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EVALUATION OF STRUCTURE USING VARIETY OF SLAB TYPE UNDER PERFORMANCE-BASED DESIGN: CASE STUDY COMMON WORKING SPACE IN SURABAYA

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Abstract

Improvement of the current construction of midrise to high-rise building in Surabaya relatively needs to be evaluated, especially for compact office building area, it is very challenging to have an optimal space to the structural system with facilitate a satisfactory capacity performance. This paper makes a comparative study of the effectivity of structural plate structure in the compact office building between conventional slab (M1), waffle slab (M2) and flat slab (M3). A typical 5-story reinforced concrete building structure is selected as a case study within 6 m symmetrically span for each model. The proposed method used in this study is based on empirical analysis followed by numerical evaluation using SAP2000. The step initiated by deriving an optimal alternative of various type of slab. This study aims to emphasize the benefits to the functionality of the structural system which more efficient in term of structural capacity and its performance. As the result, M1 and M3 offer a similar behaviour due to the reinforcement and design performance with high slab deformation compared to the M2. M2 present a lower slab deflection under the supported of waffle element with the result almost twice smaller than M1 and M3.

Keywords: Conventional Slab, Waffle Slab, Flat Slab, Performance Capacity, Numerical Modelling

Introduction

The amount of force that reinforced concrete building (RCB) exposed depends on the geometrical properties of the structure and the properties of the load-bearing system (Emmons & Sordyl, 1930). However, in buildings, the seismic effect size is determined according to the plan view which implied the irregularity, wall panel position, column shape and dimensions, plate thickness, cantilever, ceiling type, ceiling system openings, reinforcement placement. Several structural parameters were also examined to determine the effects of twist irregularities which will affect the total behaviour of RCB (Ahmed et al., 2012; Yoo, 2011). The irregularity also impacts based on the vertical and horizontal structure concept as the plate position required (Ahmed et al., 2012). In the current construction as the compact office applied, spacious area become a big concerned (Daniel, 1967; Tan & Mansur, 1996). Most of building manage to have a minimum structural dimension but still having a good capacity under seismic criteria (Mibang & Choudhury, 2020; Singh et al., 2019).

Surabaya is the second busiest city in Indonesia which is popular with the business activity. Based on the global development and economy growth, over 69% activities in Surabaya are based on construction activity and mainly focus to construct high rise building (Asian Development Bank, 2016; Caroline et al., 2021). Compared to the current building, the new one really having a concern within the space limitation, like hiding all utility below the plafond or having the spacious area to minimize the structural element dimension (Nugroho, 2013; Tan et al., 2001).

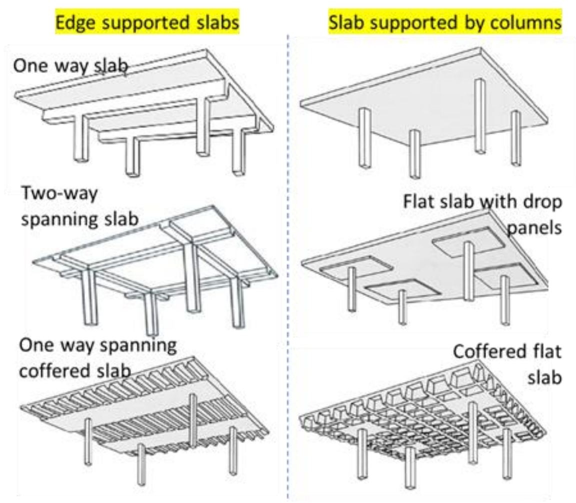


Figure 1. Type of slabs under variety conditions; edge supported slabs and slabs supported by columns

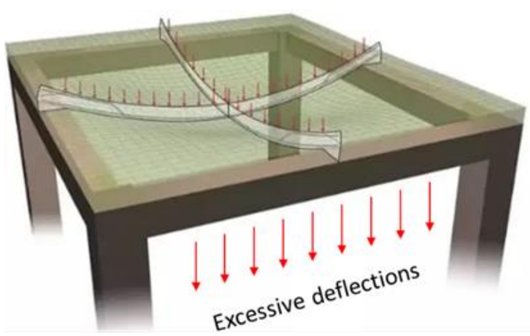


Figure 2. Deflection condition in reinforced concrete slab

One method to analyse the spacious space is maximize the structural dimension and change the concept to implement the plate to distribute the loading. In this case, eliminating the beam is one of the objective ways to have floor clearance (Hassan et al., 2017; Torunbalci, 2002).

Illustration of vary slabs conditions which are normally placed in a building presented in Figure 1, where the deflection conditions informed in Figure 2. Type of slabs accommodates based on the function of the building, still it needs to fill the required deflection specified by applicable codes. The amount of deflection which is approved is identified under empirical calculation and modelling. When the value of deflection exceeds the limit, it leads to several issues causing structural failure (Al-husainy & Al-rifaie, n.d.).

The study is conducted to investigate the effectivity of the building without adding the beam under the method of waffle slab and flat slab. A novel alternative to enhance the capacity of the structure actually can be improved by tailoring the concrete material such as add supplementary materials like fly ash (Malviya, 2020, 2021; Syarif & Djauhari, 2019), added engineered cementitious material (Bastian et al., 2020; Komara, Tambusay, Sutrisno, & Suprobo, 2019; Komara, Tambusay, Sutrisno, Suprobo, et al., 2019; Oktaviani et al., 2020) or combine a sustainable self-building material like bamboo (Nareswarananindya et al., 2021).

Three models are going to model numerically M1, M2 and M3. M1 is model as conventional slab with the beam element inside using SAP2000. This model normally considers in the normal construction when the load is received by the plate or slab and then transferred through the beam before coming to the column. The thickness of M1 is normally small but as the consequence having the large depth of beam (Koyama et al., 2008; Riyadh et al., 2020). M1 is usually provided with horizontal and vertical reinforcement within the concept of one-way slab and two-way slab. The illustration of one-way slab and two-way slab can also be seen in Figure 1. This alternative has become one of the novelties in the building development through eliminate a bulky space.

M1 mostly used in building structure as apartment, residential or any other multi-storeyed building to not really need the spacious area. M2 and M3 give the alternative to provide the clearance. Both of construction speed of M2 and M3 are quate faster compared to M1. The total weight of the structure also relatively lighter hence economical. M2 reduce the self-weight by eliminating beam element but implement hollow grid system which no compromise its structural stability. The illustration of M2 exactly like a waffle that may have a grid system where the bands run through the slabs. Normally the grid shape like square or rectangular. In addition, M2 construction demand a special handling and sophisticated formwork (Topkaya & Atasoy, 2009). In another cases, mechanical and electrical installation are very difficult to install due to the complex design (Emmons & Sordyl, 1930). The last model, M3 are the modified version from M1 and M2. It is also used as the alternative to not including the beams to transfer the load. M3 structure without beams, but with drop panels and column heads attached to the columns (Silva et al., 2019; Tambusay et al., 2017; Tilva et al., 2011). Drop panels are square or rectangular in shape and increase the slab's shear capacity. The drop panels add deflection to the slab, reducing deflections (Kartiko et al., 2021). The column heads are provided beneath the drop panels and are mostly slanted to accommodate the column dimensions. A column head, drop panel, or both can be found on a flat slab. M3 are most comm only found in non-traditional structures with no column symmetry. The column heads and drop panels act as a special beam that is limited to that specific space. The formworks are simpler than M2 because they only form a column head and drop panels (De & Wallace, 2015; Proctor et al., 1982).

Table 1. Type of slabs under variety conditions; edge supported slabs and slabs supported by columns

Item description	Load	Item description	Load
Reinforced concrete (kg/m3)	2400	Lobby, corridor first floor (kg/m2)	488
Floor Covering – ceramic (kg/m3)	24	Office (kg/m2)	245
Mix of cement - species (kg/m3)	21	Corridor after the first floor (kg/m2)	390
Ceiling (kg/m3)	18		

Installations (kg/m3)	40

$$Mn = \frac{Mu}{0,8} \quad (1)$$

$$Rn = \frac{Mn}{b\ x\ d^2} \quad (2)$$

$$m = \frac{fy}{0,85\ x\ fc'} \quad (3)$$

$$\rho_b = \frac{0,85\ x\ fc' x\ \beta_1}{fy}\ x\ \frac{600}{600 +\ fy} \quad (4)$$

$$\rho_{maks} = 0,75\ x\ \rho_b \quad (5)$$

$$\rho_{min} = \frac{1,4}{fy} \quad (6)$$

$$\rho_{used} = \frac{1}{m}\ x\ \left(1 - \sqrt{\frac{1-(2.m.Rn)}{fy}}\right) \quad (7)$$

$$A_s\ used = \rho\ x\ b\ x\ d \quad (8)$$

$$R_{max} = 0,75\ x\ \rho_b\ x\ fy\ x\ \left(1 - \left(\frac{1}{2} x\ 0,75\ x\ \rho_b x \frac{fy}{0,85\ x\ fc'}\right)\right) \quad (9)$$

Based on the previous study, choosing a slab system that transfers the load to the frame is very important when the spacious area is needed (ACI Committee, 2007; Sap, 2009a, 2009b). Another illustration also conducted numerical analysis using waffle slab for the high-rise RCB (Jones et al., 2002; Lee & Kim, 2007). The waffle slab offer effectivity in term of structural capacity over 40% than the conventional slab. Another study also consider to maximize the space by adding the web opening to have spacious area with the concern of reinforcement design (Gamage & Remennikov, 2015; Liu & Chung, 2003). The total weight of the structure is massively reduced. However, the capacity of structure can be compared. In this study, the effect of slab types in the compact office in Surabaya is compared. The study is investigated by using numerical analysis program for low-rise RCB. The conventional slab (M1) is model as the parameter control then improved by eliminating beams as a waffle slab (M2) and flat slab (M3).

Design Parameter

Plate Thickness

The following are the requirements in determining the thickness of a plate for waffle slabs and flat slabs. Table 1 inform the minimum thickness of the slab without interior beams according to Indonesian standard of SNI 03-2847-2013 (Badan Standardisasi Nasional, 2019). Regarding the thickness of the flat slab plate, plate thickness without drop panels should be greater than 125 mm and for plate thickness with drop panels >100 mm .

The limitation of the minimum thickness needs to be fill in the first place to ensure the minimum capacity to stand the load. Some condition also needs to be determined as follow:

1. Local panel thickening is provided in both directions at a distance of not less than one-sixth of the center-to-center distance of support in the direction under consideration.
2. The thickness of the panel thickness should not be less than a quarter of the plate thickness outside the local panel thickening area.
3. Another required criterion to design a waffle plates and waffle slab is based on the rib width and the clearance. Rib width ≥ 100 mm and high (h) ≤ 3.5 minimum body width. The clear space between ribs is not less than ≤ 750 mm. According to the value of h ≥ 90 mm and h≥Ln/12 , where ln is a clear space between ribs in mm (Badan Standardisasi Nasional, 2019).

Table 2. Maximum deflection based on structural component type in accordance SNI 2847-2019 (Badan Standardisasi Nasional, 2019)

Structural Component Type	Calculated deflection	Deflection Limit
Roof or floor construction supporting or attached to non-structural components that are likely to be damaged by large deflections	Part of the total deflection that occurs after the installation of non-structural components (sum of long-term deflection, due to all fixed loads acting, and instantaneous deflection due to additional live loads) [k]	L/480 ‡
Roof or floor construction that supports or is attached to non-structural components that are unlikely to be damaged by large deflections		L/240 §

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] Icr \quad (10)$$

$$I_{cr} = \frac{1}{3}\, x\, b\, x\, c^3 + n\, x\, A_s\, x\, (d - c)^2 \quad (11)$$

$$c = n\, x \frac{A_s}{b} \quad (12)$$

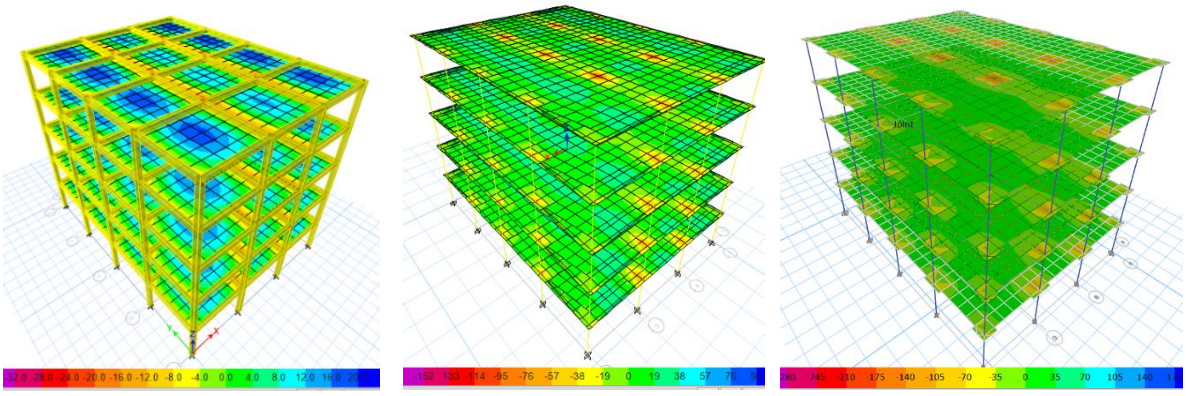
$$n = \frac{Es}{Ec} \quad (13)$$

$$d = h - (t_s + \frac{ø}{2}) \quad (14)$$

$$M_{cr} = \frac{f_r I_g}{y_t} \quad (15)$$

$$f_r = 0{,}62\, x\, \lambda\, x\, \sqrt{f\, c'} \quad (16)$$

$$y_t = \frac{h}{2} \quad (17)$$



(a) M1 (b) M2 (c) M3

Figure 3. 3D illustrated modelling; (a) conventional structure, (b) waffle slab), (c) flat slab

Reinforcement Designed

In this step, the calculation needs to calculate the area of the concrete slab, which is characterized into three variable designs, M1, M2 and M3. The easiest calculation of slab area is by multiplying the length of the slab by the width and the find the capacity criteria according to reinforcement. When the measure is a bit complex to do, break the total area into some separates areas then calculate in the same way. A minimum reinforcement also needs to be design carefully to withstand the load. Some calculation is designed by the Equation 2 – 9 (Badan Standardisasi Nasional, 2019).

Where Mn is moment nominal which is calculated by applied or ultimate moment over 0.8 as the factor of capacity. Rn is a cross-sectional capacity coefficient. To calculate Rn, b, width of the concrete section and d, effective height have to be known. b usually considers by ½ d and d usually taken by 0.9 h. For the steel specification using in this reinforcement, fy is used as the yield strength of steel where f'c is a concrete compressive strength. ϱ is a reinforcement ratio which classified into balance, maximum and minimum condition. After comparing all the condition, As, area of reinforcement will be measured.

Structural Deflection Criteria

The concept of controlling slab deflection is similar to the beam deflection. This evaluation also considered by SNI 2847 2019 (Badan Standardisasi Nasional, 2019). Two methods of controlling can be used to identify the maximum deformation. The correlation of combined load case with its limit related to the maximum limits of deflection base on the spans. The deflection limits according to structural component type can be seen in Table 3, where the calculation of the slab condition can be seen in Equation 10 – 17.

Where Mcr is a moment crack and Icr = moment inertia when it cracks while Ma is a moment maximum of the structure component. Then, fr is a modulus of fracture and Ec is modulus of elasticity of concrete with normally into account of $4700\times\sqrt{f'c}$ and Es = 2×105 MPa. yt is a distance from center axis of gross cross section and Ig is inertia of gross section. λ is a reduction factor of concrete which normally taken 1.0.

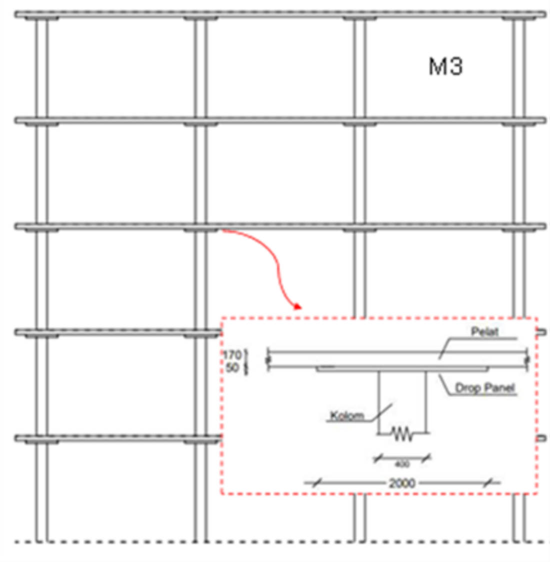


Figure 4. Detail cross section of structural modeling of waffle slab

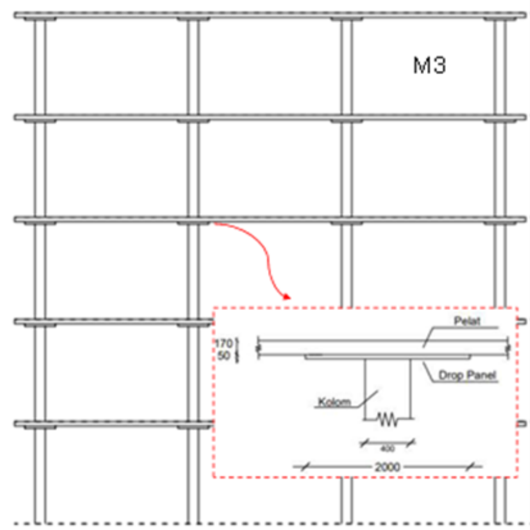


Figure 5. Detail cross section of structural modeling of flat slab

Table 3. Design evaluation – comparative result after numerical modelling

Item information	M1	M2	M3
Tension reinforcement (mm)	Ø10 - 120	Ø13 - 100	Ø10 - 120
Compression reinforcement (mm)	Ø10 - 150	Ø13 - 150	Ø10 - 150
Moment nominal (Nmm)	27.88×10^6	40.77×10^6	27.88×10^6
Moment ultimate (Nmm)	17.166×10^6	32.643×10^6	23.133×10^6
Slab deflection (mm)	24.424	12.185	24.431

Volume (m^3)	11.62	8.21	6.32

Numerical Modelling

The building is designed according to SNI 2847 2019 (Badan Standardisasi Nasional, 2019) to provide calculations and determine the distributed load subjected to the structure. Three models classified by the type of slab design are analyzed, M1, M2 and M3. The buildings have the same layout divided by five stories. The arrangement is also made symmetrically. 3D view and other perspective of the design illustrate in Figure 2 while Figure 3 presenting the detail of cross-section of each model M2 and M3 respectively.

Design parameters of the modeling including the material property and loading parameter are given the same for all models. The first model, a conventional beam design as we called as M1 is used as the parameter control, while the other, M2 and M3 as the comparative model. Density of column, beam and slab is similar 20 kN/m^3 with modulus of elasticity of concrete 4700×√(f'c) and modulus of elasticity of steel 2×105 MPa. The location of the building is modelled in Surabaya follow seismic zone coefficient and seismic load reduction factor according to SNI 1726-2019 (Badan Standarisasi Nasional, 2019). The combination of load using variation of 1.2DL + 1.6LL.

The property material specified typical with f'c = 35 MPa, fy and fu in order 400 MPa and 370 MPa. The story height is designed 4 m each level within the length and width of the building symmetrically 6 m. Column dimension is designed using 400×400 mm within the beam dimension of 300×500 mm for all models.

Research Results and Discussion

Table 4 shows the comparative result of slab type modelling, M1, M2 and M3. The effective slab method to have a spacious area can be considered to use M2 and M3. The reinforcement for M1 and M3 are exactly the same, it is considered of using the drop panel to distribute the loading. The length of reinforcement also characterizes similar. The condition is different for M2, due to the shape and the size of waffle, extra reinforcement is needed. The size reinforcement bar also taken differently compared to M1 and M. As a matter of fact, the weight and the volume using material will be decreased for M2 and M1. It is affected by not using beam elements in the structural implementation. When it comes to slab deflection, M2 has a lower deflection than M1 and M3, because of the support of waffle element.

The objective of numerical modeling using SAP2000 with drop panel and conventional plate is to analyze and design reinforced concrete slabs with varying loadings and structural configurations. Specifically, it aims to evaluate the structural behavior, including deflections, stresses, and overall performance, of slabs with drop panels and compare them to slabs without drop panels.

The results of the numerical modeling using SAP2000 can provide several important insights into the behavior of slabs with drop panels compared to conventional slabs. Here are some potential results that can be obtained:

Deflections: The analysis can determine the deflection characteristics of both types of slabs under various loading conditions. The results may show that slabs with drop panels exhibit reduced deflections compared to conventional slabs. This reduction is due to the additional stiffness provided by the drop panels, which redistribute the load and reduce the span of the slab.

Stresses: The stress distribution within the slabs can be analyzed to identify areas of high stress concentration. Slabs with drop panels may exhibit reduced stress concentrations at the panel-column connections compared to conventional slabs. This is because the drop panels help to transfer the load more efficiently to the supporting columns.

Load-carrying capacity: The modeling can determine the load-carrying capacity of both types of slabs. Slabs with drop panels typically have higher load-carrying capacities due to the additional reinforcement provided by the drop panels. This allows for the support of higher loads without compromising the slab's integrity.

Crack patterns: The analysis can also predict the crack patterns that may develop in the slabs. Slabs with drop panels may show reduced crack widths and fewer cracks compared to conventional slabs. This is because the drop panels help to distribute the load and minimize the formation of cracks.

Structural efficiency: By comparing the results of the numerical modeling, it is possible to evaluate the structural efficiency of slabs with drop panels compared to conventional slabs. This includes considering factors such as material usage, construction costs, and overall performance.

Conclusion

In this study, the analysis is prepared numerically and compared one and another of slab concept under 5 symmetrical stories building by selecting the slab type, M1, M2 and M3. The result for active forces of moment nominal and moment ultimate, reinforcement, volume of the construction and the slab deformation are compared.

There is slightly different for moment nominal and moment ultimate of M1 and M2 due to the function of drop panel and beam implying the same support behavior, when M2 characterized the waffle element to connect the slab. The lower slab deflection is presented in M2 under circumstances of waffle element with the result 12 mm almost twice smaller than M1 and M3. The reinforcement category for both tension and compression for M1 and M2 also presented similar for using Ø10 – 120 and Ø10 – 150 respectively. The upsize reinforcement bar handed for M2 since the concept of waffle need extra reinforcement.

Overall, the results of the numerical modeling using SAP2000 can provide valuable information for the design and optimization of reinforced concrete slabs, allowing engineers to make informed decisions regarding the inclusion of drop panels in their designs.

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