Effects of Crowd Behavior on Dynamic Responses of Permanent Grandstand Structure

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Abstract— Construction indusry's novel design design have resulted in an enhanced use of slender structures having low natural frequency. Enthusiastic potential behavior of people from concert, shows, and sporting events etc., causes dynamic crowd load may excite supporting slender structures such as stadium, grandstands, auditorium, bridges, malls and convention center. The combination of slender structures with dynamic crowd load induce the structure easily vulnerable to excessive vibrations and dangerously affects the safety and comfort of occupants. Hence these vibration problems due to increased structural slenderness and more lively dynamic crowd excitation becoming more common aspects. So study the behavior of dynamic crowd load is mandatory. The present work aims to find out the behavior of permanent grandstand structure under dynamic crowd load. So study investigates the behavior of grandstand structure considering load at different frequency of jumpers in the range of 1.5 Hz to 3.5Hz, different types of activity such as normal jumping, high aerobics and low aerobics and various percentage of active crowd with total crowd, also the effects of rake angle on the structure to reduce the vibration. Active dynamic crowd load was analytically developed as taken from BS 6399-Part 1 and generated as time history and applied to the structure. The passive live load as taken 5kN/m2 specified in IS875 (Part II). A three dimensional finite element model is used to model the grandstand structure. For modelling the grandstand structure and dynamic analysis finite element software, SAP2000 was used. The results obtained are compared in form of horizontal frequency, vertical frequency, acceleration, displacement, shear force and bending moment.

Index Terms— Active crowd, Crowd load, Grandstand, Human comfort, Human structure interaction, Passive crowd, Vibrations.

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1 INTRODUCTION

THE enhancement in the construction's novel design and technological development made modern public structures, such as exhibition halls, long-span floors, concert venues and grandstands, have nature of low natural frequencies. Purpose of these structures are, to held concerts, sports event, and aerobics like events that make people to make overwhelming happiness [7], [23]. It resulted structure prone to external stimuli having frequency in range of dance type activities. So crowds generate periodic dynamic loads. This due to rhythmic activities, such as jumping, bobbing, and foot stamping, in response to music. As a result, the natural frequency of the structure will be equal or close to frequency of jumpers, resonant or near-resonant vibrations will happen. The resonance impart serious structural problems [15]. Also the people feel uncomfortable, panic and even cause casualties will bring these vibrations. Hence it is mandatory to avoid at a design stage by understanding rhythmic crowd loads [5[, [11].

Nowadays crowd jumping to beats are usual for spectators at concerts or sport games. But the jumping action is one of the most severe load from all individual activities. Major problematic levels

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of incidents reported due to crowd behavior are; during a pop concert held in London in 1994, a temporary grandstand collapsed under the audiences' rhythmic jumping with the beat of music, and more than 50 people were injured. A 39-story building shook vertically for about 10 min in Seoul, South Korea in 2011, where a group of people were exercising at an aerobics. The exciting frequency was almost equal to the building's natural frequency of 2.7 Hz. A part of a temporary grandstand collapsed before a football match in Bastia, Corsica in 1992 [1], killed 17 people and injured over 2500. The London Millennium Bridge had exhibited severe lateral sway on the day of its inauguration and had to be close down for renovation. Similar incident was reported for Pont-de-Solférino in Paris. Complaints of excessive structural vibrations were reported from the crowds of Manchester United's Old Trafford Stadium [20] and Morumbi Stadium in Brazil [25]. In Rajasthan's Sri Ganganagar area, 50 peoples injured in a mishap during a tractor-race event, structure collapsed apparently due to the weight of a large number of spectators sitting over it. To tackle this problem, existing codes and guidelines, including [2], [4] and [13], [14] says that a dynamic analysis should be done for stadiums with natural frequencies below certain threshold values. However, none of these codes and guidelines provides the tools that would allow a designer to analyze the performance expected of these structures.

The use of sports stadia increased, due to it can temp large number of audience. Therefore, the grandstands at stadia bearing a more severe loading regime than took in their design. Hence check safety and serviceability of these structures was necessary. Study investigates investigate the behavior of grandstand structure considering load at different frequency of jumpers in the range of 1.5 Hz to 3.5Hz [12], different types of activity such as normal jumping, high

aerobics and low aerobics and various percentage of active crowd with total crowd, also the effects of rake angle on the structure to reduce the vibration. Active dynamic crowd load was analytically developed as taken from BS 6399-Part 1 and generated as time history and applied to the structure. The passive live load as taken 5kN/m2 specified in IS875 (Part II).

2 DYNAMIC CROWD LOAD

For the practical design and serviceability check of structures, an accurate analysis and precise investigation of grandstand structure subjected to dynamic loads are required. Moreover, it is desirable to measure and analyze the dynamic loads of spectator activities like jumping, bobbing, swaying etc. because these dynamic loads cannot be easily expressed in a numerical formula. Even though many kinds of literature [8], [9], [10], [11] and code [2] have adopted a numerical formula for calculation of load function due to individual jumping are mentioned below.

Synchronized dynamic loading caused by jumping and dancing are periodic. This mainly depend upon: static weight of the dancer(s) (G_s), period of the dancing load(s) (T_p), and contact ratio (α), i.e. the ratio of the duration within each cycle when the load is in contact with the floor and the period of the dancing. Mathematically the load at any instant (t) may be expressed as in Equation (1)

$$F_s(t) = G_s \left(1 + \sum_{n=1}^{\infty} r_n \sin\left(\frac{2n\pi t}{T_p} + \phi_n \right) \right) \quad (1)$$

Where $Fs(t)$ is the dynamic load, rn is the Fourier coefficient (or dynamic load factor) of the nth term, n is the number of Fourier terms, and $φn$ is the phase lag of the nth term. The values of rn and $φn$ for a given period of dancing Tp or a jumping frequency ($1/Tp$) in Table 1.

TABLE 1
FOURIER COEFFICIENT [8]

Human activity		n					
		1	2	3	4	5	6
Low aerobics	r_n	9/7	9/55	2/15	9/247	9/391	2/63
	$φ_n$	-π/6	-5π/6	-π/2	-π/6	-5π/6	-π/2
High aerobics	r_n	π/2	2/3	0	2/15	0	2/35
	$φ_n$	0	-π/2	0	-π/2	0	π/2
Normal jumping	r_n	9/5	9/7	2/3	9/55	9/91	2/15
	$φ_n$	π/6	-π/6	-π/2	-5π/6	-π/6	-π/2

From the above equation (1) for a normal jumping 2 Hz load was developed by choosing appropriate coefficients from Table 1 as following in Figure 1. The diagram shows two cycles of normal jumping with frequency equals 2 Hz and the contact ratio α = 1/3. Contact ratio α = 1/3 is equivalent to that only one-thirds of each cycle of the body has contact with the ground. In the figure the force is normalized so that the body weight is unity (Gs=1).
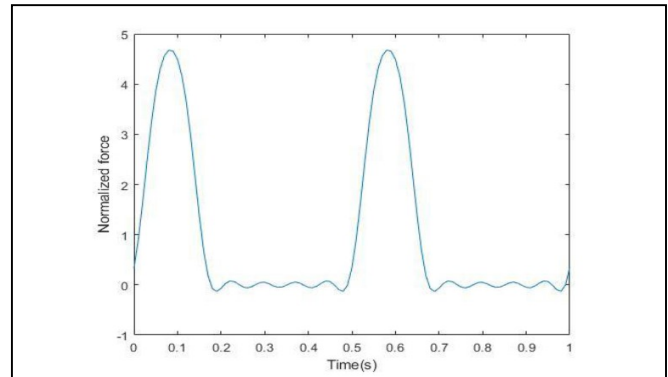

Figure 1. Dynamic crowd load (normalized) for normal jumping 2Hz

Similarly load model for different range of frequency from 1.5 Hz to 3.5 Hz at an interval of 0.5Hz for normal jumping was developed. The load taken in kN and static weight was taken as 78Kg. Also load model for different types of activity for 2 Hz frequency was developed as shown in below Figure 2. The coefficients are taken from the Table 1.
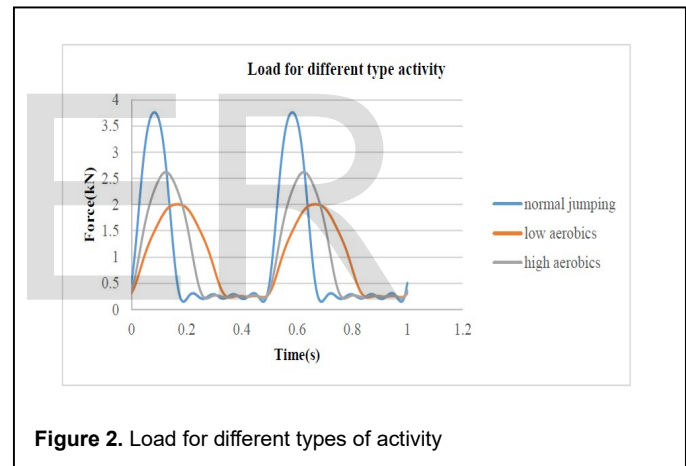

Figure 2. Load for different types of activity

3 MODELLING AND DYNAMIC ANALYSIS

3.1 Numerical Modelling

A three dimensional finite model is used to model the grandstand structure. A part of permanent grandstand structure was used for study. For modelling the grandstand structure and dynamic analysis finite element software, SAP2000 was used. For the three dimensional finite model of grandstand structure, beams and columns are modelled as frame elements (with six degree of freedom per node). Slabs are modelled with quadrilateral shell elements (with four node and six degrees per node).The dimensions selected for structure as; plan area 13.5x12m, Height of part – 6.2 m, Column size- 600x600mm, Beam size- 350x600mm, and Seating decks- Tread : 800mm and Rise : 312 mm. Figure 3 shows Plan and Sectional view of structure which considered for current work. The modelled structure in software as seen in Figure 4.
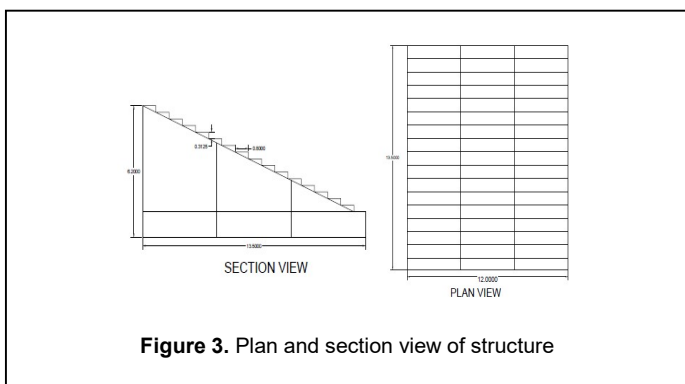
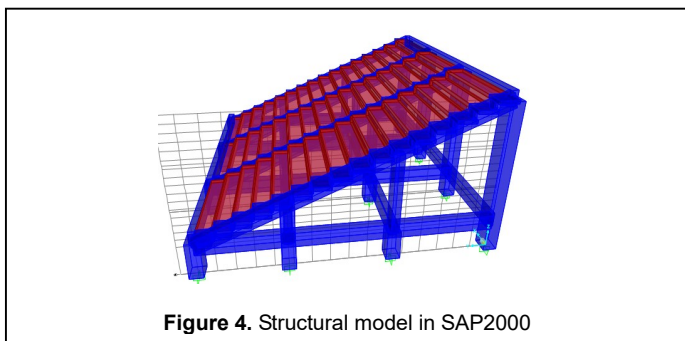**Figure 3.** Plan and section view of structure

Figure 4. Structural model in SAP2000

3.2 Materials and Section properties

Concrete material was used for the permanent grandstand structure. Concrete of M30 grade was used for columns, beams and slabs. For the reinforcement, HYSD415 bar was used for the longitudinal and mild250 was used for ties. Table 2 shows the material properties used for the members used in the structure. F_y and F_u respectively indicates the minimum yield strength and minimum tensile strength of steel.

TABLE 2
MATERIAL PROPERTIES OF MEMBERS

Material Type	Young's Modulus, E (MPa)	Poisson's Ratio, υ	Unit Weight (kN/m^3)	Design Strength (MPa)
Concrete, M30	27386.13	0.2	25	30
Longitudinal bar, HYSD415	200000	0.3	76.9729	F_y = 415 F_u = 485
Ties, Mild250	200000	0.3	76.9729	F_y = 250 F_u = 410

3.3 Load details

In this study dead load and crowd load only were considered for the analysis of the structures. The other loads such as live load, snow load, seismic load, etc. was not considered to realize the relevance of crowd load. The crowd load as already developed and explained above. For crowd load, the active load generated as time history and applied to the structure. The passive live load as taken 5kN/m2 specified in IS875 (Part II).To find the solution of problem on effects on the percentage of activeness on the total crowd load, there was used mixed combinations of dynamic active load and passive live load. The six combinations are used, such as the full passive load, 20%, 40%, 60%, 80% and full active load. The all model plan views respectively are shown below Figure 5.
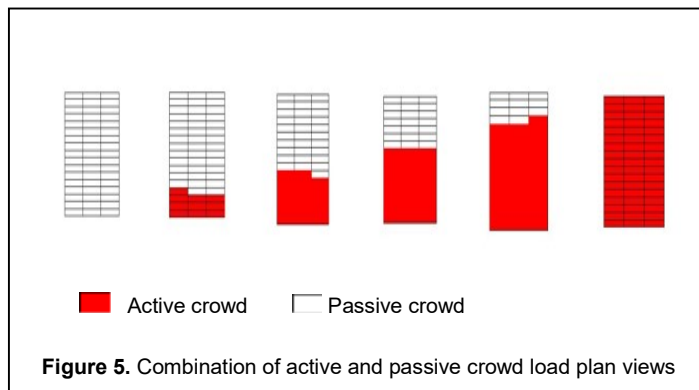

Figure 5. Combination of active and passive crowd load plan views

3.4 Dynamic Analysis

For dynamic analysis of the modelled structure SAP, structural analysis programme was used, which is user-friendly generalized analysis and design software. SAP2000 Version 15.1.0 has a powerful graphical interface with modelling, analytical, and design procedures. It is a full-featured program that can be used for the simplest problems or the most complex projects. Dynamic analysis of stadium structure has been carried out for different combinations of active and passive live load, different jumping frequencies, different activity and various rake angle. The results obtained are compared in form of horizontal frequency, vertical frequency, acceleration, displacement, shear force & bending moment.

From the results the peak acceleration response of the structure expressed as percentage of acceleration due to gravity (g). It can related to the comfort level of occupants. The comfort level of an individual to the corresponding vibration level is calculated using the specifications listed in Table 3 as given by [10] for structures like grandstands with frequency less than 10 Hz.

TABLE 3
CROWD COMFORT LEVEL FOR VARIOUS PEAK ACCELERATIONS [10]

Vibration level	Comfort level
<5% g	Reasonable
<18% g	Disturbing
<35% g	Unacceptable
>35% g	Probably cause panic

4 RESULTS AND DISCUSSION

Dynamic analysis is carried out for problems of the stadium structure specified in this study using SAP2000. The results are in form horizontal frequency, vertical frequency, acceleration, displacement, shear force & bending moment values are taken from the software SAP2000. Each problems results are shown in below. Earthquake force and any forces are not considered here because to understand the better effect of active live load.

4.1 Responses at different frequency

Analysis of structure for ranges of frequency from 1.5 Hz to 3.5 Hz was carried out and results in form of displacement, acceleration, shear force & bending moment are shown in the Figure 6. From figure realized that when the frequency of load increases, the response of structure in form of displacement, internal member forces and moment increases.
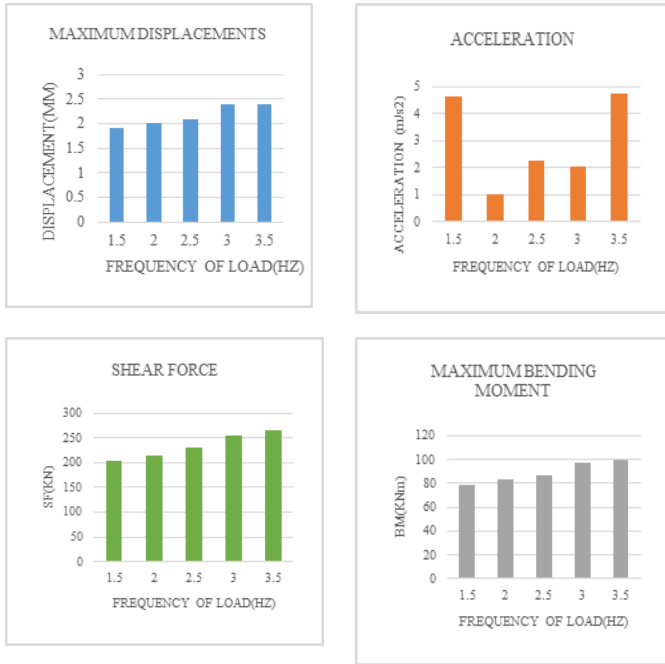
The results are in form horizontal frequency, vertical frequency, acceleration, displacement, shear force & bending moment values are shown below Figure 8. From the results, obtained that all the responses are increasing when increase the activeness of crowd. So the structure become danger for full active humans, safe for full passive humans. As per result frequency of passive human was below the active crowd, but for better result frequency should be need greater. These reduction may be due to passive crowd will induce mass to the structure, hence the frequency was reduced. Horizontal frequencies for all combinations greater than the 4.0 Hz that means it satisfies the code requirement of BS 6399 – Part 1. Full active crowd generates higher maximum displacement, acceleration, shear force and bending moment, than all other cases while full passive crowd generates less bending moment among all cases. Acceleration is one of the criteria for serviceability. For better serviceability, the acceleration of structure should be less than $0.35 \times g = 3.4335$[3, 16]. Otherwise human comfort may become panic. Figure 8 is showing the comparison of acceleration. For all models is below the desired limit. In passive case, structure acceleration is range of reasonable limit of $0.05 \times g = 0.49$. All other case is human comfort in the range of disturbing.

Figure 6. Responses at various frequency

4.2 Responses at different activity

Analysis of structure for different activity such as normal jumping, high aerobics and low aerobics was carried out and results in form of displacement, acceleration, shear force & bending moment are shown in the Figure 7. From figure realized that responses are high for normal jumping, hence it is highly effect on the structure. For the low and high aerobics responses are comparatively less, these reduction may be due to synchronous of dancers.
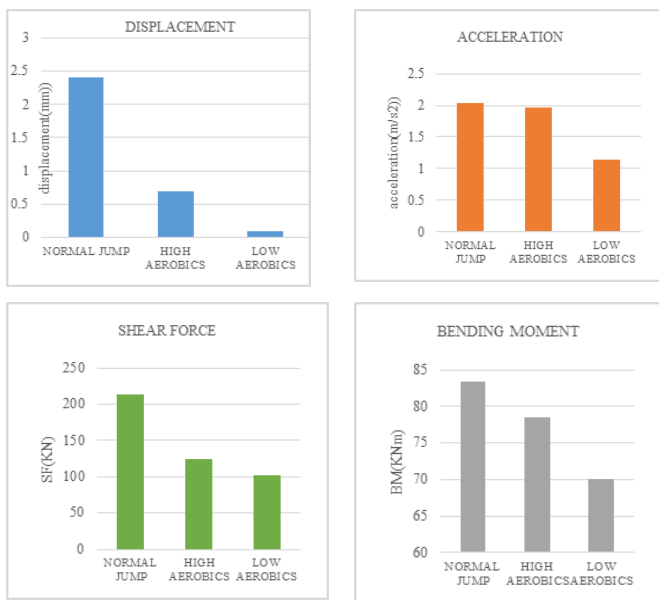

Figure 7. Responses at various activity

4.3 Responses at various percentage of activeness

Dynamic analysis is carried out for all different load combination of active live load and passive live load of the structure.

Figure 8. Responses at various percentage of activeness

4.4 Responses at various rake angle

Analysis of structure for different rake angle for 21, 25, 30 and 35 degree was carried out and results in form of vertical frequency and horizontal frequency are shown in the below table. Frequency is an important parameter for any dynamic

analysis and to prevent resonance condition. Frequency indicates cycles completed in unit time. Tables 4 and 5 gives the frequency of empty structure i.e., before the loading. Table 6 and 7 gives frequency values after applying the crowd load. From the results of vertical frequency, it is clear up to 30 degree the empty structure below the code specified value 8.2Hz. While above 30 degree the structure needed to analyze the dynamic analysis. But by the action of crowd load natural frequency was reduced, it become below the code provision value. Hence above 21 degree structure will be under critical. While for this four angles, horizontal frequency of empty structure are greater than the 4.0 Hz that means it satisfies the code requirement of BS 6399 – Part 1. Horizontal frequency of Structure should be greater than 4.0 Hz as per code provision BS 6399 – Part 1. But by the action crowd load, above 25 degree frequency becomes below the limit.

TABLE 4
VERTICAL FREQUENCY OF EMPTY STRUCTURE

Rake angle(degree)	Vertical frequency(Hz)
21	11.93
25	10.50
30	8.50
35	8.02

TABLE 5
HORIZONTAL FREQUENCY OF EMPTY STRUCTURE

Rake angle(degree)	Vertical frequency(Hz)
21	5.84
25	5.24
30	5.1
35	4.56

TABLE 6
VERTICAL FREQUENCY OF STRUCTURE UNDER CROWD LOAD

Rake angle(degree)	Vertical frequency(Hz)
21	8.43
25	7.42
30	6.01
35	5.67

TABLE 7
HORIZONTAL FREQUENCY OF STRUCTURE UNDER CROWD LOAD

Rake angle(degree)	Vertical frequency(Hz)
21	4.96
25	4.35
30	3.89
35	3.5

5 CONCLUSIONS

An analysis of dynamic loads induced by crowd movements was required for an accurate analysis of grandstand structure. Hence, the dynamic loads induced by spectators' jumping are calculated by numerical model and analyzed. This study investigated the behavior of grandstand structure considering load at different frequency of jumpers, different types of activity and various percentage of active crowd with total crowd, also the effects of rake angle by reduce the vibration. Based on study following conclusions are drawn.

- Generally, human induced frequencies are in the range of 1.5 to 3.5 Hz. So, the horizontal frequency of structure should be higher than 4Hz. While the vertical frequency should be more than 8.4Hz.

- Static design for stadium structure is safe for loading but may fail in serviceability criteria so it is necessary to perform dynamic analysis considering human structure.

- In this study, as the frequency of load increases, the response of structure in form of displacement and internal member forces increases.

- Acceleration is the one of the criteria for serviceability. As per literature acceleration should be less than 0.35g (3.5m/s2), in study for effects of frequency variation the excitation at 1.5 and 3.5 Hz was higher than limits.

- By the acts of dynamic crowd load the natural frequency of structure will decreases.

- For different types activity normal jumping is highly effect on the structure due to all responses are less for the other activity. These reduction may be due to synchronous of dancers.

- In this study results for horizontal frequency, vertical frequency, maximum displacement, maximum bending moment, maximum shear force, and acceleration are measured higher in effect of active live load in compare to passive live load.

- When the percentage of activeness increases from full passive to active at an increase of 20% activeness with respect to total crowd, the results are in form horizontal frequency, vertical frequency, acceleration, displacement, shear force & bending moment values are increases.

- All combinations of active and passive load, vibration level within the limit of .35g. So does not cause panic, but it may become disturbing one.

- In study for effects of rake angle, conclude that under crowd load above 21 degree rake angle vertical natural frequency will below the limit, needed to analyze dynamically.

- While for this four angles, horizontal frequency of empty structure are greater than the 4.0 Hz that means it satisfies the code requirement of BS 6399 – Part 1.

- The active crowd solely act as external load to the structure while passive crowd was acting solely a mass, so the

frequency of stand would decrease with the increasing size.

This study gave great importance in the dynamic analysis of long slender structures like grandstands when crowd load affected the structure. Indian standard codes may be modified to include guidelines for the same.

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