BUILDING MONITORING FOR SEISMIC RISK ASSESSMENT (II): INSTRUMENTAL TESTING OF RC FRAME STRUCTURES AND ANALYTICAL REINTERPRETATION OF RESPONSE CHARACTERISTICS

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ABSTRACT :
A joint research program by the Bauhaus-Universität Weimar (Germany), Mustafa Kemal University (Turkey) and Middle East Technical University (Turkey) has been in progress since 2005. The project is concerned with vulnerability and loss estimation studies for the earthquake preparedness of Antakya (current population 200,000), sited on the Dead Sea Fault System in the Eastern Mediterranean, and in close proximity to the East Anatolian Fault System. The ancient town, founded in 300 BC, has been an important confluence of states, faiths and peoples from its earliest times, and has suffered many major earthquakes. The city of Antakya has experienced a rapid population growth during the last 25 years, and many new buildings have been built, generally displaying architectural and structural similarities. Forced vibration tests have been conducted on two eight-storey representative RC frame buildings. The excitation is provided via an eccentric mass vibration generator. Sweeping the frequency of the vibration generator through a range including the natural frequencies of the structure and then recording the steady-state response of the structure at each operated frequency, response resonance curves are obtained. For different locations of each building the acceleration and displacement amplitudes are determined. The experimental data are compared with analytical results from the 3D structural models and a good aggrement is obtained.

KEYWORDS:
earthquake, forced vibration tests, loss estimation, Antakya region, RC frame buildings

1. INTRODUCTION

Knowledge of the behaviour of civil structures under seismic excitation is of great interest in earthquake-prone areas (Lus and Longman, 1999, Benedetti and Gentile, 1994, and Schwarz et al., 2007). For this reason many countries have equipped buildings with continuously monitoring systems in order to record the possible response of the structures during earthquakes. Before the occurrence of an earthquake, it is important to determine the parameters such as natural frequencies and mode shapes related to the dynamic response of the buildings. These parameters can be determined by mathematical models used in the dynamic analyses of structures. These mathematical models are idealizations required to represent the response of real structures to various dynamic loads (e.g. strong eartquake shaking, strong winds, forced vibration, blast etc.). The determination of the necessary parameters for the verification of the models are usually obtained by means of forced or ambient vibration tests (Hudson, 1970, Trifunac and Todorovska, 1999, Beolchini and Vestroni, 1997, and Vestroni et al., 1996). In Turkey, forced vibration testing started in 1976. Earthquake Engineering Research Center of the Middle East Technical University (METU/EERC), started a project to survey the dynamic

characteristics of several structures and apply the results to the Turkish Earthquake Resistant Design Code in 1976 (Celebi et al., 1977). In 2002, Celik (2002) tested two buildings to define their vibration characteristics.
Comparing with ambient vibration tests, forced vibration tests require larger forces to produce useful response amplitudes of full-scale structures. This force is produced by shaker (See Fig. 1.a). The force is usually applied from top layer of the building. This leads to more prominent excitation of the modes of vibration that have large amplitudes at the higher levels of the structures. However, the paths of the waves propagating trought the structure are different from those in case of earthquake shaking and wind excitation. During the interpretation of the results, consideration of such differences requires caution (Genovese and Vestroni, 1998, and Luco et al., 1987).
The presented study is a work package of the project entitled as “Building Seismic Characteristics, Vulnerability and Loss Estimation for the Earthquake Preparedness of Antakya”. This package is related to Reinforced Concrete (RC) frame structures, i.e. the predominant building type in most cities of Turkey, Greece and other countries where the structural system and arrangement of the frame must be considered as irregular. From damage surveys of recent earthquakes and the extent of observed structural damage, it may be concluded that RC frame structures may exhibit increased vulnerability and that – besides their sensitivity to design defects, workmanship and detailing construction – general design assumptions and refined analysis alone might be misleading with respect their response characteristics including the interaction between structural elements and infill walls. Despite the fact that in some cases the damage could be reinterpreted and reassessed, the discrepancies between numerical results following strictly the basis input data from structural layout and planning documents and measures quantities, indicate the need of an extended approach using instrumental data in a more systematic way to understand the transmission of seismic forces to the foundation system.
In this paper, forced vibration tests that have been conducted on two newly constructed 8-story typical representative RC frame buildings in Antakya are described. Sweeping the frequency of the vibration generator through a range including the natural frequencies of the structure and then recording the steady-state response of the structure at each operated frequency, response resonance curves are obtained. For different locations of each building the acceleration and displacement amplitudes and mode shapes are determined. The experimental data are compared with analytical results obtained from the 3D structural models.

2. DESCRIPTION OF THE BUILDINGS

2.1. Eight-Storey RC Building I (RCB-I-8s)

The first structure under study is an eight-storey (basement + 7 storeys) RC frame building **(RCB-I-8s)** built to serve as a residential building on the south side of Antakya (Fig. 2). The plan dimensions are 30.70 x 14.30 m with a height of 22.90 m from the foundation or 20.30 m from the ground level. Storey heights from the basement storey to the seventh storey are, respectively, 2.6, and 7x2.9 m. The building also has a penthouse with a height 2.7 m above the eighth storey. The structural system consist of four shear walls in each direction and also one core around the elevator. Fig. 3 shows the plan with the columns, shear walls, core and the beams of the system. The plan is structurally symmetric according to the horizontal axis (E-W direction).

Figure 1 The shaker


Figure 2 Eight-storey RC building I

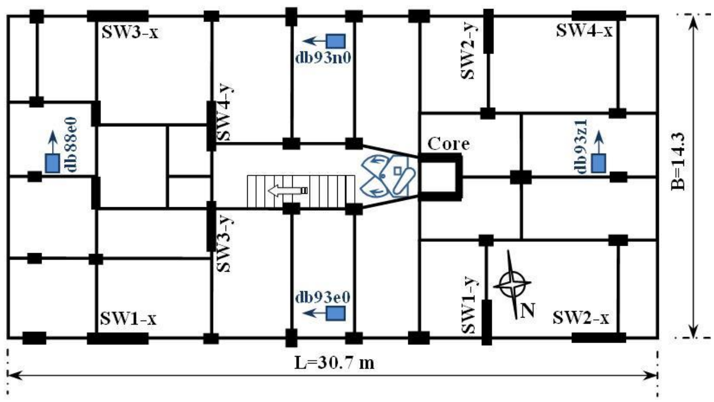

Figure 3 Plan of eight-storey RC building I

The floor system is RC slab. The used concrete is C25 (25 N/mm^2) and the reinforcement is S420 (420 N/mm^2). The interior and exterior walls are made of hollow core clay blocks. The foundation type is mat foundation. The building sits on granular soil with 1.6 N/mm^2 "allowable" strength, and 0.53 s effective period.

2.2.Eight-Storey RC Building II (RCB-II-8s)

The second structure under study is again an eight-storey (basement + 7 storeys) RC frame building **(RCB-II-8s)** built to serve as a residential building in the north side of the Antakya (Fig. 4). The plan dimensions are 30 x 19 m with a height of 24.15 m from the foundation or 21.50 m from the ground level. Storey heights from the basement storey to the seventh storey are, respectively, 2.65, 5.6, and 6x2.65 m. The ground level storey is divided to two storeys through a mezzanine.

The building also has a 2.65 m high penthouse at the top. The structural system consist of two shear walls in the short and four shear walls in long directions, and also two cores around the elevators. Fig. 5 shows the plan with the columns, shear walls and the beams of the system. The plan is structurally symmetric according to the both horizontal and vertical axes (Fig. 5). The floor system is RC slab. The concrete used is C25 (25 N/mm^2) and the reinforcement is S420 (420 N/mm^2). The interior and exterior walls are made of hollow core clay blocks. The foundation type is mat foundation. The building is settled on a soil has a 2.0 N/mm^2 allowable strength, and 0.3s effective period.

3. FORCED VIBRATION STUDY

In the early models of vibration generators, by varying the amount of weight in rotating baskets, the eccentric moment and thus the maximum force output could be changed. In this study, because of the available exciter is one of classical design (Model VG-1, product of Kinematics Inc.) the force is applied by placing various numbers of lead weights in the baskets (Fig. 1.b). The *x*-components of the inertia forces of the rotating masses cancel out, and the *y*-components combine to produce a force

$$p(t) = (m_e e\omega^2)\sin\omega t \qquad (3.1)$$

where, m_e is the total mass in the baskets, e is the distance between the mass and rotating center, ω is the exctation frequency. This force is transmitted to the structure by bolting the vibration generator to the structure (Fig. 1.a). The amplitude of this harmonic force is proportional to the square of the excitation frequency ω. For this reason, it is not possible to generate much force at low frequencies for RC buildings.

Figure 4 Eight-storey RC building II

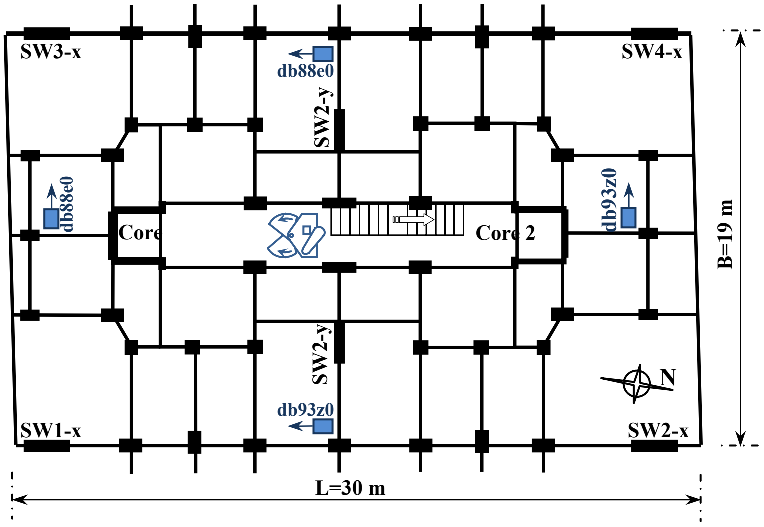

Figure 5 Plan of eight-storey RC building II

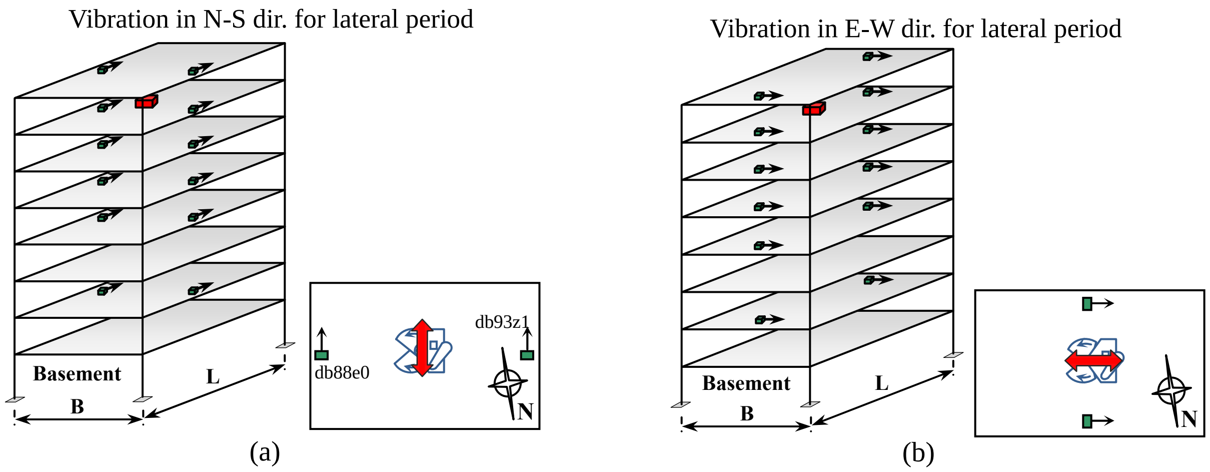

Figure 6 Accelerometer arrangements and shaking directions of **RCB-I-8s**

The vibration generator used in these tests has a working frequency of 0 to 9.7 Hz and is capable of producing a sinusoidal force with maximum amplitude of 22 kN. It has two baskets and each basket can be loaded with up to 180 kg of lead weights (Fig. 1.b). During the tests of the buildings each basket is loaded with 90 kg weights to be able to generate a maximum excitation frequency 3.4 Hz.
In this study, for both test buildings, the forced vibration studies were carried out when the RC frames, floor slabs and concrete for five stories walls had been poured. During the frequency vibration tests at a given frequency both the applied load and the response are theoretically sinusoidal with the same frequency. However, during the tests at both buildings, the workers had been constructing the walls of the fifth storey, changing the stiffness slightly during the course of the test. The treatment of the recorded data is carried out by eliminating some noises from electrical, mechanical and ambient sources.
The data acquisition system consisted of 12 single-axis feedback acceleromets and one acquisition unit. The locations of the sensors (Figs. 6,7) were selected in order to determine the first dominant lateral vibration periods in both directions (N-S and E-W) and the torsional period of the RCB-II-8s. Figs. 6 and 7 show the placement of the accelerometers in the RCB-I-8s and RCB-II-8s, respectively.

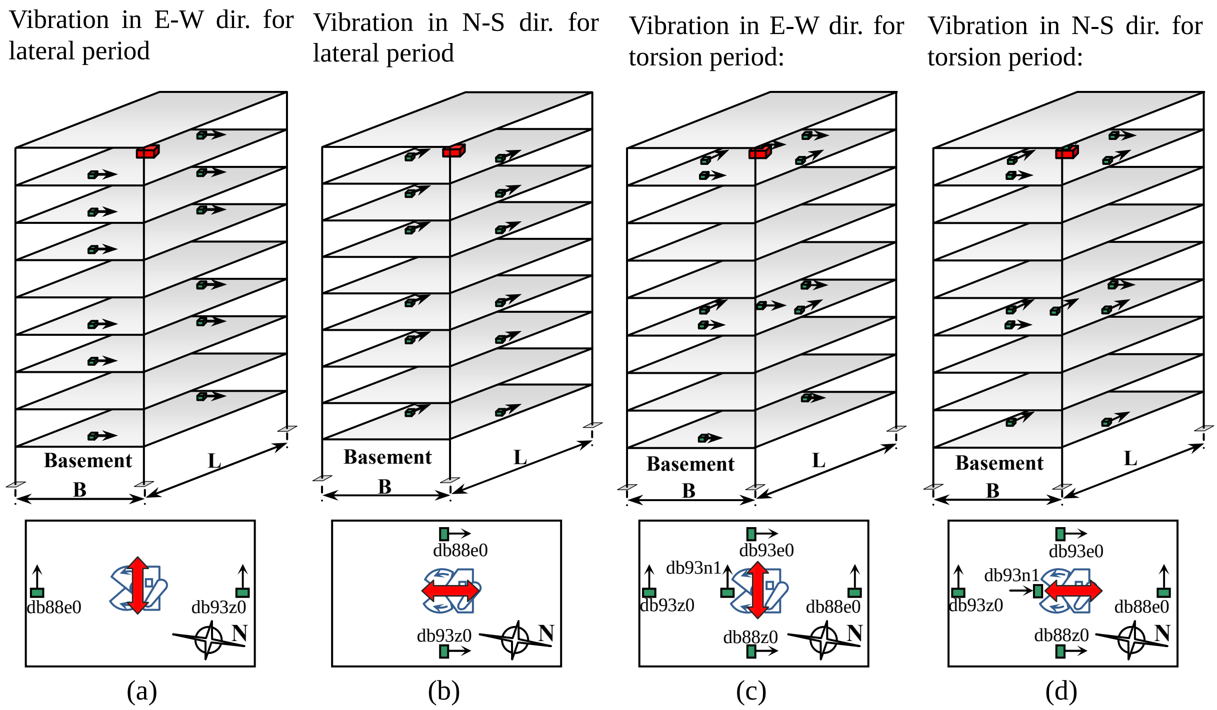

Figure 7 Accelerometer arrangements and shaking directions at eight-storey **RCB-II-8s**

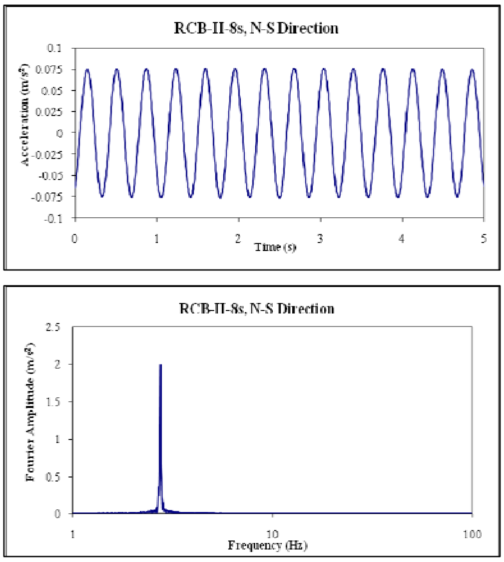

Figure 8 Acceleration-time record and Fourier spectra for **RCB-II-8s**

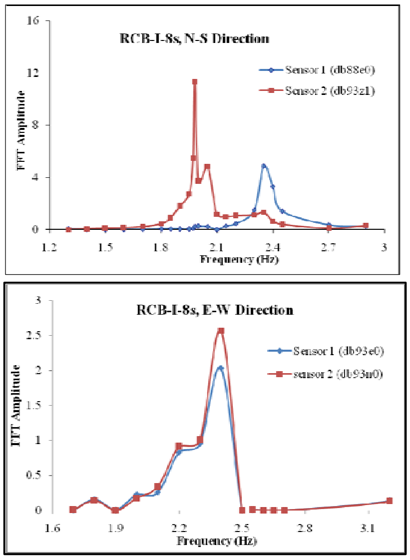

Figure 9 Acceleration-frequency response functions for the sensors at the top of **RCB-I-8s**

For building RCB-I-8s, all the accelerometers were symmetrically located on both sides of the floor center of mass in the E-W and N-S directions and distributed to the building floors as in Fig. 6 a and b.

For building RCB-II-8s, at first all the accelerometers were symmetrically located as in RCB-I-8s and distributed among the building floors as in Fig. 7 a,b. Then, two parallel accelerometers were located on both edges and one at the center of the mass in E-W direction, and two on the both sides in the N-S direction at the mid and top storey floors as shown in Fig. 7 c. Also two accelerometers were located at both sides of the ground level floor center of mass in E-W direction. After that, the directions of the accelerometers on the mass center were modified from the previous arrangement by shifting from N-S to E-W direction, and the two at the ground level floor were shifted as shown in Fig. 7 d.

The floor where the shaker was placed considered as the reference floor for all the arrangements. The recording process was started, when the vibrations were monitored from the accelerometers instrumented at this reference floor harmonic with constant amplitude. The recording period was 120 s for the RCB-I-8s and 20 s for the RCB-II-8s.

The data processing was performed using both the Seismosignal (SeismoSoft, 2002) and Matlab softwares. Fig. 8 shows typical records and corresponding Fourier amplitudes obtained from the vibration of the test building RCB-II-8s in the direction of N-S at the resonance vibration frequency.

The resonance frequencies were determined to within 0.1 Hz accuracy of the shaker frequency. The vibration amplitude in each case was determined from the difference between the upper and lower peak of the acceleration response curve. With frequency and accelaration response amplitude calculated, the amplified displacement response curve could be determined. The recorded acceleration due to this force is also dependent on frequency squared and should be divided by the square of the frequency at each point for the normalized acceleration response.

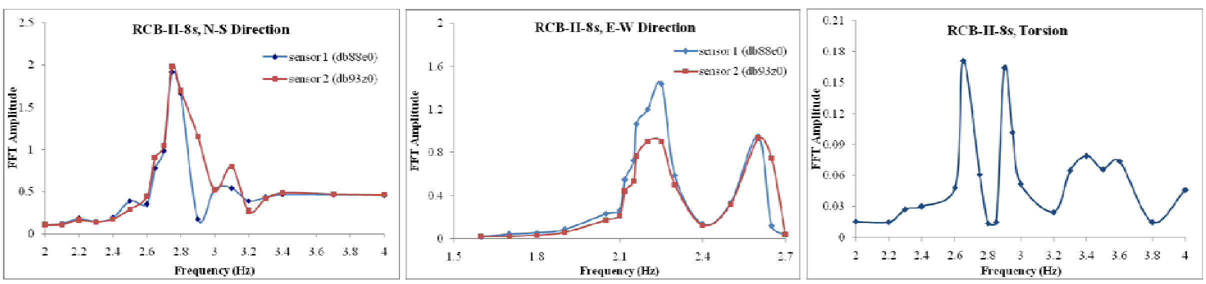

Figure 10 Acceleration-frequency response functions for the sensors at the top of **RCB-II-8s**

Also, similar relationship could be obtained as Fast Fourier Transform (FFT) amplitude-frequency response curves. Some typical curves of the top acccelerometers of both test buildings are shown in Fig. 9,10. These curves were used for the determination of resonant frequencies, damping ratios, and mode shapes. In these curves, peak amlitudes that correspond to resonance frequencies are used to obtain damping ratios based on half-power method. In order to find mode shapes at each resonance frequency of the buildings, the ratio of the displacement amplitudes in tests for the 1st and 2nd arrangements were used. The natural frequencies of vibration and the damping ratios thus determined are listed in Table 1.

4. MODELING AND ANALYSIS OF THE STRUCTURES

The structures were modeled and analysed by standard software. The program can perform linear analysis of 3D models. The systems were modeled three-dimensionally by columns, beams, shear walls and slabs. The infill brick walls were also modelled as compression struts. Because of slab continuity, the rigid body diaphram assumption was taken into account by defining the three main structural degrees of freedom at each floor as two translational and one rotational. The slabs are modeled as deck. The following modeling asumptions were made for the buildings: (a) Linear elastic material properties were used for 3D modal analysis; (b) The frames are fixed at the base of the columns and soil-structure interaction is neclected; (c) The floor diaphrams are rigid in their own planes and flexible normal to their planes; (d) The weight of columns is negligible in modal analysis; and (e) at each floor, all the mass is concentrated at the geometric center.
The resulting vibration periods of the dominant modes obtained from eigenvalue analysis are listed in Table 1 for the first and second test buildings. In order to plot mode shapes with the same units, the ordinates of the torsional mode shapes were multiplied by 7.0 and 9.5 m, the distances from floor center of mass to the first perimeter column in N-S and E-W direction of the RCB-I-8s and RCB-II-8s, respectively.

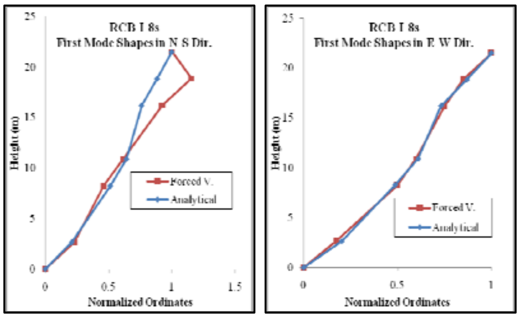

Figure 11 First mode shapes in N-S and E-W directions of **RCB-I-8s**

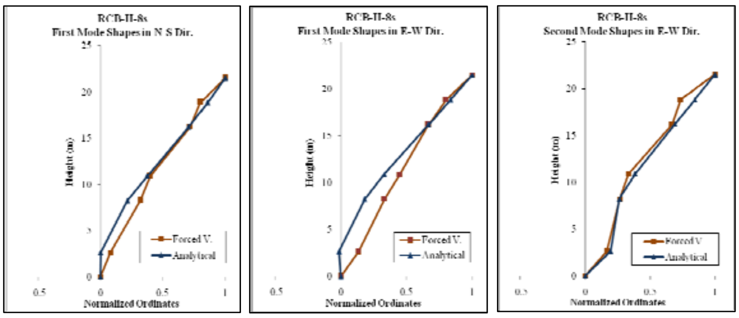

Figure 12 First mode shapes in N-S, first and second mode shapes in E-W directions of **RCB-II-8s**

Table 1 Natural vibration periods obtained from vibration tests and analytical modeling of **RCB-I-8s** and **RCB-II-8s**

Building	Mode	Mode Type	Analytical I (a) Without Walls (as mass)	Analytical II (b) Walls Modeled as Compression strut	Test (c) Forced Vibration	Differencies (a-c)/c %	Differencies (b-c)/c %
RCB-I-8s	1	N-S Translation	0.76	0.55	0.51 (2.0)	51.07	8.26
	2	E-W Translation	0.61	0.36	0.42 (1.4)	45.33	-13.18
	3	Torsion	0.65	0.47	0.43	52.32	10.72
RCB-II-8s	1	E-W Translation	0.48	0.41	0.45 (2.8)	6.14	-11.59
	2	E-W Translation	------	0.39	0.38	------	0.25
	3	N-S Translation	0.48	0.38	0.36 (2.3)	32.23	3.62
	4	Torsion	0.32	0.29	0.34	-5.19	-14.94

Values in parenthesis are damping ratios

5. DISCUSSION

The dynamic characteristics of the test buildings, i.e., natural frequencies, modes of vibration, and associated damping capacities, were determined. Because of an unexpected problem in the low voltage of the electricity supply of the city, it was only possible to excite the RCB-I-8s around its first translational mode in E-W and N-S directions, and RCB-II-8s around its first and second translational modes in E-W and first translational mode in N-S directions. Free vibration analysis of both structures were carried out to estimate these dynamic characteristics except the damping capacities (Table 1). The analytical results are obtained from the building models without the structural effect of the walls (only the mass is considered), and with the effect of the walls on the system stiffness matrix of the buildings. The mode shapes resulting from the forced vibration test is very close to that due to analytical modeling results and this agreement indicates that the modeling with walls modeled as compression strut is acceptable with respect to the mode shapes (Figs. 10 and 11).
Including the nonstructural walls in the model of RCB-I-8s and RCB-II-8s as compression strut reduces the fundamental periods considerably from 0.76 s to 0.55 s in N-S direction and from 0.61 s to 0.36 s in E-W direction, and from 0.48 s to 0.41 s in E-W direction and 0.48 s to 0.38 s in N-S direction, respectively. Comparing with experimental results, for RCB-I-8s, these values are in aggrement with 8.29 % in N-S and 13.18 % in E-W directions, and for RCB-II-8s, these values are in aggrement with 3.62 % in N-S and 11.59 % in E-W directions. For RCB-I-8s, free vibration analysis results show that the second mode natural frequencies in N-S and E-W directions are 6.43 Hz and 7.42 Hz, respectively. For RCB-II-8s, the second mode natural frequencies in N-S and E-W directions are 8.77 Hz and 2.59 Hz, respectively. Except the natural frequency in E-W direction of RCB-II-8s, these frequencies are beyond the limit of the vibration generator. It could be possible to get the second resonant frquencies if the frequency of the vibration generator could further be increased with empty baskets. However, the low voltage of the electricity supply did not allow continuing to the tests under high frequencies.
The RCB-I-8s was excited almost through the geometric center. However, during the shaking in the N-S and E-W directions, some torsional motions were observed. Response recorded by sensor 2 was greater than that recorded by sensor 1 in both directions (see Fig. 9). It is concluded that torsional motions were due to the locally distributed materials (i.e. piles of cement, sand, and brick) for constructing walls of the fifth and sixth storeys.
The RCB-II-8s was also excited through the geometric center. In this building torsional motions observed during the shaking in E-W direction. The responses recorded by sensors 1 and 2 in N-S direction were compatible with each other (see Fig. 10). It is concluded that the torsional motions were due to the ground level plan which is partially divided to two storeys.

6. CONCLUSIONS

Two vibration tests were conducted with the scope of the work package of the project entitled as "Building Seismic Characteristics, Vulnerability and Loss Estimation for the Earthquake Preparedness of Antakya". The first and second tests were performed on eight storey RC residential buildings. Frequency response curves in the form of acceleation amplitude and normalized displacement amplitude versus excitation frequency were determined. Natural periods and mode shapes for the first and one second modes of these structures were determined, too. These results were then compared with the results obtained from the analysis of 3D models of the structures. Moreover, modal damping ratios, which can not be computed directly from the structural properties or as a result of structural analysis, were also determined. Experimentally and analytically obtained first modal frequencies of both buildings are compatible with each other. The close agreement between experimental and analytical results is mainly due to the good accuracy of the analytical model obtained with considering the infill brick walls as compression strut. When only the mass of brick walls is considered, and the structure is modeled as 3D model compose of column, shear wall, beam and slab, the agreement with the experiment is poor (see Table 1). With these forced vibration tests, limited data obtained about the predominant building type, and some more tests have to be handled in the city of Antakya to have accurate layer of data for *vulnerability and loss estimation* before a earthquake. For this purpose, a joint project between Germany and Turkey is started in June 2008. The project is entitled as "Damage and seismic response prognosis for RC frame structures on the basis of hybrid approach combining instrumental and numerical data".

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