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Research paper

Effect of Footfall Induced Vibration on Flat Plate Slabs

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Abstract

In recent years, vibration in structures is becoming an increased concern due to the adoption of slender flooring systems (i.e. lighter, thinner and longer floors). Vibrations induced by footfall are more significant in slender floors and should therefore be taken into consideration in the serviceability of the reinforced concrete structures. Limited research exists in the literature focusing on dynamic analysis of flat plate slabs subjected to footfall induced vibration. Hence, this study attempts to breach this research gap by exploring a wider area through conducting a parametric investigation on the effect of floor span, floor aspect ratio, slab thickness and location of openings on the dynamic response of flat plate slabs. Structures are initially designed in accordance with Eurocode 2. Models are generated and analysed using the finite element method and dynamic responses from the footfall analysis are obtained. It was found that vertical displacement increases exponentially with the increase of floor width, aspect ratio and number of openings. However, the displacement decreases with the increase of slab thickness. Moreover, the location of openings is found to have significant effect on the responses of flat plate slabs.

Keywords: *Dynamic response; finite element modelling; flat plate slabs; footfall; reinforced concrete; vibration.*

1. Introduction

Vibration has become an important aspect in structural design, as the weight of modern structures are becoming lighter due to the adoption of slender flooring systems These type of slender flooring systems have different natural frequencies which probably coincide with the footfall induced vibration frequencies resulting in resonance. Such footfall induced vibration hardly causes failure or significant damage to a structure, however it probably creates greater nuisance to the occupants of the building. Severe vibration will also affect the accuracy of vibration-sensitive equipment in hospitals, laboratories and research buildings. Hence, vibration serviceability of structures should be taken into consideration.

Generally, flat slab is a reinforced concrete slab that is designed without any beams, while the loads are transferred solely to the columns. Flat slabs are two-way slabs that carry loads in two directions. As the flat slab system is applied, floor-to-floor height of the building can be reduced. Furthermore, flat slabs are able to admit natural light in as the windows can be extended to a higher height without beams. The amount of formworks required is reduced which leads to save the cost of construction. Moreover, it has greater fire resistance than the normal beam-slab as it does not have sharp corners. Drop panels and column heads can be designed to reduce the punching shear and increase the moment resistance simultaneously.

Harper et al. [1] are amongst the first to investigate the footfall induced forces on different floor surfaces. A force plate is used to measure the vertical, lateral and longitudinal forces from a single footstep. Vertical force is having greatest magnitude compared to lateral and longitudinal forces. The shape of vertical downward force was found to have two peaks against time. This general shape of walking force-time history was then confirmed by Galbraith and Barton [2], Blanchard *et al.* [3], Ohlsson [4] and Kerr [5] through experimental works. It was, furthermore, found that the step length and peak force magnitude increase with the walking speed. Different relationships between the walking speed and the pacing frequency with certain controlled parameters such as pacing frequency, speed or step length were investigated.

According to Lenzen [6], the transient vibration is the factor that causes human-induced excitation to the low damping floor. Human-induced excitation is related to different modes of human moving. It was concluded by Wheeler [7] that the peak amplitude, stride length and velocity increased with step frequency while the contact time decreases. A research considering two-step periodic walking conducted by Andriacchi et al. [8] shows that fundamental frequency of the lateral forces is two times lower than the vertical and longitudinal forces.

The reinforced concrete slabs, in past decades, have not been experienced with any vibration serviceability problem as it is heavier and stiffer [10]. However, slabs currently have longer spans, lower thickness and lighter, which may lower natural frequencies of structures. Petyt and Mirza [11] have conducted finite element investigation and laboratory studies on the free vibration of column supported floor slabs by simplifying the columns as pinned point-supports. It was found that the limitation of finite element modelling is the rigidity of connection. A low frequency floor is likely to be caused by resonance than the impulsive excitation caused by individual walking [12]. The vibration serviceability on long-span and pre-stressed concrete floors should be assessed through examination of vibration response rather than manipulating their natural frequencies.

Experimental modal analysis, operating deflection shapes (ODS) analysis and 'True' experimental modal analysis are several vibration analysis methods that are currently being practiced [10]. In experimental modal analysis, sensitive instrumentation and complex signal processing techniques are required to deal with environmental noise. Caetano and Cunha [13] proposed an advanced method for predicting the natural frequency, mode shapes, and modal damping ratio. The method comprises of multiple degree of freedom (MDOF) vibration parameter estimation using measured Frequency Response Function (FRF) and Finite Element (FE) modelling prior to the full-scale testing. FRF measurement uses a manually operated instrumented sledge-hammer and FE model correlation with the experimental data gathered after modal testing.

Every structure has its corresponding natural frequency; however it generally involves large range of values, which depends on the mode of vibration. For the case of human-induced vibration such as footfall, lower natural frequency is being focused, as near-resonant condition will be critical. Amplitude of the motion tends to be amplified rather than subsided as resonance occurs. There are many mode shapes when the floor structure is vibrating freely with its individual natural frequency [14]. Three general mode shapes for vertical vibration are shown in Figure 1.

Response spectrum is generally used to show the variation of relative amplitude with frequency of the vibration components that contribute to the motion. Damping is the loss of mechanical energy in a vibrating system. Ratio of actual damping, which is assumed to be viscous, to critical damping is usually expressed in studying a vibrating system. The higher the damping ratio, the lower the peak velocity is. Since the peak velocity at first harmonic is the highest, footfall analysis from design guide is normally based on the first harmonic [15]. Generally, the vibration beyond 1.5 to 2 times of the fundamental frequency is possibly damped by the structure itself. For more conservative estimation, the damping ratio is approximately 3 % to 5 % [14]. The agreed set of damping ratio for different materials used in construction industry is suggested by Bachmann and Ammann [16], where the steel and reinforced concrete have damping ratios of 0.2 % and 0.8 %, respectively.

This paper presents the dynamic responses of reinforced concrete flat plate slabs subjected to footfall induced vibration. The study focuses on four sets of varying parameters including floor span, aspect ratio, slab thickness and location of openings. Structures are initially designed in accordance with Eurocode 2. The models are generated and analysed using finite element software. Dynamic responses obtained from the dynamic footfall analysis are expressed in terms of vertical displacements and accelerations.

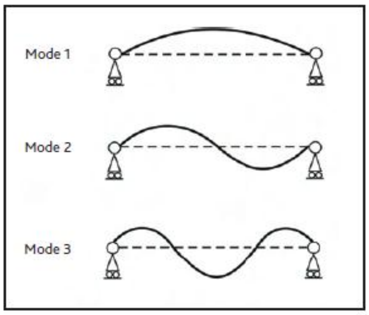

Fig. 1: Mode shape of simple supported beam [15].

2. Methodology

2.1. Finite element modelling

The flat plate slab is designed in accordance with Eurocode 2. The critical condition such as the longest span, thinnest slab and worst loading case are taken into account during the design stage. The general layout plan and isometric view of the model are presented in Figure 2. Flat plate slab does not include any beam. There are 3 bays in both x and y directions, resulting in a total of 9 panels in a floor.

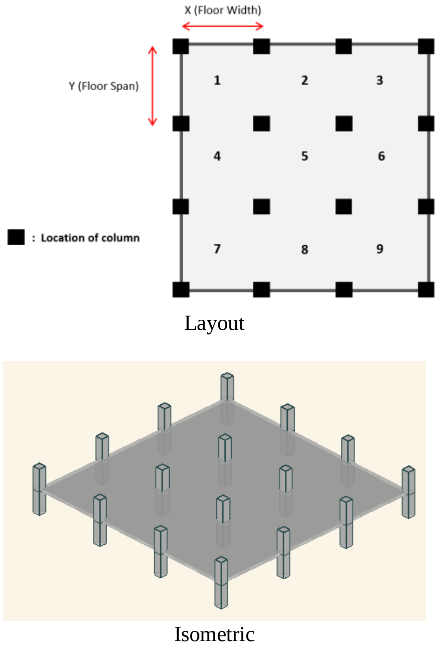

Fig. 2: General layout plan and isometric view of the model.

The simulations are carried out using finite element software, *OASYS GSA Suite 8.6* developed by Arup Limited [17]. Flat plate slabs are modelled using 2D shell elements because the elements are subjected to transversely applied normal forces and its deflection is normal to the plane of the element. Quad 8 (parabolic quad elements) is used instead of other types (e.g. Quad 4 or Tri 3) because it provides better accuracy, since a quadratic approximation of displacement over the element domain is provided. Furthermore, Quad 8 elements are able to collaborate with the geometry of flat plate slab in this study. Discretization is performed through meshing with element size of 0.25 m x 0.25 m.

In the flat plate slab, rigid constraint or master-slave link is used at the column support. The master node is selected at the centre axis of the column and the slave nodes are those around the column. The forces and moments at the slave nodes can be transferred to equivalent forces and moments at the master, so that it will reduce any unreasonable peak forces and moments around the column. The selected linkage type is all pinned, where rotation in x, y and z direction are not restrained. The edge of flat slab along the x-axis is restrained in the x and z direction, whereas the edge along the y-axis is restraint in the y and z direction.

The grade of concrete and percentage of reinforcement steel used for reinforced concrete flat plate slab is C30/37 concrete (compressive strength of 30 MPa) and 1.8 %, respectively. The flat plate slab is modelled with reinforced concrete columns of half-storey height (1.5m height) above and below the flat plate slab, with dimension of 300 mm x 300 mm made of same concrete grade. An imposed dead load of 3kN/m^2 and a live load of 3kN/m^2 are applied on the slab in vertical direction. Self-weight of the structure is taken into account.

Dynamic characteristics include natural frequencies and mode shapes of a structure can be determined using modal analysis. These dynamic responses are then used by footfall vibration analysis. For footfall analysis, the *American Institute of Steel Construction (AISC)* guideline is used. A damping ratio of 2% is used for all models. The number of footfall is set as 100 while the mass of the human is 76kg. The walking frequency is defined as a range of 1.5 to 2.5 Hz.

2.2. Parametric study

The study investigated the effect of footfall induced vibration on reinforced concrete flat plate slabs with different parameters including floor span, aspect ratio, slab thickness and location of openings. For the first case, both the floor width and span length (denoted "X" and "Y" respectively in Figure 2) is varying from 3m to 8m. Aspect ratio is the ratio of longer span length to shorter span length of the panel. For the second set, the aspect ratios are the variables by changing span length from 4m to 8m correspondingly. For varying slab thickness, the value varies from 200mm to 300mm with a constant increment of 20mm. Moreover, different types of opening are studied and compared to model without opening. A total of 26 models are studied, while the details are shown in Table 1 and the locations of openings are illustrated in Figure 3.

3. Results and discussion

Dynamic responses obtained from the analysis are expressed in terms of vertical displacements and accelerations. The maximum displacement and peak acceleration are presented to identify the degree of structural responses due to the footfall induced vibration. Responses at critical location such as mid-span of panel are, furthermore, presented.

3.1. Effect of floor span

From the contour plots of the models, it is observed that for individual panels, large displacements and accelerations mostly occurred at the centre of each panel (red colour zone indicated in Figure 4). However, for the entire floor, the high response zones (i.e. including displacement and acceleration) tend to move from corner panels to middle panel (panel 5) with the increase of floor span. The maximum displacement and peak acceleration for the models are shown in Table 2. It is observed that the maximum values are mostly located near or at the mid-span of the square panel. The maximum displacement increases exponentially with the increase of floor span from 3m to 8m, as shown in Figure 5.
The stiffness matrices coefficient (EI/L) shows that stiffness is inversely proportional to the span length, hence the stiffness decreased when the span length is increased. The load acting on the slab is also increased since the area of slab panel increased, resulting in higher displacement. For peak acceleration, the values increased with span length, while 7m span depicted highest value ($0.2181 m/s^2$). Peak accelerations may not be attributed to the length of panels because the interaction between the load models has different dynamic characteristics such as mass and stiffness, associated to each structural model [18]. Hence, the mass of floor span might outweigh the other factor such as stiffness. The proportion of mass of floor structure is increased more than the reducing proportion of stiffness of the structures.
The displacements at each panel of models with different floor spans are plotted in Figure 6. For model with 3m, 4m and 5m span, the displacements for all nine panels are nearly constant. For floor with 6m, 7m and 8m span, higher displacements recorded at panel 2, 5 and 8, which are higher compared to left and right panels. Overall 8m span has the highest values. When floor span increases, the maximum displacement response starts to move towards the middle panel. This might be due to the loading and self-weight that concentrates more at the interior panel after increasing the span to 6m.

Table 1: List of models with varying floor span, aspect ratio, slab thickness and openings

Model	Span (m)	Width (m)	Aspect Ratio	Thickness (mm)	Opening
Varying Floor Span (Width)	3	3	1.00	240	No
	4	4	1.00	240	No
	5	5	1.00	240	No
	6	6	1.00	240	No
	7	7	1.00	240	No
	8	8	1.00	240	No
Varying Aspect Ratio	4	4	1.00	240	No
	5	4	1.25	240	No
	6	4	1.50	240	No
	7	4	1.75	240	No
	8	4	2.00	240	No
Varying Slab Thickness	6	4	1.50	200	No
	6	4	1.50	220	No
	6	4	1.50	240	No
	6	4	1.50	260	No
	6	4	1.50	280	No
	6	4	1.50	300	No
Varying Location of Openings	5	5	1.00	240	No
	5	5	1.00	240	Panel 1
	5	5	1.00	240	Panel 2
	5	5	1.00	240	Panel 3
	5	5	1.00	240	Panel 5
	5	5	1.00	240	Panel 1 & 5
	5	5	1.00	240	Panel 2 & 5
	5	5	1.00	240	Panel 1 & 4
	5	5	1.00	240	Panel 1, 5 & 9

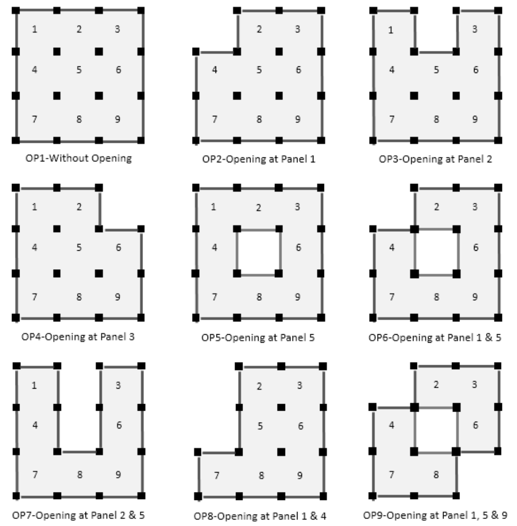

Fig. 3: Illustration for different types of openings.

Table 2: Maximum displacements and peak acceleration with different floor spans

Floor Span (m)	Maximum Displacement (mm)	Peak Acceleration (m/s^2)	Location
3	0.001042	0.0007278	Panel 1, 3, 7 & 9, center
4	0.001941	0.0014570	Panel 2 & 8, center
5	0.003163	0.0029210	Panel 4 & 6, center
6	0.005746	0.0140800	Panel 5, center
7	0.010360	0.0218100	Panel 5, center
8	0.014900	0.0183200	Panel 5, center

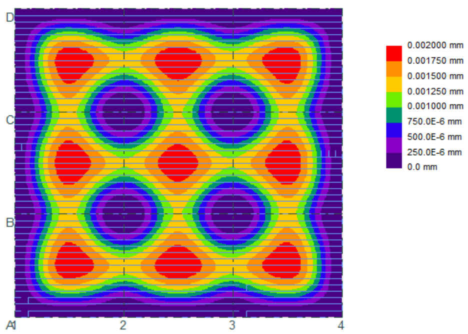

Fig. 4: Displacement contour for flat plate slab with 4m width and 240mm thickness.

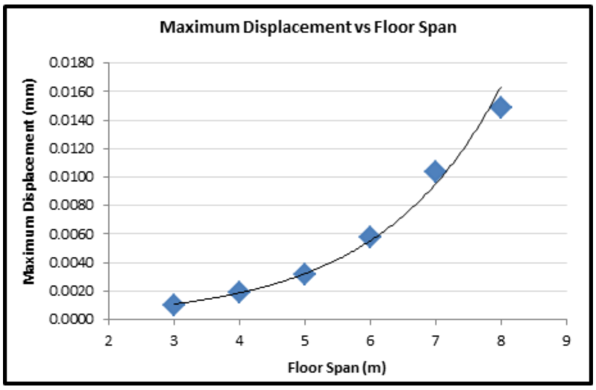

Fig. 5: Maximum displacement vs floor span of flat plate slab.

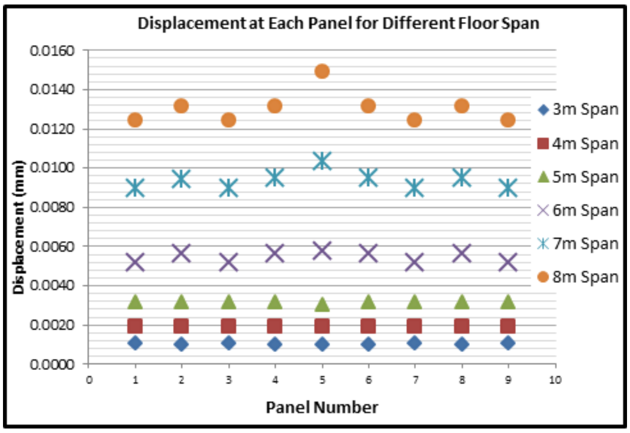

Fig. 6: Displacement at each panel for models with different floor span.

3.2. Effect of slab thickness

Displacement and acceleration contours show similar pattern, where high responses initially took place at mid-span of middle bays (panel 2, 5 & 8) for thickness of 200mm. With the increase of slab thickness, the high responses are then spread and distributed to larger area and affecting the bays at both sides, as shown in Figure 10. The maximum displacement and peak acceleration are all located on panel 8, while the responses decrease exponentially with the increase of slab thickness (Figure 11). This also explained that although the dynamic responses are distributed to larger area, the magnitude is being scaled down. The flexural stiffness is proportional to EI/L, where *E* is Young's modulus and *I* is the second moment of inertia. Increasing the thickness (*h*) will also increase the moment of inertia ($I=bh^3/12$), hence flexural stiffness increases due to its direct proportionality to *I*, resulting in larger resistance to dynamic loading.

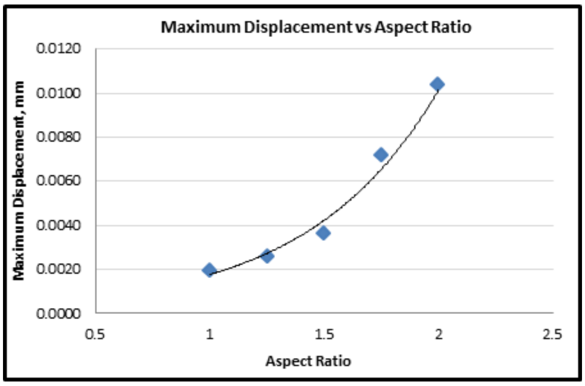

Fig. 8: Maximum displacement vs aspect ratio of flat plate slab.

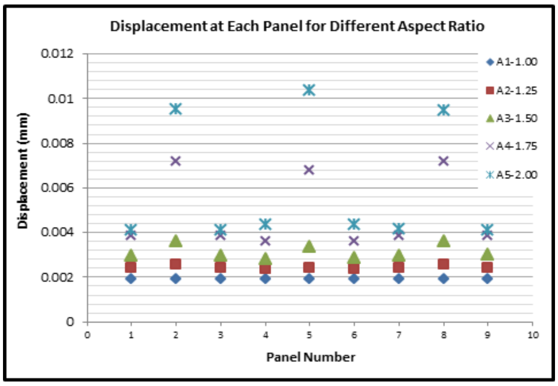

Fig. 9: Displacement at each panel for models with different aspect ratio.

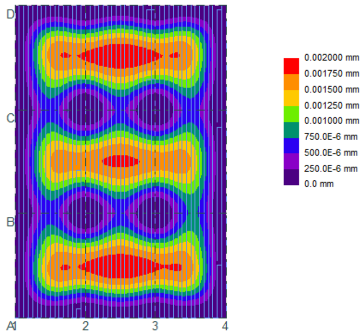

Fig. 10: Displacement contour for flat plate slab with thickness of 300mm.

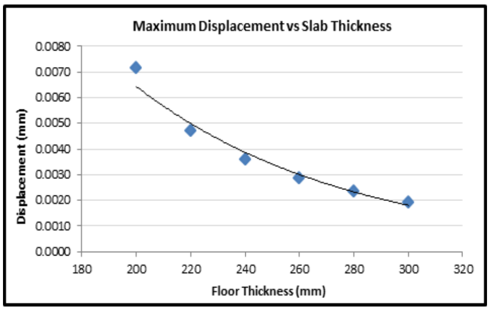

Fig. 11: Maximum displacement vs thickness of the flat plate slab.

The displacements at each panel for models with different slab thicknesses are plotted in Figure 12. It is noticed that the middle bays (panel 2, 5 and 8) show higher values than the adjacent bays at left and right sides. The behavior is obvious for thickness of 200mm, and getting less significant with the increase of slab thickness. Meanwhile, panels near the edge (panel 2 & 8) show larger value that at the center bay (panel 5). It should be highlighted that any further increase in slab thickness results in higher mass and more construction materials to be used; nevertheless reduction in dynamic response is insignificant [19]. Hence, it is not an economical solution.

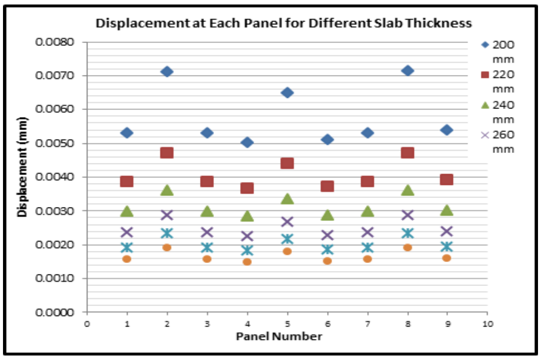

Fig. 12: Displacement at each panel for models with different slab thickness.

3.4. Effect of openings

The contour pattern for model without opening is similar to pattern shown in Figure 7(a). For models with openings, it is observed that high responses are always located near the opening of floor slab, which could be attributed to stiffness irregularity. An example of displacement contour is shown in Figure 13, with opening at left corner (panel 1 & 4). The maximum displacements and peak accelerations for flat slab with different types of openings are tabulated in Table 3.

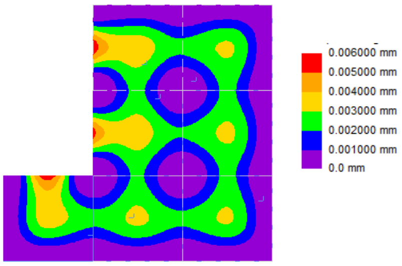

Fig. 13: Displacement contour for flat plate slab with opening at the panel 1 & 4 (left corner).

Table 3: Maximum displacement for flat plate slab with different openings

Model	Opening Location	Maximum Displacement (mm)	Peak Acceleration (m/s^2)
OP1	Without Opening	0.003163	0.002921
OP2	Panel 1	0.005720	0.004669
OP3	Panel 2	0.005797	0.004724
OP4	Panel 3	0.005720	0.004669
OP5	Panel 5	0.005443	0.004366
OP6	Panel 1 & 5	0.005940	0.004994
OP7	Panel 2 & 5	0.005813	0.004742
OP8	Panel 1 & 4	0.005814	0.004742
OP9	Panel 1, 5 & 9	0.006171	0.005157

4. Conclusion

The effects of footfall induced vibration incurred by walking people on reinforced concrete flat plate slabs has been investigated in this paper. Four sets of varying parameters are studied, which are floor span, aspect ratio, slab thickness and location of openings. The results of footfall analysis are expressed in term of vertical displacements and accelerations. The main findings are highlighted below:

(a) Dynamic responses (vertical displacement and acceleration) increase exponentially with increasing floor span. However, the acceleration for 8m span shows a drop after reaching peak at 7m. The high responses tend to move from corner panels to middle bays with the increase in floor span.
(b) Responses also increase exponentially by increasing the aspect ratio. Acceleration for the aspect ratio of 2 shows a drop rather than an increase.
(c) Displacement and acceleration decrease exponentially with the increase of slab thickness. Nevertheless, any further increase in slab thickness results in higher mass, which is believed not to be economical due to insignificant reduction in responses.
(d) Dynamic responses increase with the increased number of openings in a floor slab. High responses are always located at the edge of opening where discontinuity in structural rigidity exists.

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