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Crowd Actions and Grandstands

Effet des foules sur les tribunes

Einwirkung von Menschenmassen auf Tribünen

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SUMMARY

This paper deals with the response of grandstands to dynamic loads generated by crowds. It considers the available guidance for design and the relevant findings of current research work. The dynamic loads are examined in terms of intensity, frequency range, attenuation due to crowd effects and numerical modelling. Then the interaction between crowds and structures is considered and the results are presented. The findings from a number of site tests on grandstands are given and main points discussed along with an indication of where further work is required.

RÉSUMÉ

L'article traite de la réaction des tribunes sous charge dynamique due aux spectateurs. Il expose les directives d'étude disponibles et les résultats correspondants des travaux de recherche actuels. Il examine les effets dynamiques sous forme d'intensité, plage de fréquences, réduction due aux effets de foule et modèles numériques. Il compare leurs interactions avec la structure et présente les résultats fournis par des essais in situ sur des tribunes. Il récapitule l'ensemble des effets et propose des recherches futures.

ZUSAMMENFASSUNG

Der Beitrag behandelt die Reaktion von Tribünenbauten auf die dynamische Belastung durch Menschenmengen. Er berücksichtigt die verfügbaren Entwurfsrichtlinien und Ergebnisse der gegenwärtigen Forschungsarbeit. Die dynamischen Einwirkungen werden hinsichtlich Intensität, Frequenzbereich, Abminderung infolge der Wirkung der Menschenmenge und numerischer Modellbildung untersucht. Hernach werden ihre Wechselwirkungen mit dem Tragwerk einbezogen und die Ergebnisse aus Feldversuchen an Tribünen angeführt. In einer Rekapitulation der Haupteinflüsse wird Ausblick auf zukünftige Arbeiten gegeben.

1. INTRODUCTION

The response of temporary grandstands to dynamic loads is currently considered to be an important safety issue and this has been emphasised by the collapse of part of a temporary stand at Bastia, in Corsica, in May 1992, which resulted in 13 dead and 1300 injured spectators. This paper looks at many aspects of this problem, including the available guidance for design and the relevant findings of current research work at the Building Research Establishment (BRE). It considers the dynamic loads which can be produced by crowds and how crowds interact with structures. It also discusses the measurements taken by BRE on a range of grandstands and the preliminary findings from these tests.

Within the UK, an engineer who was given the task of designing a temporary grandstand, would probably first examine the UK loading code [1] to see what guidance was given on dynamic loads, but would find the statement 'this does not allow for the dynamic loads due to crowds'. Further investigations would lead him to the ISE publication on this topic [2]. This document discusses the 'natural frequency' of a structure (presumably meaning the fundamental vertical natural frequency) and the need for it to be above 4 Hz so as to avoid resonance from rhythmic events involving a group of people, the most applicable range being 1½ to 3 Hz. It is also noted that in the case of jumping, the periodic forces can create significant dynamic loading at double the rhythmic frequency up to 6 Hz. However, the document is somewhat limited and provides little clear guidance for the designer and does not differentiate between sway and vertical loads, which is actually very important.

Examination of the CEB guide on vibration problems [3] provides more information about lateral swaying of audiences. This publication suggests a lower bound fundamental frequency of 2.5 Hz for sway motion of spectator galleries, and 3.4 and 6.5 Hz for vertical motions for 'soft' and 'hard' pop concerts respectively. This latter point, which considers different design loads for different types of event, is an important issue and is discussed later.

2. CROWD ACTIONS - DYNAMIC LOADS

A densely packed crowd will produce significant loads with both static and dynamic components. If the crowd movement is not co-ordinated then the dynamic component is likely to be much smaller than the static component; however there are certain types of co-ordinated movement where the dynamic component is larger than the static component and these should be considered. Perhaps the worst case is when the crowd jumps in time to music. The music serving to co-ordinate the crowd and the jumping providing significantly higher loads than the equivalent static load of the crowd.

A further factor to consider is that of resonance. If the frequency of the dynamic load occurred at a natural frequency of the structure on which it was imposed, a resonant situation would arise whereby the response would be amplified greatly. Hence it can be appreciated that a significant dynamic load occurring at a natural frequency of a structure can induce excessive vibrations, therefore it is a situation to be avoided.

When considering loads it is also important to consider direction because vertical or sway loads are not only different in magnitude but they are also different in frequency content. For temporary grandstands the primary interest is for sway loads whereas for dance floors and cantilevered grandstands the vertical loads are important.

2.1 Intensity

With a densely packed crowd there may be up to six people per square metre, although on occasions higher densities have been observed at particular events. Six people of average weight equates to approximately 4.8 kN/m^2, which is slightly below the UK design load of 5.0 kN/m^2. When the crowd are seated the density reduces and 4.0 kN/m^2 is often used in design.

The dynamic loads generated by a crowd are dependent upon the activity being undertaken by the crowd. If the worst case is considered, which is when an individual is jumping, then the load can be evaluated. Jumping creates a load at the jumping frequency and at whole number multiples of that frequency. This is discussed in detail in ref. (4) and the following table is extracted from that reference.

Activity	Contact Ratio	Dynamic load factors			
	α	1	2	3	4
Pedestrian movement Low impact aerobics	2/3	1.29	0.16	0.13	0.04
Rhythmic exercises High impact aerobics	1/2	1.57	0.67	0.00	0.13
Normal jumping	1/3	1.80	1.29	0.67	0.16
High jumping	1/4	1.89	1.57	1.13	0.67

Table 1 Dynamic load factors for various activities involving jumping

The factors given in the table require some explanation. The contact ratio is the ratio of time when the jumper is on the ground to the time for one cycle of the jump, thus a contact ratio of 1 would mean that the person was always in contact with the ground. The load can be split into its Fourier components for the jump frequency and whole number multiples of it, the multiples 1, 2, 3 and 4 being shown in the table. The dynamic load factors are the amplitude of the harmonic term of the Fourier component. For example for the high impact aerobics, where $\alpha=1/2$, the first dynamic load factor (which occurs at the jump frequency) is 1.57. The dynamic load factor shows the load amplitude in addition to the static load which is defined as 1.0. Thus it can be appreciated that the dynamic loads can exceed the static loads and that significant loads can occur at whole number multiples of the jump frequency, which is important when possible resonances are considered.

Jumping is likely to produce the largest vertical loads, but horizontal loads are important for the sway vibrations of a structure. The information on sway loads is rather sparse and this subject has not yet been investigated by BRE, the best current information being found in the CEB guide [3] which suggests a load factor of 0.3 for sway at 0.6 Hz.

2.2 Frequency

With dynamic loading the ratio of load frequency to the fundamental structural frequency is important due to the possibility of resonance. For example, if a person was jumping at the fundamental frequency of a floor which had a damping value of 2% critical, the amplification due to resonance could be up to 25 times. For jumping the frequency range over which a person can jump is 1.5 to 3.5 Hz, although there is reason to believe that for a crowd the upper frequency is 2.8 Hz. The fact that for jumping, significant energy is generated at whole number multiples of the jump frequency, leads on to a rule which has been suggested, that to avoid resonance a fundamental frequency of a structure should be above three times the dance frequency. This figure actually relates to safety where displacement or stresses are of concern and is not applicable for accelerations which may be a serviceability issue.

For sway vibrations information is again available from the CEB guide which suggests the load is mainly at slow rhythms between 0.8 to 1.4 Hz, with the lateral body swaying at half the beat frequency giving a range of 0.4 to 0.7 Hz. The guide suggests a lower bound fundamental frequency of 2.5 Hz for sway motion.

2.3 Crowd Effects

In section 2.1 the maximum crowd density and the loads produced by individuals were mentioned, but when considering the loads produced by crowds there are one or two factors which should be considered. First there is the interaction between crowd and structure which can be important and this is considered in the next section. Secondly there is the expectation that if a crowd all tried to jump at the same frequency, which may be the case for some dances, then there is a likelihood that their co-ordination will not be perfect and there will be a resulting attenuation of the overall load. The imperfections in co-ordination may be due either to individuals not dancing at exactly the beat frequency, which may be more common at the extremes of the frequency range, or due to phase differences between individuals. A theoretical study of the attenuation due to phase differences is given in ref. [5] and suggests a likely attenuation of approximately 1/3 for a large crowd. However, this is primarily for vertical loads and horizontal loads have not yet been studied.

2.4 Modelling of dynamic loads

It is relatively simple to model sway loads for individuals and models for jumping loads are also available [6]. Given the number of people involved, the frequency of the co-ordinated movement and the crowd effect, the overall load can be determined. To simplify the dynamic calculations, it is possible to consider just the fundamental mode of vibration. The actual jumping load can be expressed as the sum of the Fourier terms in which the amplitudes of the terms are shown in the previous table.

In order to calculate response, it is necessary to evaluate the fundamental structural characteristics (i.e. natural frequency, damping, mode shape and modal stiffness), and for some structures this may neither be straightforward nor accurate. The best mechanism for providing accurate estimates of structural characteristics is a combination of experience from previous analysis plus feedback from field tests. Besides the basic structural characteristics there is the interaction between crowd and structure which is discussed in the following section.

3. CROWD ACTIONS - HUMAN BODY EFFECT

For a number of important vibration problems, the interaction between a group of people and a structure is significant and evaluating this interaction is critical if overall behaviour is to be assessed; but, at present, there are no authoritative studies on this subject. The current general understanding is demonstrated by a Canadian Code [7] which treats the human body as a 'dead' mass on the structure, and this results in a simple reduction of the natural frequency of the structure. Measurements on a large cantilevered stand by the authors [8] indicated that the involvement of spectators changed the dynamic characteristics of the stand. For the empty stand a well defined fundamental mode was recorded, but when the crowd were present two modes to either side of the original frequency were observed. This suggested that the human body, or a group of people, acts as a spring-mass-damper system, rather than a 'dead' mass.

3.1 Laboratory tests

Following the observations on the cantilevered stand a series of simple experiments were undertaken in the laboratory. The first involved taking measurements on a small simply supported beam. The frequency of the beam was measured at 18.7 Hz. When a person stood or sat on the beam, the frequency increased and the damping value increased significantly. When a rigid mass equivalent to that of the person was placed on the beam, the beam frequency decreased and the damping value remained unchanged. This indicated that the person acted as an additional mass-spring-damper system, and it was also noted that the human spring stiffness varies with posture. The tests, and subsequent analysis suggested that the human frequencies were in the range 8 - 10 Hz when standing and 4 - 6 Hz when seated.

For the case where people were jumping, stamping and running on the spot, their mass was not vibrating with the beam and it was found that the human involvement was as a load only, with the characteristics of the beam measured during the tests being the same as the bare beam. Hence for calculation of an event where people are jumping the characteristics of the bare structure should be used.

3.2 Human-structure vibrations

Complementary theoretical work has been developed at BRE examining several aspects including the theory of human-structure vibrations, floor vibrations induced by dance type loads and the indirect measurement of the human whole-body frequency.

If the beam and the person are each considered to be one degree-of-freedom systems, the person standing on the beam will provide a two degree-of-freedom system. The frequencies of the beam and of the person are always between those of the two frequencies of the person-beam system. With the experiment where the measured frequency of the beam seemed to increase, only one of the two modes of vibration was being observed; the other mode, which occurs at a lower frequency, was not observed. If the situation arises where the structure and human frequencies are similar, then both modes of the combined system will be seen, which has both been seen for a large cantilevered grandstand and has been verified experimentally in the laboratory. If the condition occurs where the structural frequency is below the human frequency, the observed structural response for the combined system appears at a lower frequency than that of the bare structure.

The development of the theoretical methods of modelling human-structure vibrations also leads to methods of measuring the frequencies of crowds or individuals and calculating system behaviour. To date work has not been undertaken on sway vibrations, but the required experimental procedures are clear and the mathematical models used for vertical vibrations should be valid. Sway tests should be conducted by BRE in 1994.

4. SITE EXPERIMENTS ON GRANDSTANDS

BRE have examined a number of temporary grandstands and two permanent cantilevered stands in order to get some practical experience with these types of structure. It is only by obtaining such experience that the real problems and solutions can be identified. Also there are some characteristics, e.g. damping, which cannot be predicted, but where experimental values are required for any calculation of dynamic behaviour; however, these values are not yet available for a wide range of structures.

For each structure, BRE adopted the following experimental procedure:

1. Test the structure when empty to identify the system behaviour and define the fundamental mode in each direction (vertical, sway and front-to-back).
2. Monitor the response of the structure as the spectators get seated, throughout the event and as the spectators leave.
3. Analyse 2. to see
   a. peak response
   b. frequency at which peak response occurs
   c. changes in structural (system) characteristics due to crowd

Theoretically it is possible to derive modal loads from measured response knowing the system characteristics but this is only viable on relatively simple systems.

A range of structures has been examined for various types of event, but in this paper only a few of the findings can be mentioned. For the two cantilevered grandstands, one had a fundamental frequency approximately equal to the crowd frequency, hence two frequencies were observed with the crowd present. The other had a frequency much less than the crowd frequency hence when the crowd was present a lower frequency was recorded in comparison with the empty condition. Although one of the cantilevered stands had a relatively low fundamental frequency it didn't suffer significant vibrations because the large crowd did not have any co-ordinated actions.

For the temporary grandstands, the fundamental vertical frequencies were sufficiently high to avoid safety problems from dynamic loading, however, the frequency of the fundamental sway modes were often very low, especially for the taller systems. For the lower frequency modes changes were noted in the frequencies when crowds were present, the observed changes supporting the human-structure model. For a lot of events the vibrations, were relatively low level, with the wind providing a significant vibration source for outdoor events. However, for pop concerts where stamping and jumping was common, response at the jumping frequency and whole number multiples thereof was observed for vertical vibrations and a corresponding pattern was seen for horizontal vibrations. This latter point is of particular interest as it shows that vertical loading is being channelled into horizontal vibrations, and hence provides a mechanism for producing significant vibrations at higher frequencies than simple sway vibrations.

5. DISCUSSION

To date the experimental work has identified a number of points. For temporary grandstands the sway frequencies are relatively low, suggesting that resonance at the basic load frequency is possible, however this is only likely to happen at events like pop concerts where crowds respond to music. This is likely to be a problem for taller grandstands. For temporary grandstands the vertical frequencies are usually quite high hence vertical response is likely to be adequate. For cantilevered stands or dance floors, vertical motion is likely to be of concern, but again only for certain events. As the dynamic loads generated by jumping are far greater than for non co-ordinated movements, it begets the question as to whether it is reasonable to introduce classifications with different loads for grandstands when different types of crowd behaviour can be guaranteed. However, significant loading cases cannot be attributed solely to pop concerts, for example in Brazil football crowds tend to sing and dance to their favourite songs when goals are scored, hence compounding the problems which have been noted in the Maracana stadium.

The common method of avoiding resonance, and the potential problems which it introduces, is to set a minimum fundamental frequency (in the appropriate direction) above the range of expected excitation frequencies. It should be noted that this is only reasonable when considering displacements, and cannot be justified for accelerations; the reasons for this are given in ref. [6]. Two points should be borne in mind when considering a minimum frequency. First, the interaction between crowd and structure will affect the frequency, and second, the question again arises as to whether different types of event justify different frequency limits.

For vertical loads the frequency range and likely load amplitudes are known, albeit further work is required on the crowd effect, which models the reduction in load due to a lack of synchronisation of a large crowd. For sway loads more work is required on estimating both load amplitude and frequency range, and on the transference of vertical loads into sway motion. For human structure interaction, work is required on modelling human whole body motion, both for sway motion and for evaluating dynamic effects. For grandstands, tests to monitor the response to co-ordinated jumping should be sought and further measured values of damping are required.

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