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MONITORING THE DYNAMICS OF A CONCRETE BUILDING ENDURING EARTHQUAKE AND WIND EXCITATION

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SUMMARY

Earthquake and wind induced acceleration data has been systematically collected in a 14-story reinforced cast-in-place concrete building over period of 14 years. The building has been subjected to repeated earthquake and wind induced excitation. The earthquake database for the building presently contains records from over 100 events ranging from magnitude 2½ to 6½ with acceleration amplitudes of up to 22% g. The wind data catalogue is larger but generally contains lower amplitude data. The recorded acceleration data is used for system identification of the building. The dataset provides an opportunity to observe, and better understand the variances in the basic dynamic properties of the building, i.e. the natural frequencies and critical damping ratios for the main modes of vibration. Changes in the system parameters are observed, which apparently depend both on time as well as excitation level. A slow increase in flexibility is observed during the whole observation period, in addition to an instantaneous decrease in natural frequencies after each earthquake. A pronounced decrease in natural frequencies after the bigger earthquakes is followed by a recovery period where the natural frequencies increase slowly and tend towards the 'initial' ones. The 'instantaneous' decrease in natural frequencies is accompanied by increase in corresponding critical damping ratios, which support the interpretation of weak non-linear behaviour. Analysis of the resulting data should lead toward a better understanding of building response.

1. INTRODUCTION

Natural frequencies of a soil-structure system are known to vary under different levels of excitation and current research [Clinton et al., 2006; Kohler et al., 2005] indicates that during small shaking events, there is a measurable change in recorded natural frequencies of various types of structures. Having a realistic estimate of structural frequencies is important for seismic design. Also, the dynamic properties of structures are used in structural health-monitoring in association of damage assessment. Therefore wandering in natural frequencies is significant for the engineering community.

This study evolves around a 14-story reinforced cast-in-place concrete office building. Earthquake and wind induced acceleration data has been systematically collected in the building over periods of 14 years. The earthquake databank from the building consists of records from over 80 events ranging in magnitude from 2½ to 6½ with response acceleration amplitudes of up to 22% g. The wind data catalogue is larger, counted in recorded time series, but contains lower amplitude data. The purpose of the paper is to observe the variability in the basic dynamic properties of the building, i.e. the natural frequencies and critical damping ratios, for the main modes of vibration, during different levels of wind and earthquake induced excitation. The instrumentation of the building

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is described and the recorded structural response data presented. System identification analyses of the building are carried out applying a previously verified parametric method to the recorded data [Snæbjörnsson 2002].

2. THE BUILDING, INSTRUMENTATION AND DATA ACQUISITION

2.1 The structure

The Commerce Building in Reykjavik is 14 stories high (45 m) office building. It is a reinforced cast-in place concrete structure, basically composed of shear walls and slabs. The geometry of the building is rather complex, as the floor plans vary, changing vertically, as shown in Figs. 1 and 2. The 14th floor plan is about 8 m wide and 18 m long. The alignment of the building is such that the translational modes of vibrations are approximately in the ESE-WNW and NNE-SSW directions. Some earlier investigations of the building and its response to wind and earthquake excitation have been reported [Snæbjörnsson and Reed 1991; Snæbjörnsson et al. 1996].

Figure 1. The Commerce Building in Reykjavik, view from Northwest.

2.2 Instrumentation

The building was instrumented in January 1989. The instrumentation is located at three levels (see Figure 2): the basement, the 8th floor and the 14th floor. A tri-axial accelerometer is located in the basement, measuring the three components of base (ground) acceleration. On the 8th floor two uni-axial accelerometers are located measuring the two horizontal components of the response. On the 14th floor (the top floor) three uni-axial accelerometers are located, one measuring motion in the N-S direction and two measuring in opposite corners (i.e. N-E and S-W) measuring motion in the E-W direction. This makes it possible to detect torsional effects on the 14th floor (see Figure 2). The eight sensors (channels) are connected to two interconnected data acquisition units. The sampling rate is 200 Hz. The data acquisition starts automatically when the acceleration on the 14th floor exceeds a specific trigger level, which is at present 0.5% g.

2.3 Earthquake data and response

The system has recorded 80 earthquakes at all eight channels. The recorded earthquakes range in magnitude between 2½ and 6½. Figs. 3 and 4 give an overview on the recorded earthquakes. The geographic location of the epicenters is shown on Figure 3 in relation to the location of the building. Figure 4 shows the earthquake magnitude and maximum horizontal ground and response acceleration as a function of epicentral distance. The acceleration values shown are based on time-series, which have been corrected and filtered to account for the characteristics of the sensors, noise, zero offset and drift. It should be noted, that earthquakes often occur in sequence, in which case several events are recorded within a time frame of few days or less.

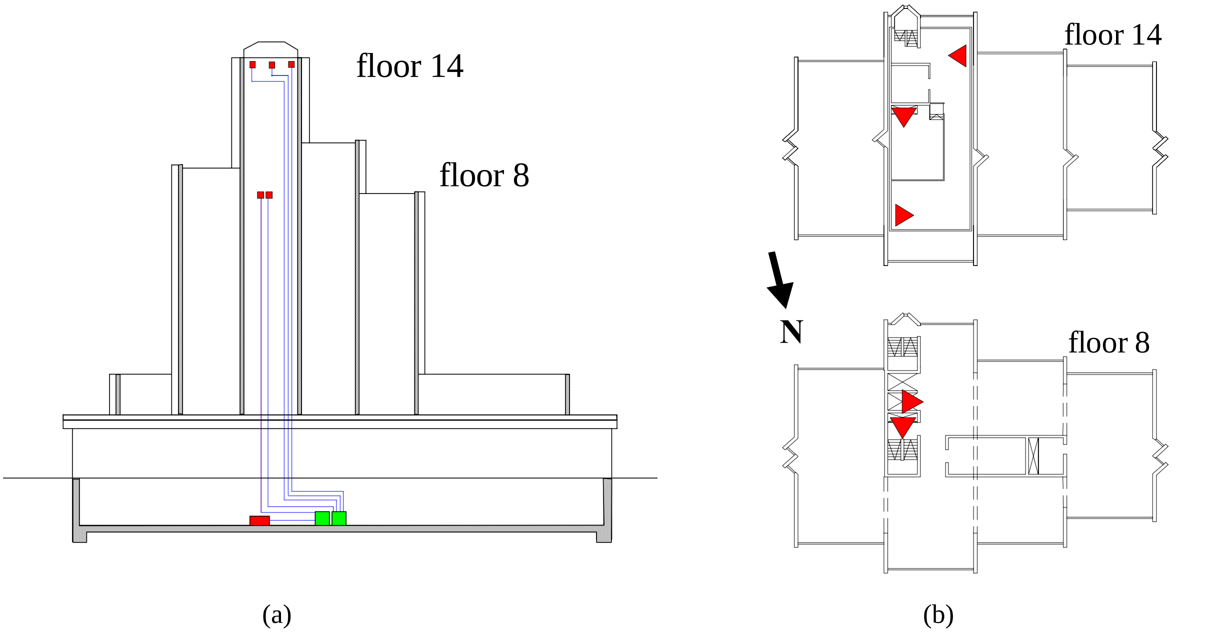


Figure 2: The instrumentation arrangement: (a) Vertical section, and (b) floor plans of the building, showing the location of instrumentation (▲ uni-axial accelerometer, ■ tri-axial accelerometer and ■ data acquisition).

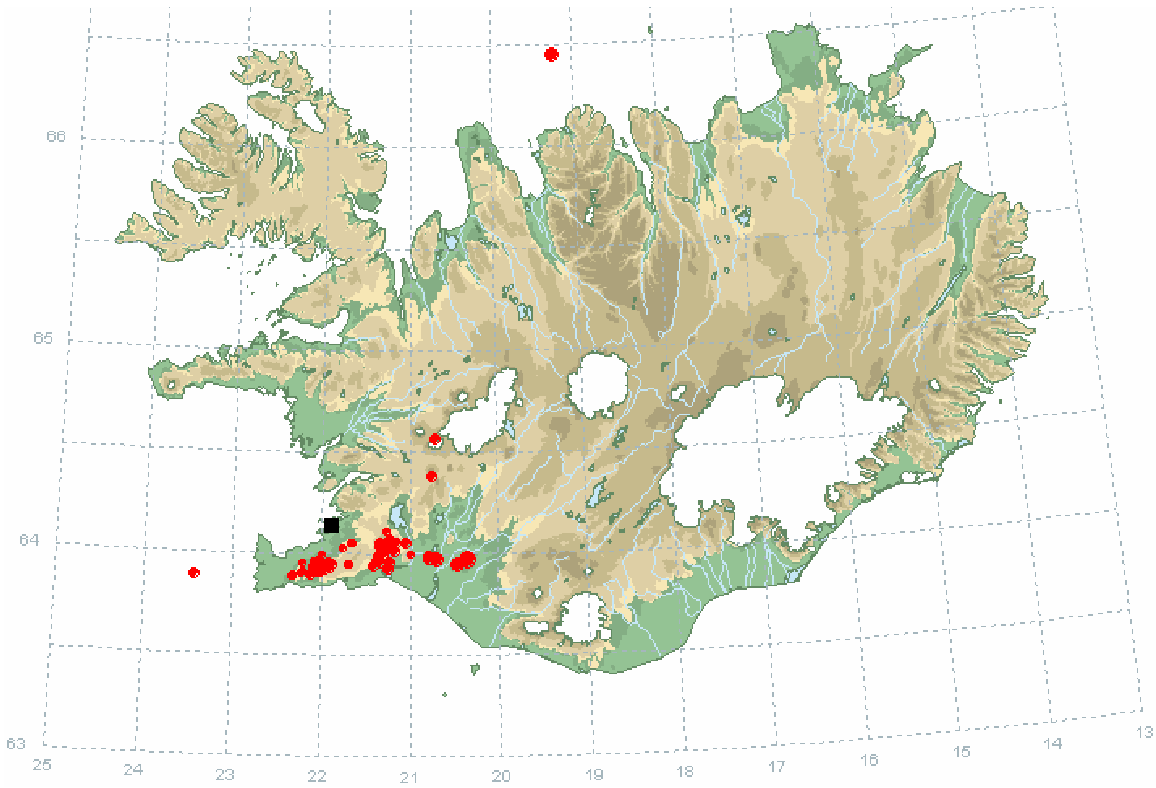


Figure 3: A map showing Iceland and the location of the Commerce building (the black square) and the epicenters of recorded events (red dots).

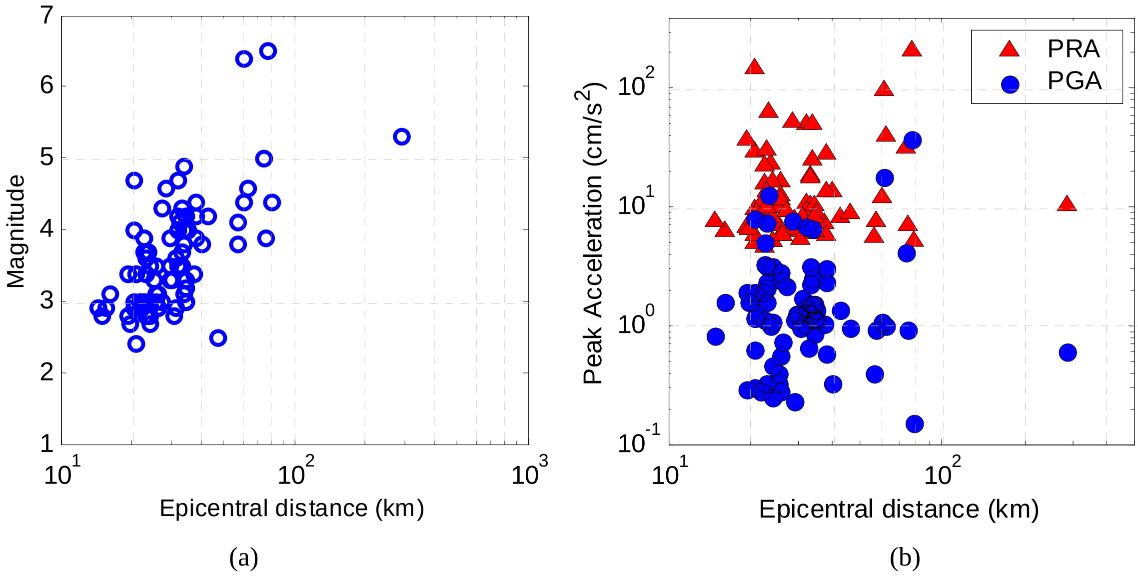


Figure 4: (a) Earthquake magnitude as a function of epicentral distance to the Commerce building and (b) the corresponding peak ground acceleration (PGA) values and peak response acceleration (PRA) values as a function of epicentral distance.

3. SYSTEM IDENTIFICATION

3.1 Methodology

The recorded acceleration data was used for system identification of the building. The aim was, to estimate the natural frequencies and critical damping ratios for the main modes of vibration; to examine the variability of the system parameters and to study their dependence on excitation conditions. Furthermore, to check if any changes in structural behaviour could be observed throughout the observation period, which included two 6.5 magnitude events that induced acceleration peaks of 22% g in the building. For this purpose a parametric method was applied, using a state-space model identification (SMI) toolbox [Verhaegen 1997]. After proper pre-processing of the data, only two parameters are required for an output-error model identification problem: the upper bound on the optimal order of the system and the true order of the system to be extracted from the data. The upper bound on the optimal system order can be determined trough the Akaike criterion of an AR-SISO model of increasing order [Ljung 1987]. A SISO approach, where a single input (ground acceleration series) and a single output (response acceleration series) are modeled, was found to give more consistent results than any multi input, multi output (MIMO) combination. After establishing the natural frequencies of the structure a sharp band-pass FIR filter was applied around each natural frequency band to improve the damping estimation. A more general discussion on various system identification techniques may be found in [Alvin et al. 2003]. The model used, is a locally linear, time-invariant system, which is not strictly appropriate for strong motion records which are non-stationary and the vibrating structures are likely to show time-variant and even nonlinear characteristics [Jeary 1996]. Nonlinear identification models are difficult to use because of complexity and identifiability problems. On the other hand, it is possible to evaluate the dynamic characteristics of non-linear systems as equivalent linear, time-invariant systems for relatively short-time segments of each record. This has been referred to as time-variant linear models [Tobita 1996]. Since strongly nonlinear behaviour is not to be expected for the two buildings studied this was considered an acceptable methodology. The outlined procedure was therefore applied to the acceleration data at hand and the results are presented in the following.

3.2 Results

The records from the Commerce building were analyzed sequentially, in order to establish a temporally organized databank of system parameters. Figure 5 gives an overview on the modal frequencies. There are three modes strongly excited during vibration in the ESE-WNW direction, just below 2 Hz, just above 4 Hz and at 8 Hz. For vibration in the NNE-SSW direction, two modes dominate the response, at just above 2 Hz and at 8 Hz. All the modes of vibration are influenced by torsion because of the irregular building shape and the asymmetric location of the shear-core around elevators and staircase in the centre tower.

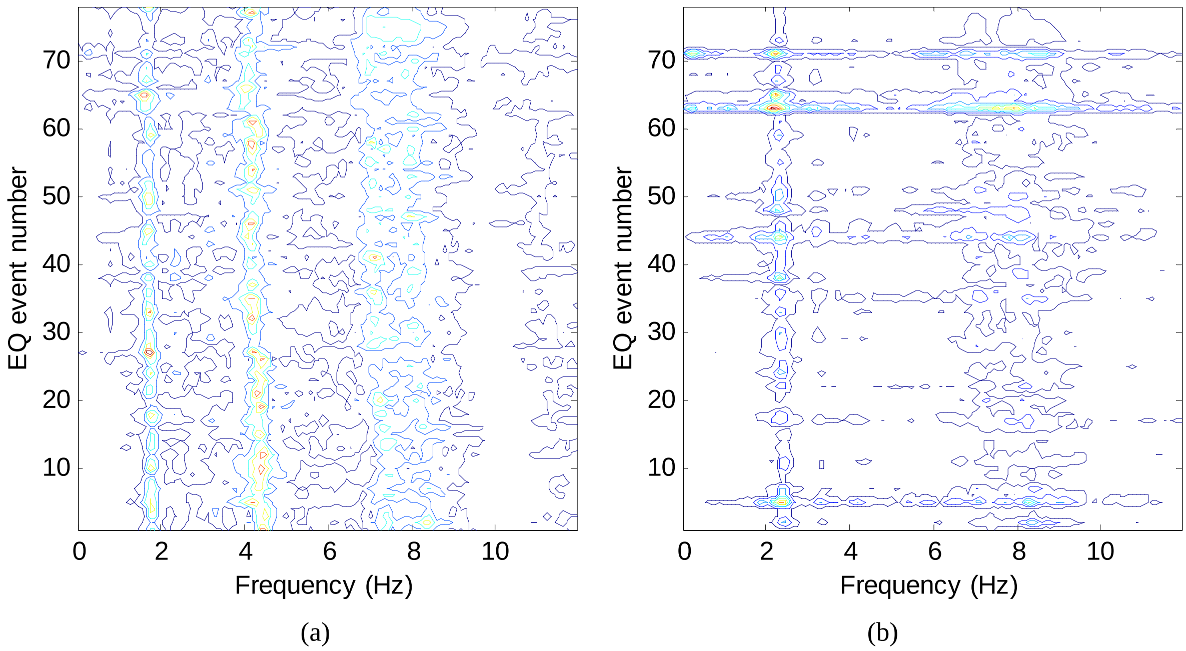


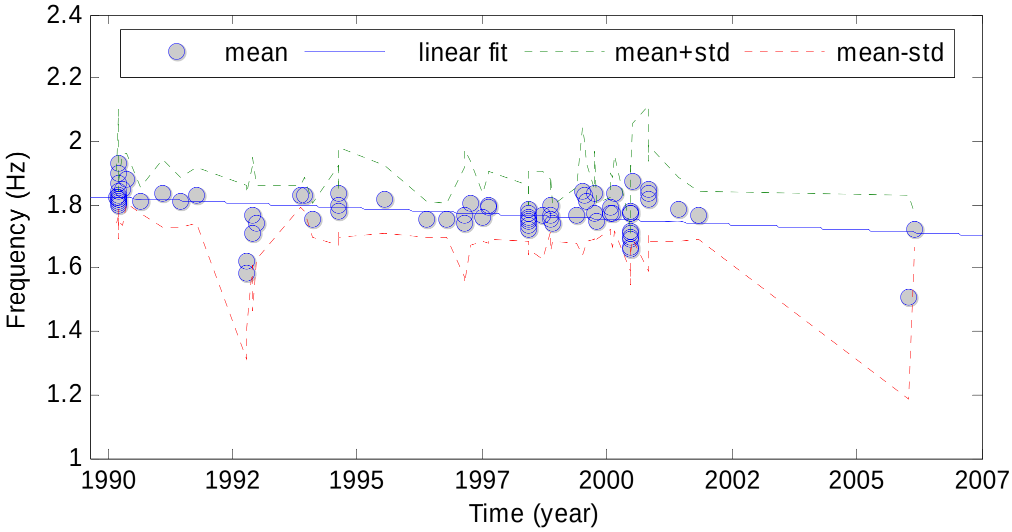
Figure 5: Contour graphs of the Fourier spectrum for the 78 events analyzed. (a) For vibration in the ESE-WNW direction. (b) For vibration in the NNE-SSW direction.

Figures 6 and 7 give an overview of the evolution and variability in natural frequency of first two ESE-WNW modes during a 16 years observation period of earthquake and wind induced motion. Figure 6 shows the mean natural frequency estimated for each recorded earthquake event. The variation in natural frequency within each recorded event is demonstrated through dotted lines which represent the mean value +/- one standard deviation. Figure 7 shows the same information, but for recordings during ambient wind excitation. Wind excited motion was recorded during winter storms every year until 1995, then the trigger level was increased, which explains why the wind excited recordings are fewer for latter part of the observation period. Both the wind and the earthquake induced data demonstrate a continuous decrease in natural frequency over the observation period for these two modes of vibration. The total reduction of the natural frequency for these modes is ~5%, based on a simple linear fit through the mean values for each event. This type of temporal decrease in natural frequency has been seen in other instrumented buildings, such as the Milikan Library at CalTech [Clinton et al. 2006].

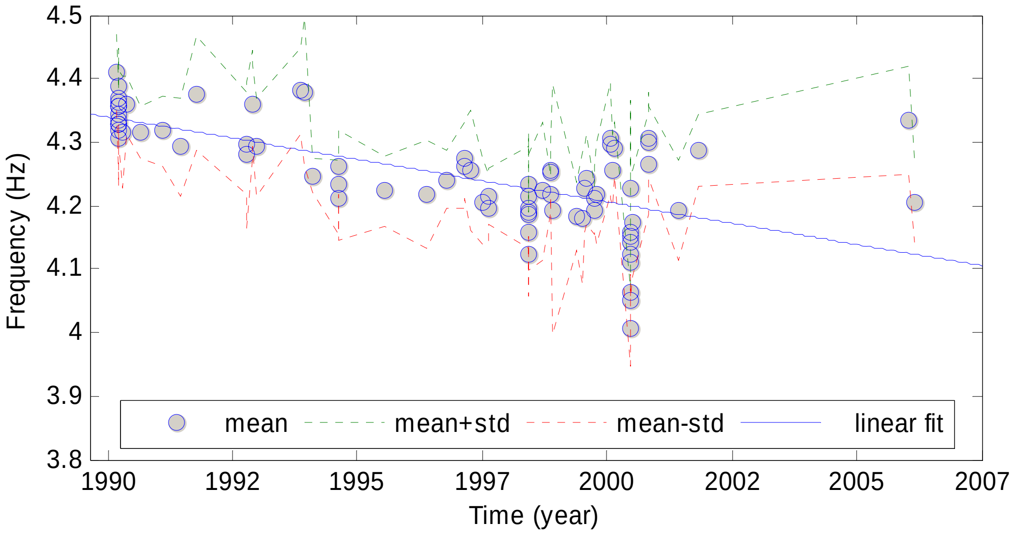
Comparing the variations in natural frequency during earthquakes (Figure 6) and wind induced excitation (Figure 7), it is seen that the variations are considerably less for the wind induced events. This is mainly related to the different nature of the excitation, but also partly due to the fact that wind induced events give time series of longer duration and therefore more reliable and consistent estimate of system parameters [Snæbjörnsson et al., 1996].

In Figure 6 it can be seen that the frequency estimates for the two E-W modes of vibration do not always follow the same trend. This is for instance evident for recordings in 1992 and again in 1996, where the data gives relatively low values for the 1. E-W mode, but relatively high values for the 2. E-W mode. The causes for this behavior are not well understood. But short term wandering in natural frequencies has been known to be influenced by weather conditions such as extremes in temperature, rain and wind [Bradford et al. 2006]. There are indications that this may also be the case for this building. For instance the noticeable difference in natural frequency during storm recordings in the winter of 1992-1993 (see Figure 7b) are most likely linked to temperature effects as the high frequency values are estimates based on acceleration recorded in December of 1992, in temperatures well below 0 °C. Corresponding high frequency value can be seen in Figure 6 during the same time period.

As seen in Figure 4, most of the earthquake response data is induced by small earthquakes. However, the data set contains records from two moderate sized earthquakes of magnitude 6.5 that occurred in South Iceland in 2000. The effect of these two events on the natural frequencies of the building can be seen in Figure 6, particularly for the second E-W mode which shows a dramatic reduction in natural frequency. These events will be discussed further in the following.



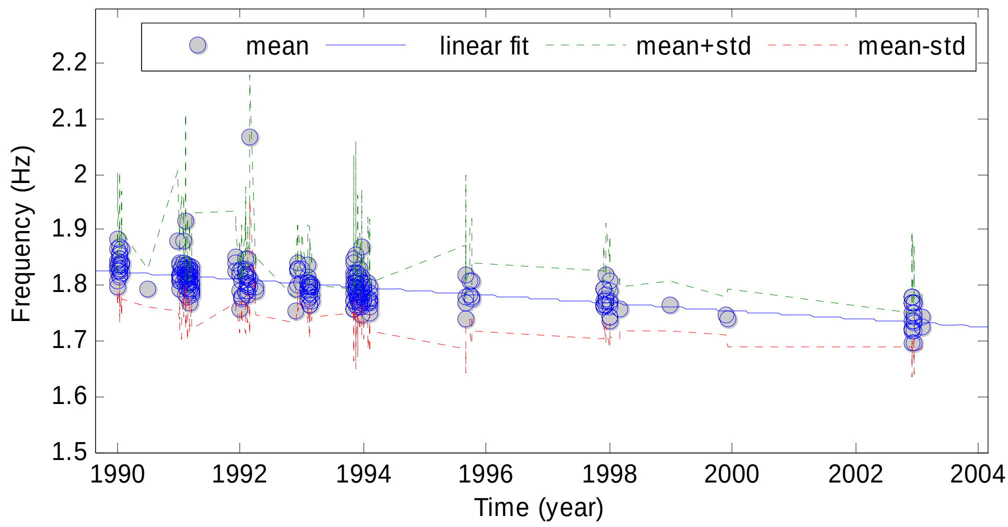
(a)



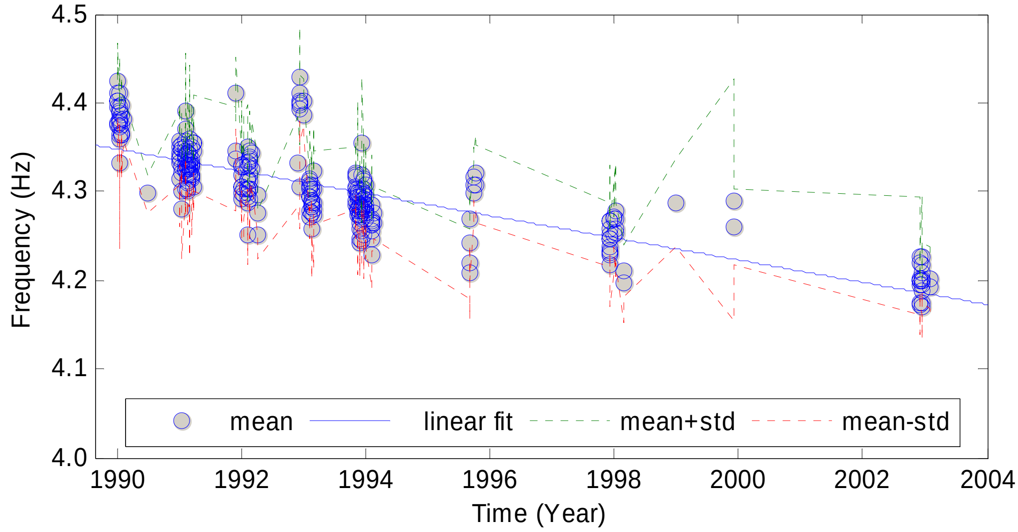
(b)

Figure 6: Natural frequency as a function of the time for (a) the first E-W mode of vibration and (b) for the second E-W mode of vibration. The frequency estimates are based on earthquake induced acceleration during the period of 1990 to 2006.

Figure 8, shows peak acceleration (top) and natural frequency estimates for the first two E-W modes of vibration for each analyzed time series segment of earthquake events recorded shortly before, during and after the South Iceland earthquakes in June 2000, i.e. records from the period of October 1999 to November 2001. There is a considerable drop in natural frequency during the two events on June 17 and June 21 in 2000, especially the first one (~10%). The structure is seen to recover somewhat after the main events the natural frequency seems to be reestablished at 4.2-4.3 Hz. However, it takes the structure a considerable time to reach that point. Especially considering that 8 smaller events are recorded during the 4 days between 17 and 21 of June. Another 6 events are recorded in the period after that, in July and November 2000 and then two in 2001. This indicates that the ‘rebound’ of a structure undergoing excitation, seemingly within the linear range of response, is not instantaneous but a process that may take few days, weeks or longer. Because only triggered data are available, there is not a clear evidence of the time frame for this recovery.



(a)



(b)

Figure 7: Natural frequency as a function of the time for (a) the first E-W mode of vibration and (b) for the second E-W mode of vibration. The frequency estimates are based on wind induced acceleration during the period of 1990 to 2006.

Individual series from the 6.5 magnitude earthquake from June 17 in 2000 [Thorarinsson et al 2002; http://www.ISESD.hi.is] are also studied. The objective was to establish, if and how the system parameters change within each event. What makes the June 17 event special is that the recordings combine three different earthquakes. The first one was of magnitude 6.5 and located 77 km east of the building in the South Icelandic Seismic Zone (SISZ). The second earthquake, Mw~5, occurred 26 s after the SISZ event, about 23 km SSE of the building. The third earthquake occurred 4 s later, 12 km to the west or about 22 km south of the building, near the eastern shore of Lake Kleifarvatn. Timing suggests that these earthquakes were triggered dynamically by shear waves from the SISZ event traveling at a velocity of 2.5 km/s. This phenomena, is displayed by the time series in Figure 9, which shows the observed E-W response of the NE corner on the 14th floor, recorded during the earthquake. The E-W direction lies across the weaker axis of the structural system therefore the building response (acceleration) is always strongest for that direction. The frequency content of the acceleration changes throughout the earthquake and the response has three separate bursts of peak acceleration with centers at around 13 s, 22 s and 27 s. The high frequency and high amplitude acceleration burst at 22 s can be traced to the second event with epicenter 23 km SSE of the building. Few seconds later there is a lower frequency acceleration burst that can be traced to the epicenter 22 km south of the building.

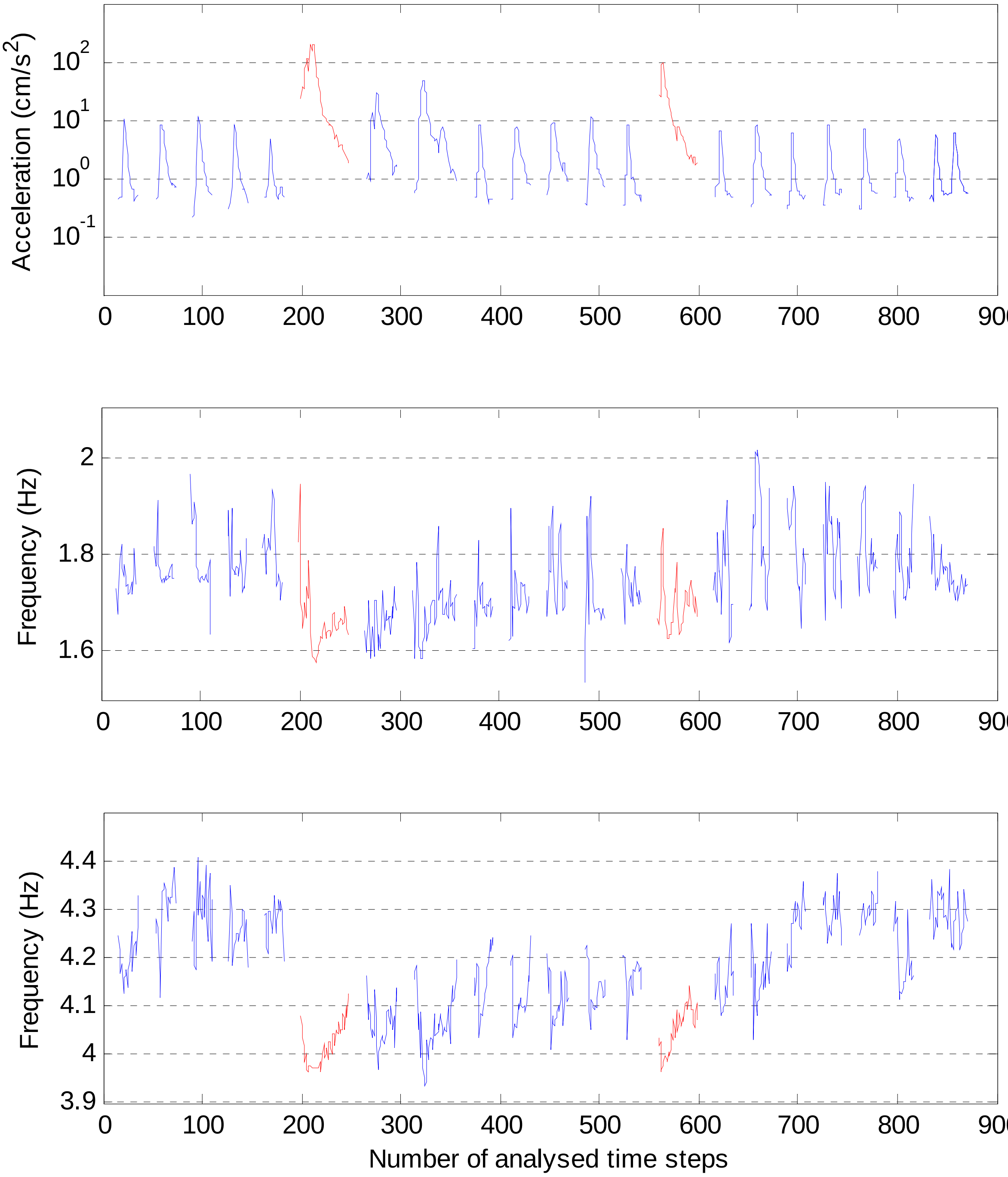


Figure 8: Segmental peak acceleration (top) and natural frequency estimates for the first two E-W modes of vibration as a function of the number of analyzed time steps. Estimates are based on earthquake induced acceleration during the period of October 1999 to November 2001.

The time-series of natural frequency show partly how the frequency changes with amplitude but also how that the participation of the modes varies throughout the earthquake. The second mode is clearly increasingly active throughout the peak of the earthquake and then its participation reduces and the frequency increases towards it starting value. On the other hand, the first mode starts out strong, then its participation reduces while the first arriving waves of higher frequency content have passed, at which time its participation increases again and dominates the decay of the motion. The estimated damping is bit chaotic, but is in general seen to increase as the amplitude increases. This is found to be in general agreement with the findings from other studies such as [Farrar and Baker, 1995]. The variation is seen to be greater for the first mode, where the damping repeatedly exceeds 5% of critical, while the damping of the second mode is more stable around 2%. This is not unreasonable as damping is generally related to velocity or displacement controlled processes [Wyatt 1977], and both velocity and displacement are considerably larger for the first mode than the second.

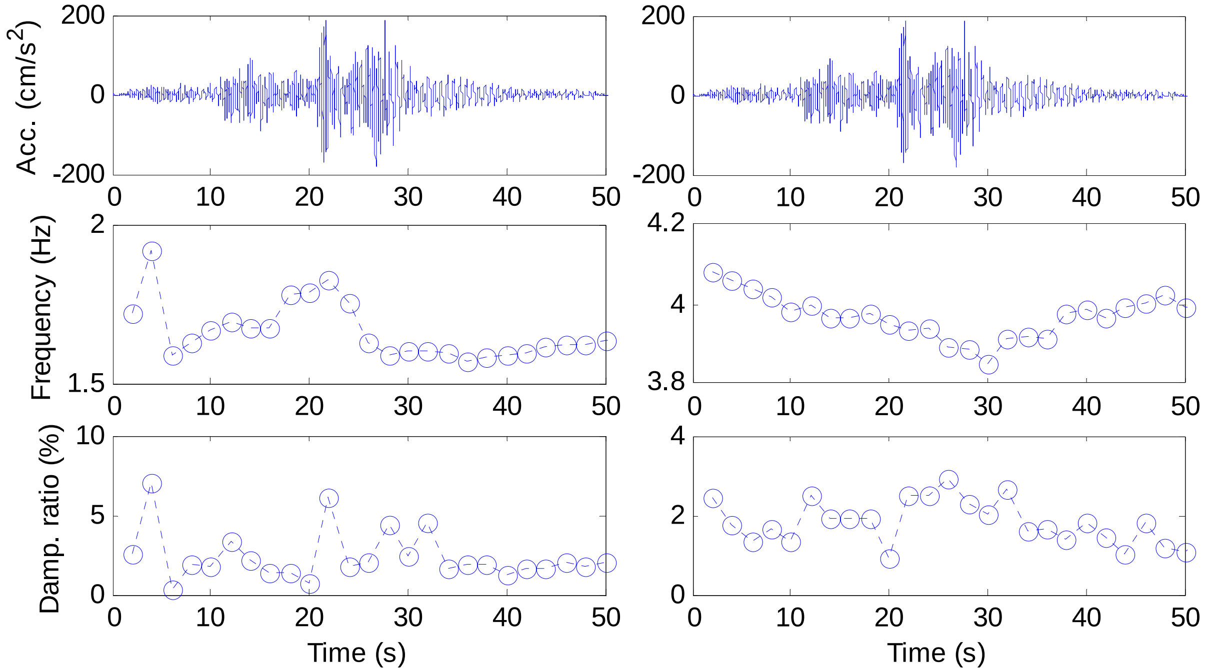


Figure 9: The acceleration time series from the June 17 main event along with the frequency and damping 'time-series' from the same event for the first and second modes of ESE-WNW vibration.

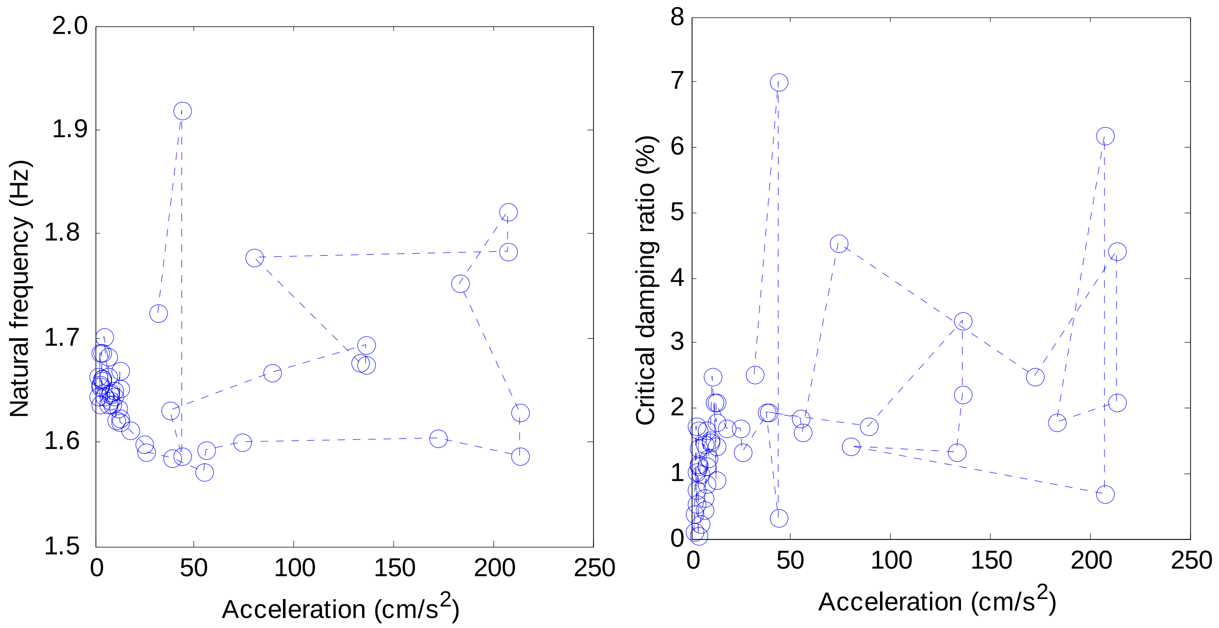


Figure 9: Natural frequency and critical damping ratio for the first mode of E-W vibration as a function of acceleration amplitude during the June 17 main event.

Plotting natural frequency and critical damping ratio versus the peak acceleration amplitude for each time step within the event, gives another view on how the SI-parameters are changing during the earthquake. This is done in Figure 9 for the first E-W mode of vibration. The result is a trace that in some ways resembles a displacement trace during a non-linear response. This underlines the fact that it is not just the overall amplitude of motion that affects the SI-parameters, but rather the relative contribution of the modes of vibration at each time step.

4. DISCUSSION AND FINAL REMARKS

The presented study of the dynamic long-term behaviour of a multi-storey reinforced concrete building in seismic environment reveals some interesting features. The building, which is a cast-in-place concrete structure, has been subjected to repeated earthquake and wind induced excitation. System identification and the available recordings are used to assess the basic dynamic properties of the building, natural frequencies and damping. Changes in the system parameters are observed, which apparently depend both on time as well as excitation level. The findings support the thesis that the dynamic behaviour of structures is determined by several external factors on very different timescales. A slow increase in flexibility is observed during the whole observation period, in addition to an instantaneous decrease in natural frequencies after each earthquake. This pronounced decrease in natural frequencies after moderately large earthquakes are followed by a recovery period where the natural frequencies increase slowly and tend towards the 'initial' ones. The 'instantaneous' decrease in natural frequencies is accompanied by increase in corresponding critical damping ratios, which support the interpretation of weak non-linear behaviour. The results do also indicate that other factors, for instance weather conditions such as the outside temperature, may influence the structural parameters. Further studies of the environmental influences as well back calculations applying a non-linear computational model are needed to better understand the observed dynamic behaviour. It should be noted that 5% decrease in natural frequency corresponds to a 10% reduction in stiffness for the whole structure. This is a significant change, however, at the same time it is not easy to define whether this is a large or moderate decrease in natural frequency, particularly when this occurs without appreciable structural damage.

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