Effects of crowd behavior on dynamic responses of permanent grandstand structure

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Abstract. Constructions industry’s novel design and technological development have resulted in an enhanced use of slender structures having low natural frequency. The overwhelming happiness in concert, shows, sporting events etc., potentialize enthusiastic behaviour of people causes dynamic crowd load i.e., synchronized rhythmic movements may excite supporting slender structures such as stadium, grandstands, auditorium, bridges, malls and convention centre. The combination of slender structures with dynamic crowd load makes the structure easily vulnerable to excessive vibrations and dangerously affects the safety and comfort of occupants. Hence the vibration problems due to increased structural slenderness and dynamic crowd excitation have become more common. So studies regarding the behaviour of dynamic crowd load are mandatory. The present work aims to find out the behaviour of permanent grandstand structure under dynamic crowd load. Here we investigate the behaviour 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 IS 875 (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.

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 low natural frequencies. Purposes of these structures are, to hold concerts, sports event, and aerobics like events that make people to make overwhelming happiness [7, 23]. This resulted the structure to be prone to external stimuli having frequency in range of dance type activities. So crowds generate periodic dynamic loads 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 imparts serious structural problems [15]. Also the people feel uncomfortable, panic and even cause casualties as a result of these vibrations. Hence it is mandatory to avoid unnecessary vibrations 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 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 people 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, as it can accommodate large number of audience. Therefore, the grandstands at stadia bearing a more severe loading regime are usual. Hence a precise check for safety and serviceability of these structures was necessary. Studies investigating 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 IS 875 (Part II).

2. Dynamic crowd load
For the practical design and serviceability check for 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 ($\alpha$), 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)

$$F_s(t) = G_s \left( 1 + \sum_{n=1}^{m} r_n \sin \left( \frac{2\pi nt}{T_p} + \varphi_n \right) \right)$$  (1)
Where $F_d(t)$ is the dynamic load, $r_n$ is the Fourier coefficient (or dynamic load factor) of the $n$th term, $n$ is the number of Fourier terms, and $\varphi_n$ is the phase lag of the $n$th term. The values of $r_n$ and $\varphi_n$ for a given period of dancing $T_p$ or a jumping frequency ($1/T_p$) in Table 1.

| 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|
|                    | $\varphi_n$| $-\pi/6$| $-5\pi/6$| $-\pi/2$| $-\pi/6$| $-5\pi/6$| $-\pi/2$|
| High aerobics      | $r_n$| $\pi/2$| 2/3 | 0   | 2/15| 0   | 2/35|
|                    | $\varphi_n$| 0   | $-\pi/2$| 0   | $-\pi/2$| 0   | $\pi/2$|
| Normal jumping     | $r_n$| 9/5 | 9/7 | 2/3 | 9/55| 9/91| 2/15|
|                    | $\varphi_n$| $\pi/6$| $-\pi/6$| $-\pi/2$| $-5\pi/6$| $-\pi/6$| $-\pi/2$|

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 $\alpha = 1/3$. Contact ratio $\alpha = 1/3$ 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 ($G_s=1$).

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 0.5 Hz for normal jumping was developed. The load taken in kN and static weight was taken as 78 kg. 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 at different activity.](image)

### 3. Modelling and dynamic analysis

#### 3.1. Numerical modelling

A three dimensional finite element model is used to analyse 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 structure as modelled in software is shown in Figure 4.

![Figure 3. Plan and section view of structure.](image)
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.

| Material Type  | Young’s Modulus, \(E\) (MPa) | Poisson’s Ratio, \(\nu\) | Unit Weight (kN/m³) | 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. were not considered so as 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 are shown in Figure 5.
3.4. Dynamic analysis
For dynamic analysis, SAP, the structural analysis software 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 angles. 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 be 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.

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

4. Results and discussions
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 problem’s 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. It is realized that when the frequency of load increases, the response of structure in form of displacement, internal member forces and moment increases.
4.2 Responses at different activity

Analysis of structure for different activities such as normal jumping, high aerobics and low aerobics were carried out and results in form of displacement, acceleration, shear force & bending moment are shown in the Figure 7. From Figure 7, it is 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 6. Responses at various frequency.
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. The responses of the structure such as 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 becomes risky for full active humans, safe for full passive humans. As per the responses, frequency of passive human was below the active crowd, but for better result frequency should be greater. Passive crowd will induce mass to the structure, hence the frequency was reduced. Horizontal frequencies for all the combinations greater than the 4.0 Hz means that 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 $0.35g = 3.4335$ [3, 16]. Otherwise human comfort may become panic. Figure 8 is showing the comparison of acceleration. For all the combinations, it is below the desired limit. In passive case, structure acceleration is range of reasonable limit of $0.05g=0.49$. 
4.4. Responses at various rake angles

Analysis of structure for different rake angle for 21, 25, 30 and 35 degree was carried out and results 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 that for rake angle upto 30 degrees, there is no need of dynamic analysis, as the frequency is above the code specified value 8.2 Hz. While above 30 degree the structure needs dynamic analysis. But by the action of crowd load natural frequency was reduced, it is below the code recommendation. Hence for rake angle above 21 degree structure will be critical and need dynamic analysis.

Figure 8. Responses at various percentage of activeness.
While for four angles, horizontal frequencies of empty structure are greater than the 4.0 Hz, 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 is below the recommended 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) | Horizontal 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) | Horizontal 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, and the effects of rake angle. Based on the study, the 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. The 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 for active live load in comparison with 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 responses like 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 0.35g. So does not cause panic, but it may become disturbing one.
- In the study for effects of rake angle, it could be concluded that under crowd load above 21 degree rake angle, the vertical natural frequency will be below the limit, needed to be analyzed dynamically.
- While for the four angles, horizontal frequencies 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 acts 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.

6. References
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