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Dynamic response of dancing floor: An example of designing RC floor of a wedding hall

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ABSTRACT

Building new wedding halls has been flourishing as one of the catching investments in Sudan in recent years. These halls typically require large open spaces with no permeant partitions or furniture that reduces the superimposed dead load considerably. This paper presents an example of designing a reinforced concrete wedding hall floor, using two flooring systems, namely, flat slab and two way solid slab considering dancing induced dynamic load. Firstly an initial sizing based on only dead and live load was carried. The dynamic response was assessed following three methods: 1) the fundamental frequency limit; 2) equivalent static load; and 3) the acceleration limit. The results of the dynamic assessment has shown that a little to no-design alteration has to be made in the concrete flooring systems to satisfy safety. However, problems of vibration perception and comfort may require further structural adjustment to meet the acceptable level of vibration in the project specification based on the anticipating floor usage.

1 Introduction

In recent years, the construction of new wedding halls has become a lucrative investment in Sudan. These halls are in high demand due to the limited space in houses and other venues, as well as the growing need for spacious areas to accommodate large wedding ceremonies. Typically, these halls are designed with large spans and thin floors to create open spaces without partitions or furniture [1]. However, this design approach poses a risk of vibration-related failure if human-induced vibrations are not properly considered [1].

Human-induced vibrations can cause annoyance and discomfort to occupants of the structure [2, 3]. In extreme cases, such as when a large group of people engages in rhythmic activities and synchronized dancing, these vibrations can lead to significant damage or even catastrophic failure of the floor [1]. Past experiences have shown that concrete building

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structures with large crowds have encountered various vibration problems and failures, some of which are summarized in Table 1. These failures have resulted in injuries and loss of life for the occupants.

Therefore, it is crucial to emphasize the importance of conducting a comprehensive dynamic analysis of floor slabs during the structural design phase, particularly when they will be subjected to crowd rhythmic activities [2]. By considering the potential effects of human-induced vibrations, designers can ensure the safety and structural integrity of wedding halls and other similar structures [1, 4]. This study aims to address this issue by investigating the dynamic behaviour of floor slabs under crowd loads and providing guidelines for their design to mitigate vibration-related risks. The novelty of this work lies in its focus on the specific challenges posed by crowd rhythmic activities and its contribution to improving the safety and reliability of reinforced concrete floor slabs in wedding halls in Sudan.

Table 1Cases of failure or vibration problem in concrete floors.

Type of building and location	**Date**	**Type of construction**	**Consequences /Cause**	**Complaints form**	**Solution implemented**
Apartments/housing 1.Texsa,USA [5]	2017	Composite floor	A dancing party caused the partial collapse of the thirdfloor	Occupant below, Safety	Relocation* and rebuilding the collapsed section
Concert Hall-USA [6]	1992	Composite floor	Un comfortable vibrations during dancing. The shutteringwasremovedfrom the floorbeneath a dance and social hall.	Occupant, Participants	Installation of vertical and inclinedcolumns. Strengthening of the main beams.
Concert Hall-Israel [7]	2001	Unsafe light-weightcoffered concrete	The thirdfloor of a 4-story building collapsed. 23 people died and 356injuredduring a wedding.	Safety, Occupants	Demolition of the building
Concert Hall- USA [8]	2014	Composite floor	Pop concert/ movements and visible crack	Safety occupants and participants	Relocation*
Dance floor (concert venue) -USA [9]	2014	Reinforcedconcrete	Plasterfellfrom the ceilinginjuring 3 people.	Participants, safety	Relocation*
Dance floor (night clubs) -Spain [10, 11]	2017	Reinforcedconcrete	Collapse injuring 40 people	Occupants, participants, safety	Complete collapse
Dance floor (night club) -Spain [12]	2018	Reinforcedconcrete	Ceiling collapse injuring 26 people.	Participants, Safety	-

*Relocation of activity: Either the source of vibration (e.g., aerobics or machinery) or the sensitive occupancymayberelocated. For example, a plannedaerobicsexercise area mightberelocatedfrom the top floor of a building to the ground or first floor or placingthemnear a column **[**13**]**.

2 Background

The dynamic loads due to human activities were first considered in the British Standards in 1984, version BS6339 Part -1. It was represented by a static live load of 10 kN/m^2 which is equivalent of twice the static imposed load given in the previous CP3 code [4]. In 1985, National Building Code of Canada stopped specifying frequency limits for avoiding resonance response and recommended performing dynamic analysis for floors subjected to dancing loads of fundamental frequency below 6 Hz [14]. In 1990, the 6 Hz limit was abandoned and a design criterion was proposed to determine minimum fundamental natural frequency considering the acceleration limits, forcing frequency, and the weight of the floor [15]. For dance and concert halls without fixed seating, allowable floor frequency was proposed to be higher than the frequency of the second harmonic of the dynamic force from a group dancing with a loading frequency of 3.0 Hz [16]. In the 1996 version of the BS 6399: Part 1 a new clause was added stating that to avoid resonance effects, the vertical natural frequency should be greater than 8.4 Hz [17]. The approach to designing for dance type loading used in BS6399 Part 1 1996 (2002 edition) was then used in the Eurocode [18]. The minimum fundamental natural frequency limits given above are aimed at reducing the probability of adverse comments due to human-induced vibrations. The limit minimizes the likelihood of resonant when the excitation frequency coincides with the harmonic components of the natural frequency of the floor slab. It does not, however, give any indication of the level of floor response in service condition [19].

3 Methods of the floor dynamic response

Three methods will be discussed in this paper to assess whether the floor is adequate for use as a wedding hall with dancing activities or not. The first method is the fundamental frequency limit which is the most popular method of avoiding resonance between the loading frequency and fundamental natural frequency of floor. The second method is the equivalent static load method which assumes resonance has already occurred, and estimates the additional loads on the floor resulting from resonance of fundamental frequency with one of the dynamic loading first six harmonics. In the third one the acceleration limit is calculated by performing a full dynamic analysis on the floor using a finite element method, to determine the maximum acceleration on the floor and compare it to the design limits. These methods are discussed in the following subsections.

3.1 Fundamental frequency limit

According to BS 6399-1, if the fundamental frequency of the floor exceeds 8.4 Hz [17], the floor may be considered insensitive to resonant effects in the case of ultimate limit state design condition, but not necessarily in the of serviceability limit state design [19]. Where the floor cannot be designed to have a minimum fundamental frequency of 8.4 Hz, it should be designed to resist the anticipated dynamic loads, which should be considered as an additional imposed load case. In this section some simple calculations methods of the fundamental frequency are presented.

3.1.1 The static deflection method

One of the simplest and most common methods that is used for regular floorplates. It assumes that the fundamental frequency is equal to the natural frequency of a single simply supported beam [15]. The fundamental natural frequency f_n (in Hz) is calculated as function of mid-span deflection Δ of the member relative to its supports as a result of dead load and some percentage of the live load, Equation 1.

$$f_n = \frac{18}{\sqrt{\Delta}} \tag{1}$$

3.1.2 Concrete society simplified and approximate method

This method is more accurate as it incorporates the stiffness and mass contribution of adjacent bays for floors with an adjacent row of parallel bays [20]. The frequency is calculated using Equation 2 where K_{fm} and K_f are multipliers, D_y is the stiffness of the floor in the long direction, m is the mass per unit surface area of the slab, and L is the span length.

$$f_n = K_{fm}\mathrm{K}_f\sqrt{\frac{D_y}{mL^4}} \tag{2}$$

3.1.3 Steel Construction Institute (SCI) formulas for isotropic plates

The first natural frequency of a two-way slab is likely to be in the form of a one-way slab deflecting in a cylindrical form. For column-supported structures, a two-way action resists the applied transverse loads, and the first mode of vibration can be that of a one-way strip [21]. This formula is given in Equation 3 where b is the span length in X-direction is, E is the modulus of elasticity, h is the slab thickness (mm), ν is Poisson's ratio, and m is the mass per unit surface area of the slab.

$$f_n = (1.57\ /\ b^2)\sqrt{\frac{Eh^3}{12\,m(1-\nu^2)}} \tag{3}$$

3.1.4 Dunkerley approach

This approach is used for calculation of natural frequency of solid slab systems, where the presence of beams creates complex mode shapes. The Dunkerley approach is an approximation for the case that the relevant mode shape is complex and can be considered as a superposition of simple modes, for which the natural frequencies can be determined, Equation 4 [1]. f_1 is the composite beam and a plate mode with the frequency; f_2 is the floor plate frequency.

$$\frac{1}{f}=\frac{1}{f_1}+\frac{1}{f_2} \tag{4}$$

3.2 *The equivalent static load*

In this method, the dynamic load has to be assessed to ensure that it is not exceeding the ultimate static impose load. If the equivalent static load of dynamic loads is higher than the factored impose loads, an ultimate limit state design should be carried out to ensure that a collapse due to dynamic load will not occur. The floor should be designed to resist the anticipated dynamic loads due to rhythmic activity, which should be considered as an additional imposed load case with factor of safety of one (i.e. γ_f =1.0) [19]. In these circumstances, the force per unit area can be calculated using the Equation 5, 6 and 7, assuming an appropriate crowd density to the floor. Where $F(t)$is the dynamic load; G is the static weight of participant; $n$is the number of harmonics to be considered 1,2, 3…; $r_n$is the dynamic load factor for the n^{th} harmonic to be considered; $T_P$is the period of dance loading; t is time;ϕ_nPhase angle for the n^{th} harmonic to be considered,$\phi_{1,n}$is the phase angle of the first mode relative for the n^{th} harmonic to be considered,$D_{\delta,n}$is the dynamic amplification factor for displacements for the nth harmonic of the activity frequency, calculated from Equation (7) [19], $\beta$is the frequency ratio (taken as Load frequency/fundamental frequency or $\frac{fp}{f_1}$), and $\xi$is the damping ratio assumed 2% of the critical damping.

$$F(t)=\ G\left[1+\sum_{n=1}^{\infty} r_n\, D_{\delta,n}\sin(\frac{2n\pi}{T_P}t+\phi_n+\phi_{1,n})\right] \tag{5}$$

$$\phi_{1,n}=\frac{-2n\beta\xi}{1-(n\beta)^2} \tag{6}$$

$$D_{\delta,n}=\frac{1}{\sqrt{(1-n^2\beta^2)+(2n\xi\beta)^2}} \tag{7}$$

To determine the maximum force, the activity frequency should be chosen so that one of the harmonics n which corresponds to the lowest frequency of the floor $fp=\frac{f_1}{n}$. This occurs when the harmonic is in phase with the loading cycle. The worst case is when the sine term is equal to the unity. Assuming this is to be the case, to reduce the amount of calculation effort, Equation **Erreur ! Source du renvoi introuvable.**) can be simplified by making the conservative assumption that all of the harmonics peak at the same time [19].

3.3 *Acceleration limit*

The main criterion used in vibration design guides is to limit the peak acceleration as percentage of the gravitational acceleration (%g). Digest 426 [2] gives a recommended peak acceleration 5%g for the passive person, and 18%g for participants after which the vibration becomes disturbing [2]. The AISC Design Guide 11 provides acceleration limit range of 4 to 7%g for rhythmic activities. SCI P354 suggests 3.5 %g for the passive person ,12.7 %g for the participants in the activity is acceptable for dance floors in night clubs, where the loud music and low lighting will reduce the perception and vision [19].

4 Assessment of the dynamic response the RC slab floor of the wedding hall, an example

4.1 *Materials and loadings*

In this example, the following assumption were taken to reduce the complexity of the calculations: i) Concrete is assumed to behave linearly elastic and isotropic, ii) The cladding of building will be assumed to act as simple support preventing any lateral movement [1], therefore, no lateral loads are considered and only the vertical competent of the vibration is considered, and iii) Dead and live load are only considered in the determining of beam and slab sizes while the loading is divided into two phases, static and dynamic phase.

In the first phase, static phase, the fundamental frequency is calculated. The self-weight, finishes and 10% of the imposed load provided by the BS6399-1 are applied. The static imposed load for a concert hall without fixed sitting is 5 kN/m^2, according to BS 6399-1. This is based on the assumption that there is an extreme crowd density case of six persons per square meter [6]. With this approach, there is a small chance that resonance can occur [17].

The second phase is dynamic phase. The dynamic loads are predicted using Equation (5) as per BS 6399-1 which expresses the dancing loads mathematically, as a Fourier series, representing the variation of load with time as a series of sine functions. The BS 6399-1:1996 specifies a value for the contact ratio $\alpha = 0.5$ for rhythmic activities and high impact aerobics [17] and a value of 0.67 to be multiplied by the dynamic load $F(t)$to allow for the lack of perfect synchronization in large crowds [22]. Table 2 provides Fourier coefficients and phase lag for constant ratio of 0.5 [22].

However, when considering dynamic loads, the actual static load appropriate for the activity on the floor should be used, which is taken as 1.67 kN/m^2 for the case of rhythmic dancing activity [19]. The frequency range depends on the type of rhythmic activity and the number of participants in the activity, where BS 6399-1 recommends a range of 1.5 to 2.8 Hz.

Table 2 – Fourier coefficients and phase lag for constant ratio of 0.5 [22].

n	1	2	3	4	5	6
r_n	1.5708	0.6667	0	0.1333333	0	0.05719
ϕ_n	0	$-\frac{\pi}{2}$	0	$-\frac{\pi}{2}$	0	$-\frac{\pi}{2}$

4.2 Initial sizing

The case study floor is reinforced concrete slab proposed for a wedding hall in Sudan. The floor is assumed to not have fixed seating or dead loads other than the self-weight and the finishes. It has a total area of 2414 m^2 (71x34) m. The slab rested on 4.5 m columns, where internal columns dimensions is 300x300 mm, and external columns dimensions is 300x500 mm as shown in Figure 1. Two flooring systems were considered the flat slab system and the solid slab system.

The flat slab system has an initial slab thickness of 260 mm, with edge beams around the parameter of the slab with sections 300x750 mm. Partitions are assumed to be applied only as line loading on the top of the edge beam.

The initial sizing of the solid slab with beams in the two directions (i.e two-way slab) yields a slab thickness of 250 mm and beams cross section of 300x550 mm.

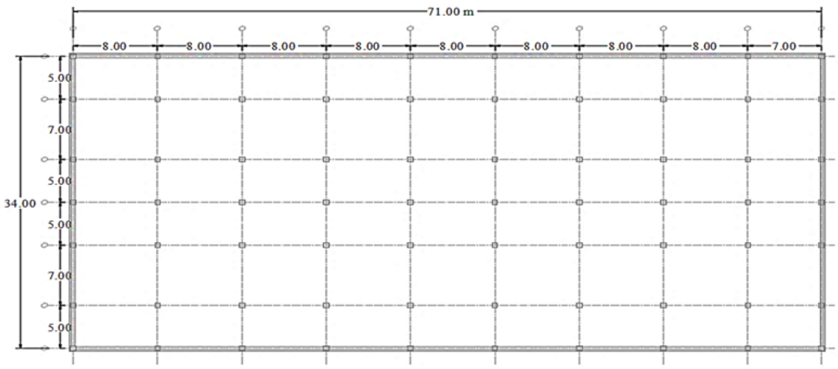

Fig. 1 – The geometry of the wedding hall slab floor

4.3 Finite element modelling of the RC slab dynamic response

The slab is modelled as a planar 3D shell element while the beams and columns 3D wire elements, using ABAQUS finite element (FE) software [23]. The FE software is used for dynamic analysis to obtain natural frequencies and accelerations. CSI SAFE 2016 and SAP2000 are used to confirm the fundamental natural frequency obtained using ABAQUS. The slab beam connections are modelled using general contact property (completely rigid). To ensure full composite action between the slab and beam, an offset distance equal to half the slab thickness have been provided from centre of the slab. The material was defined as elastic concrete using dynamic elastic modulus of 39 GPa, and mass density of 3.2 tons/m^3 (in addition to self-weight the finishes and 10% of the imposed load considered as permeant load). The boundary conditions were applied as pinned at the centre of the column’s heights and around the outer parameter of the floor to take into account the facade effect. It worth mentioning that, Equation (5) has a limit for the number of 64 person or less, therefore, it can only be applied to a limited area of the floor to obtain the most critical loading case. In this case study the largest panel has the dimension of 7x8 m and will be the main focus of study.

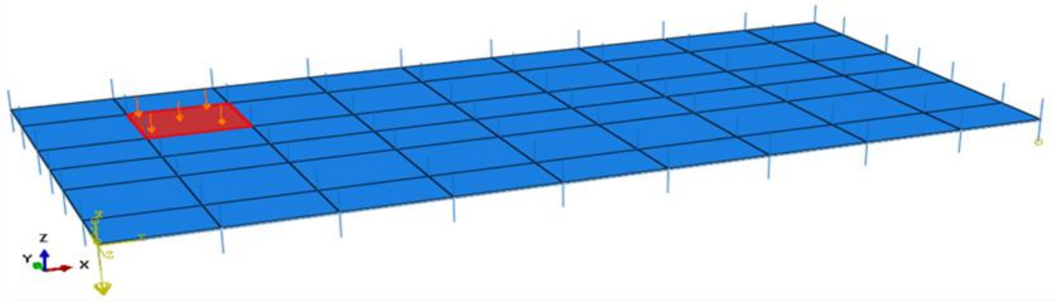

Fig. 2 – Floor slab FE model showing the loads in the critical panel

5 Results and discussions

Firstly, the limit for the fundamental frequency and the equivalent static load to avoid safety problems in floors is considered, both hand calculations methods and various computer software (i.e. ABAQUS, SAFE, and SAP) are used to determine the fundamental frequency in the first mode. For example, Figure 3 shows a 3D FE model of the first mode of vibration using ABAQUS. Then the maximum acceleration is obtained and compared with the limits of vibration design guidelines.

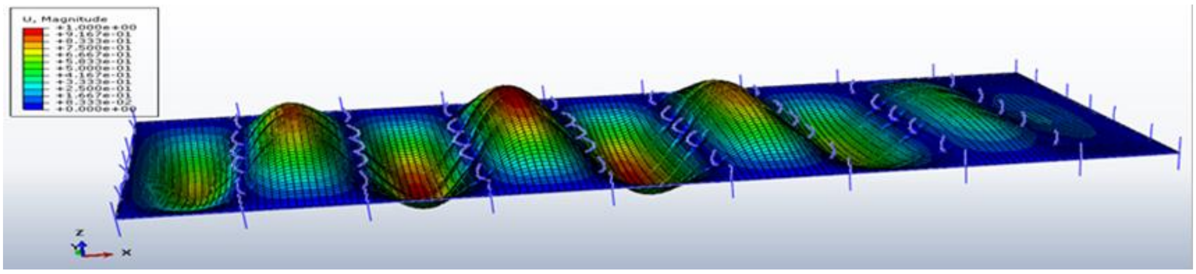

Fig. 3 – 3D FE model results of the first mode of vibration

5.1 Fundamental frequency limit

In this section the method of the fundamental frequency limit is used for the two design options: flat slab and solid slab (i.e. slab with beam).

For flat slab of 260 mm thickness, the calculation using the static deflection method gives a fundamental natural frequency of 6.37 Hz which is less than 8.4 Hz limit [23]. This suggest that the resonance could take place under the dynamic activities such as rhythmic activities such as dancing. Therefore, the fundamental frequency was checked for different slab thicknesses from 260 mm up 350 mm. For each thickness, the natural frequency was calculated using both hand calculations (i.e. SCI, concrete Society method and Static deflection method) and software as shown in Figure 4. The use of software tools like ABAQUS, SAP, and SAFE, along with the concrete society method, has led to the determination of closed fundamental natural frequencies. This suggests that the combination of these methods and tools has been effective in accurately predicting or calculating the natural frequencies. It was found that to fulfil BS 6339 -1 criterion the flat slab thickness has to be increased to nearly 300 mm (11%), as yielded by all methods except static deflection method. Regardless avoiding the resonance, this solution is not an economical option, moreover it leads to the increase of the dead loads on the building.

For the solid slab (i.e. slab with beams), the Dunkerley approach is used to calculate the fundamental natural frequency considering the superposition of the both of beam and slab frequencies. It was found that for beam of 300 mm depth the fundamental frequency of the solid slab is 6.4 Hz (< 8.4 Hz) which suggests the beam depth has to be increased. Then, the fundamental frequency was checked for different beam depths from 300 mm to 750 mm using different approach. The finite element results using ABAQUS shows that the depth of 500 mm will be just adequate with fundamental frequency of 8.55 Hz while SAP gives just a frequency of 8.4 Hz for 550 mm beam depth as illustrated in Fig. . It worth mentioning that the methods other than finite element (i.e. static deflection method and isotropic plate method) do not yield an adequate solution. This design option could be considered is not costly although a reduction in the clear floor height will be the result. The minimum fundamental natural frequency limits mentioned above are set to reduce the likelihood of negative feedback caused by vibrations induced by participants. These limits help minimize the chance of resonance occurring when the fundamental natural frequency aligns with the second harmonic component of the activity [16]. Resonance occurs when an object is subjected to a periodic force that has the same frequency as its natural frequency, leading to increased vibration amplitude and potential structural damage or failure. Therefore, it is crucial to ensure that the natural frequency of a structure is not close to any harmonic components of the activity. However, it is important to note that these limits do not provide information about the actual level of floor response experienced in normal operating conditions.

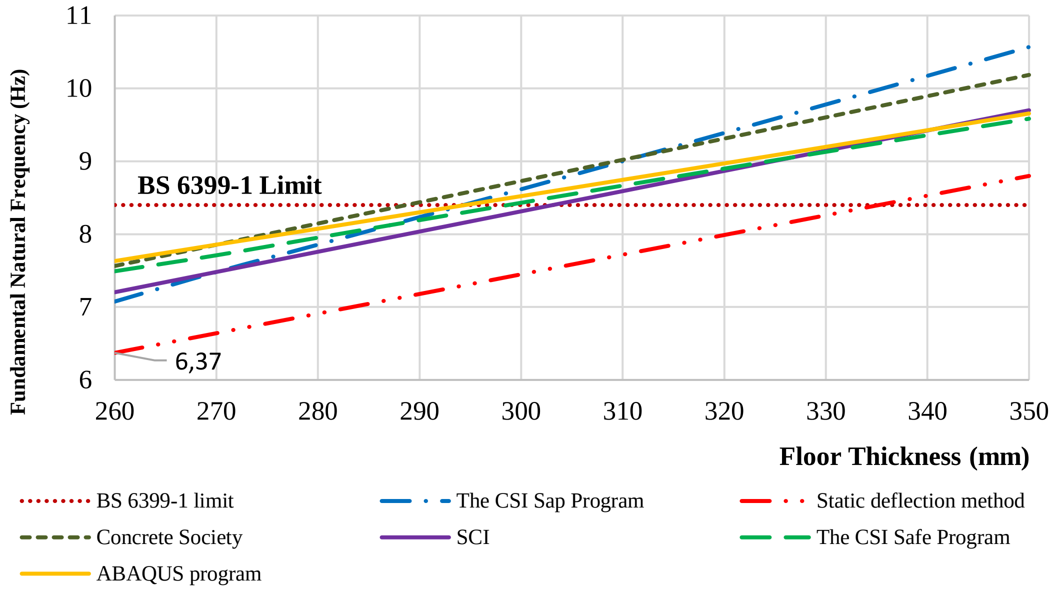

Fig. 4 – Fundamental natural frequency of flat slab for different thicknesses using different calculation methods

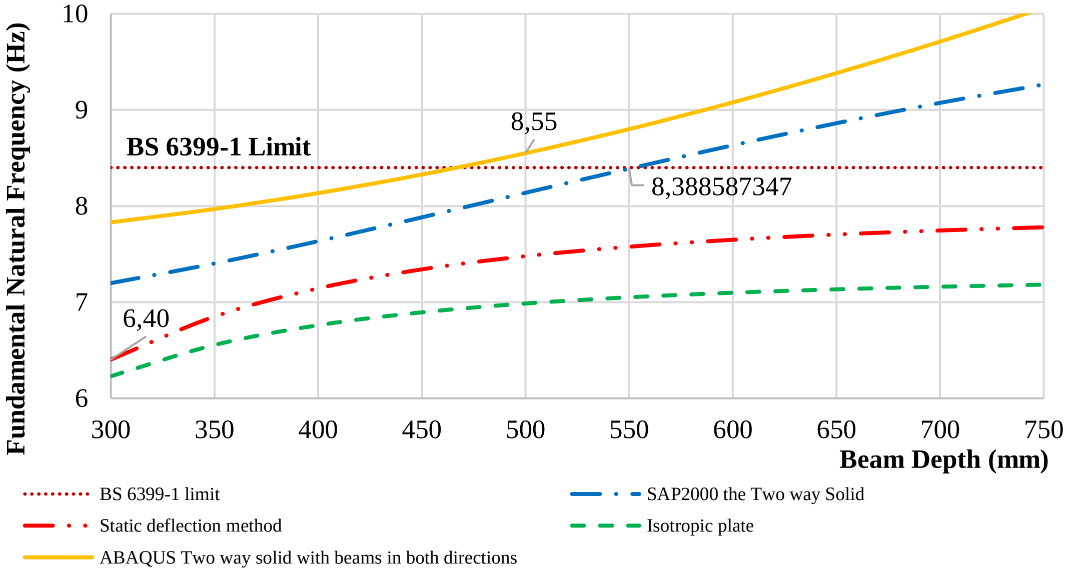

Fig. 5 – Fundamental natural frequency of 250 mm solid slab for different beam depths using different methods

5.2 Equivalent static load

In this method the dynamic response of the slab systems is investigated. **Erreur ! Source du renvoi introuvable.**shows the dynamic load in the cases of flat slab, solid slab, and the case of applying 8.4 Hz in comparison to the SCI equivalent static load and the factored imposed load. The SCI formula assuming the maximum effect when the sine term of the Equation (3) equals the unity, which gives the equivalent static load equals to 6.63 kN/m^2 in this example which is coincided with the peak value for all cases. This value is less than the factored imposed load (i.e. 8 kN/m$^{2)}$ which means that there is no significant displacements or stresses in the ultimate limit state design will likely be generated during the application of the dynamic loads (i.e. dancing). However, this value is greater than the un-factored imposed loads (i.e. 5 kN/m^2) which means the serviceability limit state design has to be conducted to ensure the dynamic loads do not cause issues.

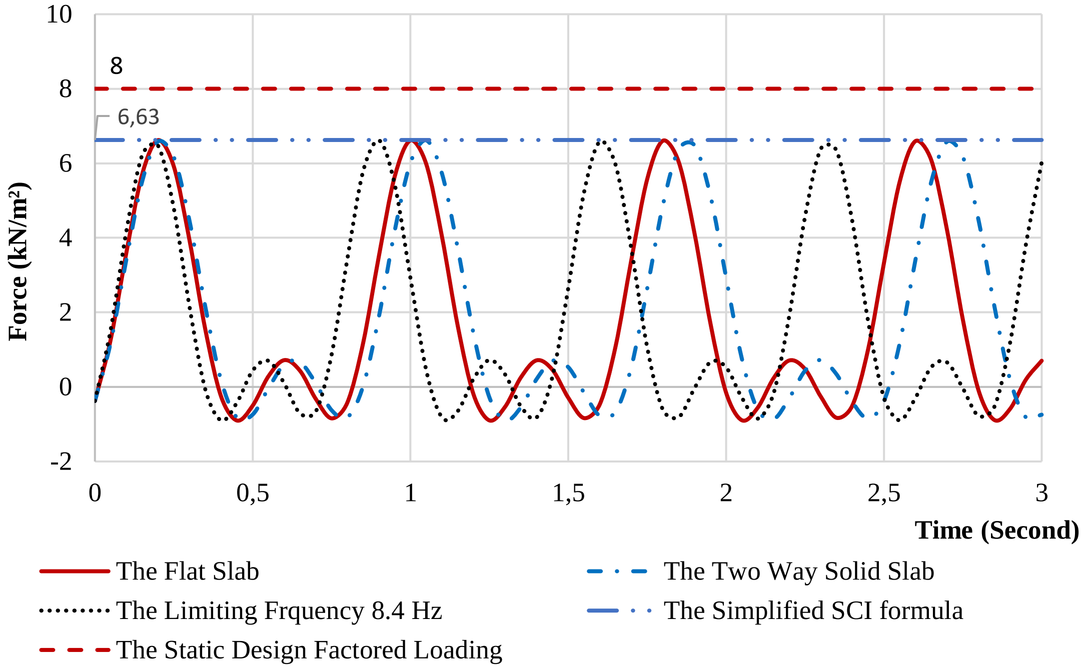

Fig. 6 – The Equivalent Static Design Load for the different flooring systems

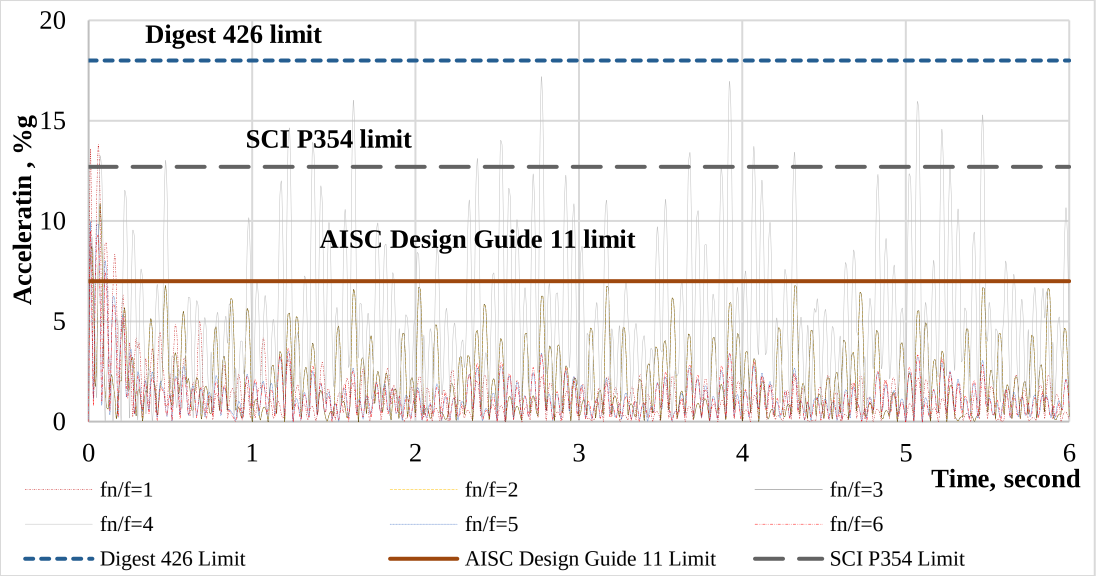

Fig. 7 – Flat slab depth 260mm acceleration response.

5.3 Acceleration limit

From Figure 7, the first three harmonics accelerations are found to be less than the AISC Design Guide 11 limit of 7%g [15]. Although all accelerations are below the Digest 426 limit of 18%g, which means no disturbing effect of the vibration can be expected [2]. Some accelerations are above SCI P354 limit of 12.7%g which means there might be a disturbance in cases of less extreme sound and light imposed on the participants [19]. It was found that, the increase of the flat slab depth to 270 mm fulfils all acceleration limits, Figure 8.

The acceleration response of solid slab flooring systems as % gravity is similar to the flat slab system, as shown in Fig. 9 –, the fourth loading harmonic as in the previous case produce the maximum accelerations. All accelerations are below the Digest 426 limit of 18%g, and SCI P354 limit of 12.7%g which means no disturbing effect of the vibration can be expected [2].

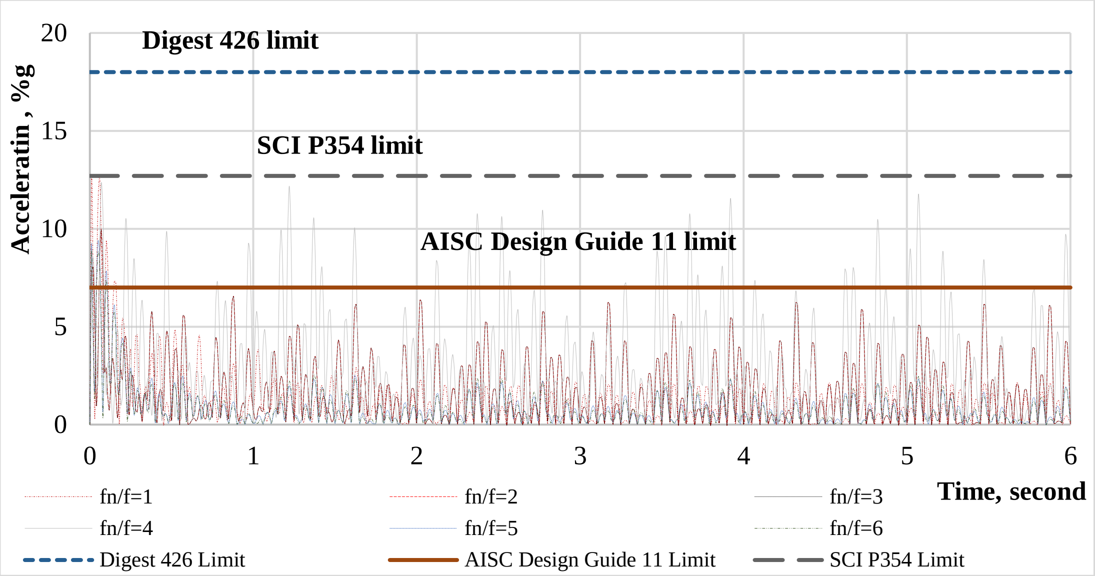

Fig. 8 – Flat slab static design depth 270mm acceleration response

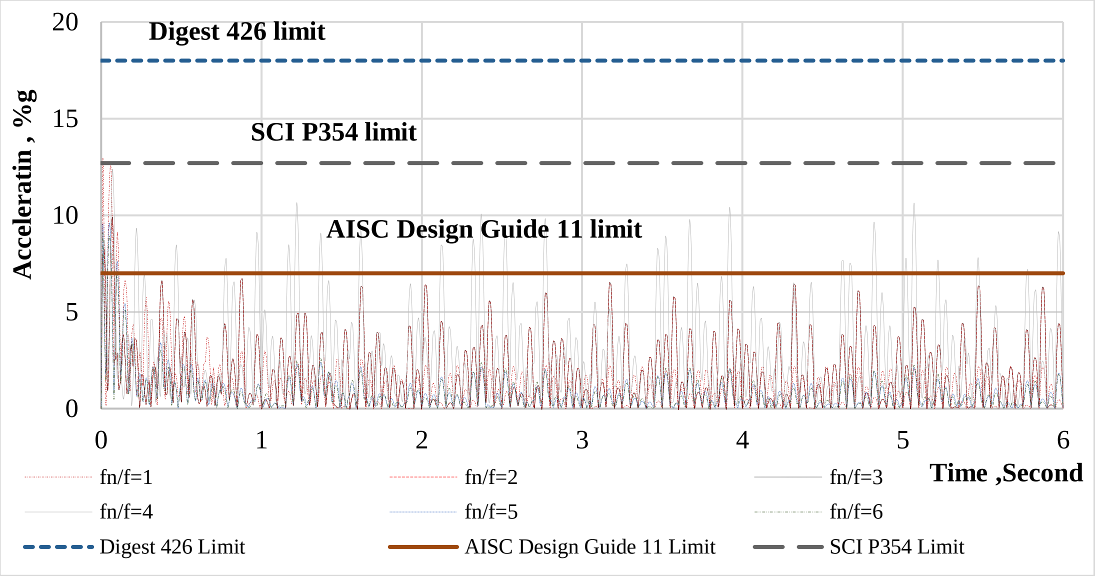

Fig. 9 – Solid slab with beams in both direction acceleration response.

6 Conclusions

Recently, an increase demand for wedding halls has been noticeably increasing specially in Khartoum. Although there are few wedding halls constructed on reinforced concrete (RC) slabs yet the dynamic load induced by dancing is not considered is the design stage. This paper presents an example of design of reinforced concrete wedding hall comparing two floor systems: flat slab and two-way solid slab considering the dynamic response. After initial design of the floor systems for only dead loads and live loads, the dynamic response was assessed considering three methods: the fundamental frequency limit; equivalent static load; and acceleration limit.

The fundamental natural frequency for the two systems is calculated and compared to the BS 6399-1: 1996 dynamic limit. The design was found to be not fulfilling the limit. Therefore, flat slab thickness the two-way solid slab beam depth were increased. This has yielded uneconomical sizes for the two systems.

The equivalent static load under dynamic condition was determined using the SCI P354 formula. This is giving the equivalent static load 6.63 kN/m^2 which is less than the factored imposed load 8 kN/m^2 meaning no significant displacements or stresses in the ultimate limit state design will likely be generated during the application of the dynamic loads. However, the peak value 6.63 kN/m^2 is higher than the un-factored imposed loads 5 kN/m^2 the displacements during serviceability limit state design have to be investigated.

The dynamic analysis using acceleration limit yielded that all accelerations on the flooring systems are below the Digest 426 limit of 18%g. For the flat slab system, the acceleration is below both the SCI P354 limit of 12.7%g and AISC Design Guide 11 limit of 7%g, indicating that some disturbance from vibration can be expected. Increasing the flat depth from 260mm to 270mm will solve this issue. On the other hand, the solid slab with beams in the long direction is below the AISC Design Guide 11 limit of 7%g but above the SCI P354 limit. The SCI P354 (2009) compared to the AISC Design Guide 11 limit (2003) using acceleration criteria established in 1990 by the National Building Code. The acceleration results suggest that no alteration is required in the concrete flooring systems for safety purposes. However, further structural adjustments may be needed to address vibration perception and comfort issues. The project specification should determine the acceptable levels of vibration, taking into account the floor's anticipated usage. The owner's involvement is crucial in deciding whether more stringent vibration criteria should be selected, as it may impact costs. Setting sensible targets for acceptable levels of vibration can guide the design of an economical floor structure tailored to its usage requirements.

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