Stiffness, Vibration, and Strength of Flat Slab and Flat Plate Lightweight Concrete Slabs

Manar Zahid Zaman¹*, Salah R. Al-Zaidee²

Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
manar.ali2001m@coeng.uobaghdad.edu.iq¹, Salah.R.Al.Zaidee@coeng.uobaghdad.edu.iq²

ABSTRACT

Flat slabs made of two-way reinforced concrete are a common, effective, and affordable structural method. Thin layer slabs and lightweight are of great importance in modern building construction without the need to increase the cross-section of columns, walls, and foundations. Consequently, it becomes more important to cover all aspects related to stiffness, vibration, and strength of lightweight concrete slabs. To achieve serviceable flat slabs from lightweight concrete (LWC), the comparison between LWC flat plate and flat slab is studied in this article for strength and stiffness. The construction of the flat plate is much easier than other slabs even though the problem facing the flat plate is the punching shear. Hence, the addition of the drop panel as a solution. However, the two LWC slabs are exposed to a uniform pressure of dead load and human live load. The vibration of the slab is related to the stiffness in the form of the natural frequency. These floor systems should satisfy walking excitation criteria of acceleration limit $a_0$, which is equal to 0.50% of g for office occupancies. This study aims to analyze a flat plate and flat slab with a drop panel for strength and stiffness. The analysis is carried out in ABAQUS software. The results of the analysis show that the flat slab has an effective increase in strength of about 60% compared to the stiffness which was lower by about 2.2%. However, the stiffness of both slabs is within the limits of walking excitation criteria.

Keywords: Strength and stiffness of slabs, Flat plate and flat slabs, and Lightweight concrete slabs.
الصلابة والاهتزاز وقوة البلاطة المسطحة والألواح الخرسانية خفيفة الوزن

منار زاهد زمان *, صلاح حميم اليدي
قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة
تعتبر الألواح المسطحة المصنوعة من الخرسانة المسلحة في اتجاهين طريقة هيكلية شائعة وفعالة وبأسعار معقولة. تعتبر الألواح ذات الطبقات الثقيلة وخفيفة الوزن مع أرضيات إضافية ذات أهمية كبيرة في إنشاءات المباني الحديثة دون الحاجة إلى زيادة المقطع العرضي للأعمدة والجدران والأساسات. وبالتالي، يصبح من المهم تعليمة جميع الجوانب المتعلقة بصلابة واهتزاز وقوة البلاطات الخرسانية خفيفة الوزن. من أجل تحقيق ألواف مسطحة صالحة للخدمة من الخرسانة خفيفة الوزن، تم دراسة المقارنة بين اللوحة المسطحة LWC والبلاطة المسطحة في هذه المقالة من حيث القوة والصلابة. إن بناء اللوحة المسطحة أسهل بكثير من الألواح الأخرى على الرغم من أن المشكلة التي تواجه اللوحة المسطحة هي قص التثقيب. وحل هذه المشكلة عن طريق إضافة اللوحة المسقطة كما في البلاطة المسطحة. ومع ذلك، فإن لوحات LWC تتعرض لضغط منتظم من الحمل الميت والحمل الحي البشري. ورتبط اهتزاز البلاطة بالصلابة على شكل تردد طبيعي. يجب أن تلبي أنظمة الأرضية هذه معايير الإثارة ، والذي يساوي 0.50% من g، والتي يساوي 0.50% من القدرة الديناميكية لحداثة المشي. نتجت هذه الدراسة إلى تحليل الوضع المثالي من ABAQUS لحل المشكلات. تهدف هذه الدراسة إلى تحليل الوضع المثالي من ABAQUS. أظهرت النتائج التحليل أن البلاطة المسطحة لديها زيادة فعالة في القوة حوالي 60% مقارنة بالخلاصة الأساسية للألف بحوالي 2.2%. ولكن صلابة كلا اللوحين تقع ضمن معايير الإثارة أثناء المشي.

الكلمات المفتاحية: قوة وصلابة الألواح ، اللوح المسطح ، البلاطة المسطحة ، والألواح الخرسانية خفيفة الوزن.

1. INTRODUCTION
The slab is an essential structural element in building construction. The thickness of the slab is relatively small in comparison to its length and width. Hence, it is referred to as a thin planar surface component that transfers transverse loads to its supports, such as beams, columns, and walls (Ahmed, 2023; Park and Gamble, 2000). Flat slabs are commonly used in various structures such as buildings, parking garages, and shopping centers. They offer a significant surface area and have static efficiency, enabling the achievement of large span-depth ratios. The reinforced concrete flat slabs carry the columns directly without any beams, providing the advantages of flexibility in room layout, time construction becomes shorter, saving the height of the building, and installing mechanical and electrical services is easy (Gharbi and Mahmoud, 2020; Muhammed and Karim, 2022).

The flat plate and the flat slab are shown in Fig. 1. A flat plate slab is also known as a flat slab without a drop panel. This flat plate is a two-way reinforced concrete slab that transfers loads to the supporting columns directly without using any beams, drop panels, or capitals. A flat slab is a two-way reinforced structural system that incorporates drop panels or column
caps on columns. These additions help the slab withstand heavier loads, allowing for longer spans (Al-Zahra et al., 2021; Khanushiya and Butala, 2021).

![Figure 1. Two-way slabs (a) flat plate and (b) flat slab (Adan et al., 2010).](image)

Conventional concrete is widely recognized as the primary building material used worldwide and it is constantly evolving (Salman and Daud, 2022). Lightweight concrete is a type of concrete that has been made lighter than conventional concrete through various methods (Hussein et al., 2021; Neville, 1995). Currently, there is an established practice of using structures that have lower dead loads and higher strength. The purpose of this is to increase the live load-bearing capacity and minimize the impact of earthquakes (Allahyari et al., 2017). In structural reinforced concrete, the main design limitation of the slab is the span between the columns. To design a large slab span between columns, it is better to add beams and/or construct very thick slabs. This leads to an increase in the weight of the structure due to the increased amounts of concrete that go into making them (Al-Azzawi et al., 2019; Singh and Saini, 2018). The total dead load in reinforced concrete buildings is in large proportions to the self-weight of the structural floor system (Cao et al., 2023; Qi and Yang, 2021). Lightweight aggregate concrete (LWAC) flat slabs without shear reinforcements are not effective in resisting punching shear due to the significant influence of aggregate interlocking action and the friction angle on the failure surface generatrixes for concrete sliding failure (Yang et al., 2023; Fernández Ruiz et al., 2013; Said et al., 2020; Urban et al., 2019). Additionally, LWC has some disadvantages compared to normal-weight concrete. These disadvantages are higher shrinkage and creep, larger deflection, and low splitting tensile strength (Adam et al., 2020). Taking the same properties and dimensions of the flat plate in the Design Guide for Vibrations of Reinforced Concrete Floor Systems (Fanella and Mota, 2014). The difference between the two slabs is the drop panel, which has been designed according to the ACI code (ACI Committee 318, 2019). Human activities include walking, jumping, and running can cause annoying vibrations which is a serviceability problem for long floor systems. In concrete slab systems, there is a common vibration problem when designed using the ultimate strength capacity (Alami et al., 2021).

In general, the response of the human to floor vibration is very complex. The amount of motion is only one factor that has an impact on perception and acceptability. For example, steady-state (continuous) motion can be more bothersome than transient (infrequent) impact. Also, the human response to vibration depends on what a person is doing; people in quiet offices or residences or people at rest will generally perceive floor motion more readily than people who are participating in an activity such as dancing or aerobics. Floor systems that can dampen the effects of vibration in a short period are likely to be perceived as less annoying compared to those systems that cannot dampen vibration quickly (Fanella and Mota, 2014).
Vibration can occur when individuals walk on a floor system. The level of irritation or potential harm caused by this vibration can vary depending on several factors for individuals in the affected area. The International Standards Organization has developed recommended acceleration limits for vibrations caused by specific human activities. These limits have been widely implemented and have proven to be effective in ensuring human comfort (ISO, 1989). This standard establishes limits for various occupancies based on the root-mean-square (RMS) acceleration, expressed as a multiple of a baseline curve. Recommended multipliers are as follows (Fanella and Mota, 2014; AISC, 1997; Allen and Murray, 1993):

- 10 for offices and residences.
- 30 for shopping malls, indoor footbridges, dining and dancing.
- 100 for rhythmic activities and outdoor footbridges.

Fig. 2, shows the maximum acceleration for human comfort for vibrations due to human activities (Fanella and Mota, 2014).

**Figure 2.** Recommended maximum acceleration for human comfort for vibrations due to human activities (David and Mike, 2014).
1.1 Human Movement Criteria

The most basic pedestrian modeling disregards the random variation among the human population and assumes that individuals produce identical and completely repeatable footfalls. However, in reality, the loading scenario involves pedestrians who will never generate the same footfall. They randomly enter the bridge and can move freely, each with its unique characteristics in terms of loading amplitude, frequency, velocity, and phase. Therefore, there is a need to transition from a deterministic approach to a probabilistic modeling of pedestrian behavior (Lai and Mulas, 2016). On the other hand, a pedestrian crosses a bridge by taking frequent steps. These steps represent impulses that have the potential to induce vibrations in the bridge. The tendency of a bridge to vibrate is primarily influenced by four factors: its stiffness, mass, the magnitude of the external force applied to the structure, and the damping properties of the bridge (Bond and Hielmgren, 2018).

1.2 Vibration Imposed by Pedestrians

The floor slab vibrates by excitation from a vibration source, where the natural vibration frequency of the floor slab falls in the vibration of the frequency range of the floor slab induced by that vibration source (Xia et al., 2018). Upon impact, the foot of a pedestrian is not just moving in a downward and forward direction. As a person walks, the center of mass moves from side to side, resulting in forces being exerted in the lateral direction of the bridge. The force exerted by a walking human on a footbridge can be broken down into three components. These three components are illustrated in Figs. 3 and 4 in which they explain how the lateral forces are generated (Bond and Hielmgren, 2018).

Figure 3. Lateral, longitudinal, and vertical force components from a footfall (Bond and Hielmgren, 2018).
This work aims to study the effect of drop panels in increasing the strength and stiffness of lightweight concrete slabs. Also, the behavior of lightweight flat plates in strength and stiffness is in the limitation's acceptance criteria. The difference between flat plate and flat slab and their analysis was investigated using the ABAQUS software.

2. DROP PANEL DESIGN

The main issue in the design of concrete flat plates is the high concentration of shear stresses near the connection between the column and the slab. This can lead to sudden punching shear failure, even when the load is well below the flexural strength of the slab (Oukaili and Salman, 2014; Paultre and Moisan, 2002).

Drops are an important criterion in increasing the shear strength of the slab (Munthe and Jatmiko, 2020). In this article, the drop panel has been designed according to ACI318-19 requirements. The drop panel should extend in both directions from the centerline of support for a distance that is at least one-sixth of the span length, measured from the center-to-center of the supports in that direction (ACI Committee 318, 2019) as shown in Fig. 5.

While for the thickness of the drop panel according to the ACI318-19, for exterior panels without edge beams, the thickness is equal to a fourth of the distance from the face of the column to the edge of the drop panel (h_d, height of drop panel which is found to be 175 mm) (ACI Committee 318, 2019).
3. **FINITE ELEMENT MODELING**

ABAQUS is a software for finite element analysis (FEA) that allows for the simulation of the mechanical behavior of structures and materials subjected to different loading conditions. It can be utilized for various applications, including linear and nonlinear structural analysis, dynamic response analysis, thermal analysis, and fatigue analysis (Lee, 2023). Abaqus is a highly regarded finite element package that is well-known for its extensive operational and verification experience. Additionally, it offers excellent pre-and postprocessing capabilities. Abaqus is a registered trademark of Dassault Systèmes (Khennane, 2013). According to (Yasir et al., 2019), Abaqus offers solutions for a range of constitutive equations, making it simpler for users to select the appropriate solution for their analysis model.

3.1 Flat Slab Simulation

ABAQUS software was used for modeling the flat plate and flat slab. The concrete modeling parts are slab, drop panel, and columns. The reinforcement parts in concrete are the slab longitudinal and distribution rebar of the slab, the column rebar, and stirrups. The properties of the materials used are $f_c' = 28 \text{ MPa}$, $f_y = 420 \text{ MPa}$, and $E_c = 12290 \text{ MPa}$. Tie constraints were used for the simulation of the connections between slab concrete and columns for the flat plate and between slab, drop panel, and columns for the flat slab. Embedded region constraints were used for steel reinforcement in the slab and column. The mesh model for flat plate and flat slab structure is shown in Fig. 6.

![Figure 6. Mesh Model in ABAQUS.](image)

3.2 Load and Boundary Condition Simulation

Applied loads in the form of pressures have been used in the load module for the static general step. Limit conditions (Fixed) have been defined and assigned through the default initial, as shown in Fig. 7. The sum of the superimposed dead load, the live load (design), and live load (vibration) is 0.96 MPa according to (Fanella and Mota, 2014). This load is referred to as the normal-weight flat slab (Fanella and Mota, 2014) and is applied for these two lightweight slabs for the effect of the strength.
4. STIFFNESS ANALYSIS

Stiffness analysis is related to the natural frequency of the structure according to the natural frequency equation (Fanella and Mota, 2014) shown below.

\[
f_i = \frac{k_2 \lambda_i^2}{2\pi l_i^2} \left[ \frac{k_1 E_c h^3}{12\gamma(1-v^2)} \right]^{1/2}
\]

where \( h \) is the overall thickness of the flat plate or voided slab, 
\( \gamma \) is the mass per unit area of the plate, 
\( \nu \) is Poisson’s ratio, 
\( l_1 \) is the longer of the two center-to-center span lengths of the plate panel, 
\( \lambda_i^2 \) is a function of the panel aspect ratio \( l_1/l_2 \) and \( \nu \) (dimensionless parameter). Values of \( \lambda_i^2 \) for the fundamental mode of vibration are given in Table 2. 
\( k_2 \) is constant accounts for the effect of rigidity at the joint between the slab and the columns and is based on column size \( c_1 \),

\[
k_2 = \begin{cases} 
1.9 & \text{for } c_1 \leq 24 \text{ in.} \\
2.1 & \text{for } c_1 > 24 \text{ in.} 
\end{cases}
\]

\( k_1 \) is constant accounts for the level of cracking in the concrete slab. It can be calculated by dividing the effective moment of inertia (\( I_e \)) by the gross moment of inertia (\( I_g \)). When the value of \( k_1 \) is less than 1.0, it indicates that the stiffness of the slab is lower than the gross stiffness. As a result, the natural frequency of the system is decreased (Fanella and Mota, 2014). Values of \( \lambda_i^2 \) are 7.12, 8.92, and 9.29 for \( l_1/l_2 \) 1.0, 1.5, and 2.0 respectively (Fanella and Mota, 2014). Despite that neglecting the \( k_1 \) parameter, the estimated natural frequency calculated from Eq. (1) is equal to 7.93 Hz. The error of the model that was modified for neglecting the effect of the \( k_1 \) parameter would be:

\[
Error_{\text{for flat plate}} = \left( \frac{9.77 - 7.93}{9.77} \right) \times 100 = 18.8 \%
\]
Error for flat slab = \( \frac{9.54 - 7.93}{9.54} \times 100 = 16.8\% \)

The acceptance criterion for walking excitation of floor systems is:

\[
a \geq \frac{65e^{-0.35f_n}}{\beta w} \leq a_0 \tag{2}
\]

where \( w = 2Mg, M \) is the fundamental modal mass. \( w = 1587.7 \times 32.2 = 51124 \text{ lbs.} \)

Then:

\[
\frac{a_p}{g} = \frac{65e^{-0.35\times7.93}}{0.03 \times 51124} = 0.00264
\]

**Figure 8.** The two-way slab’s natural frequency results in ABAQUS.

Finite element analysis in this study has shown that the flat plate is slightly stiffer than the flat slab. The result comes in agreement with the findings of (Thu Htun et al., 2018), who studied a 12.5-story RC building and how the flat plate building is more beneficial than flat slab building as the structural behavior of flat plate building has a better stiffness than flat slab building. According to the comparison of structural behavior by (Thu Htun et al., 2018), the flat plate system is safer than the flat slab system and the flat plate system is more economical than the flat slab system for this residential RC building by comparing the steel area of both slabs.

5. **STRENGTH ANALYSIS**

The strength analysis simulated with nonlinear finite element analysis using a concrete damaged plasticity model for material modeling in ABAQUS. The results of the strength analysis due to applying pressure loads are shown in **Fig. 9** below.
The results from the strength analysis showed the flat plate resistance to compressive stress is on the lower slab surface around the column. While the resistance of the flat slab to compressive stress is on the middle of the upper surface of the slab. This led to increasing the compressive strength of the flat slab using the drop panel. However, the two slabs have not reached the compressive strength for the concrete due to tensile failure. From the load-deflection curves shown in Fig. 10, the effectiveness of the drop panel in increasing strength is triple that of the flat plate. It should be noted that the difference in displacement is small compared to the applied load.
6. CONCLUSIONS

- The results of the stiffness analysis showed the acceleration for $g$ of 0.26% in the case of the theoretical natural frequency 7.93 Hz (which is lower than the results from the numerical natural frequency) is smaller than the acceleration limit $a_0$ which is equal to 0.5% of $g$ for walking excitation. The slabs are satisfactory in case of neglecting the effect of the parameter $k_1$.
- For the strength analysis, the results for the strength showed the flat plate failure load pressure is at 0.02 MPa, and for the flat slab is at 0.05 MPa.
- The strength of a flat slab is 60% higher than that of a flat plate. As for the stiffness, the natural frequency is 2.2% lower than that of the flat plate.
- As a result, an increase in the strength of a flat slab is more effective than the stiffness compared to the flat plate. Leading to considering these aspects in the design phase. In general, the lightweight flat slab can be reliable in multi-story structural buildings due to the consideration of adding a drop panel.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>$C_n$</td>
<td>Frequency constant</td>
<td>$k_1$</td>
<td>The level of cracking in the concrete slab</td>
</tr>
<tr>
<td>$E$</td>
<td>Modulus of elasticity; Young’s modulus, MPa.</td>
<td>$k_2$</td>
<td>A constant that accounts for the rigidity</td>
</tr>
<tr>
<td>$f_i$</td>
<td>Natural frequency, Hz.</td>
<td>$\lambda_i^2$</td>
<td>Function of the panel aspect ratio $l_1/l_2$</td>
</tr>
<tr>
<td>$I_e$</td>
<td>Effective moment of inertia, mm$^4$</td>
<td>$\nu$</td>
<td>Poisson’s ratio</td>
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Credit Authorship Contribution Statement

Manar Zahid and Dr. Salah Al-Zaidee– review & editing, writing, validation, and software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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