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Earthquake Resistance of Masonry-Infilled RC Frames Strengthened with Expanded Metal

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Abstract

This research aimed to investigate the compressive strength of lightweight concrete walls before and after reinforcement using the expanded metal reinforced with ferrocement jacketing method and to evaluate the performance level of lightweight concrete walls in reinforced concrete rigid frames. Masonry infill walls were tested using seven samples of lightweight concrete with an average size of 600×600 mm under axial force. The study results were found that in the part of control, non-plastered lightweight concrete wall (CWL) bore an average compressive strength of 2.52 MPa, and plastered lightweight concrete (WPL) bore an average compressive strength of 2.95 MPa. It indicated that plastering on masonry infill walls was able to bear higher impact strength at 1.17 times due to the bonding force of plastering cement at the masonry infill wall. Lightweight concrete walls reinforced with expanded metal, which were able to bear the maximum compressive strength, were lightweight concrete walls reinforced with 1 layer of expanded metal (WPL-E1) that bore the maximum compressive strength capacity, which was equal to 6.40 MPa. When compared with plastered lightweight concrete walls (WPL) samples, masonry infill walls had 2.16 times higher strength capacity. It was shown that reinforcement using the ferrocement technique significantly increased compressive strength capacity. However, in this research, WPL samples, the plastered lightweight concrete walls, were selected as the control samples, and WPL-E1 test samples with the highest compressive strength were used to evaluate the performance level of the reinforced concrete rigid frame. It was found that lightweight concrete walls reinforced with expanded metal were able to bear higher strength at 1.92 and 3.66 times, respectively. When compared to unreinforced masonry infill wall samples and the bare rigid frame, reinforcement with expanded metal effectively was able to increase the strength and stiffness of the reinforced concrete rigid frame.

Keywords: Expanded Metal; Ferrocement; Lightweight Concrete; Masonry; Performance Level.

1. Introduction

Thailand is located in an area less affected by earthquakes compared to many neighboring countries such as Burma and China. Thailand has important active faults in the northern region, including the Mae Chan Fault, Mae Hong Son Fault, Maetha Fault, and Phrae Fault. The faults in the western region are the Si Sawat fault, Three Pagodas Fault, and Moei Fault, and the faults in the southern region included Ranong Fault and Khlong Malui Fault. When an earthquake occurs from these faults, as a result, the buildings shake. This has caused awareness among general people about the safety of various buildings. Especially in Bangkok, where there are many tall buildings. Over the years, a large number of buildings have been built, and the design does not take into account the effect of earthquake force on the structure. Therefore, strengthening the old buildings is an option for strengthening buildings that must be inspected, evaluated,

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and strengthened to be able to resist earthquake vibration focused on the building's performance level and earthquake intensity level. Setting a goal on the performance level is the first step of the building strengthening process, which the designer and the building owners must have a collective agreement on. The purpose of building strengthening was to modify building structure to make it strong according to the goal and objective. The goal of strengthening the building structure was to resist earthquake force (ASCE 41-23). The performance level of buildings was classified into 4 levels: Operational Level (OP), Building Occupancy Level, Immediate Occupancy Level (IO), Life Safety Level (LS), and Collapse Prevention Level (CP), as shown in Figure 1.

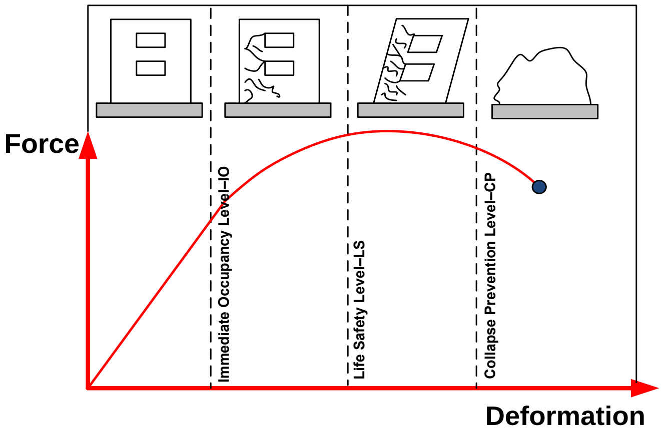


Figure 1. Performance level

Masonry infill walls, generally used for architectural purposes, can be divided into external walls and internal walls. The external walls are responsible for protecting the buildings from various environmental conditions such as rainstorms, sunlight, or heat. The internal walls are used to divide the space into different functional zones within the building and are also used as soundproofing to prevent disturbance. In addition, some parts of the walls also serve to bear reinforced concrete load, and some do not bear load. In wall construction, the materials commonly used in wall construction include bricks, block concrete, lightweight concrete, etc. Because infill walls in building structures are not originally designed to be able to bear earthquake force, especially in the case of walls that have openings by doors and windows, they have very low resistance; therefore, studying the reinforcement method and earthquake resistance behavior of masonry infill walls is very useful to the buildings.

The previous research on techniques and methods of strengthening masonry infill walls was to improve reinforcement of masonry infill walls in order to make the walls have a structural behavior with a better capacity for bearing load and have ductility in order to be able to resist lateral force due to earthquake force and be able to bear shaking underactive force in a cyclic manner effectively. A technique for reinforcing masonry infill walls using steel plates provided higher lateral resistance and stiffness compared to unreinforced [1-3], and there was also research on reinforcing masonry infill walls with CFRP materials, and CFRP reinforcement provided higher lateral resistance as well, but the price of CFRP materials was still expensive [4-8]. The reinforcement technique using shotcrete reinforcement also resulted in higher lateral resistance when compared to unreinforced control samples [9-11]. Research on strengthening masonry infill walls with expanded metal found that strengthening masonry infill walls with expanded metal increased the lateral resistance capacity of reinforced concrete rigid frames [12, 13].

The previous research results on the evaluation of a building’s earthquake resistance performance using the pushover analysis method, commonly applied in building performance evaluation through simulation analyzed by the program to find the building’s performance level goal and earthquake intensity level [14-16], using and analyzing reinforced concrete buildings using the pushover analysis method with the SAP2000 program. The study results showed the evaluation of the building’s performance subjected to structural failure according to the Collapse Prevention Level (CP), which occurred at the plastic hinge point. It was an easy building analysis with the SAP2000 program for evaluating the earthquake resistance of masonry infill walls in a reinforced concrete rigid frame. Also, the study results showed that masonry infill walls were able to increase earthquake resistance when compared to bare rigid frames and increased the overall stiffness value of the rigid frame [17, 18].

The recent study by Tian et al. (2024) [19] investigated the technique of strengthening masonry walls with polypropylene mesh, both before and after strengthening, under cyclic loading conditions. The behavior of the masonry walls was simulated using the Abaqus finite element program to analyze the failure modes. The study found that strengthening with polypropylene mesh significantly increased the load-bearing capacity compared to the unreinforced masonry wall samples. This demonstrates that the use of polypropylene mesh effectively enhances the shear strength and deformation capacity of masonry walls. In the analysis using the Abaqus program, the results closely aligned with experimental data, showing similar shear strength value and failure characteristics. The research by Zhong et al. (2024) [20] investigated masonry walls reinforced with high-polymer cementitious composite materials. The test specimens included unreinforced masonry walls, earthquake-damaged masonry walls, and masonry walls reinforced with high-polymer cementitious composite materials under cyclic loading. The study results showed that the reinforcement technique using high-polymer cementitious composite materials is effective in enhancing the seismic performance of masonry walls. It significantly increases the lateral load-bearing capacity and energy dissipation capability. Even for severely damaged masonry walls, the lateral load-bearing capacity, lateral stiffness, and overall ductility of the walls after reinforcement with high-polymer cementitious composite materials were restored or even improved beyond those of the undamaged specimens. Furthermore, the method also enhanced the energy dissipation capacity of the reinforced walls compared to unreinforced ones.

Zoppo et al. (2024) [21] presented a technique for strengthening masonry walls through out-of-plane reinforcement using inorganic composite materials. This study investigated the effectiveness of an innovative inorganic composite material, namely fiber-reinforced mortar. The test specimens included unreinforced masonry walls and masonry walls reinforced with inorganic composite material on both sides. The results showed that inorganic composite materials were highly effective in significantly enhancing the out-of-plane load-bearing capacity of masonry walls. In addition, the research by Jafarian et al. (2024) [22] investigated the reinforcement of masonry walls using low-carbon textile-reinforced mortar, in which cement was partially replaced with natural zeolite. The study showed that masonry walls were tested both before and after reinforcement under three-point bending tests. The examined parameters included the number of fiber layers, the application on one or both faces, and the effect of natural zeolite as a substitute for cement. Additionally, tensile tests were conducted to study the interaction between the fibers and mortar under tension. The test results demonstrated a significant increase in the load-bearing capacity and ductility of the reinforced specimens. The use of low-carbon textile-reinforced mortar with varying reinforcement ratios showed a direct impact on the maximum load-bearing capacity. Tensile tests consistently showed that the ultimate strength decreased as the amount of zeolite increased with a 20% substitution ratio. Additionally, the technique of strengthening masonry walls using wire rope and neoprene was explored in the research by Chavoshan et al. (2024) [23]. The study examined masonry walls both before and after reinforcement with wire rope and neoprene under cyclic loading. The test results indicated that the energy absorption capacity of the unreinforced walls was very low, with observed effects of narrowing and asymmetry in the hysteresis curve. The proposed reinforcement system effectively enhanced the lateral load capacity, initial stiffness, deformation capacity, and energy dissipation capabilities.

The previous studies introduced various interesting approaches, each utilizing different techniques for strengthening masonry walls. The primary goal of these reinforcement methods was to enhance the lateral load-bearing capacity and overall stiffness of masonry wall specimens. However, no prior research investigated the application of experimentally derived mechanical properties of masonry walls to the simulation of reinforced concrete building frames. Therefore, the objective of this research was to study the compressive strength of lightweight concrete walls before and after reinforcement using the expanded metal reinforced with the ferrocement jacketing method, which is a simple reinforcement technique. The tested sample will be a sample with a size of 600 × 600 mm and was tested under axial force to obtain the properties of the materials, including compressive strength, elastic modulus of the materials, and Poisson's ratio to be applied for simulating earthquake resistance behavior of reinforced concrete rigid frame using the seismostruc2024 program in simulating behavior using pushover analysis.

2. Methodology

This study outlines the research process, as shown in Figure 2, which consisted of three main steps: determining the mechanical properties of the materials used in the research, testing the masonry walls, and assessing the performance level of lightweight concrete walls reinforced with concrete rigid frames.

2.1. Materials

In this study, the construction materials used for making masonry infill walls were lightweight concrete with a size of 75 × 600 × 200 mm, which were generally available in the market in Thailand, as shown in Figure 3a. A compressive strength test was performed according to the ASTM C170-90 standard [24]. The test resulted in an average compressive strength of 3.26 MPa. The expanded metal used in the research was a standard diamond shape, as shown in Figure 3b, which was produced according to the JIS G3351 standard [25], with (SW) 8.6 mm in width, (LW) 20.0 mm in hole length, (T) 0.60 mm in thickness, and weight per sheet was 0.69 kg/m2. The tensile strength of expanded metal was tested according to the ASTM D5034-21 standard [26]. The test result showed that the tensile strength at the yield point and the ultimate tensile strength were 337 and 400 MPa, respectively; the water-cement ratio w/c for cement for laying and plastering was equal to 0.35, and the water-cement ratio w/c for cement for laying and control was equal to 0.40. The water used for mixing cement for plastering cement was tap water. Compressive strength of laying and plastering cement was tested according to ASTM C349-97 standard [27]. The test result showed that the compressive strength of laying and plastering cement at 28 days of curing was 21.8 and 14.0 MPa, respectively.

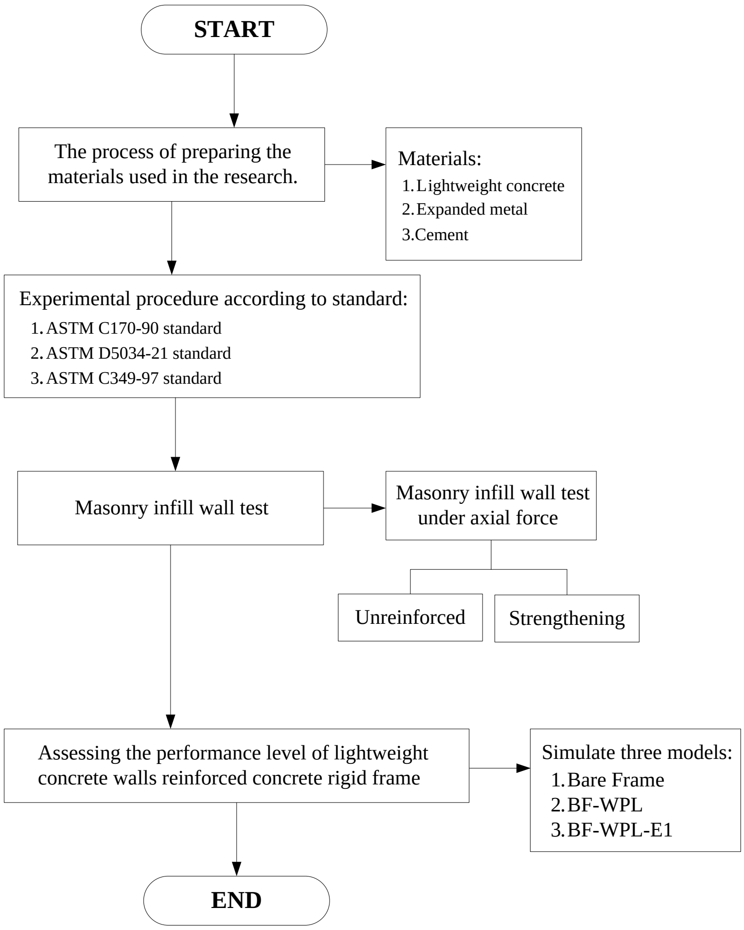
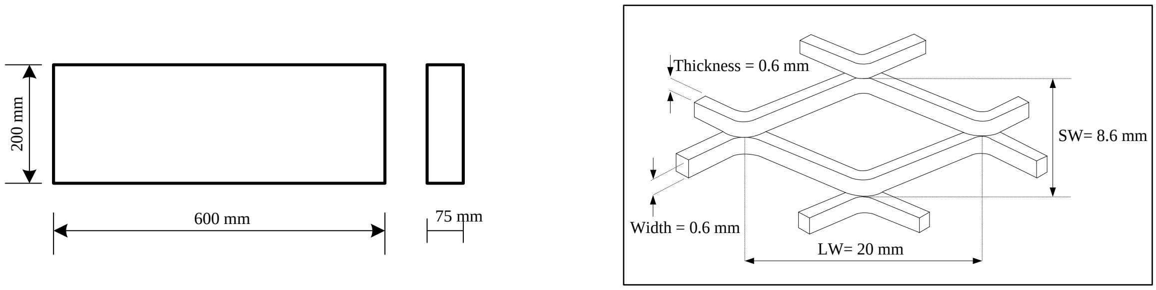


Figure 2. Flowchart of the research methodology



(a) (b)

Figure 3. Materials used in the research: (a) lightweight concrete with size of 75×600×200 mm; (b) Expanded metal

2.2. Masonry Infill Wall Test

Masonry infill walls were tested under compressive strength as shown in Figure 4 by taking a sample of masonry infill walls with a size of 600 × 600 mm with the sample symbol as shown in Table 1, then compressive strength was tested until the failure of a piece of masonry infill wall samples occurred, the test results was applied to compare masonry infill wall samples unreinforced with masonry infill walls reinforced with expanded metal using ferrocement jacketing method.

In preparation for the test of masonry infill walls, lightweight concrete samples will be laid with the amount of 3 pieces, leaving the samples for 24 hours for cement to be set. After that, masonry infill walls will be reinforced with expanded metal, strengthened with the ferrocement jacketing method, as in Figure 5. In bonding expanded metal, the nuts were used to fasten the body of lightweight concrete, and then samples were plastered according to the thickness of 100 millimeters. For the sample size control, corner bead was used to fix the angle before plastering the samples to make the samples have the plane with a suitable angle before testing the compressive strength of the testing samples, then leave the samples at the age of 28 days to wait for the test with the Universal Testing Machine. The research presented the Granulation Diagram for the preparation of the masonry wall samples, as shown in Figure 6.

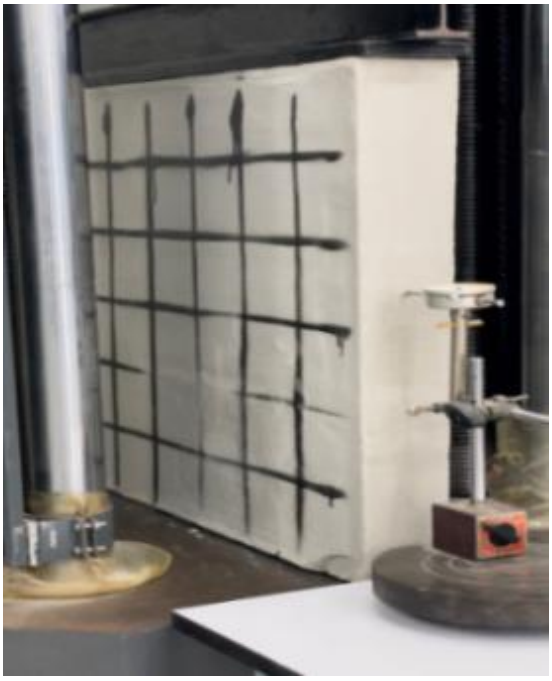


Figure 4. Masonry infill wall test under axial force

Table 1. Sample of masonry infill walls used in research

Example of masonry infill walls	Symbol	Size: Width × length × thickness (mm)
Non -plastered Lightweight concrete walls	CWL	600×600×75
Plastered Lightweight concrete walls	WPL	620×620×100
Lightweight concrete walls reinforced with 1 layer of expanded metal	WPL-E1	620×620×100
Lightweight concrete walls reinforced with alternating weaved expanded	WTL	620×620×100
Lightweight concrete walls reinforced with diagonal expanded metal	WXL	620×620×100
Lightweight concrete walls reinforced with horizontal expanded metal	WHL	620×620×100
Lightweight concrete walls reinforced with vertical expanded metal	WVL	620×620×100

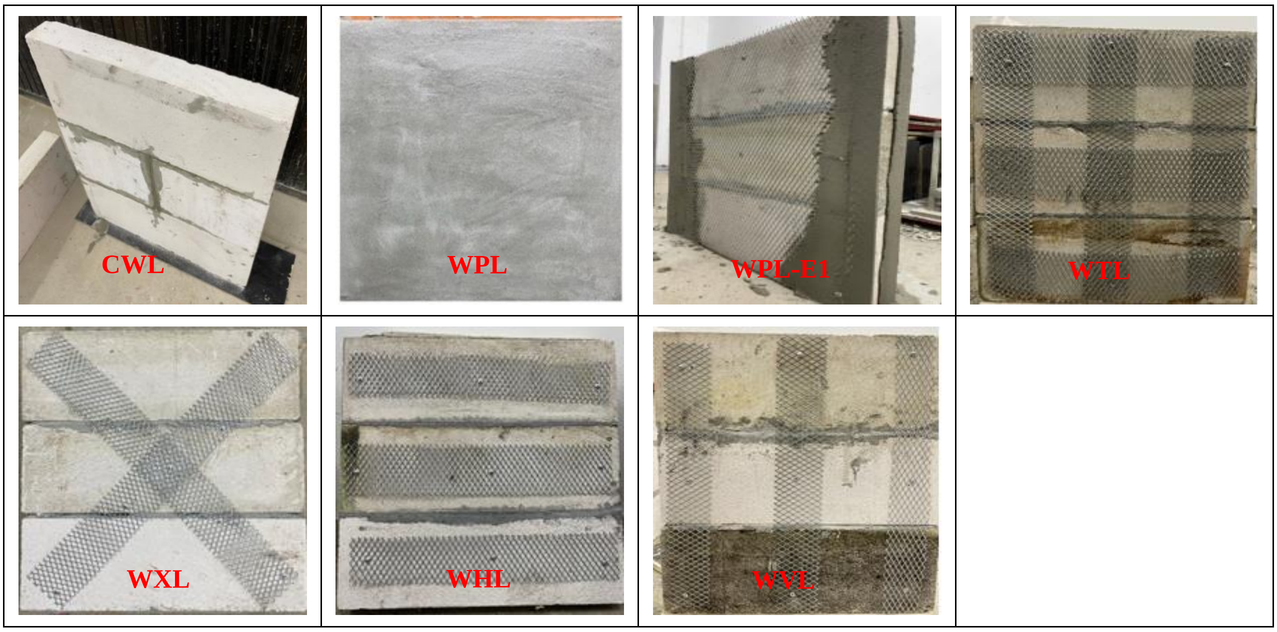


Figure 5. Strengthening with various forms of expanded metal

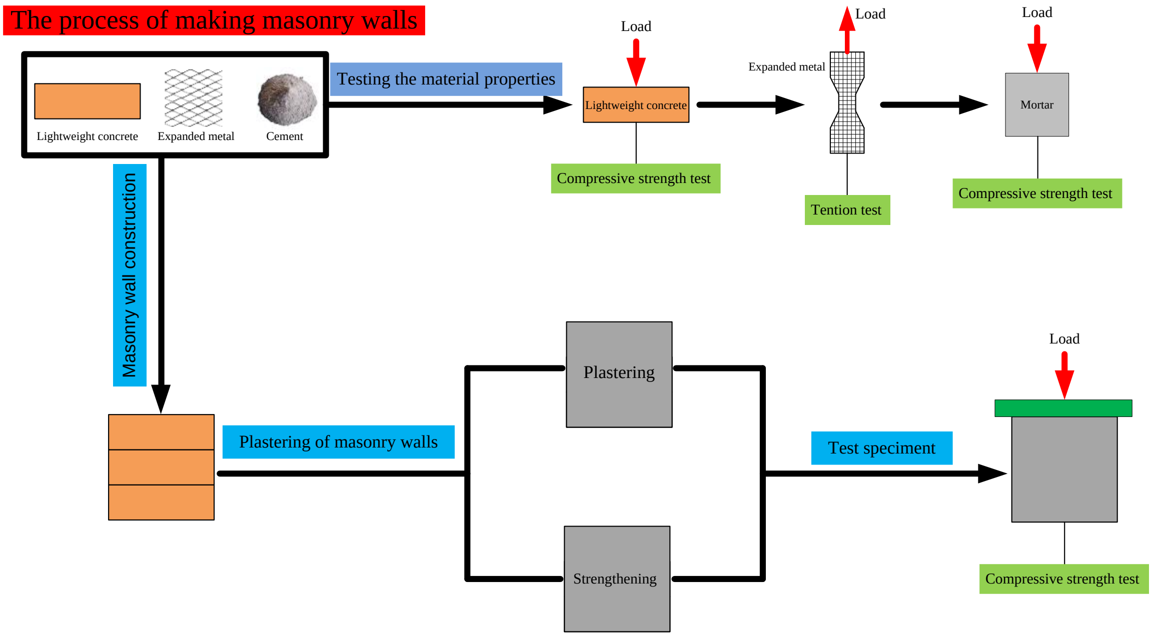


Figure 6. Granulation Diagram

2.3. Assessing the Performance Level of Lightweight Concrete Walls in Reinforced Concrete Rigid Frame

At this step, the basic characteristics of tested masonry infill walls were applied to simulate the behavior of reinforced concrete rigid frames by considering the reinforced concrete rigid frame with the behavior of strong beams and weak columns. The rigid frame used in the research was 4000 mm in width and 3000 mm in height. The reinforced concrete column with a cross-sectional size of 200 × 200 mm consisted of the ratio of steel reinforcement to concrete cross-section of 1.13%. The reinforced concrete beam with a cross-sectional size of 200 × 400 mm consisted of the ratio of steel reinforcement to concrete cross-section of 1.00%. The above behavior was a model of strong beams and weak columns. In this study, the compressive strength of concrete and elastic modulus were 20, 21019.04 MPa, respectively. The steel used in the simulation had the yield strength and elastic modulus of 445, 200000 MPa, respectively, as shown in Figure 7-a. The behavior simulation of a reinforced concrete rigid frame constructed with lightweight concrete walls reinforced with expanded metal with the ferrocement jacketing method to evaluate the performance of the reinforced concrete rigid frame using pushover analysis to push the structure into failure according to the Collapse Prevention Level (CP), which will occur at the plastic hinge point as shown in Figure 7-b.

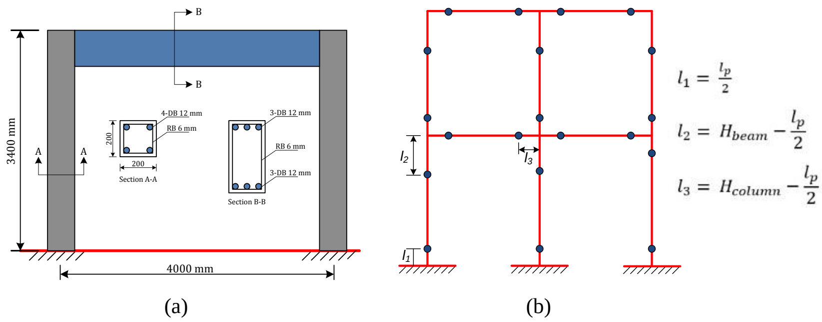


Figure 7. (a) Reinforced concrete rigid frame (b) Plastic hinge

3. Results and Discussion

3.1. The Test Results for the Compressive Strength of Axial Masonry Infill Walls

The test results for compressive strength of axial masonry infill walls reinforced with expanded metal were tested on 7 samples at 28 days of age, with 3 samples per set, an average size of 600×600 mm, including non-plastered lightweight concrete walls (CWL), plastered lightweight concrete walls (WPL), lightweight concrete walls reinforced with 1 layer of expanded metal (WPL-E1), lightweight concrete walls reinforced with alternating woven expanded metal (WTL), lightweight concrete walls reinforced with diagonal expanded metal (WXL), lightweight concrete walls reinforced with horizontal expanded metal (WHL), and lightweight concrete walls reinforced with vertical expanded metal (WVL). The test results were shown in Table 2, and the comparative strength results of masonry concrete walls were shown in Figure 8.

Table 2. Results of Axial active force test of masonry infill walls

Samples	Expanded metal (m^2)	Compressive strength (MPa)	Poisson's ratio	Elastic Modulus (MPa)
CWL	0.00	2.52	0.33	1890.0
WPL	0.00	2.95	0.27	2212.5
WPL-E1	0.72	6.40	0.16	4800.0
WTL	0.50	6.20	0.21	4650.0
WXL	0.24	5.82	0.24	4365.0
WHL	0.36	5.74	0.25	4305.0
WVL	0.36	5.52	0.25	4140.0

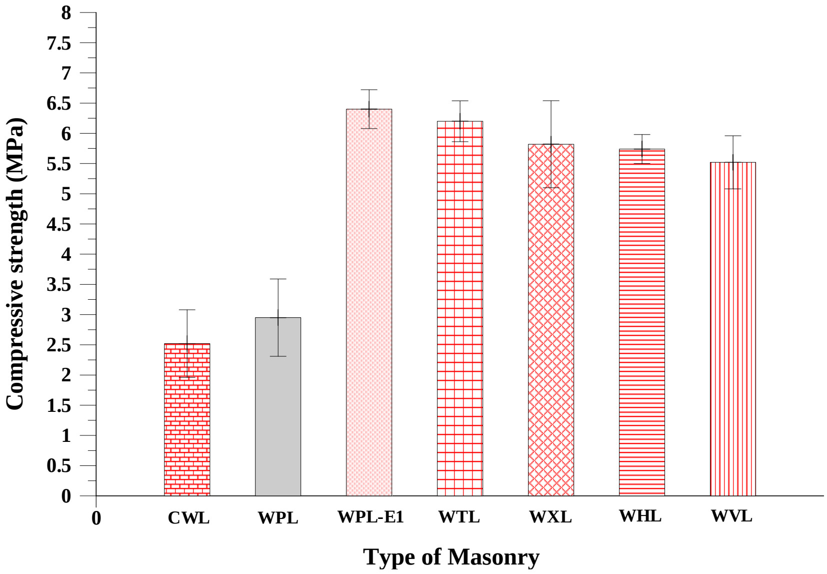


Figure 8. Compressive strength of lightweight concrete wall

Figure 8 showed the vertical compressive strength of masonry infill wall samples at 28 days of age. It was found that the average compressive strength of CWL, WPL, WPL-E1, WTL, WXL, WHL, and WVL samples was 2.52, 2.95, 6.40, 6.20, 5.82, 5.74, and 5.52 MPa, respectively. The standard deviation of testing was in the range of 1.2–4.2, indicating that the test data set had a difference of not more than 15 percent when comparing to the average compressive strength of the three test samples. For CWL control samples compared to WPL samples, it showed that plastering on masonry concrete walls increased compressive strength by 1.17 times because the increased bond strength and thickness affected compressive strength. The binder acted to distribute the force to the cross-section of masonry, which was consistent with the research of Donduren et al. (2016) [28], indicating that plastering mortar acted as a bond between the masonry materials, resulting in an increase of masonry infill walls load-bearing ability.

In comparison of the masonry infill walls reinforced with expanded metal with WPL samples, it was found that WPL-E1, WTL, WXL, WHL, and WVL walls had higher compressive strength of 2.16, 2.09, 1.96, 1.94, and 1.86 times, respectively. Reinforcement with expanded metal using the ferrocement technique can significantly increase the compressive strength of masonry infill walls, which was consistent with the research of Leeanansaksiri et al. (2018) [12] on the reinforcement of expanded metal of masonry infill walls, which stated that reinforcement by the ferrocement method or thin wall, which required the bond force between mortar and woven bonding material such as expanded metal, chicken wire mesh, and wire mesh, the reinforcement can effectively increase the strength-bearing capacity of masonry infill walls. According to the research of Leeanansaksiri et al. (2018) [12], the test result of reinforcement with square and hexagonal chicken wire mesh with different sizes of expanded metal was found that reinforcement with expanded metal can increase the strength of masonry infill walls by 1-1.6 times when compared to reinforcement with chicken wire mesh. According to Table 2, the Poisson's ratio of masonry infill walls was in the range of 0.16-0.33, which was consistent with the research of Ismail et al. (2011) [29], which showed that Poisson's ratio masonry infill walls were in the range of 0.25.

According to Figure 9, it showed the relationship between the compressive strength and settlement of the test samples. When CWL and WPL samples were compressed vertically until they failed, the settlement values were 4.8 and 7.2 mm, respectively. For the lightweight concrete walls reinforced with expanded metal, the reinforcement not only increased the vertical strength of the wall but also made the masonry infill wall samples stronger and more resistant to failure. The graphs of lightweight concrete walls reinforced with expanded metal of WPL-E1, WTL, WXL, WHL, and WVL samples showed the highest settlement values in the range of 5.7-8.2 mm, respectively. It was found that the reinforcement with expanded metal using the ferrocement method increased the toughness of the samples compared to the samples with non-reinforcement.

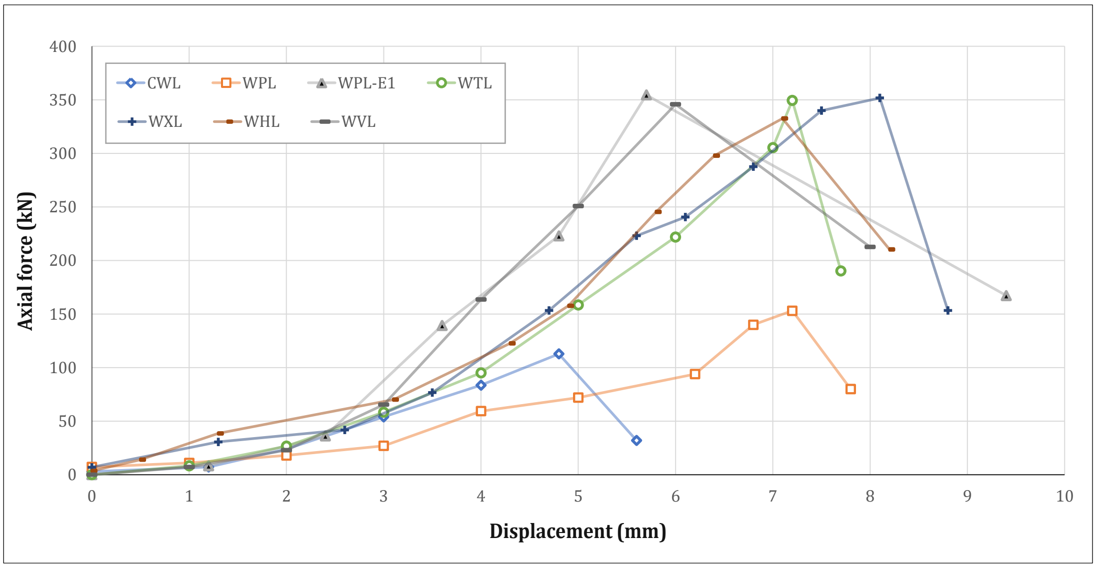
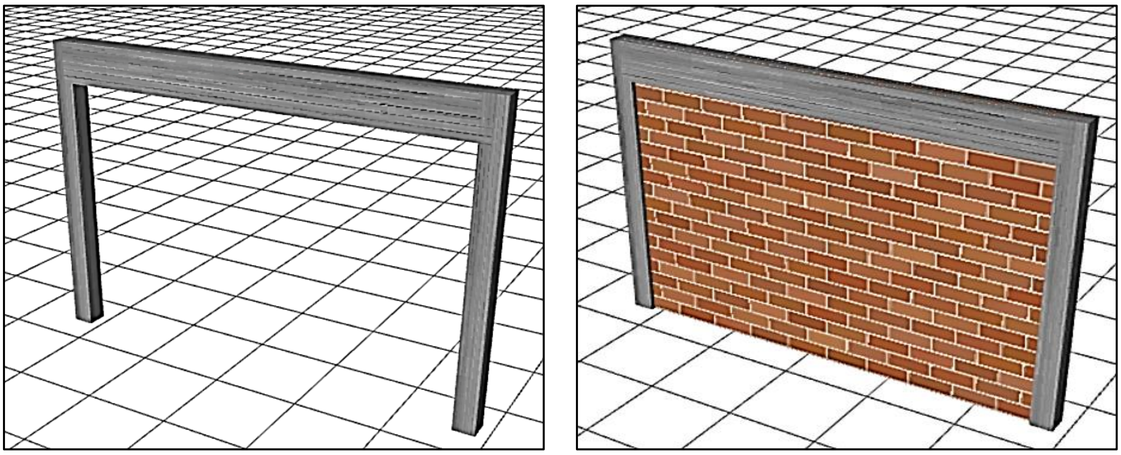


Figure 9. Axial force and Displacement in the samples test

3.2. Performance Evaluation Results of Reinforced Concrete Rigid Frame

In this research, WPL samples, plastered lightweight concrete walls, were selected as control samples, and test samples of WPL-E1 with the highest compressive strength were used to evaluate the performance level of reinforced concrete rigid frame using the properties in Table 2, namely, compressive strength, elastic modulus of materials, and Poisson's ratio. These properties will be applied to simulate the earthquake behavior of a reinforced concrete rigid frame using the Seismostruc2024 [30] program to simulate the behavior using pushover analysis. The prototype was shown in Figure 10-a, and the reinforced concrete frame with internal walls was shown in Figure 10-b. The study results were shown in Table 3, and the relationship between base shear and lateral displacement was shown in Figure 11.



(a) (b)

Figure 10. Modeling in seismostruc2024 program: (a) bare reinforced concrete frame; (b) reinforced concrete rigid frame with internal walls

Table 3. Analysis results of reinforced concrete structure

Samples	Max. Base shear (kN)	Displacement (mm)	Stiffness (kN/mm)
Bare Frame	19.28	36.00	1520
BF-WPL	36.77	33.60	5950
BF-WPL-E1	70.60	33.60	9400

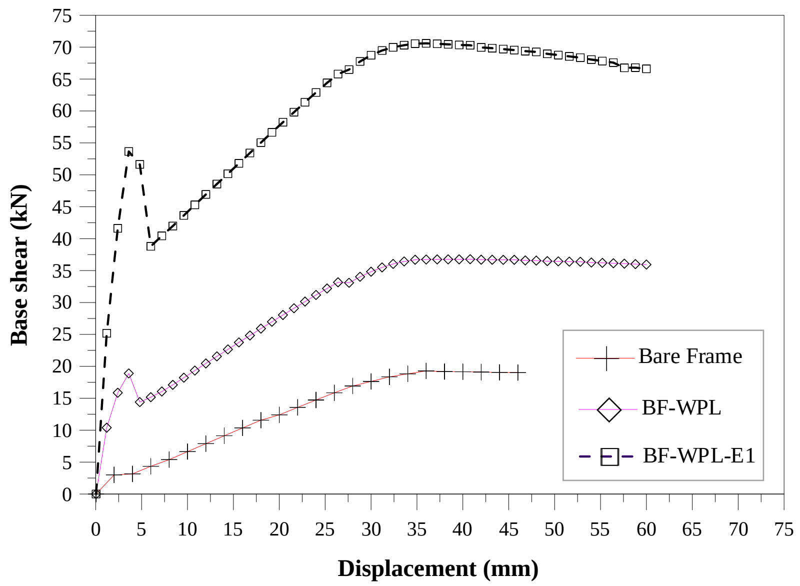


Figure 11. Relationship between base shear and displacement of reinforced concrete rigid frame

The evaluation of the performance level of bare frame showed that the maximum base shear was 19.28 kN and the maximum lateral displacement was 36.0 mm. The analysis results showed that the model of bare reinforced concrete rigid frame failed at the plastic hinge of reinforced concrete columns as shown in Figure 12-a. This indicated that bare reinforced concrete rigid frame with behavior of strong beams and weak columns was not designed to resist earthquake forces. For the evaluation of the performance level of reinforced concrete rigid frame using the properties of BF-WPL wall in analysis, the maximum base shear was 36.77 kN and the maximum lateral displacement was 33.6 mm. From the strength evaluation, the strength increased for1.91 times comparing to bare reinforced concrete rigid frame sample, which was consistent with the study result of compressive strength of masonry infill walls from step 2.2.1. The masonry infill walls were able to increase the strength of reinforced concrete rigid frame, which was consistent with the study of Milheiro et al. (2016) [17] and in the evaluation of the performance level of reinforced concrete rigid frame using the properties of BF-WPL-E1 wall in analysis, the maximum base shear was 70.6 kN and the maximum lateral displacement was 33.6 mm comparing to reinforced concrete rigid frame samples using BF-WPL wall and Bare frame. From the strength evaluation, the strength increased for 1.92 and 3.66 times. For the analysis model of BF-WPL and BF-WPL-E1 samples, the failure occurred at plastic hinge at reinforced concrete columns as shown in Figures 12-b and 12-c, respectively.

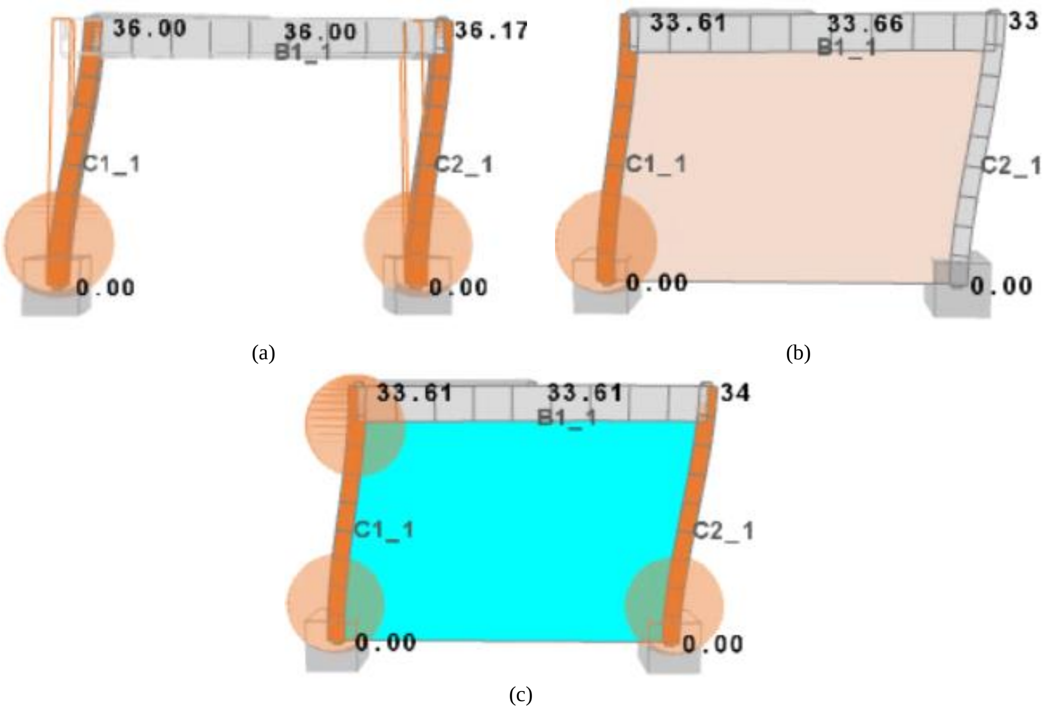


Figure 12. Failure at plastic hinge of reinforced concrete rigid frame: (a) Bare Frame; (b) BF-WPL; (c) BF-WPL-E1

According to Figure 11, the stiffness values of the analyzed reinforced concrete rigid frame of the Bare Frame, BF-WPL, and BF-WPL-E1 samples were 1520, 5950, and 9400 MPa, respectively. In the initial period, the behavior of the BF-WPL and BF-WPL-E1 curves had a high slope, indicating that masonry concrete walls and masonry concrete walls reinforced with expanded metal made the overall stiffness of the reinforced concrete rigid frame stronger. The reinforcement with expanded metal can effectively increase the strength and stiffness of the reinforced concrete rigid frame, which was consistent with the research of Abdelaziz et al. (2019) [18].

In this research, since the study applied properties obtained from the testing of masonry walls, such as axial strength, modulus of elasticity, and Poisson's ratio, to simulate reinforced concrete frame structures only, without testing real samples, a prediction of strength was made using the equation from Saneinejad & Hobbs (1995) [31]. This was applied to estimate the seismic resistance of masonry walls in reinforced concrete frame structures for comparison with the simulation results obtained from finite element analysis using the Seismostruc2024 program.

The prediction of the load-bearing capacity of masonry walls was conducted using an equivalent strut modeling approach, as shown in Figure 13-a. This method accounted for the interaction of lateral forces between the masonry wall and the bare frame. The analysis of the total resistance capacity was divided into two components. The first component involved evaluating the resistance capacity based on the cyclic behavior of the masonry walls within the reinforced concrete frame. These included three types of resistance: diagonal compressive strength, shear sliding resistance, and corner compression resistance. The second component assessed the resistance capacity of the bare frame itself. Once the capacity of both components was determined, they were combined to represent the total resistance capacity, which reflected the contributions of both the masonry wall and the bare frame. For modeling lateral forces and inter-story drift, as shown in Figure 13-b, it was necessary to determine various parameters as the basis for the model. These parameters included the initial stiffness k_o, the shear force at the yield point V_y, and the inter-story drift at the yield point Δ_y. Beyond the yield point, the model captured the maximum shear force, V_m and the maximum inter-story drift, Δ_m, which defined the post-yield stiffness, αk_o.

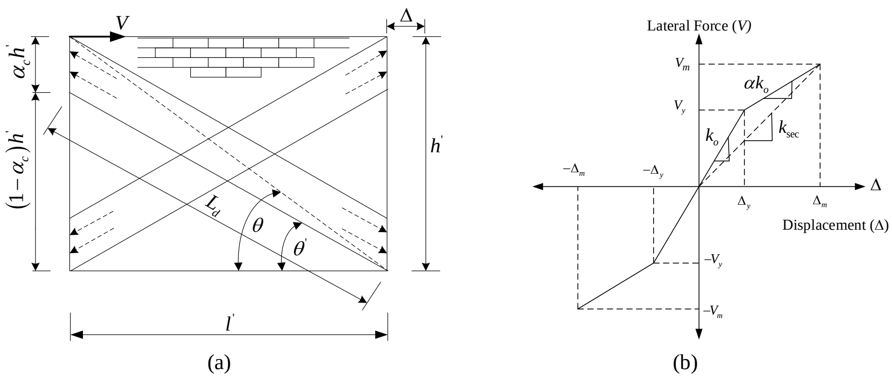


Figure 13. (a) Equivalent strut model; (b) Force envelope of masonry infill wall

This study incorporated diagonal compressive resistance and corner compressive resistance to predict the seismic resistance capacity. According to the findings of Leeanansaksiri et al. (2018) [12], tests on the load-bearing capacity of masonry walls within a reinforced concrete frame revealed that unreinforced masonry walls typically fail due to diagonal compressive failure, while reinforced masonry walls failed due to corner compressive resistance. Therefore, to estimate the maximum load-bearing capacity, the prediction model considered these two failure mechanisms to evaluate seismic resistance obtained from finite element analysis using the Seismostruc2024 program.

For unreinforced masonry walls, failure was predicted to occur as diagonal compressive failure. The maximum shear force in a masonry wall can be calculated by using the diagonal compression strut force.

$$V_m = R_{DC} = \frac{0.5h' t f_a}{cos\,\theta} \tag{1}$$

where $f_a = 0.6\phi f'm$, t = thickness of masonry infill wall, h' = height of masonry infill wall and θ is the inclination of the diagonal strut.

To determine masonry infill wall displacement Δ_m, it can be calculated directly from the stress-strain relationship of experimental result of masonry prism as shown in Figure 14. It should be noted that a bilinear representation may be required for the stress-strain curve of un-strengthened masonry prism.

$$\Delta_m = \frac{\varepsilon_m L_d}{cos\,\theta} \tag{2}$$

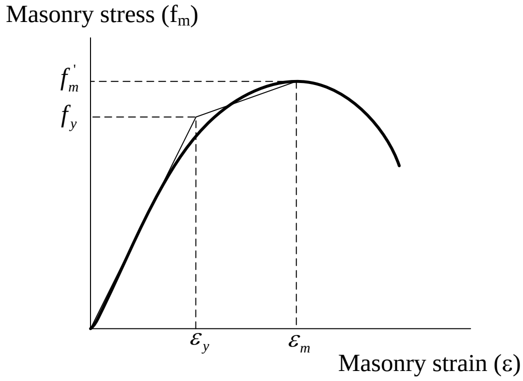


Figure 14. Typical stress-strain relationship of masonry prism test

where ε_m is the strain corresponding to the yield point and the maximum value of masonry, L_d is the length of the equivalent diagonal strut, and it can be calculated as follows:

$$L_d = \sqrt{(1-\alpha_c)^2 h'^2 + l'^2} \tag{3}$$

For the case where the failure mechanism is controlled by the corner compression resistant, the maximum lateral force in the masonry panel V_m can be calculated as follows:

$$V_m = R_{cc} = \frac{(1-\alpha_c)\alpha_c th\sigma_c + \alpha_b tl\tau_b}{\cos\theta} \tag{4}$$

where $\alpha_b, \alpha_c, \sigma_c, \tau_b$ can be calculated as follows:

$$\alpha_c = \frac{1}{h}\sqrt{\frac{2M_{pj}+2\beta_c M_{pc}}{\sigma_c t}} \tag{4-1}$$

$$\alpha_b = \frac{1}{l}\sqrt{\frac{2M_{pj}+2\beta_b M_{pb}}{\sigma_b t}} \tag{4-2}$$

$$\sigma_c = \frac{f'_m}{\sqrt{1+3\mu^2 r^4}} \tag{4-3}$$

$$\sigma_b = \frac{f'_m}{\sqrt{1+3\mu^2}} \tag{4-4}$$

$$\tau_b = \mu\sigma_b \tag{4-5}$$

where h, l are the center to center dimension of the height and the length of the frame, respectively.

The resistance capacity of a bare frame refers to its lateral force behavior in the absence of walls that brace the structure. Consequently, the effects of the three failure mechanisms are not considered. Instead, the focus is placed on the plastic moment capacity of columns, beams, and the moments at beam-column connections, as shown in Figure 15. The resistance capacity of the bare frame can be calculated as follows:

$$R_{BF} = \frac{2(M_{pc}+M_{pj})}{h} \tag{5}$$

where M_{pj} is the lower value of the plastic moment between M_{pc}, M_{pb} , and M_{pc} is the plastic moment of the column, and h is the distance between the centerline to the centerline of the height of the frame structure.

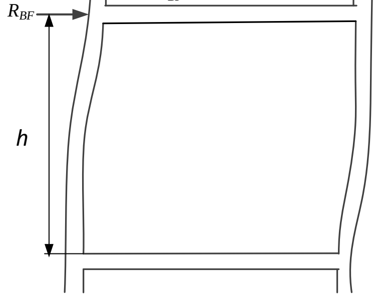


Figure 15. Reinforced concrete bare frame

The predicted earthquake resistance capacity of the bare reinforced concrete frame structure is calculated from the plastic moment in the column (M_{pc}). In using the CSI-Column program, the plastic moment was found to be 25.27 kN-m, and the plastic moment at the beam-column joint (M_{pj}) was 5.4 kN-m. The earthquake resistance capacity of the bare frame structure (R_{BF}) is calculated to be 20.44 kN. For the case with masonry walls in the reinforced concrete frame, the results are compared with the earthquake resistance capacity obtained from the finite element method, as shown in Table 4.

Table 4. The predicted strength of the masonry wall was compared with the evaluated strength, which was calculated using the finite element method

Samples	Prediction		FEM by Seismostruc2024	
	Max. shear (kN)	Displacement (mm)	Max. shear (kN)	Displacement (mm)
Bare Frame	20.44	34.70	19.28	36.00
BF-WPL	38.20	31.11	36.77	33.60
BF-WPL-E1	73.46	30.78	70.60	33.60

From Table 4, the predicted strength of the masonry wall is compared with the evaluated strength, as determined using the finite element method. The results indicated that the predicted strength values were close to those obtained through the finite element analysis. When comparing the predictions for bare frame, BF-WPL, and BF-WPL-E1, the predicted values exceeded those from the finite element evaluation by 5.67%, 3.74%, and 3.89%, respectively. The inclusion of the mechanical properties of the masonry wall, such as axial load capacity, modulus of elasticity, and Poisson's ratio, in the evaluation enhances the reliability of the strength predictions. This aligns with the research of Leeanansaksiri et al. (2018) [12]. Research on the reinforcement of masonry walls using various techniques, such as steel plates, CFRP reinforcement, shotcrete reinforcement, polypropylene mesh, high-polymer cementitious composites, inorganic composite materials, wire rope, neoprene, and low-carbon textile-reinforced mortar, showed that these materials can increase the load-bearing capacity of masonry walls by a factor of 1.5 to 3.0 [20, 29], depending on the type of masonry. However, the results of these studies indicated that all of these techniques can improve the lateral load resistance and increase the overall stiffness of the structure. The key consideration, though, is whether the original structure can accommodate the increased load capacity of the reinforced masonry wall. This is because the reinforcement alters the failure mode from a diagonal compression failure to a compression failure at the wall corners, which can impact the reinforced concrete frame. Therefore, before applying reinforcement techniques, an assessment of the earthquake resistance performance must be conducted. Additionally, the cost-effectiveness of the materials used for reinforcement should be considered. For example, the reinforcement technique using expanded metal mesh is easily sourced locally and is relatively inexpensive compared to polymer-based materials.

4. Conclusion

The study results of the compressive strength of lightweight concrete walls before and after reinforcement using the expanded metal reinforced with the ferrocement jacketing method were as follows: Plastering and non-plastering masonry infill walls with bonding materials had a direct impact on the compressive strength of masonry infill walls. The masonry infill walls with cement plaster increased compressive strength, which was a result of the bonding force and increased thickness, which affected compressive strength. The bonding material acted to distribute the force into the cross-section of the wall materials. In the part of lightweight concrete walls reinforced with expanded metal using the ferrocement method, it was found that WPL-E1, WTL, WXL, WHL, and WVL walls had higher compressive strength of 2.16, 2.09, 1.96, 1.94, and 1.86 times, respectively, compared to the WPL sample. Therefore, the reinforcement with expanded metal using the ferrocement technique can effectively increase the compressive strength of masonry infill walls. Reinforcement with 1 layer of expanded metal in full cross-section had the highest compressive strength, but the reinforcement with expanded metal in various forms also had significantly higher strength. When WPL samples, the samples of control plastered lightweight concrete walls and WPL-E1 test samples with the highest compressive strength were selected to evaluate the performance level of reinforced concrete rigid frame using a finite element program, it was found that the strength capacity of lightweight concrete walls reinforced with expanded metal increased by 1.92 and 3.66 times, respectively. When compared to the non-reinforced concrete wall samples and the bare frame, the reinforcement with expanded metal was able to increase the strength and stiffness of the reinforced concrete rigid frame effectively.

5. Declarations

5.1. Author Contributions

Conceptualization, W.K. and A.L.; methodology, W.K., P.T., and A.L.; software, A.L.; validation, W.K., P.T., and A.L.; formal analysis, W.K and A.L.; investigation, W.K., P.T., and A.L.; writing—original draft preparation, P.T.; writing—review and editing, W.K. and P.T.; project administration, W.K. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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