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A Comparative Study of Flexural Capacity of Precast Light Concrete Plate Building with Experimental and FEM Analysis

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Abstract

The use of precast structural elements in the construction industry has grown rapidly. This study aimed to determine the first crack value and maximum load of lightweight concrete slabs; the crack patterns of lightweight concrete slabs; and the comparison of the first crack value and floor slab displacement in experimental testing and finite element modeling. This study used the four-point loading which was validated by finite element method (FEM). The experimental test specimens consisted of two variants, namely PN-1 and PN-2 for flexural testing, and PN-A for FEM with 120 mm x 600 mm x 2970 mm in dimensions. The results showed that the displacement values at the first crack for PN-1 and PN-2 were 2.05 and 2.03 mm, respectively. The load capacities for PN1, PN2, and PNA were 24.40, 24.50, and 24.30 kN, respectively, with the first crack occurring at 8.33, 8.34, and 8.33 kN. The initial crack originated at the loading point and subsequently propagated along the tensile plane of the plate. It is recommended to conduct research on the impact of shear connectors in the 3D modeling of flexural plates.

Keywords: building, concrete, flexure, plate

1. Introduction

Nowadays, the use of precast structural elements in the construction industry has grown rapidly. According to the Europe Precast Concrete Market Trends 2023 report (Grand View Research, 2024), in Europe, approximately 25% of total residential construction projects use lightweight concrete panels as floor elements, particularly in countries like Germany and the Netherlands, which focus on energy efficiency and reducing construction loads (Elena *et al.*, 2023). The use of lightweight floor panels in Asia, especially in Japan and South Korea, has also increased significantly due to the need for earthquakeresistant structures and rapid urban development (Andreini *et al.*, 2022). The advantages of this system include ease of installation, reduction of building dead loads, and time and cost efficiency (Bing and Jie, 2010; Meriggi *et al.*, 2020). However, the use of lightweight concrete in structural applications, particularly in floor slab elements, still requires further study regarding its flexural capacity (Mugahed, 2016).

The flexural capacity of slab elements is crucial to ensuring the overall strength and stability of a building (Yu and Ye, 2024). On the other hand, computational technology has enabled the development of more efficient analytical methods, such as the finite element method (FEM), which offers analytical simulations that can be used to predict the structural behavior of various materials and building elements. However, FEM simulation results often require validation through field experiments to ensure their accuracy.

Furthermore, advancements in material technology within the construction sector have led to the development of lightweight concrete with increasingly better quality. Lightweight concrete not only reduces the load on building structures but also possesses better thermal properties, which can enhance a building's energy efficiency (Campanale *et al.*, 2015; Narayanan and Ramamurthy, 2000a). However, despite its many advantages, lightweight concrete is often criticized for its lower strength compared to conventional concrete (Maryoto *et al.*, 2018). Therefore, it is essential to thoroughly evaluate how this material behaves under flexural loading conditions in slab structures.

On the other hand, experimental methods for assessing the performance of lightweight concrete slabs often require significant time and cost. Laboratory testing necessitates specialized equipment and facilities, as well as careful sample preparation. Additionally, field experiment results can be influenced by various factors such as material variability, production quality, and environmental conditions during testing (Chunmei *et al.*, 2023). Therefore, alternative methods such as numerical analysis using FEM can offer a solution to mitigate these challenges.

Finite element method has become a highly popular method in structural analysis due to its ability to model geometric complexities and non-linear material behavior (Hrabok and Hrudey, 1984; Irindu *et al.*, 2021; Chunmei *et al.*, 2023). Using FEM, structural simulations can be conducted more quickly and economically compared to experimental testing. However, to ensure that

FEM results are reliable, validating the simulation results with real experimental data remains a crucial step. Discrepancies between simulation results and experimental outcomes often arise due to assumptions within the FEM model.

This research not only focuses on comparing the results between experimental testing and FEM simulations (Greimann and Lynn, 1970) but also on further analysis of the factors affecting the flexural capacity of precast lightweight concrete slabs. Factors such as slab geometry, the type of lightweight concrete used, and the reinforcement configuration significantly influence the analysis results (Maryoto *et al.*, 2018). By identifying these key parameters, it is hoped that better design recommendations can be developed for the use of precast lightweight concrete slabs in construction projects.

Moreover, the first crack is also considered to understand the behavior of concrete structures and to ensure their safety and structural integrity (Yun *et al.*, 2011; Orie and Ogbonna, 2023). The crack load is a significant value for predicting the location of panel slab damage, which is useful for assessing performance and determining appropriate strengthening methods. Additionally, the first crack plays a role in measuring the integrity and durability of buildings, predicting damage behavior, and influencing planning stages and structural behavior (Meinhardt and Keuser, 2017).

Finally, the results of this research are expected to make a significant contribution to strengthening the knowledge base on the structural performance of precast lightweight concrete. Additionally, this research can assist civil engineers in selecting appropriate analytical methods to evaluate structural elements that use innovative materials such as lightweight concrete. Thus, future construction projects can be designed to be more efficient, safe, and sustainable (Lu *et al.*, 2018).

Unlike conventional plate, the presence of lightweight concrete and reinforcement has a positive impact on the performance of the plate. On the other hand, the flexural performance of the plate is crucial to achieve the requirements (Irindu et al., 2021). Based on this reason, this study was designed to investigate the performance of precast plate, which need to be re-evaluated using a finite element approach for bending testing.

2. Methodology

This research used an experimental approach validated with numerical analysis using FEM as follows:

2.1 Specimens

The test specimens consist of two normal panels (PN1 and PN2) with 120 x 600 x 2,970 mm in dimensions. Both test specimens were subjected to flexural testing, while the FEM analysis of the flexural slab was conducted on a panel (PA). The testing apparatus is illustrated in Figure 1.

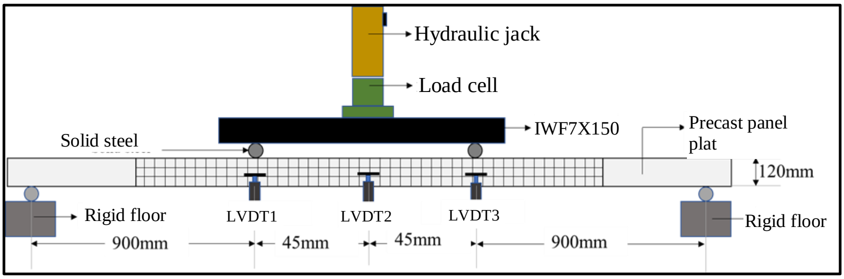

Figure 1. Schematic of flexural testing

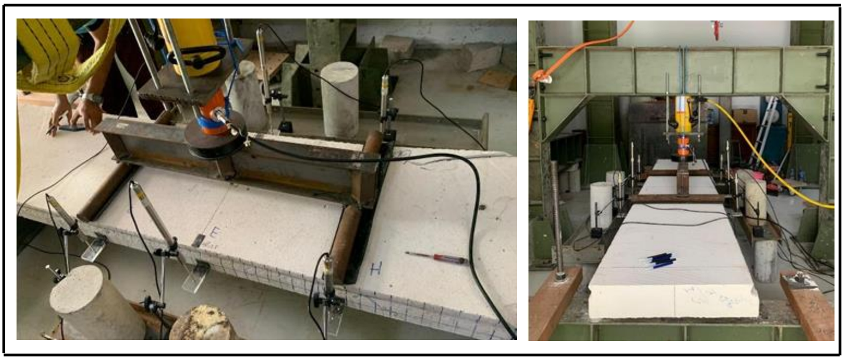

Figure 2. Experimental testing

The flexural testing was conducted using a four-point loading, with linear variable differential transducers (LVDTs) at four points loading (American Society for Testing and Materials (ASTM) (D6272-17e1, 2020). A 50-ton capacity load cell was utilized for the test specimens positioned on an IWF 75 x 150 mm. The flexural loading used solid round steel with a diameter of 50 mm.

2.2 Physical Test and Characteristic of Materials

2.2.1 Tensile Test

The tensile test was conducted at the Building Materials Laboratory, Faculty of Engineering, Yogyakarta State University. The tests were performed on three different diameters: 4.5, 6, and 6.7 mm, respectively. The tests were carried out until the ultimate tensile stress to determine the tensile capacity of the reinforcement steel (ASTM E8/E8M-13a, 2013).

2.2.2 Compressive Strength

The compressive strength of the specimens was assessed using cube specimens with dimensions of 100 x 100 mm, subjected to loading up to the maximum capacity, in accordance with ASTM (C109/C109M-20, 2020) and the following references: Ramamurthy and (2000), Narayanan and Ramamurthy (2000b), and Nambiar *et al.* (2008). The mix proportions based on Standar Nasional Indonesia (SNI) 03-3449-2002 (2002), expressed per cubic meter (m^3), were as follows: sand (360 kg), Portland cement (500 kg), mil (30 kg), water (200 L), water reducer (0.4 L), and foam agent (1,380 L). A total of eight specimens were tested, with each specimen evaluated under both dry and wet conditions.

2.2.3 FEM Analysis

Properties of Materials

The material parameters, as shown in Table 1, were input into the software according to the existing conditions of the test specimens (Huan, 2011).

Table 1. Parameter "property"

No.	Parameter	Value
1	Specific gravity	780 kg/m^3
2	Modulus of elasticity	17,636.54 MPa
3	Poisson rasio	0.2
4	Dilatation angle (ψ)	30
5	Eccentricity (ϵ)	0.0156
6	fbo/fco	1.8981
7	K	0.504
8	Viscosity	0

Damage Plasticity Model on FEM

Under uniaxial tension, the stress-strain behavior followed a linear elastic pattern up to the failure stress, which marks the beginning of micro-cracking in the concrete (Abaqus, 2020). After the failure stress was reached, the development of micro-cracks was modeled by a softening stress-strain curve, leading to strain localization within the concrete structure. In uniaxial compression, the response remained linear until the initial yield stress was reached. Once in the plastic regime, the behavior was typically characterized by stress hardening, followed by strain softening once the ultimate stress was surpassed. While this model was somewhat simplified, it effectively captured the key characteristics of concrete's response as Figure 3 and Figure 4.

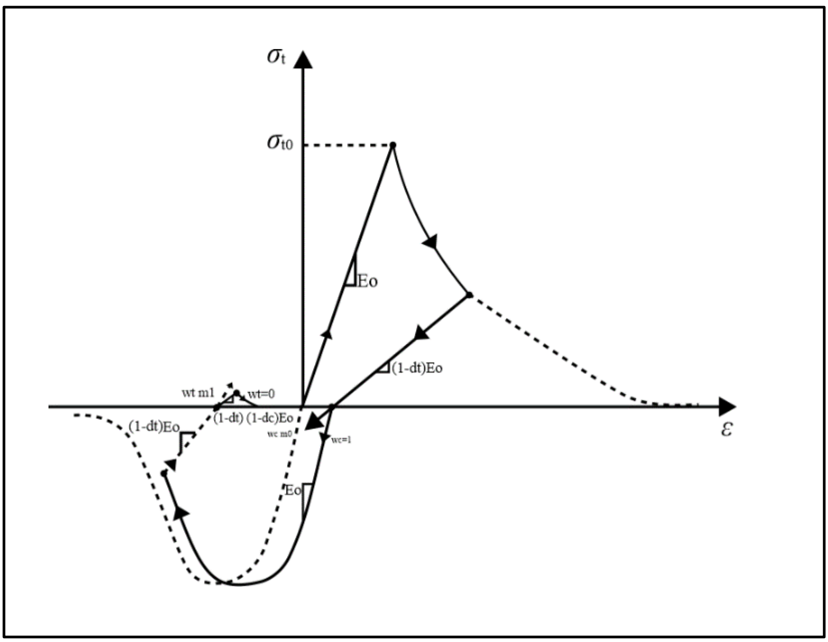

Figure 3. Strength and strain on concrete

It was assumed that the uniaxial stress-strain curve can be converted into a stress-strain curve with plastic deformation. This conversion was performed automatically by the FEM program from the stress and strain data.

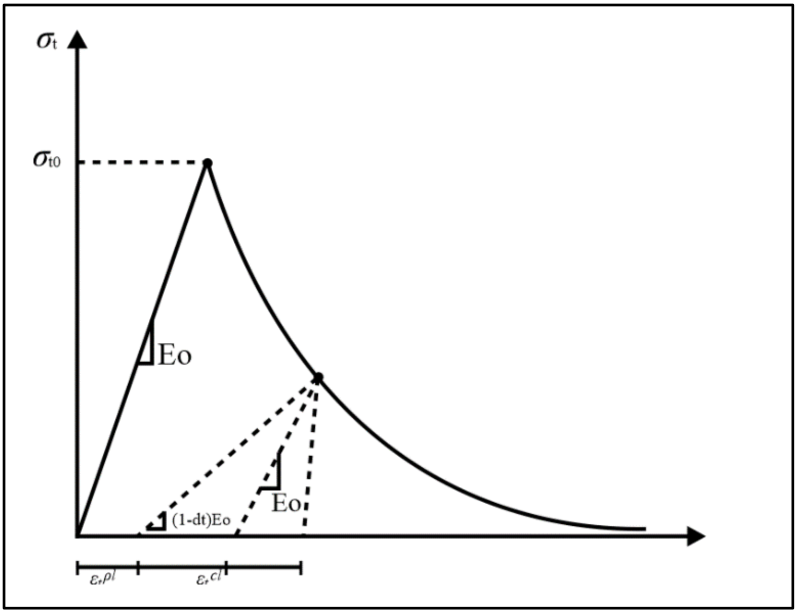

Figure 4. Tensile model on FEM

$$\sigma t = \sigma t\,(\tilde{\varepsilon}_t^{pl}, \dot{\varepsilon}_t^{pl}, \theta, fi) \tag{1}$$

$$\sigma c = \sigma c\,(\tilde{\varepsilon}_c^{pl}, \dot{\varepsilon}_c^{pl}, \theta, fi) \tag{2}$$

where the subscripts t and c refer to tensile and compressive stresses, respectively; $\tilde{\varepsilon}_t^{pl}$ and $\tilde{\varepsilon}_c^{pl}$ represent the equivalent plastic strains; $\dot{\varepsilon}_t^{pl}$ and $\dot{\varepsilon}_c^{pl}$ denote the rates of equivalent plastic strain; θ represents temperature; and fi, ($i = 1, 2, \ldots$) are other pre-defined field variables.

3. Results and Discussion

3.1 Tensile Test

The FEM analysis was conducted using a three-dimensional nonlinear model, with testing until the failure limit was reached.

Table 2. Tensile test of specimens

Diameter	Specimens	Massa (gram)	Tensile strength R_m (MPa)
4.5	T1	59.96	605
	T2	59.79	585
	T3	60.31	580
	Average	60.02	590
6.0	T1	87.52	645
	T2	88.37	635
	T3	88.34	630
	Average	88.07	636.67
6.7	T1	101.23	625
	T2	100	640
	T3	100	620
	Average	100.41	628.33

Based on the test results in Table 2, the average tensile strengths of the reinforcement for diameters D4.5, D6, and D6.7 were 590 MPa, 636.67 MPa, and 628.33 MPa, respectively. The steel used in this testing was wire mesh embedded as reinforcement in precast floor panels.

3.2 Compressive Strength of the Concrete

The results of the concrete compressive strength testing are presented in Table 3.

Table 3. Compressive strength of concrete cube

Conditions	Specimens	Mass (g)	Load (kN)	Compressive strength
Dry	C1D	621,73	52,50	5.25
	C2D	632,41	55,43	5.54
	C3D	621,68	43,09	4.31
	C4D	625,91	52,75	5.28
	Average			5.09
Wet	C1W	723,97	46,13	4.61
	C2W	720,31	49,71	4.97
	C3W	764,93	46,04	4.60
	C4W	756,36	36,58	3.66
	Average			4.46

The average compressive strength testing results for dry and wet conditions were 5.09 and 4.46 MPa, respectively. These results meet the requirement for lightweight concrete according to SNI 03-3449-2002 (2002), American Concrete Institute (ACI) 523.4R-09 (2009), and Feng *et al.* (2024).

3.3 Flexural Strength (Experiment and FEM)

3.3.1 Flexural Strength

The results of the flexural testing, as shown in Figure 5 up to Figure 6, were conducted using a nonlinear approach up to the failure. Figures 5 and 6 present the results of the bending tests on the plate. The first crack load was measured at 9.50 MPa, with a displacement of 2.50 mm, while the corresponding crack moment for both test specimens ranged between 4.40 and 4.50 kNm.

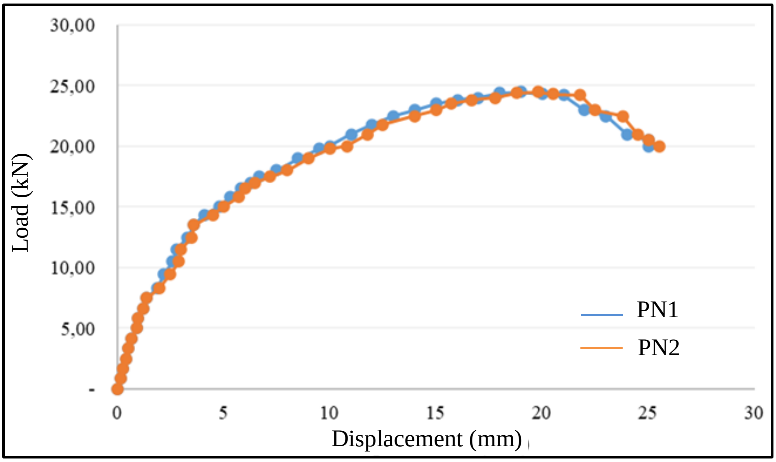

Figure 5. Load versus deflection (PN1 and PN2)

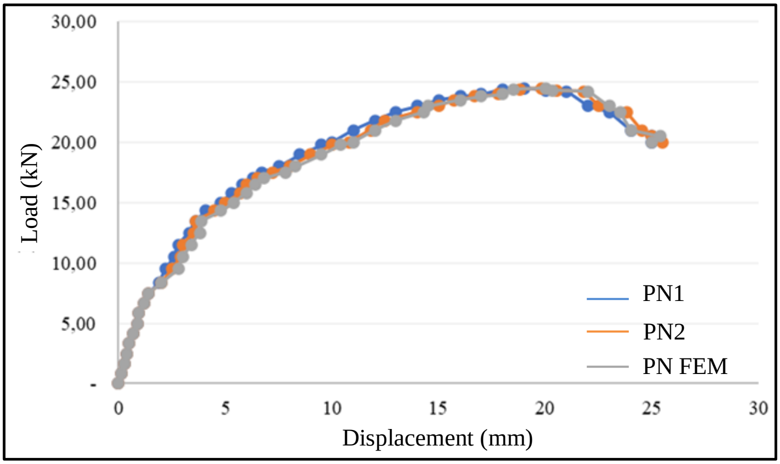

Figure 6. Load versus deflection (PNI, PN2, and PN FEM)

According to SNI 2847-2019 (2019), the deflection at the first crack for the panel was 8.25 mm. These results demonstrated that the observed deflection complied with the bending criteria based on analytical calculations, indicating that the floor slab is structurally safe for use in building construction.

The results of the testing for PN1, PN2, and PN FEM are presented in Figure 7 to 10. The FEM approach demonstrated good accuracy, with the first crack value matching that of the other two experimental test specimens (PN1 and PN2), at 7.5 kN.

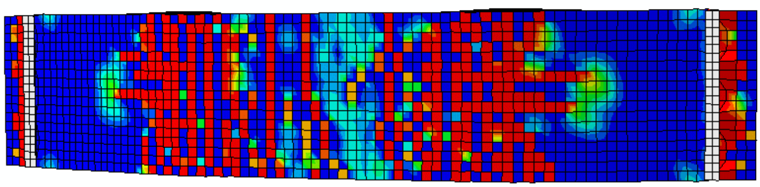

Figure 7. Crack pattern using FEM

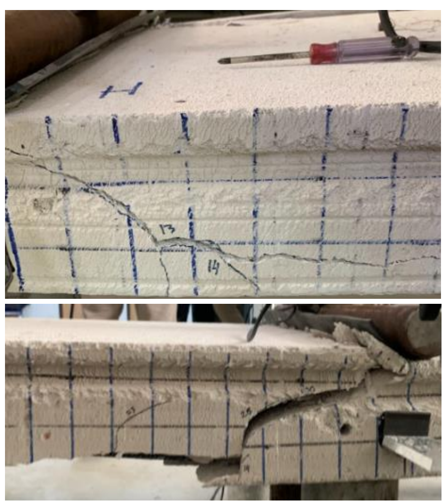

Figure 8. Crack pattern from experimental test

The crack pattern in the FEM model showed cracks occurring on the left and right sides of the slab, starting from the loading points, then moving towards the supports, and finally to the mid-span (Nasim *et al.*, 2007; Jamil *et al.*, 2017;

Faidzi, 2021). At the bottom of the panel, the model exhibited severe cracking, as evidenced by the distribution of red color at the panel's lower section. Green and yellow colors indicated moderate cracking, while orange and red colors signified significant cracking caused by stresses exceeding the material's maximum stress limit (Al-Thairy *et al.*, 2023; Tong *et al.*, 2023).

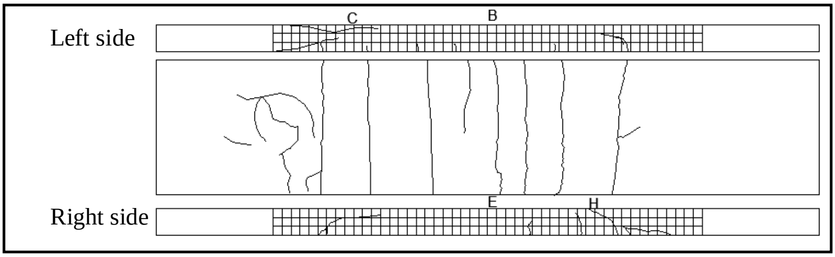

Figure 9. Crack pattern testing for PN1

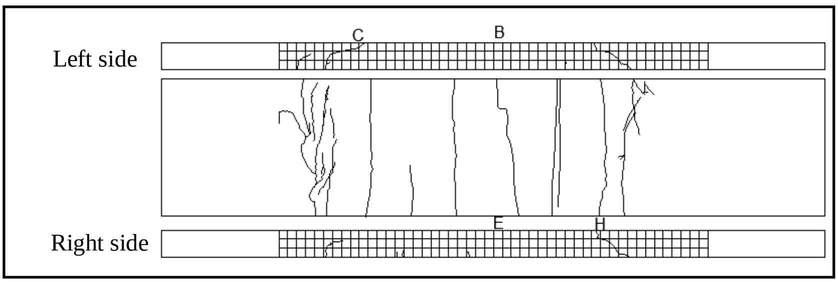

Figure 10. Crack pattern testing for PN2

The results of the testing showed that the concrete experienced cracking, which were flexural cracks occurring on both sides of the slab due to the applied axial load. This finding is consistent with the research by Zhang (2014). Cracking increases with the addition of load. New cracks can develop in addition to the existing ones, and increasing the load can both widen and lengthen these cracks. Initial cracks occur in the loading areas and at the mid-span.

4. Conclusion and Recommendation

As demonstrated, the results from the experiments and FEM showed that from the load-deformation curves, the first crack values for PN1 and PN2 were observed at displacements of 2.05 and 2.03 mm, respectively. The maximum load capacities for PN1, PN2, and PNA were 24.40, 24.50, and 24.30 kN, respectively, with first crack loads of 8.33, 8.34, and 8.33 kN. The initial cracking began at the loading points and then propagated along the tensile surface of the plate. It is recommended to apply a finishing layer using mortar on the compression area as an effort to increase the rigidity of the plate structure. Additionally, the friction between the new and old interface should be studied to assess the bond strength between the two different materials. Future work should aim to minimize the use of concrete materials for floor slabs to reduce the environmental impact caused by using cement.

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