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Experimental modal analyses of buildings during the Cook Strait earthquake sequence

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ABSTRACT: With the recent high levels of earthquake activity experienced throughout New Zealand there is a growing awareness of the need for quick and reliable determination of whether buildings are safe to work and live in. In parallel, on-going advances in sensor technology worldwide have resulted in the potential for new and innovative sensing systems which could change the way that civil infrastructure is monitored, controlled and maintained. A number of data sets from computational and laboratory analyses are readily available that provide information on the seismic response of buildings, but there are a limited number of data sets currently available worldwide that have building response records from real ground motions.

Following the 21 July 2013, M_W 6.5 Cook Strait earthquakes, a number of buildings in the Wellington Central Business District (CBD) were instrumented with low-cost accelerometers. During the period from 19 July - 16 August, 2013 there were more than 2500 aftershocks in the magnitude range of 2.0 - 6.6, and these sensor arrays were able to collect high quality building response data sets. A summary of the data analysis for six structures that were instrumented during the Cook Strait earthquake sequence are presented, along with the major challenges and opportunities related to the future monitoring of existing civil infrastructure.

1 INTRODUCTION

Civil infrastructure such as bridges, buildings, pipelines and dams are a central component necessary for a functional society, playing an important role in providing safety and security to the community. Buildings are one element of the built environment that are continually subjected to a combination of irregular dynamic and static forces. These forces influence the structural integrity and overall performance of the structure. It has been found that many buildings are undergoing structural decay due to age, lack of repair, and in some cases because they were not designed for the current loading demands (Ren & De Roeck, 2002). The need to evaluate the real-time health and performance of buildings is an area of particular interest to engineers and building owners, especially at this time in New Zealand following the 2010-2011 Canterbury earthquake sequences and the more recent July 2013 Cook Strait and January 2014 Eketahuna earthquake sequences.

During seismic excitations, the actual response and damage sustained to a building does not always replicate the designed response. It is a difficult task to determine the actual performance of a building due to variations arising during construction, the lack of structural drawings for older buildings and the unknown quality and type of materials used. Currently there are no quick and reliable diagnostic tools available to determine the in-place integrity of infrastructure and no effective and proven way to validate the assumed design parameters once construction is complete. Instead, the standard practice to determine the integrity of a structure involves inspections where highly qualified personnel must visually inspect the building. Structural damage frequently propagates from within the structure itself, meaning that indicators of loss of integrity may be hidden from the human eye and consequently go unseen. Traditional visual inspections are often expensive, time consuming, and result in a subjective opinion. In combination with visual inspections, the installation of a system of sensors to monitor and record the in-place performance of a structure has the potential to provide a new, quick and reliable inspection method for existing infrastructure.

Damage to a building can be defined as a change in dynamic characteristics of the building (Ren & De Roeck, 2002). Non-destructive techniques can be used to help determine the performance and detect damage sustained to a building. There are two different levels of monitoring that can be performed on a structure, which are categorised at the local and global level. Monitoring at the global level is associated with understanding the behavioural performance of the whole building, whereas monitoring at the local level is associated with the behaviour of an individual element inside a building, such as a concrete beam, and the performance of the materials that constitute that specific element. Non-destructive techniques at the global level involve detecting changes in dynamic characteristics of a building, which include modal frequencies, mode shapes, modal curvatures and frequency response functions. Local detection techniques include the use of acoustic emission, ultrasonic and eddy current scanning and x-ray inspections. The experimental use of local detection techniques were outside the scope of the reported study, and instead a method for monitoring structures at the global level is examined.

2 MONITORING EXISTING CIVIL INFRASTRUCTURE

The change in modal parameters of a structure provides an indication of structural damage, and therefore the accurate determination of natural frequencies, mode shapes, and modal damping is a necessary and important task in the seismic design of civil engineering structures (Farrar & Worden, 2007). The ability to determine the dynamic behaviour of existing structures will enhance the reliability of seismic vulnerability analyses, which currently need to rely on estimations via visual screening and generic values extrapolated from tables (Michel, Guéguen, & Bard, 2008). Research has shown that vibration-based damage detection techniques are useful for the structural health monitoring (SHM) of civil engineering structures. There are a number of possible vibration-based methods that can be used to excite and determine the dynamic characteristics of an existing structure, which include ambient vibration tests, forced vibration tests, free vibration tests, and earthquake response measurements (Beskhyroun, Wotherspoon, Ma, & Popli, 2013; Hans, Boutin, Ibraim, & Roussillon, 2005).

Vibration-based techniques detect damage on the global scale by monitoring any changes in vibration frequencies (natural frequencies) and spatial distribution of vibration response amplitudes (mode shapes) (Beskhyroun et al., 2013). Several studies have highlighted associated challenges and limitations when using vibration-based techniques for detecting damage. A major setback is that frequency shifts are highly sensitive to changes in temperature and other environmental conditions and are therefore often insensitive to damage (Salawu, 1997; Yan, Kerschen, De Boe, & Golinval, 2005). More research is required to fully understand how changing environmental conditions affect the dynamic characteristics of an existing structure.

The ability to record and analyse data on an actual structure from earthquake response measurements is a challenge in itself, due to the fact that actual earthquakes of reasonable magnitude are needed to occur at a close proximity to the structure being tested. One of the key advantages of collecting data from actual earthquake excitations is that the measured building response is most realistic because the source of excitation occurs naturally and therefore eliminates the need for many assumptions. The July 2013 Cook Strait aftershock sequences provided a unique opportunity to experimentally examine the dynamic performance of existing buildings from earthquake response measurements. Once data is collected, there are a range of different methods available that can be used to analyse and extract critical modal information. The effectiveness of different methods for determining the dynamic properties of existing structures subjected to natural excitations was investigated, as reported below.

2.1 Methods used for calculating modal parameters

The methods used to calculate modal parameters included three frequency domain based methods and one time domain based method. The frequency based methods used are peak picking (PP), frequency domain decomposition (FDD) and enhanced frequency domain decomposition (EFDD), while the time domain method is stochastic subspace identification (SSI). Two variations of the SSI method are used (referred to later as SSI1 and SSI2), so theoretically five different methods are analysed and compared. These methods were identified using the System Identification Toolbox (SIT) program developed at the University of Auckland (Beskhyroun, 2011).

To ensure an adequate correlation of mode shapes generated from the adopted damage identification methods, the modal assurance criteria (MAC) is used. MAC values corresponding to the i^{th} mode shapes, $\boldsymbol{\phi}_i$ and $\boldsymbol{\phi}_i$*, is defined by Equation 1, where n is the number of elements in the mode shape vectors (Ewins, 2000).

$$MAC_i = \frac{\left[\sum_{j=1}^{n} \phi_{ij}\phi_{ij}^{*}\right]^2}{\sum_{j=1}^{n} \phi_{ij}^{2} \sum_{j=1}^{n} \phi_{ij}^{*2}} \tag{1}$$

A perfect correlation between two mode shapes represents a MAC value of unity, whereas a value close to zero indicates that the mode shapes are orthogonal. MAC values greater than 0.8 indicate an adequate correlation.

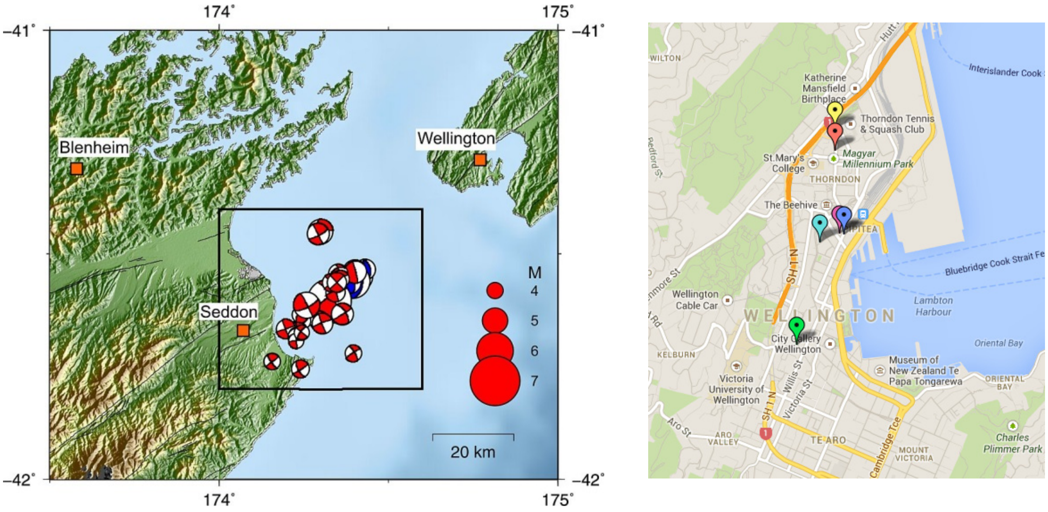
2.2 Type of sensors used

The installation of a dense array of traditional tethered sensors into a building is restricted by the high costs associated with wires spanning from each sensor to the central repository unit (Lynch & Loh, 2006). The sensors used in this research each had sufficient power supply and data storage to operate continuously at a sampling frequency of 40 Hz for approximately three weeks. The sensors were able to be mounted at any location within the building, as no wiring between the individual sensors was required. The sensors were able to measure and record accelerations in the x, y and z planes.

3 EXPERIMENTAL INVESTIGATION

The aim of the investigation was to experimentally determine the modal parameters of existing buildings from earthquake response measurements and to compare the effectiveness of various methods for interpreting the data.

The opportunity to capture data on the performance of buildings during actual ground motions arose after the initial M_W 6.5 Cook Strait earthquake which occurred on 21 July 2013. Figure 1a shows the locations of the earthquake epicentres, which were approximately 50 km from Wellington CBD (GNS Science, 2013). Six buildings located in the Wellington CBD were instrumented during the Cook Strait aftershock sequence, as shown by the approximate locations in Figure 1b. Sensors were first installed into four buildings on 24 July, and all sensors were retrieved by 28 November, 2013. A range of building types were instrumented, including a variety of different construction materials, structural designs, soil types, number of storeys and age of building. For confidentiality reasons, the first four instrumented buildings are referred to in this paper as Buildings 1-4. The remaining two buildings, the Old Public Trust Building (Fig. 2a) and the Saint Mary of the Angels Church (Fig. 2b), were instrumented on 9 September, 2013.



(a) Locations of the Cook Strait earthquakes (b) Relative locations of the instrumented buildings

Figure 1. Locations of the Cook Strait earthquakes and the approximate locations of the instrumented buildings in the Wellington CBD.

3.1 Results

Each building had a different number of sensors installed ranging from 6 to 32, based on the geometry and size of the buildings. At least one sensor was installed at ground level to record the earthquake intensity experienced at each site. The remaining sensors were placed at various levels within the structure and specifically at the extreme boundaries to help capture the global dynamic characteristics of each building.

The sensors recorded approximately 540 earthquakes with a magnitude greater than M_W 3.0 during the period from 24 July to 28 November, 2013. The sensors proved to be very sensitive and recorded high quality data sets with high signal to noise ratios. On average the level of recorded noise was 0.08 m/s^2 for each sensor. The maximum recorded peak ground acceleration (PGA) was 0.138 g, which was generated during the M_W 6.64 aftershock on 16 August and resulted in 0.410 g recorded on level 6 of Building 1. The recorded site PGA values in the NS, EW and vertical directions for selected buildings is summarised in Table 1.

(a) Old Public Trust Building (b) Saint Mary of the Angels Church

Figure 2. Images of two buildings that were instrumented.

Table 1. Summary of the maximum recorded event and site PGA values for selected buildings.

Building	Magnitude at epicentre (M_W)	Distance to epicentre (km)	Max PGA NS (g)	Max PGA EW (g)	Max PGA Vertical (g)
Building 1	6.64	72.6	0.1140	0.0922	0.0302
Building 2	6.64	72.6	0.1271	0.1384	0.0305
Building 3	5.39	61.7	0.0128	0.0125	0.0029
Old Public Trust Building	4.67	43.2	0.0128	0.0057	0.0036
Saint Mary of Angels Church	4.33	56.5	0.0023	0.0014	0.0022

Figure 3 shows the acceleration response and the associated power spectral density function (PSD) for a sensor installed on level 4 of the Old Public Trust building during a M_W 4.29 event. The peak PSD value at a frequency of 2.5 Hz in Figure 3 corresponds to the first mode frequency in the EW direction, which was also determined to be the natural frequency of the structure. The damping value for the structure at this frequency was evaluated as 3.5%. The natural frequency values determined for other instrumented buildings can be found in Table 2. It was found that earthquake response measurements recorded from events greater than M_W 3.5 were effective in exciting the first mode frequency of all structures. The determination of higher mode frequencies was more difficult to accurately calculate, and was only possible to determine during high magnitude events on buildings that had a dense array of sensors installed.

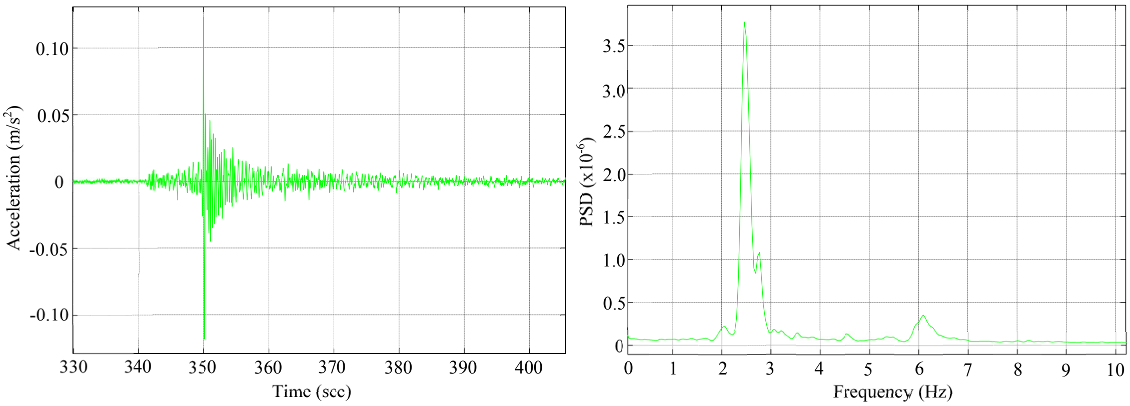


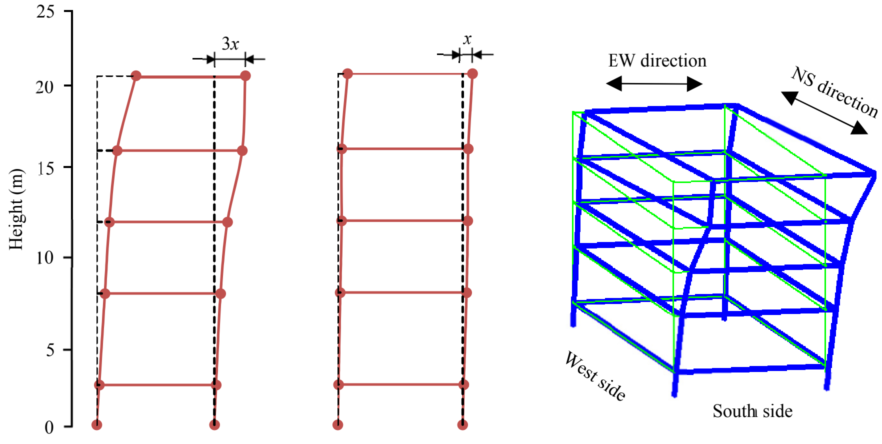
Figure 3. Acceleration response and associated power spectral density function for a sensor in the Old Public Trust building during a M_W 4.29 event.

The maximum recorded accelerations at the locations of the instrumented buildings were compared to the current code requirements by using the site hazard spectra equations from NZS 1170:5:2004. Table 2 shows a summary of the spectral accelerations, C(T), calculated using a hazard factor of 0.40 and return period of 500 years, as found in NZS 1170 (Standards New Zealand Technical Committee, 2004). The maximum recorded PGA values at the locations of the instrumented buildings were compared against the calculated design spectral accelerations to determine what percentage of the design acceleration was evident during the largest recorded event (right column in Table 2). It was found that Building 2 was excited to the highest percentage of its design load, which was 15.5% during a M_W 6.64 event.

Table 2. Summary of the recorded PGA at ground level against the current NZS 1170 code spectral acceleration values at the locations of selected buildings.

Building	Natural frequency (Hz)	Period (s)	Subsoil Class	Max PGA at base (g)	Code spectral acceleration C(T)	% Excited to Code
Building 1	1.8	0.56	D	0.1140	1.160	9.8
Building 2	1.2	0.83	D	0.1384	0.892	15.5
Building 3	1.6	0.63	C	0.0128	0.672	1.9
Old Public Trust Building	2.5	0.40	C	0.0128	0.944	1.4
Saint Mary of Angels Church	3.5	0.29	C	0.0023	0.944	0.2

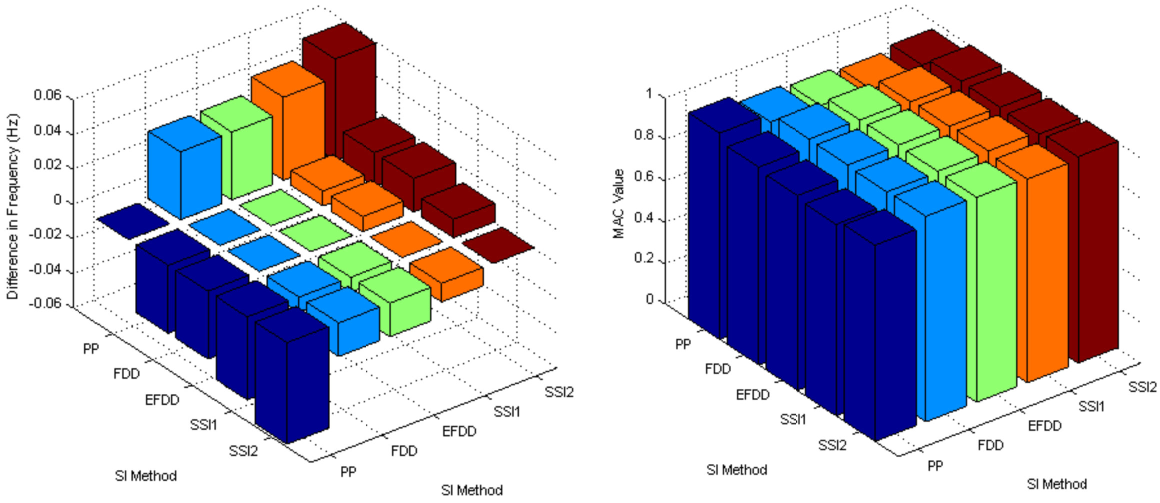
The earthquake response measurements were analysed to also determine the first mode shapes of the structures. For buildings that had a low number of sensors, interpolation of modal amplitudes was necessary to obtain values at all floor locations and at all four corner columns. The data collected from buildings that had a dense number of sensors at many corner locations and floors were most effective in producing accurate and reliable mode shapes. The Old Public Trust building was one structure that was heavily instrumented, and the first translational mode shape was able to be determined with a high level of accuracy. The first translational mode shape ocurred in the EW direction, due to the rectangular geometry of the building. Figures 4a and 4b reveal the modal amplitude displacements of the first translational mode shape for the Old Public Trust building at the Southern and Northern ends of the building, respectively. It was found that the modal amplitudes at the Southern side were nearly three times larger than the modal amplitudes at the Northern side, which can be shown by the 3D representation of the first mode shape in Figure 4c. The difference in modal amplitudes at each end of the building is due to the relatively high stiffness at the Northern end from structural strengthening which occurred in the 1980's.



(a) South Side (b) North Side (c) 3D representation

Figure 4. Normalised first translational mode shape for the Old Public Trust Building in the EW direction.

The accuracy of the four system identification techniques, PP, FDD, EFDD and SSI, for deteriming modal parameters were compared using MAC values. Data collected during the M_W 4.29 event for the Old Public Trust building is shown as an example in Figure 5, below. Figure 5a reveals that all five techniques returned natural frequency values within 0.06 Hz, and the high level of accuracy between techniques is reinforced in Figure 5b with all MAC values greater than 0.95.



(a) Difference in frequency values

(b) MAC values showing a strong correlation

Figure 5. Comparison of the four system identification techniques for detecting modal parameters.

The data collected from buildings which had a high number of sensors installed was able to produce additional information regarding the behaviour of the building, such as the acceleration profiles of wall and diaphragm elements. The profile in Figure 6 shows the out-of-plane accelerations of a floor diaphragm relative to the accelerations measured at ground floor. The colours indicate the level of accelerations, where red represents a high level of acceleration and blue represents a low level of acceleration. These acceleration profiles allow the actual response of an element within a building to be monitored to better understand how that element performed during extreme loading events, such as in Figure 6 where the high accelerations near the centre of the diaphragm indicate that a flexural motion occurred.

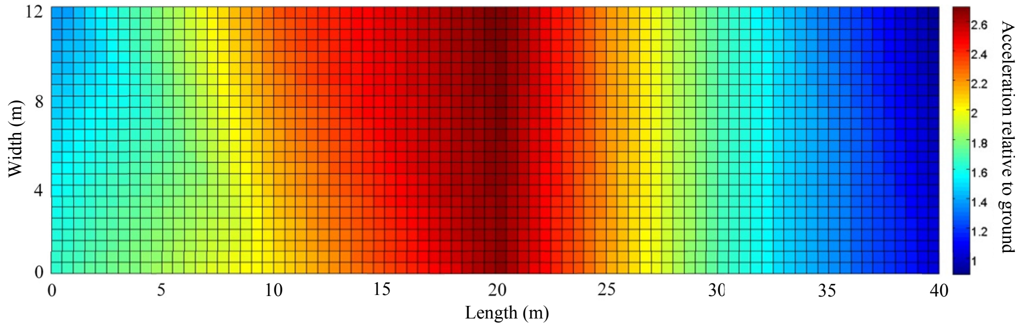


Figure 6. Example of an acceleration profile of a diaphragm during a M_W 4.67 event.

4 CHALLENGES AND OPPORTUNITIES

Literature has shown that modal parameters are sensitive to changing environmental factors, such as temperature (Salawu, 1997). The exact relationship of environmental factors on modal parameters is largely undetermined and more research is required so that the influence can be understood and the effects mitigated.

The data collected from instrumented buildings can be used to evaluate how modal parameters behave over time and during different earthquake magnitude intensities. The collected data can be further analysed to understand the performance of specific elements within a structure, which could assist engineering calculations and inspections. By monitoring the response of buildings over time, there is an opportunity to evaluate the real time performance of the building, and to ideally indicate the presence of damage once any occurs.

5 CONCLUSIONS

A method to determine the modal characteristics of existing buildings from natural ground excitations was reported. The July 2013 Cook Strait aftershock sequences provided a unique opportunity to instrument existing buildings with sensitive and low-cost sensors to record the structural response. The data collected from six instrumented buildings in the Wellington CBD was of high quality and enabled modal characteristics to be determined with a high level of accuracy and confidence. The earthquake response measurements were effective in determining the fundamental frequencies and mode shapes of each building, which is traditionally regarded as the most important mode in the seismic design of engineered structures. The four system identification techniques used were successful in extracting modal information from the recorded data sets, and the accuracy between each technique was verified using the modal assurance criteria (MAC).

With the recent high level of earthquakes in New Zealand, there is a growing demand from building owners to understand the health and extent of possible damage to their buildings. Installing a grid of sensors that is capable of monitoring and analysing the real-time performance and modal characteristics of a building is a solution that is accurate, reliable and low-cost.

6 ACKNOWLEDGEMENTS

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