ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

DESIGN OF SYDNEY OLYMPIC STADIUM FOR MITIGATION OF CROWD-INDUCED VIBRATION

Graham Brown, Peter Erdmanis, Ross Emslie and David Hanson

Structural Dynamics Group, Sinclair Knight Merz
St. Leonards, Sydney, NSW 2065, Australia
gpbrown@skm.com.au

Abstract

Increasingly, crowd-induced vibration is seen as an important issue in the design of assembly occupancies, especially large stadia, which are used for pop concerts, involving rhythmic activity, as well as sporting events. This paper presents an overview of an investigation undertaken by Sinclair Knight Merz into the response of the Sydney Olympic Stadium due to crowd-induced vibration.

The first part of the investigation involved the construction of a finite element model of the stadium which was subjected to dynamic loading to simulate the likely response of the structure to concert loads. The vibration responses were evaluated in terms of design specifications based on the Canadian Building Code. The results of these simulations, and a review of crowd-induced vibration in the literature, were used to develop the original stadium design to reduce predicted vibration responses. The design approach, together with the final design and its implementation are described in the paper.

The second part of the investigation involved the subsequent testing of the structure during a concert performance. Accelerations were recorded at ten locations on the structure over the duration of the concert and the structure was shown to meet the performance requirements for crowd-induced vibration.

1. INTRODUCTION

Sinclair Knight Merz Structural Dynamics Group conducted an evaluation of the dynamic performance of the Sydney Olympic Stadium due to crowd-induced dynamic loads during the design of the structure. The results were assessed according to design specification requirements and as a result of this assessment the design of the stadium was significantly altered.

Increasingly, crowd-induced vibration is seen as an important issue in the construction of assembly occupancies [1]. The Canadian Building Code [2] has contained recommendations on allowable vibration levels since 1985, while in 1996 design clauses covering crowd rhythmic behaviour and resultant vibration were introduced into the British Standard, BS6399 ‘Loading of Buildings’ [3].

1.1 Vibration Specification

The design specification for the Sydney Olympic Stadium contained limits for acceptable vibration levels from the point of view of human perception to vibration based on the Canadian Building Code [2] and Allen [4]. Vibration limits were specified for each area of the structure depending on the intended occupant usage and activities envisaged for those areas. For the terraced seating areas an acceleration limit of 7%g_{peak} applied during concerts and sports events, while maximum accelerations were limited to 2.5%g_{peak} in the private suites located within the mid-tier cantilever structure.

1.2 Crowd Dynamic Loads

The largest forces arising from crowd behaviour occur in the frequency range 0-3Hz. Also, related to crowd activities of an impulsive nature such as stamping and clapping are other force components (higher harmonics of the primary crowd forces) that occur at multiples of the primary forcing frequency. This extends the frequency range over which significant forces can occur to 6Hz [4]. The higher harmonics of the crowd forces are reduced in magnitude compared to the primary forces, reflecting the fact that most of the energy associated with crowd activity is related to the primary force. However, it is the second harmonic of crowd activities that most commonly defines the vibration response of a building structure as this force tends to occur at a frequency that corresponds more closely with the structures' resonant frequencies. At resonance the vibration response is greatly amplified, the resultant acceleration level depending on the amount of damping present. The forcing function applied during the dynamic analysis of the stadium represents audience participation by stamping. This is shown in Figure 1.

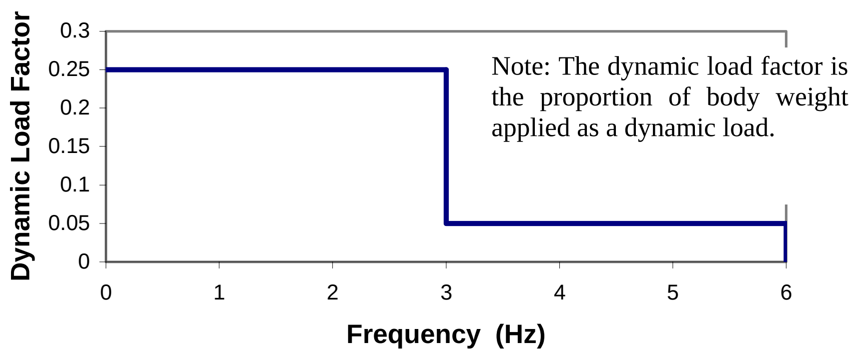

Figure 1: Audience dynamic forcing function

1.3 Finite Element Analysis

A finite element model of the Olympic Stadium, as shown in Figure 2, was built during the detailed design phase of the project and crowd dynamic loads were applied in accordance with the Canadian Building Code [2] and Allen [4]. The entire structure was modelled using beam and shell elements. The concrete seating plats were represented by beam elements along which the dynamic loads were uniformly distributed. Numerous dynamic simulations of crowd-induced motion were carried out on this and other smaller, more detailed models, which were primarily used for assessing the sensitivity of results to different boundary conditions and for design iterations.

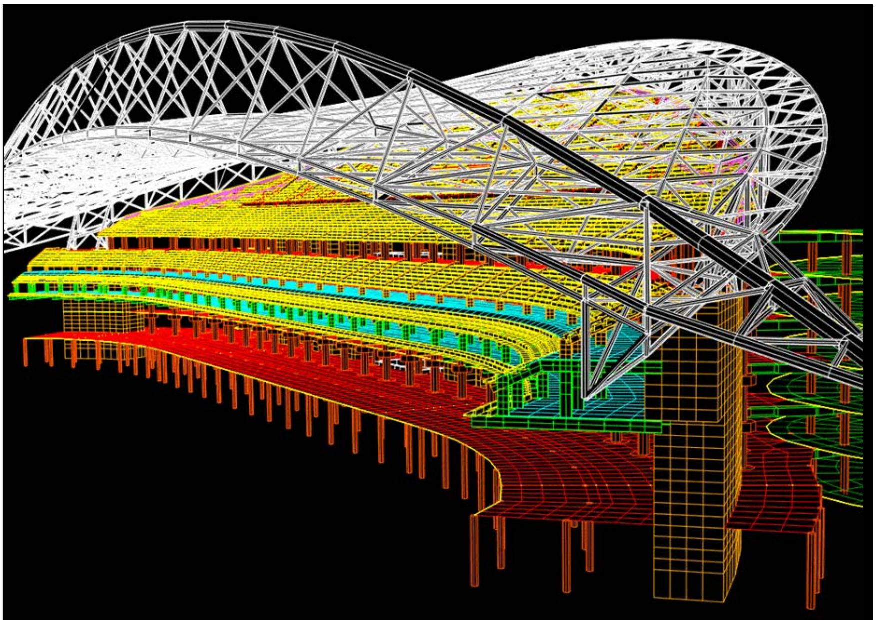

Figure 2: Finite element model of Stadium Australia

1.4 Simulation Results

The result of the finite element simulation showed that the initial concept design for the seated areas of the stadium did not comply with the design specification for vibration. Exceedance of the allowable vibration levels occurred on both the mid and upper-tier sections of the stands, with the cantilevered areas at the front of the upper-tier and the mid-tier proving to be the most critical. The natural frequency of the mid-tier cantilever was approximately 4.5Hz for the concept design and the peak acceleration response at the cantilever tip was predicted to be 19%g compared to the allowable level of 7%g. The upper-tier structure contained several natural modes of vibration in the range 0 - 6Hz that interacted with the forcing function to produce a significant vibration response. The mode of vibration excited by crowd-induced loads applied to the mid-tier concept design is shown in Figure 3. Also shown is a plot of the peak vibration acceleration versus position along the cantilever at 4.5Hz.

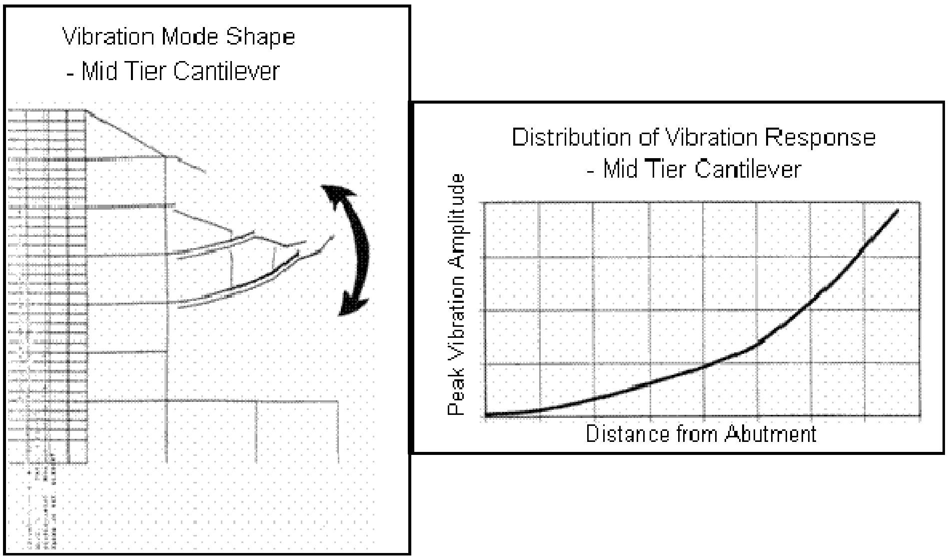

Figure 3: 4.5Hz mode of vibration of original mid-tier design (left) and peak vibration response of original mid-tier design (right)

1.5 Design Approach

Taking into account the available literature on the subject of crowd-induced vibration at the time of the design and the need for certainty within a fast-track design program, the technical approach adopted to address the vibration problem was to stiffen the structure, thereby moving the frequencies of significant natural modes of vibration to beyond 6Hz. This reduces the vibration response of the structure by moving the resonant frequencies beyond the range of the second harmonic of any crowd-induced load.

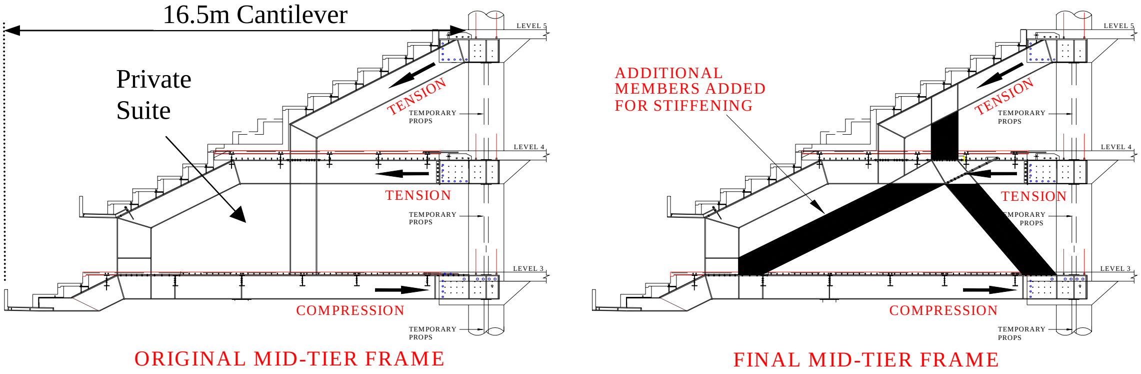

Figure 4: Modifications to stadium design to achieve compliance with vibration specification

After an extensive programme of design iteration, modifications were made to the initial concept that enabled the structure to satisfy the requirements set out in the design specification. The calculated natural frequency of the critical mid-tier cantilever was shifted to 6.5Hz, bringing the maximum expected peak vibration acceleration to below 7%g. Similarly, the maximum expected vibration level in the upper-tier was reduced to an acceptable level. Aspects of the mid-tier structural design that were modified to achieve compliance with the vibration specification are shown in Figure 4. A photo of the modified mid-tier structure taken during stadium construction is given in Figure 5.

Figure 5: The modified mid-tier frames during construction

2. TESTING

2.1 Experiment Setup

The Sinclair Knight Merz Structural Dynamics Group recorded vibration measurements on the Stadium mid-tier structure during the Bee Gees concert on 27-3-1999. These measurements were taken with a view to reporting the maximum accelerations on the structure during the concert event and comparing vibration response levels to allowable levels specified in the stadium design brief. A cross-section of the stadium structure showing the location of the mid-tier is given in Figure 6.

Prior to the concert event, a total of ten accelerometers were installed on the Eastern side of the stadium. Vibration levels were monitored for the duration of the concert at a matrix of locations spanning three seating bays. The seating bays to be monitored were chosen on the basis that they were expected to be fully occupied during the concert event and for their proximity to a convenient data recording point. The vibration monitoring locations are shown in Figure 7.

Positions 1, 2, 3, 4 and 8 are on the steel raker beams below level 3 of the stadium. Positions 6, 9 and 10 are mid-span on the underside of the concrete seating plats, while positions 5 and 7 are at the quarter points of a concrete seating plat.

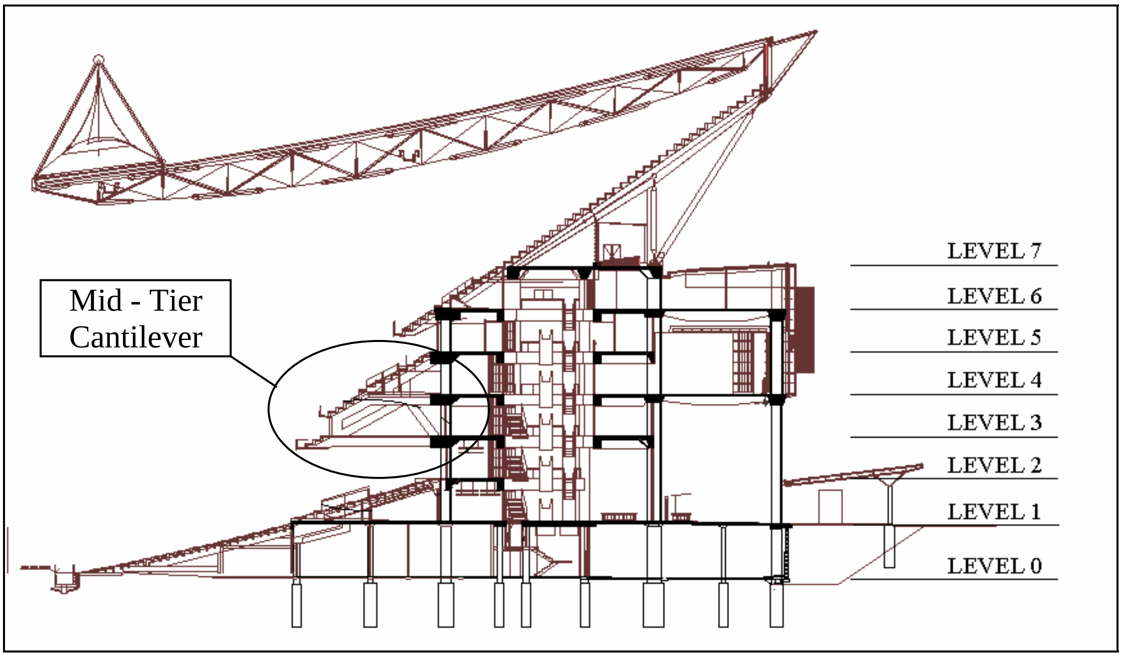

Figure 6: Stadium Australia mid-tier cantilever structure

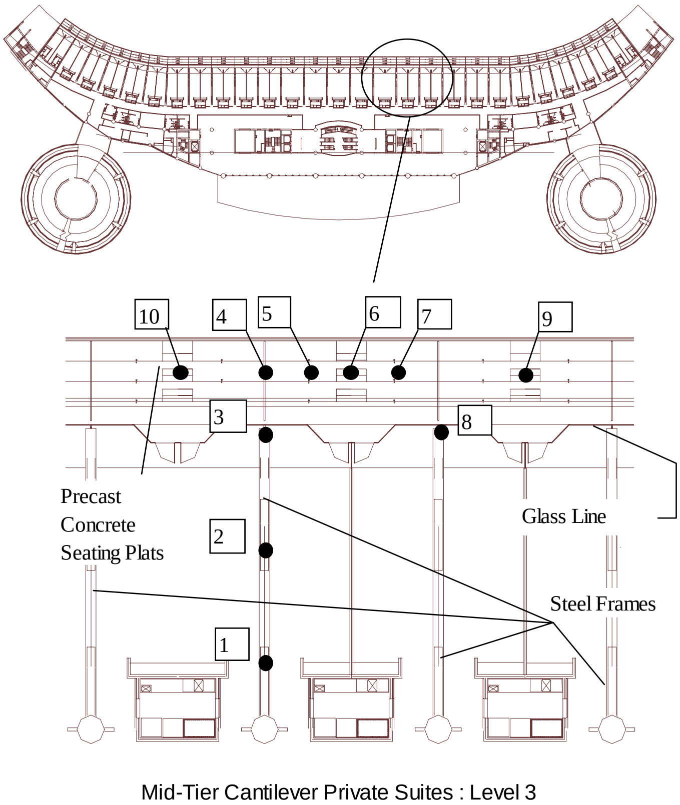

Figure 7: Vibration monitoring locations

2.2 Measured Vibration Responses

The acceleration response of the structure was recorded for the duration of the Bee Gees performance (approximately 2 hours). Prior to the concert, the vibration generated by people moving around the stadium was used to verify the design natural frequency of 6.5Hz for the mid-tier cantilever.

The measured data was initially recorded using a 16 channel digital audio tape capable of good frequency response to zero Hertz. The data was then resampled using a Somat field computer with a sample rate of 100Hz and bandpass filtered between 0.5Hz and 10Hz to remove signal drift and audio frequencies. Figure 8 is a data record for the full concert measured at position 6, the mid span of the seating plat at the tip of the cantilever. Some of the more significant events are annotated in the figure.

Figure 9 presents an expanded plot of approximately 5 seconds of the acceleration time waveform surrounding the peak vibration response for position 6, which was recorded during the song 'The Spics and The Specs'. The beat frequency of the music, 2.17Hz, together with second and third harmonics are clearly evident in signal.

The peak vibration response was recorded for each measurement position. The maximum vibration level recorded during the concert was 2.2%g_{peak} at position 10.

The level of activity observed on the mid-tier cantilever over the measurement positions was logged for the duration of the concert. From the log of observations it is apparent that the majority of the concert was accompanied by relatively low levels of crowd action and participation. There were, however, a number of songs that resulted in vigorous audience participation in the form of stamping and dancing, during which the majority of the audience was on its feet. These activities correlate strongly with measured increases in vibration levels on the structure.

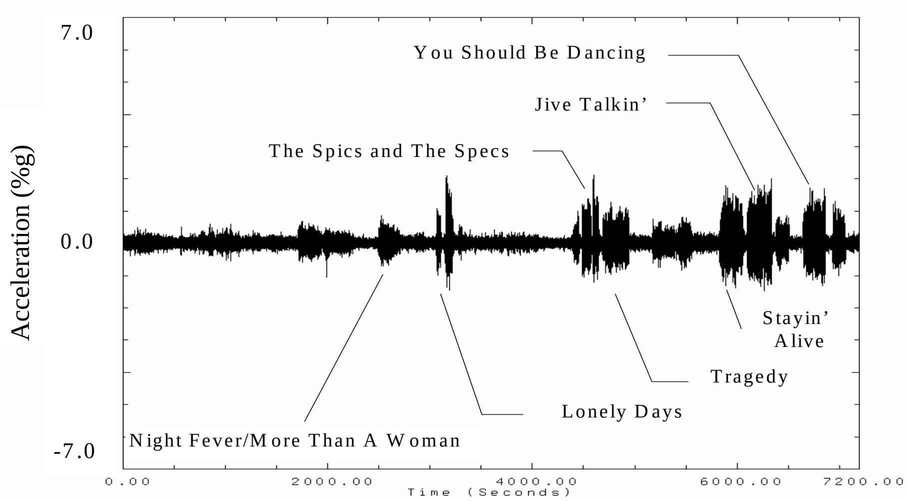

Figure 8: Concert acceleration data for measurement position 6

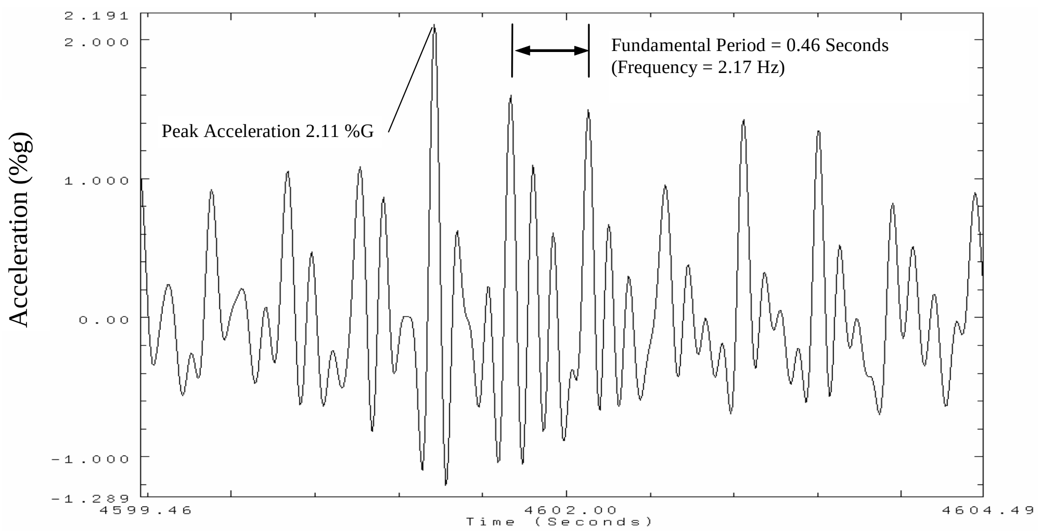

Figure 9: Expanded time waveform corresponding to position 6 peak vibration response

3. DISCUSSION

The design specification for the Sydney Olympic Stadium contained limits for acceptable vibration levels from the point of view of human perception to vibration. Vibration limits were specified for each area of the structure based on the intended occupant usage and activities envisaged for those areas. The vibration criteria and dynamic loads were derived from the National Building Code of Canada and supporting technical papers.

The specified maximum acceptable acceleration on the seated area of the structure during a concert was 7%g. The corresponding allowable vibration level for the private suites was 2.5%g. The maximum peak vibration response recorded during the Bee Gees concert on the tip of the mid-tier cantilever structure seated area was 2.2%g, and 0.57%g on the private suite floor at the glass line. Based on the measured vibration performance of the structure, the mid-tier cantilever and private suite areas were shown to be in compliance with specified vibration criteria for this concert event.

The Bee Gees concert, whilst not likely to be the most severe event for crowd-induced vibration at the stadium, was accompanied by several periods of sustained rhythmic crowd activities such as dancing and stamping in time to music. These activities could be expected to be representative of typical crowd behaviour during a concert event. Given that the measured vibration levels were low in comparison to the vibration criteria, it can be concluded that the structure has the capacity to preserve spectator amenity for vibration for a range of events of significantly greater severity than the event that was monitored.

Since the time of the design of the Sydney Olympic Stadium in 1996-97, there has been more research in the field of crowd-induced vibration for assembly occupancies. The National Building Code of Canada was updated in 2006 based partly on "experience" [5], with allowable vibration levels for stadia now significantly higher than ten years ago. There have also been many papers published that focus on individual aspects of stadium dynamics and a number that attempt to develop more extreme load cases, such as synchronised jumping, for application to stadia based on loads that have been measured in a laboratory situation, for example, [1]. The level of vibration that is considered to be disturbing is critically dependent on the context <u>and</u> activity that the participants are carrying out [5]. It is therefore important that any loads that are developed are benchmarked against actual crowd loads and are considered together with actual subjective reactions at sports and concert events to form a realistic, matched set of design loads and vibration criteria for serviceability in the stadium context. This remains an issue as there is little guidance on the relationship between crowd activity and subjective responses to vibration in the published literature. Some researchers appear to be headed for more stringent serviceability guidelines for vibration, while others have moved in the other direction.

4. CONCLUSIONS

Serviceability for crowd-induced vibration is sometimes the governing design load case for the seated areas of a stadium and therefore has an impact on the cost of the structure, requiring a balance between dynamic performance and costs. The design approach, crowd dynamic loads and vibration criteria presented by the authors successfully preserved spectator amenity for vibration on the Sydney Olympic Stadium. However, the modifications made to the concept design to meet the vibration specification resulted in a significant additional cost to the project. It is important for designers to understand the impacts that serviceability standards for vibration have on stadium design and costs and to incorporate appropriate allowances for dynamics into stadium projects at an early stage. It is also important that further research be carried out into crowd dynamic loading and vibration criteria to reach a broad-based consensus on an appropriately matched set of dynamic loads and vibration criteria for use in the stadium context.

5. REFERENCES

[1] J.G. Parkhouse and D.J. Ewins, "Crowd-induced rhythmic loading", *Proceedings. of the Institution of Civil Engineers, Structures and Buildings* 159, October 2006, **585** pp247-259.

[2] Canadian Building Code, Users Guide NBC 1995, *Structural Commentaries (Part 4)*, NRCC.

[3] British Standards Institution. *BS6399 Loading of Buildings. Part 1: Code of practice for dead and imposed loads*, BSI, London, 1996.

[4] D.E. Allen, "Building vibrations from human activities", *Concrete International*, June 1990, pp66-73.

[5] Canadian Building Code, Users Guide NBC 2005 *Structural Commentaries (Part 4 of division B)*, NRCC