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Monitoring Stadiums under Crowd Motion for Serviceability

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ABSTRACT: Sports stadiums reserve a significant place among other civil engineering structures as to being excessively excited by the crowd that they accommodate. Aside from being constructed relatively slenderer than typical structures for architectural reasons, aesthetics etc., they might be compelled to critical limits for serviceability and even safety that might not have been considered during the design stage. Stadium utilization for concerts and various events other than sports games exacerbates this problem. Since the source of the excitation is human and the coordinated motion of the people can be unpredictable, it is inevitably important to mitigate or eliminate the problem of excessive vibration. In this study, vibration acceptability of a grandstand portion is investigated under different human excitation types in reaction to certain events that occur during the game. The evaluation is made through commonly used measures based on a widely used guidance.

1 INTRODUCTION

Assembly type structures among others constitute distinct characteristics in different aspects. Although there are codes and guidance specifically put together for these structures, they are inadequate representing the real behavior under dynamic loading. The investigation of the problem in a literature review by Jones et al. (2011) clearly states that every stage of this problem needs further understanding. This can only be achieved by going deeply into the critical matters such as generating accurate load models for flexible structures and expanding it to lively crowds, using the correct methodology to identify human structure interaction and crowds' operational effects on the dynamic properties. Subsequently, proposing new serviceability criteria for a better assessment of vibration acceptability might be possible. The findings of some recent studies show that there are obvious weak points in the assessment procedure and more extensive and reliable measures need to be found. For instance, Salyards & Hanagan (2007) carried out a long-term monitoring of a football stadium. Researchers used ISO 2631-1 standard to acquire maximum transient vibration value (MTVV) and vibration dose value (VDV) of their recordings so as to make an assessment on the severity of the vibration. They concluded that the vibration values showed a significant and persistent raise during accompaniment of the crowd to continuous rhythmic beats and this observation had never been as severe as any other event during the game. They also pointed out the risk of this phenomenon was more likely to occur during concert events since continuous rhythmic beats were easier to realize. In another study, Caprioli et al. (2007) compared two widely used standards namely ISO 2631 and BS6841 in terms of their vibration acceptability measures. The data received from four rock concerts of two different bands were evaluated. Differences in weighting functions and their contribution to the assessment values were discussed along with the discrepancies. Although the difference in weighting functions did not seem to engender a significant change, the main concern that might mislead the interpretation was the time duration of measurements to use in calculation of root mean square (RMS), root mean quad (RMQ) and VDV as to being ambiguous in both codes. It was advised by the authors that the comfort limits found in the current guidance should be revised since there was no agreement between them and the actual perception reported by the audience.

Reynolds & Pavic (2006) presented the detailed results of modal testing and in-service monitoring of a large contemporary cantilever grandstand during an international football game. It was shown that the modal parameters of a stadium could be affected by the crowd occupation considerably. They also indicated that previously proposed methods for assessment of vibration serviceability could lead to inconsistent results due to their sensitivity to the data acquisition and analysis techniques used. Reynolds et al. (2007) conducted forced and ambient vibration tests to analyze the dynamic characteristics of a stadium. They mentioned that calculated frequencies were lower than the measured frequencies and this might be the result of the extra stiffness caused by the non-structural elements that were not included in the design. Catbas et. al. (2009-2010) showed results of an on-going monitoring study of a stadium during different games in two consecutive studies.

The objective of this study is to present a continuous monitoring system that was deployed in a stadium, to illustrate vibration histories and to apply different vibration acceptability measures on the acquired data. Firstly, preliminary look of a stadium field monitoring study is presented along with the examples from different measurement sets recorded during two different games. Then human comfort analysis as it is pointed out in ISO 2631-1 is carried out.

2 MONITORING FRAMEWORK

The stadium in question of this study hosts football games with the capacity of 45,000 seating for spectators on 101,171m^2 (25 acres) of land since 2007. In scope of this study, a small portion of the stadium is investigated. It has a typical inclined architecture to provide the best line of sight for the audience (Figure 1).

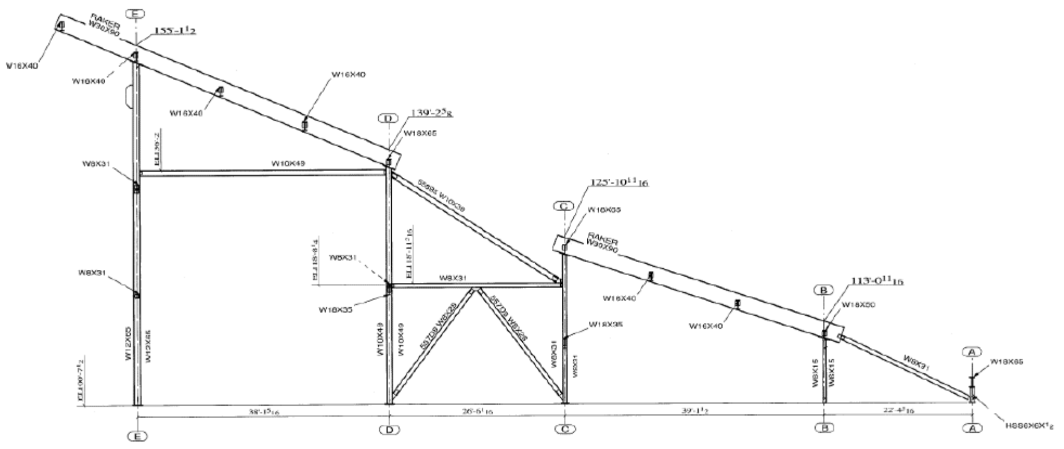

Figure 1 Profile view of the monitored section from the original project

Figure 2 is an illustration of the sensor locations at the upper and lower deck of the section pointed out in Figure 1. The movements of main girders, floor beams, and stringers are measured in both vertical and horizontal direction. For the upper and the lower stringers, channels 3, 4, 11 and 12 are placed in the middle. The upper and the lower floor beams, together with the upper main frame girder are monitored through channels 1, 2, 5, 6, 9, and 10. Finally, channels 7 and 8 are installed at the main beam and stringer connection of the upper deck.

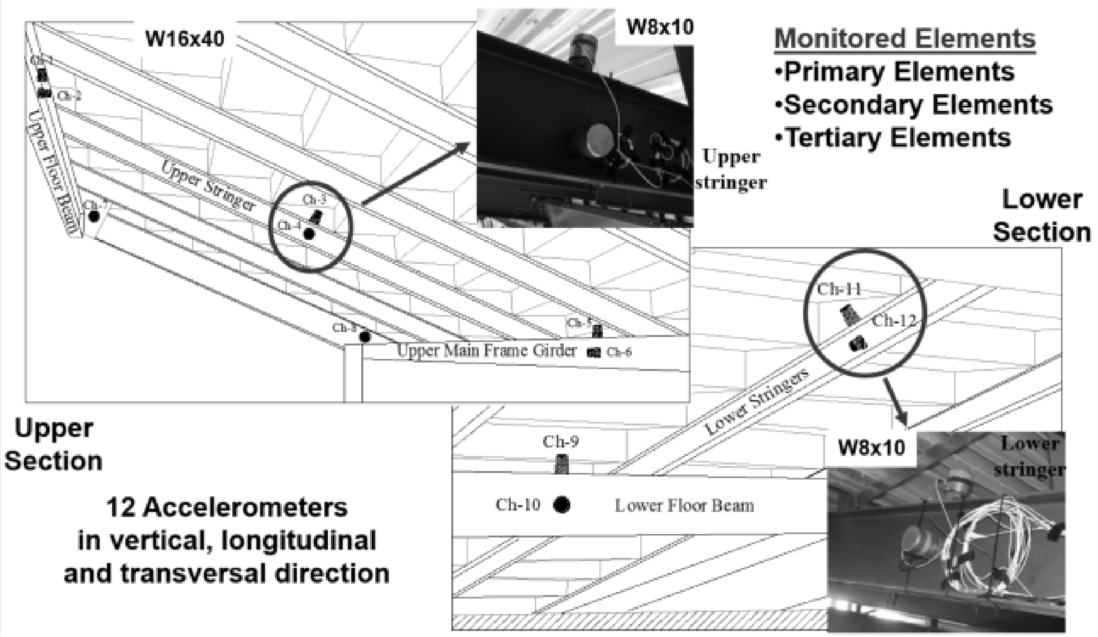

Figure 2 Sensor locations

The transducers used in this monitoring study are PCB 393C general purpose seismic type accelerometers with the sensitivity of 1000mV/g (Figure 2). VXI data acquisition system is used to record the vibration data. The sampling frequency is chosen as 100 Hz and 200Hz variably. For each game, recording duration is chosen as 10 minutes and several recordings are saved throughout the game.

3 PRELIMINARY DATA ANALYSIS

During 2014 fall football season, the stadium was monitored during four different games. In scope this study, randomly selected datasets from the games 1, 2 and 4 are presented.

In Figure 3, vibration histories from four channels located in the upper deck of the stadium are seen. The highest amplitudes are observed during stamping and jumping of the crowd. For the stamping, acceleration value of 0.97g is observed whereas it is 0.91g jumping. The first reaction observed in the recording is the "Zombie Nation" song played during the game. This response creates 0.24g of acceleration. Vibration amplitudes seem to be condensed among channels 3 and 4 and have higher amplitudes than the first two channels. This difference takes its source from upper stringers being slenderer than the main girders that support it (Figure 2).

Following the same pattern as in Figure 3, vibration amplitudes of channels 9-12 are realized in Figure 4. The response to the song creates a peak around 0.66g whereas two stamping motions results in vibration magnitudes of 0.30 and 0.87g respectively. The response from the jumping of the crowd creates 0.46g peak acceleration.

All the observations from the recordings are summarized in Table 1. It can be concluded that stamping and jumping are more likely to create higher values of acceleration since these excitations are short in duration and have really strong impact characteristics. Although the spectators occupying the monitored section move in a coordinated motion, vibration magnitudes that can create human discomfort differs from one location to another. Looking at both Figure 2 and Table 1, it is obvious that the highest acceleration values are obtained on slenderer members and in lateral direction.

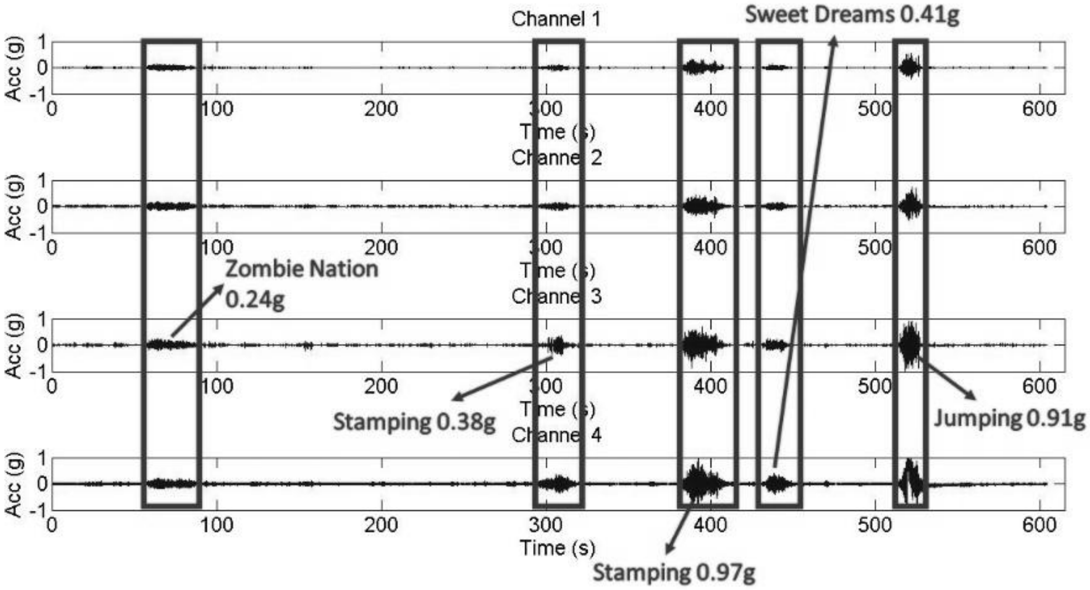

Figure 3 Acceleration histories from the first 4 channels when the game was in progress.

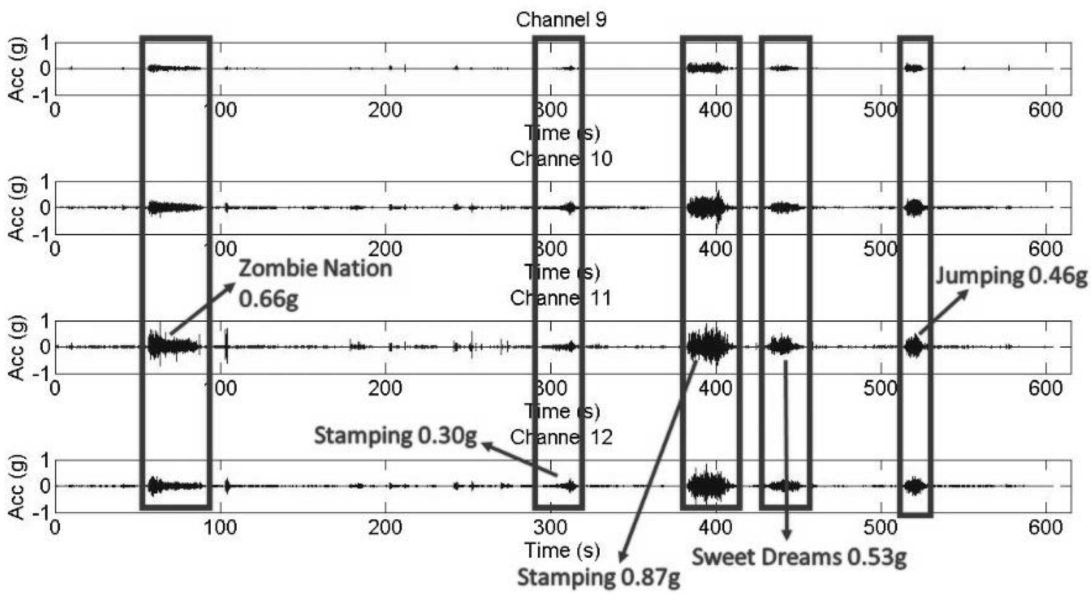

Figure 4 Acceleration histories from the last 4 channels as game was in progress.

Table 1 Distribution of acceleration amplitudes over channels

	Channels 1-4	Channels 5-8	Channels 9-12
Zombie Nation song	0.24g	0.22g	**0.66g**
Stamping	**0.38g**	0.25g	0.30g

Stamping	**0.97g**	0.37g	0.87g
Sweet Dreams song	0.41g	0.20g	**0.53g**
Jumping	**0.91g**	0.46g	0.46g

4 VIBRATION ACCEPTABILITY

For the assessment of comfort levels, the procedures given in ISO 2631-1 (1997) are followed. Decision on the severity of vibration magnitudes is made through the weighted root mean square (RMS) acceleration which shall be calculated using Equation 1:

$$a_w(t_0) = \left[\frac{1}{\tau} \int_{t_0-\tau}^{t_0} \left[a_w(t) \right]^2 \mathrm{d}t \right]^{\frac{1}{2}} \tag{1}$$

Where $a_w(t)$ is the weighted acceleration (translational or rotational) as a function of time (time history) and τ is the duration of the measurement, in seconds. Weighted acceleration record shall be acquired by multiplying the frequency domain representation of vibration time history with total weighting function and converting the resultant data back to time domain.

In order to form the total weighting function, frequency weightings of interest need to be chosen based on the clauses (health, comfort, perception and sickness). Since the scope of this study is human comfort and perception, the principal frequency weightings related to these levels are calculated and applied both on vertical and horizontal directions separately.
In Equation 1, τ is taken as 1s due to recommendation in ISO 2631. However this choice is not justified by any means. Computation of running RMS values are then matched with the human comfort levels tabulated in the standard (Table 2). However, the source of this tabulated values has no foundation and can be taken as tentative. There are not any strict considerations on defining the right comfort levels so far.

Table 2 RMS values and their corresponding comfort levels, ISO 2631-1 (1997)

RMS Value (m/s^2)	Corresponding Situation
<0.315	Not Uncomfortable
0.315-0.63	A little Uncomfortable
0.5-1	Fairly Uncomfortable
0.8-1.6	Uncomfortable
1.25-2.5	Very Uncomfortable
>2	Extremely Uncomfortable

In both ISO2631-1:1997 and BS6841:1987, another index called vibration dose value (VDV) is also presented since it is more sensitive to peaks than the basic evaluation method. VDV uses fourth power instead of the second power of the weighted acceleration time history (Equation 2).

$$\mathrm{VDV} = \left\{ \int_0^T \left[a_w(t) \right]^4 dt \right\}^{\frac{1}{4}} \tag{2}$$

Table 3 VDV values and their corresponding comfort levels, Ellis and Littler (2004)

VDV (m/s$^{1.75}$)	Corresponding Situation
<0.66	Reasonable for passive person

0.66-2.38	Disturbing
2.38-4.64	Unacceptable
>4.64	Probably causing panic

Vibration dose values are calculated through Equation 2 and the decision on comfort level is made by comparing the resultant with the values suggested by Ellis and Littler (2004) (Table 3).

5 RESULTS AND DISCUSSIONS

Figure 5 shows the processed data from Game 1 and the resultant RMS values after human comfort and perception analysis. When maximum RMS value is matched with corresponding comfort levels from Table 2, it is observed that the stamping movement of the audience creates fairly uncomfortable situation. Other than this significant observation, during the time period of recording, vibration levels stay at "not uncomfortable" level. Vibration dose value is also found as 0.49 $m/s^{1.75}$ which corresponds to reasonable for passive person level.

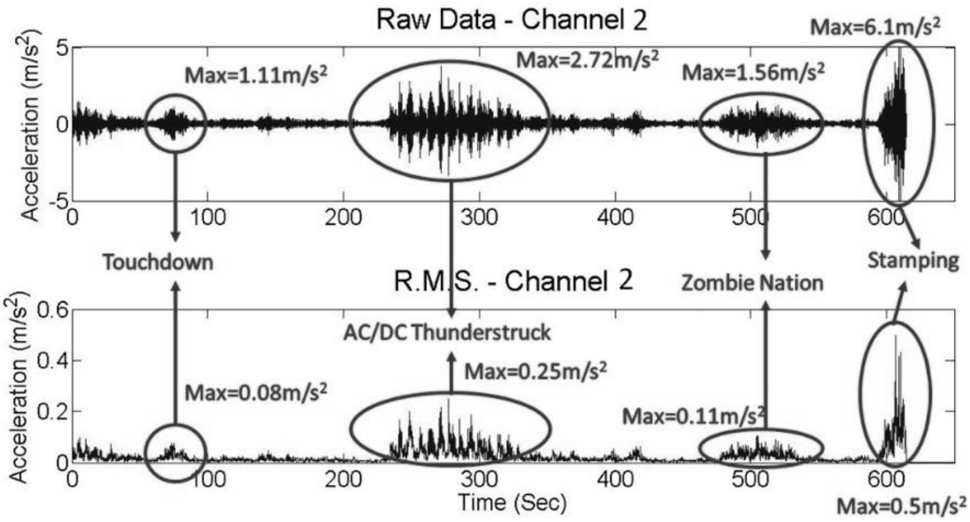

Figure 5 Game 1 Channel 2 (Lateral) RMS values and maximum measured vibration magnitudes.

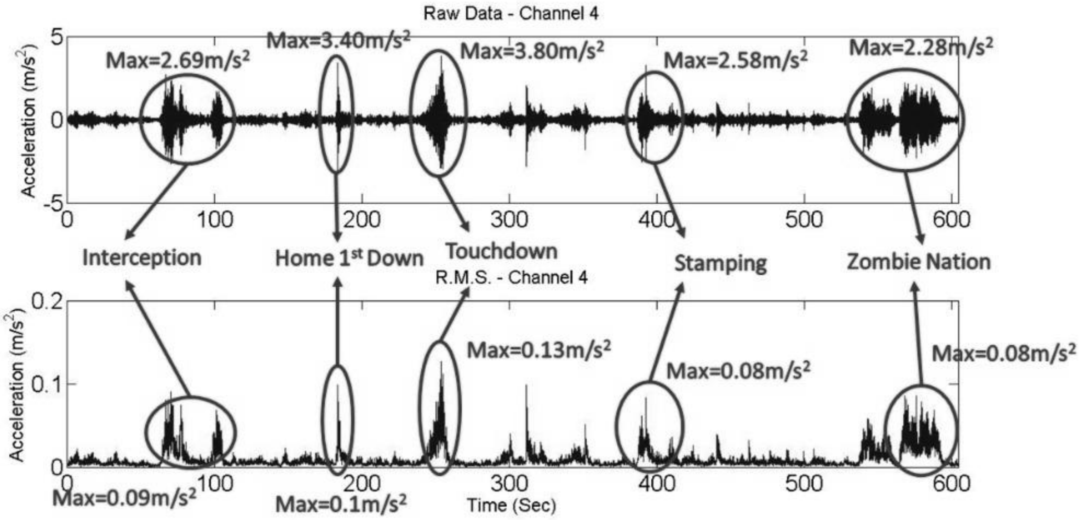

Figure 6 Game 2 Channel 4 (lateral) RMS values and maximum measured vibration magnitudes

Figure 6 shows a sample recording from Game 2. This is a great example of many significant events occurring in the same recording. The vibration levels though, stay at "not uncomfortable" zone during the whole recording. An interesting observation can be made by looking at Figure 5 and 6 together. Although some raw vibration values are close to each other, RMS values can fall in different comfort levels. Vibration dose value is also found as 0.162.17 $m/s^{1.75}$ which corresponds to reasonable for passive person level.

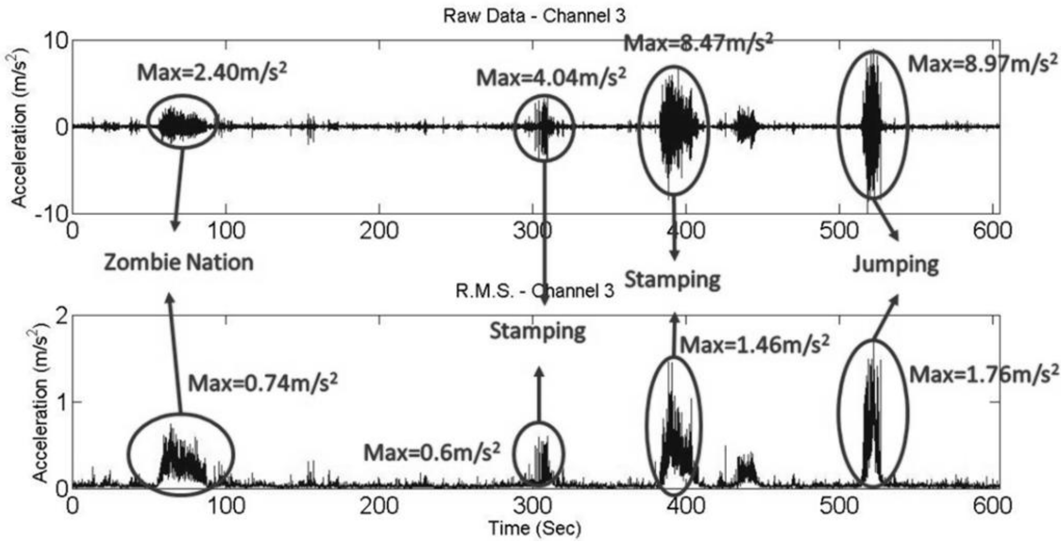

Figure 7 Game 4 Channel 3 (Vertical) RMS values and maximum measured vibration magnitudes.

Finally, Figure 7 shows a more diverse characteristics in terms of comfort levels since the RMS values found are relatively higher when compared to two different recordings above. This is mostly seen in stamping and jumping behavior of the audience. When looking at the processed data, accompaniment to the song "Zombie Nation" creates "fairly uncomfortable" comfort level whereas the two stamping movements following after falls in "little uncomfortable" and "uncomfortable" zone. The last jumping action creates the most severe discomfort with the level of "very uncomfortable". Vibration dose value is also found as 2.17 $m/s^{1.75}$ which corresponds to disturbing level.

RMS and VDV values found from the analysis are tabulated in Table 4.

Table 4 VDV - RMS Comparison

Game #	**VDV ($m/s^{1.75}$)**	**RMS (m/s^2)**
1	0.49	0.5
2	0.16	0.13
4	2.17	1.76

6 CONCLUSIONS

The human comfort and perception analysis as it is pointed out in ISO 2631-1 (1997) is carried out utilizing RMS and VDV measures. They have somewhat similar characteristics in terms of their assessment scale.

It can be concluded that stamping and jumping are more likely to create higher values of acceleration since these excitations are short in duration and have really strong impact characteristics. Although the spectators occupying the monitored section move in a coordinated motion, vibration magnitudes that can create human discomfort differ from one location to another. It is obvious that the highest acceleration values are obtained on slenderer members and in lateral direction which is expected from strength of material sense and from the nature of steel structures.

The duration of measurement is the most controversial part of the standard and has been the main concern of all the past studies since it might affect the magnitude of the RMS values that are to be calculated for evaluation. The standards advise the user to measure the vibration for a sufficient amount of time without setting any limits. This puts the reliability of the method under question since it is basically a time domain integration.

Although these recording may show RMS and VDVvalues fall in the range of discomfort zones, no complaints from the audience were received during any of the games monitored. This might indicate that the RMS and VDV methods might not be an accurate way of making decisions on comfort levels as it was also mentioned in various different studies.

There is a strong need for a better method of human comfort and serviceability assessment as the methods in the standards are far away from providing realistic results.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

BRE Digest 426, *The Response of Structures to Dynamic Crowd Loads*, 2004. 2nd Edition (Ellis B. R. and Ji, T.) Garston: BRE

British Standards Institution BS 6841. *Measurement and Evaluation of Human Exposure to Whole-Body Mechanical Vibration*. London, 1987.

Caprioli, A., Reynolds, P., Vanali, M. Evaluation of Serviceability Assessment Measures for Different Stadia Structures and Different Live Concert Events” *Proceedings of the 25th International Modal Analysis Conference*, 2007, Orlando, FL.

Catbas, F.N., Gul, M. Dynamic Response Monitoring and Correlation to Crowd Movement at a Football Stadium, *27th International Modal Analysis Conference* (IMAC XXVII). 2009. Orlando, FL.

Catbas, F.N., Gul, M., Sazak, O., Dynamic Response Monitoring and Correlation to Crowd Movement at a Football Stadium, *28th International Modal Analysis Conference* (IMAC XXVIII). 2010. Orlando, FL.

Ellis, B.R., and Littler, J.D., Response of Cantilever Grandstands to Crowd Loads: Part 1: Serviceability Evaluation, *Proceedings of the Institution of Civil Engineers, Structures and Buildings*, vol. 157,n 4, 235-241, 2004.

International Organization for Standardization, ISO 2631-1. *Mechanical Vibration and Shock Evaluation of Human Exposure to Whole-Body Vibration. Part 1: General Requirement*. Geneva, 1997.

Jones, C. A., Reynolds, P., and Pavic, A. (2011). “Vibration serviceability of stadia structures subjected to dynamic crowd loads: A literature review.” *Journal of Sound and Vibration*, 330(8), 1531–1566

Kasperski M., (1996). “Actual Problems with Stand Structures due to Spectator Induced Vibrations”, *Proceedings of the 3rd European Conference on Structural Dynamics: EURODYN ’96*, 5-8 June 1996, Florence, Italy. Rotterdam: Balkema, Vol 1, pp.455-461

Reynolds, P. and Pavic, A. Vibration Performance of a Large Cantilever Grandstand During an International Football Match. *Journal of Performance of Constructed Facilities*, 2006. 20(3): p. pp. 202-212.

Reynolds, P., Pavic, A., and Carr, J. Experimental Dynamic Analysis of the Kingston Communications Stadium. *The Structural Engineer*, 2007. 85(8): p. pp. 33-39.

Salyards, K.A. & Hanagan, L.M. Analysis of Coordinated Crowd Vibration Levels in a Stadium Structure, *Proceedings of the 25th International Modal Analysis Conference*. 2007, Orlando, FL.