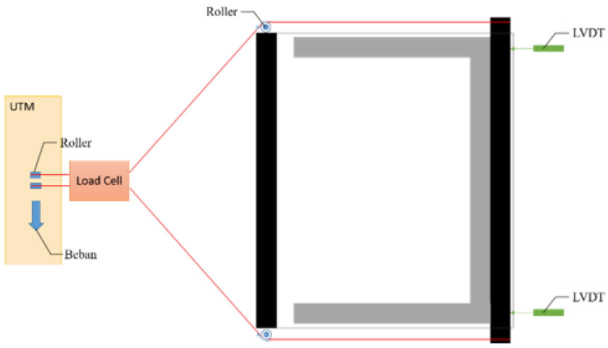


(a) scheme of set-up test for U-Ori and U-1

Figure 5 (b)). This deliberate modification in the specimen configuration provides a nuanced perspective on how altering the load application point can influence the structural response of the masonry walls. Such details are vital for a comprehensive understanding of the performance variations in different reinforcement



(a) scheme of set-up test for U-Ori and U-1



(b) scheme of set-up test for U-2

Figure 4 Failure pattern

scenarios, resolving on the optimal strategies for strengthening masonry structures against lateral forces. The outcomes of these tests contribute significantly to the body of knowledge regarding seismic resilience in masonry constructions, informing future endeavours in enhancing the safety and stability of such structures.

(a) Perforated plate installment (b) Mortar passing through the holes

Figure 5 The process of making the specimens

RESULTS AND DISCUSSIONS

In this section, experimental results would be discussed, including both material tests and lateral pushover tests.

A. MATERIAL TESTS

Table 1 presents a comprehensive overview of the material test results encompassing brick, mortar, and zinc alloy perforated plate properties. These findings serve as essential reference points for assessing the structural performance and integrity of the masonry system under consideration.

Starting with brick properties, the average brick compression strength (f_b) is determined to be 3.209 MPa. This metric is crucial as it gauges the ability of the brick to withstand compressive loads, which is fundamental in masonry construction.

Moving on to mortar, both compression strength (f_{mor}) and flexural strength ($f_{mor,flex}$) are key indicators. The tests reveal an average mortar compression strength (f_{mor}) of 5.983 MPa, signifying its capacity to endure compressive stresses. Meanwhile, the flexural strength ($f_{mor,flex}$) stands at 2,883 MPa, offering insights into its resistance to bending forces.

Turning attention to the zinc alloy perforated plate, mechanical properties are examined. The average of the yield strength (f_y) and tensile strength (f_u) are noteworthy at 90.992 MPa and 200.327 MPa, respectively. These values underpin the plate's ability to withstand yielding and tensile forces. Additionally, the average strain (ε) and Young's Modulus (E) are calculated as 0.030 and 46894.80 MPa, providing valuable information regarding the plate's deformation characteristics and stiffness.

These material test results collectively form the foundation for a comprehensive understanding of the structural components involved and their respective capabilities within the masonry system under investigation. Such data is pivotal in making informed decisions and optimizing the design and performance of the masonry wall.

Table 1 Material Properties

Material	Property	Value	
Brick	f_b	3.209	MPa
Mortar	f_{mor}	5.893	MPa
	$f_{mor,flex}$	2.883	MPa
Zinc alloy perforated plate	f_y	90.992	MPa
	f_u	200.327	MPa
	ε	0.030	
	E	46894.80	MPa

B. LATERAL PUSHOVER TESTS

The pushover test results provide a comprehensive insight into the intricate relationship between load (P) and displacement (Δ) as detailed in Table 2 and visually represented in Figure 6. These findings unravel distinctive behaviors among different specimens, shedding light on the structural dynamics of masonry walls.

Table 2 Lateral pushover test results

Specimen	P_{cr} (N)	Δ_{cr} (mm)	P_{cr} (N)	Δ_{cr} (mm)	Ductility μ
U-Ori	3138.24	2.45	3922.8	4.13	1.68
U-2*	3726.66	2.55	3922.8	2.68	1.05
U-1	1765.26	1.85	1765.26	1.85	1.00

*different loading directions

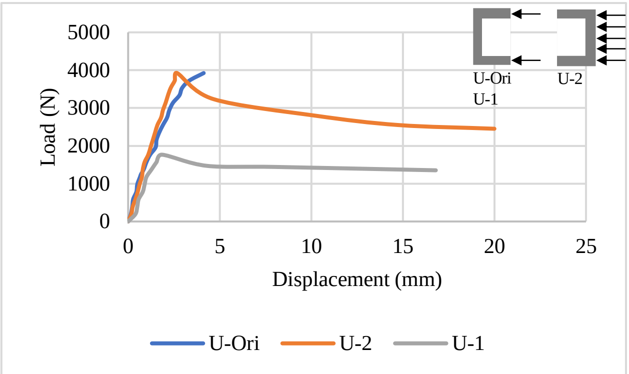


Figure 6 Load-displacement curve of the lateral pushover tests

Notably, the unreinforced walls (U-Ori) exhibited a remarkable resilience, withstanding a substantial load of 3138.24 N before initiating cracking at a displacement of 2.45 mm and experiencing failure at 3922.8 N with a displacement of 4.13 mm. In stark contrast, the reinforced wall (U-1) experienced earlier failure, cracking, and immediate collapse at a load of 1765.26 N with a displacement of 1.85 mm. This stark divergence in performance underscores the greater ductility of U-Ori compared to U-1. The introduction of a perforated plate in U-1, intended to enhance reinforcement, inadvertently compromised the unity of the masonry wall, resulting in reduced load-bearing capacity. The ultimate load (P_{ult}) comparison reveals that U-1's load capacity is diminished by 55% when compared to U-Ori.

Specimen U-2 was loaded differently, with the load applied to the web wall instead of the flange walls. The web wall is stronger than the flange walls, so the load applied to it is expected to be greater than the load applied to the flange walls. This was done to assess the behaviour of the

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(a) Failure pattern of U-Ori (b) Failure pattern of U-1

(c) Failure pattern of U-2

Figure 7 Failure pattern

walls and determine of the reinforced web wall could handle a greater load compared to unreinforced flange walls in U-Ori, where the load is applied to the flange walls.

The results showed that U-2 withstood a load of 3726.66 N, which is the same as the load borne by the flange walls in U-Ori. If the capacity of the web wall in U-2 is similar to the flange walls in U-Ori, it indicates that the flange walls in U-2 have a lower capacity that U-Ori.

Figure 7 shows the failure patterns of specimen U after conducting horizontal pushover tests. The failures observed are flexural slip failures in both the mortar-to-brick joints and the mortar-to-perforated plate joints. Slip failure in mortar-to-brick joints can occur when the bricks are not adequately moistened, resulting in weak bonding between the bricks and mortar. Insufficient moisture prevents dry bricks from effectively absorbing wet mortar and adhering to the bricks, leading to slip failure. Slip failure also occurs in perforated plates due to insufficient mortar bonding. The mortar cannot fully fill the holes in the plates, preventing cohesive bonding between the mortar and the perforated plates. This can happen because the length of the protrusions is insufficient and the hole is not big enough, resulting in ineffective mortar binding.

From the experimental pushover testing, it can be concluded that the perforated plates installed in the layers of the brick masonry damage the unity and integrity of the brick masonry wall. The failure pattern is a combination of in-plane (IP) and out-of-plane (OOP) failures. In the case of U-Ori and U-1, the flange walls experience IP failure, while the web wall experiences OOP failure.

CONCLUSIONS

The research findings yield several noteworthy conclusions. To begin with, when considering the lateral load capacity, U-Ori demonstrates an impressive capacity of 3922.8 N, accompanied by a displacement of 4.13 mm. U-2 also exhibits a lateral load capacity of 3922.8 N but with slightly lower displacement of 2.68 mm, while U-1 displays a load capacity of 1765.26 N, with a displacement of 1.86 mm. These figures provide critical insights into the structural behaviour of these masonry configurations.

Secondly, the assessment of ductility in these structures reveals significant variations. U-Ori boasts a remarkable ductility value of 1.68, indicating its capacity to undergo substantial deformation under load. In contrast, U-2 and U-1 exhibit lower ductility values of 1.05 and 1, respectively, signifying comparatively limited deformability. These findings underscore the importance of considering ductility as a crucial factor in evaluating the performance of masonry walls.

Thirdly, an analysis of the failure patterns unveils that both in-plane (IP) and out-of-plane (OOP) failures occurred, accompanied by crack and slip failures in the mortar joints. These failure modes further illuminate the vulnerabilities and challenges associated with these masonry wall configurations during lateral loading conditions.

Notably, the addition of perforated plates within the masonry wall was initially intended to bolster the integrity of perpendicular walls. However, the research outcomes unveil an unexpected revelation – damage primarily transpired within the joints between mortar and brick, as well as between mortar and perforated plates, rather than within the joints connecting the perpendicular walls. This unexpected results prompts the conclusion that the incorporation of perforated plates within the layers of masonry appears to have an adverse effect, diminishing the strength, load-bearing capacity, and overall cohesiveness of the masonry wall. This revelation underscores the importance of careful consideration and thorough testing when implementing innovative solutions in construction to ensure that they achieve their intended objectives without compromising structural integrity.

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LIST OF NOTATIONS

ε	is the steel strain
E	is the Young's Modulus
f_b	is the brick of compressive strength
f_{mor}	is the mortar compressive strength
$f_{mor,\mathrm{flex}}$	is the mortar flexural strength
f_y	is the yield strength
f_u	is the tensile strength

P_{cr} is the load when cracking occurred
P_{ult} is the ultimate load
Δ_{cr} is the displacement when cracking occurred
Δ_{ult} is the displacement under the ultimate load
μ is the ductility