Evaluation of Timber-concrete Floor Performance under Occupant-induced Vibrations Using Continuous Monitoring

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Abstract. This paper describes the design of a system to monitor floor vibrations in an office building and an analysis of several months' worth of collected data. Floors of modern office buildings are prone to occupant-induced vibrations. The contributing factors include long spans, slender and flexible designs, use of lightweight materials and low damping. As a result, resonant frequencies often fall in the range easily excited by normal footfall loading, creating potential serviceability problems due to undesirable levels of vibrations. This study investigates in-situ performance of a non-composite timber-concrete floor located in a recently constructed innovative multi-storey office building. The floor monitoring system consists of several displacement transducers to measure long-term deformations due to timber and concrete creep and three accelerometers to measure responses to walking forces, the latter being the focus of this paper. Floor response is typically complex and multimodal and the optimal accelerometer locations were decided with the help of the effective independence-driving point residue (EfI-DPR) technique. A novel approach to the EfI-DPR method proposed here uses a combinatorial search algorithm that increases the chances of obtaining the globally optimal solution. Several months' worth of data collected by the monitoring system was analyzed using available industry guidelines, including ISO2631-1:1997(E), ISO10137:2007(E) and SCI Publication P354. This enabled the evaluation of the floor performance under real operating conditions.

Introduction

An innovative three-storey office structure, using self-centering, post-tensioned timber shear walls as the main horizontal load resisting system and lightweight non-composite timber-concrete floors has recently been completed in New Zealand for the Nelson Marlborough Institute of Technology (NMIT). The project is expected to be the trailblazer for similar, possibly taller, structures to be more widely adopted locally. Performance based design requires the understanding of structural responses to the various loads acting on structures. In-situ, full-scale structural monitoring and testing can provide invaluable insights and help avoid the many simplifications and assumptions present in analytical or numerical simulations and laboratory experimentation. Permanent instrumentation was installed in the building investigating several aspects of structural performance relevant for timber structures, both dynamic and long-term. As a part of this comprehensive research exercise, dynamic performance of floors due to occupant-induced vibrations is also being monitored and is the focus of this paper.

The outline of this paper is as follows. Firstly, the NMIT building and its structural systems are briefly described with the focus on the seismic and wind load bearing shear walls and non-composite timber-concrete floors. The comprehensive monitoring system designed for the building and comprising sensors to measure both long-term and slowly varying timber deformations due to creep and temperature and humidity variations, as well as dynamic responses produced by wind, ground shaking and, in case of floors, footfall is outlined. A literature survey is then included that highlights previous research attempts aiming at a better understanding of the issues in dynamic performance of lightweight floors. One of the challenges of monitoring the vibrations of irregular floors is optimal placement of a limited number of sensors and the paper goes on reporting on how this was approached. Next, a preliminary assessment of floor vibration serviceability performance using monitoring data is outlined and conclusions drawn.

Description of Building Structural Systems and Instrumentation

This section intends to provide only a brief overview of the structural systems and instrumentation adopted for the building. Interested reader will find more detail in [1]; the numerous experiments and analyses of testing and monitoring data conduced to date, but not necessarily related to floor vibrations, are also described therein.

The NMIT Arts building is a combination of staff offices and small classrooms. Structurally, the building has non-moment resisting frames for vertical loads. The key innovation is the provision of dual timber post-tensioned shear walls in both directions (Fig. 1). The laminated veneer lumber (LVL) shear walls are designed to rock from side to side in a major earthquake and have energy dissipating devices between the two panels of each shear wall pair.

The majority of the floors use a proprietary LVL Potius floor system with 36mm thick LVL panels and 75mm thick concrete topping, while cantilevered parts are reinforced concrete. The main floor beams are double units 750×175mm spanning 9.60m, with a 20mm sawn pre-camber and 16mm diameter shear connectors to provide composite action with the concrete topping. The secondary beams are 360×90mm and span 6.00m. The concrete topping was cast independently over the secondary cross-beams using a membrane to minimize composite action and shrinkage was allowed to occur before the main beams infill toppings were poured. Figure 2 shows the arrangement of floor timber beams.

The monitoring system has some 90 channels of data and can be conceptually broken into four parts: i) a set of 10 tri-axial accelerometers and an anemometer to capture overall dynamic responses of the building due to seismic and strong winds excitation, ii) instrumentation of shear walls to measure their dynamic and long-term responses, iii) strain gauges, LVDTs, and temperature and humidity sensors for measuring long-term deformations of structural timber components, and iv) a set of three uni-axial, vertical accelerometers measuring footfall induced floor vibrations, which are the focus of this paper.

Footfall-induced Floor Vibrations and Their Monitoring

Modern floors with large spans are lightweight constructions with low stiffness and low natural frequencies, and are therefore more easily excited by dynamic footfall loading. With an increasing number of floors failing in their vibration serviceability, robust methods for the assessment of floor vibration have become essential. Excessive floor vibrations due to walking and similar activities appear to be the most persistent floor serviceability problem encountered by designers.

The difficulty in vibration design is the poor correlation between the outcome of computations at the design stage and the response of the floor constructed accordingly. In addition to the uncertainties inherent in material properties, damping characteristics and boundary conditions, the level of vibrations perceived by individuals, the vibration that is considered objectionable, and the force and frequency of foot drop are all highly subjective and prone to large variations [2].

Figure 1. Structural system of the Arts building with shear walls (courtesy Aurecon).

Figure 2. Arrangement of floor beams.

During walking, a pedestrian produces a dynamic time varying force which has components in all three directions: vertical, horizontal-lateral and horizontal-longitudinal. The vertical component of the force is relevant for floor vibrations and has been experimentally quantified. A reliable statistical description of normal walking frequencies was given by Matsumoto et al. [3], who investigated a sample of 505 persons. They concluded that the frequencies followed a normal distribution with a mean pacing rate of 2.0Hz and standard deviation of 0.173Hz. For an open plan office, an upper limit of 2.1Hz for walking pace is acceptable. For low height partitioned office spaces and labs, 1.8Hz is more appropriate. In the absence of more detailed information, a walking frequency of 2.0Hz is recommended. Being periodic but non-sinusoidal, walking forcing time histories have significant higher harmonics in addition to the fundamental one. Frequencies of these are integer multiplies of the fundamental walking frequency (1.5-2.5Hz) and have the potential to excite the fundamental or other vibration resonances [2]. In design and analysis, the inclusion of several loading harmonics and higher structural modes is often necessary.

In-service floor vibration studies through long-term monitoring are infrequent, indicating the need for more such research. Samarajiva and Choudhuri [4] monitored structural vibrations in a fitness center area and adjacent computer server room. The vibration levels due to simulated aerobic activities in the computer server room were significantly above the acceptable threshold for the computer equipment room. It was recommended that the floor be modified to reduce vibrations.

Salyards et al. [5] investigated complaints of disturbing vibration levels from the occupants of an academic building. A remote monitoring system was used for floor vibration monitoring. Analysis of the collected data revealed the vibrations were not due to walking but were attributed to several other sources ranging from wind to traffic to mechanical equipment to leg jiggling.

Huston et al. [6] describe monitoring of floor vibrations in a steel frame research building housing delicate precision instruments that can be adversely affected by even small floor vibrations. The measurements were compared with industry standards and with measurements taken at nearby reinforced concrete buildings. The efforts at reducing the vibrations due to the mechanical systems of the building were also assessed.

Optimal Sensor Location for Floor Vibration Monitoring

Theory. Office floors are often irregular in plan, have openings, uncertain boundary conditions and complex structural systems resulting in complex dynamics. The loading due to their usage may lead to multimodal response that needs to be captured by a limited number of strategically positioned sensors. A great deal of research has been conducted on optimal sensor placement using a variety of placement techniques and criteria. Meo and Zumpano [7] compared six different optimal sensor placement techniques and concluded that the effective independence-driving point residue (EfI-DPR) method provides an efficient method for optimal sensor placement to identify the vibration characteristics. This section briefly describes the underlying theory of EfI [8].

Consider a problem of acquiring the maximum amount of information about responses of K modes, using N sensors, which can be placed in M possible locations, in such a way that spatial independence of modes and signal strength are maximized. The K mode shapes at all possible M locations form a matrix:

$$\mathbf{\Phi}_{M\times K}=\left[\boldsymbol{\varphi}_{M\times 1}^{(1)}\quad \boldsymbol{\varphi}_{M\times 1}^{(2)}\quad \ldots\quad \boldsymbol{\varphi}_{M\times 1}^{(K)}\right], \tag{1}$$

where $\boldsymbol{\varphi}_{M\times 1}^{(i)}$ is the i-th mode shape measured at M locations. The vector of the measured structural responses, $\mathbf{y}_{M\times 1}$, can be resolved as a combination of K modes through the expression:

$$\mathbf{y}_{M\times 1}=\mathbf{\Phi}_{M\times K}\mathbf{q}_{K\times 1}+\boldsymbol{\omega}_{M\times 1}, \tag{2}$$

where $\mathbf{q}_{K\times 1}$ is the vector of modal coefficients and $\boldsymbol{\omega}_{M\times 1}$ is the vector of stationary, uncorrelated, zero-mean Gaussian white noises with a diagonal covariance matrix $\sigma^2\mathrm{I}_{M\times \mathrm{M}}$. Acquiring information about the modes of interest means estimating their modal coefficients with minimum covariance matrix of the error. The covariance matrix is given by:

$$\mathbf{P}=\frac{1}{\sigma^2}\left(\mathbf{\Phi}_{M\times K}^{T}\mathbf{\Phi}_{M\times K}\right)^{-1}=\frac{1}{\sigma^2}\mathbf{Q}_{K\times K}^{-1}, \tag{3}$$

in which $\mathbf{Q}_{K\times K}$ is the Fisher information matrix. Maximizing a suitable norm of $\mathbf{Q}_{K\times K}$, such as its determinant $|\mathbf{Q}_{K\times K}|$, leads to the optimal estimation of the modal coefficients. The contribution of each sensor location to the determinant can be calculated taking the diagonal entries of the following matrix:

$$\mathbf{E}_{M\times M}=\mathbf{\Phi}_{M\times K}\left(\mathbf{\Phi}_{M\times K}^{T}\mathbf{\Phi}_{M\times K}\right)^{-1}\mathbf{\Phi}_{M\times K}^{T}. \tag{4}$$

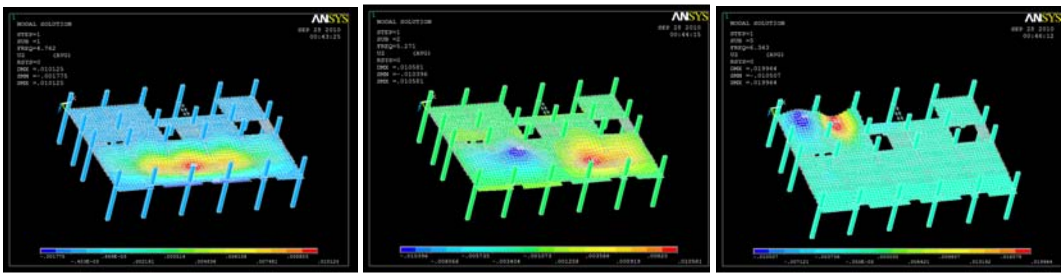
In order to more effectively eliminate locations with low energy content, the diagonal entries of $\mathbf{E}_{M\times M}$ are further weighted by the corresponding driving point residue [7]:

$$E_{Dii}=\mathbf{E}_{ii}\sum_{j=1}^{K}\frac{\mathbf{\Phi}_{ij}^{2}}{2\pi f_j}, \tag{5}$$

where f_j is the j-th natural frequency in Hz.

The method starts with calculating the values of E_{Dii} (Eq. (5)) for all possible locations and arranging them according to their magnitudes. The location with the least contribution is then dropped. Because the ranking of contributions of the remaining locations may change after a location is dropped, recalculation of E_{Dii}'s is required. The iterative process stops when the desired number of sensors N is reached. However, removing just the location with the least contribution may lead to a suboptimal solution. In the modification we propose here, after the number of candidate locations is suitably reduced by the above traditional elimination approach, at the final optimization steps the search is based on evaluating all possible combinations of N sensors over the remaining locations. Doing so reduces the risk of arriving at a suboptimal solution.

Application to Floor Monitoring. The floor was modeled using the finite element software ANSYS. The LVL beams were modeled using beam elements and concrete topping using shell elements. Columns of the stories above and below the analyzed floor were also included in the model to take into account their influence on floor vibrations. Young's modulus and density were



4.76Hz 5.27Hz 6.34Hz

Figure 3. Selected lowest modes of floor vibrations by FEM analysis.

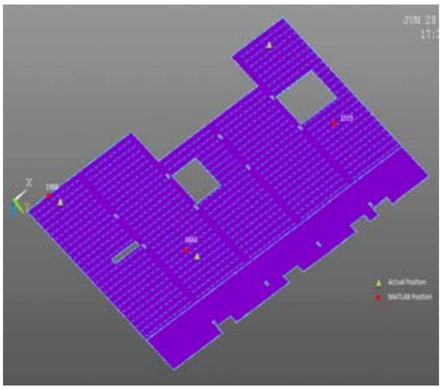


Figure 4. Optimal (red dots) and actual (green triangles) locations of floor accelerometers.

assumed as 10.7GPa and 570kg/m^3 for timber and 30GPa and 2,400kg/m^3 for concrete, respectively.

Modal analysis revealed that there were 22 modes below 12.5 Hz. These were taken into account for optimal sensor placement simulations as they were in the range that could be excited by footfall harmonics. Figure 3 shows three examples of the lowest frequency modes. It can be seen that due to irregularities and openings in the floor they are localized in either the lower part of floor, where several small classrooms are located, or in the upper corners used for offices and galleries.

The EfI-DPR technique was used to obtain the optimal sensor locations for three sensors. An initial set of 2,189 candidate locations were considered. These were spread fairly evenly over the offices and classrooms but excluded galleries. It was decided that those selected areas, intended for quiet work and thus having more stringent vibration acceptance criteria, received priority. First, locations which gave the least contribution to the determinant $|Q_{22\times22}|$ were eliminated one by one. When there were 25 candidate locations left, all combinations of three locations out of these 25 remaining were checked. The combination with the highest value of $|Q_{22\times22}|$ out of the $25!/(3!\times22!)=2,300$ possibilities is shown in Fig. 4 using red dots. Based on the above simulations, three Kistler K-beam 8312B2 capacitive solid state uni-axial accelerometers with 540μg resolution and 1000mV/g sensitivity were fixed at the points indicated by green triangles. The actual and optimal locations are nearly the same for two sensors but the third one is located in another room – these shifts were due to practical constraints.

It is noted that switching between the optimal solution search methods increased the computational effort by a factor of less than two. However, the location achieved with the traditional search was only 2,253rd best amongst all the candidates. In fact, the optimal location of three sensors obtained by the proposed approach retained the amount of information comparable to the case of four sensors had the traditional approach to eliminating locations been used to the very end of the search. The actually selected location was ranked 1344th best, still better than the traditionally obtained one, and indicating that shifting the accelerometers due to practical considerations did not deteriorate the monitoring system optimality strongly.

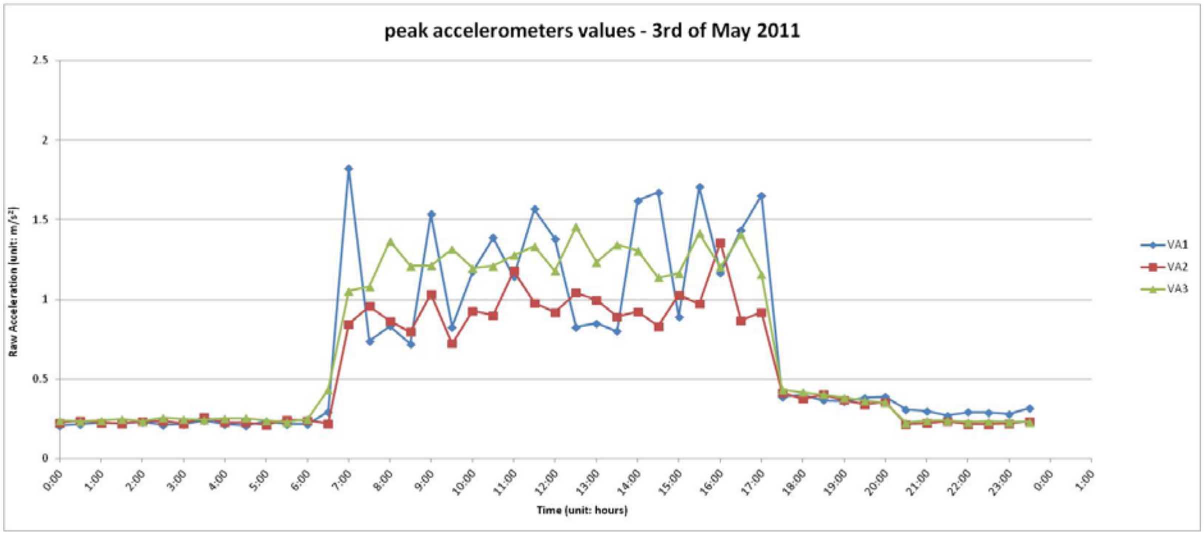


Figure 5. Peak weighted floor accelerations for a single day using 30 minute intervals.

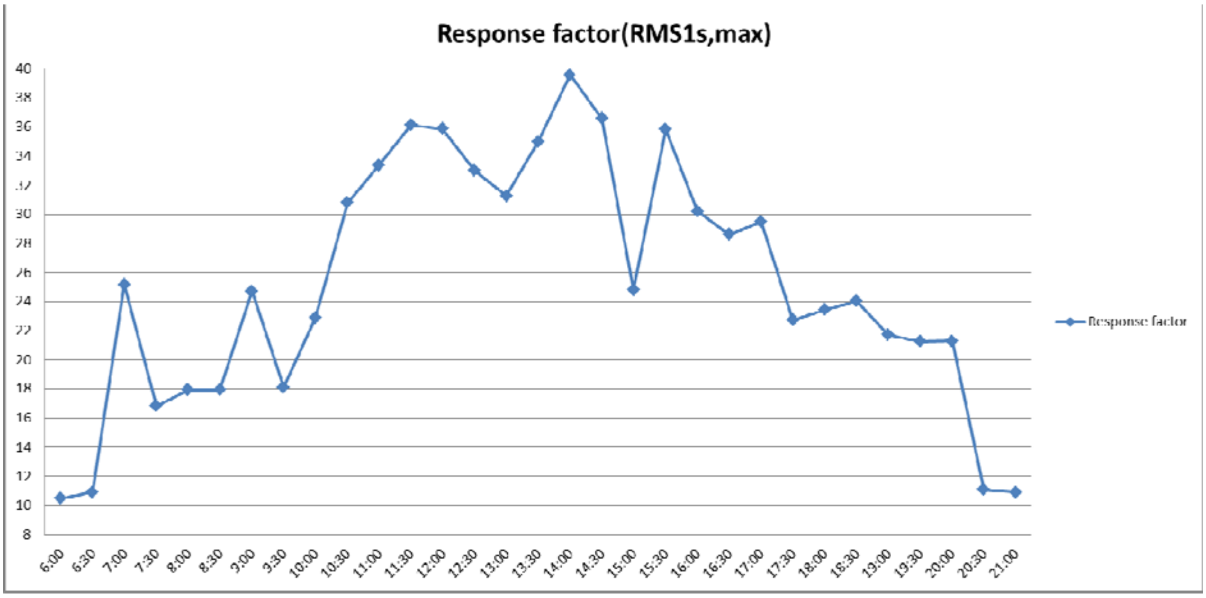


Figure 6. Response factors for the worst one second of weighted acceleration for a single day.

Analysis of Floor Vibration Monitoring Data

Serviceability Assessment Procedure. Procedures for evaluation of the effect of vibrations on humans are laid down in documents such as ISO2631-1:1997(E) [9], ISO10137:2007(E) [10] and SCI Publication P354 [11], the relevant approaches being those to asses vibration levels for human perception criteria. In the case of measurements of vibration of a supporting surface for a standing person, ISO2631-1:1997(E) [9] requires raw measured acceleration to be frequency weighted to account for the variable sensitivity of humans to vibrations. Frequency weighting is a complex function applied to vertical vibrations producing weighted acceleration $a_w(t)$. Vibration levels for comparison with acceptable limits are to be calculated using frequency weighted data. Frequency weighting is such that vibrations between 0.7Hz and 13.0Hz are be perceived particularly strongly.

A quantity to be used to characterize an average level of vibration is the root mean square (*RMS*) of weighted accelerations. To take into account the often-encountered spikiness of response, the

RMS value for the worst one second of weighted acceleration can be used and compared to a threshold of 0.005 m/s^2 to produce the response factor R [9]:

$$R = \max_{all\ t} \sqrt{\frac{1}{1s} \int_{t}^{t+1s} a_w^2\left(t\right) dt} \Big/ 0.005\ m/s^2 \,. \tag{6}$$

Comparison of the response factors with their corresponding thresholds can serve as a way of assessing vibration serviceability, despite the fact that available advice on threshold values varies widely in the available literature [11].

Preliminary Monitoring Data Analysis. Figure 5 shows, as an example of typical trends, peak weighted accelerations for 30 minute intervals for a single day, Monday, May 3rd, 2011. A clear pattern can be seen where any appreciable activities occur, as expected, only between 7.00am and 8.30pm. The peak weighted acceleration values are typically less than 1.5m/s^2, though at times they can reach up to nearly 2.0m/s^2. By observing peak daily weighted accelerations for a period of several weeks another expected pattern is confirmed where a much larger level of response, up to approximately 2.0m/s^2, occurs during weekdays, with much smaller vibrations during weekends. Figure 6 shows response factors for the worst one second of weighted acceleration (Eq. (6)) extracted from 30 minute long intervals on Monday, May 3rd, 2011. The response factors reach the maximum values of up to nearly 40.

Conclusions

An innovative three-story timber building, using self-centering, post-tensioned timber shear walls as the main horizontal load resisting system and lightweight non-composite timber-concrete floors, has been extensively instrumented for continuous monitoring. The continuous monitoring system intends to measure both slowly varying structural responses due to timber creep and fast dynamic responses due to excitations such as seismic and wind and floor vibrations due footfall loading. To that end, the monitoring system comprises about 90 channels of data from strategically positioned sensors measuring structural and ground accelerations, wind speed, static and dynamic displacements, strains, temperature and humidity.

One of the challenges of measuring the multimodal floor dynamic response due to footfall loading was the optimal placement of a limited number of accelerometers. This was approached by the EfI-DPR method. The novel approach to solving the optimization problem was the use of a combinatorial search algorithm that increases the chances of obtaining the globally optimal solution, while keeping the computational effort at an acceptable level. It has been demonstrated that the proposed algorithm compared favorably with the traditional approach.

Several months' worth of data collected by the floor vibration monitoring system were analyzed using industry guidelines, such as ISO2631-1:1997(E), ISO10137:2007(E) and SCI Publication P354, to evaluate of the floor serviceability performance under real operating conditions. Clear temporal trends, such as increased levels of vibrations during daytime and weekdays, are clearly discernible in the data. Quantitatively, response factors reaching up to nearly 40 were calculated, indicating a lively floor.

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