Performance of Prefabricated Foam Concrete as Infilled Wall Under Cyclic Lateral Loading

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ABSTRACT

Every year earthquakes occur in various regions in Indonesia because Indonesia is located near earthquake faults. The cyclic lateral loading test in the laboratory has been widely used to simulate lateral loads caused by earthquake events. This research is an experimental study on the behavior of prefabricated foam concrete as an infill wall against lateral cyclic loads. Prefabricated foam concrete was used in this study to make it an alternative to brick and autoclaved lightweight concrete (ALC) blocks that have been widely used as infill walls. This study analyzes the relationship between performance levels, lateral loads and drifts ratio on RC infilled prefabricated foam concrete. Lateral cyclic loading with displacement control method was applied to evaluate the structural behavior where the test refers to ASTM E2126-02a. This study adopts FEMA 273, which regulates the performance levels to be achieved by the structure of a building. The results showed that at performance levels Operational Level (OL), Immediate Occupancy (IO) and Life Safety (LS), the RC frame infilled with prefabricated foam concrete blocks had a drift ratio of 0.2%, 1.2% and 2.4%, respectively. Damage to the RC frame infilled with prefabricated foam concrete blocks was similar to the masonry infilled RC frame.

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NOMENCLATURE

ALC	Autoclaved Lighweight Concrete	LS	Life Safety
RC	Reinforce Concrete	CP	Collapse Prevention
FEMA	Federal Emergency Management Agency	MPa	Mega Pascal
ASTM	American Standard Testing and Material	LVDT	Linear Variable Displacement Transducer
OL	Operational Level	Δm	Ultimate Displacement
IO	Immediate Occupancy	N	Newton

1. INTRODUCTION

In Indonesia, non-engineered buildings can generally be found in two forms. The first form is a traditional building built based on local customs and wisdom passed down from generation to generation. The second non-engineered building is a masonry building found in the form of one to two-story residential houses or three or four-story buildings used for residential and commercial purposes. RC frame infilled with masonry is widely used as main element to build the residential house. However, it is widely known that sometimes the RC frame of a residential house is built using inappropriate design standards and insufficient work specification details. Concerning the material for exterior walls and interior walls of residential houses, until now the most commonly used material is burnt clay brick, some use bataco (block made from a mixture of coarse sand and cement). In recent years autoclaved concrete (ALC) blocks have been widely used as walls [1, 2].

In recent decades many researchers and construction experts have focused on the efficient cross-section of structural elements such as beams, columns and foundations. In this regard, the manufacture of walls

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based on lightweight materials is carried out to reduce the dead load carried by structural elements in the form of beams, columns, and foundations.

Foamed concrete is a type of lightweight concrete that in fresh condition takes the form of slurry principally made of cement paste or mortar with about 20% of its volume as foam bubbles. Hardened foamed concrete has a density (weight per unit volume) and compressive strength of about 400-1800 kg/m^3 and 1-20 MPa, respectively [3–6].

Foamed concrete is a concrete made by portland composite cement and natural sand mixture provided that it cannot exceed the volume weight maximum of concrete 1850 kg/m^3 [7]. Lightweight concrete can be further divided into three groups based on the level of density and strength of the concrete produced and based on the type of lightweight aggregate used [8–10].

a. Insulating concrete : Lightweight concrete with a weight (density) between 300 - 800 kg/m^3 and compressive strength ranges from 0.69 to 6.89 MPa, which is usually used as heat-resisting concrete (heat insulation) is also called Low Density Concrete.
b. Moderate strength concrete : Lightweight concrete with a weight between 800 - 1440 kg /m^3, which is usually used as lightweight structural concrete or as fill concrete.
c. Structural concrete : Lightweight concrete with a weight (density) between 1440 - 1850 kg/m^3 which can be used as structural concrete if it is mechanical (compressive strength) can meet the requirements at the age of 28 days having compressive strength ranges from > 17.24 MPa.

Hardened lightweight foamed concrete provides favorable solutions to decrease the self-weight of building, where as the inner voids with less than 5 mm in size and interconnected to form networks make it suitable for use as thermal insulation, sound absorbance, and fire-resistant hence can be appropriately implemented as infill walls. RC frames filled with prefabricated lightweight foamed concrete blocks as non-structural infill wall have developed and become part of the construction of multi-story buildings and residential houses in many countries worldwide.

The use of foam concrete material in high-rise building structures and residential houses is part of sustainable innovation based on environmentally friendly materials. The use of foam concrete material as infilled wall can be reduced the borne load by structural elements so as to reduced the dimensions of beams, columns and foundations which have implications for reduced the use of concrete materials. Fuel consumption can be reduced by the used of prefabricated element structures with those made of foam concrete.

In pursuit of recent development of foam concrete technology and application, Eco Material and Concrete Laboratory, Civil Engineering Department, Hasanuddin University collaborated with a local real estate development company to develop prefabricated foam concrete blocks for the exterior walls and inner walls of residential houses. The main innovation of this development activity lies in the use of fly ash-based blended cement produced by a national company used as a cementitious material where together with local river sand and foam agent and water are mixed to make prefabricated foam concrete blocks. With the widespread availability of prefabricated foam concrete blocks on the market, people have additional wall materials other than the commonly known ones.

Most of Indonesia's areas are prone to earthquakes [11]. Post-earthquake study showed that many buildings were heavily damaged, including non-engineered buildings mostly dominated by residential houses [12]. Most recent earthquake events (Palu earthquake, 2018 and Majene-Mamuju earthquake, 2021) proved the seismic vulnerability of non-engineered buildings with RC frame infilled with masonry.

In harsh earthquake events, the ground motion shaking induces large lateral deformation and caused seismic damage to buildings, including residential houses. Currently, masonry as a wall was considered a non-structural element that does not carry the load and is still neglected in calculating the structure of a building. A number of post-earthquake technical reports indicate that masonry as a wall was mostly damaged. It is well known that the reversed cyclic loads behave seismic loads that arise during the earthquake event, hence, the artificial reversed cyclic load generated from lateral loading device was used to evaluate RC frame with masonry infill and without masonry infill specimens in the laboratory [13].

The primary purpose of the structural design of the building is to ensure safe life, maintenance function, and property safeguarding in the event of a disaster, including earthquake event during the service life. In Indonesia, concerning building damage caused by earthquakes, efforts to emphasize the necessity for building performance-based design have increased in recent years. As mentioned in many available technical investigation reports [14], the RC frame infilled with masonry is essential in building performance, including residential houses. Accordingly, this study aimed to examine the use of prefabricated foam concrete blocks on the performance of RC frame. Specifically, the damage that increases with an increase in amplitude of the applied lateral load is classified according to FEMA's reference level of performance. In the future, the performance level of RC infilled with prefabricated foam concrete resulted from this research can be used as a reference for performance based design of RC frame infilled with prefabricated foam concrete.

2. BUILDING PERFORMANCE LEVELS

The level of damage caused by an earthquake will be different for each building according to the capabilities of each constituent material or structural element of the building. FEMA 273 has set up the performance level for a building [15].

Table 1 summarized the damage control and building performance levels based on FEMA 273, whereas concrete structural performance levels and damage is reported in Table 2. This study adopted FEMA 273 to determine building performance levels. The performance level of interest can be described as Immediate Occupancy (IO), Damage Limitation (DL), Life Safety (LS) and Near Collapse (NC). Figure 1 shows the location of IO, DL and LS in the graph of the relationship between lateral load and deflection.

3. RESEARCH MATERIALS AND METHOD

3. 1. Materials Table 1 stated the properties of the RC frame. This study tested experimentally one infilled RC frame. In this research, concrete with compressive strength of f'c 22.60 MPa was used to produce the bottom beam, and 31.87 MPa concrete for the columns and the top beam of the RC frames. Coarse aggregates with a maximum diameter of 10 mm were used to make concrete for the columns and the bottom beam of RC frames because of their thinner shape.

A plain bar with a diameter of 8 mm was installed every 125 mm in the bottom beam as transverse reinforcement. A plain bar with a diameter of 10 was used as longitudinal reinforcement. In both columns, plain bar with a diameter of 8 mm was used which is installed every 125 mm to function as a transverse reinforcement.

TABLE 1. Damage control and building performance levels [15]

Target building performance levels	Overal Damage	General	Non-structural components
OL (Operational Level)	Very light	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. All systems essential to normal operation are functional.	Negligible damage occurs. Power and other utilities are available, possibly from standby sources.
IO (Immediate Occupancy)	Light	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions and ceilings as well as structural elemements. Elevators can be restarted. Fire protection operable.	Equipment and contents are generally secure, but many not operate due to mechanical failure or lack of utilities.
LS (Life Safety)	Moderate	Some residual strength and stiffness left in all stories. Gravity-load-bearing elements function. No out-of-plane failure of walls or tipping of parapets. Some permanent drift. Damage to partitions. Building may be beyond economical repair.	Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged.
CP (Collapse Prevention)	Severe	Little residual stiffness and strength, but load-bearing columns and walls function. Large permanent drifts. Some exits blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse.	Extensive damage.

TABLE 2. Structural (concrete frame) performance levels and damage [15]

Structural performance levels	Primary	Secondary	Drift
IO (Immediate Occupancy)	Minor hairline cracking. Limited yielding possible at a few locations. No crushing (strains below 0.003).	Minor spalling in a few places in ductile columns and beams. Flexural cracking in beams and columns. Shear cracking in joints <1/16" width.	1% transient; negligible permanent
LS (Life Safety)	Extensive damage to beams. Spalling or cover and shear cracking (<1/8" width) for ductile columns. Minor spalling in non-ductile columns, joint cracks <1/8" wide.	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	2% transient; 1% permanent
CP (Collapse Prevention)	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some non-ductile columns. Severe damage in short columns.	Extensive spalling in columns (limited shortening) and beams. Severe joint damage. Some reinforcing buckled.	4% transient or permanent

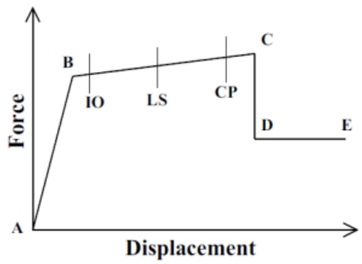

Figure 1. Performance levels IO, LS dan CP

In the upper beam, plain reinforcement with a diameter of 8 mm was installed every 125 mm used as transverse reinforcement. A deformed bar with a diameter of 13 mm was used as longitudinal reinforcement in the beams as well as in the columns of RC frames. A plain bar with a diameter of 8 mm has yield stress and peak stress of 377.87 MPa and 420.96 MPa, respectively. Deformed bars with a diameter of 13 mm have yield stress and peak stress of 473.74 MPa and 643.15 MPa, respectively.

Plain bars with a diameter of 10 mm used as stirrups in the beams and columns have yield stress and peak stress of 469.76 MPa and 598.88 MPa, respectively. Deformed bars with a diameter of 13 mm used as longitudinal reinforcement in beams and columns have yield and peak stress of 473.74 MPa and 643.15 MPa, respectively.

The dimension and reinforcement of the concrete frame infilled with prefabricated foam concrete are shown in Figure 2.

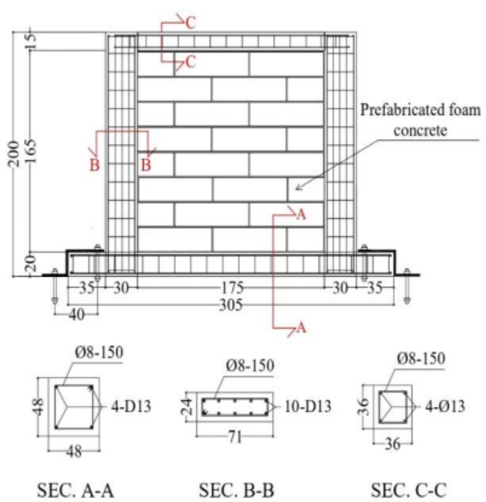

Figure 2. Prefabricated foam concrete infilled RC frame

3. 2. Prefabricated Foam Concrete

The compressive strength test was carried out on cylindrical specimens with a diameter of 10 x 20 cm (height), showing that foam concrete had a compressive strength of 7.38 MPa and modulus of elasticity of 12,768 MPa, respectively. The result of the tensile splitting strength test on the cylindrical specimen with a diameter of 100 x 200 mm (height) showed that foam concrete has a tensile strength of 0.75 MPa. The size of prefabricated foam concrete was 40 mm (thickness) x 700 mm (length) and height of 400 mm.

3.3. Mortar

The mortar used to bind prefabricated foam concrete had a compressive strength of 3.32 MPa. The thickness of the mortar was 25 mm.

3. 4. Test Setup, Instrumentation and Procedure

This study operated a displacement-controlled lateral loading procedure. A hydraulic actuator equipped with a load cell was used to impose cyclic lateral in-plane load at the middle of the top beam. A linear variable displacement transducer (LVDT) was installed in the center of the upper beam to measure the displacement caused by the lateral loading. An electronic data acquisition system was used to monitor and record the load and LVDT reading.

Figure 3 shows the set up of RC frame infilled with prefabricated plain-foamed concrete blocks specimen. According to the standard test for cyclic lateral load testing ASTM E2126-02a tests, the test consists of three-test methods, namely testing with method A (Sequential-Phased Displacement), testing with method B (ISO 16670 Protocol), and testing with method C (CUREE Basic Loading Protocol). This study used a cyclic lateral loading test of method B where the amplitudes' order is shown in Table 3.

The first displacement pattern consisted of fully reversed five single cycles at 1.25, 2.5, 5, 7.5, and 10% of maximum displacement at maximum load. The second displacement pattern consisted of phase, each containing three cycles of equal inverse amplitude, at 20, 40, 60, 80, 100, and 120% displacement of the maximum displacement Δm.

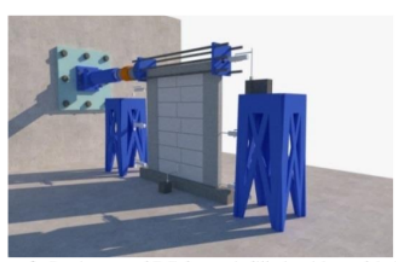

Figure 3. Setting up of RC frame infilled with prefabricated plain foamed concrete blocks specimen

TABLE 3. Test method B—Amplitudes of the reversed cycles

Pattern	Step	Minimum number of cycle	Amplitude, % Δ_m	Horizontal displacement (cm)	Drift ratio (%)
1	1	1	1.25	0.00	0.025
	2	1	2.50	0.10	0.05
	3	1	5.00	0.20	0.10
	4	1	7.50	0.30	0.15
	5	1	10.00	0.40	0.20
2	6	3	20.00	0.80	0.40
	7	3	40.00	1.60	0.80
	8	3	60.00	2.40	1.20
	9	3	80.00	3.20	1.60
	10	3	100.00	4.00	2.00
	11	3	Additional increments of 20 (until specimen failure)	4.80	2.40

4. RESULTS AND DISCUSSION

4. 1. Load and Displacement Relationship

The relationship between load and displacement on the specimen is shown in Figure 4. It can be seen that until the end of the tested, the strength of the specimen had a strength of 44.88 kN under push lateral loading and 52.30 kN under pull lateral loading. Displacement readings under push loading and pull loading were 50 mm and 52.9 mm, respectively.

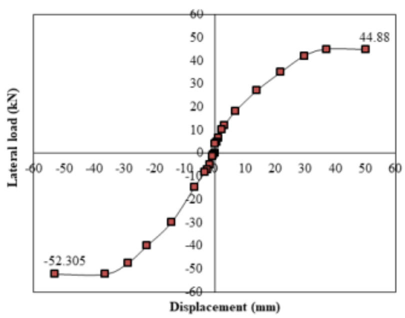

Figure 4. Load and displacement relationship

With an increased in cyclic loading, there is a gradual change in behavior of the prefabricated foam concrete infill wall a linear gradient which turned into a non-linear gradient which showed an inelastic behavior when it reached the post yield zone, so this change caused a change in the lateral stiffness of the specimen.

4. 2. Performance Levels and Drift Ratio

Table 4 shows the performance level of RC infilled with prefabricated foam concrete, which had a relationship between %Δm, drift ratio, and lateral load, which was the test result in this research. It can be seen that structural (concrete frame) performance levels and damage Immediate Occupancy (IO) and Life Safety (LS) occurred at a drift ratio of 1.2 and 2.4%, respectively. Meanwhile, based on FEMA 273 IO and LS occurred at 1.0 and 2.0%. Thus, the IO and LS levels of the RC frame infilled with prefabricated foam concrete blocks are 20% greater than the performance levels of FEMA 273.

TABLE 4. The performance level of RC infilled with prefabricated foam concrete [10]

Structural (concrete frame) performance levels and damage	Lateral load (N)		Δm (%)	Drift Ratio	Description
	Push (+)	Pull (-)			
Operational level (OL)	8,100	7,900	10.00	≈ 0.2%	RC and infills (prefabricated foam concrete blocks) were considered undamaged
Intermediate Occupancy (IO)	22,230	15,540	60.00	≈ 1.2%	Some of RC parts and infills (prefabricated foam concrete blocks) were slightly damaged but can be easily and economically repaired
Life Safety (LS)	52,310	41,220	120.00	≈ 2.4%	A significant number of infills (prefabricated foam concrete blocks) were severely damaged and repairability questionable, lives are not threadened

4. 3. Performance Level and Damage Pattern Figure 5 shows the damage levels of RC frame infilled with prefabricated foam concrete blocks in performance level OL (drift ratio 0.2%). Cracks that occurred in prefabricated foam concrete blocks have spread to the joints between blocks where the lateral load at that time was 8,100 N with %Δm of 10.00%, respectively.

Figure 6 depicts the damage levels of RC frame infilled with prefabricated foam concrete blocks in performance level IO (drift ratio 1.2%). Damage patterns in the form of increasing new cracks and previous cracks that were getting longer and wider occurred in prefabricated foam concrete blocks and joints between blocks. New cracks appeared in the joints between beams and columns. Previous cracks in beams and columns spread and grew in width. This damage pattern occurred at lateral loads, and %Δm were 22,230 N and 60.00%, respectively.

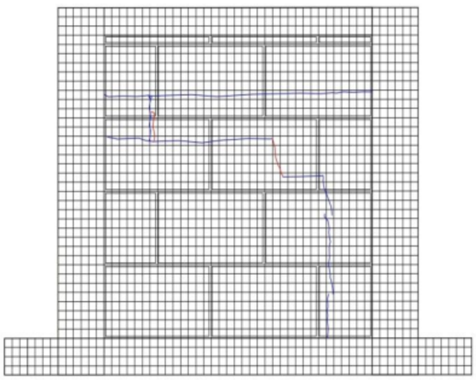

Figure 5. Damage pattern at OL (drift ratio 0.2%) performance level

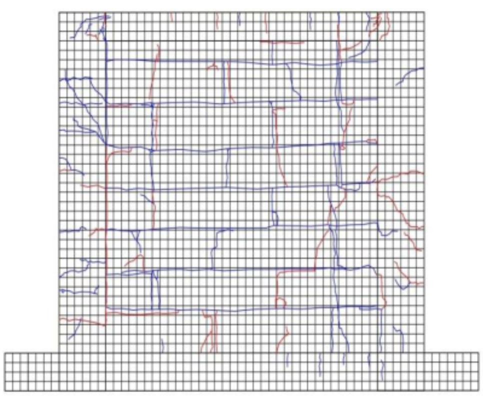

Figure 6. Damage pattern at IO (drift ratio 1.2%) performance level

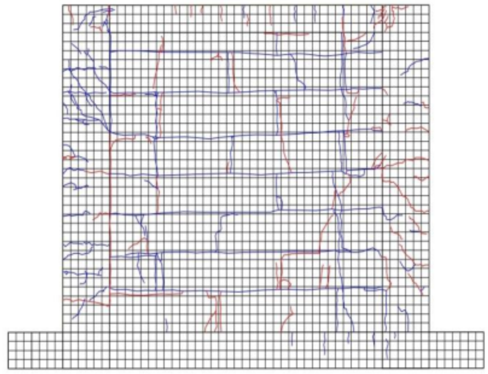

Figure 7. Damage pattern at IO (drift ratio 2.4%) performance level

Figure 7 shows the damage levels of RC frame infilled with prefabricated foam concrete blocks in LS (drift ratio 2.4%). The damage pattern was in the form of cracks in prefabricated foam concrete blocks, between blocks, on the sides of beams and columns, connections between beams and columns, on beams and columns that were increasingly spreading and growing. Spalling of cover concrete in several places in columns and beams occurred, which formed severe damage. This damage occurred at lateral and %Δm loads of 52.310 N and 120.00%, respectively.

Based on Figures 5, 6, and 7, it can be concluded that the damage pattern that occurred in prefabricated foam concrete as infilled walls are in the form of cracks that form corner crushing, diagonal compression, sliding shear, and diagonal cracking. The damage pattern was similar to the damage pattern of the masonry infilled RC frame were the infill made of clay bricks. In contrast, the damage pattern that occurred in the beam and column was shear cracks.

Prefabricated foam concrete panels can be used as an alternative material for infilled wall of reinforced concrete frame structures to replace bricks, hebel, bricks, etc. In most buildings, the wall was not part of the structural element, but served as a stiffener and insulated or separator between building spaces. However, the results of this study indicate that prefabricated foam concrete panels which were used as infill materials have a good structural response in received seismic loads or earthquake loads.

5. CONCLUSION

1. At performance levels OL, IO and LS, the RC frame infilled with prefabricated foam concrete blocks had a drift ratio of 0.2, 1.2, and 2.4%, respectively.

2. Damage to the RC frame infilled with prefabricated foam concrete blocks was similar to the masonry infilled RC frame.

6. ACKNOWLEDGMENT

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Persian Abstract

چکیده

هر ساله زمین‌لرزه‌هایی در مناطق مختلف اندونزی رخ می‌دهد زیرا اندونزی در نزدیکی گسل‌های زلزله قرار دارد. آزمایش بارگذاری جانبی چرخه‌ای در آزمایشگاه به طور گسترده‌ای برای شبیه‌سازی بارهای جانبی ناشی از حوادث زلزله استفاده شده است. این تحقیق یک مطالعه تجربی بر روی رفتار فوم بتن پیش ساخته به عنوان دیوار پرکننده در برابر بارهای سیکلی جانبی است. در این مطالعه از فوم بتن پیش ساخته استفاده شد تا آن را به عنوان جایگزینی برای بلوک‌های آجری و بتن سبک اتوکلاو شده (ALC) که به طور گسترده به عنوان دیوارهای پرکننده استفاده می‌شود، تبدیل کند. این مطالعه رابطه بین سطوح عملکرد، بارهای جانبی و نسبت رانش را بر روی بتن فوم پیش ساخته پر شده با RC تجزیه و تحلیل می‌کند. بارگذاری چرخه‌ای جانبی با روش کنترل جابجایی برای ارزیابی رفتار ساختاری در جایی که آزمون به ASTM E2126-02a اشاره دارد، اعمال شد. این مطالعه FEMA 273 را اتخاذ می‌کند که سطوح عملکردی را که باید توسط ساختار یک ساختمان به دست می‌آید تنظیم می‌کند. نتایج نشان داد که در سطوح عملکرد، سطح عملیاتی (OL)، اشغال فوری (IO) و ایمنی زندگی (LS)، قاب RC پر شده با بلوک‌های فوم بتنی پیش ساخته به ترتیب دارای نسبت رانش ۰/۲ ٪، ۱/۲ ٪ و ۲/٤ ٪ بود. آسیب به قاب RC پر شده با بلوک‌های بتنی فوم پیش ساخته مشابه قاب RC پر شده با بنایی بود.

Performance of Prefabricated Foam Concrete as Infilled Wall Under Cyclic Lateral Loading

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