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Dynamic Response of Composite Floor Slab Under Human Rhythmic Activity

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Abstract

Modern construction structures are built with slender longer spans in an economical manner. Generally slender longer spans create annoyance like Vibration to the occupants. Man induced rhythmic activities like jumping, aerobics, dancing on floor structures lead vibration problems. These vibrations create discomfort to the occupants. The reasons for vibration problems may also be due to decreased natural frequency with increased longer spans and also due to decreased mass and dampness in building. Jumping exercises create periodic force which results in Harmonic overtone. It is recommended that problems related to vibration should be analysed during structural design period itself based on the occupancy usage and if it is required, proper provisions should be given to eradicate such vibration problems. The aim of this paper is to analyse the floor panel which is a composite concrete steel structure of size 12m x 16m. The panels are analysed using ANSYS 11. From ANSYS software, Modal analysis, Harmonic analysis and Transient analysis are done on these panels and the results which are obtained from these panels are compared with various recommendations. From the results it is suggested whether the panel is considered for dynamic analysis under human rhythmic activity like jumping, and dancing is suitable for human comfort.

Key words: Dynamic, Vibration, rhythmic , amplitude, frequency, resonance, ANSYS

Introduction

Sustainability requires multi-storey buildings to be built for different occupancy use. As a result, the large floor span of light weight structures with minimal number of columns is designed. One of the recent trends is the construction of composite panel like structures which prove to have adequate strength but creates vibration problems due to the human induced rhythmic activities like jumping.

In such constructions, some of the problems due to vibrations need to be considered. One such case of structural failure that caused many lives was the collapse of Hyatt Regency Hotel Walkway in Kansas city, US, which happened during a weekend "tea dance" in 1981[13]. In the absence of appropriate theories and information at that time, no one really understood the cause of this destruction.

Another case is the problem occurred at the Millennium Footbridge. On the day that steel bridge was inaugurated, it began presenting lateral oscillations with an amplitude of about 20 cm, along its 345 m long span, due to the action of persons moving on the bridge

This example serves to illustrate the importance of obtaining a correct description of the loads generated by people and the need to take into account in design, the dynamic effects that these loads can generate. The significant growth in building floors subjected to unwanted vibrations is caused by the fact that a significant number of structural engineers disregards, or even do not know how to incorporate the dynamical actions in the structural analysis. This procedure limits current structural designs to a simple static analysis, which, in extreme cases, can compromise the structure behaviour.

The main objectives of this paper are

- To analyse the dynamic floor response.
- To compare the results of panels with various suggested recommendations.

This paper emphasize that a human is allowed to jump and after some time he comes to rest due to natural damping. During jumping, the floor is getting excited and in anyone of the situation if the natural frequency of such floor is matching with the exciting frequency, resonance will occur. The formation of resonance should be avoided or otherwise it leads to fatigue failure of structures.

Previous Research:

Reiher and Meister proposed a scale diagramatic representation describing the human perception and the acceptance levels to continuous vibration.

Lenzen have done many case studies on different structures and modified the Reiher and Meister scale for the floors with damping ratio less than 5%.

C.P.HeinsJr CH.Yoo have undergone a case study on a Maryland state college multipurpose room of the student union building. Their research was based on analytical and experimental and natural frequency of 2-3 *Hz* they got during analysis. They concluded there was a chance of resonance. After experimental studies they suggested the entire supports to be provided along the main girder and columns should be placed at each mid span of the main girder also.

Allen(1990) recommended that human activities like jumping produce periodic forces. These are not sinusoidal but they are in harmonic overtones. He explained that the first, second and third harmonic actions are responsible which may likely to cause resonance.

Faisca (2003) [9] considered the dynamic loads, based on results achieved through a long series of experimental tests made with individuals carrying out rhythmic and non-rhythmic activities. The load modeling is able to simulate human activities like aerobic, gymnastics, dancing and free jumps. In this paper, the hanning function is used to represent the human dynamic actions since it is verified that this mathematical representation is very similar to the signal force obtained through experimental tests.

The mathematical representation of the human dynamic loading is described by Eqn. (1). This expression requires some parameters like the activity period T, contact period with the structure *Tc*, period without contact with the model *Ts*, impact coefficient *Kp*, and phase coefficient *CD*, as shown fig. and Table .

$$F(t) \; = CD\left\{KpP\left[0.5 - 0.5cos\left(\frac{2\pi}{Tc}\,t\right)\right]\right\}, for\; t \leq Tc$$

$$F(t) = 0, for\; Tc < t \leq T$$

Where:
F (t): dynamic loading, in (N);
t: time, in (s);
T: activity period (s);
Tc: activity contact period (s);
P: weight of the individual (N);
Kp: impact coefficient;
C_D: phase coefficient.

Fig-1 illustrates the phase coefficient variation *CD*, for some human activities, initially, considering a few numbers of individuals and later extrapolating for a larger number of people (Faisca, 2003). Figure 5 presents an example of dynamic action related to human rhythmic activities using the following parameters: *T* = 0.53s, *Tc* = 0.43s, *Ts* = 0.10, *Kp* = 2.78 and *CD* = 1.0, as shown in Table.

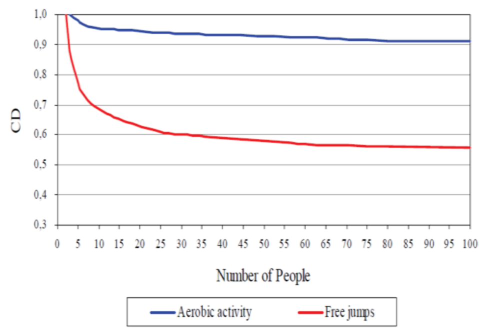

Figure 1: Phase coefficients for the studied activities[9]

Table 1: Parameters used for human rhythmic activities representation

Activity	T (s)	Tc (s)	Kp
Aerobics	0.44 ± 0.09	0.34 ± 0.09	2.78 ± 0.60

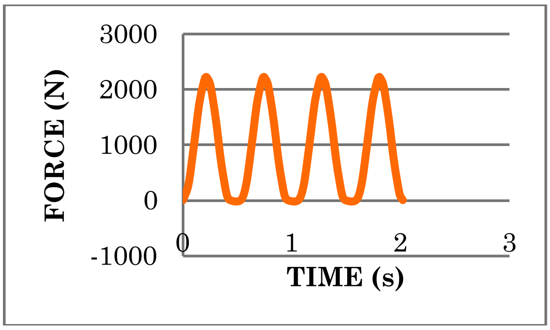

Figure 2: Time Vs Force

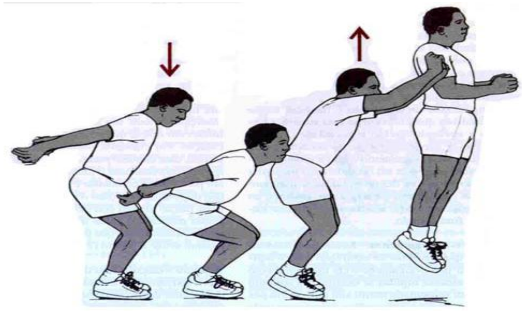

Figure 3: Dynamic Loads Induced by Aerobics Associated to the following Parameters, *T=0.53s, Tc=0.43s, Ts=0.10, KP=2.78 and CD=1.0*

Structural Floor Details

The investigated structural model is associated to a floor composed by steel beams and a concrete slab, and is presented in Fig 4 & 5. The structural system is a typical floor used as an Aerobics floor.

The composite floor system consisted of 16m x 12m with adopted steel sections made with 300 mPA yield stress steel grade[9]. A value of $2.05x10^5$ mPA Young's modulus[9] is used for the steel beams. The concrete slab has 25 mPA specified compression strength and a $2.4x10^4$ mPA Young's Modulus. The structural model geometrical characteristics are shown in Table-2

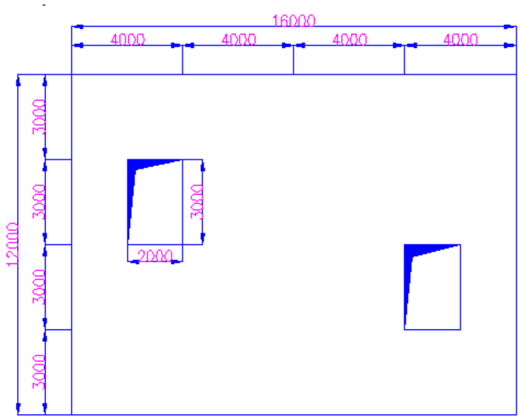

Figure 4: Floor plan Details(All dimensions are in m)

Table 2: Structural Model Geometric Properties

Floor plan dimension	Main member	Secondary member	Concrete topping thickness
16m x 12m	ISMB350	ISMC 150	135mm

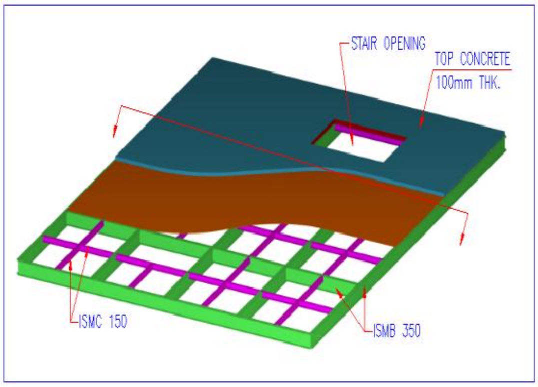

Figure 5: Structural model three-dimensional sectional view

Table 3: Properties of Members[11]

Description	ISMB350	ISMC 150
Weight	514 N	160.9N
Height	350mm	150mm
Area	6671mm^2	2088 mm^2
I_{xx}	13630.0x 10^4 mm ^{4}	779.1x 10^4 mm ^{4}
I_{yy}	537.7x 10^4 mm ^{4}	102.3x 10^4 mm ^{4}

Web thickness	8.1mm	5.4mm
Flange thickness	14.2mm	9.0mm

Finite Element Model Using Ansys

Numerical modeling techniques are powerful tools to stimulate the Engineering structures. Without Numerical techniques, it will be difficult to solve practical structural problems with reasonable degree of accuracy.

In the present study typical composite concrete floor is stimulated in the Numerical model using the Computer Program ANSYS. The details of the Numerical modeling are described below. . The proposed computational model, developed for the composite steel with concrete floor dynamic analysis, adopted the usual mesh refinement techniques present in finite element method simulations implemented in the ANSYS program (ANSYS, 11). In the present computational model, the floor steel beams are represented by three-dimensional beam elements (BEAM44), tension, compression, bending and torsion capabilities. The floor slab is represented by shell finite elements (SHELL63).

In this investigation, it is considered that both materials (steel beam and slab) presented total interaction and have an elastic behavior. The finite element model has 19581 nodes, 21721 three-dimensional beam elements (BEAM44), and shell elements (SHELL63) .

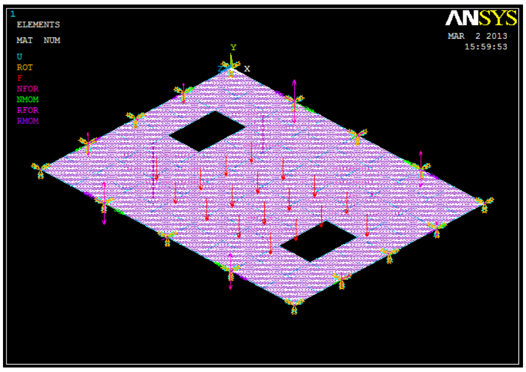

Figure 6: ANSYS FE Model

Element Features: The main elements used in the Finite element modeling are as follows,

- BEAM44 - 3-D Elastic Tapered unsymmetric Beam
- SHELL63 - Elastic Shell
- *BEAM44 - 3-D Elastic Tapered* unsymmetric Beam

BEAM44 is a uniaxial element with tension, compression, torsion, and bending capabilities. The element has six degrees of freedom at each node, translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes.

This element allows a different unsymmetrical geometry at each end and permits the end nodes to be offset from the centroidal axis of the beam. The effect of shear deformation is available as an option, which is not available in other BEAM elements.

Analysis of Floor Model

Introduction

In this present study the numerical model is done using finite element analysis, and it deals with human induced loading and different types of analysis are carried out.

Loading Scheme

The live load considered in this analysis corresponds to one individual for each 4.0m^2 (0.25 person/m^2). The load distribution is considered symmetrically centered on the slab panel, as depicted in Fig- 7. The present investigation also assumed that the weight of an individual person is equal to 800 N (0.8 kN) and the adopted damping ratio is equal to, ξ=3% (ξ = 0.03).

In the current investigation, the human rhythmic dynamic loads are applied to the structural model corresponding to the effect of 2, 4, 8, 10, and 18 individuals practicing aerobics and measured under point A,B and C as in Fig-7. Hence practicing of 18 individual practicing is the full load condition for the numerical model.

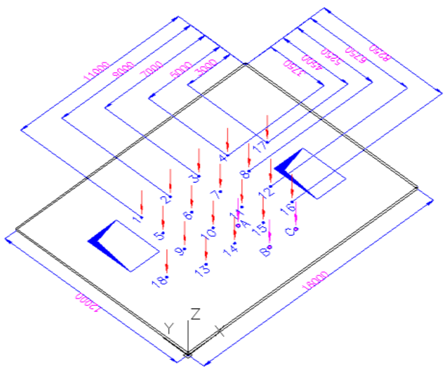

Figure 7: Load distribution Scheme associated to eighteen individuals practicing Aerobics

Methods of Analysis**:** The following analysis are performed for the numerical model,

- Static analysis
- Model Analysis
- Harmonic analysis
- Transient Analysis

Static Analysis

Static Analysis is done to determine the Amplitude; stress induced due to the dead weight and live loads acting on the numerical model is calculated. The following Fig-8. shows the mappings of stress contour, which states that the floor system, is stable and stresses are within the permissible stress limits.

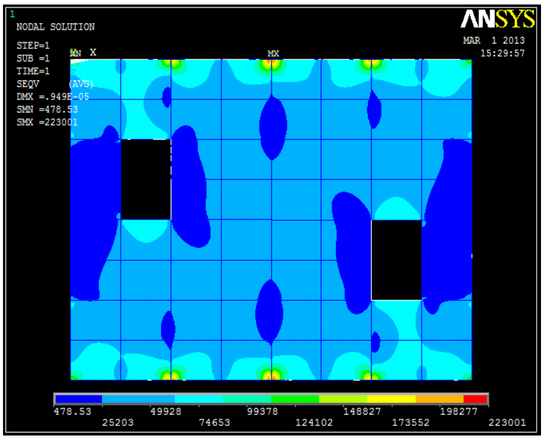

Figure 8: Stress contour Result

Modal Analysis

The natural frequencies of bare steel with concrete floor are determined with the aid of the numerical simulations. The vibration mode shapes for the structural system and the natural frequency values are tabulated. This natural frequency from model analysis are inputs for Harmonic Analysis.

Mode shapes And Natural Frequencies

The natural frequencies for the composite structure are determined with the aid of the numerical simulations. Six mode shape and their corresponding natural frequencies are as illustrated in the following Table 4.

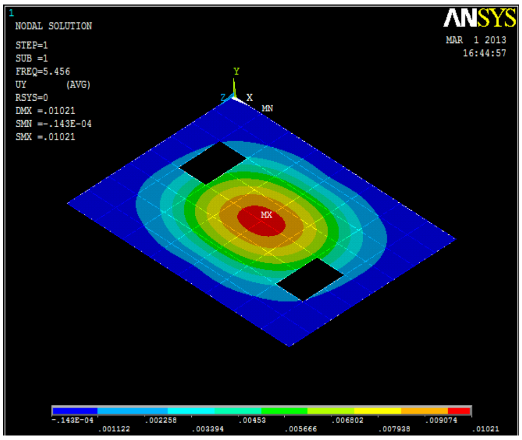

Figure 9: Vibration mode related to the first natural Frequency-5.456Hz

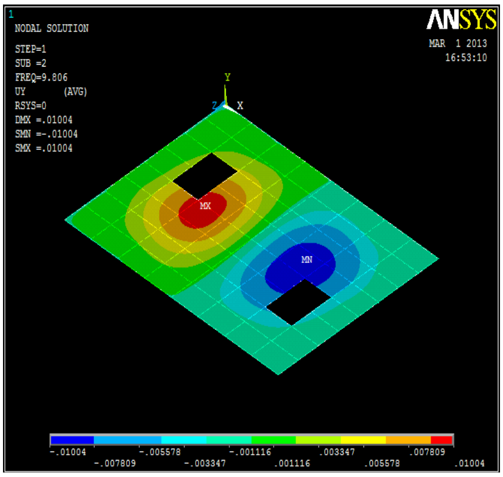

Figure 10: Vibration mode associated to the second natural; frequency: F02=9.806

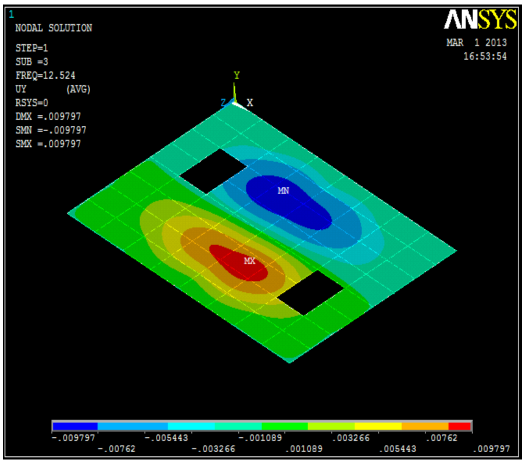

Figure 11: Vibration mode associated to the Third natural frequency: F03=12.524

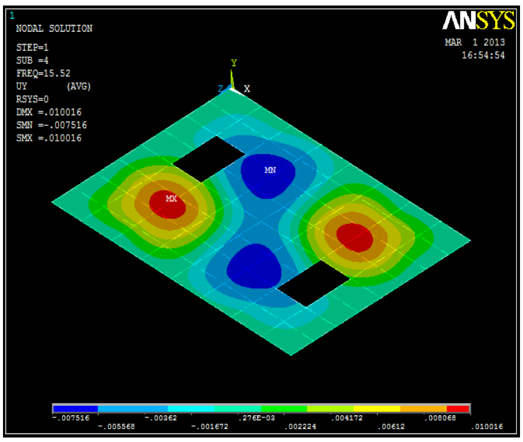

Figure 12: Vibration mode associated to the fourth natural frequency: F04=15.520

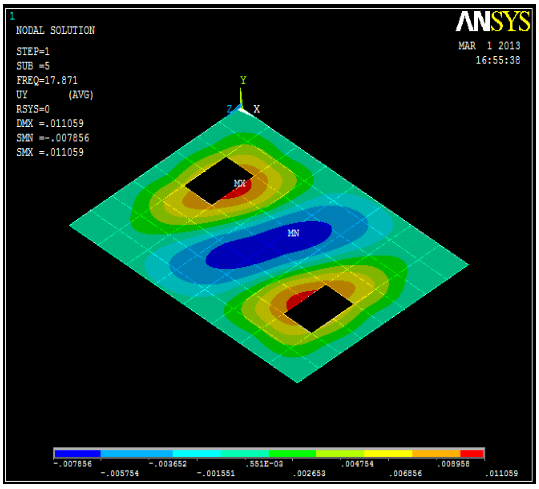

Figure 13: Vibration mode associated to the fifth natural frequency: F05=17.871

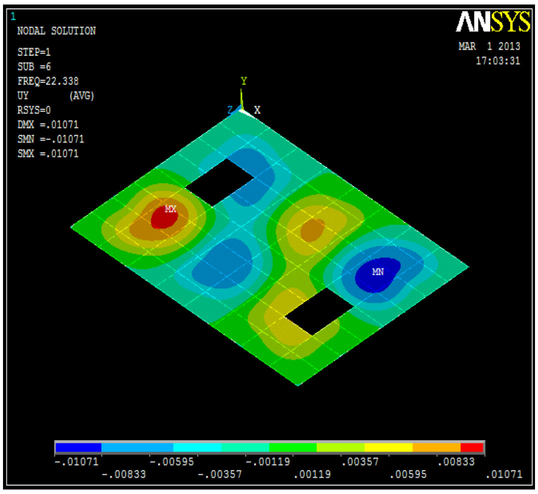

Figure 14: Vibration mode associated to the sixth natural frequency: F06=22.338

Table 4: Mode shapes and their frequencies

Mode shapes	Natural frequencies (*Hz*)
1	5.456
2	9.806
3	12.524
4	15.52
5	17.871
6	22.338

Harmonic Analysis

The Finite Element model of composite floor is subjected to human activities such as (dancing & aerobics). The mode-superposition method available in ANSYS computer program is adopted for the Harmonic analysis, which is advantageous in tracing the harmonic response curve. The FE Model subjected to the forcing frequency range obtained from the modal analysis and corresponding amplitudes are measured. The dynamic response of FE model floor amplitudes are compared by varying number of person's activities.

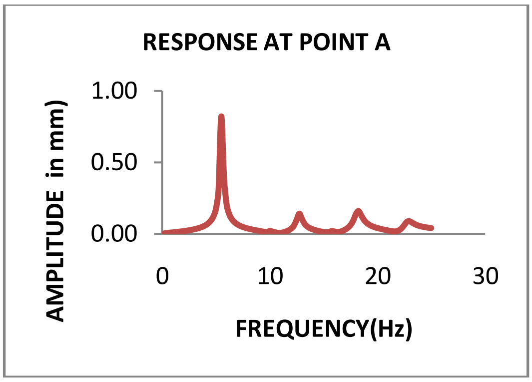

Figure 15: Frequency Vs Amplitude for one person at Measuring Point A

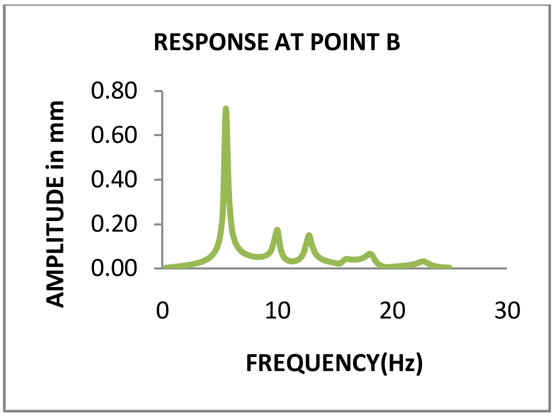

Figure 15: Frequency Vs Amplitude for one person at Measuring Point B

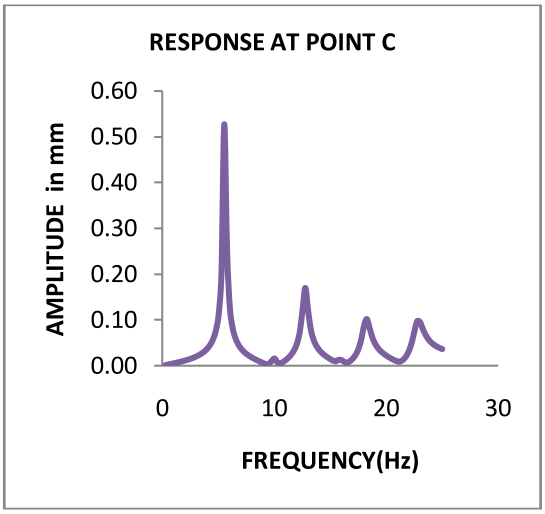

Figure 16: Frequency Vs Amplitude for one person at Measuring Point C

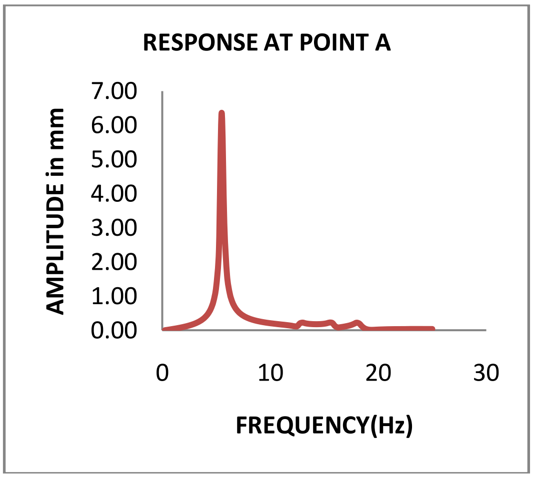

Figure 17: Frequency Vs Amplitude for Ten persons at Measuring Point A

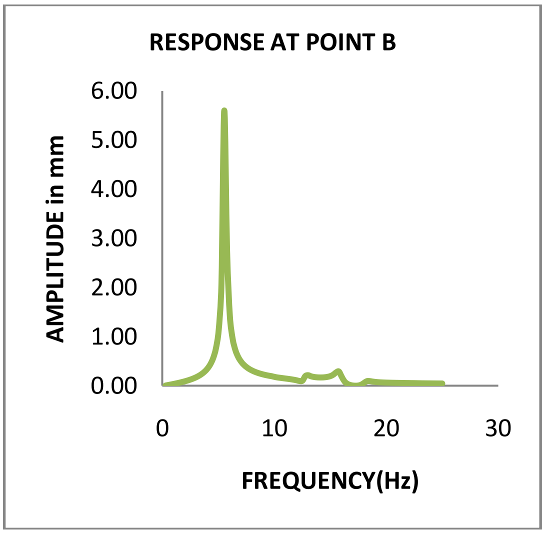

Figure 18: Frequency Vs Amplitude for Ten persons at Measuring Point B

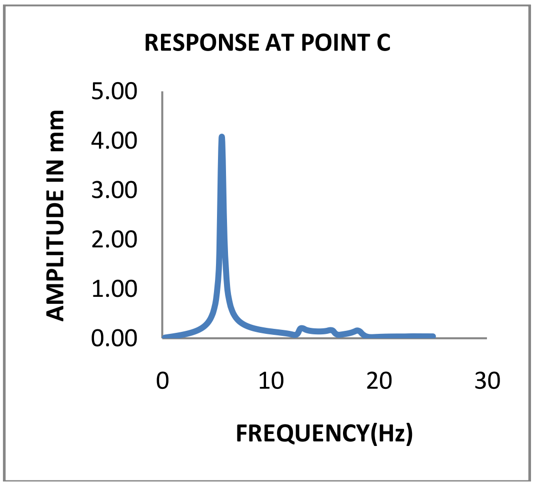

Figure 19: Frequency Vs Amplitude for Ten persons at measuring Point C

Transient Analysis:
The linear time-domain analysis is performed throughout this study. The evaluation is done for the structural systems vibrations levels when subjected to dynamic excitations coming from human rhythmic activities (aerobics and dancing).

The FE model is generated for the steel with concrete floor subjected to transient dynamic loading for a period of 5.2 seconds. The mathematical representation of the human dynamic loading is described by Eqn (1). This expression requires some parameters like the activity period *T*, contact period with the structure *Tc*, period without contact with the model *Ts*, impact coefficient *Kp*, and phase coefficient *CD*[9].

The composite concrete floor dynamic responses is determined in terms of its Amplitudes and accelerations with respect to time. The results of the dynamic analysis are obtained from an extensive numerical analysis, based on the finite element method using the ANSYS program (ANSYS, 2011). The results are tabulated and compared with design recommendations.

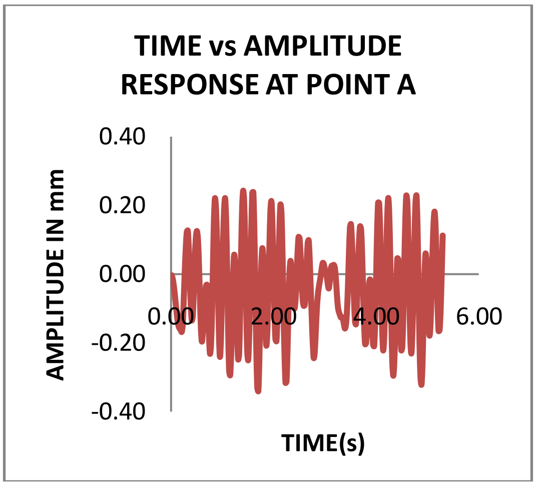

Figure 20: Time Vs Amplitude for One person at Measuring Point A

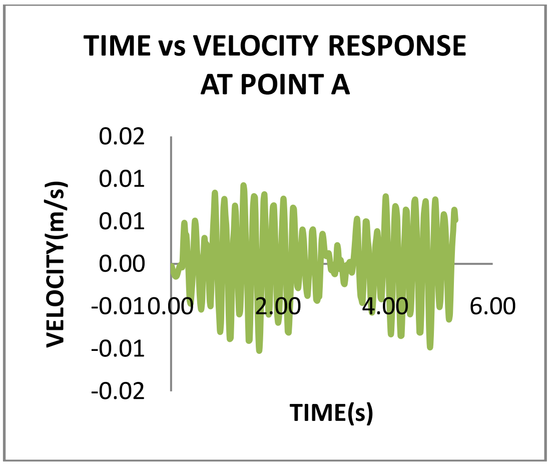

Figure 21: Time Vs Velocity for One person at Measuring Point A

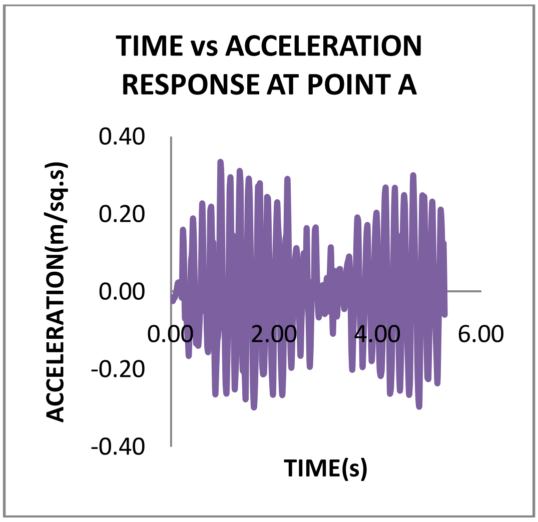

Figure 22: Time Vs Acceleration for One person at Measuring Point A

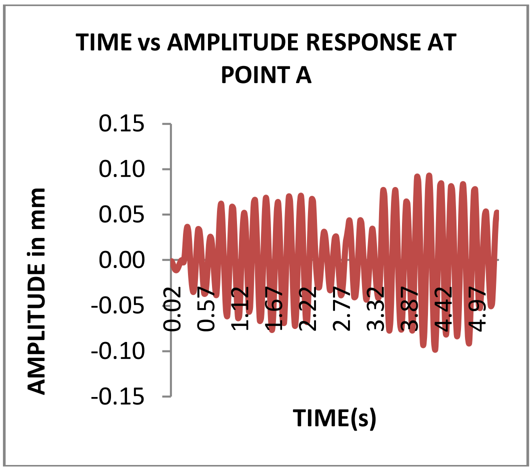

Figure 23: Time Vs Amplitude for Ten persons at Measuring Point A

Table 5: comparison of Harmonic and transient analysis with maximum amplitude

Number of persons	Maximum Amplitude					
	Point A		Point B		Point C	
	H	T	H	T	H	T
1	0.82	0.39	0.719	0.284	0.51	0.214
2	1.64	0.682	1.44	0.585	1.05	0.434
4	3.3	1.35	2.91	1.15	2.12	0.856
8	5.79	2.31	5.1	2.03	3.72	1.47
10	6.35	3.26	5.59	2.88	4.07	2.08
18	10.6	4.09	9.31	3.63	6.78	2.62

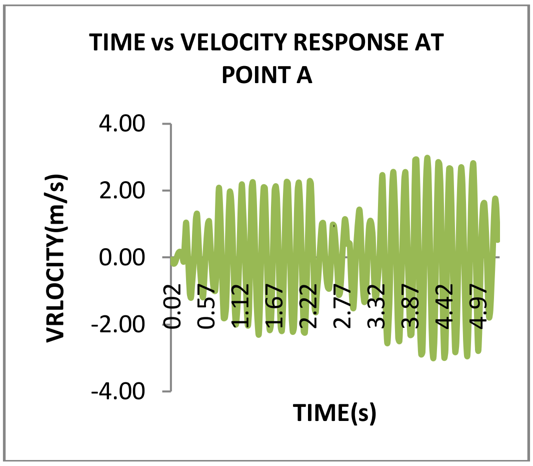

Figure 24: Time Vs Velocity for Ten persons at Measuring Point A

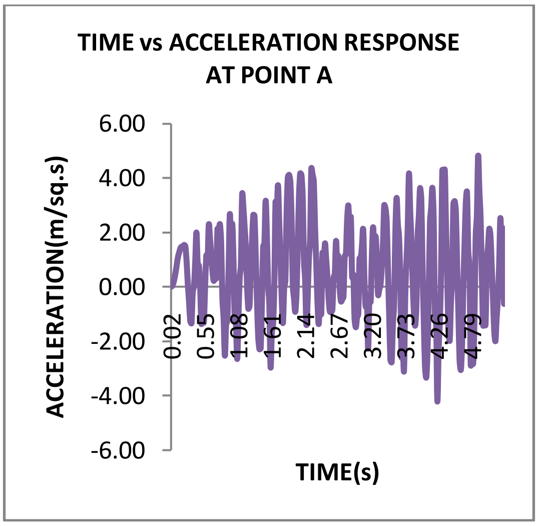

Figure 25: Time Vs Acceleration for One person at Measuring Point A

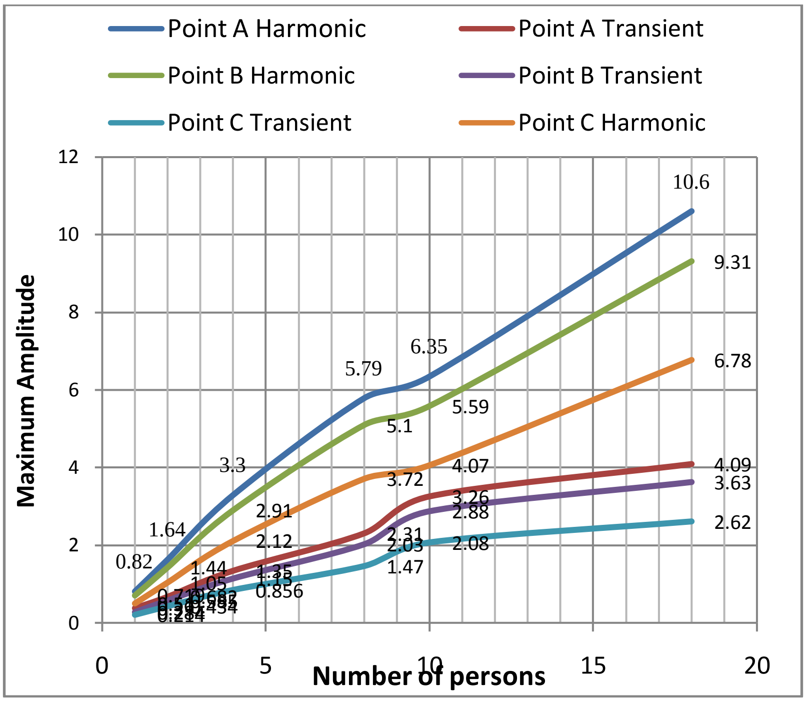

Figure 26: Comparison between harmonic and transient analysis

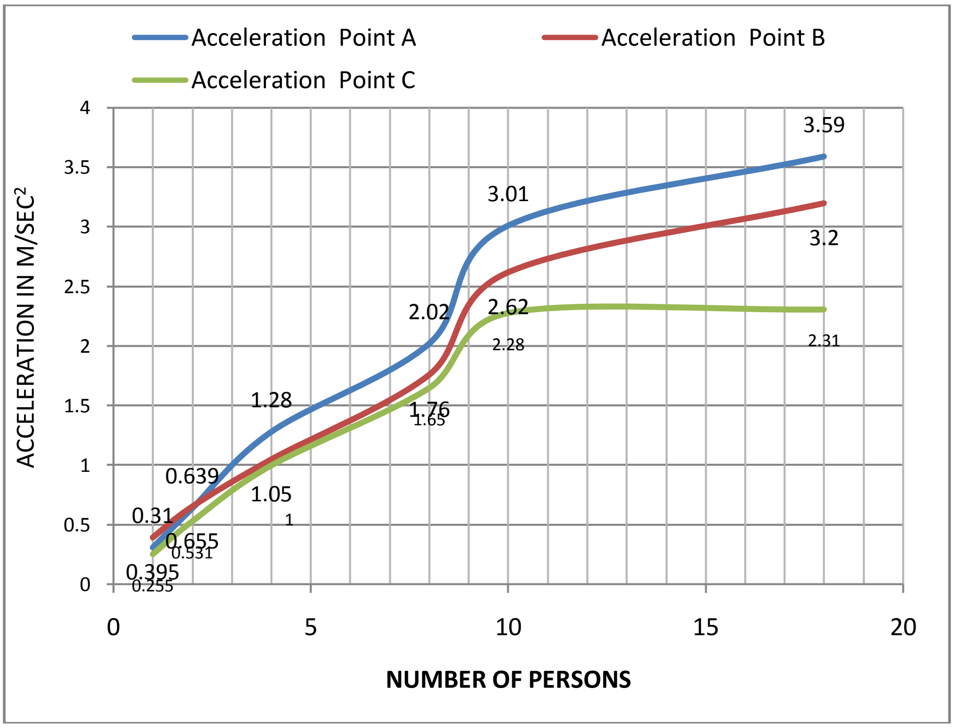

Figure 27: Acceleration Values on Point A, B and C

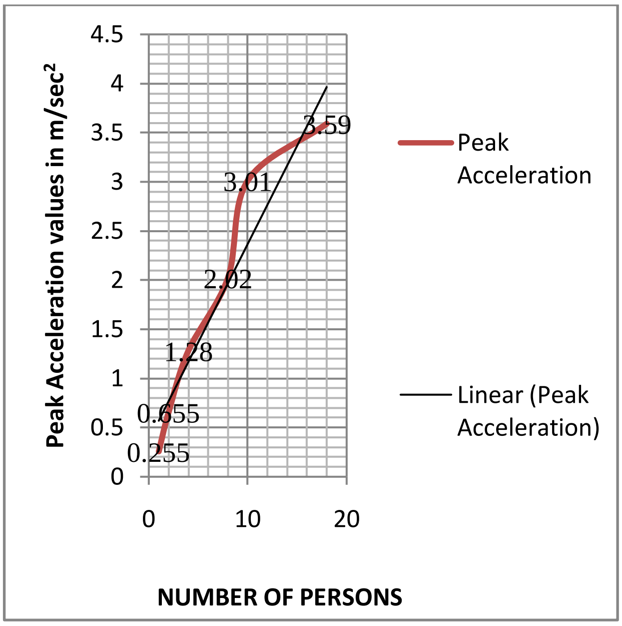

Figure 28: Peak Acceleration Values

Discussions

The theory developed by earlier researchers have been consolidated. The discussion and final conclusions were arrived considering few common and acceptable procedures with respect to practical considerations based on the various situations and the standards adopted from few countries. The discussions with respect to few predominant theories are stated below

*Modified Reiher*Meister perceptibility chart*[10].

a) One Person Loading

Maximum Amplitudes for one person loading for both Harmonic and transient analysis for points A,B and C except point C in transient which is coming under slight perceptible are in Distinctly perceptible zone by considering the frequency ranges from 5 Hz to 10 Hz.

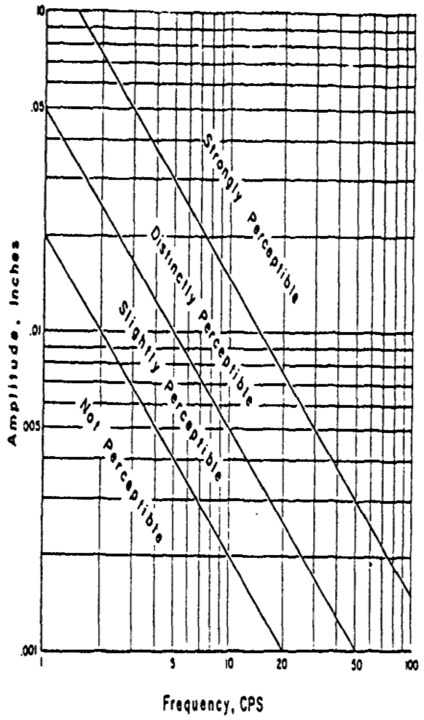

Figure 29: Modified Reiher*Meister perceptibility Chart

b) Two persons Loading

Two persons loading and four persons loading at transient for point B and C ; Two persons under Harmonic for point C and under transient for point A are also lying in the Distinctly perceptible area.

c) Loading with Multiple persons

For 8 persons,10 persons, 18 persons loading under both harmonic and Transient ,the Amplitudes values are in Strong perceptible zone.

It is concluded that the panel may not support beyond 8 persons doing rhythmic activities as the values lie in strong perceptile zone.

Comparison with Bruce Ellingwood Theory[5]

According to Ellingwood, the acceleration value lies between 0.01 to 0.02 with 3% damping. The considered floor structure is assumed to have 3% dampness and the peak values for one person loading is 0.255 which is violation of the recommendation.

The annoyance threshold vibration values mentioned in his chart for Transient condition with 3% damping the acceleration values lie between 0.01 to 0.02

He suggested acceleration limit by occupancy, for multifamily apartments with 3% damping as 0.02.

Compared with all above recommendations the acceleration values obtained from three different points as A.B and C on the floor panel are higher. It is not satisfying the recommendations suggested by Ellingwood.

Comparison with Allen Theory[3]
Allen suggested that for vibration under human Rhythmic activities, the acceleration limits is 4%g to 7%g.

He comments" Resonance is the most important factor affecting aerobics vibration, hence frequency is the most important structural design parameter. The problem is to get the natural frequency away from the three harmonics".

He recommended the minimum natural frequency that needs to be designed for stadia for composite steel concrete floor should be 9Hz.

The values obtained in this paper are not matching with the recommended values for acceleration and also the natural frequency for first mode shape and second mode shape are 5.456 and 9.806 Hz respectively which are lesser and closer to 9 HZ. Hence the values of natural frequency and acceleration are not matching with guideline values suggested by Allen.

H.Bachman[4] recommended the minimal natural frequency of structures with man induced vibrations for Dance halls, concert halls without fixed seating under different structures:

Reinforced structures >6.5Hz
Prestressed concrete structures > 7 Hz
Composite steel structures>7.5Hz
Steel structures >8 Hz

Under this analysis, the natural frequency for the first three modes is lesser compared to the minimum frequency requirement as in composite steel structures and steel structures. The first natural frequency may be supporting the formation of resonance in the structure.

From ISO 2631-1:1997(E)
It suggests the comfort reactions to vibration environment based on acceleration values.

According to the results obtained through the analysis, acceleration values from one person at point B and C is the comfort place whereas loading of 2 persons at all points are in little uncomforting place. For four persons loading , the acceleration values are in uncomfortable range. With eight persons loading, the values are very uncomfortable. For eighteen persons full loading it occupies entire uncomfortable place.

From Steel design Guides the recommended values for aerobics for heavy floor with 5kPa, forcing frequency is 8.25 Hz, the natural frequency should be 8.8 Hz under a_o/g as 0.06

For Dancing and Dining for heavy floor with 5kPa, forcing frequency is 3, the natural fundamental frequency requirement should be 6.4 Hz and for the same in light floor with 2.5kPa, the frequency is 3. The natural fundamental frequency requirement should be 8.1 Hz under ao /g as 0.02. The first mode of natural frequency for 12mx 16m panel anaysis is 5.456Hz which is below the recommended value.

Allen and G.pernica- Minimum floor frequency for rhythmic activity like dancing and dining for concrete floor recommendation is 9Hz.

With the first mode of frequency value of 5.24 which is lesser than 9Hz, it is the critical place where there is possibility of resonance.

IS 800 -2007: The present code of practice in steel (IS 800-2007) limits the maximum acceleration levels to a value of 0.5% g = 0.05m/sec^2 which is a very stringent vibration criteria. The first natural frequency of the floor system is computed as 5.438 (Hz) which is within the critical range of frequencies suggested by IS800-2007. Since such a system is having high flexibility and low frequency it is found to be more vulnerable, if the analysis is continued with the input

Conclusion

The trend towards light flooring system with composite structural action has resulted in decreased stiffness and low frequencies of flooring system. Flooring system supporting aerobics activities with rhythmic jumping are increasing the vulnerability of such flexible floors to large deflection levels. The present code of practice in steel (IS 800-2007) limits the maximum acceleration levels to a value of 0.5% g = 0.05m/sec^2 which is a very stringent vibration criteria.

Towards studying the actual vibration levels of rhythmic human jumping acting on a aerobics floor, a typical floor plan of 16mX12m is taken as modular floor plan and analyzed for dynamic action of human induced load. After performing the normal design procedure using the dead load and live loads on the floor, the suitable sections details are arrived at and used in the dynamic analysis.

The force-time relationship of activity of jumping and rhythmic movements are complicated and difficult to measure, but have been successfully approximated by suitable for time function by various researches[9].

Using this force time relationship, a series of dynamic analysis is performed on the floor slab-beam system using ANSYS (2011). The types of dynamic analysis that have been performed includes,

a) Static Analysis
b) Modal Analysis
c) Harmonic Analysis
d) Transient Analysis

Modal Analysis involves only extraction of dynamic characteristics of the floor system, which is used as input in the harmonic and transient dynamic analysis. The first natural frequency of the floor system is computer as 5.438 (Hz) which is within the critical range of frequencies suggested by IS800-2007. Since such a system is having high flexibility and low frequency is found to be more vulnerable, the analysis is continued with the input. The transient analysis involves modeling the force-time history as exact and suggested[9] . Whereas in the harmonic analysis, the loading is assumed as an equivalent harmonic sinusoidal load having the same force magnitude as in transient dynamic analysis.

For the purpose of loading number of persons participating in the jumping is sequentially increased from 2, 4, 8, 10, & 18. A spacing of 1.5m between each person is assumed in the analysis. Following significant conclusions are drawn from this interesting study;

1. The maximum vertical response acceleration at critical measurement points in the floor system are found to be 0.395m/sq.s, and for 2, 4, 8, 10, & 18 persons respectively from the results of transient dynamic analysis. This shows that there is not a substantial increase due to cumulative loading of number of persons simultaneously jumping on the floor as compared to single person or a couple jumping. There is a non-linear relationship found from the study between the maximum peak response acceleration versus number of persons inducing dynamic excitation
2. However it is concluded and cautioned that even for the two persons generally the rhythmic activity response acceleration is for higher than what is permitted in IS800-2007 as the governing maximum acceleration. Hence is suggested that suitable stiffening or enhanced damping shall be available for floor system meant for these kinds of rhythmic activities.
3. It may be seen that contact period for jumping (on-air) time duration are little fizzy and there could be a variation in their exact values. Towards capturing the maximum response acceleration a harmonic analysis is also performed, varying the excitation frequency from 0 to 25 Hz. The response clearly shows peaks at each of the natural frequency of the floor system have 5.456 Hz, 9.806 Hz, 12.524 Hz, 15.520 Hz, 17.871 Hz & 22.338 Hz. It is also seen that the response such has shown a ratio of 3-4 times the values as predicted by the transient dynamic analysis. It is also seen that such a critical situation can arise when the time period of frequency match with the natural time period of the flooring system.

To summarize and to counteract the above theories, the designer during designing stage itself should identify the usage of floors with any induced human activities like Gymnastics, aerobics, office usage, dancing activities. Based on the usage requirement, the floors can be analysed under dynamic loading condition and the natural frequency for such floors should be higher than that of forcing frequency.

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