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Temporary demountable grandstands: dynamic response

IP 3/00

JD Littler, PhD

BRE Centre for Structural Performance

Concern has been expressed about the safety and serviceability of various forms of grandstands when subjected to human loading, particularly loading which is synchronised and periodic as may occur at some pop concerts. This paper gives details of

the main results obtained from BRE full-scale tests on fifty temporary demountable stands. The dynamic behaviour of the empty stands in terms of their natural frequencies, damping values and mode shapes are presented. The results from twenty-three stands that were monitored during live events are also

presented in terms of the peak accelerations and displacements obtained, and the changes in natural frequency and damping that occurred as the stand was loaded. This paper will be of interest to those engineers who are responsible for designing stands or for local authority licensing of stands.

Introduction

In May 1989 the Institution of Structural Engineers (IStructE) issued a report entitled *Safety considerations for the design and erection of demountable grandstands*^[1]. This was the first guidance document issued in the UK to address the dynamic response of demountable structures and to contain advice relating natural frequencies to the proposed use of the stand. In March 1992, BRE began a research programme

sponsored by the then Department of the Environment (DOE; now DETR) looking at the dynamic response of retractable and demountable seating. This was partly due to the concerns raised by the Standing Committee on Structural Safety^[2]. The collapse of a temporary grandstand at a soccer stadium in Bastia, Corsica, in May 1992 killed 17 people and injured over 2500. This tragedy was a timely reminder of the potential consequences of dynamic crowd loads on flexible structures.



One type of temporary demountable grandstand



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To assess the safety implications for the design and use of these structures, BRE began a series of tests measuring the dynamic characteristics of empty temporary demountable grandstands and then monitoring them during various events. Fifty empty demountable stands were tested over the next five years, about half of these then being monitored during subsequent pop and rock concerts or sporting events. In addition to these full-scale tests, BRE carried out analytical and laboratory-based studies^[3,4]. The full-scale tests confirmed the analytical work which showed that the critical loading case was that where rhythmic loading was applied to the structure^[5,6]. Results from this work were incorporated within the DOE interim guidance on temporary grandstands^[7] and later the IStructE guidance document on temporary demountable structures^[8], which was updated in a second edition issued in March 1999^[9].

As well as the tests on demountable stands, BRE has carried out some similar tests on retractable and permanent stands. These showed that both these types of stands have a different dynamic behaviour to demountable ones and so require separate consideration^[10,11].

A revised UK loading code (BS 6399-1) was issued in 1996^[12]. Unlike previous codes this specifically covers dynamic loads, and includes a section on synchronised dynamic crowd loads. Further background information on this topic is given in BRE Digest 426^[13]. A new edition of the *Guide to safety at sports grounds* (the 'Green Guide') was also issued in 1997^[14]. This also has a section on dynamic loading, although this mainly refers to permanent structures.

Two different considerations apply to any analysis on temporary grandstands: the safety of the structure depends on maximum displacement or stress, and the serviceability (in terms of crowd comfort and concern) of the stand depends on human perception of motion and hence acceleration.

Throughout this paper, measurements of the response of the stands are described in terms of three mutually orthogonal directions: vertical, front-to-back (FtoB) and sway.

Tests on empty stands

Test procedure

The fifty demountable stands tested were of fifteen different types. Their capacity ranged from 243 to 3500 seats. The sway dimensions varied from 11.2 to 118.6 m while the FtoB dimensions varied from 5.3 to 34.9 m. Only two of the stands had larger FtoB dimensions than sway ones. The maximum height of the back of a stand above the ground was 14.8 m.

Every stand was tested when empty. For stands erected outdoors, ambient vibration tests were carried out involving recording the response of the stand to wind-induced vibration. Fast Fourier transform (FFT)

techniques were used on the recorded data. The peaks in the autospectra that this analysis produces identify the natural frequencies of the stand. Simple impact tests were used at indoor and some outdoor venues. The same FFT techniques were used to obtain natural frequencies from the recorded response. Steady-state forced vibration tests were conducted on twenty-five of the stands. In these tests a known force was applied to the structure at a known frequency. This type of test can be used to determine mode shapes and damping values as well as natural frequencies. The methodology of these tests is described in detail in reference 15.

Natural frequencies

Various design guidance documents give frequencies above which the safety of the structure should not be influenced by resonance problems due to human loading and below which the effects of dynamic loading should be assessed. These frequencies are determined by the loading, and are independent of the structure to which the loading is applied. BS 6399-1 states that 8.4 Hz is the relevant frequency in the vertical direction. The figure of 8.4 Hz is three times 2.8 Hz, which is considered to be the highest frequency that a large number of people can co-ordinate their movements. Only one of the demountable stands had a vertical mode below 9 Hz. However, this stand (which had a fundamental vertical mode at 7.9 Hz) was erected at a sporting event where there was no prospect of synchronised dynamic loading. The tests showed that the vertical natural frequency of a demountable stand is unlikely to be the critical factor in its design.

Table 1 shows the distribution of horizontal natural frequencies (to the nearest 0.1 Hz) for the tested stands. With two exceptions, the fundamental sway frequencies ranged from 1.8 to 6.0 Hz. The two exceptions were demountable stands that were effectively permanent installations and were much stiffer. The fundamental FtoB natural frequencies ranged from 2.1 to over 10 Hz. Only seven stands had lower FtoB natural frequencies than sway ones. This is the opposite finding to the one on retractable stands^[10].

Table 1 Distribution of fundamental horizontal natural frequencies

Frequency	Number of stands	
	Sway	FtoB
Under 3.0 Hz	15	10
3.0 to 3.9 Hz	17	13
4.0 to 4.9 Hz	13	9
5.0 Hz or over	5	18

BS 6399-1 states that horizontal natural frequencies of the empty stand in excess of 4 Hz are required in order to avoid resonance effects caused by synchronised dynamic loading. Just over half of the demountable stands tested met this criterion in the FtoB direction, but only 36% of the stands met this criterion in the sway direction.

However, it is important to recognise that most of the stands were erected for events where synchronised dynamic loading was unlikely to occur, and therefore the 4 Hz criterion would not apply. Only seven of the demountable stands were erected for pop and rock concerts. None of these stands had a fundamental FtoB natural frequency under 4 Hz. Three of them had fundamental sway natural frequencies under 4 Hz. These were all of the same late 1970s design and were supplied before any design guidance on the dynamic response of demountable stands was available. The frequencies of these stands ranged from 2.0 to 3.4 Hz.

The majority of the designs were not tested at concert venues. It is not known which of the designs that were tested at only sporting venues are also used at concert venues; or what, if any, modifications are made to these stands if they are used at concert venues.

As extra bracing can be added to most demountable stands with little difficulty, there is no apparent reason why the 4 and 8.4 Hz frequency criteria cannot be met where stands are erected for events where synchronised dance loading is expected. Reference 16 shows how bracing should be applied to stands to maximise the effective stiffening for a given number of bracing elements. Some measurement of the frequencies of a few stands erected from proprietary systems for pop and rock concerts may be required to ensure that the frequencies calculated by manufacturers are being achieved in practice. However, once this calibration exercise has been performed and the manufacturer's calculations verified, there should be no need for regular monitoring of these structures.

There was an opportunity to compare fourteen stands of the same design at a single event. The stands varied in shape and overall dimensions, but their construction was the same. There was a clear decrease in the frequency of the fundamental sway mode as the height of the stand increased. There was also a trend showing a decrease in the sway frequency as the FtoB dimension of the stand increased. Although there was a corresponding trend for the frequency of the FtoB mode to decrease as the height of the stand increased, it was less marked than for the sway mode.

Damping

Damping could be assessed only on those stands where steady-state forced vibration tests were carried out. The measured damping values for the fundamental sway modes were in the range 1.5 to 4.5% critical. The damping values for the fundamental FtoB modes were in the range 2.2 to 6.0% critical, with one exception where a value of about 17% critical was obtained.

Mode shapes

Mode shapes could be measured only on those stands where steady-state forced vibration tests were carried out. Some of the stands had mode shapes which showed that the stand acted as a single body, while on other stands parts of the same structure acted independently.

Almost all of the sway mode shapes were very similar. They showed that the greatest movement was at the back of the stand. The response decreased almost linearly towards the front of the stand where the smallest response was recorded. The same amplitude of motion was measured all the way along the stand, all the measured responses being in-phase. The one exception had the two ends of the stand moving in anti-phase with each other. However this stand was unusual in two ways: the two ends of the stand were at an angle to the main part of the stand, and there were exits at several positions along the back of the stand so that the back five rows were broken up into blocks of seating.

The fundamental FtoB mode shape was successfully measured on sixteen stands. In ten of these the response was primarily on the block of seating being excited with very little response further along the stand. The response on the block of seating being tested was greatest at the back of the stand and smallest at the front. In four of the stands the mode shape was monolithic, ie seating blocks further along the stand were responding at a comparable level to the one being excited. However, there were three different types of response within this monolithic behaviour. On two of the stands all the response was in phase. Another stand was excited in the centre and this produced a mode shape where one end of the stand responded in phase with the centre and at roughly the same amplitude but there was very little response at the other end of the stand. Ambient tests suggested that each end of this stand had its own FtoB mode. Yet another pattern was found on a stand which had a canopy attached to it. Here the response at the ends of the stand was in antiphase with the response in the centre.

All of the measured horizontal mode shapes showed that, as expected, the greatest response takes place at the back of the stand. This is an important difference from the mode shapes for retractable stands where the greatest response occurs between the mid-height and the back of the stand.

Monitoring during events

Monitoring

Twenty-three stands were monitored when occupied by a crowd during an event. Six of these events were pop or rock concerts and one was a drama festival. The remaining sixteen were sporting events. These comprised motor racing (5), soccer (4), golf (3), tennis (2), horse racing (1) and boxing (1).

All of the stands which were monitored had been previously subjected to steady-state forced vibration testing when empty. On the day of an event, accelerometers (sometimes supplemented by displacement transducers) were fixed to the underside of the stand at various locations to measure the response in three directions throughout the duration of an event. The transducers were usually positioned where the mode shapes showed that the largest responses were to be expected, but in some cases the preferred position had to

be changed to one which was more practicable. The response from the transducers was recorded on a digital tape recorder and analysed after the event. Each recording was divided into a number of contiguous records of equal duration (usually 51.2 seconds). The basic analysis conducted for each data channel determined the peak response (acceleration) during each individual record and the frequency of maximum response in the autospectrum produced from each record. This analysis showed how the characteristics of the stand were altered by crowds on them, the response of the structure during the particular event, and the frequency content of the response.

Effect of loading and unloading

Significant changes in horizontal frequency were observed when some of the grandstands were loaded with people. Figure 1 shows how the fundamental sway frequency of a stand varied during eight hours of a tennis tournament. In this case each record was 204.8 seconds in length. Play was interrupted by rain, hence the stand was loaded and then unloaded three times over the length of the recording. It can be seen how the natural frequency reduced from about 2.7 to 1.7 Hz as the stand filled. In this case the crowd was fairly sedate and the natural frequency of the stand (excited by the wind) rather than the forcing frequency of the people on it predominated. Similar behaviour was also observed on some of the other stands although in most cases only a single cycle of loading and then unloading was recorded.

Changes of frequency with loading were observed on thirteen stands. In all these cases the natural frequency of the sway mode fell as the stand was loaded. In terms of frequency change, these falls varied from 0.4 to 2.0 Hz, averaging 1.1 Hz. As a percentage, these changes varied from 11 to 48% and averaged 33%.

Five of these stands also showed a change in the frequency of the FtoB mode. These changes were always less than those observed for the sway mode. On four stands a reduction in frequency of between 0.3 and 0.8 Hz

(9 to 36%) was noted as the stand was loaded, but on one stand there was an increase of 0.8 Hz (22%) as it was loaded^[17].

On a few stands it was possible to observe a change in damping as the stand filled. In each of the five stands where this was observed the damping in the fundamental sway mode was greater when the stand was full than when it was empty. However, in each case the non-stationarity of the data precluded quantifying the change in damping.

Effect of type of event

The type of loading varied significantly from one event to another. In particular there was a major difference between the type of loading at sporting events and that which occurred at the pop and rock concerts.

At the events where there was a fairly sedate crowd (tennis, golf, drama festival) the peak accelerations tended to be caused by people moving to or from their seats rather than reacting to some event they were watching. Whilst the crowd at the horse racing event could not be said to be sedate, the maximum recorded accelerations also occurred whilst people were moving on and off the stand rather than when they were watching a race. At the beginning of most of the recordings from 1994 onwards a vertical impact test was performed on the stand directly above the measurement position. At the events where these were measured where the crowd was fairly sedate (golf and the drama festival) these impact tests produced greater accelerations than anything produced by the people on the stand.

At the soccer and boxing events the peak accelerations almost always coincided with the people on the stand reacting to events on the field of play (eg rising to their feet as a goal was scored or stamping their feet in approval). Some of the maxima at the motor racing events occurred as people reacted to events on the track while others occurred as people left or entered the stand. At almost all of these events the accelerations produced by an impact

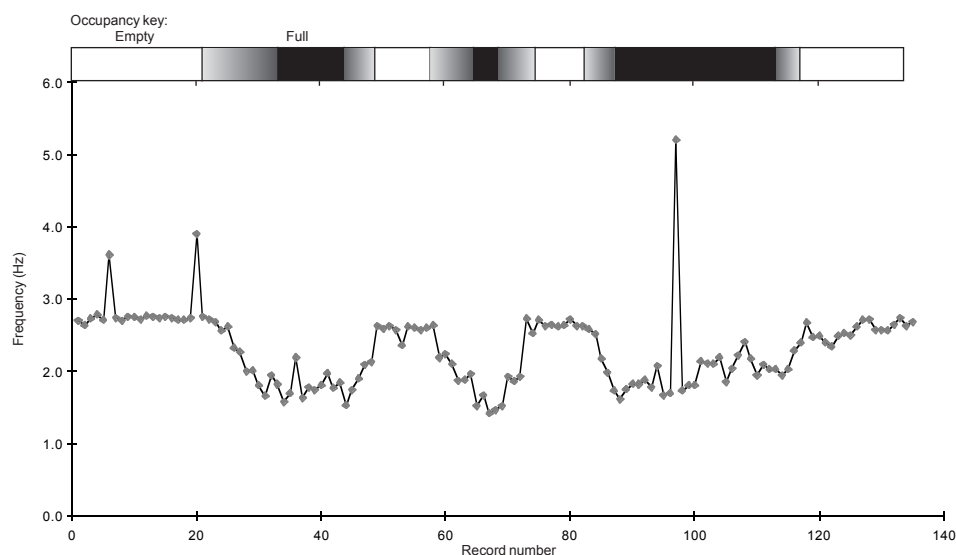


Figure 1 Variation in the fundamental sway frequency of a stand over 8 hours of a rain-affected tennis tournament

test were less than those measured during the event.

The upper part of Figure 2 shows a time history from the monitoring of a stand during a soccer game. This shows the peak acceleration during the whole recording as the home side just failed to score. The lower part of the figure is the autospectrum resulting from this time history

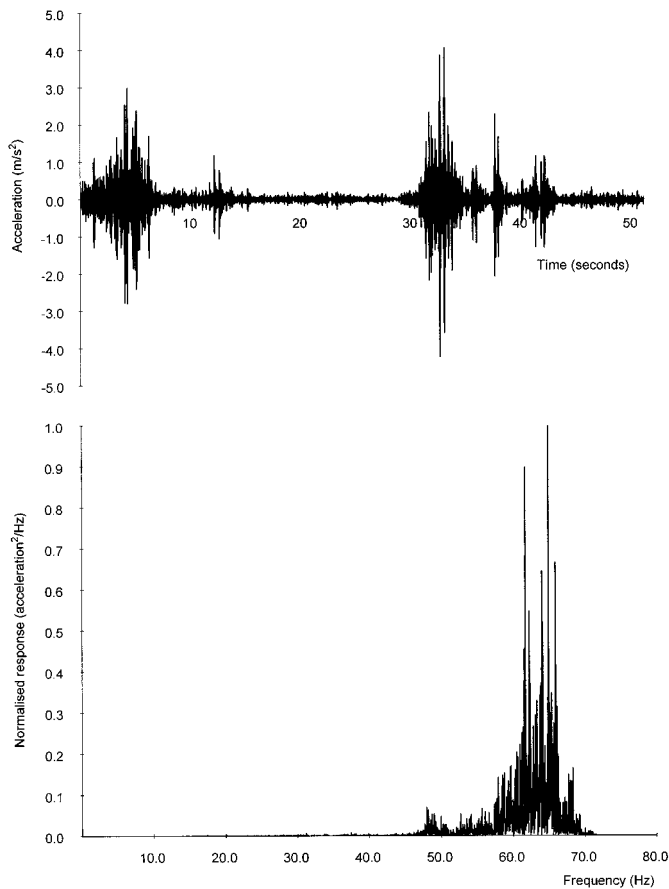


Figure 2 Time history for 51-second record and the resulting autospectrum from an accelerometer in the sway direction during a soccer game

and shows that the main frequency content of the response was between 50 and 70 Hz. This is typical of the peak responses obtained at the sporting events where the peak response is caused by the crowd reacting to something they are watching. The highest accelerations measured at any sporting event were measured on another stand during a soccer game as the crowd leapt to their feet as the home side scored a goal. These accelerations were 45, 28 and 24 m/s^2 in the vertical, sway and FtoB directions respectively. However, these maximum accelerations did not occur at the fundamental frequencies of the stand. Filtering the relevant time histories showed that the maximum accelerations with frequency components below 15 Hz were over an order of magnitude smaller than the values quoted. The principal frequency at which the accelerations occur has a significant effect on human perception.

The maximum peak accelerations at the pop and rock concerts occurred during one of two types of activity. The audience was either stamping for an encore or jumping up and down in time with the beat of the music (pogoing). In contrast to what happens at the sporting events, the forcing frequency dominates the response at pop and rock concerts where the crowd jumps or stamps in time to the music. Figure 3 is a 10-second extract from a time history obtained during a concert. The beat frequency of the music can be seen clearly as maximum responses of relatively short duration and therefore high frequency content. Figure 4 shows the autospectra obtained for the three mutually orthogonal accelerometers mounted in one position during this 102.4-second record. These show the main beat frequency of the music (2.03 Hz in this case), 1.5 times this frequency, and all the integer multiples from 2 to 6 of this frequency. The maximum vertical acceleration during this record was one-third larger than the maximum acceleration in the sway direction and 70% larger than the maximum acceleration in the FtoB direction. However, on other occasions people jumping

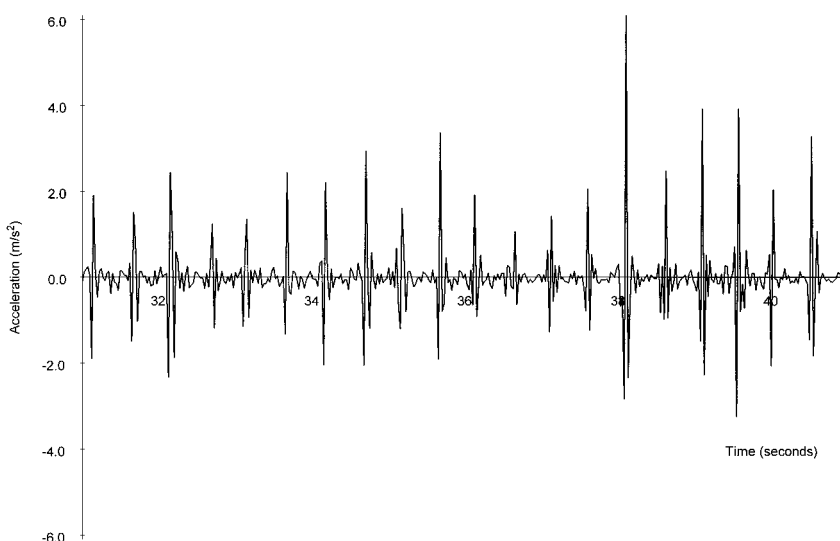


Figure 3 A 10-second extract from a time history measured in the vertical direction on a stand during a pop concert

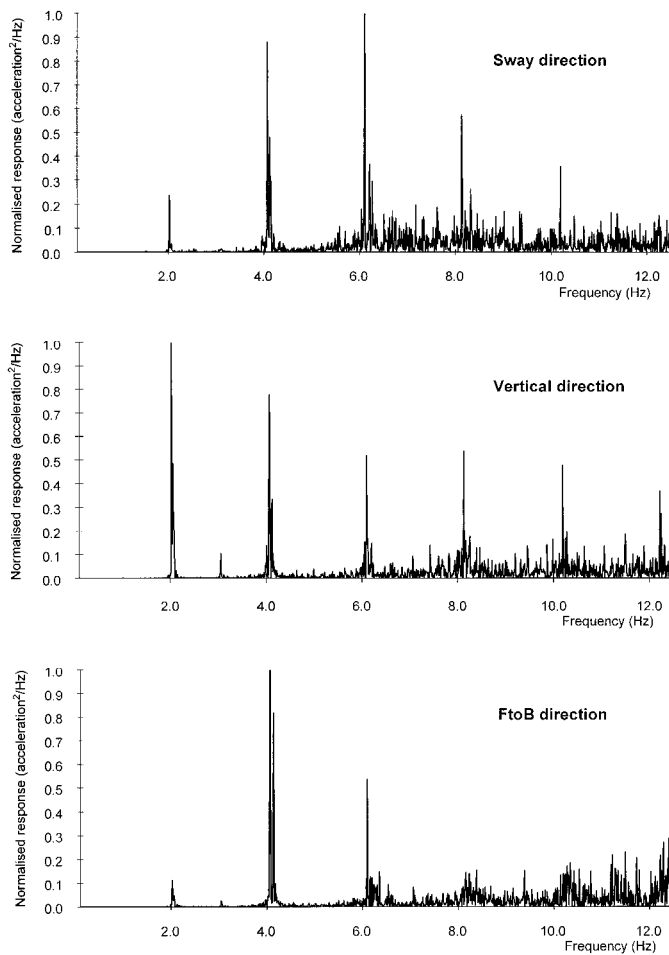


Figure 4 Autospectra from three mutually orthogonal accelerometers for a 102-second record on a stand during a pop concert

and stamping at pop concerts produced higher accelerations in the horizontal direction than the vertical direction. Indeed, at four of the six pop and rock concerts that were monitored there were larger accelerations in the horizontal than the vertical direction. It should be noted that although the maximum accelerations such as that shown in Figure 3 occurred when the audience was jumping at the beat frequency of the music, the frequency content of these accelerations was different from the beat frequency as they were caused by a succession of individual impacts. Most of the frequency content of these individual impacts was in the range 30 to 60 Hz. Filtering the time histories showed that the maximum accelerations occurring at the beat frequency of the music, or twice this frequency, were over an order of magnitude smaller than the unfiltered maximum values.

Most of the graphs of the frequency of maximum response plotted against record number for stands during pop and rock concerts tended to show that during the concert the response was at a distinct frequency for several records and then switched to a different frequency. These frequencies correspond to the beat frequency of the song or a multiple of it.

Table 2 Maximum measured peak accelerations (m/s^2)

Event	Unfiltered		Filtered at 10 Hz (low-pass)	
	Vertical	Horizontal	Vertical	Horizontal
Pop/rock concert	20.4	59.5	2.1	12.7
Pop/rock concert	23.8	32.5	0.9	1.5
Pop/rock concert	19.6	28.9	1.5	0.7
Pop/rock concert	8.3	3.8	—	—
Pop/rock concert	7.1	4.0	—	—
Pop/rock concert	4.5	5.1	—	—
Soccer	45.1	27.7	4.1*	0.6*
Soccer	25.0	23.5	2.8	1.3
Soccer	14.9	21.1	0.7	0.2
Soccer	3.8	11.5	0.7	0.4
Boxing	8.2	2.8	—	—
Motor racing	9.4	15.7	0.4	0.3
Motor racing	8.6	3.3	2.2	0.6
Motor racing	3.9	10.8	0.3	0.2
Motor racing	7.8	7.2	0.1	0.1
Motor racing	3.8	3.7	0.2	0.2
Horse racing	3.1	1.0	0.4	0.1
Golf	10.7	4.2	0.7	0.1
Golf	3.8	2.7	0.3	0.8
Golf	1.1	0.6	0.2	>0.05
Tennis	4.4	1.6	0.3	0.1
Tennis	—	0.1	—	—
Drama festival	1.9	4.9	0.1	0.1

* 15 Hz filter used

Table 2 gives the maximum measured peak accelerations for all of the events that were monitored, with similar events grouped together to aid comparison. For the tests performed from 1993 onwards the maximum acceleration with frequency components below 10 Hz is also given. Comparing the unfiltered and filtered values for the same event shows that almost always there is an order of magnitude difference between them. This, and comparison with the relevant impact test data, shows that most of the unfiltered peak accelerations are probably localised and caused by people jumping or causing some other form of impact close to the accelerometer positions.

Serviceability

The frequency criteria in the various design guidance documents are concerned with the structural safety of the grandstand structures, not their serviceability. Therefore, even if structures meet the frequency criteria, they may well have serviceability problems, although this does not imply that the stands are unsafe.

Motion was perceptible on some stands during concerts, and instantaneous deflections of two stands erected for soccer games were also noted. A maximum acceleration of $0.05g$ (0.5 m/s^2) has been suggested as a possible serviceability criterion for human comfort. However, this would be totally inadequate for demountable stands. On twenty-two of the twenty-three stands monitored the measured unfiltered maximum acceleration exceeded this suggested acceleration in both the vertical and horizontal directions. On eight of the stands the unfiltered acceleration exceeded the suggested one by more than a factor of ten in both directions. Even if the measured acceleration is filtered to remove all the components above 10 Hz, the maximum measured accelerations still exceeded the suggested accelerations at all the pop and rock concerts, most of the soccer games in both the horizontal and vertical directions, and at some other sporting events in one if not both directions. Even if a higher acceleration level were adopted, the BRE tests have indicated that most of the measured peak accelerations are likely to be highly localised. Thus a stand might 'fail' the acceleration criterion at one position but 'pass' almost everywhere else, or vice versa. All of these problems mean that it is not practicable to adopt a sensible serviceability criterion for demountable stands which is based on peak accelerations alone. The best way forward appears to be to use a dose measurement which uses both a frequency weighting and a measure of the duration of each acceleration level.

Audience response to event

Figures 2 and 3 show examples of the typical time histories obtained for peak responses at sporting events and pop concerts respectively. Figure 5 shows a time history obtained on a stand during a soccer game. This is fairly similar to Figure 3 in that it shows a succession of impacts at roughly equal intervals. Whilst not noted, this could well be when the crowd was stamping in time to a chant. In this particular case the loading was fairly short lived and the crowd was not very good at keeping to a particular beat. However, if they were better co-ordinated (say by reacting to music played over the public address system) then there is certainly the potential for a repetitive low-frequency loading to be applied by this mechanism.

A direct measure of displacement was made on three of the stands. The maximum peak displacements recorded on a stand at a pop concert were between 0.8 and 2.0 mm. These all occurred as the audience was dancing, on most occasions when the crowd was pogoing. Filtering the displacement data showed that, in contrast to the accelerometer data, almost all of it had frequency components below 10 Hz, the vast majority of it being at the beat frequency of the music or its second harmonic. For example, the maximum unfiltered vertical displacement of 1.88 mm at one event reduced to a displacement of 1.74 mm when passed through a 10 Hz low-pass filter.

At most of the events monitored by BRE, none of the personnel undertaking the testing were able to sit on the stand. However, one stand at a soccer match was seen by the BRE personnel under it to deflect as the home side scored and the accelerations of up to 45 m/s^2 given in Table 2 occurred. Motion of some of the stands monitored during pop and rock concerts was both visible and perceptible in certain songs when sections of the crowd were dancing.

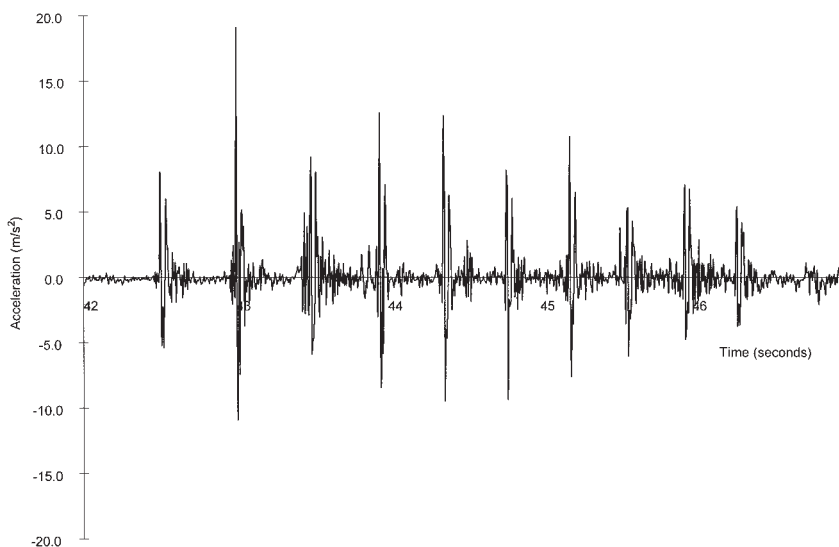


Figure 5 A 5-second extract from a time history measured in the vertical direction on a stand during a soccer game

Figure 4 is typical of the spectra obtained during concerts in that the stand was excited at the beat frequency of the music (the frequency at which people are dancing or jumping) and the integer multiples of this frequency. Which spectral peak is the largest varies from stand to stand and song to song. In general the multiple of the beat frequency closest to the natural frequency of the stand gave the largest spectral (acceleration) response, although this was certainly not always the case. However, where displacement rather than acceleration was being measured, the peak spectral response was almost always at the beat frequency of the music (the forcing frequency) not a higher harmonic.

Conclusions

There appears to be little problem with demountable stands meeting the vertical frequency criterion given in BS 6399-1. However, in almost every case the fundamental sway natural frequency was critical: only 36% of the tested stands passed the frequency criterion for the sway direction, 54% passed for the front-to-back direction. As extra bracing can be added to most demountable stands with little difficulty, there is no apparent reason why the 4 and 8.4 Hz frequency criteria cannot be met where stands are erected for events where synchronised dance loading is expected. The synchronised loading of pop concert audiences to music produced responses at the beat frequency of the music and its harmonics. In some cases these excited the natural frequencies of the stands and visible motion was produced.

Acknowledgements

Most of the work presented in this paper has been sponsored by the Department of the Environment, Transport and the Regions (DETR). I would also like to thank the companies that erected the grandstands, and the venues, for their co-operation in the testing, and the colleagues who took part in the testing and analysis.

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ISBN 1 86081 363 1