Chapter 41
Recent Issues on Stadium Monitoring and Serviceability: A Review

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Abstract Unlike most of civil engineering structures whose static and dynamic responses are estimated accurately through several codes and guidance, stadiums reserve a distinctive place especially when it comes to their dynamic behavior. This difference takes its source from several factors such as influence of crowd size, motion and slenderness of the structure. The most noticeable form of this difference shows itself as excessive vibration levels which is actually a threat to the serviceability of these structures. Eventually, it becomes essential to carefully evaluate several steps of this particular problem starting from correct representation of crowd activity through accurate loadings and human-structure interaction models to arranging acceptable vibration serviceability limits. This publication intends to point out the newly developed techniques and discovered issues on several stages of the problem during the last decade.

Keywords Stadium • Serviceability • Vibration • Crowd loading • Human structure interaction

41.1 Introduction

Stadiums are prominent structures when compared with other structural engineering counterparts as to hosting large crowds and having slender structural members in return for their unique architectures (Fig. 41.1). These characteristics in conjunction with the effects such as occupant-mass ratio, actions of the occupants during events and the inherent abilities of the human body make the loadings described in current design approaches either over conservative or away from predicting true nature of crowd motion [1–3].

Serviceability problem for stadiums are handled in three steps namely input/excitation/source, system/path/structure and output/response/receiver [1, 2]. The input represents the estimation and recreation of loading functions utilizing either direct mathematical and statistical representations or recreation of real-life force time histories. In the last decade, there has been valuable research on this part of the problem by proposing stochastic modelling and computer vision methods. These are explained along this study.

Research topics regarding the system (stadium) hovers around alterations in dynamic parameters caused by the density of the crowd, active or passive occupants and their activities. More detailed insight on this issues is earned in light of the recent research. The issues related to output are serviceability and human comfort. The methods related to the assessment of risky perception levels in codes and standards need a better investigation for several reasons such as the insufficient explanations on the calculation of these values, disparity of perception from person to person, the inability of running controlled experiments to create serious discomfort levels, etc. This current study is intended to convey a brief information on the new approaches to the solution of those problems surveying the literature picking up from the year 2008 [2].

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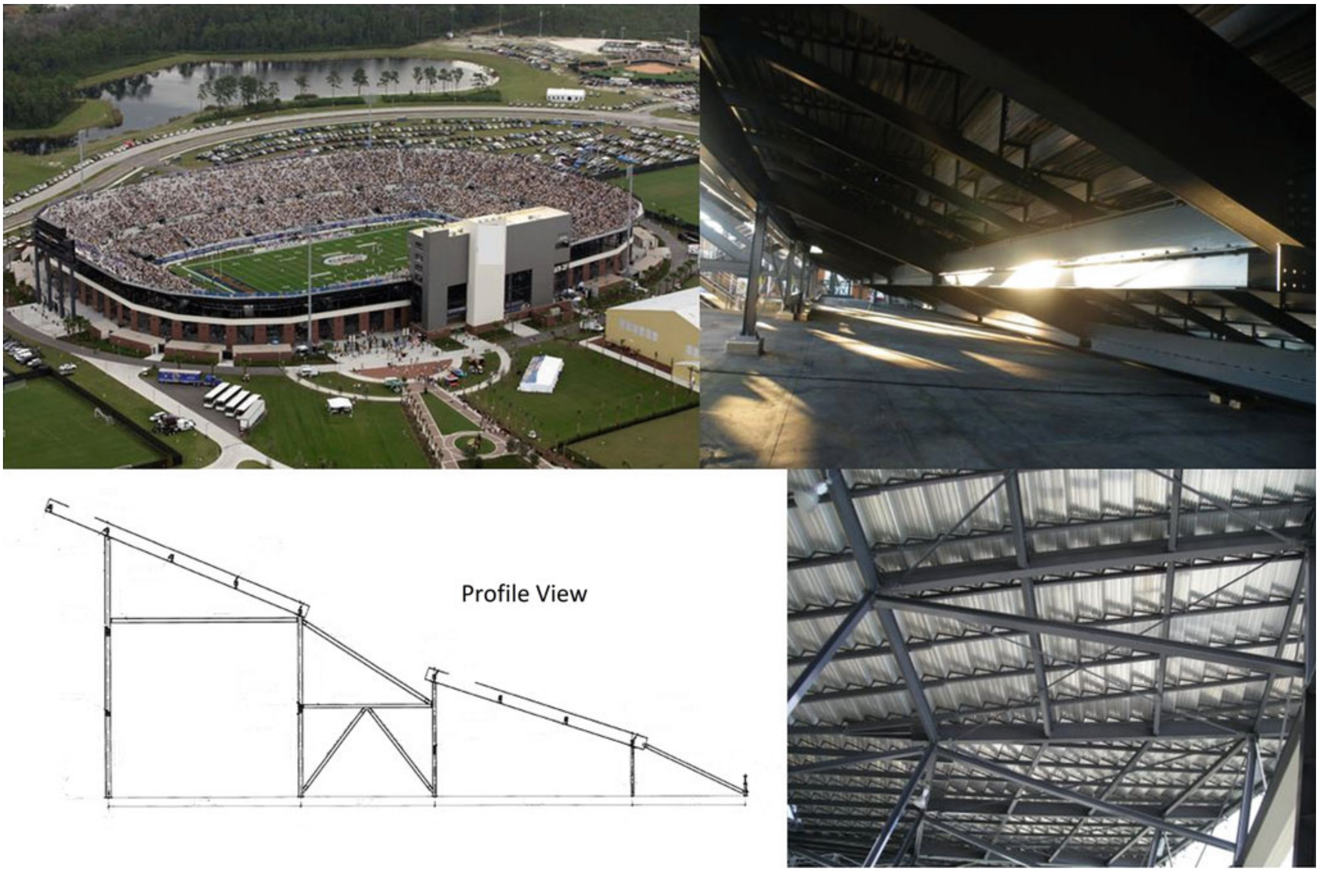

Fig. 41.1 Architectural and structural details of a stadium as a demonstration of their slender nature

41.2 Load Modeling

Recent research is condensed mainly on the rehabilitation of conventional recreated force-time history measurements and relatively new image-based techniques. It has been shown by various researchers [3–7] that walking and jumping loads are not perfectly periodic and are narrow-band phenomenon (intra-subject variation) by evincing the leakage around higher harmonics and frequently varying phase lags Fig. 41.2.

These first approaches considering the altered morphology, variability of both peak to peak intervals and amplitudes of real jumping records are made through an autoregression model [8]. However, due to cosine-squared functions being inadequate to fit into imperfectly shaped pulses and representing full frequency band, the problem is resolved with a novel approach [9–11] using stochastic processes in which combination of different Gaussian functions are used. Synthetic force time histories are generated utilizing a closed-loop trajectory in three dimensional space laying on a unit circle in the plane. This method seems to be the most realistic method by far.

Problems measuring the jumping and bobbing forces using force plates such as distorted patterns and additional inertial forces [12–14] are tried to be resolved using motion tracking technologies in which several data markers are attached to the subject's body and each body part is evaluated separately [15]. The data markers are tracked down by a high frequency optoelectronic device and GRFs are estimated accordingly.

There has also been novel studies on load estimation by making use of image processing and computer vision techniques as well as a comparison of these methods with previously mentioned data marker tracking [16]. The first works carried out in this area are based on the fundamental family of algorithms such as correlation in consecutive images [17], contour detection [18, 19] and Bayesian clustering methods for crowd tracking [20]. Subsequently, calculation of forcing functions, motion measurement of people and the patterns of their behavior in terms velocity amplitude and frequency [21, 22] or utilization of off the shelf regular or thermal imaging cameras on a portion of a real grandstand [23, 24] become viable. Some studies [25, 26] among these come forward with their ability to be performed in both laboratory and real life stadiums. Despite the idea of expanding an individual forcing to crowd, the proposed method uses the motion of the crowd directly for generating forcing functions.

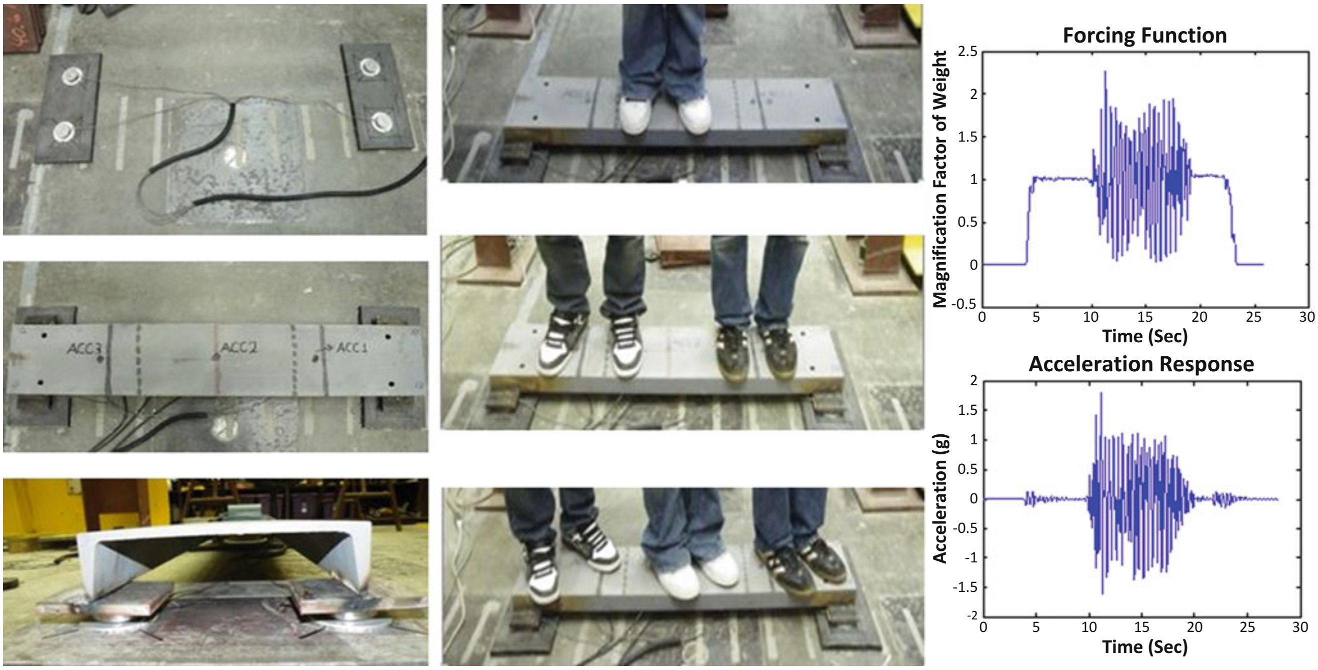

Fig. 41.2 Forcing function measurements showing non-periodic nature

41.3 Human Structure Interaction

Recent research dwells on the effects of as mass ratio of occupants to structure, distribution of the crowd, portion of the crowd being active or passive, and the posture of the occupants. One study provides results from an experimental study by narrowing this investigation down to passive crowds by looking at their distribution, mass ratios and different postures [27]. Results from three different postures (standing-straight knees, standing-bent knees and seated) on a composite slab which is excited by an electromechanical shaker states that the sparse or dense distribution of the crowd does not seem to have an effect on the dynamic properties for the same number of people. Alterations of frequencies and damping ratios in relation with the size and posture of the crowd are also given. This work, in a continuous sense, is further detailed into the investigation of only standing with straight knees and standing with bent knees postures of completely passive crowds by interacting with the slab structure which is specially designed to simulate adjustable first dominant frequencies and cantilever effect [28, 29]. These studies indicate that the natural frequency is also effective on damping ratio as well as the posture by making comparisons to British Joint Working Group (JWG) models. Under and over estimations are stated based on the experimental results and JWG recommendations. Subsequently, a new SDOF passive implementation is proposed.

A new factor called "drop out- *p*" which is defined as the minimum force at resonance divided by the value away from resonance where the force reaches its typical jumping level and which is an insight about the significance level of human-structure interaction, is shown as a result of the tests that are conducted under six different scenarios involving change of mass and damping [30]. Further suggestions are made on the reduction of dynamic load factors (DLFs) [2] and might serve to creation of adaptable and useful curve to better fit in performance design. Two more possibilities being group absorbing and supplying energy from and to the system regarding DLF reduction are also realized in another study [31] on a specially built laboratory grandstand [32, 33] simulator that has adjustable rigid and flexible support conditions.

Some additional studies propose a revision to mass-spring-damper models by advising the addition of the effect of the seat type pointing out the outcomes of experiments which are done using different seat types (a grandstand seat, a work desk chair, a swivel chair and a rigid seat) occupied by subjects having different postures along with changing occupant-structure mass ratios [34, 35].

Determination of the correct OMA method to be applied on stadium data is investigated in a comparative manner by implementing different operational modal analysis methods, namely singular value decomposition (SVD), stochastic subspace identification (SSI), Natural Excitation Technique (NExT) are put to test in a comparative manner [36, 37]. Every technique is applied on six different sets of data namely: empty structure, crowd filling, crowd seating, half-time, crowd leaving and goal followed by weak and strong aspects of each method one over another. The same cases and the structure are used in another study for the comparison of two well-known methods: PolyMAX and SSI [38]. It can be clearly stated that the parameter estimation is highly affected when there is crowd excitation and different methods must be applied on the same data to assure a robust identification.

Another point to be considered is the reliability of the current OMA methods to be applied on stadium identification since some of the assumptions such as excitation of the whole frequency band, a linear and time invariant structural system and most importantly, excitation being Gaussian random white noise need to be satisfied. However, Gaussian white noise assumption, time dependent variation of dynamic parameters and the possibility of having nonlinear systems [39] are to be questioned.

All the techniques mentioned here have their benefits yet constrained with their limitations. Since the reliability of the identification procedure is put to question due to crowd excitation, these techniques might be implemented and optimum solutions might be sought.

41.4 Perception and Human Comfort

The assessment methodology is generally carried out by following the well-known and widely used guidance [40–42]. Assessment measures given in these standards such as root mean square (RMS), running RMS, maximum transient vibration value (MTVV), fourth power vibration dose value (VDV) or root mean quad (RMQ) have slight differences regarding their calculations as to measurement directions, subject's posture, application of frequency weightings, etc.

The research in the last decade mainly focus on the application of health, perception, motion sickness and comfort classification measures by emphasizing on sport events [5, 6, 43], concerts [44, 45] or hybrid type involving both of them and for a long term [46–49].

A psychophysical experimental method called subjective scaling was used to distinguish the two concepts as perception and comfort from each other in both sitting and standing positions [50]. The subjects are required to scale their responses via text descriptors provided and their choices were compared with frequency weighted acceleration of two particular standards [40, 51]. Extreme perception levels are seemed to be occurring before the feeling of discomfort making it more important for serviceability assessment.

Following the same scaling method [50], a possible new vibration assessment method is proposed depending upon the root mean square (RMS) of the normalized ground reaction forces (GRF) (when standing) time history or the normalized foot point acceleration time history [52] since the GRFs obtained with stationary measurements are different when on a moving grandstand [53]. GRF oscillations show the same characteristics as the grandstand oscillations for frequencies of excitation lower than 2 Hz whereas GRF wave forms are found to be randomly inconsistent and almost in nonlinear trend in higher frequencies.

In most cases, perception or human discomfort levels assessed looking at the measurement scale do not match with the observed behavior of the occupants in reality which again is a sign of questioning the appropriateness of the application on grandstands.

41.5 Conclusions

- Stochastic load modeling approach brings about quite reliable and realistic insight for the recreation of force-time histories by incorporating several variations from one pulse to another and having the ability of having arbitrary length recordings. Besides, each harmonic as in the real recordings are acquired.
- As well as stochastic load modeling approach, motion tracking, image processing and computer vision methods seem promising as to being alternative to force plate measurements, having field free characteristics, contactless measurement of loads and being able to track large number of people. The weak points such as difficulty of data markers being tracked in a crowd, placement of cameras, large amount of data and illumination conditions are yet to be developed.
- Although many of the findings fall in line with the previous literature stating that frequencies are to be decreased and damping ratios to be increased with the increasing mass, some studies bring new questions by showing otherwise or claiming that these changes also depend on both posture and frequency. Additionally, the interaction of the passive and active crowds as well as their effects on the structure are still in question.
- Structural identification methods that have been used so far in different studies show distinctive results on the same data outperforming one another on certain estimation steps. However, the convenience of these methods for stadium

problems are to be explored for the reasons such as Gaussian white noise assumption, time dependent variation of dynamic parameters and the possibility of having nonlinear systems.

- As to vibration serviceability assessment measures, of all the preceding research, the main point of discussion is actually the applicability and compatibility of these operating machinery based standards on grandstand serviceability problem as the excitation type have different inherence compared to machinery based vibrations. The idea of forming new type vibration serviceability limits or rehabilitation of existing ones taking human induced excitation and building characteristics into account is widely agreed upon since the ones currently in use are not capable of reflecting a true state.

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References

1. ISO 10137:2007: Bases for Design of Structures - Serviceability of Buildings and Walkways Against Vibrations. International Organization for Standardization (2007)
2. Jones, C.A., Reynolds, P., Pavic, A.: Vibration serviceability of stadia structures subjected to dynamic crowd loads: a literature review. J. Sound Vib. **330**(8), 1531–1566 (2011)
3. Brownjohn, J.M., Pavic, A., Omenzetter, P.: A spectral density approach for modelling continuous vertical forces on pedestrian structures due to walking. Can. J. Civ. Eng. **31**(1), 65–77 (2004)
4. Newland, D.E.: An Introduction to Random Vibrations, Spectral and Wavelet Analysis. Wiley, New York (1993)
5. Catbas, F.N., Gul, M.: Dynamic response monitoring and correlation to crowd movement at a football stadium. In: Proceedings of the 27th International Modal Analysis Conference, Orlando (2009)
6. Catbas, F.N., Gul, M., Sazak, H.O.: Dynamic testing and analysis of a football stadium. In: Dynamics of Civil Structures, vol. 4, pp. 195–203. Springer, New York (2011)
7. Sazak, H.O., Catbas, F.N., Gul, M.: Structural health monitoring and evaluating structural performance of a stadium. In: Proulx, T. (ed.) Civil Engineering Topics, vol. 4, pp. 365–372. Springer, New York (2011)
8. Sim, J., Blakeborough, A., Williams, M.S., Parkhouse, G.: Statistical model of crowd jumping loads. J. Struct. Eng. **134**(12), 1852–1861 (2008)
9. Racic, V., Pavic, A., Brownjohn, J.M.W.: Mathematical modelling of near-periodic jumping force signals. In: Proceedings of the 28th International Modal Analysis Conference, Jacksonville (2010)
10. Racic, V., Pavic, A.: Mathematical model to generate asymmetric pulses due to human jumping. J. Eng. Mech. **135**(10), 1206–1211 (2009)
11. Racic, V., Pavic, A.: Mathematical model to generate near-periodic human jumping force signals. Mech. Syst. Signal Process. **24**(1), 138–152 (2010)
12. AMTI User Manuals. AMTI User Man (2008)
13. Perry, J.: Gait Analysis: Normal and Pathological Function. SLACK Incorporated, Thorofare (1992)
14. Racic, V., Brownjohn, J.M.W., Pavic, A.: Measurement and application of bouncing and jumping loads using motion tracking technology. In: Proulx, T. (ed.) Civil Engineering Topics, vol. 4, pp. 201–210. Springer, New York (2011)
15. Racic, V., Brownjohn, J.M.W., Pavic, A.: Novel experimental characterisation of human-induced loading. In: Proceedings of the 27th International Modal Analysis Conference, Orlando (2009)
16. Feng, Z., Racic, V., Brownjohn, J.M.W., Elliot, M.T., Wing, A.: Vision-based tracking of human body motion. In: Proceedings of the 32nd IMAC, pp. 171–174. Springer, New York (2014)
17. Hoath, R.M., Blakeborough, A., Williams, M.S.: Using video tracking to estimate the loads applied to grandstands by large crowds. In: Proceedings of the 25th International Modal Analysis Conference (2007)
18. Beucher, S., Lantuejoul, C.: Use of watersheds in contour detection. In: International Workshop on Image Processing: Real-time Edge and Motion Detection/Estimation, Rennes (1979)
19. Blake, A., Isard, M.: Active Contours. Springer, New York (1998)
20. Brostow, G., Cipolla, R.: Unsupervised Bayesian detection of independent motion in crowds. In: IEEE Conference on Computer Vision and Pattern Recognition, New York, pp. 594–601 (2006)
21. Caprioli, A., Manzoni, S., Zappa, E.: Crowd motion measurement based on image processing. In: Proceedings of the 26th International Modal Analysis Conference (2008)
22. Caprioli, A., Manzoni, S., Zappa, E.: People-induced vibrations of civil structures: image-based measurement of crowd motion. Exp. Tech. 173 **35**(3), 71–79 (2011)
23. Caprioli, A., Cigada, A., Sala, R., Zappa, E.: Image based measurement of a stadium excitation due to jumping people. In: Proceedings of the 24th International Modal Analysis Conference (2006)
24. Cigada, A., Zappa, E.: Analysis of jumping crowd on stadium stands through image processing to security purposes. In: Proceedings of the 2006 IEEE International Workshop on Measurement Systems, pp. 56–61. IEEE, Alexandria (2006)
25. Jones, C.A., Reynolds, P., Zappa, E., Manzoni, S., Cigada, A.: Verification of crowd dynamic excitation estimated from image processing techniques. In: Proulx, T. (ed.) Dynamics of Civil Structures, vol. 4, pp. 205–216. Springer, New York (2011)

26. Mazzoleni, P., Zappa, E.: Vision-based estimation of vertical dynamic loading induced by jumping and bobbing crowds on civil structures. Mech. Syst. Signal Process. **33**, 1–12 (2012)
27. Salyards, K.A., Firman, R.J.: Human-structure interaction: effects of crowd characteristics. In: Proulx, T. (ed.) Civil Engineering Topics, vol. 4, pp. 247–254. Springer, New York (2011)
28. Noss, N. C., Salyards, K. A.: Development of a laboratory test program to examine human-structure interaction. In: Society for Experimental Mechanics Series, pp. 7–16. Springer, Jacksonville (2012)
29. Salyards, K.A., Noss, N.C.: Experimental evaluation of the influence of human-structure interaction for vibration serviceability. J. Perform. Constr. Facil. **28**(3), 458–465 (2014)
30. Harrison, R.E., Yao, S., Wright, J.R., Pavic, A., Reynolds, P.: Human jumping and bobbing forces on flexible structures: effect of structural properties. J. Eng. Mech. **134**(8), 663–675 (2008)
31. Comer, A.J., Blakeborough, A., Williams, M.S.: Rhythmic crowd bobbing on a grandstand simulator. J. Sound Vib. **332**(2), 442–454 (2013)
32. Comer, A., Blakeborough, A., Williams, M.S.: Grandstand simulator for dynamic human-structure interaction experiments. Exp. Mech. **50**(6), 825–834 (2010)
33. Comer, A.J., Blakeborough, A., Williams, M.S.: Human-structure interaction in cantilever grandstands-design of a section of a full scale raked grandstand. In: 25th International Modal Analysis Conference (2007)
34. Pedersen, L.: Aspects of prediction accuracy in human-structure interaction. In: Proceedings of the 27th International Modal Analysis Conference, Orlando (2009)
35. Pedersen, L.: An aspect dynamic human-structure interaction. In: Proceedings of the 26th International Modal Analysis Conference (2008)
36. Prasenjit, M., Reynolds, P., Pavic, A.: Statistical analysis of online response data of a stadium structure. In: Proceedings of the 23rd International Modal Analysis Conference (2005)
37. Reynolds, P., Prasenjit, M., Pavic, A.: Use of operational modal analysis on empty and occupied stadia structures. In: Proceedings of the 1st International Operational Modal Analysis Conference (IOMAC), Copenhagen (2005)
38. Peeters, B., Van der Auweraer, H., Vanhollebeke, F., Guillaume, P.: Operational modal analysis for estimating the dynamic properties of a stadium structure during a football game. Shock. Vib. **14**(4), 283–303 (2007)
39. Jones, C.A., Reynolds, P.: Finite element modelling and updating of a stadium structure using in-service data. In: Proceedings of the 27th International Modal Analysis Conference, Orlando (2009)
40. BS 6841: Guide to Measurement and Evaluation of Human Exposure to Whole-Body Mechanical Vibration and Repeated Shock. British Standards Institution (1987)
41. ISO 2631-1: Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole-Body Vibration. Part 1: General Requirements. International Organization for Standardization (1997)
42. ISO2631-2: Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole-Body Vibration. Part 2: Vibration in Buildings (1Hz to 80 Hz). International Organization for Standardization (2003)
43. Salyards, K. A., Hanagan, L.M.: Analysis of coordinated crowd vibration levels in a stadium structure. In: Proceedings of the 25th International Modal Analysis Conference (2007)
44. Caprioli, A., Reynolds, P.: Evaluation of serviceability assessment measures for different stadia structures and different live concert events. In: Proceedings of the 25th International Modal Analysis Conference (2007)
45. Salyards, K.A., Hanagan, L.M., Trethewey, M.: Comparing vibration serviceability assessment measures for stadium rock concert data. In: Proceedings of the 24th International Modal Analysis Conference (2006)
46. Cappellini, A., Fagiani, R., Vanali, M.: Serviceability assessment of two different stadium grandstand during different events. In: Dynamics of Civil Structures, vol. 2, pp. 299–310. Springer, New York (2015)
47. Caprioli, A., Vanali, M., Cigada, A.: One year of structural health monitoring of the Meazza stadium in Milan: analysis of the collected data. In: Proceedings of the 27th International Modal Analysis Conference, Orlando (2009)
48. Caprioli, A., and Vanali, M.: Comparison of different serviceability assessment measures for different events held in the G. Meazza Stadium in Milano. In: Proceedings of the 27th International Modal Analysis Conference, Orlando (2009)
49. Salyards, K.A., Hanagan, L.M.: Evaluation of vibration assessment criteria and their application to stadium serviceability. J. Perform. Constr. Facil. **24**(2), 100–107 (2010)
50. Nhleko, S.P., Williams, M.S., Blakeborough, A.: Vibration perception and comfort levels for an audience occupying a grandstand with perceivable motion, Orlando (2009)
51. BS6472: Guide to Evaluation of Human Exposure to Vibration in Buildings (1 Hz to 80 Hz). British Standards Institution (1992)
52. Nhleko, S.P., Blakeborough, A., Williams, M.S.: Ground reaction forces on vibrating structures. In: Proceedings of the 27th International Modal Analysis Conference, Orlando (2009)
53. Yao, S., Wright, J.R., Pavic, A., Reynolds, P.: Experimental study of human-induced dynamic forces due to jumping on a perceptibly moving structure. J. Sound Vib. **296**(1-2), 150–165 (2006)