

SYSTEM IDENTIFICATION OF A 13-STORY REINFORCED CONCRETE BUILDING THROUGH AMBIENT AND FORCED VIBRATION

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Abstract. *This paper describes a unique research program that investigated the dynamic behavior of a full scale 13-story reinforced concrete building under forced vibration, ambient vibration and distal earthquake excitation. Modal parameters of the building were identified using the System Identification Toolbox (SIT) developed at the University of Auckland, New Zealand utilizing a range of methods in both the frequency and time domain. Initially, an eccentric mass shaker located on the upper floor of the building was used to excite the building while instrumented with eight accelerometers. Ambient vibrations were then recorded over a period of two weeks utilizing 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. System identifications were carried out using test data from each excitation source, and comparisons were made between the results of each. Correlation of mode shapes was evaluated using the modal assurance criterion (MAC) and the variation in the natural frequency and damping values were statistically evaluated. Overall, consistent results were observed for modal parameters obtained from various methods. The influence of the excitation force characteristics on the performance of various system identification techniques was also investigated.*

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 [1]. 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 [2, 3]. 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 hence the distribution of the input forces across the structure will affect the quality of the identified modal parameters [4, 5]. Researchers also emphasize that for output-only analysis to be successful it is important to have sufficient quality data with good signal-to-noise ratio [6]. 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 [7]. 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) [8] 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 [9], 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.

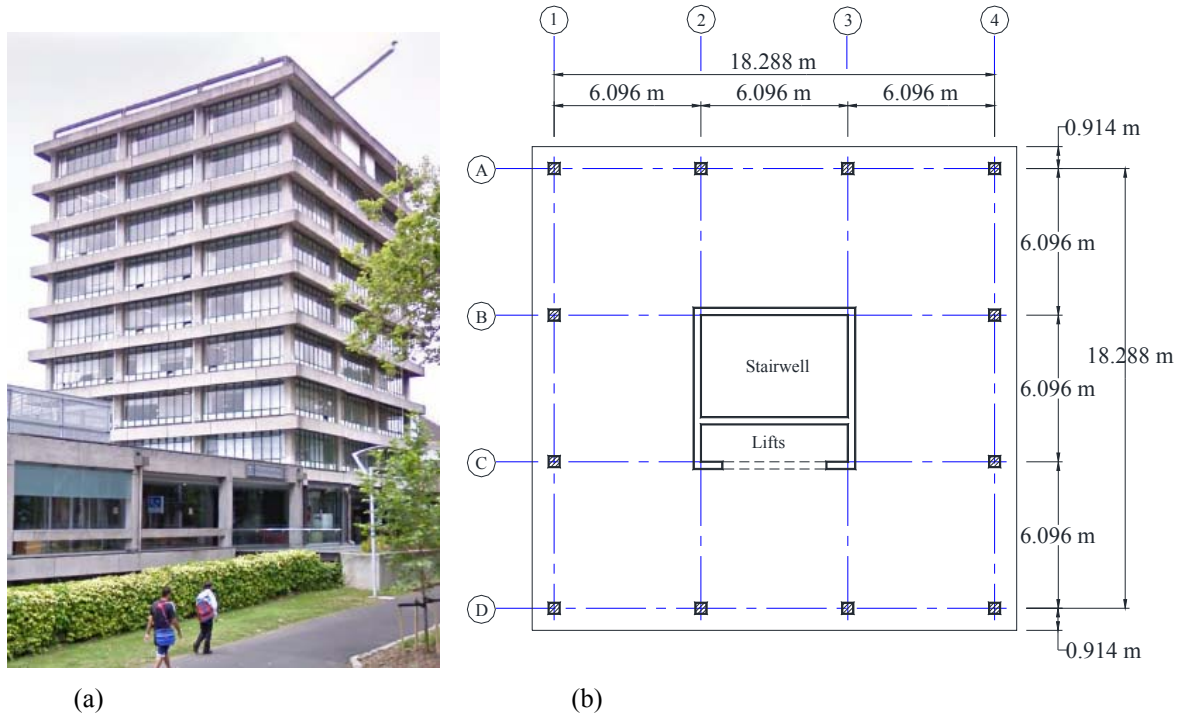


Figure 1: (a) Engineering office building at the University of Auckland, (b) Plan view of levels 5 to 12.

3 DYNAMIC TESTS

3.1 Forced vibration testing

A forced vibration test was conducted on the building in 2002 using an eccentric mass shaker located on the top floor by Associate Professor John Butterworth and his Master student Jin Hee Lee [9]. 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

An ambient vibration test was conducted on the building in 2012 using large number of MEMS accelerometers. 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 center of the building. Prior to setting up, the real time clock (RTC) of each accelerometer was synchronized 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 analyzed 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 utilized to analyze 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.

Spectrogram shows the frequency spectrum of the signal and how it changes over time. It returns the time-dependent Fourier transformation for a sequence and displays this information as a spectrogram. The spectrogram is, therefore, a view of the frequency content of the signal as a function of time. It is a useful tool to understand how different modes are excited over time and it can also be used to select the best time intervals for identifying particular modes. Figure 2 shows the acceleration response at level 12 of the building and the associated spectrogram from earthquake, wind and operational use excitation, respectively. Comparison of the spectrogram function from each loading type clearly indicates that the operational use excitation was the most efficient in exciting multiple modes.

4 MODAL PARAMETERS IDENTIFICATION

4.1 Time domain versus frequency domain identification techniques

Modal parameters of the building were identified using the System Identification Toolbox (SIT) program developed at the University of Auckland [10]. Three frequency domain based methods; peak picking (PP), frequency domain decomposition (FDD) [11], enhanced frequency domain decomposition (EFDD) [12] and one time domain based method; stochastic subspace identification (SSI) [13, 14] were utilized 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 [11] 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 (SSI1) uses singular value decomposition of the power spectral density function (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.

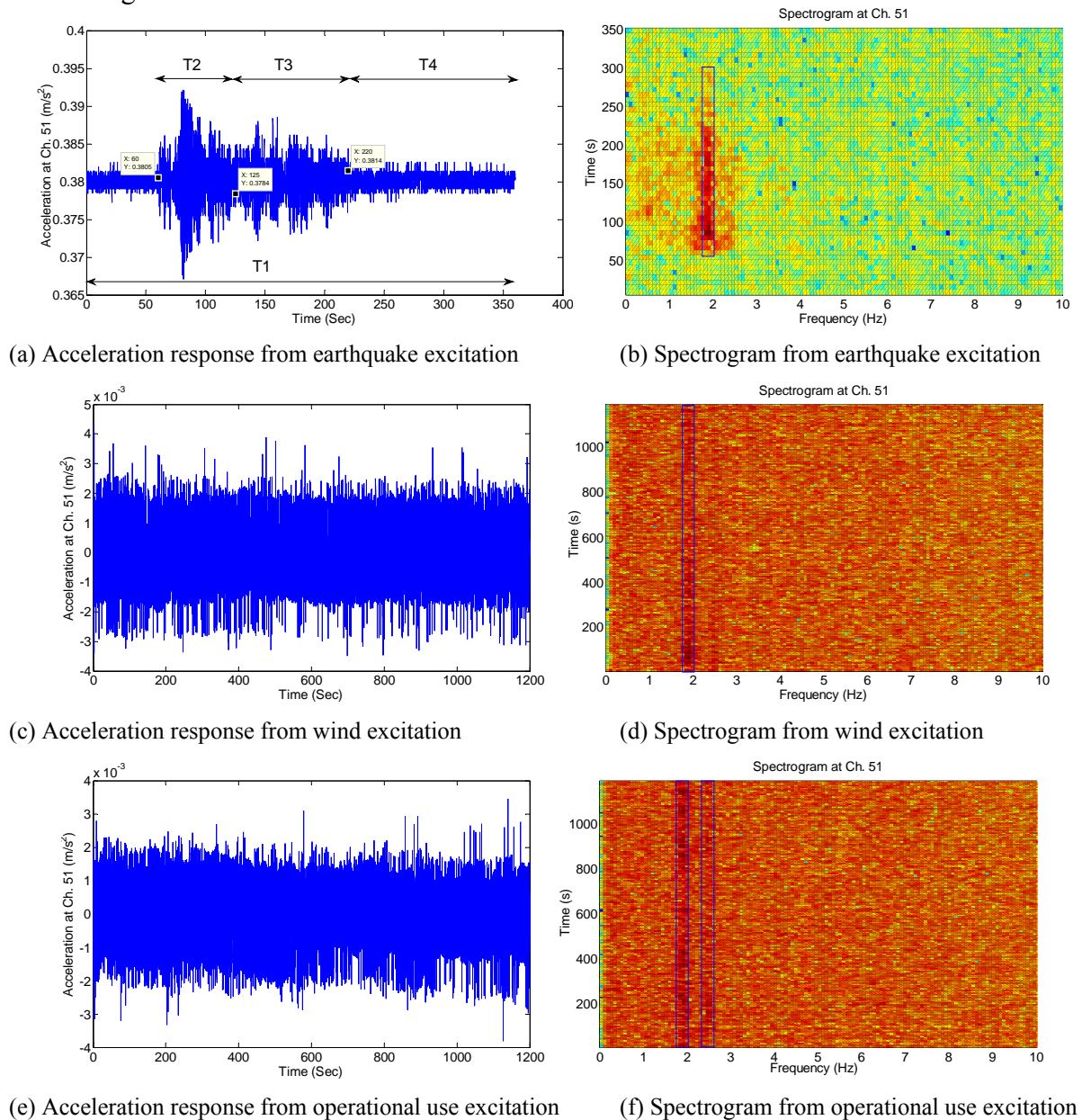


Figure 2: Acceleration response and the associated spectrogram from different excitation sources.

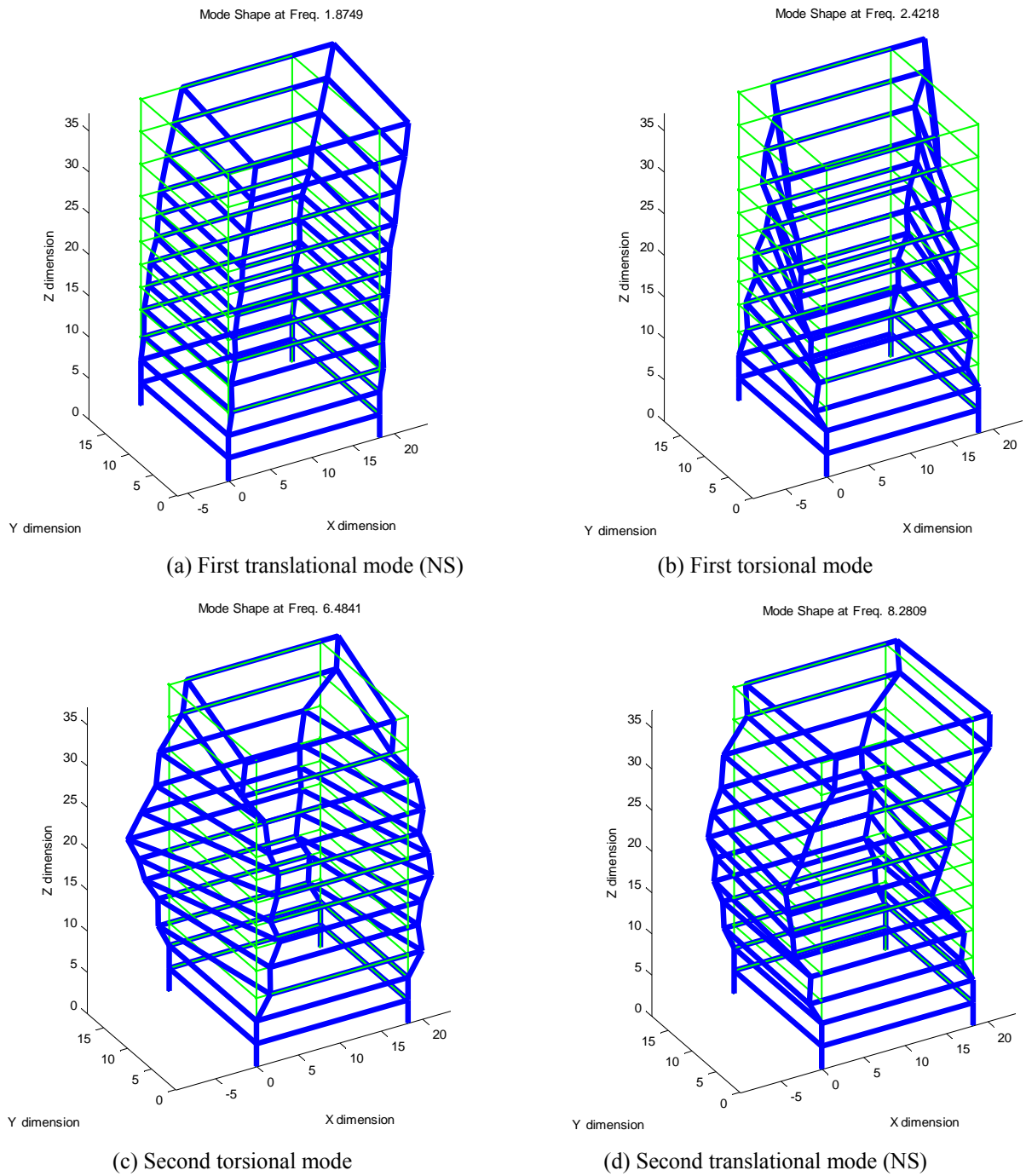


Figure 3: Mode shapes developed with operational use ambient vibration records.

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, ϕ_{ij} and ϕ_{ij}^* , is defined as [8]:

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

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 the second torsional mode identified by PP, FDD, EFDD, SSI1 and SSI2 methods. Each bar in the figure represents the MAC value when comparing a specific mode extracted from a pair of system identification methods. MAC values ranged from 0.80 to 1.00 for the first three modes (first translational, first torsional and second translational) which indicated a very high correlation between mode shapes identified by time domain and frequency domain identification techniques. 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 utilized 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 [9]. 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.

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

Mode Shape	PP	FDD	EFDD	SSI1		SSI2	
	Freq. (Hz)	Freq. (Hz)	Freq. (Hz)	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)
Wind							
1 st Trans. (NS)	1.88	1.84	1.84	1.85	1.17	1.85	1.17
1 st Torsional	2.34	2.42	2.42	2.45	1.41	2.45	1.4
Operational Use							
1 st Trans. (NS)	1.88	1.88	1.88	1.87	1.95	1.87	1.95
1 st Torsional	2.42	2.46	2.46	2.44	1.77	2.44	1.77
Earthquake							
1 st Trans. (NS)	1.88	1.84	1.84	1.84	1.23	1.84	1.22
1 st 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		20kg		40kg	
	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)
1 st Trans. (NS)	1.91	1.525	1.90	1.556	1.88	1.707
1 st Torsional	2.48	1.394	2.46	1.466	2.45	1.64

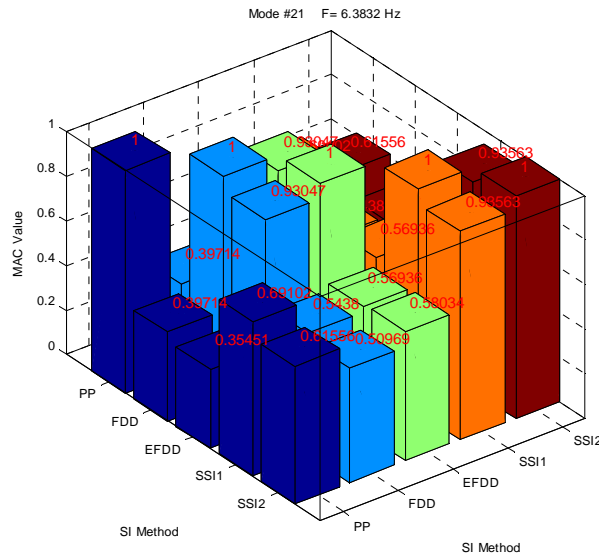


Figure 4: Comparison of the second torsional mode shape identified by different techniques using MAC.

4.2 Modal parameters identification from non stationary vibration

In operational modal analysis and output-only modal identification it is assumed that the excitation is unknown and can be modelled by a Gaussian white noise. This assumption can be accepted with confidence in case of using ambient vibration data produced by wind, nearby traffic or operational use as the response is typically stationary and we can assume that the excitation signal is a Gaussian white noise. However, for the earthquake excitation this assumption is not valid especially in case of strong earthquakes.

The test building was excited by a M6.5 earthquake roughly 350km away and high quality acceleration data was recorded especially at the top floors. It was therefore decided to divide the time history response to three sections as shown in Figure 2a to investigate the influence of using non stationary vibration on the identified modal parameters. As indicated in this figure, the second section T2 in the time interval between 60 and 125 seconds included the most non-stationary vibration while section T3 in the time interval between 125 and 220 seconds was considered the closest to the stationary signal. The first translational and the first torsional mode shapes identified by the SSI method using the time history response in sections T2 and T3 are shown in Figure 5 (a) through d, respectively. It is clearly shown in these figures that using the response data in the non-stationary interval resulted in a poor representation of all mode shapes despite the fact that the first translational mode was strongly excited during this interval as indicated in the spectrogram of the data (Figure 2b). Similar observations were found when frequency domain techniques were utilised to extract modal parameters.

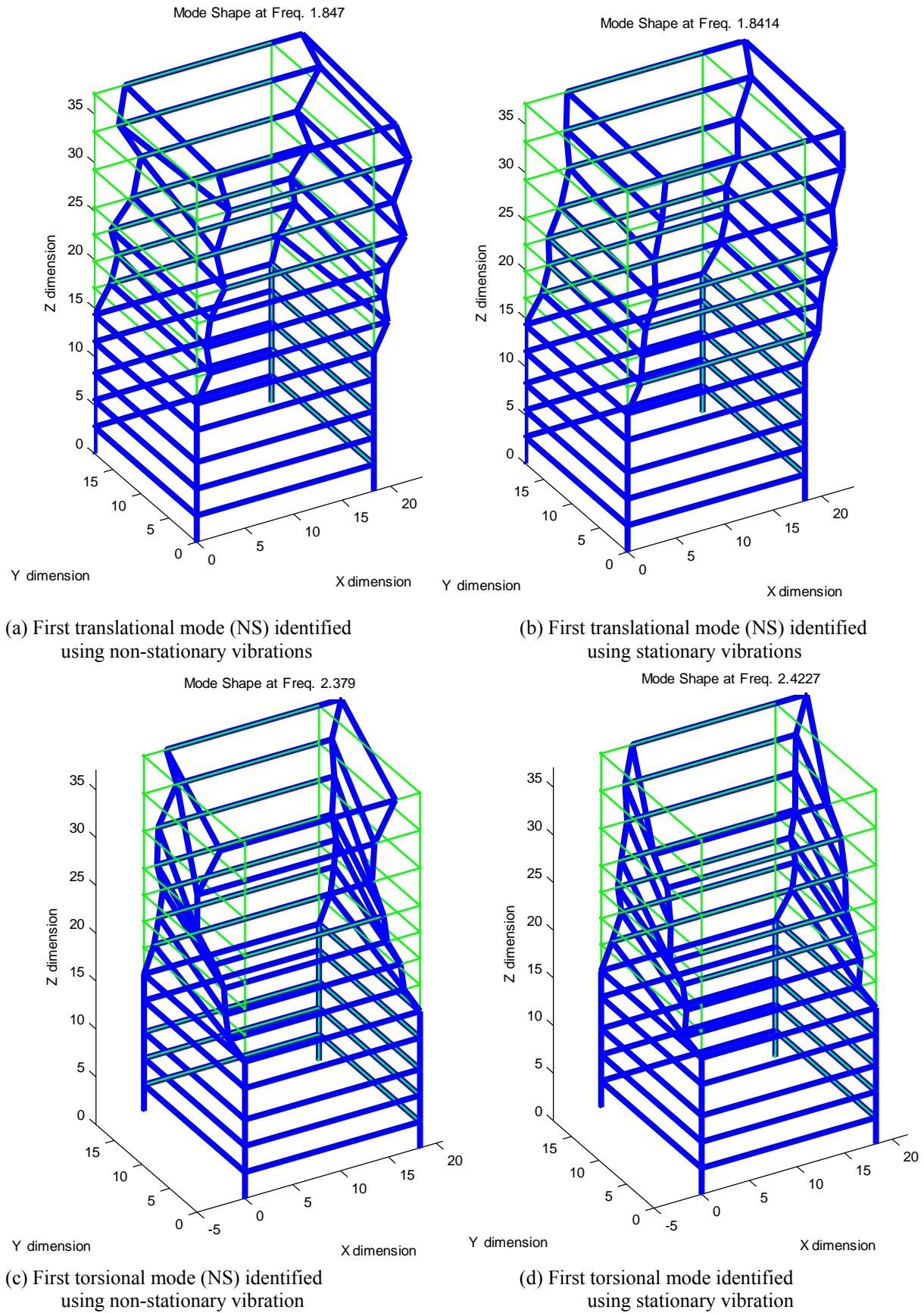


Figure 5: Comparison of the second torsional mode shape identified by different techniques using MAC.

5 CONCLUSIONS

A comparison between full scale forced and ambient vibration dynamic tests conducted on a 13-storey reinforced concrete building in the University of Auckland, New Zealand has been investigated in this paper. An eccentric mass shaker fixed at the top of the building was used to excite the structure and eight wired accelerometers captured the vibration 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. It has been shown that the near stationary vibration data can produce accurate estimates of modal parameters. However, further study is required to estimate the level of non stationarity in the signal and facilitate the application of output only modal parameters identification techniques with non-stationary data.

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