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Case study on the effects of retrofitting on changing structural dynamic characteristics by microtremor measurements and finite element analysis

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Abstract. Determination of dynamic parameters of a structure such as predominant frequency and damping ratio is one of the most important subjects in dynamics of structures. Different methods are used to determine predominant frequency. These methods are different in the cost, implement accessibility, accuracy, speed, applicability in different conditions, simplicity of calculations and required data accessibility. Calculation of damping ratio by using common experimental procedures is very difficult and costly, then it is assumed as a constant value in most calculations. Microtremor measurements and using spectral ratio method to determine the predominant frequency and damping ratio of structure is of interest in recent years. In this paper, as a case study, the effects of retrofitting on structural dynamic parameters of two four-story buildings by using microtremor measurements and also finite element analysis, is investigated. The results of this study show that microtremor measurements can be utilized to assess the improvement of dynamic behavior of the retrofitted structure and the effectiveness of the method of retrofitting.

Keywords: microtremor measurements; finite element analysis; spectral ratio method; predominant frequency; damping ratio; random decrement method

1. Introduction

The study of the response of a structure in earthquake and calculation of internal forces in structural members are the most important topics in design of earthquake resistant structures. Predominant frequency and damping ratio of the structure are main dynamic parameters in these studies. Predominant frequency calculation of a structure can be very important in resonance phenomena surveys (Gosar 2010, Herak 2009, 2011, Cole 1973). For preventing the resonance phenomena, predominant frequency of soil and structure should be calculated and compared, especially in retrofitted structures after retrofitting. Different methods can be used for predominant frequency calculation of a structure such as modeling the structure in software or performing different tests like free and forced vibration of structure (Shingu *et al*. 2004).

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One of the effective factors on dynamic behavior of structure is the energy loss of an oscillating system which is called damping. Many participant mechanisms have effect on damping in a real structure such as: friction in steel connections, opening and closing of microscopic cracks in concrete, friction between structural and nonstructural elements like partitions. The ability of a structure to dissipate energy can be considered by damping ratio. On the other hand, determination of damping ratio which is the most important structural and soil dynamic characteristic in earthquake studies is not possible by using direct methods such as modeling in related software, and also because of difficulties in estimation of this parameter by ordinary experimental methods it is assumed as a constant value in many calculations.

Microtremor measurements and using spectral ratio method to process them is the simplest and the most reliable method for determining soil and structure dynamic characteristics such as predominant frequency and damping ratio. Microtremors are usually generated by environmental vibrations such as wind excitations, traffic, industrial machinery, sea waves etc. Many researchers reviewed, introduced and applied microtremor analysis for these two purposes (Herak 2009, 2011, Cole 1973, Farsi *et al.* 2010, Irie and Nakamura 2000, Nakamura *et al.* 2009). Also Nakamura and Sato (2002) used microtremor measurements for estimating the vulnerability of structures.

Usage of floor spectral ratio (FSR) for determining predominant (natural) frequency of structure was proposed by Gosar (2010) for the first time. Floor spectral ratio (FSR) has been estimated by spectral ratio of horizontal component of acquired microtremor data of structure to ground or free-field. One of the first researchers who worked on damping in tall buildings by using random decrement method (RDM) was Jeary (1986). In later years, researchers such as Davenport and Hill-Caroll (1986), Lagomarsino (1993), Tamura *et al.* (1993), Kareem and Gurley (1996), Arakawa and Yamamoto (2002, 2004), Satake *et al.* (2003) used random decrement and other methods for determining damping ratio. Iiba *et al.* (2004) pointed out that by using random decrement method (RDM) on microtremor data, the damping ratio of the structure can be calculated. Herak (2009, 2011) applied RDM, nonparametric analysis and spectral analysis to derive natural frequencies and damping ratios and also showed that damping ratios and frequencies derived by ambient noise (microtremor) is stable. Farsi *et al.* (2010) showed that natural frequency and damping ratio resulted by combining spectral and RDM analysis depend on strength of building.

Also in many existent and historical buildings, the materials characteristics and also the structural details are not accessible. Then modeling of these structures by finite element softwares is almost impossible, and use of microtremor measurements is very applicable to investigate their dynamic characteristics (Cimellaro and Stefanoa 2014).

In this study an EXPLORATION SEISMOGRAPH PASI 16S-N (24 CHANNELS) instrument is used for microtremor measurements. This device is consisted of a vibration recorder instrument, 3-D sensors, related connector cables to the velocity meter and a power supply. By using 3-D velocity meter sensors, it is possible to record data of the roof and ground (free-field) at the same time.

In this paper, as a case study, the predominant frequency and damping ratio of two four-story buildings by using microtremor measurements and also finite element analysis are evaluated and the effects of retrofitting on these dynamic parameters by FSR and RDM methods (Nakamura *et al.* 2009, Sungkono *et al.* 2011) are studied. These two buildings have totally identical architecture and primary structure on the same soil condition but one of them is retrofitted while the other is not. Further, the effectiveness of the method of retrofitting on increasing the stiffness and improving the dynamic behavior of structure is examined by microtremor measurements.

Fig. 1 The instrument

2. Microtremor measurements

2.1 FSR Method

For determining predominant frequency of structure, the use of horizontal-to-vertical spectral ratio (HVSR) is not recommended (Herak 2009, 2011), although it might be reasonable for frequency estimations in some cases. However, in HVSR method, the natural frequency of ground may affect the building natural frequency. Therefore, spectral ratio of microtremor data between the upper floor and basement (free-field near the building) can be used in each horizontal direction (X or Y) for determining accurate natural (predominant) frequency (Herak 2011, Gosar *et al.* 2010). This method proposed by Gosar *et al.* (2010) which is named floor spectral ratio (FSR) (Herak 2011).

In this research, for spectral analysis, each record is split into 25 s-long non-overlapping windows. A Fast Fourier Transform (FFT) is calculated for each window in each component. Average amplitude spectra for each component are computed from selected windows.

For smoothing the data in the FSR method, two procedures are used: split into windows and Konno and Ohmachi method. The purpose of the first method is to keep the most stationary parts of ambient vibrations, and to prevent the transients often associated with specific sources as footsteps, close traffic, wind, etc. In this procedure each record splits into several windows and detecting of transients is based on a classical comparison between the short term average and the long term average (SESAME 2004). In the second method a logarithmic function uses for smoothing the data (Konno and Ohmachi 1998, Warnana *et al*. 2011).

2.2 Data acquisition and analysis

Data acquisitions are done by using the EXPLORATION SEISMOGRAPH PASI 16S-N (24 CHANNELS) and its related sensors and cables (Fig. 1). The Seismograph is operated by a program based on Windows XP in which the software will start automatically permitting the user manage the acquisitions. It will be possible to carry out acquisitions using 24 channels. Each

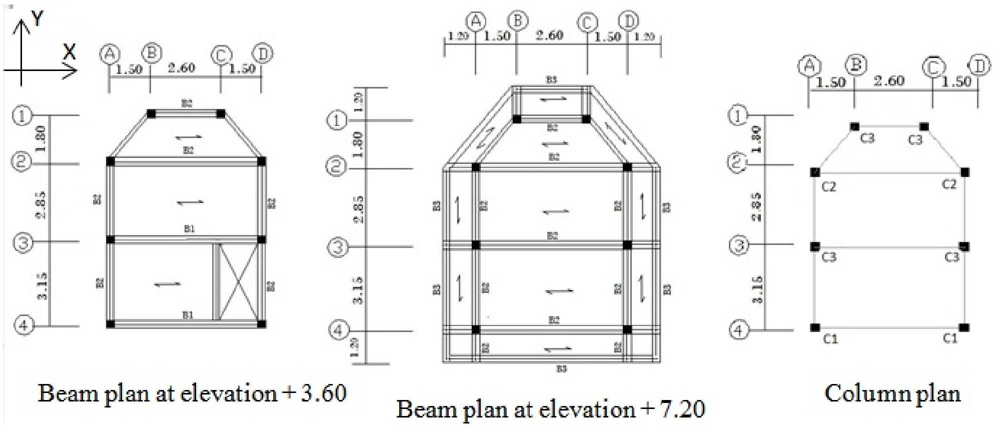


Fig. 2 Beam and column plan in two stories of structure

Fig. 3 View of the structure

geophone (sensor) has two orthogonal horizontal components and a vertical component, which make simultaneous data acquisition in three directions possible. Acquisitions are done in different times in 120 second periods to assure that they are done correctly and extra ambient noise entrance is prevented. The time interval between the data is considered 1 and 2 mili-seconds. Acquisitions are done in the middle of the night and when the dormitories were closed to decrease the effects of environmental noises on the data. The acquisition sampling rate of the velocity meter is adjustable between 500 to 2000 data per second. All the acquired data are expressed according to the FLOATING-POINT notation and processed at 32 bit. The spectral ratio of horizontal component of microtremor data, acquired by using the instrument, of the roof of the structure to the ground (free-field) should be calculated $\left(\frac{H_s}{H_b}\right)$. By drawing this spectral ratio, the first frequency which has the maximum amplitude in the graph shows the predominant (natural) frequency of the structure.

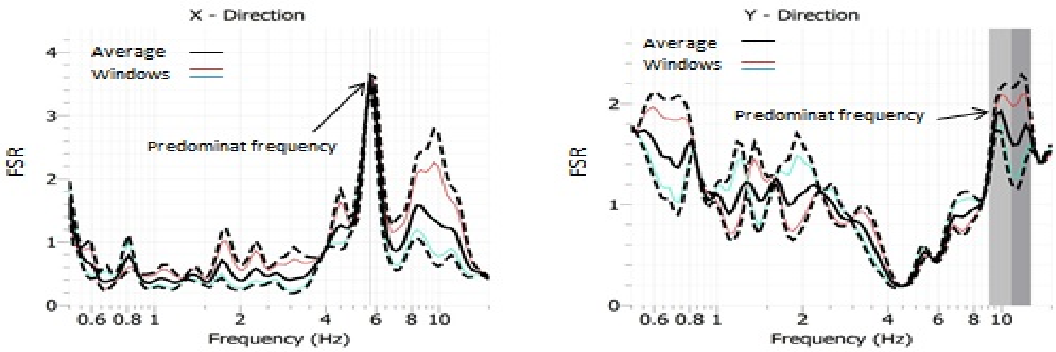
Table 1 Characteristics of beams and columns in the two-story structure

BEAM	B1	B2	B3
	40×30 concrete+6 Φ 20	40×30 concrete+4 Φ 20	30×30 concrete+4 Φ 16
COLUMN	C1	C2	C3
	45×35 concrete+10 Φ 25	45×35 concrete+8 Φ 25	30×30 concrete+8 Φ 25

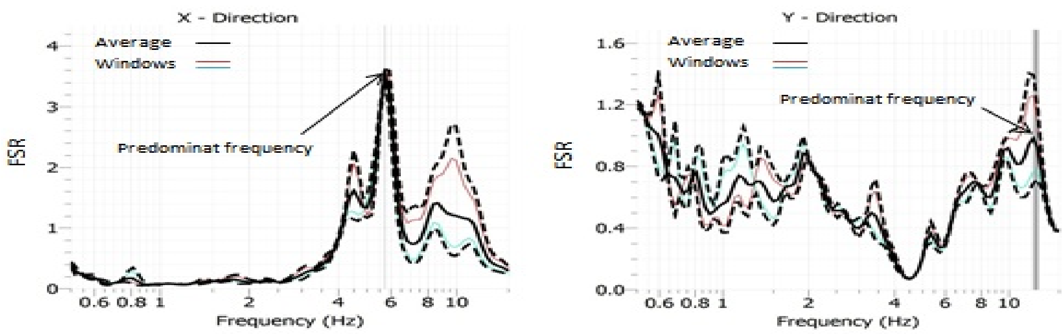
2.3 Comparison of microtremor measurements and finite element analysis

At first, a new constructed two-story concrete building which all the plans and structural details is accessible is selected for checking the accuracy of microtremor measurements. Moment resistant frame with infill panels and some internal partition walls in the second floor which causes increasing the dead load of the structure are some apparent characteristics of this structure. The floors of the structure are concrete block-joist with 25 cm thickness (5 cm slab and 20 cm block) and the height of each floor is 3.6 meters and the total height from base is 7.2 meters. Beam and column plans of the structure are shown in Fig. 2. The view of the structure and structural characteristics of the beams and columns are shown in Fig. 3 and Table 1, respectively.

Structural modeling is done by finite element software. Analyzing the structure in the software

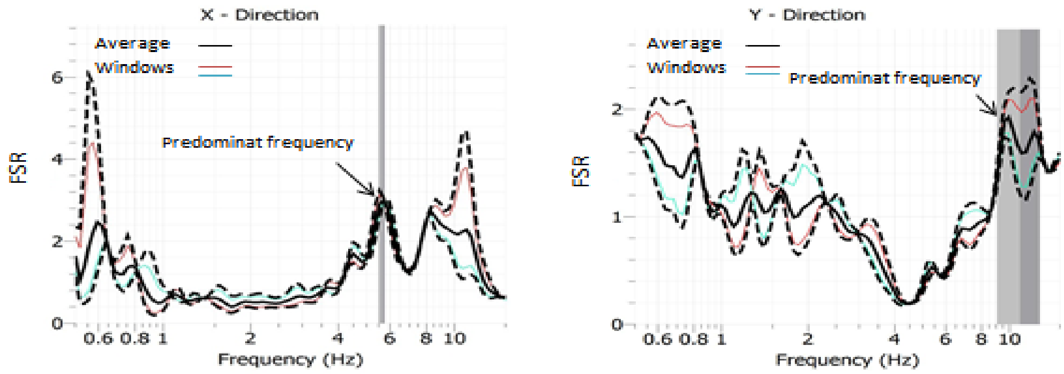


(a) Acquired data number 1

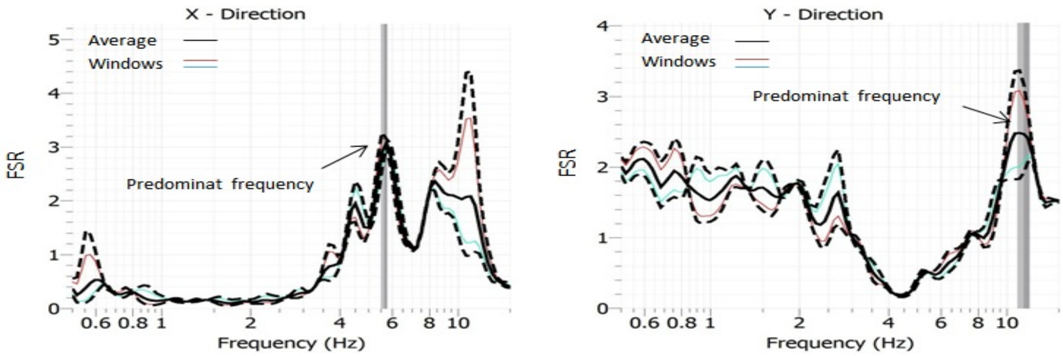


(b) Acquired data number 2

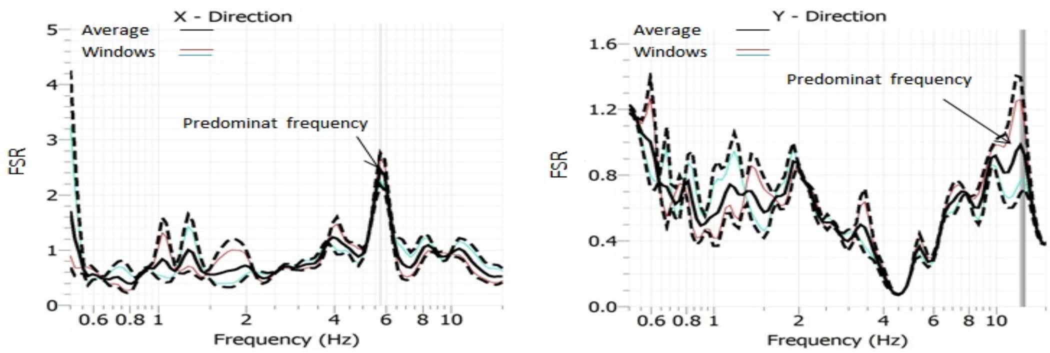
Fig. 4 Graphs of different acquired data



(c) Acquired data number 3



(d) Acquired data number 4



(e) Acquired data number 5

Fig. 4 Continued

shows that vibration frequency of the first and second modes are 5.29 and 9.71 Hz, respectively. The first mode is related to the selected *X* direction and the second mode is related to the selected *Y* direction with regard to the software output.

The acquired data are divided to time windows and the spectral ratio diagram of each window is drawn separately. The desired spectral ratio is acquired by averaging the result of these

Table 2 Predominant frequency of each data acquisition

Number of Acquired Data	*X*-Direction Frequency (Hz)	Y-Direction Frequency (Hz)
1	5.70	10.7
2	5.60	11.37
3	5.65	10.57
4	5.81	10.71
5	5.74	11.41

Table 3 Comparison of the FSR and software results

	X-Direction Frequency (Hz)	*Y*-Direction Frequency (Hz)
FSR method	5.72	11.02
Software	5.29	10.78

windows. The average spectral ratio and spectral ratio of different windows are shown in Fig. 4. Left graphs show the spectral ratio of data in *X* direction and right graphs show the spectral ratio in *Y* direction. The predominant frequency of each acquisition is shown in Table 2.

As it is shown in Table 3, the mean predominant frequency of the acquisitions in *X* and *Y* directions are 5.72 and 11.02 Hz, respectively, which are very close to the results of modeling in the software.

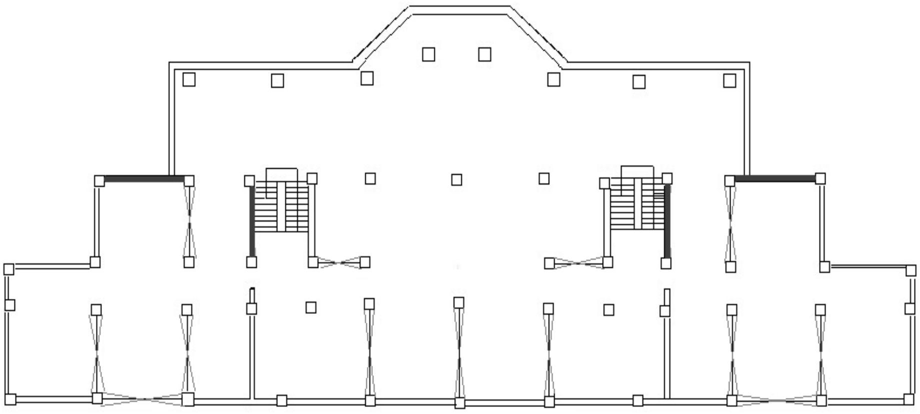
3. Changes of structural dynamic parameters by retrofitting

In this part, by measuring microtremors and using FSR method, the changes on predominant frequency of two constructions are evaluated. These two constructions have totally identical architecture and primary structure, and they have same soil condition, but one of them is retrofitted while the other is not. Also damping ratio of these structures is measured by using random decrement method (RDM) as proposed by (Iiba *et al*. 2004).

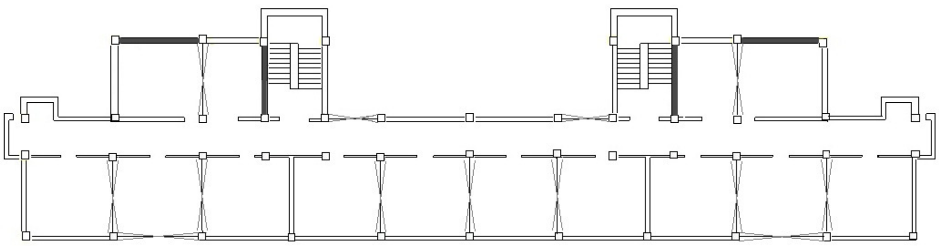
3.1 Characteristics of structures

Constructions illustrated above are four-story steel structures with block-joist roofs and have residential applications (student's dormitory) as shown in Fig. 5. The height of each floor is 3.4 meters and total height from base is 13.6 meters. One of these structures is retrofitted by adding shear walls, *X*-braces and *V*-braces as shown in Figs. 6 (a) and (b) while it did not have any shear walls, *X*-braces or *V*-braces before retrofitting. The structure without retrofitting has only infill panels as resistant members against lateral loads. Simple seated-beam connections (Satchel connections) are used in these structures. Frames with satchel connections should be designed only for vertical loads and do not have good performance in lateral loads. Then lateral loads should be supported by other systems such as braces and this is the main cause of using shear walls, *X*-braces and *V*-braces for retrofitting. Columns in the first and second floor are double IPE180 and in the third and fourth floor are double IPE160 for both structures. In these structures, the beams are double IPE220 that they are located on both sides of the columns. For modeling of masonry infill panels, the SHELL elements with 15000 kg/cm^2 modulus of elasticity are used.

Fig. 5 The view of the structures



(a) The position of columns, shear walls and *X*-braces in the ground floor of retrofitted structure



(b) The position of columns, shear walls and *X*-braces in other floors of the retrofitted structure

Fig. 6 The position of columns, shear walls and *X*-braces in different floors of retrofitted structure

3.2 Microtremor measurements

For sake of decreasing the environmental noises, data acquisitions are done in a totally calm

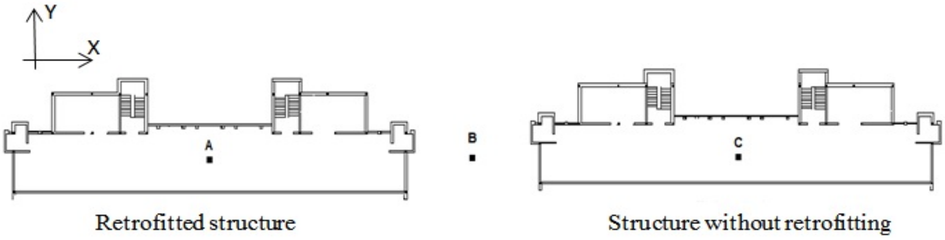
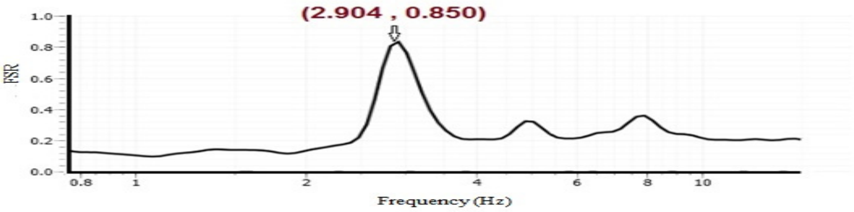
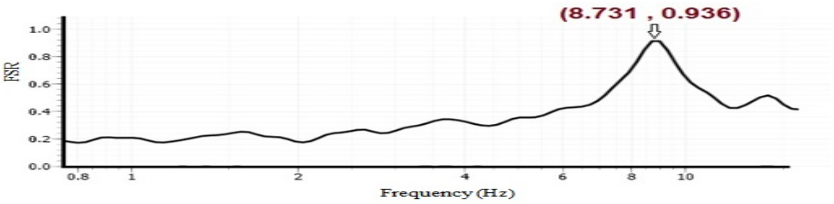


Fig. 7 The position of geophones on the roofs and ground



(a) Calculated frequency by FSR method in the structure without retrofitting in *x*-direction



(b) Calculated frequency by FSR method in the retrofitted structure in *x*-direction

Fig. 8 Calculated frequency by FSR method in both structures

environment (in the middle of the night and when the dormitories were closed). It is essential to measure microtremors on the roof of the structure and ground at the same time for calculating structural dynamic parameters (Herak 2011, Gosar *et al.* 2010). Microtremor records are done simultaneously by using three 3-D geophones on the roof of two structures and ground as shown in Fig. 7. Acquisitions are done in 3 minute periods with 0.002 second intervals.

Fig. 8(a), shows the spectral ratio diagram in *x*-direction for the structure without retrofitting. The predominant frequency and period of this structure are 2.0904 Hz and 0.344 second in *x* direction with regard to this graph. The spectral ratio graph for the retrofitted structure is also shown in Fig. 8(b) for *x* direction, as the predominant frequency and period of this structure is 8.731 Hz and 0.114 second, respectively. It is evident that by adding lateral bracing and so increasing the lateral stiffness in the retrofitted structure, the natural frequency of this structure will be increased. Then by microtremor measurement the effectiveness of the method of retrofitting on increasing the stiffness and improving the dynamic behavior of structure can be examined.

Finite element softwares such as Sap2000 or Etabs2000 can be used for modeling two mentioned structures. The software calculates natural frequencies and periods of these structures. Results of the analysis by finite element software are compared with the results of spectral ratio method in Table 4, which show that they have good compatibility.

Table 4 Comparison of the FSR and the finite element results

		Frequency (Hz)
Retrofitted structure	FSR method	8.731
	Finite element analysis	8.207
Structure without retrofitting	FSR method	2.904
	Finite element analysis	2.686

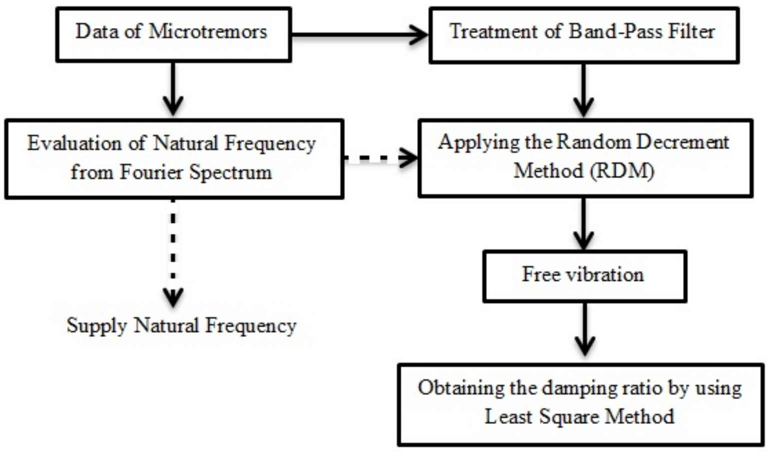


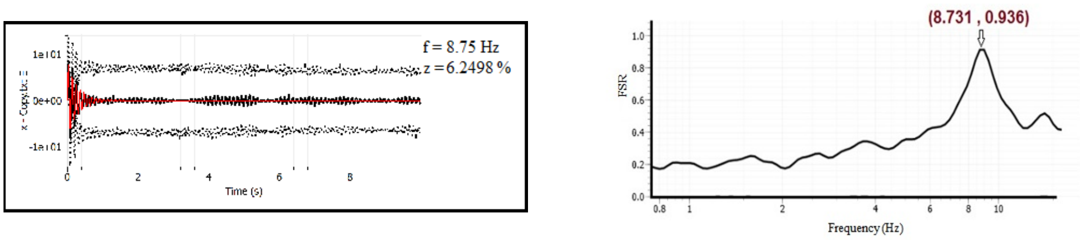
Fig. 9 The algorithm for calculation of damping ratio by using RDM method Modified by Iiba *et al.* (2004) (Sungkono *et al.* 2011)

4. Calculation of damping ratio by Random Decrement Method (RDM)

Damping is a mathematical approximation to present the energy loss in the structure. In fact, the energy loss mechanism is difficult to model accurately because it is function of many parameters such as: viscous effects (dashpot, shock absorber), external friction (slippage in joints), internal friction (characteristic of materials) and structural nonlinearities. But it generally is possible to determine an appropriate equivalent viscous damping (velocity proportional) by experimental methods (Clough and Penzien 1995). For this purpose, the experimental method of microtremor measurements is used in this paper.

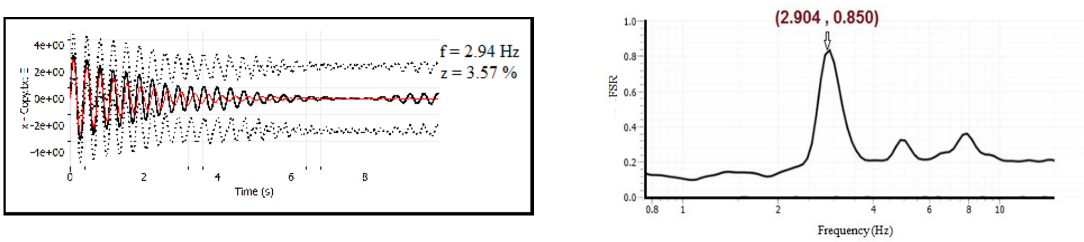
Damping ratios are evaluated by employing RDM method. A band pass filter is used before processing with RDM. Parameters of filter are arranged according to predominant frequency resulted from FSR method. For calculating damping ratio, natural frequency of structure is needed (Iiba *et al.* 2004). Thus, structure spectrum and RDM should be used simultaneously. Fig. 9 shows the algorithm of finding damping ratio.

Dunand *et al.* (2002), pointed out that by increasing natural frequency, damping ratio will be increased, too. So, for checking the reliability of damping ratio of building, natural frequencies resulted from FSR and RDM must be close. If it is not close, analysis for calculating damping ratio should be repeated. If we use the SESAME (2004) software and conventional methods to analyze the microtremor data, the RDM cannot identify damping ratio of multimode and just estimate damping ratio of primary natural frequency or fundamental natural frequency (Sungkono *et al.*



(a) (b)

Fig. 10 (a) Damping analysis using RDM on *X* direction in the retrofitted structure (b) FSR on *X* direction in retrofitted structure.



(a) (b)

Fig. 11 (a) Damping analysis using RDM on *X* direction in the structure without retrofitting (b) FSR on *X* direction in the structure without retrofitting

2011). But by using other software or the other method of analysis this purpose may be done (Nagarajaiah and Basu 2009, He *et al.* 2011).

Fig. 10(a) and 11(a) present damping analysis using RDM on *X* direction in the retrofitted structure and the structure without retrofitting, respectively, in which solid black line is the mean and dashed black line is the standard deviation of RDM, and also solid red line shows the fitted exponential decreasing function. The comparison between predominant frequencies of both structures is also shown in Fig. 10(b) and 11(b). For retrofitted structure, the natural frequency (f) identified by RDM is 8.75 Hz and by FSR is 8.731 Hz, and for structure without retrofitting are 2.94 and 2.904 respectively. It can be seen that the natural frequencies resulted by RDM and FSR methods are very close for fundamental mode. The frequencies are about 8.75 Hz for the retrofitted structure and 2.94 Hz for structure without retrofitting. The damping ratios (z) are calculated 6.25% for retrofitted structure and 3.57% for the structure without retrofitting which shows that by increasing natural frequency the damping ratio will be increased.

5. Conclusions

Determination of structural dynamic characteristics is very important in estimating the structural response against earthquake. Different theoretical and experimental methods are applicable for determining predominant frequency and damping ratio of soil and structure such as rope-cut or impact (force) vibration experiments but each of them needs special conditions and using them is not simply possible. As shown in this study, microtremor measurements and spectral ratio method and random decrement method can be a reasonable replacement for common method of determining predominant frequency and damping ratio. Also comparison the frequencies obtained by finite element analysis and the results of microtremor measurements shows that they have good compatibility.

By comparison the results of microtremor measurements for the structure without retrofitting and retrofitted structure, the improvement of dynamic behavior and the effectiveness of the method of retrofitting, can be realized.

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