Vibration monitoring of a grandstand in Dragon Stadium

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ABSTRACT: The present communication focuses on the importance of the dynamic actions induced by groups of people with synchronous movements and the need to perform dynamic analysis in the corresponding structural elements. Special attention herein is given to the case of stadium structures.
The continuous optimization in structural design made possible, in certain cases, to resist to high loading values in ultimate limit states but still have serviceability deficiencies. Problems with excessive vibration on recently built structures have been reported (SCOSS 2001). This can cause human discomfort, crowd panic or collapse of the structure.
Simple methods like adopting a frequency threshold cannot always be applied since they may result in a substantial increment in cost or are impossible to accomplish due to architectural constraints. This is the reason why it is unavoidably necessary to model and evaluate the dynamic response of certain structures.
This article presents also some results of the monitoring of two events in a grandstand on Dragon Stadium in operating conditions.

1 INTRODUCTION

On assembly structures the consequences of a structural collapse or disturbing movement causing panic amongst an occupying crowd could be very negative, since a large number of people might be involved. There are two major factors contributing to this problem: increasingly lively human-induced loadings and greater flexibility of grandstands.

The design trends often imposed by building functionality, aiming at open spaces without columns (resulting in flexible floors) and the need of large spans, lead to low natural frequencies of the structures that sometimes fall into the range where concerted human action can produce significant excitation. On the other hand, a change on the behaviour of the assistance of public events is currently evident being more vivid than before. This happens where pop concerts are held and also where visual and audio stimulations and organized supporters exist to encourage a lively atmosphere during matches. An additional concern with modern stadia is that they are increasingly being used to host non-sporting events such as pop/rock concerts. In these cases, there can be a strong musical beat that acts to synchronise activities of spectators such as dancing or jumping. This synchronised loading may be much more onerous than the loading that can be expected when there is no music present. In some cases the structure has had to be modified or its use restricted to limit the risk of unacceptable dynamic response (IStructE 2001).

This paper presents data from in-service monitoring of a grandstand in Dragon Stadium. The in-service monitoring was carried out during a football match being the stadium full to capacity. Afterwards a group of volunteers performed a number of coordinated movements like swinging and jumping.

The testing performed on the structure is described and some tests results are shown. The main results are discussed and some conclusions about vibrations levels and user's comfort are pointed out.

2 DYNAMIC ACTIONS DUE TO HUMAN ACTIVITIES

The structural design of a building is strongly influenced by the estimation of the loading environment which the structure is to sustain an under which it must serve its function throughout its lifetime. The capacity of a structure to resist extreme loading events (ultimate limit states) and to perform without excessive deformations or vibrations (serviceability limit states) strongly depends upon matching the actions considered in the design and those that effectively act upon the structure during its existence

The actions considered in most building codes have as main concern the strength of construction materials of the structure and the resistance of structural systems. In structures where the gathering of people is to be expected, as in a stadium grandstand, the loading is due almost entirely to human activities that exert dynamic loads in the horizontal and vertical directions

The loads currently considered in the design of such structures are generally specified to be applied as equivalent static forces being implicit that the specified values include a weighed static force plus an aggravation to account for induced dynamic effects. These values have been developed on the basis of resistance criteria to prevent the collapse of the structure but are not adequate for the verification of the performance in service.

Some more recent regulations and standards (BSI 1996, 2002) consider the need for a more refined analysis of the dynamic response of structures exposed to dynamic actions. The present state of knowledge of the dynamics of these structures, however, is not sufficiently advanced to allow a sensible analysis to be performed. The reason for this is that current knowledge and practice are deficient in some areas, such as: the human-induced loading definition; the human/structural system modelling; systems analysis and final assessment of the resultant vibration level for serviceability criteria.

The problem arises because when we take assumptions on the safe side it is difficult to get results that are representative of the reality. For this reason, the models should have its validity proven by recourse to calibration using the data obtained from tests performed on an environment next to the real one.

Following the guidance given by the eurocode EN1990 (BSI 2002), the ISO 10137:1992 standard on "Serviceability of buildings against vibration" (ISO 1992) was adopted to evaluate the stand performance. This standard provides quantitative recommendations on dynamic actions from human activities such as jumping and on criteria of acceptable vibration levels for humans, for building contents and building structure. Guidance is given on analysis methods for solving vibration problems and on methods of vibration control and isolation. In the latest version (Rainer 2005) the actions due to human activities have been updated to reflect recent extensive measurements of forces produced during walking and jumping. Also new criteria for vibrations for stadia and assembly halls under coordinated crowd action are given and 200 times the base curve is considered acceptable. Vibration levels with a multiplier of 400 should not be exceeded to avoid panic situations.

3 TESTS

It was considered to be essential the data obtained in the structural monitoring for the validation of options and criteria established in the design phase (IStructE 2002). The monitoring of two events in the Dragon Stadium was carried out, namely a football match on April 25th, 2004 and tests in the north stand on April 28th. It was intended, with these tests, to get a validation of the dynamic load model used in the design phase and to establish an evaluation of the performance of the structure in service. These objectives were pursued through the measurement of the amplification of structural displacements originated by spectators' movement on the seating deck units and the measurement of vibration levels.

3.1 *Structure and test loading characterization*

The tests took place in the Dragon Stadium on the North stand (sectors 26 and 27).
The stands are formed by a series of T-shaped overlapped precast seating deck units (Fig. 1) spanning 8.0m between the concrete stand beams (Fig. 2). This has become a very common form of construction for modern stadia.

The seating deck units are connected in five points by a steel rebar ø 20mm in an alternated sequence. Between the units without connectors EPDM (Ethylene Propylene Diene Monomer) rubber plates are interposed to ensure a uniform support between the parts (Fig. 1).

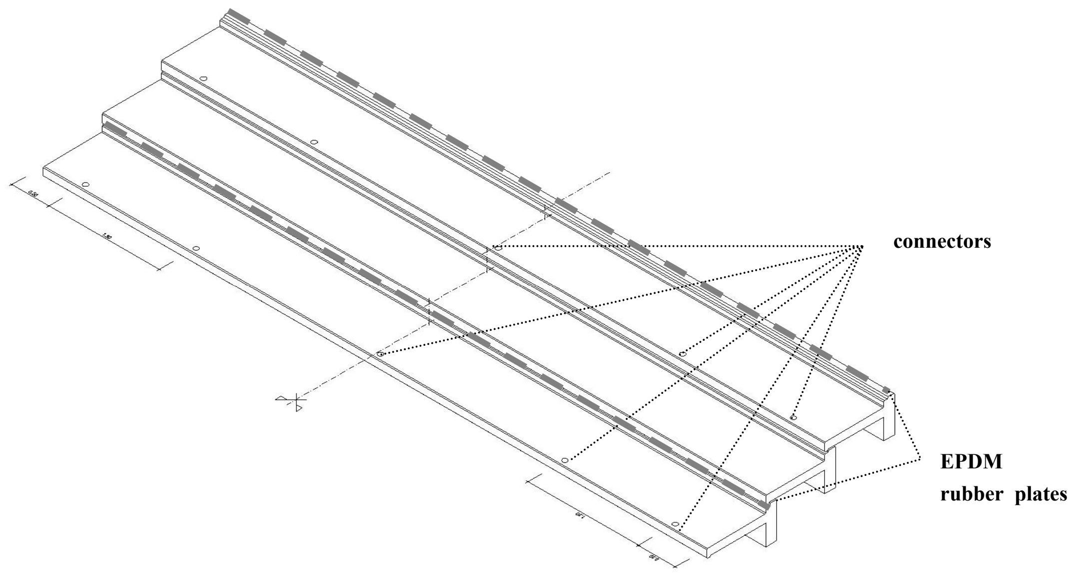


Figure 1. Seating deck - system of the assembly

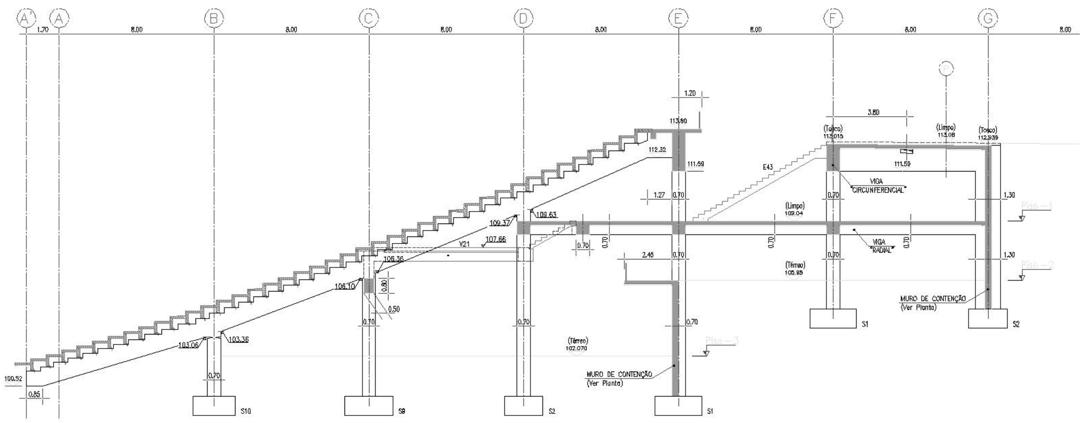


Figure 2. Structural system of the North stand, including the main beams and respective supports

Two seating deck units were chosen for testing, namely units 16 and 17, which are connected by the link described.

In order to simulate the load due to occupation of the spectators that actually constitute the stand service loading, 34 persons were involved in the tests (Fig. 3), with an average mass of 76,6 kg. In addition a load consisting of concrete cubes, with a total mass of 317 kg, was suspended right bellow the seating deck centre. The load was supported by a cable that was cut off in order to simulate the application of an impulsive load.

Figure 3. Group of volunteers during the tests

3.2 *Equipment*

As already mentioned, tests were carried out on two terrace units (16 and 17) but, since the behaviour was believed to be similar in both units, the instrumentation was mainly concentrated in the lower unit (unit 16).

The instrumentation was installed in 6 sections along the unit 16 using LVDT´s (Linear Variable Differential Transformers) for measuring displacements and relative movements (Fig. 4). Complementarily, a seismograph was also used in order to mesure and record the accelerations in the longitudinal, transversal and vertical directions; its acquisition rate was set to 100Hz.

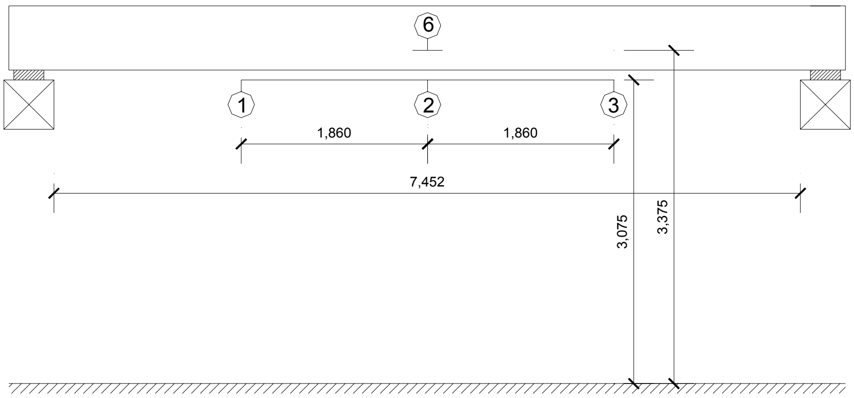


Figure 4. LVDT's numbering and positioning – elevation view

3.3 *Tests methodology*

On April 25th several events were recorded (A1 to A7) during the monitoring of a football match. In that day the stadium was completely occupied and the crowd had a lively behaviour.

On April 28th the tests were carried out with the contribution of a group of 34 voluntary students of the FEUP. The accomplishment of a test series with the measurement of deformations and acceleration was planned in the following phases:

- coordinated jumps to a frequency of 2 Hz (events E1, E12, E14 E15)
- coordinated jumps to a frequency of 1 Hz (events E2A and E11)
- 1 Hz frequency jumps of two groups with ½ phase asynchronous motion (events E3, E5 and E13)
- free jumps (events E2B and E4)
- goal scoring simulation (event E6)
- damping evaluation with impulsive load and people seating (events E7 and E10)
- damping evaluation with impulsive load and people standing (events E8 and E9)

The synchronization of the volunteers was obtained by playing sound files with matching frequency of the movement that was intended to be obtained.

3.4 *Monitoring results*

The results obtained in the different phases of the tests allowed the evaluation of some of the parameters that were intended to be observed. Some illustrative examples are shown bellow in order to support the conclusions that were possible to draw.

Figure 5 shows one of the seismograph records with application of a 20Hz low-pass filter and high-pass filter with 1Hz cutoff frequency, corresponding to event A3 during the game on April 25th.

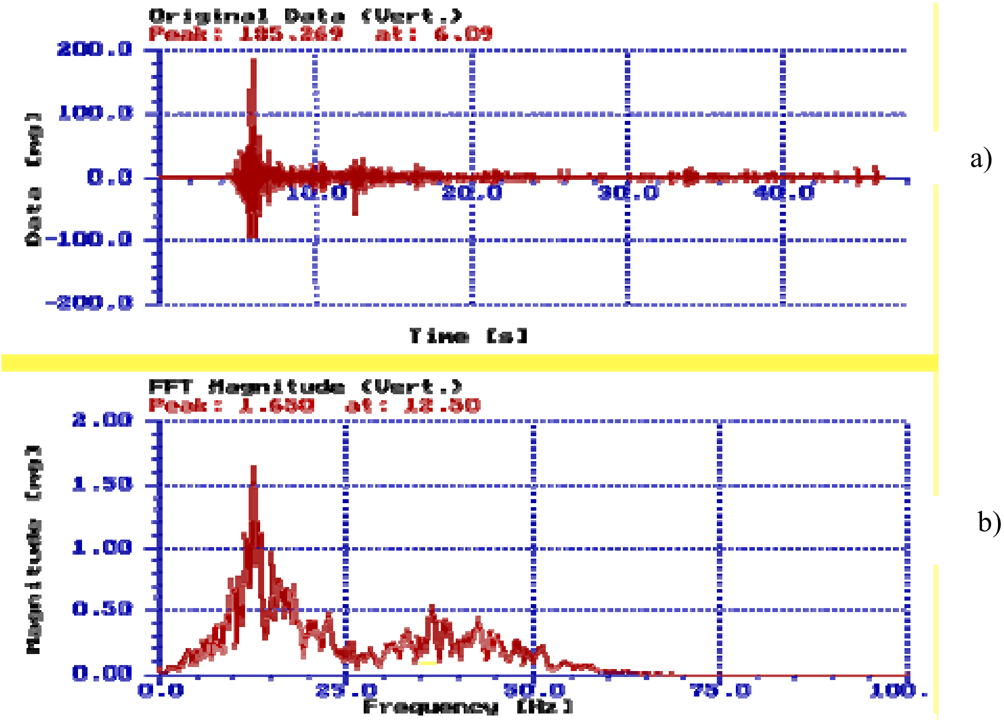


Figure 5. Event A3: a) vertical accelerations time history on April 25th (20:44:47.05) and b) respective frequency domain analysis (peak acceleration value: 185 cm/s^2)

Table 1 includes the summary of the main results gathered from events A1 to A7 during the referred April 25th game.

Table 1. Vertical acceleration data of the events recorded on April 25th

event	**duration (sec.)**	**peak acceleration (cm/s^2)**	**f1 (Hz)**	**RMS acceleration (cm/s^2)**
A1	92	50	11,23	2,75
A2	12,5	28	13,09	3,65
A3	46	185	12,5	8,62
A4	35	35	12,9	1,99
A5	105	40	12,5	3,44
A6	86	37	12,7	3,66
A7	94	36	13,18	3,86

Similarly, Figure 6, Figure 7 and Table 2 report on results gathered from events of the tests carried out on April 28th. Figure 6 shows acceleration time histories from event E1, whereas figure 7 highlights a portion of the same event and corresponding frequency analysis. Table 2 summarises the main results of these test events showing results from different time interval samples for each event.

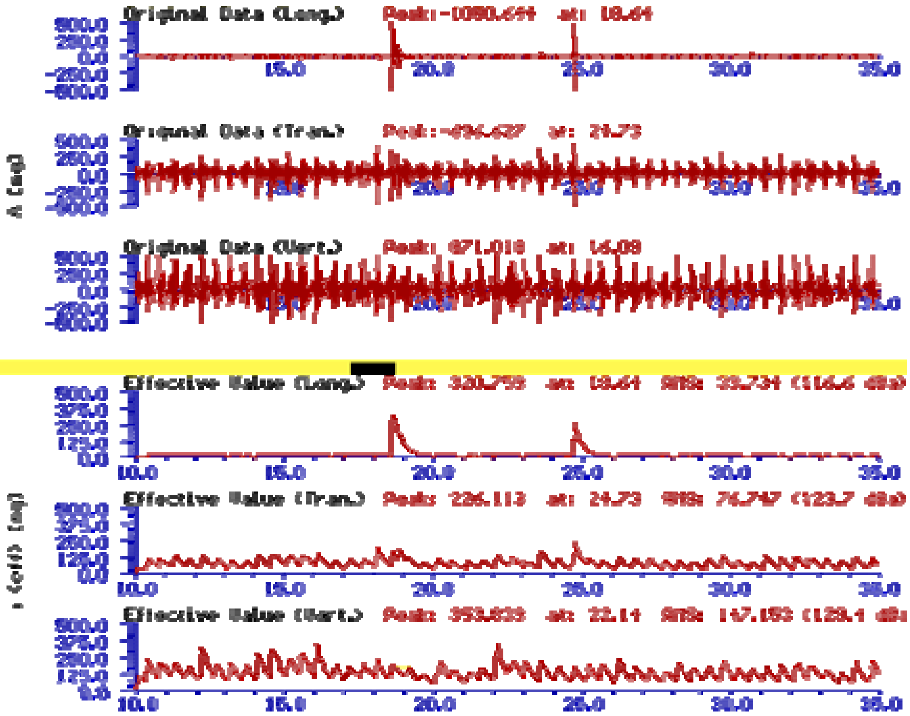
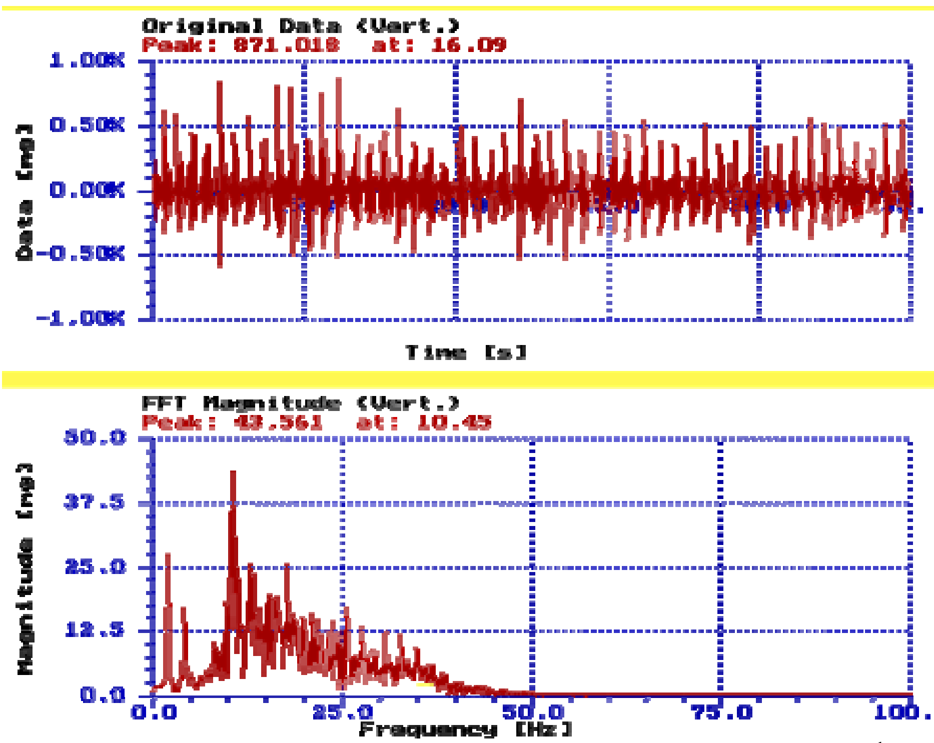

a)
b)

Figure 6. Event E1: a) acceleration time histories in the three directions (longitudinal, transversal and vertical) recorded on April 28th (15:43:07.42) and b) effective values of accelerations (maximum vertical RMS acceleration value: 147 cm/s^2)



a)
b)

Figure 7. Event E1: a) vertical acceleration time history recorded on the April 28th (15:43:07.42) and b) respective frequency domain analysis (peak acceleration value: 871 cm/s^2)

Table 2. Vertical acceleration data of the events recorded on April 28th

event	duration (sec.)	peak acceleration (cm/s^2)	f1 (Hz)	RMS acceleration (cm/s^2)
E1	25	871	10,45	147,15
E2A	18	1238	10,45	179,96
E2B	8	744	12,11	131,51
E3	20	1100	10,45	174,79
E4	12	668	10,25	179,67
E5	17	855	10,25	95,62
E5	36	922	10,16	137,97
E6	3	356	10,16	103,85
E6	2	638	10,94	127,71
E11	42	785	10,45	111,40
E12	7	760	12,7	124,79
E12	7	521	10,74	120,51
E12	6	615	10,35	136,23
E14	20	964	10,64	88,86
E15	49	992	10,63	140,35

After the result analysis the following observations can be pointed out:

- The results obtained with the group of volunteers produced much higher accelerations and displacements than those recorded during the monitoring of the game on April 25th.
- The maximum value of peak acceleration during that game on April 25th did not exceed 0.2 g, see Table 1.
- During the several test phases on April 28th, the events during which volunteers produced higher accelerations corresponded to the coordinated jump at 2Hz with 1.4g peak acceleration, see Table 2.
- The natural frequency of the stand was found different in the data collected on April 25th and 28th, although similar values can also be found.

It is worth mentioning that the observation of the peak accelerations measured during vibration is a very rudimentary method of assessing the severity of vibration since they are very sensitive to short nonrepresentative transient vibration events (Reynolds & Pavic 2006). They are also highly dependent on the data acquisition equipment and parameters used, particularly the methods of filtering. As a result, this method of vibration magnitude assessment is becoming obsolete and not recommendable.

The impact of vibrations on humans can also be evaluated using the root-mean-square (RMS) acceleration calculated from the time history acceleration records. However, for transient vibrations, the RMS acceleration may be misleading because it can underestimate the severity of the vibrations due to apparent variation of RMS acceleration depending on the duration of the observation interval. As shown by the values of RMS acceleration (Tab. 2) may vary according to the interval of observation.

As previously mentioned the ISO10137 standard establishes, for stadia, that the RMS vertical acceleration bellow 200 times the base curve is considered acceptable. Vibration levels with a multiplier of 400 should not be exceeded to avoid panic situations (Fig. 9).

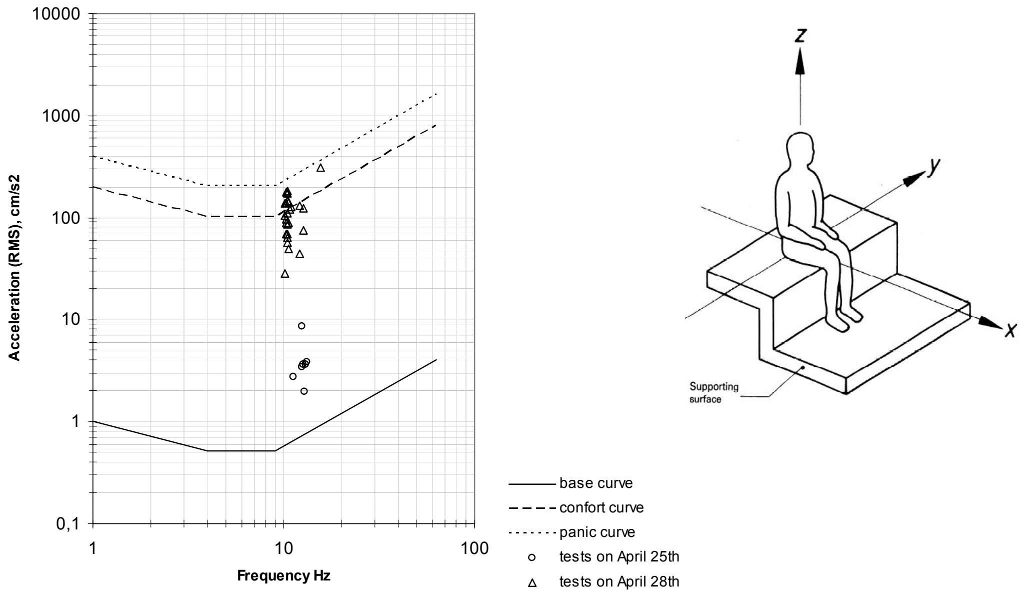


Figure 9. Vibration z-axis limits curve for acceleration (foot-to-head direction) and test values

From the data obtained during the April 25th, it is clear that acceleration values are much below the referred limits; in the tests of April 28th, the maximum value of vertical RMS acceleration was 180 cm/s2 that fits in the interval above 126 cm/s2 (comfort) but below 252 cm/s2 (panic). Since it represents a case of extreme loading we may consider that the performance is acceptable.

The discrepancy observed in the natural frequency values of the seating deck may be due to changes of the involved mass and to possible alterations of the test conditions that were not possible to identify because tests have occurred in different days. However tests in similar seating deck units carried out by other authors (Caetano 2004) led to values for the natural frequency of 11.31 Hz.

The activities that produced the strongest response in terms of acceleration, the coordinated jumps, have also produced dynamic amplification of displacements as high as 1.7 (Fig. 8).

The results obtained from displacements evaluation were similar to those obtained in previous tests carried out by other authors that led to dynamic amplification factors on the order of 2.0 (Figueiras 2004).

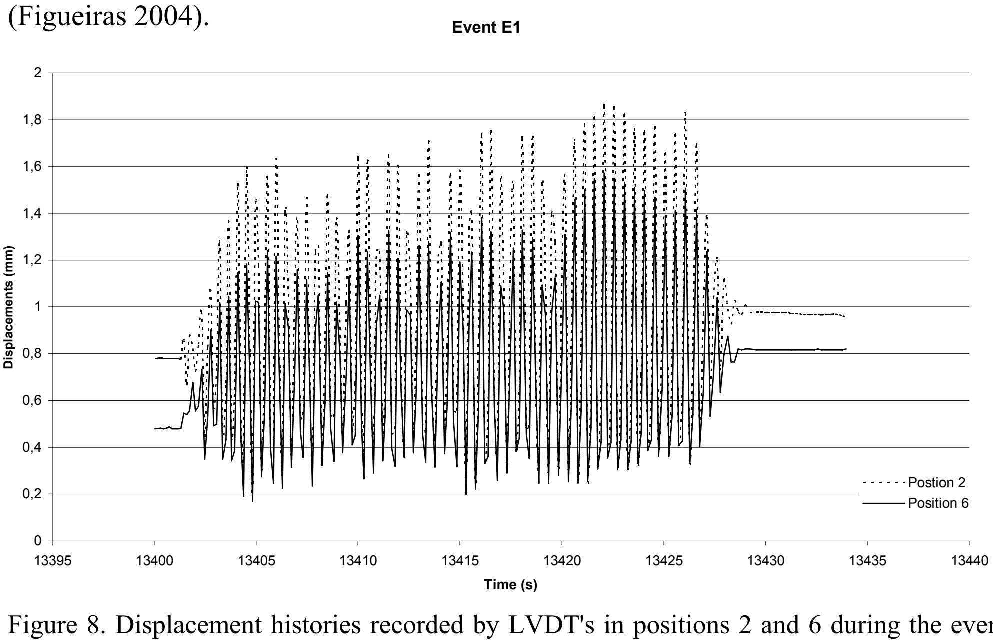


Figure 8. Displacement histories recorded by LVDT's in positions 2 and 6 during the event E1 (coordinated jump at 2Hz)

4 CONCLUSIONS

In the present paper the main characteristics of dynamic loading induced by crowds with synchronous movements were presented and some aspects of the evaluation of its dynamic effects on elements were also referred.

Special attention was given to stadium structures, presenting some results of tests carried out in the Dragon Stadium. The measurement of displacements and vibrations in the stadium allowed evidencing levels of comfort within the prescribed limits.

This study tried to emphasize the importance of the consideration of dynamic loading induced by crowds and the need of further addressing some aspects that may allow structural engineers to develop their skills on accurate identification of dynamically responsive structures and subsequent adequate design within structural performance requirements.

5 ACKNOWLEDGEMENTS

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