Ambient and Forced Vibration Testing of a 13-Story Reinforced Concrete Building

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ABSTRACT: Dynamic testing is essential to understand and interpret the in-service dynamic behaviour of structures. The need for full scale testing of existing structures arises from the fact that creating accurate laboratory models or finite element models for complex structures is not an easy task and it requires substantial experience and skill to deal with difficulties in modelling material properties, geometric layout and boundary conditions. This paper describes a research program that investigated the dynamic behaviour of a full scale 13-story reinforced concrete building under forced vibration, ambient vibration and distal earthquake excitation. An eccentric mass shaker located on the upper floor of the building was used to excite the building, while ambient vibrations were recorded over a period of two weeks utilising over 40 tri-axial accelerometers. During this period the building was also excited by a M6.5 earthquake roughly 350km away and high quality acceleration data was recorded. Modal parameters of the building were identified using the System Identification Toolbox (SIT) developed at the University of Auckland and comparisons made across the results from each excitation source. Correlation of mode shapes was evaluated using the modal assurance criterion and the variation in the natural frequency and damping values were evaluated.

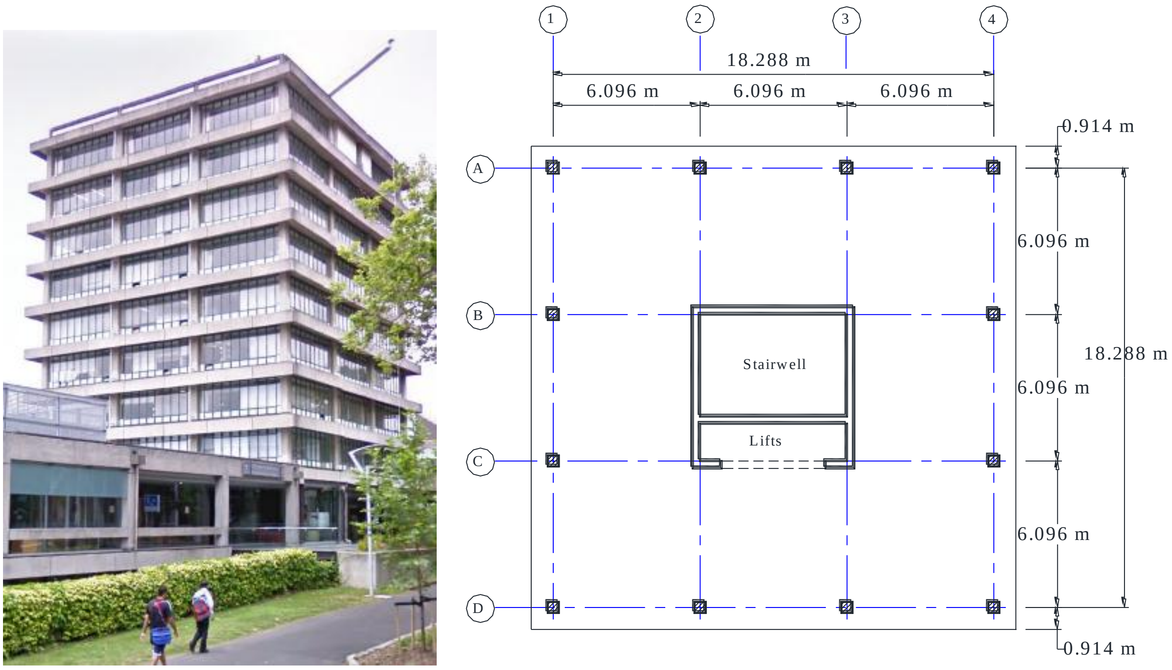
1 INTRODUCTION

The identification of dynamic characteristics such as natural frequencies, mode shapes, and modal damping is a necessary and important task in the course of seismic design of civil engineering structures (Farrar 1997). To accomplish this task, ambient vibration tests, forced vibration tests, free vibration tests, and earthquake response measurement can be carried out. Among these field tests, ambient vibration experiments are most common as they are economical, non-destructive, and fast and easy to implement. However, as the input excitation in ambient vibration tests is usually weak, these tests are not as effective in obtaining an accurate estimation of the higher modes data, and uncertainties remain as to whether the modal information applies in the higher strain ranges. Forced vibration tests overcome these issues by providing higher input forces. However, they are substantially more expensive, time consuming to conduct, and often require special permissions as there is an increased likelihood of damaging the structure. As ambient vibration testing is output driven, it is highly cost effective and is regarded as being harmless to the integrity of the structure (Endrun et al. 2010, Celebi et al. 2010, Celebi 2009). In ambient vibration measurements, the input force is unknown, thus output-only modal parameter identification techniques must be applied for modal analysis. Some researchers suggest that output-only analysis is superior with multiple-input data and the distribution of the input forces across the structure may affect the quality of the identified modal parameters (Au et al. 2012, Brownjohn 2003). Researchers also emphasise that for output-only analysis to be successful it is important to have sufficient quality data with good signal-to-noise ratio (Brincker et al. 2003). Another important issue that needs further investigation is whether output-only analysis can work well in both the time and frequency domains. This paper investigates some of these issues.

The successful implementation of large sensing networks is limited by the high cost of installing and maintaining the extensive lengths of wiring needed in a large civil structure to connect individual sensors to a central repository (Çelebi 2002). As a result of these high costs, micro-electro-mechanical system (MEMS) accelerometers became a potential economical alternative to conventional wired sensors. As these accelerometers generally have low power consumption, they can operate for an extended period of time powered only by a battery. Moreover, some battery operated MEMS accelerometers have the analogue-to-digital conversion and data recording capability built in, further simplifying the set up and permitting a higher number of points to be monitored than usual. In this research program, 49 tri-axial MEMS accelerometers were used to record ambient vibrations from a 13-storey concrete building over a two weeks period. During this period the building was also excited by a M6.5 earthquake roughly 350 km away and high quality acceleration data was recorded. System identification was carried out for each of the excitation sources, and comparisons made between the results of each. Correlation of mode shapes was evaluated using the modal assurance criterion (MAC) (Ewins 2000) and the variation in the natural frequency and damping values were evaluated.

2 TEST BUILDING

Forced and ambient vibration tests were performed on a 13-storey concrete office building in the University of Auckland (Figure 1 (a)). The tower block was built in 1964 and is structurally separate from the adjoining 3-4 storey buildings that were constructed in 2003. The height of the tower is 40.45 m and is serviced by two elevators and stairwells located at its centre. From level 5 onwards the building is essentially square with 18.288 m dimensions on either side (Figure 1 (b)). The building is supported by 12 reinforced concrete columns around its perimeter and pre-stressed shear walls at its core. The pre-stressed shear walls at the core provide the building with the majority of its lateral strength and stiffness (Lee 2003), which are 305 mm thick throughout the entire structure. The thickness of all the floor slabs is 200 mm except on level 14 where the slab is 120 mm thick.



(a) (b)

Figure 1: (a) Engineering office building at the University of Auckland, (b) Plan view of levels 5 to 12.

3 DYNAMIC TESTS

3.1 Forced vibration testing

The forced vibration test on this building was conducted in 2002 using an eccentric mass shaker located on the top floor by Associate Professor John Butterworth and his master student Jin Hee Lee

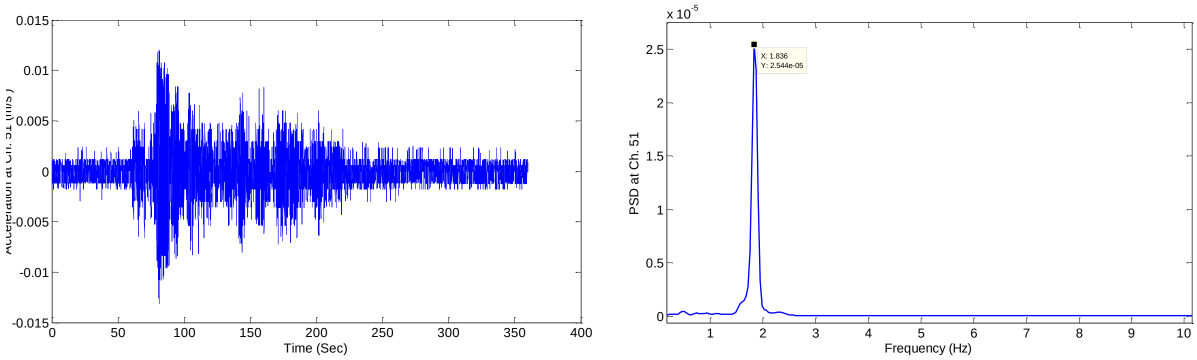
(Lee 2003). Three different sets of mass, 10, 20 and 40 kg, were attached to the shaker and produced the excitations to the building with various force amplitudes. The building accelerations caused from the vibrations were measured through a network of eight wired accelerometers placed on the stairs landing of each floor and at the corners of the top floor in the building. The modal damping ratios were estimated using four different methods (half power bandwidth, logarithmic decrement, hybrid method and least squares exponential). Two types of forced vibration tests were conducted, frequency sweep and free vibration decay method. Using the frequency sweep method, four distinct modes of the structure were identified. The main conclusions drawn from the results of this testing were that damping is force amplitude-dependent, higher damping occurs in higher modes, and that damping is not purely viscous. These experimental results were then compared with the finite element model which showed good correlation (less than 10% discrepancy). The results from this forced vibration testing will be used later in this paper and compared with the modal properties derived using other excitation sources.

3.2 **Ambient vibration testing**

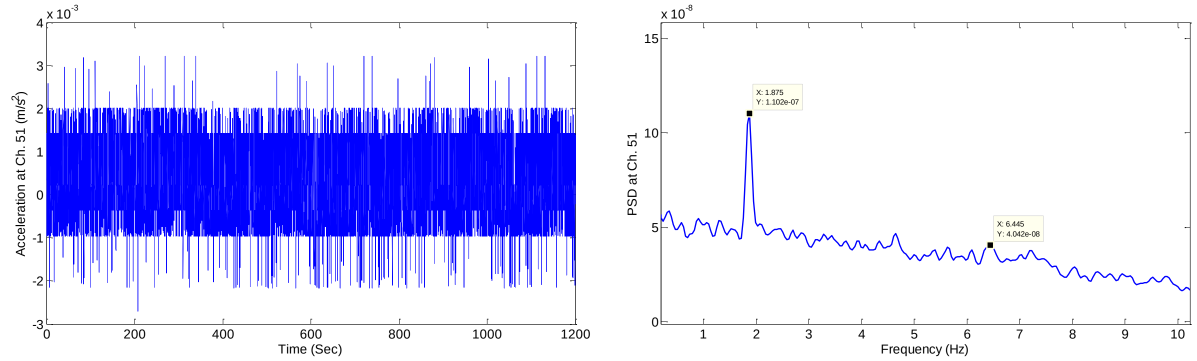
49 MEMS tri-axial accelerometers were placed throughout the test building to measure ambient vibrations induced by wind, traffic and operational activities. 38 accelerometers were placed in the four corners of each floor, apart from level 3 and level 4 where only three corners were accessible. The remaining 11 accelerometers were positioned on the stairs running through the centre of the building. Prior to setting up, the real time clock (RTC) of each accelerometer was synchronised to a common computer to ensure that each accelerometer had a common timestamp. The accelerometers were set to a sampling rate of 40 Hz, which was deemed appropriate for the measurement of the first four modes of the building based on simple calculations. At this sampling rate the accelerometers could be operated for a period of two weeks using a D-cell battery. During the recording period the building was also excited by a M6.5 earthquake roughly 350 km away and high quality acceleration data was recorded. Detailed information about the earthquake was obtained from the GeoNet website (http://www.geonet.org.nz). Three dynamic load cases were analysed wind, operational use and the earthquake. To find the most desirable time intervals for wind loading recordings, 10-min interval wind speed data was generated for the test period using data from the National Institute of Water and Atmospheric Research (NIWA) (www.niwa.co.nz). The time periods with maximum wind speed were utilised to analyse the response of the building to wind loading. The peak operational use of the building was estimated as being around 4-5pm. During this period there is heavy use of the lifts as people head home. Additionally, the traffic on the nearby road is at its peak. Figure 2 shows the acceleration response at level 12 of the building and the associated power spectral density function (PSD) from earthquake, wind and operational use excitation, respectively. Comparison of the PSD function from each loading type clearly indicates that the operational use excitation was the most efficient in exciting multiple modes.

4 **RESULTS**

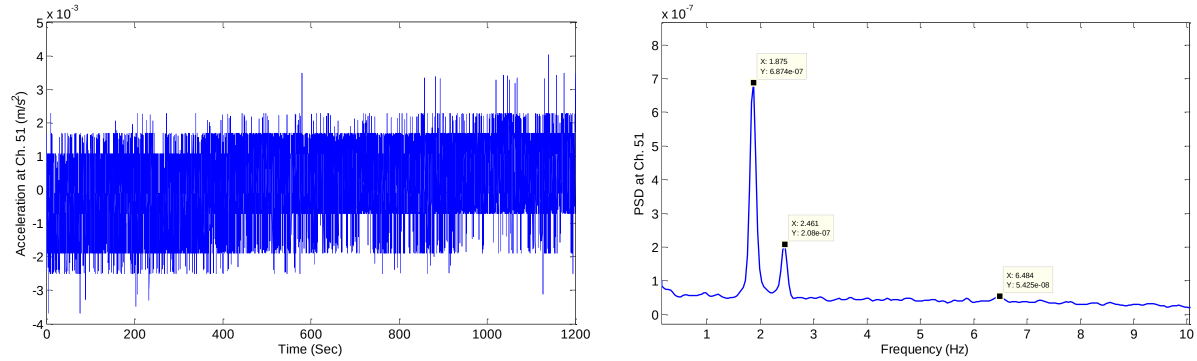
Modal parameters of the building were identified using the System Identification Toolbox (SIT) program developed at the University of Auckland (Beskhyroun 2011). Three frequency domain based methods; peak picking (PP), frequency domain decomposition (FDD) (Brincker 2000), enhanced frequency domain decomposition (EFDD) (Jacobsen 2007) and one time domain based method; stochastic subspace identification (SSI) (Overschee et al. 1996, Katayama 2005) were utilised to estimate the modal parameters of the building. Two techniques were implemented to find stable poles in the SSI method. In both techniques the algorithm starts with a high system order, which is then reduced by two on each iteration until the final iteration was run with a system order of two. Stable poles identified in each of these iterations were compared by two techniques. In the first technique (SSI1), the stable poles identified around the singular values generated from the singular value decomposition of the power spectral density matrix (Brincker 2000) are compared. If two consecutive poles within a predefined offset of the singular value have change in frequencies, change in damping and a modal assurance criterion (MAC) within user defined values, both poles will be kept and averaged. If both poles do not meet these criteria the first pole is discarded and the second pole is compared to the subsequent one. This series of comparisons continue until all stable poles in the frequency range are found and averaged. The resulting mode shapes, natural frequencies and damping ratios are the combination of several stable poles and therefore provide a robust method of system identification. While the first technique (SS1) uses singular value decomposition of the PSD matrix to identify stable poles, the second technique (SSI2) breaks up the entire frequency range tested into bands. Those bands with the most poles are considered to contain true modes and are then used to find stable modes. Stable poles are found within each band and averaged using the same procedures as in the previous SSI1 technique. Figure 3 shows the first four modes of the building as estimated by the PP method using 20 minutes of vibration data induced by operational activities in the building and nearby traffic. These figures clearly indicate that the high quality acceleration data captured by the accelerometers has resulted in a very clear identification of mode shapes. This is also true for the higher modes, despite the fact that ambient vibration tests are traditionally not as effective in obtaining an accurate estimation of the higher modes due to the low signal to noise ratio.



(a) Acceleration response from earthquake excitation (b) PSD from earthquake excitation



(c) Acceleration response from wind excitation (d) PSD from wind excitation



(e) Acceleration response from operational use excitation (f) PSD from operational use excitation

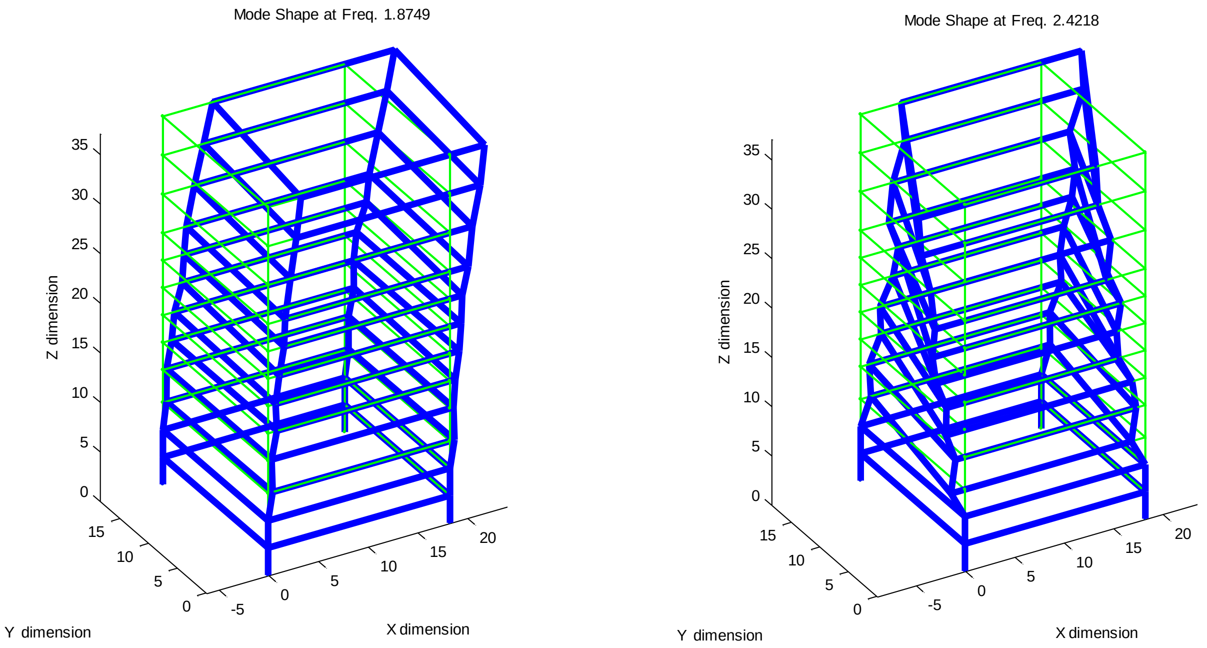
Figure 2: Acceleration response and the associated PSD from different excitation sources.

The modal assurance criterion (MAC) is generally used as a measure of the correlation between two mode shapes. For the current study, the MAC value was used to compare mode shapes from various system identification methods. The MAC value corresponding to the i^{th} mode shapes, $\boldsymbol{\phi}_{ij}$ and $\boldsymbol{\phi}_{ij}$*, is defined as (Ewins 2000):

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

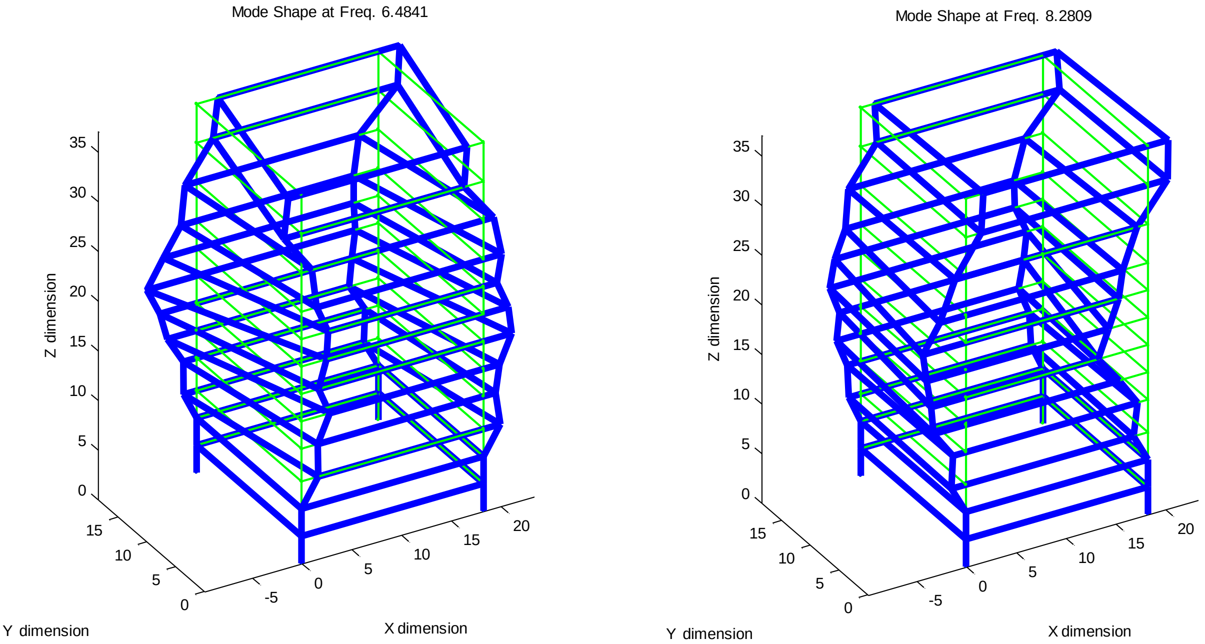
where n is the number of elements in the mode shape vectors. A MAC value close to unity indicates perfect correlation between the two shapes and values close to zero indicate shapes that are orthogonal. Figure 4 shows MAC values for four mode shapes identified by PP, FDD, EFDD, SSI1 and SSI2 methods. Each bar in these figures represents the MAC value when comparing one specific mode extracted from a pair of system identification methods. MAC values ranged from 0.80 to 1.00 which indicated a very high correlation between mode shapes identified by the different system identification methods. A near perfect correlation was shown for the first bending mode and the first torsional mode. The perfect correlation of mode shapes identified by time domain and frequency domain based methods indicates that both techniques can be efficiently utilised with output-only data. The operational use data produced the most accurate mode shapes and can be attributed to the good distribution of input forces across the structure. The input force resembled a white noise signal and the drift in the accelerometers RTC was negligible shortly after the start of the test period.

Table 1 shows the natural frequencies of the first translational and first torsional modes of the building determined through PP, FDD, EFDD and SSI for the three different load cases. The natural frequencies determined using these techniques for the different load cases are very similar and the small variation (below 0.14 Hz) in these values can be attributed to mathematical errors or differing noise levels in the data. Table 2 summarizes the modal parameters determined for the building through forced vibration analysis (Lee 2003). The frequencies generated for the first two modes decrease in value as the force applied by the eccentric mass shaker is increased. The first translational mode frequency is between 1.88-1.91 Hz and the first torsional mode frequency is 2.45-2.48 Hz. All modal parameters from ambient and forced vibrations tests were very well correlated and only small differences were observed.



(a) First translational mode (NS)

(b) First torsional mode



(c) Second torsional mode (d) Second translational mode (NS)

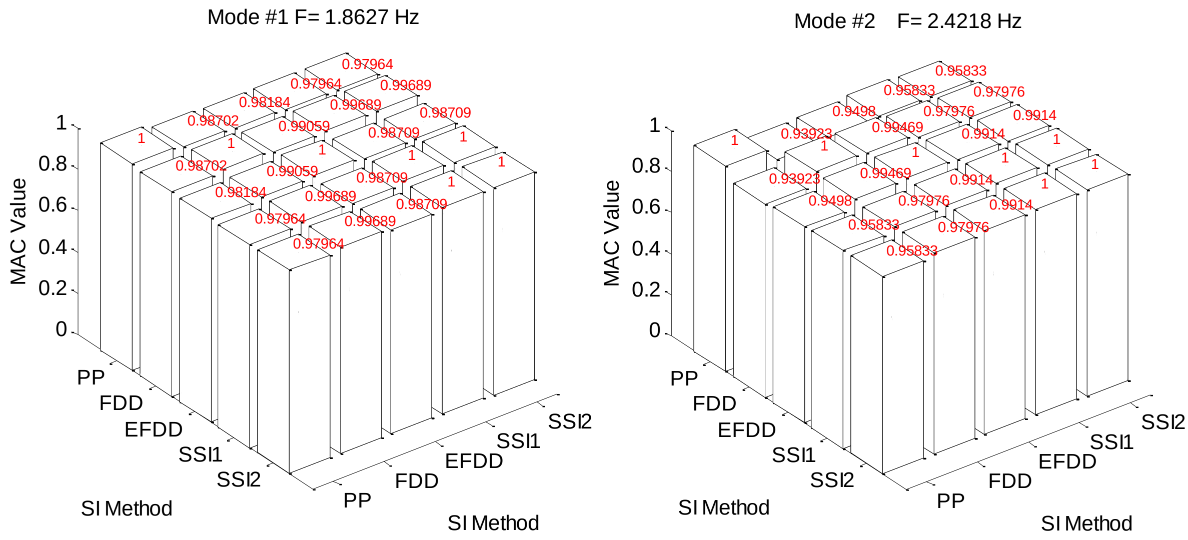
Figure 3: Mode shapes developed with operational use ambient vibration records.

Table 1: Modal parameters developed from full scale ambient vibration testing.

Mode Shape	PP Freq. (Hz)	FDD Freq. (Hz)	EFDD Freq. (Hz)	SSI1 Freq. (Hz)	 Damp. (%)	SSI2 Freq. (Hz)	 Damp. (%)
Wind							
1st Trans. (NS)	1.88	1.84	1.84	1.85	1.17	1.85	1.17
1st Torsional	2.34	2.42	2.42	2.45	1.41	2.45	1.4
Operational Use							
1st Trans. (NS)	1.88	1.88	1.88	1.87	1.95	1.87	1.95
1st Torsional	2.42	2.46	2.46	2.44	1.77	2.44	1.77
Earthquake							
1st Trans. (NS)	1.88	1.84	1.84	1.84	1.23	1.84	1.22
1st Torsional	2.27	2.31	2.31	2.41	1.62	2.41	1.62

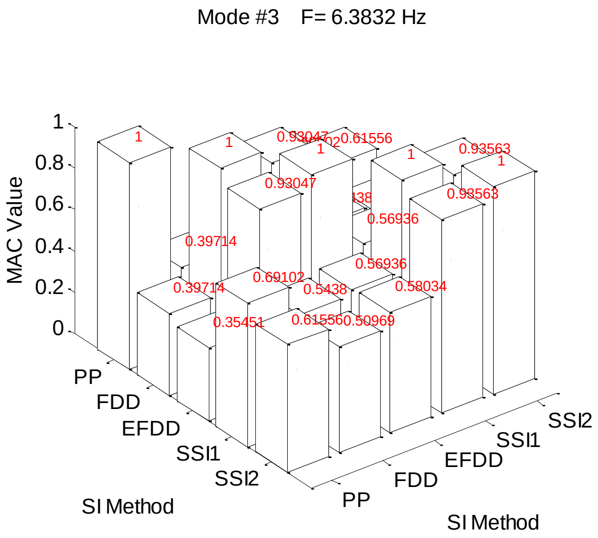
Table 2: Modal parameters developed from full scale forced vibration test.

Mode Shape	Level of excitation 10kg Freq. (Hz)	 Damp. (%)	 20kg Freq. (Hz)	 Damp. (%)	 40kg Freq. (Hz)	 Damp. (%)
1st Trans. (NS)	1.91	1.525	1.90	1.556	1.88	1.707
1st Torsional	2.48	1.394	2.46	1.466	2.45	1.64



(a) MAC values for the first translational mode

(b) MAC values for the first torsional mode



(c) MAC values for the second torsional mode

Figure 4: Comparison of mode shapes identified by different techniques using MAC.

5 CONCLUSIONS

This paper presented a comparison between full scale forced and ambient vibration dynamic testing conducted on a 13-storey reinforced concrete building in the University of Auckland. An eccentric mass shaker fixed on the top of the building excited the structure and eight wired accelerometers captured the dynamic response. A dense array of low cost MEMS accelerometers successfully recorded very small amplitudes of the building vibration under different forms of ambient excitation. Four system identification techniques, peak picking (PP), frequency domain decomposition (FDD), enhanced frequency domain decomposition (EFDD) and stochastic subspace identification (SSI) were implemented to extract modal parameters of the building. The recorded ambient data produced very accurate estimates of the modal parameters of the instrumented buildings including higher modes. Both time and frequency domain techniques provided very accurate estimates of modal parameters when used with output-only data. Strong correlation between modal parameters from the implemented methods was found. The modal parameters determined through ambient vibrations were comparable with the forced vibration analyses, providing substantial evidence that ambient vibration testing can be as effective as forced vibration testing in determining modal parameters for similar structures.

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