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VIBRATION PERFORMANCE OF FLAT PLATE CONCRETE FLOORS WITH CODIFIED MINIMUM THICKNESS

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ABSTRACT: Limiting vibrations to ensure occupant comfort is a serviceability requirement that should be considered in the design of floor systems. Current concrete design codes do not explicitly address the issue of vibrations when providing guidelines for calculation of the slab thickness of a flat plate floor. Concrete codes have introduced several methods of determination of the slab thickness or span-to-thickness ratio on the basis of deflection control. The objective of this article is to investigate to what extent a flat plate floor with codified minimum thickness would meet the requirement for walking-induced vibration control. The modal properties of flat plate floors spanning 6-9 m were determined and the 90th percentile velocity response to walking excitation was calculated using probability-based design charts developed by a European guideline on floor vibrations. For deflection control, on average the floor designed following the European concrete code was 6% thinner than the floor designed using the American concrete code and 34% thinner than the floor designed according to the Australian concrete code. It was interestingly found that the vibration of a floor that was dimensioned for deflection control as per any of the three concrete design codes well met the acceptance criteria for human comfort in office buildings, residential buildings, hotels and schools. In addition, the vibration of a 9-m-span floor whose slab thickness was determined using the Australian concrete code provisions could even be acceptable for critical areas.

Keywords: Concrete floor, Deflection, Modal Analysis, Vibration, Human comfort

1. INTRODUCTION

In the design of building structures, the serviceability limit states relate to the function of the building or structural members under normal use, the comfort of people and the appearance of the construction works [1]. Slender long-span floors are more vulnerable to vibrations caused by various human activities, which may adversely affect occupant comfort [2]. Proper estimation and control of floor vibrations during the design stage is essential because rectification of the floor subject to excessive vibration after completion of construction could be costly and annoying [3-5]. Supriyadi found that the maximum vertical displacement of an auditorium floor doubled as a result of a group of persons dancing in unison in response to live music [6]. Walking is a common type of dynamic loading that needs to be considered when designing a floor [7]. In fact, there have been reports of disturbing floor vibrations caused by normal walking excitation [3]. To address the issue of human-induced floor vibrations, several design guidelines have been developed, the most popular being the North American design guide AISC DG11, the UK documents SCI P354 and CCIP 016, and the European technical reports EUR 21972 and EUR 24084 [8-12]. Each floor vibration guideline normally includes three key elements which are the characterization of the excitation force, the methodology for estimation of the floor response, and the acceptance criteria. Maximum vibration limits for human comfort are dependent on the floor function (e.g., retail, office, critical areas, etc.) and vary with the floor frequency with the most stringent being over the 4-8 Hz range. The constraints describing the serviceability limit state for vibrations generally consist of vibration quantities in terms of acceleration or velocity, usually in combination with frequency or a frequency range [13].

With regard to walking-induced vibrations, a floor with a fundamental frequency less than 9-10 Hz is classified as a low-frequency floor where resonance of the floor frequency with a multiple of the step frequency can occur. On the other hand, resonance would be less important compared with transient response in a high-frequency floor with a fundamental frequency greater than 9-10 Hz [8-10,14]. The damping ratio of a floor, which represents the vibrational energy dissipation, depends not only on the material and structural type but also on the architectural components and non-structural elements attached to the floor [15,16]. Cao et al. tested a long-span prestressed concrete floor to be used in the lounge of a major airport. It was showed that the floor was quite flexible with a fundamental frequency of 8.9 Hz and damping ratio of around 2.2% [17]. Measurements made on hollow-core concrete floors revealed a fundamental frequency of 6.1 Hz for a span of 10 m and 3.9 Hz for another span of 15.6 m [18]. A post-tensioned concrete floor spanning 10.2 m was found to have a natural frequency of 7.60 Hz and damping ratio of 1.40% when the floor was tested in a bare condition without furnishing [19]. Similarly, Dal Lago et al. recently performed heel-drop and walking tests on a number of concrete floors made with voided members and found that the floors had a fundamental frequency of around 8 Hz and an equivalent viscous damping ratio of just 1% in the absence of finishes, furnishing and partitions. The measured root-mean-square acceleration response due to walking was up to 0.051 m/s^2 which exceeded the recommended thresholds for human comfort in an office environment [20]. In another study, the dynamic tests performed on 26 waffle concrete floors revealed a modal damping of at least 3.4% thanks to the contribution of non-structural elements such as partition walls [21]. For design purposes, floor vibration guidelines recommend taking the damping ratio of a furnished concrete floor system as 2-4% depending on the level of fit-out [8-12].

A flat plate floor, which is a two-way system supported directly on columns, is one of the most common forms of construction of reinforced concrete floors in buildings. The thickness of the concrete slab is a parameter that has a significant influence on the mass and stiffness, and hence the natural frequencies and vibration response of the floor. According to contemporary codes on concrete structures, the slab thickness is selected mainly for deflection control [22-24]. Codified procedures for calculating the deflection consider the decrease in structural stiffness due to concrete cracking in the tensile zones and the additional deflection due to creep and shrinkage. As an alternative to complicated deflection calculations, design codes introduce deflection control rules based on limiting the span-to-thinkness ratio of the slab. The span-to-thickness ratio method is the most popular approach whereby serviceability requirements are deemed satisfactory if a required minimum thickness is provided to the slab [25,26].

The objective of this study is to assess the vibration performance of flat plate concrete floors designed with code-specified minimum thickness and subjected to walking excitation. Specifically, the finite element (FE) model of a typical flat plate floor system was created where the slab thickness was selected in accordance with the American, European and Australian codes for design of concrete structures. The footfall-induced vibration level and the perception class of the floor were found. This helps to determine whether the deflection-based thickness meets the vibration control requirement specified for the floor function.

2. RESEARCH SIGNIFICANCE

Current concrete design codes do not explicitly address the issue of vibration control when providing guidelines for calculation of the slab thickness [22-24]. The significance of this study is to provide design engineers with useful information on the vibration serviceability of concrete floors with code-determined thickness. Indeed, if only the strength and deflection requirements are considered then a general office floor and a critical workspace floor can be designed with the same codified thickness, live load, steel reinforcement and deflection. However, people who work in a general office environment can tolerate (without complaining) a much higher vibration level than those working in critical areas [8-13]. Therefore, the vibration level of a floor with a certain thickness may be acceptable for general office areas but may not ensure the comfort of the tenants in premium areas.

3. MATERIALS AND METHODS

3.1 Case Study Floor

The investigated floor consisted of 9 square panels with 3 spans in each direction as shown in Fig.1. The steel reinforcement had a yield strength f_y of 500 MPa and modulus of elasticity E_s of 200000 MPa. The concrete had a characteristic compressive strength f_c of 30 MPa and modulus of elasticity E_{cm} of 32840 MPa. The European floor vibration guidelines recommend taking the dynamic value of the modulus of elasticity for the concrete as 1.1 times E_{cm} in dynamic analysis of floor structures [11,12].

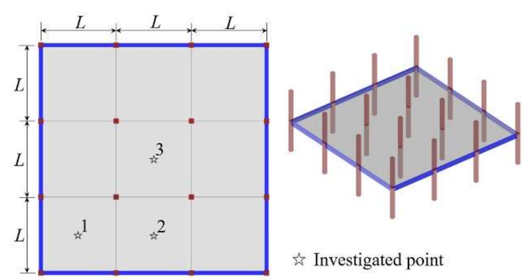

Fig.1 FE model of case study floor

FE models of the case study floor with a span length L of 6 m, 7.5 m and 9 m were created in SAP2000 with the floor object meshed into plate elements of sizes 500-750 mm [27]. SAP2000 allows using either thin-plate (Kirchhoff-Love) formulation which neglects transverse shearing deformation, or thick-plate (Reissner-Mindlin) formulation which includes the effects of transverse shearing deformation. The accuracy of thick-plate formulation is sensitive to mesh distortion and large aspect ratios. Thick-plate formulation is generally recommended when the span-to-thickness ratio is less than approximately 10 hence the contribution of shearing deformation becomes significant [27]. For the case study floor, since the span-to-thickness ratio was far greater than 20, thin-plate formulation was employed. Moreover, using thin plate elements for slab modeling is recommended in real applications since this method is more computationally effective than using solid elements and still ensures accuracy [28]. Neither drop panels nor interior beams were used in the case study floor. The floor had edge beams with cross-sectional dimensions of 300x400 mm, 300x500 mm and 300x600 mm for L = 6 m, 7.5 m and 9 m, respectively. The slab thickness D was first determined for deflection control using concrete code provisions presented in Section 3.2. Once the natural frequencies and mode shapes of the floor were determined via modal analysis in SAP2000, the floor response to walking can be evaluated using a method discussed in Section 3.3. The vibration level and acceptability at points 1, 2 and 3 (Fig.1) which were the centers of the corner, edge and interior panels, respectively, were examined.

3.2 Code Provisions for Slab Thickness

According to ACI 318, the minimum thickness D of slabs without drop panels, without interior beams and with edge beams can be taken as $L_n/33$ for f_y = 420 MPa and $L_n/31$ for f_y = 520 MPa where L_n is the length of clear span, measured face-to-face of supporting columns. It can hence be interpolated that $D = L_n/31.3$ for f_y = 500 MPa. The ACI 318 provisions are based on experimental research [22].

The European code provisions for deflection control are based on a parametric study of flexural members with rectangular cross sections. According to Eurocode 2 (EC2), using the slab thickness with the span-to-thickness ratio given by Eq. (1) will be adequate for avoiding deflection problems in normal circumstances [23]:

$$\frac{L}{d} = k\left[11 + 1.5\sqrt{f_c}\frac{\rho_0}{\rho} + 3.2\sqrt{f_c}\left(\frac{\rho_0}{\rho} - 1\right)^{3/2}\right] \quad (1)$$

where L is the span, d is the effective thickness, k is the factor dependent on the structural system type, taken as 1.2 for flat slab; ρ_0 is the reference reinforcement ratio, taken as $0.001\sqrt{f_c}$; ρ is the required tension reinforcement ratio at mid-span to resist the moment due to the design loads. For flat slabs where the greater span exceeds 8.5 m, the value of L/d given by Eq. (1) should be multiplied by $8.5/L$. The expression (1) works for $\rho \le \rho_0$. In case $\rho > \rho_0$ the formula for L/d will change a bit as given in [23].

Regarding the Australian concrete code AS 3600, the provision for the span-to-thickness ratio for control of the total deflection of flat slabs can be expressed as [24]:

$$\frac{L_{ef}}{d} \le k_3 k_4 \left[\frac{(\Delta/L_{ef})1000E_c}{(1+k_{cs})g + (\psi_s + k_{cs}\psi_l)q}\right]^{1/3} \quad (2)$$

where L_{ef} is the effective span, taken as the lesser of $(L_n + D)$ and L; d is the effective thickness, k_3 is taken as 0.95 and 1.05 for flat slabs without and with drop panels respectively; k_4 is taken as 1.75 and 2.1 for end span and interior span, respectively; E_c is the modulus of elasticity of concrete, in MPa; g and q are the characteristic dead load and live load per unit area respectively, in kN/m^2. The deflection limit (Δ/L_{ef}) is taken as 1/250. The factor k_{cs} takes account of the additional long-term deflection due to creep and shrinkage, depending on the ratio of the compression reinforcement area and tension reinforcement area at midspan, being equal to 2 when compression reinforcement is not used. The short-term factor ψ_s and long-term factor ψ_l for offices, residential and domestic floors are taken as $\psi_s = 0.7$ and $\psi_l = 0.4$ [29].

3.3 Determination of Floor Response to Walking

A common deterministic approach to estimating the floor response to walking excitation is to perform a time history analysis where the floor model is subjected to a standardized walking load function. This approach requires the body weight and step frequency of the pedestrian, which characterize the walking load function, to be pre-selected [8-10]. However, the response evaluation method utilized in this paper is based on a comprehensive European guideline on floor vibration design which follows a probabilistic approach [11,12]. In the development of the European floor vibration guideline, statistical data on the step frequency and body weight of actual pedestrians were collected. The guideline then performed time history analyses of a series of single-degree-of-freedom systems with various natural frequency, mass, and damping values. Each system was subjected to 700 load cases that were generated from 700 combinations of the step frequency and pedestrian weight. The root-mean-square velocity (V_{RMS}) response to each load case was calculated. The cumulative distribution of V_{RMS} values from 700 load cases can then be determined. The 90% upper limit of V_{RMS} was obtained and defined as the one-step root-mean-square-90 value, OS_RMS$_{90}$, after being normalized to a reference velocity of 1 mm/s. For example, an OS_RMS$_{90}$ of 0.2 indicates that the 90th percentile V_{RMS} is 0.2 mm/s. The above procedures resulted in a system of design charts where the OS_RMS$_{90}$ value and its association to perception classes A to F can be read off based on the natural frequency, modal mass and damping of the floor. Each point in a design chart is based on the statistical evaluation of 700 combinations of pedestrian weight and step frequency. Fig.2 provides an example for such a design chart for a damping ratio of 3% [12]. Using such a pre-calculated chart, designers can estimate the floor response based on the modal properties of the floor without having to perform multiple time history analyses.

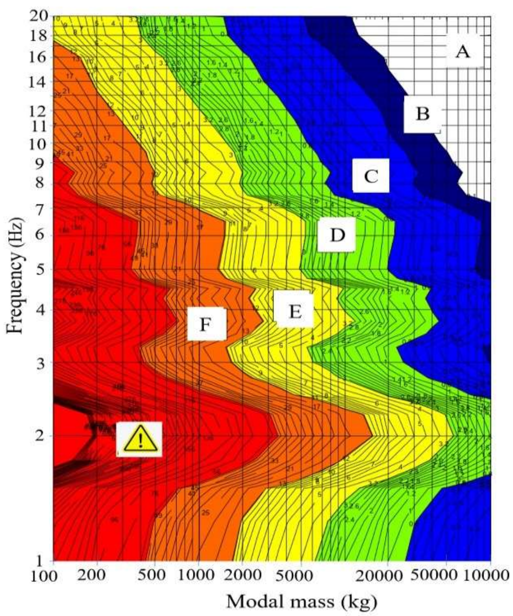

Fig.2 Design chart for 3% damping [12]

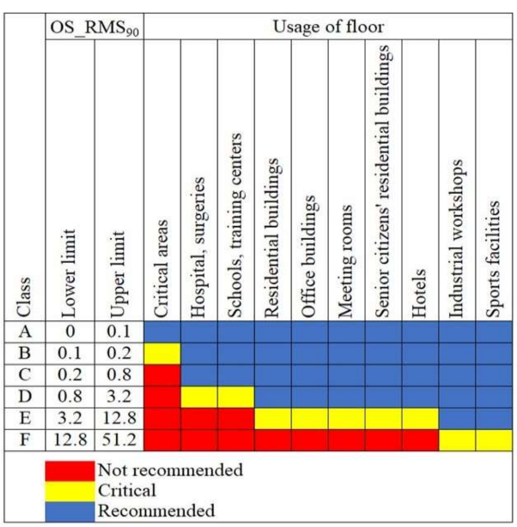

Fig.3 Allocation of perception classes [12]

In addition, the European guideline has recommended the allocation of perception classes to comfort classes for various floor functions as shown in Fig.3. For example, a vibration level corresponding to classes D, C, B or A is considered acceptable for general office areas and residential buildings while only class A is recommended for critical areas.

4. RESULTS AND DISCUSSION

4.1 Thickness of Concrete Slab

While the slab thickness can be determined easily using ACI 318, the selection of the slab thickness using Eq. (1) as per EC2 required an iterative process involving estimation of the thickness and determination of the bending moment and reinforcement of the slab. It should be noted that the ultimate load combination ($1.35g + 1.5q$) was used when computing the reinforcement of the slab based on EC2 [23]. Moreover, since compression reinforcement was not provided at midspan of the slab, the parameter k_{cs} in Eq. (2) was taken as 2 when determining the slab thickness based on AS 3600. Table 1 presents the slab thickness calculated for different span lengths according to the American, European and Australian concrete codes. It can be seen that the slab designed as per the Australian concrete code was 24-31% thicker than the slab designed in accordance with the American concrete code and 31-36% thicker than the one designed using the European concrete code, for the same span length.

Table 1 Slab thickness

L (m)	D (mm)		
	ACI 318	EC2	AS 3600
6	180	165	225
7.5	230	210	285
9	275	275	300

4.2 Modal Properties of Floors

For each case study floor, a modal analysis (eigenvector analysis) was run in SAP2000 to determine the free-vibration mode shapes and frequencies. Eigenvector analysis involves the solution of the generalized eigenvalue problem:

$$[\boldsymbol{K} - \boldsymbol{\Omega}^2 \boldsymbol{M}]\boldsymbol{\Phi} = \boldsymbol{0} \quad (3)$$

where $\boldsymbol{K}$ is the stiffness matrix, $\boldsymbol{M}$ is the diagonal mass matrix, $\boldsymbol{\Omega}^2$ is the diagonal matrix of eigenvalues (the square of the circular frequencies), and $\boldsymbol{\Phi}$ is the matrix of corresponding eigenvectors (mode shapes) [27].

The analysis results of a typical floor, which had a span L of 7.5 m and slab thickness D of 210 mm according to EC2, are detailed below. Figs.4-6 depict the first nine mode shapes of the floor with significant participation of the investigated points 1, 2 and 3. The investigated points were found not to engage in modes 10 and higher, hence the inclusion of the first 9 modes was adequate. Table 2 shows the natural frequencies f_i, modal masses M_i, and unity-normalized mode shape values z_{i1}, z_{i2} and z_{i3} at points 1, 2, and 3 respectively, for each of the first nine modes. The z_{i1}, z_{i2} and z_{i3} values were obtained from the mode shapes shown in Figs.4-6 and normalized against the maximum modal displacement of each mode. Modes 1, 5 and 9 were found to be most critical to the interior panel since maximum modal displacements were located at point 3 which was the center of the interior panel. Similarly, modes 6 and 7 were most critical to point 1 which was the center of the corner panel while point 2 of the edge panel was seen to engage most in mode 3.

The natural frequencies that are critical to a floor panel can also be verified using an FE simulation of the heel drop impact on the floor. For instance, Fig.7 depicts the response in the time domain and frequency domain of point 3 of the floor with L = 7.5 m and D = 210 mm when point 3 was subjected to a ramp loading function whose magnitude decreased from 1 kN to zero within 0.05 seconds. The floor response in the time domain was resulted from a time history analysis carried out in SAP2000. The corresponding response spectrum in the frequency domain, which was obtained using a Fourier transform, clearly shows 3 peaks at frequencies of 7.5 Hz, 8.4 Hz, and 10 Hz which were the natural frequencies of modes 1, 5 and 9 previously found by the modal analysis. This observation verified that the vibration of the interior panel was most contributed by modes 1, 5 and 9.

Table 2 Modal properties (L = 7.5 m, D = 210 mm)

Mode i	f_i (Hz)	M_i (kg)	z_{i1}	z_{i2}	z_{i3}
1	7.5	33480	0.48	0.11	1.00
2	7.5	67620	0.00	0.99	0.00
3	8.0	60428	0.71	1.00	0.00
4	8.0	60428	0.40	0.28	0.00
5	8.4	56739	0.40	0.62	1.00
6	8.4	65403	1.00	0.00	0.00
7	8.6	60996	1.00	0.79	0.00
8	8.6	60996	0.45	0.30	0.00
9	10.0	88058	0.77	0.90	1.00

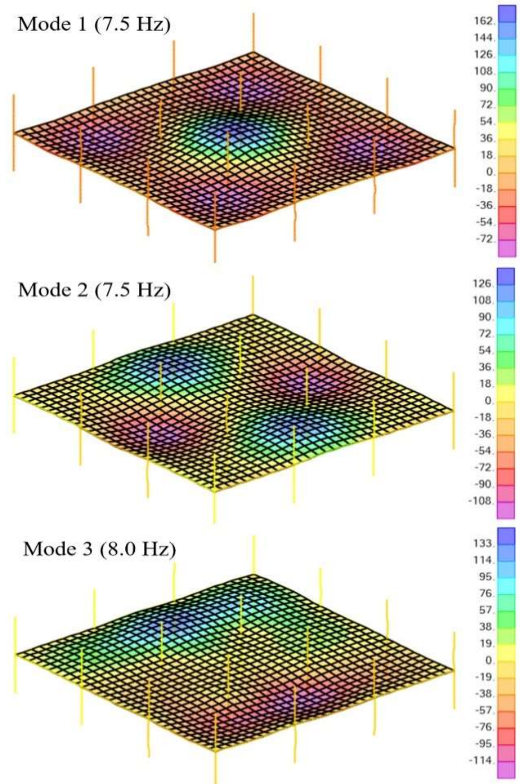

Fig.4 Modes 1, 2, 3 for L = 7.5m , D = 210 mm

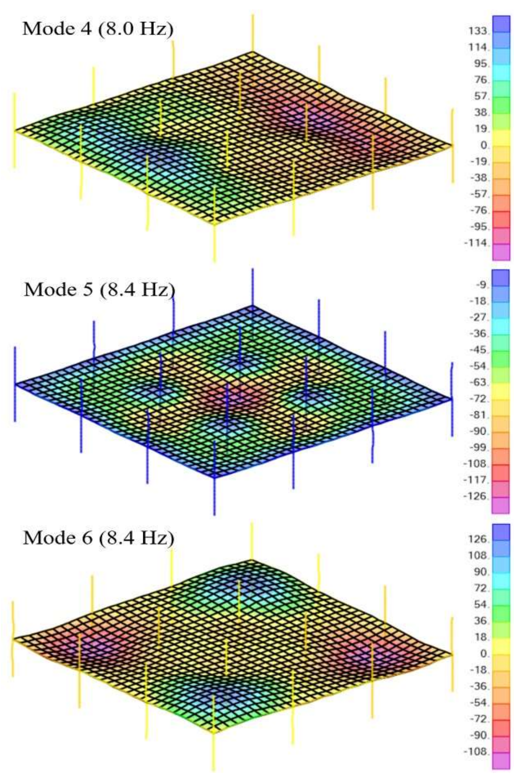

Fig.5 Modes 4, 5, 6 for L = 7.5m , D = 210 mm

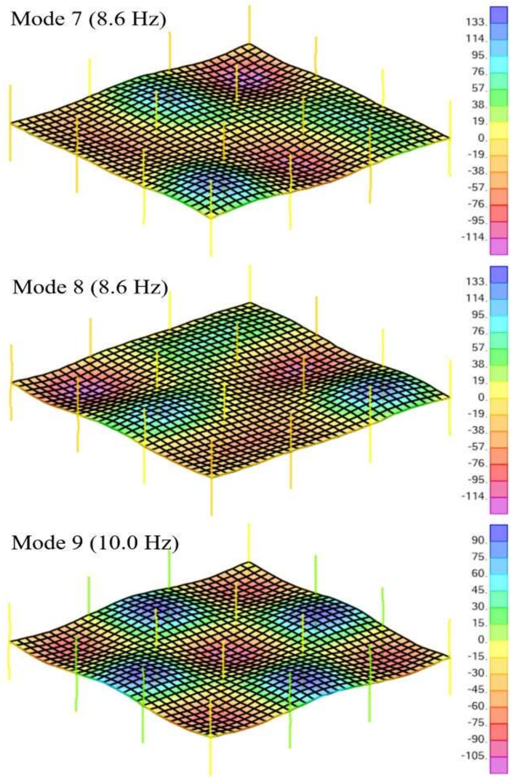

Fig.6 Modes 7, 8, 9 for L = 7.5m , D = 210 mm

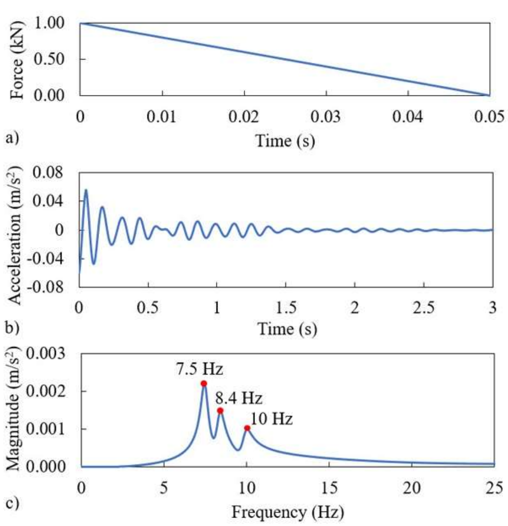

Fig.7 Point 3 response to simulated heel drop

Similar analyzes were performed for all floors whose L and D are given in Table 1. Table 3 summarizes the fundamental natural frequency of the floors with the thickness selected as per the ACI 318, EC2 and AS 3600 codes for different span lengths. It was found that the lowest and highest frequences were associated with the thicknesses based on EC2 and AS 3600, respectively.

Table 3 Floor fundamental frequency

L (m)	f_1 (Hz)		
	ACI 318	EC2	AS 3600
6	10.1	9.3	12.1
7.5	8.0	7.5	9.4
9	6.5	6.5	7.9

4.3 Response Level and Perception Class

In calculating the floor response to walking, the damping ratio ζ was taken as 3% as recommended by current design guides for concrete floors with typical fitout [8-12]. The design chart of Fig.2 was used to estimate the response in each mode of vibration i based on the natural frequency f_i, modal mass M_i, and damping ratio ζ. The total OS_RMS$_{90}$ value can then be determined as a combination of the OS_RMS$_{90}$ values obtained for each mode of vibration, using the square-root-of-sum-of-squares (SRSS) method [12] and considering the modal displacement z of the point of interest:

$$OS\_RMS_{90} = \sqrt{\sum (z\ OS\_RMS_{90})_i^2} \quad (4)$$

Table 4 Floor response: L = 7.5m, D = 210 mm

Mode	OS_RMS$_{90}$		
	Point 1	Point 2	Point 3
1	0.12	0.03	0.25
2	0.00	0.13	0.00
3	0.07	0.10	0.00
4	0.04	0.03	0.00
5	0.05	0.08	0.13
6	0.10	0.00	0.00
7	0.12	0.10	0.00
8	0.05	0.04	0.00
9	0.02	0.03	0.03
Total	0.23	0.21	0.28

Table 5 Total response for all investigated cases

L (m)	Point	OS_RMS$_{90}$ with D selected as per code		
		ACI 318	EC2	AS 3600
6	1	0.23	0.27	0.13
6	2	0.22	0.26	0.12
6	3	0.36	0.49	0.15
7.5	1	0.15	0.23	0.09
7.5	2	0.13	0.21	0.09
7.5	3	0.20	0.28	0.09
9	1	0.20	0.2	0.04
9	2	0.16	0.2	0.04
9	3	0.20	0.2	0.04

Table 4 presents the response in each mode and the total response of points 1, 2 and 3 of the case study floor with L = 7.5 m and D = 210 mm. Similar calculations were performed for all floors whose L and D are given in Table 1. Table 5 provides the total OS_RMS_{90} at points 1, 2 and 3 of the floors whose span was 6-9 m and thickness was selected as per various structural concrete codes.

The perception class of the case study floor was determined based on the maximum total OS_RMS_{90} obtained from the three investigated points of the floor, as illustrated in Fig.8. It can be seen that the vibration level of the floor with a span of 6-9 m and a thickness selected according to either the American or European concrete codes fell into class C which is acceptable for schools, offices, hotels and apartments. When the slab thickness was increased to meet the Australian concrete code, the vibration level was seen to decrease considerably. Fig.8 reveals that the use of a thicker slab for L = 7.5-9 m as per AS 3600 resulted in the vibration level aligned with the perception class A which is deemed acceptable for critical areas.

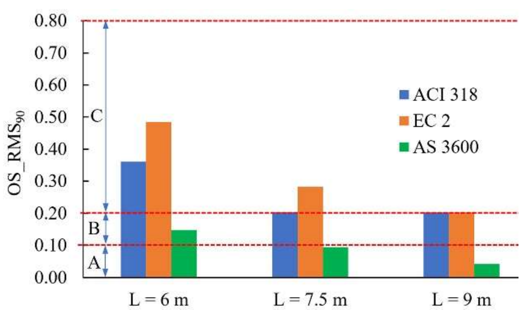

Fig.8 Maximum response and perception class

5. CONCLUSION

In this paper, the vibration level and acceptability of concrete flat plate floors under walking excitation were numerically investigated. The slab thickness corresponding to a span length of 6-9 m was selected based on codified provisions for deflection control. On average, the floor designed according to the European concrete code was found to be 6% thinner than the floor designed using the American concrete code and 34% thinner than that designed following the Australian concrete code. The fundamental natural frequency of the floor designed in accordance with EC2 was 6% lower than that of the floor designed as per ACI 318 and 26% lower than that of the floor designed conforming to AS 3600. Interestingly, when the selection of floor thickness followed any of the three investigated concrete codes, the vibration level of the floor well met the acceptance criteria for human comfort in office buildings, residential buildings, hotels and schools. Moreover, the vibration of a 9-m-span floor can even be acceptable for critical working areas once the thickness was determined using the Australian concrete code provisions. The discussed results correspond to flat plate floors with square panels, concrete compressive strength of 30 MPa, and floor damping ratio of 3%. Future research may consider floors with different aspect ratios and shapes as well as various concrete strength grades.

6. ACKNOWLEDGMENTS

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