The Institution of Structural Engineers
The Department for Transport, Local Government and the Regions
The Department for Culture, Media and Sport

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Dynamic performance requirements for permanent grandstands subject to crowd action

Interim guidance on assessment and design

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SUMMARY

The Guidance has been prepared by a joint Working Group of the Institution of Structural Engineers, the Department for Transport, Local Government and the Regions, and the Department for Culture, Media and Sport, as a supplement to the 4th Edition (1997) of the *Guide to Safety at Sports Grounds* and particularly the guidance given therein on structural dynamics for permanent structures.

Guidance is given on vertical natural frequencies necessary to provide safety and adequate comfort for different categories of use in permanent grandstands in steel, concrete or composite construction of a size (supported spans greater than 6m or cantilevers greater than 2.5m) considered likely to be significantly affected by dynamic loading due to crowd action. Recommendations are also made for horizontal load resistance.

The Guidance deals with both existing and new grandstands. The main recommendations are summarised in Figures 1 and 2, concerned respectively with assessment and implementation, and Table 1 dealing with horizontal load resistance. The remainder of the document provides the background to the recommendations to enable informed application of the principles by both the designer and the Local Authority responsible for the issue of a Safety Certificate. Particular guidance is given to the managers of existing facilities that have natural frequencies for vertical vibration of an empty stand less than 3Hz. Stands with the minimum vertical natural frequency greater than 6Hz are considered suitable for all kinds of events, including pop-concerts, provided the requirements for horizontal load resistance are satisfied.

The Guidance highlights that grandstand design and assessment are specialist topics that require the involvement of a Chartered Engineer with experience in structural dynamics and knowledge of human induced dynamic loading in the context of grandstand design. The need for more information on the performance of grandstands in service is also noted with a recommendation for the maintenance of a central database containing information on design criteria, dynamic performance and crowd reaction from grandstands in the UK.

The Working Group is currently preparing separate Notes on the procurement and conduct of tests to determine natural frequencies of grandstands and on the calculation of natural frequencies. These Notes will be complementary to the Interim Guidance.

1 Introduction

The design of sports venues has seen much development over the last decade. Designers have accommodated the positive recommendations of the Popplewell[1] and Taylor[2] safety Inquiries and, with the publication of the Fourth Edition of the Green Guide[3] in 1997, have available a comprehensive review of the factors influencing safety in sports grounds. As a consequence, there have been significant improvements in the safety of sporting venues whilst, at the same time, design has been affected by a need to respond to the changing needs of the sports business itself.

Modern sporting events are now part of the global entertainment business and what was once two hours standing on a terrace to support the home team has now become a full day-out with multiple events and entertainment at high-technology facilities. As owners and operators look to maximise revenue, sporting venues are increasingly used for 'total' entertainment on match day and also for additional functions that use the full arena, such as pop and rock concerts. These extensions of use will necessarily produce new kinds of loading on the fixed facilities, including grandstands, which need to be considered in design and assessment. In particular, the expected dynamic loading associated with crowd movement will be more severe than it was historically. Experience has already shown that these increased loadings can induce motion sufficient to cause concern to spectators. As a result, some existing grandstands have required modification.

Designers have recognised that new sporting venues must now be designed to provide a safe and comfortable environment for spectators/visitors for any one of a number of entertainment events and constructed accordingly. It is also recognised that older venues, that were constructed before and during the changes towards mixed use, must be assessed for their performance, given the changes in the way in that they may now be used.

In addition to the change of use of sports venues, the nature of their construction has also developed through the design of cantilevered tiers that permit unobstructed views of events. These cantilevers are becoming longer and more exposed, as seating bowls/tiers are compressed to bring spectators ever closer to the central arena action. As a result, tiers have become more flexible and often have lower natural frequencies of vibration. The combination of lower natural frequency and livelier crowd behaviour means that dynamic loading must be seriously addressed.

The variety of structural form and usage of grandstands presents difficulties for both the designer and the relevant authority responsible for licensing the use of a sports ground or issuing a Safety Certificate for an event. These difficulties are not fully addressed in either the Green Guide[3] or BS 6399[4]. Both the Guide and the Standard set 'trigger values' for natural frequencies as a precursor to a requirement for a more detailed dynamic evaluation. This Interim Guidance is intended to take this process further by recommending dynamic structural performance criteria for different categories of use particularly related to permanent grandstand structures of a size for which dynamic effects will be of importance. As a rough guide, this can be taken to be where seating decks, in steel, concrete or composite construction, have supported spans greater than 6m or cantilever more than 2.5m.

There are wide differences between permanent and temporary grandstands in materials, form of construction and use. Accordingly, the present guidance is not intended for use with temporary structures. These are normally in place for a short time, generally no more than 28 days, and designed to be erected and dismantled many times. Separate guidance is already available for such temporary demountable structures[5]. Additionally, the particular requirements of telescopic or retractable stands have not been considered in preparing this Guidance. The CEN Committee TC315 is currently preparing a European Standard for telescopic and demountable seating structures.

2 Background to appraisal and design of grandstands

2.1 Role of the Working Group

The structural design of grandstands in the UK is currently based on requirements of Building Regulations, relevant British Standards, in particular BS 6399[4], and the Green Guide[3]. As outlined in Section 1, these requirements are not fully sufficient for either the design or assessment of grandstands. No guidance is available for detailed analysis of dynamic response and there is an absence of performance criteria other than indicative or trigger values of natural frequency. Successful design accordingly requires the involvement of an experienced designer with knowledge of structural dynamics and crowd behaviour to interpret the requirements in a way that is relevant to grandstand structures and their variety of usage.

The Joint Working Group of the Institution of Structural Engineers, Department for Environment Transport and the Regions (DETR)* and the Department for Culture Media and Sport (DCMS) was set up in January 2000 to consider what additional guidance is required and to make recommendations in relation to the dynamic performance and design of stadia structures and seating decks. It was soon evident that guidance is needed on appraisal and testing of existing structures, methods of analysis to support detailed design and on performance criteria relevant to different categories of use.

As a first step, the Working Group has prepared this Interim Guidance on performance requirements for grandstands subject to different kinds of crowd loading. Even with guidance of this sort, assessment and design of grandstand structures will not be a clear-cut business and will generally need the involvement of an experienced Chartered Engineer with appropriate experience in structural dynamics and knowledge of the effects of human induced dynamic loading.

2.2 Dynamic issues for grandstands and sporting events

Values of the fundamental natural frequencies for vibration in the vertical or lateral directions have become the currency for comparing grandstand performance and assessing acceptability for purposes of certification. This is, at best, a coarse measure and needs to be considered in combination with other factors such as the intended use of the stand, the way the use is controlled, the provision of structural damping and, for existing structures, experience of how these have actually behaved.

Evidence provided to the Working Group confirms that existing grandstand structures have, with few exceptions, performed satisfactorily when used for spectators watching football matches. There have been two recent instances where grandstands have needed to be modified structurally following the occurrence of vertical dynamic movement sufficient to cause concern to spectators and officials. Both structures had fundamental natural frequencies below 3Hz for vertical motion. The best information currently made available to the Working Group on grandstands used for football, suggests that the great majority of existing grandstands have higher natural frequencies and consequently would be expected to have better dynamic performance.

Nevertheless, it is a matter of concern that grandstands with such low natural frequencies were in use. The problems associated with dynamic crowd loading are not confined to grandstands used to watch football. There is therefore a need for Local Authorities to focus attention on the existing stock of grandstands to ensure that all stands meet at least the minimum levels of performance proposed in this Interim Guidance.

The playing of music and singing of club songs as part of the entertainment can stimulate co-ordinated crowd movement and induce dynamic excitation. Ground Managers, Event Organisers and Certifying bodies need to be aware of the circumstances in which playing of music – even without the excitement of a rock beat – might lead to unacceptable motion.

2.3 Dynamic issues for pop concerts

Since publication of its twelfth Report in 1999, the Standing Committee on Structural Safety[6] (SCOSS) has communicated its concerns on the consequences of dynamic excitation caused by synchronised crowd movement. The most severe synchronised excitation is likely at events

*Later, DTLR, the Department for Transport, Local Government and the Regions

such as pop concerts where there is a heavy and rapid musical beat and where the crowd may jump, bounce, stamp, clap or sway in time to the music. The induced loading is markedly greater than that due to spectators watching football or other sports and can have a significant effect at higher frequencies than the actual beat of the music. It is important that this is recognised by stadium managers, as the dynamic loading induced by such crowd activity might not have been considered in the design of many existing grandstands. The management of such a facility should arrange for a suitably experienced Chartered Engineer to assess the adequacy of the structure before planning to use their grandstand for events where synchronised crowd activity is at all likely. It is also important to realise that any damage occurring to stands during a pop concert will have a safety impact upon subsequent sporting events. Because of this, and the possibility of cumulative damage if grandstands are used frequently for pop-concerts or similar high activity events, it is important that the structure is inspected regularly as part of a programme of planned maintenance.

The principal issue for both assessment and design is to ensure safety of the occupants of the grandstands and to provide an appropriate level of serviceability and comfort. Considering just structural behaviour, the requirement for safety means that the grandstand, or part of the grandstand, should not collapse and any motion must not be such as to cause panic of the occupants.

The Working Group is satisfied that properly constructed and maintained grandstands designed to satisfy the current building regulations, the static loading requirements of BS6399[4], together with the additional safeguards for lateral stability and minimum natural frequencies specified in this guidance note, are extremely unlikely to suffer structural collapse, even under synchronised crowd loading. Therefore, the focus for this guidance is on the way that individuals react to induced motion, the avoidance of panic and the provision of acceptable levels of comfort.

2.4 Serviceability issues and behaviour of existing grandstands

Serviceability for seating structures relates to the comfort of spectators and the continued operation of fixtures and fittings. For grandstands, human perception is of primary importance with any tendency to panic or feeling of discomfort being related to the dynamic response of the structure, in particular, the amplitude of vibrations and associated accelerations. All structures deflect to some extent or move under load and human perception is such that vibrations are noticed long before they are generally deemed uncomfortable.

Frequency limits provide only an indirect way of limiting motion to acceptable levels as the displacement and acceleration amplitudes are dependent on other factors including the nature of the loading, geometry, mass of the structure and damping. However, there are many venues with vertical natural frequencies within the frequency ranges proposed herein where experience in use has been reportedly satisfactory, including the staging of lively pop concerts. There is also a limited amount of information available from the results of measurements taken on grandstands during concerts and sporting events.

The UK Building Research Establishment has monitored the accelerations due to crowd loading in grandstands at a number of different events[7]. Measurements during concerts on seven grandstand tiers with vertical natural frequencies all above 4.6Hz, gave a maximum acceleration of 8.2%*g*. For the four stands with natural frequencies in the range 5.7Hz to 6.8Hz the maximum acceleration recorded over a total of six concerts was 3.9%*g*. Kasperski[8] obtained higher accelerations at pop-concerts when monitoring two grandstands with natural frequencies of 4.5Hz. These latter results are of particular interest as the investigation had been prompted by complaints from people attending earlier events. Nine different pop or rock 'groups' were involved in fourteen concerts at which the maximum recorded acceleration varied between 6.0%*g* and 19.0%*g*. To put these values in context**, Kasperski[9] suggests an acceleration of 35%*g* as the lower limit for the onset of panic whilst the Commentary to the National Building Code of Canada[10] prescribes acceleration limits of 4%*g*-7%*g* for design for rhythmic activities. Intermediate values of acceleration would relate to different levels of discomfort ranging from the tolerable to bordering on panic.

Although more results from monitoring are desirable, it is reassuring that the acceleration level for panic was not approached in any of the concerts where measurements were made and

** The accelerations quoted from the BRE tests are filtered values in which the recorded values have been passed through a 10Hz low pass filter. This eliminates higher frequency components that are less significant in affecting human comfort. The values from Kasperski are not filtered but are still significantly below the level associated with the onset of panic

that the lowest recommended design serviceability level for rhythmic activity (4%*g*) was exceeded only in some stands and that these had vertical natural frequencies less than 5Hz.

Even with these results, deciding what is acceptable is a complex and subjective matter. The Interim Guidance should be viewed in this context and where possible applied with regard to past experience of the venue and the 'group' appearing at a pop-concert.

2.5 Interim Guidance and the analysis of detailed dynamic behaviour

Currently the only guidance on dynamic human loads in the UK codes is 'limited guidance for jumping' in Annex A to BS 6399[4]. Applying this to grandstand structures with crowd loading leads to much higher responses than have so far been found in practice. The differences are so large that the Working Group is convinced that there is a need to review the loading, the analysis methodology and the acceptance criteria. This will form part of the longer-term activity of the Working Group. In the meantime, and in preparing this Interim Guidance, the Working Group has chosen to be guided primarily by the evidence available from observations on actual grandstands coupled with an understanding of the dynamic behaviour of structures.

3 Structural dynamics

3.1 Dynamic loading

Powerful dynamic loading can occur during a pop concert when a crowd responds physically in a rhythmic manner to music having a strong beat. However, a crowd can also behave rhythmically during a football or other sporting event, when music is played, when a team 'scores' or when spectators sing without musical accompaniment. Dynamic loading will occur when a group of people jumps, sways, claps or stamps in unison. A single event, such as the crowd suddenly rising or sitting together, can also produce a dynamic response but it is repeated events that can lead to significant motion. Loading can occur in both the vertical and horizontal directions. It can cause both vertical bounce and horizontal sway of either a component part (e.g. a seating deck), or of the facility as a whole (e.g. the entire stand).

Annex A to BS 6399[4] recommends that a frequency range for vertical excitation of 1.5Hz–3.5Hz should be considered for individual loads from dancing and jumping but that the range reduces to 1.5Hz–2.8Hz for larger groups due to difficulties of coordination at the higher frequencies. More recent work[11] suggests that this range might be narrowed to 1.8Hz–2.3Hz for large groups as occur at pop-concerts.

There is less information available on horizontal excitation due to crowd action. On the basis of experience with demountable stands, Dickie[12] has advised the Working Group that the frequency of horizontal excitation by a seated crowd could be as high as 0.9Hz for energetic sway but that this is not likely to be sustainable and that 0.7Hz might be considered a more representative value for purposes of design.

3.2 Description of rhythmic loading due to crowd activity

It may be shown that any rhythmic load time history may be represented as the superposition of a number of load components corresponding to integer multiples of the frequency of the basic motion. For example, crowd motion at frequency f will lead to load components at f (first harmonic, or fundamental frequency), $2f$ (second harmonic), $3f$ (third harmonic) etc. The magnitudes of the components decrease as the harmonic order increases, i.e. the first harmonic (or fundamental) is the largest.

For an individual, the magnitude of the different harmonics increases with the intensity of dynamic activity and whether it involves an 'impacting' motion such as jumping. Rhythmic jumping leads to the highest loads, which include significant components from the third and fourth harmonics[13]. This pattern of loading is somewhat modified when a large number of individuals attempt to jump simultaneously, even when accompanied with a musical beat.

When a group of people moves rhythmically, imperfect co-ordination between the load time histories associated with each person leads to some attenuation of the dynamic load generated by the group. This reduction, in average load per person, is greater for the higher harmonic components so that the third and fourth load harmonics become far less significant for crowd loading than for jumping by an isolated person or a small well-synchronised group. However, it must still be recognised that the ability of a group to act in a co-ordinated manner improves in the presence of an external stimulus of increasing strength, be it aural and/or visual.

Thus, the importance of the higher harmonic load components is believed to increase as the event scenario progresses to increased levels of likely crowd dynamic participation and as the nature of the motion progresses from 'non-impacting' to 'impacting', for example,

- Spectator event with no singing or music played; first harmonic dominant.
- Event with singing, but without musical accompaniment; some influence of second harmonic.
- Event with some audience participation with singing to musical accompaniment but without impacting motion; first and second harmonics significant.
- Dedicated pop or rock concert with audience participation and likelihood of jumping; first and second harmonics very important with the third harmonic becoming influential only if the audience reaction were unusually well synchronised.

This progression is utilised in defining the guidance in this note because the risk of a higher load

component causing a significant dynamic response will increase as the strength and impacting nature of the stimulus increases.

3.3 Response to rhythmic loading

The effect of dynamic loading from rhythmic activity of a crowd depends upon the proximity of the first or higher harmonic frequencies of the activity to any of the natural frequencies of the structure. The worst case occurs when one of the excitation frequency components is at or near to a natural frequency of the structure. Then, a resonant dynamic response can occur. For resonance, the response builds up rapidly cycle by cycle until a maximum limiting response is reached. The resulting cyclic motion can lead to discomfort or, in extreme cases, spectator panic or structural damage. It should be noted that, even at resonance, the response is limited by the mass of the structure, level of damping and by the inability of the crowd to sustain the motion in a synchronised manner.

3.4 Natural frequencies and modes of vibration

Apart from the loading and the type of crowd behaviour, the critical factor determining the severity of dynamic response is the lowest relevant natural frequency of the structure. Associated with each natural frequency is a 'mode shape', being a characteristic deformation pattern of the structure when it is undergoing vibration at one of its natural frequencies. With this terminology, the structure can vibrate in one or other or a combination of 'modes'.

- A 'vertical' mode is one that has a significant component of vertical displacement at the seating deck, such that it may be excited by the vertical dynamic load due to the crowd.
- A 'horizontal' mode is one that has a significant component of horizontal displacement in the front-to-back ('lateral') or side-to-side ('longitudinal') directions at the seating deck, such that it may be excited by a horizontal dynamic load introduced by the crowd.

Although the distinction between vertical and horizontal modes is generally a helpful one, it should be recognised that some vertical modes may involve horizontal motion and vice-versa. For example, a significant horizontal response has been observed[14] as a consequence of vertical jumping activity of a crowd. This could occur because a vertical mode with a horizontal response component has been excited. Alternatively, the jumping motion could have introduced a horizontal load component that excited a dominant horizontal mode. Similarly, depending on the structure, vertical response can be expected to accompany sway excitation. It is important to bear these complications in mind particularly when reviewing the results of testing used to confirm or determine values of natural frequency.

Depending upon the relative dynamic characteristics of the seating deck and of the main supporting structure, a mode shape may involve motion of the deck alone or could involve significant motion of the entire stand. It is also important to point out that there may be several modes of vibration close in frequency and that any detailed evaluation of dynamic response will need to allow for this.

The natural frequencies of the empty structure may be estimated using a comprehensive dynamic analysis or modal test programme. However, it is difficult to assess how the effect of the crowd should be included in the evaluation of dynamic response. Therefore, in developing this Interim Guidance, it has been assumed that in practical situations there will be some reduction in natural frequencies due to the effect of any in the crowd that are not contributing to the exciting activity.

4 Guidance

4.1 Grandstands used solely for viewing events including sport

For grandstands used for events where crowd activity will not be stimulated by music or otherwise synchronised, the aim of the guidance in this note is that resonant excitation at the first harmonic (or fundamental) frequency of crowd movement should be avoided. If the lowest vertical natural frequency is above 3.5Hz for an empty stand, then it will be outside the range that can be excited significantly at resonance by the first harmonic (or fundamental) loading component. Even a natural frequency of 3Hz is likely to be sufficiently high to meet the aim of avoiding resonance at the first harmonic.

In the absence of jumping or extremely lively and well synchronised crowd movement, as might occur in response to music, avoidance of resonance, by ensuring that all the vertical natural frequencies of a grandstand are greater than 3.5Hz, should ensure both safety and comfort for spectators in the seating tiers. Additionally, it will be reassuring to note that grandstands designed to the current UK codes of practice, and having a vertical natural frequency greater than 3.5Hz, are extremely unlikely to fail structurally, even if subject to rhythmic spectator loading.

However, it should be recognised that any structures with a natural frequency less than 3Hz empty, could experience significant resonant response if a group were to engage in deliberate and synchronised jumping (as could occur with so-called 'vandal' loading). Such structures must be considered vulnerable if there is any prospect of excited crowd movement, whether or not this is formally synchronised by the playing of music.

4.2 Incidental music

It is common practice to play incidental music at events. The crowd remain seated or standing and, in contrast to pop and rock concerts, the music usually provides little stimulus for jumping. In most instances, music of this sort this will not promote dynamic loading sufficient to cause discomfort. However, there is some experience that music in the form of chants and club songs, even without a strong beat, can stimulate a crowd to develop dynamic loading sufficient to excite grandstands having relatively low natural frequencies so causing possible discomfort to seated spectators.

Ground management needs to be aware that there is a risk that the more lively kinds of incidental music may occasion discomfort in stands that have natural frequencies near the bottom of the recommended frequency range. The risk becomes less the higher the natural frequency of the stand and can probably be ignored for stands with fundamental vertical natural frequencies greater than 5Hz. It is recommended that ground management monitor the use of incidental music and use the results in selecting the programme for later events.

4.3 Pop concerts and their requirements

For structures used for pop concerts and similar events the aim is to avoid resonant excitation at the second harmonic frequency of crowd movement. This is because a strong musical beat will be present so causing crowd action to be both co-ordinated and livelier than if the crowd were to act merely as a collection of quiescent spectators. If the lowest vertical natural frequency is above 6Hz for an empty stand it will be outside the range that can be excited significantly at resonance by the second harmonic loading component. In setting this limit it is considered that higher load harmonics can be disregarded due to the difficulties of achieving sufficient synchronisation of the crowd loading. Besides providing safety from collapse and the onset of panic, grandstands with vertical natural frequencies greater than 6Hz should provide adequate levels of comfort for all but the most extreme pop-concert style excitation.

4.4 Control of horizontal motion

Crowds moving impulsively or rhythmically impart horizontal as well as vertical loads to a structure. The Green Guide[3] recommends a minimum natural frequency of 3Hz for horizontal excitation for all grandstands as a substitute for a full dynamic evaluation. This Interim Guidance is intended to go some way to fulfilling the need for such detailed analysis. However, there is little information available on the horizontal response of permanent grandstands to crowd loading and for the cantilever and long span structures that are the subject of this

guidance there is a view that vertical excitation will normally be the controlling influence in design. In contrast to this, the provision of adequate horizontal stiffness to provide stability and an adequate horizontal dynamic response is a key requirement in the design of temporary demountable grandstand structures. In the absence of more complete information, it is recommended that similar procedures are adopted in the design and assessment of the permanent grandstands covered by this guidance.

Current UK codes require designers to consider horizontal wind loads or notional sway loads on a structure but make no specific reference to horizontal crowd loads. However, to meet the need for adequate horizontal strength and stiffness and, notwithstanding the difficulty of providing bracing in zones required for concourses etc., it is recommended that grandstands are designed to resist the additional static horizontal loading given in Table 1(see p 17). This follows from the Institution of Structural Engineers 1999 report on Temporary Demountable Structures[5] but omitting the provision for geometric imperfections considered necessary when dealing with demountable structures.

4.5 Reservations on the use of frequency limits

For simplicity and convenience, the Interim Guidance has been set out by specifying a minimum desirable vertical natural frequency dependent on the intended use to which the stadium will be put, together with a requirement for additional horizontal load resistance. This gives those charged with assessing and certifying such facilities a simple measure with which to judge the likely dynamic performance. The rationale for this approach has been given in the previous section, but it should again be noted that this is a coarse-grained and indirect approach to assessing the dynamic performance of a viewing structure.

Subtleties, such as the transmission of vibrations from one area of high activity to another of lesser activity, the presence of hospitality suites, and the beneficial effects of high mass and high levels of damping, are overlooked with this approach. In these circumstances, the Working Group would still wish to recommend a more detailed assessment to predict the levels of vibration that will occur in practice under crowd loading. However, such an assessment goes beyond the scope of this Interim Guidance.

4.6 Practicalities concerning human tolerance of motion

There can be no pretence at precision in meeting the need to provide comfort, or at least an absence of discomfort, to all users of a grandstand. People vary, and tolerance of motion and an inclination to panic is subjective and different from one individual to another. What is an interesting or pleasurable experience for one person may provide cause for alarm in another. The range of possible reactions is very wide if considered in the context of the possible range of age, personality, experience and expectation of people in a crowd. So, it must be recognised that even with grandstands that meet all the requirements of this Interim Guidance, there is still the possibility that, on occasion, there will be some spectator comment or complaint concerning motion. The incidence of such complaints should be small but, in dealing with human nature, it must be evident that some reaction at some time is inevitable.

4.7 Nature of the guidance

The recommendations on frequency limits for different categories of use are summarised in Figure 1 (see p 17). The boundaries between the different categories of use are shown unambiguously as corresponding to the frequency levels given in paragraphs 4.1–4.3. However, in using the Guidance, notice should be taken of the complications and uncertainties referred to in paragraphs 4.5 and 4.6. In effect the boundaries should be regarded as having a degree of fuzziness that should allow or promote a considered discussion of factors other than natural frequency that would affect the dynamic response. These factors might include mass, damping, mode shapes, the degree of control and supervision and, for an existing grandstand, experience from actual events. Such a discussion would be most appropriate for a stand with a vertical natural frequency close to a boundary for a category of use as shown in Figure 1.

4.8 Estimation of natural frequencies

Whether by analysis or test, the aim should be to determine the relevant natural frequencies and their associated mode shapes. Calculation of the natural frequencies must be carried out as accurately as is reasonably practicable taking into account three-dimensional effects, connections and the flexibility and mass of secondary elements such as seating planks. Short-

cut methods for determination of natural frequency based on the deflected shape under static loading or on rules of thumb may not be adequate and can be very misleading. For use with this Guidance, natural frequencies should be calculated for an empty stand, i.e. with no mass included for the crowd loading. As part of its continuing work, the Working Group intends to issue specific guidance on the calculation of natural frequencies.

For existing stands, natural frequencies of the empty stand should be determined by both calculation and testing and adequate agreement achieved between the results. Specialised equipment and appropriate expertise is required in undertaking tests to determine natural frequencies. The Working Group is currently preparing specific guidance on the procurement and conduct of testing to determine natural frequencies of grandstand structures.

5 Recommendations related to assessment and design

5.1 Scope

This Guidance refers to permanent grandstand structures with seating decks in steel, concrete or composite construction, with supported spans greater than 6.0m or cantilevers greater than 2.5m. The present recommendations supplement Section 4.5 of the Green Guide[3] (Structural dynamics for permanent structures) by providing additional frequency limits related to categories of use as an alternative to undertaking the dynamic evaluation required in the Guide for structures with vertical natural frequencies less than 6Hz and/or horizontal natural frequencies less than 3Hz.

5.2 Existing structures (refer to Figures 1 and 2 and Table 1)

Management

The Management needs to be aware of the vertical natural frequencies of the seating tiers in grandstands in its responsibility and the risks of dynamic response due to crowd loading. If knowledge of the natural frequencies is not available, management should engage a Chartered Engineer***, with experience in structural dynamics and knowledge of human induced dynamic loading in the context of grandstand design, who will undertake calculations and advise on the appointment of an appropriately experienced testing agency to undertake tests to establish natural frequencies and other relevant parameters. If the vertical natural frequency of any seating deck is below 3.5Hz, immediate action should be taken as described in the flow diagram, Figure 2.

Continuing professional structural engineering advice

The Management should engage a Chartered Engineer to undertake the annual structural survey required under the Safety Certificate issued by the Local Authority. The Engineer appointed should have experience in structural dynamics and knowledge of human induced dynamic loading in the context of grandstand design.

Vertical motion

The category of use of existing grandstands should be assessed using the frequency criteria for vertical excitation provided in Figure 1 in the context of the discussion in Section 4. If the vertical natural frequency of a seating tier is below 3.5Hz, management should take immediate action as indicated in Figure 2.

Natural frequencies

Natural frequencies of seating tiers should be determined by calculation and by testing and sufficient agreement obtained between the results. The values should be for an empty stand, i.e. excluding the mass associated with crowd loading.

Horizontal strength

All grandstands irrespective of the category of use should be checked to determine whether they meet the requirements of Table 1 for horizontal load resistance.

Experience in use

In assessing the suitability of an existing grandstand for a particular kind of event, attention should be given to experience of its performance for earlier events of a similar nature if adequate records are available. Management should monitor the use of incidental music and take any action necessary to reduce risk as part of its operational procedures.

Up-grading

No particular recommendations are made regarding action that might be necessary to upgrade an existing grandstand. This could involve structural strengthening, stiffening or possibly the introduction of damping devices to reduce the effects of vibration.

Reporting

The Engineer undertaking an initial assessment or annual survey should prepare a report for the grandstand management recommending or confirming a category of use and recommending

***The Institution of Structural Engineers maintains a list of firms with appropriate expertise. Enquires should be addressed to the Chief Executive and Secretary of the Institution at 11, Upper Belgrave Street London SW1X 8BH

any reinstatement, strengthening or vibration mitigating measures that are required. The report should include details of any calculations for natural frequency and, when testing is employed, an account of the procedures used and the detailed results. The report will be the property of the grandstand owner or operator but it is strongly recommended that a copy of the report be provided to the Local Authority, for reference and use at the Authority's discretion.

5.3 Implications for design of new grandstand structures (refer to Figure 1 and Table 1)

General

The structural design of grandstands should be under the close direction of a Chartered Engineer with experience in structural dynamics and knowledge of human induced dynamic loading in the context of grandstand design.

Design brief

It is essential that the design brief is unambiguous on the intended use of the grandstand and that the grandstand management understand the limitations associated with the categories of use.

Strength

Grandstands should be designed for the dead and imposed static loading recommended in BS 6399[4] together with wind loads and the additional lateral load given in Table 1.

Serviceability

Grandstands should be designed to provide a minimum natural frequency for vertical excitation corresponding to the category of use according to the values given in Figure 1.

Reporting

The designer should provide the grandstand management with a report summarising how the requirements for dynamic performance have been met and including calculations of natural frequencies. The report will be the property of the grandstand owner or operator but it is strongly recommended that a copy of the report be provided to the Local Authority for reference and use at the Authority's discretion.

TABLE 1

DESIGN FOR HORIZONTAL STRENGTH AND STABILITY

In addition to wind loading specified in BS 6399, grandstands should be capable of withstanding the lateral loading given below:

Type of use	**Additional lateral load** as a percentage of the design vertical live load
All grandstands other than those used for pop concerts or similar lively synchronised activity	5%
Grandstands for which the intended use includes pop concerts or other lively events	7.5%

NOTE: The above lateral loads are applied horizontally at the level of the corresponding vertical loading for all load cases involving vertical live loads. The partial safety factors to be used in each load case are those specified for vertical live loads in the appropriate code of practice for the structural material involved (i.e. BS 5950 for steel[15], BS 8110[16] for concrete, etc.).

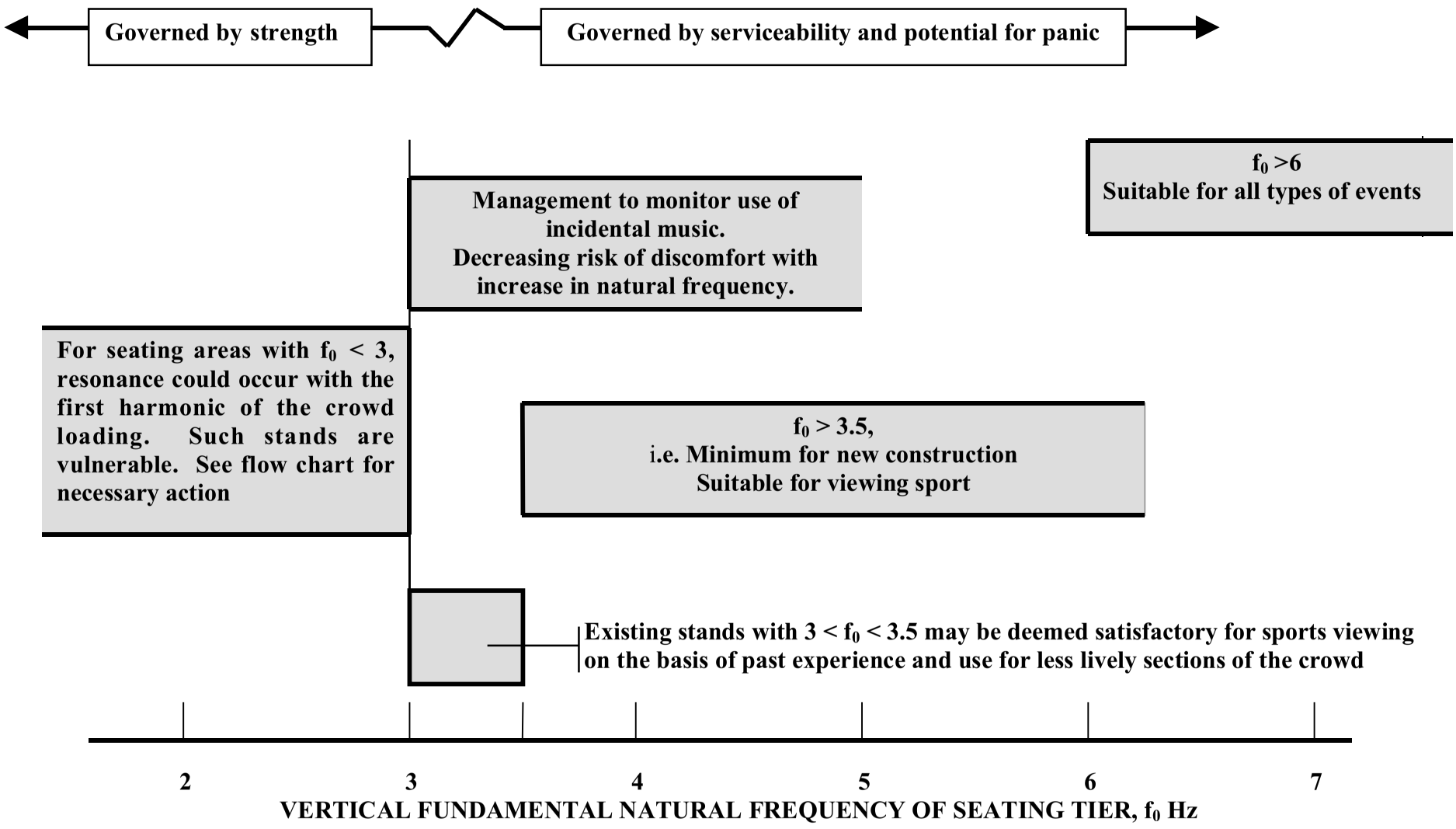

Figure 1 Frequency criteria for assessment and design

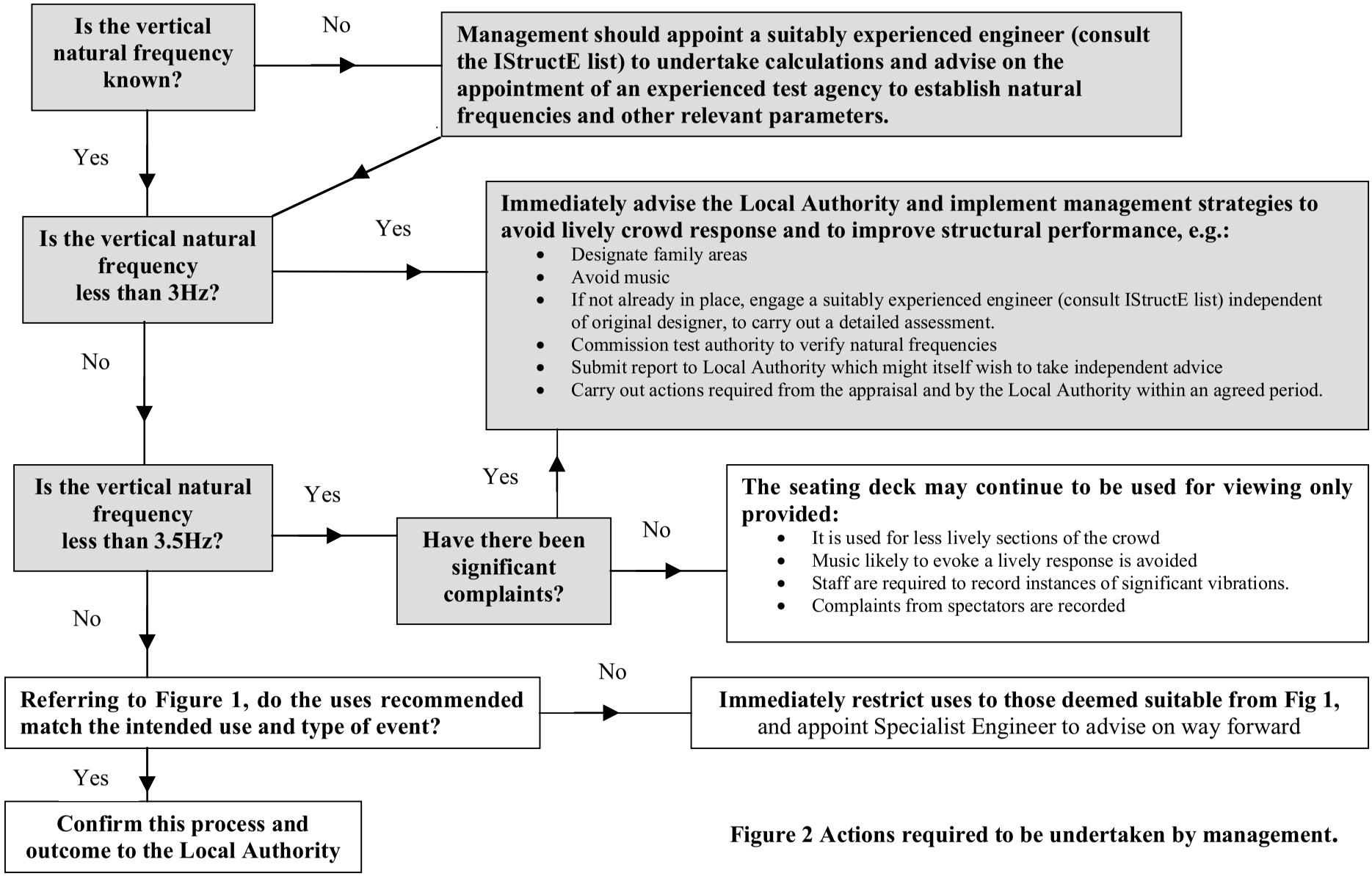

Figure 2 Actions required to be undertaken by management.

6 Implementation and feedback: the need for a central database

The safety of viewing facilities is the responsibility of the management of the facility. The Local Authority is available to advise management on how to meet this responsibility and will issue a Safety Certificate that includes conditions to be met in operating the facility. In addition, in England and Wales, the Football Licensing Authority has an overall supervisory role in promoting standards of operational safety of football grounds, and their associated facilities, and legislation has been proposed to extend this remit to all sports through the establishment of a Sports Ground Safety Authority (SGSA). The Working Group see this as a positive contribution to further increases in safety of spectator facilities generally with the prospect of increased uniformity in practice and greater retention of information and records.

In preparing this guidance it has been noted that information on design and performance of existing grandstands in the UK is scant and not necessarily reliable. Furthermore, there are evidently few records of feedback from spectators or stewards relating to crowd reaction to movement in grandstands. Without such information, it will be difficult to develop further the recommendations given in this Interim Guidance. Also, in implementing the Guidance there will be a need for sharing of experience between Local Authorities and feedback of concerns and suggestions.

The Working Group recommends that, in its extended role as the future SGSA, the present FLA should have a role in coordinating the efforts of Local Authorities in implementing this Guidance. It is understood that the Government will respond to this recommendation and request the Licensing Authority to include information relating to the design and performance of grandstands in its present database. Accordingly, the Licensing Authority can be expected to take on the task of maintaining such records, which should comprise information obtained from the design and testing of grandstands and from reports of crowd reaction when grandstands are in use. This will require the active co-operation of Local Authorities. However, the Working Group believes that the benefits in terms of knowledge of grandstand behaviour and safety will be substantial.

This Interim Guidance recommends that the annual structural report required under the safety certificate should include a report from a suitably qualified engineer recommending a category of use and, where necessary, providing detailed calculations, or the results of testing, to show how the grandstand relates to the present Guidance. It is proposed that, with the co-operation of the Local Authorities, relevant information from these reports should be passed to the Licensing Authority for retention in its database. It would be additionally helpful if relevant information from any subsequent reports on the performance of grandstands in service could be passed to the Authority for inclusion in the database.

The Working Group is not in a position to suggest the working arrangements between the Local Authorities and the future SGSA that will be necessary in order to make the database effective and useful. It is, however, clear on the value of such a database in underpinning public safety in the use of grandstand structures and as basic information when developing future guidance.

7 The way forward

The Working Group has prepared these interim recommendations based on its evaluation of existing knowledge and practice but also in the knowledge that more detailed guidance is needed. The Working Group aims to develop a better understanding of the loading experienced by grandstand structures and the way in which the dynamic response of the structure may be predicted reliably from the loading. Associated with this is the need to agree appropriate criteria for movement in terms of what can be tolerated without discomfort and what might lead to panic. These are difficult and connected topics but the Working Group would hope to report with further more detailed recommendations in eighteen months time. In the meantime, it is important that whatever knowledge there is of the behaviour of actual grandstand structures is made available to the Working Group. Owners and operators of grandstands, certifying authorities, architects and engineers concerned with design who have questions, comments or who can contribute knowledge of actual behaviour are invited to communicate these concerns or information to the Working Group Secretary:

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