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Design criteria for dynamic performance of a suspended structure for competition grade tennis courts

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ABSTRACT

The redevelopment of the Melbourne Park Tennis Centre incorporates something not previously seen at the home of a "Grand Slam" tournament – courts on the roof of a carpark building. To determine an appropriate structural design criterion for the suspended slabs, a study was undertaken on how vibrations induced by the players and external sources would be perceived. Following testing on existing courts and undertaking real time studies on forces exerted by tennis players, a series of criteria for acceptable vibrations in the structure was developed. The structure has now been successfully used during the 2013 and 2014 Australian Open tournaments.

Introduction

The Eastern Plaza and National Tennis Centre are part of the Melbourne Park Redevelopment project which is being managed by Major Projects Victoria for Sport and Recreation Victoria, the Melbourne and Olympic Parks and Tennis Australia. The recently completed Eastern Plaza project incorporates world-class tennis courts on the roof of the new carpark building. The new tennis courts are both indoor and outdoor, with the indoor courts covered by a metal and glass-clad architectural envelop as shown in the image above. Constructing international standard courts on top of a building is something not previously seen at the home of a "Grand Slam" tournament. This presented the design team with a new challenge – to determine an appropriate structural design criterion for the suspended slabs. The "stiffness" of the structure needed to be considered, in particular how vibrations induced by the players and external sources would be perceived. Following testing on existing courts and undertaking real time studies on forces exerted by tennis players, a design criteria for acceptable vibrations was developed for the suspended structure supporting the tennis courts.

This paper is not a "cook book" on how to design international standard competition courts on a suspended structure, as each case will vary. However it does provide guidance on the main parameters that should be considered, and describes the design approach that was successfully applied at the Melbourne Park venue.

Background

Most tennis courts suitable for international competition are located at ground level, on stable loadbearing layers supported by the ground. The structural design methodology for these courts is reasonably well understood within the

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structural engineering fraternity. However site constraints within the Melbourne Park complex dictated that for the new Eastern Plaza extension, opened just prior to the 2013 Australian Open, eight inside warm up courts and six outside courts needed to be located over the 1000 car carpark building. The Eastern Plaza extension also includes a player's gymnasium, a running track, and associated facilities which the design team identified could induce vibrations in the structure.

A study of major tennis venues around the world did not identify any design precedents for suspended "international standard" courts, so a design approach needed to be developed. The main concern was structure-borne vibrations, i.e. whether the movement of players or other external sources would cause unacceptable levels of vibration.

Structure-borne vibrations can be initiated from a number of sources. The simplest form of initiator is a single strike. Once struck, the structure will oscillate at its fundamental frequency or natural frequency. The length of time over which it will oscillate and the rate at which energy dissipates is a function of the inherent damping of the structure, which is influenced by the fixtures, services and furnishings attached to the structure, and the original form of the structure.

At the other end of the spectrum is the case where a cyclical load induces what could be considered a regular series of strikes on the structure. The effect of this type of loading is very dependent on the frequency of this cyclical load. If the load frequency does not match the natural frequency of the structure, then the resultant vibrations may not be significant. However when the load frequency matches the structure's natural frequency (or an integer multiple of the natural frequency), then significant vibrations can be induced.

In reality a tennis slab structure would be subjected to a wide range of forces, from single strikes generated by players jumping; a series of rhythmic strikes from players running; forces randomly generated from the movement of weights in the gymnasium; transient forces from cars moving around in the carpark or trains passing Melbourne Park on the nearby rail lines; and continuous forces from machinery in plantrooms. Each of these cases needed to be investigated.

Whilst the study of structure-borne vibrations can become quite technical, it was the desire of the client group (in particular Major Projects Victoria and Tennis Australia) that a quantifiable design approach be developed, so that this may be able to be used on similar future projects.

General principles of dynamics

Under the influence of an applied load, or series of loads, a series of vibrations will be induced in the structure. One of the simplest forms of an oscillating element is a guitar string. Once plucked, it will vibrate back and forth at its "natural frequency". At the moment just before it is released it has its maximum displacement and zero acceleration. Once released it will quickly return to its "at-rest" position, at which time its velocity would have accelerated to its maximum and its displacement will be zero. Momentum will drive the string beyond the at-rest position but it will decelerate until the moment it reaches its maximum negative displacement, at which time its acceleration will again be zero. As the string will be affected by friction from the air around it, and there will be some stretch in the string itself, there is an amount of "damping" in this system. The string will continue oscillating for some time, although the damping will ensure that in every cycle the displacement is slightly less than the previous, such that it will eventually cease. A structure however, is significantly more complex than a guitar string. It will generally consist of slabs, beams, columns and foundations, all of which can influence the frequency of the structure. Instead of having one natural frequency, as is the case of the guitar string, a structure can have a number of resonant frequencies (frequencies at which parts of the structure will resonate).

The main design parameter associated with an investigation into structure-borne vibration is usually the resultant acceleration. A person standing on the vibrating structure will feel this vibration. What they are actually sensing is the cycles of accelerations and decelerations. Remember that whilst sitting in a car travelling at a constant velocity we do not generally sense the motion. It is the accelerating force and the braking force (deceleration) that we feel. Interestingly, some people are more sensitive to the oscillating motion than others, and some people are more tolerant of this motion than others (and this may even change depending on the player's temperament).

Whilst the behaviour of the oscillation of a floor system can be quite complex, in simple terms under an applied striking force the following will occur:

- The structure will vibrate at its "natural frequency" or one of its resonant frequencies
- The length of time over which it will oscillate is a function of the magnitude of the force and the damping in the building
- People will sense the acceleration of the slab caused by the vibration

There are various ways to measure and report accelerations, the relevance of which is dependent upon the type of floor and the predominant forcing loads. In this instance, it was determined that the as the forcing load during play was a single strike, the most important structural response parameter is the peak acceleration induced in the structure.

A significant body of research has been undertaken over many years studying the perceptions of vibrations, particularly in North America based on work by Thomas Murray and David Allen. Much of this work has been published over a 30+ year period, and has formed the basis of the National Buildings Code of Canada's design criteria [1] and the American Institute of Steel Construction's Design Guide No. 11 [2]. These studies have identified that humans are most susceptible to vibrations in the range of 4–8 Hz. This means we are less concerned with vibrations that occur less than 4 times per second or more than 8 times per second. It was also identified that people are more tolerant of vibrations in structures such as footbridges