University of Baghdad
College of Engineering
JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.jcoeng.edu.iq

Volume 30 Number 6 June 2024

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

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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.

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Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2024.06.10

Article received: 23/08/2023
Article accepted: 21/10/2023
Article published: 01/06/2024

الصلابة والاهتزاز وقوة البلاطة المسطحة والألواح الخرسانية خفيفة الوزن

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قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

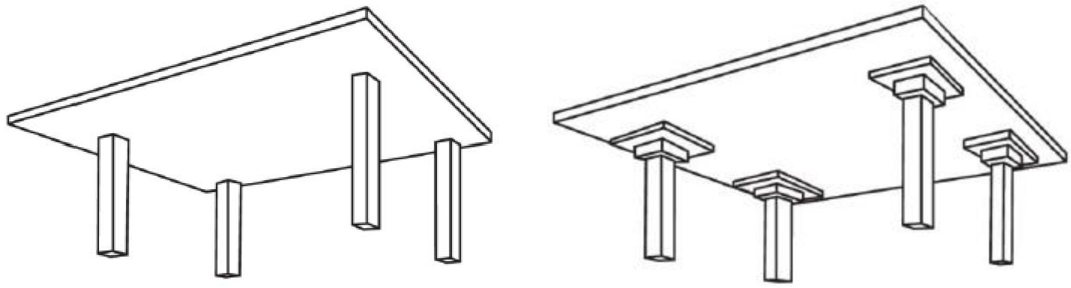
تعتبر الألواح المسطحة المصنوعة من الخرسانة المسلحة في اتجاهين طريقة هيكلية شائعة وفعالة وبأسعار معقولة. تعتبر الألواح ذات الطبقات الرقيقة وخفيفة الوزن مع أرضيات إضافية ذات أهمية كبيرة في إنشاءات المباني الحديثة دون الحاجة إلى زيادة المقطع العرضي للأعمدة والجدران والأساسات. وبالتالي، يصبح من المهم تغطية جميع الجوانب المتعلقة بصلابة واهتزاز وقوة البلاطات الخرسانية خفيفة الوزن. من أجل تحقيق ألواح مسطحة صالحة للخدمة من الخرسانة خفيفة الوزن، تمت 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 لوحتي LWC تتعرضان لضغط منتظم من الحمل الميت والحمل الحي البشري. ويرتبط اهتزاز البلاطة بالصلابة على شكل تردد طبيعي. يجب أن تلبي أنظمة الأرضية هذه معايير إثارة المشي المُرضية لحد التسارع a_0، والذي يساوي 0.50% من g لشغل المكاتب. تهدف هذه الدراسة إلى تحليل اللوح المسطح والبلاطة المسطحة ذات اللوحة المسقطة من أجل القوة والصلابة. تم إجراء التحليل في برنامج ABAQUS. أظهرت نتائج التحليل أن البلاطة المسطحة لديها زيادة فعالة في القوة بحوالي 60% مقارنة بالصلابة الأقل بحوالي 2.2%. لكن صلابة كلا اللوحين تقع ضمن معايير الإثارة أثناء المشي.

الكلمات المفتاحية: قوة وصلابة الألواح ، اللوح المسطح والبلاطة 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).**



(a) (b)

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

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).**

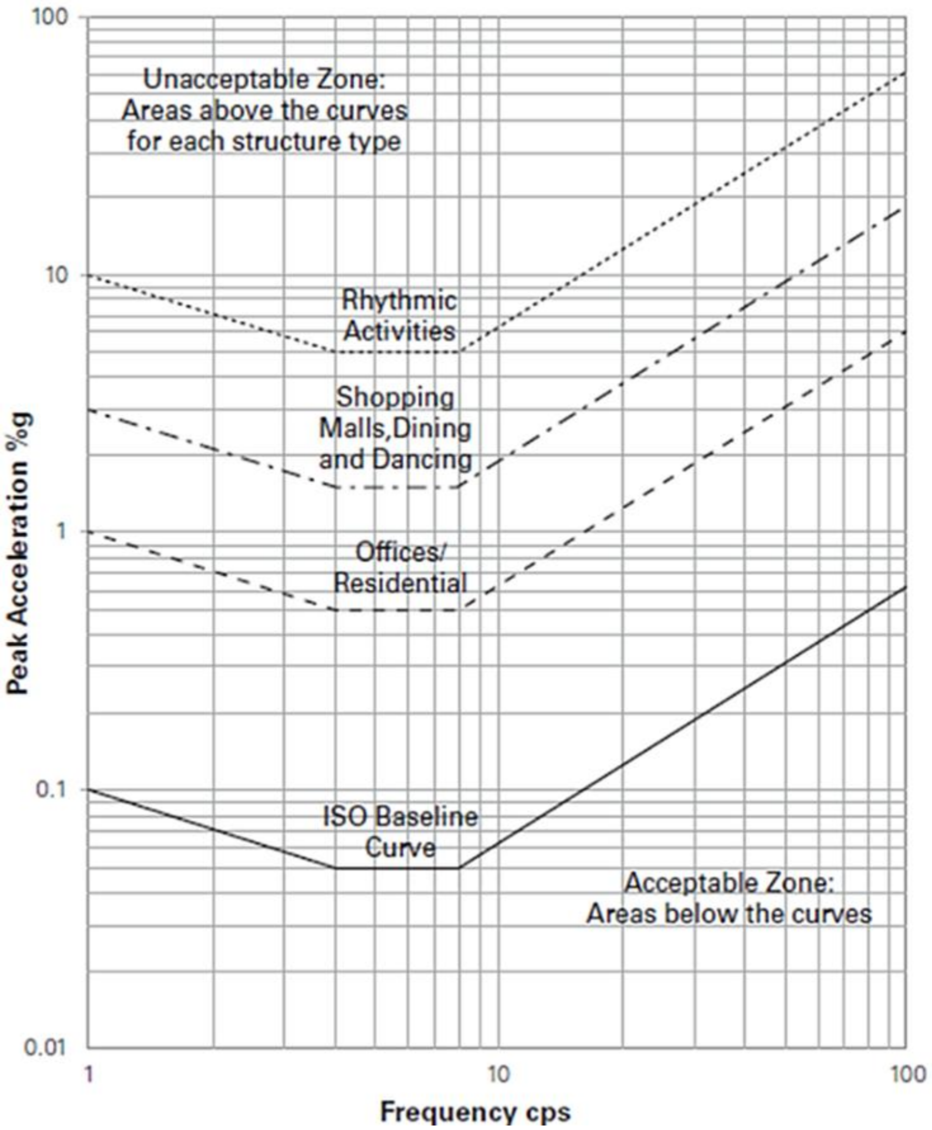


Figure 2. Recommended maximum acceleration for human comfort for vibrations due to human activities **(David and Mike, 2014).**

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)**.

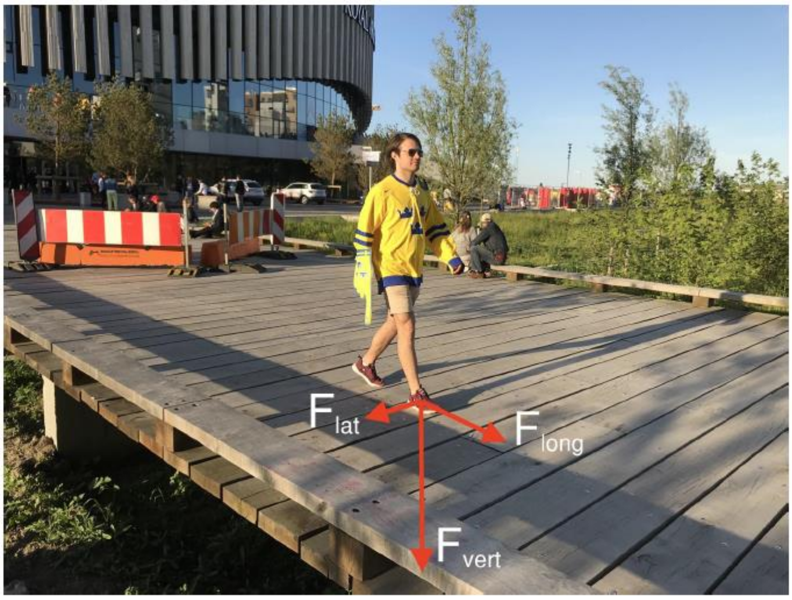


Figure 3. Lateral, longitudinal, and vertical force components from a footfall **(Bond and Hielmgren, 2018).**

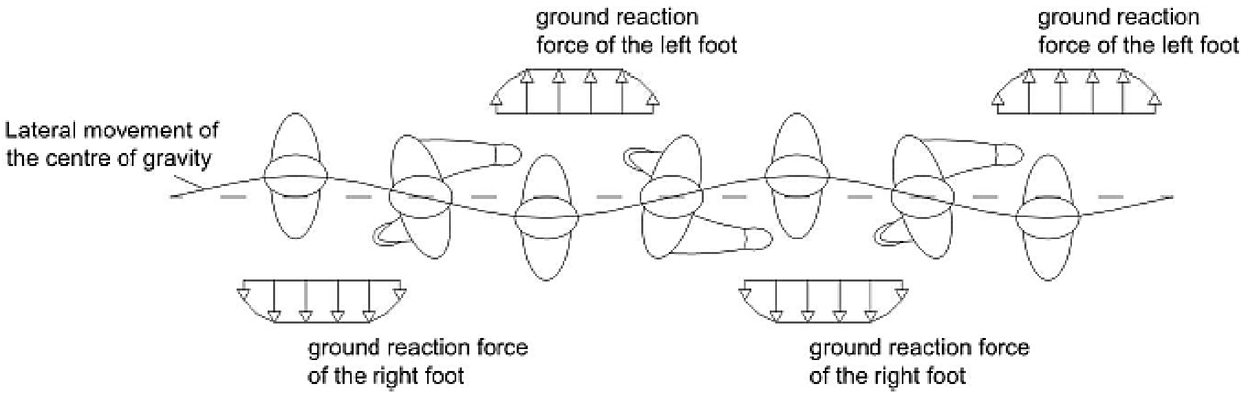


Figure 4. Lateral forces are imposed by walking humans **(Bond and Hielmgren, 2018).**

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**.

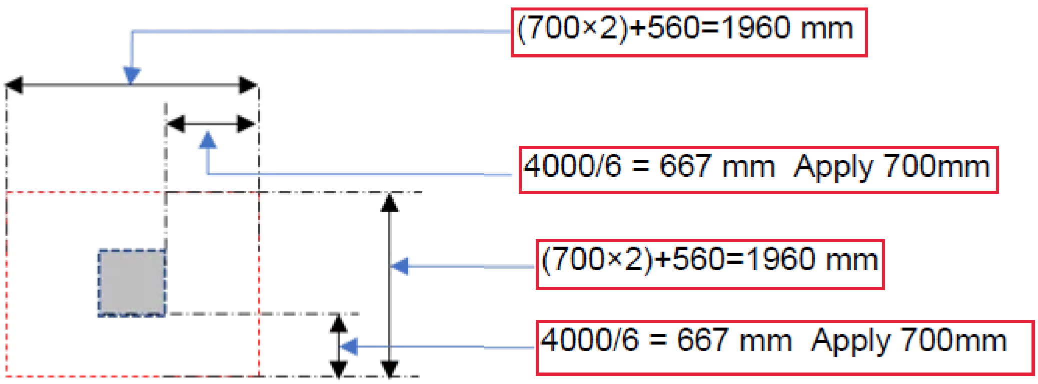


Figure 5. Drop panel design**.**

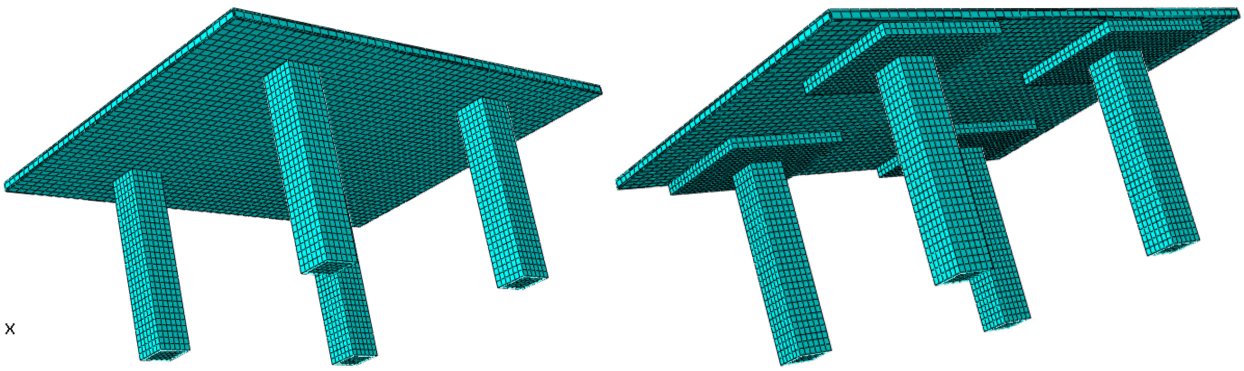
While for the thickness of the drop panel according to the ACI318-19, for exterior panels without edge beams, the thickness is equal to a fourth of the distance from the face of the column to the edge of the drop panel (h_d, height of drop panel which is found to be 175 mm) (**ACI Committee 318, 2019**).

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 $f_c' = 28\ MPa$, $f_y = 420\ MPa$, and $E_c = 12290\ MPa$.
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**.



flat plate flat slab

Figure 6. Mesh Model in ABAQUS.

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.

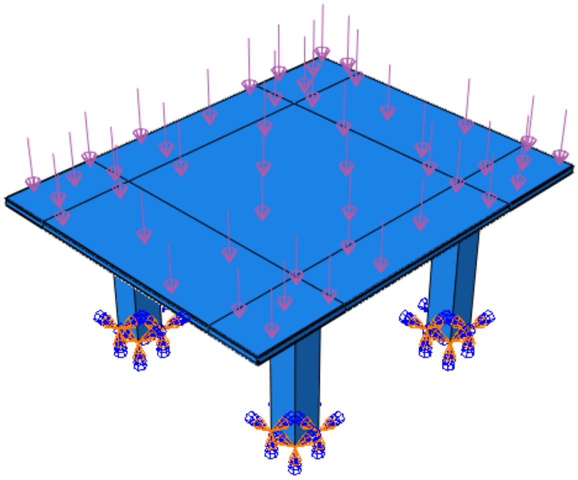


Figure 7. Applying Pressure Load in ABAQUS.

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.

$$f_i = \frac{k_2 \lambda_i^2}{2\pi l_1^2}\left[\frac{k_1 E_c h^3}{12\gamma(1-v^2)}\right]^{1/2} \quad (1)$$

where h is the overall thickness of the flat plate or voided slab,
γ is the mass per unit area of the plate,
v is Poisson's ratio,
l_1 is the longer of the two center-to-center span lengths of the plate panel,
λ_i^2 is a function of the panel aspect ratio l_1/l_2 and v (dimensionless parameter). Values of λ_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,

$$k_2 = \begin{cases} 1.9 \; for \; c_1 \leq \; 24 \; in. \\ 2.1 \; for \; c_1 > \; 24 \; in \end{cases}$$

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 λ_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:

$$Error_{for\ flat\ plate} = \left(\frac{9.77 - 7.93}{9.77}\right) \times 100 = \; 18.8\ \%$$

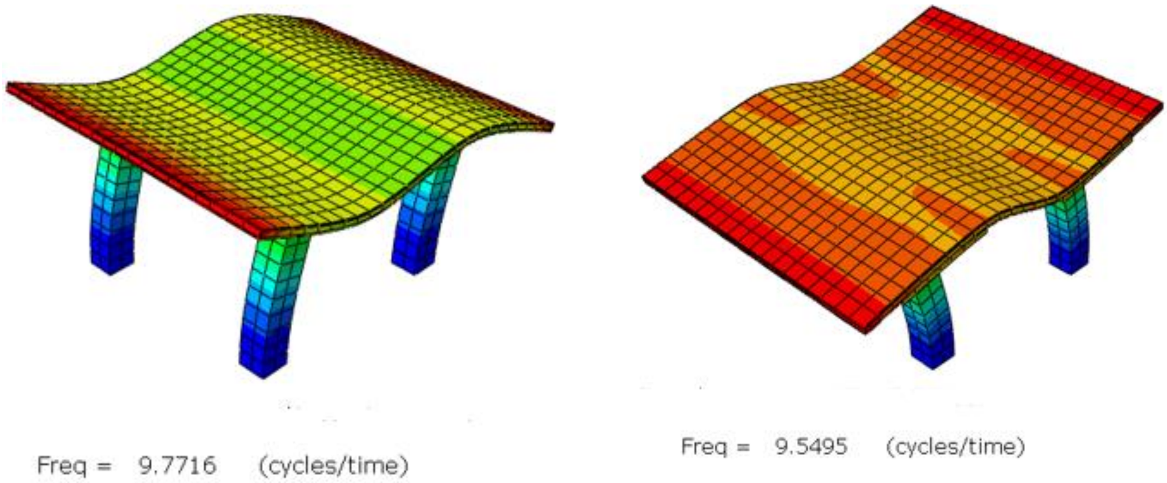
$$Error_{for\ flat\ slab} = \left(\frac{9.54 - 7.93}{9.54}\right) \times 100 = 16.8\ \%$$

The acceptance criterion for walking excitation of floor systems is:

$$\frac{a}{g} = \frac{65e^{-0.35fn}}{\beta W} \leq \frac{a_0}{g} \tag{2}$$

where $w = 2Mg$, M is the fundamental modal mass.$w = 1587.7 \times 32.2 = 51124$ lbs. Then:

$$\frac{a_p}{g} = \frac{65e^{(-0.35\times7.93)}}{0.03 \times 51124} = 0.00264$$



flat plate flat slab

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.

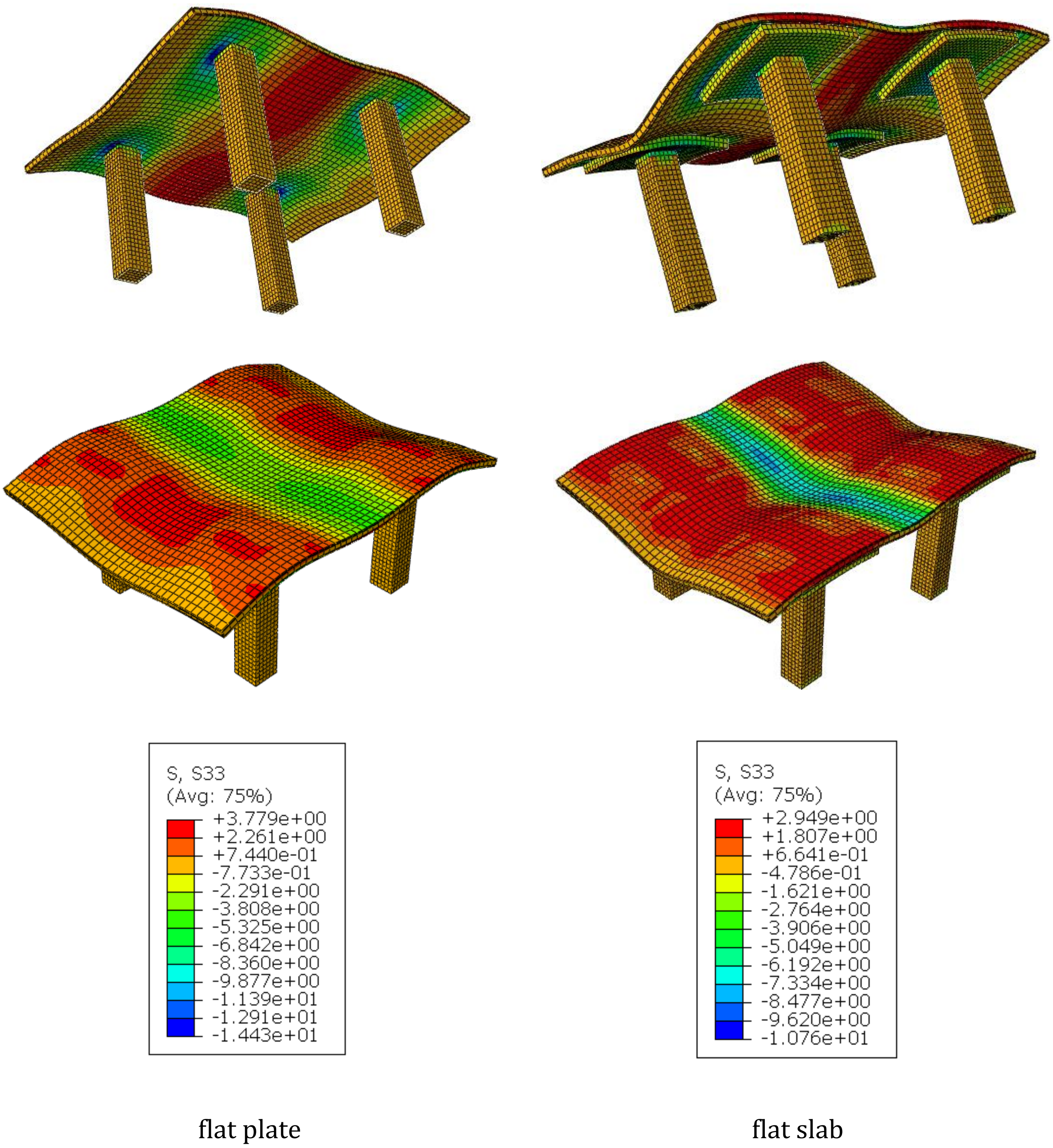
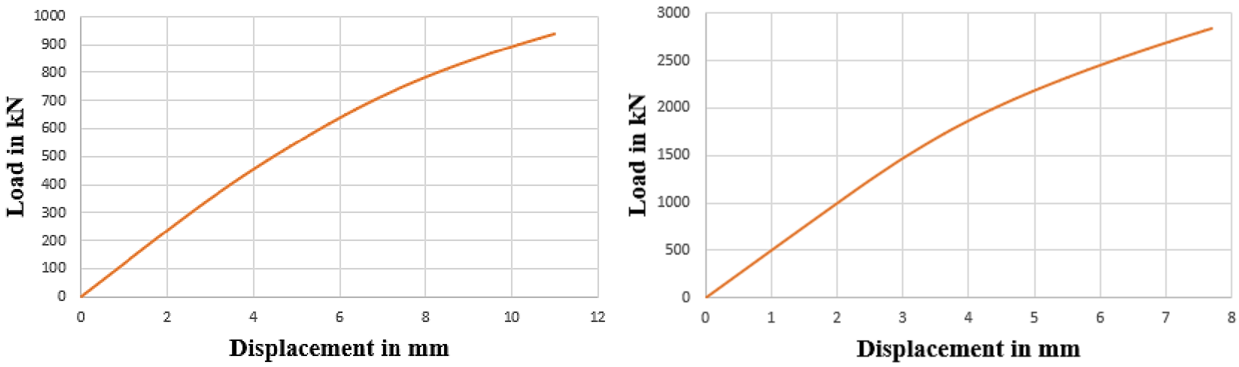


Figure 9. Two-way slab strength results in ABAQUS.

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.



flat plate flat slab

Figure 10. Load-deflection curve.

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 $a_\circ$ 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

Symbol	Description	Symbol	Description
C_n	Frequency constant	k_1	The level of cracking in the concrete slab
E	Modulus of elasticity; Young's modulus, MPa.	k_2	A constant that accounts for the rigidity
f_i	Natural frequency, Hz.	λ_i^2	Function of the panel aspect ratio l_1/l_2
I_e	Effective moment of inertia, mm^4	ν	Poisson's ratio

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.

REFERENCES

ACI Committee 318. 2019. Building Code Requirements for Structural Concrete (ACI 318R-19), American Concrete Institute.

AISC, 1997. Floor Vibrations Due to Human Activity – Steel Design Guide Series No. 11. American Institute of Steel Construction, Chicago, IL

Al-Zahra, B.I.A., Alwash, M., Baiee, A. and Shubbar, A.A., 2021. Limitations on ACI code minimum thickness requirements for flat slab. *Civil Engineering Journal*, *7*(11), pp.1918-1932. Doi:10.28991/cej-2021-03091769

Adam, M.A., Said, M., Arafa, A.E., Abdelsattar, A.M., 2020. Analytical analysis of Light-weight Concrete slabs under punching Load. *Al-Azhar University Civil Engineering Research Magazine (CERM)*, 42(1), pp. 58-68

Adan, S.M., Luft, R. and Naguib, W.I., 2010. Deflection considerations in two-way reinforced concrete slab design. In *Structures Congress,* pp. 1991-2002. Doi:10.1061/41130(369)181 .

Ahmed, M.S., 2023. Natural frequencies of RC concrete slab with opening. *Academic Journal of Nawroz University*, *12*(3), pp.158-164. Doi:10.25007/ajnu.v12n3a1905

Alami, F., Helmi, M. and Noorhidana, V.A., 2021, April. Fiber reinforced polymer as potential solution for vibration problem in concrete slab for supporting human comfortable. In *IOP Conference Series: Earth and Environmental Science* (Vol. 739, No. 1, p. 012025). IOP Publishing. Doi:10.1088/1755-1315/739/1/012025

Allahyari, H., Nikbin, I.M., Rahimi, S. and Allahyari, A., 2018. Experimental measurement of dynamic properties of composite slabs from frequency response. *Measurement*, *114*, pp.150-161.Allen, D.E., Murray, T.M., 1993. Design Criterion for Vibrations due to Walking. Engineering Journal, AISC, 4th Quarter, 117-129. Doi:10.1016/j.measurement.2017.09.030

Bond, J., Hielmgren, V., 2018. Dynamic and Economic Aspects of Carbon Fiber Reinforced Polymer Footbridge. Master Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Cao, T.A., Nguyen, M.T., Pham, T.H. and Nguyen, D.N., 2023. Experimental Study on Flexural Behavior of RC–UHPC Slabs with EPS Lightweight Concrete Core. *Buildings*, *13*(6), p.1372. Doi:10.3390/buildings13061372 .

Fanella DA, Mota M. Design guide for vibrations of reinforced concrete floor systems: the first design guide developed to assist structural engineers with vibration analysis of reinforced concrete floor systems. Concrete Reinforcing Steel Institute; 2014.

Gharbi, A.H. and Mahmoud, A.S., 2020. Punching shear behavior of reinforced concrete slabs under fire using finite elements. *Journal of Engineering*, *26*(5), pp. 106-127. Doi:10.31026/j.eng.2020.05.08

Al-Azzawi, A.A., 2019, August. Punching shear behaviour of solid and bubble reinforced light weight aggregate concrete two-way slabs. In *IOP Conference Series: Materials Science and Engineering* (Vol. 584, No. 1, p. 012013). IOP Publishing. Doi:10.1088/1757-899X/584/1/012013

Hussein, N.A., Salman, M.M., Jarallah, H.K., 2021. Analytical and Experimental Study of the Piles Cap Normal and Light Weight Aerated Concrete: Literature Review. *Journal of Engineering*. Baghdad, Iraq. 27(10), pp. 86-105. Doi:10.31026/j.eng.2021.10.06

ISO, 1989. Evaluation of Human Exposure to Whole-Body Vibration – Part 2: Human Exposure to Continuous and Shock-Induced Vibrations in Buildings (1 to 80 Hz), ISO 2631-2, International Standards Organization

Khanushiya, M.S., Butala, A.M., 2021. Comparative study of multistory building of flat slab and grid slab system with conventional slab system. International Research Journal of Engineering and Technology (IRJET), 8(5), pp.1-7

Khennane, A., 2013. *Introduction to finite element analysis using MATLAB® and Abaqus*. CRC Press. ISBN:1466580208, 9781466580206

Lai, E. and Mulas, M.G., 2016. Pedestrian-footbridge dynamic interaction: a probabilistic assessment of vibration serviceability. *Meccanica dei materiali e delle Strutture*, *6*(1), pp.211-218.

Lee, R., 2023. ABAQUS for Engineers: Engineering Fatigue Analysis with Fe-Safe. South Korea.ISNN: 979-8379359331

Muhammed, T.A. and Karim, F.R., 2022. The Influence of Drop Panel's Dimensions on the Punching Shear Resistance in Ultra-High-Performance Fiber-Reinforced Concrete Flat Slabs. *Construction*, *2*(1), pp.55-65. Doi:10.15282/cons.v2i1.7581

Munthe, A.T. and Jatmiko, G., 2020, May. Planning Parking Building Using Flat Slab And Drop Panel As A Replacement Conventional Beam With Analyzing Bending Moment Value & Sliding Style Based On SNI 1726-2012. In *Journal of World Conference (JWC)* (Vol. 2, No. 3, pp. 1-12).

Neville, A.M., 1995. *Properties of concrete* (Vol. 4, p. 1995). London: Longman, United Kingdom

Oukaili, N.K., Salman, T.S., 2014. Punching Shear Strength of Reinforced Concrete Flat Plates with Openings. *Journal of Engineering*, 20(1), pp. 1-20. Doi:10.31026/j.eng.2014.01.01

Park, R. and Gamble, W.L., 1999. *Reinforced concrete slabs*. John Wiley & Sons. ISBN:0471348503, 9780471348504

Paultre, P. and Moisan, C., 2002. Distribution of moments in reinforced concrete slabs with continuous drop panels. *Canadian Journal of Civil Engineering*, *29*(1), pp.119-124. Doi: 10.1139/l01-076

Qi, J. and Yang, H.C., 2021. Improvement of a truss-reinforced, half-concrete slab floor system for construction sustainability. *Sustainability*, *13*(7), p.3731. Doi: 10.3390/su13073731

Fernández Ruiz, M., Mirzaei, Y. and Muttoni, A., 2013. Post-punching behavior of flat slabs. *ACI Structural Journal*, *110*, pp.801-812. Doi: 10.14359/51685833

Said, M., Adam, M.A., Arafa, A.E. and Moatasem, A., 2020. Improvement of punching shear strength of reinforced lightweight concrete flat slab using different strengthening techniques. *Journal of Building Engineering*, *32*, p.101749. Doi: 10.1016/j.jobe.2020.101749

Salman, N.N., Daud, R.A., 2022. Finite Element Modeling of One-Way Recycled Aggregate Concrete Slabs Strengthened using Near-Surface Mounted CFRPs under Repeated Loading. *Journal of Engineering*. 28(11), pp. 32-46. Doi:10.31026/j.eng.2022.11.03

Singh, M. and Saini, B., 2019. Analytical and experimental study of voided slab. In *Proceedings of the 1st International Conference on Sustainable Waste Management through Design: IC_SWMD 2018 1* (pp. 438-448). Springer International Publishing.

Htun, P.H.T., Phone, N. and Win, K.Z., 2018. Comparative study on analysis and design between flat slab and flat plate system for RC building. *Int. J. Sci. Eng. Appl*, *7*(9), pp.313-317.

Urban, T., Gołdyn, M., Krawczyk, Ł. and Sowa, Ł., 2019. Experimental investigations on punching shear of lightweight aggregate concrete flat slabs. *Engineering Structures*, *197*, p.109371. Doi:10.1016/j.engstruct.2019.109371

Xia, Q., Qu, W., Li, Y. and Zhao, J., 2018. Analysis of natural vibration frequency of different support slabs under the traffic vibration based on field measurement. *Instrumentation, Mesures, Métrologies*, *17*(2). P. 219. Doi: 10.3166/I2M.17.219-233

Yang, K.H., Mun, J.H., Song, J.K., Kim, S.H., Hwang, S.H. and Chang, C.H., 2023. Punching shear capacity of lightweight aggregate concrete flat slabs without shear reinforcements. *Magazine of Concrete Research*, *75*(6), pp.296-309. Doi:10.1680/jmacr.21.00324

Yasir, A., Effendi, M.K., Taveriyanto, A. and Apriyatno, H., 2019. Analysis of Strengths of Reinforced Concrete Beam Structures with CFRP Sheet Using Abaqus Software 6.14. *Jurnal Teknik Sipil dan Perencanaan*, *21*(1), pp.9-19. Doi:10.15294/jtsp.v21i1.19364