Numerical Simulation of Shaking Table Test of a RC Shear Wall Structure with Torsional Irregularity

Saeideh Nazirzadeh, Vesile Hatun Akansel & Ahmet Yakut
Middle East Technical University, Ankara, Turkey.

SUMMARY:
In this paper, 3D behavior of a ¼ scaled 3 story RC shear wall structure is investigated under different bi-directional seismic excitations applied through AZALEE shaking table at CEA facilities in Saclay, France. The main objective is to obtain an analytical model of the tested mock-up such that the experimentally observed and measured response could be matched by a reasonable accuracy. The model building has been tested under a set of ten synthetic and three real ground motions that have varying intensities; peak ground accelerations ranging from 0.1g to 1g. Displacements and accelerations measured at different locations on the plan at third story were compared with the numerically computed values in order to check the validity of the Finite Element Model that has been obtained in ANSYS ver. 12.1. Comparisons indicated that modeling all components of experimental set up such as shaking table has a significant influence on the results.

Keywords: Non-linear modeling, Shaking Table, Shear Wall Structure, Finite Element Method, ANSYS.

1. INTRODUCTION

Simulating the non-linear response of reinforced concrete (RC) buildings subjected to a sequence of input earthquake records, is an extremely complex concern in the field of the Earthquake Engineering. Buildings with no symmetry in plan have much more complicated behavior under earthquake effects than symmetric buildings. Torsional irregularity in plan is the main topic of many current researches. In previous decades, considerable amount of numerical and experimental studies have been conducted, but more researches are needed in order to confirm a better understanding of the concept of seismic behavior of these structures. This study is the complementary to the benchmark contest Phase 1b of the SMART 2008 (Seismic design and best – estimate Methods Assessment for Reinforced concrete buildings subjected to Torsion and non – linear effects) project. This structure was a highly idealized ¼ scaled mock – up of a French shear wall nuclear power plant structure component. It was subjected to the AZALEE shaking table tests in which different seismic excitation simulations were carried out in Saclay, Paris, in France under the leadership of Commissariat Energie Atomique (CEA). Experimental behavior of the mock-up has been simulated through numerical modeling and analyses. For time history analysis, micro-modeling is preferred due to giving permission to include the nonlinear effects of the concrete and steel for analysis. The response parameters (acceleration and displacement) obtained from analytical results were compared with the values measured in experiments to be able to test the validity of models and simulation.

2. LITERATURE REVIEW

Review of analytical methods for static and dynamic calculations for the design of shear wall buildings returns to the 1960's. Due to low speed and capacity of computers, researchers were forced to use simplified methods and hand calculations in design offices (Khan and Sbarounis, 1964). With progression of technology of computers, after the 1960's, a large amount of substantial analytical and experimental research, executed all through the world, using commercial software based on finite element methods. Those researches, collected many practical information on the earthquake response of shear wall structural systems. Also, starting from 1950's a considerable body of information was assembled on performance of buildings in actual earthquakes. The most general method that is used for simulating the behavior of RC elements using micro-modeling, is finite element method. The FEM is powerful tool for the analysis of RC structures, including three-dimensional and nonlinear analysis. The FEM of analysis is capable of tracking the member's global behavior (e.g. member forces and displacements) in addition to its local behavior (e.g. crack pattern, material stresses and strains). Many researchers have used micro modeling approach to simulate the experimental measurements (Kwak and Kim, 2004; Palermo and Vecchio, 2007). Macro-modeling represents the overall behavior of the RC element. The global behavior of the RC element using a macro-model should be calibrated using an experimental verification to adjust the parameters needed for the model (Ile and Reynouard 2003, 2005; Kazaz et al, 2006; Ile et al., 2008; Fischinger and Isakovic, 2000; K.Galal and H. EL-Sokkary, 2008). ANSYS, ABAQUS, VecTor 2 and 3, ADINA and DIANA are some of the finite element softwares.

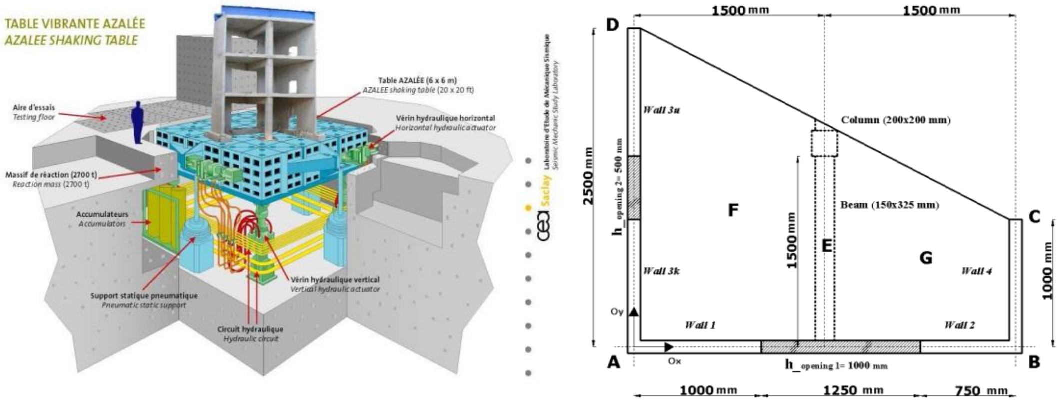
Many shaking table tests have been performed to evaluate the inelastic seismic response of lightly reinforced concrete wall, and a modeling strategy and numerical modeling for RC walls was proposed. Jingjiang et al. (2007) performed earthquake simulator tests of a RC frame-wall model and compared the analytical and experimental results, and presented conclusions related to seismic design and damage evaluation of RC structures. Kim et al. (2002) performed the shaking table test of a six-story building with a weak/soft story having torsional irregularity at the first story. Palermo and Vecchio (2002) studied the behavior of three-dimensional reinforced concrete shear walls under static cyclic displacements. Shaking table tests for full-scale seven-story RC wall structures and six-story RC wall frame buildings were performed by using large shaking tables in USA and Japan, respectively. Several previous studies by the authors were conducted to investigate the seismic response of the three individual building models having different layouts of the vertical earthquake-resistant elements in the lower soft stories. (Lee HS et al. 2007). The effect of torsion and the seismic behavior of a lightly reinforced wall specimen under bi-directional loading was reviewed by Ile and Reynoaurd (2003). The dynamic performance of two reinforced concrete buildings tested on a shaking table during the CAMUS 2000 experimental research program was simulated using two different simplified modeling strategies (a fibre and a beam model) and two resolution schemes (implicit and explicit, respectively) by J.Mazars et al. (2004). Ile et al. (2004) compared numerical and experimental results of the U-shaped walls subjected to lateral cyclic loadings applying the shell refined model . Two structures, considering the "multifuse" and "monofuse" concept, using Bernoulli multi-layered beam elements and advanced constitutive laws based on damage mechanics and plasticity, were simulated, CAMUS I and CAMUS III, in order to test the ability of the proposed numerical tools, (Spatial and time discretization, modeling and damping mechanism and materials constitutive relations) to simulate the non-linear behavior of the structures following different design philosophies (Kotronis et al. 2005). They also conducted dynamic shaking table tests on AZALEE shaking table. Kazaz et al. (2006) using ANSYS simulated the seismic response of a 5-story RC shear wall specimen on shaking table subjected to progressive damage under sequence of ground motions. Dynamic interaction between the shaking table and the structure has been studied by Le Maoult et al. (2010). They demonstrate that most of the interaction for AZALEE shaking table is due to the platform deformation during the tests.

3. MODEL BUILDING AND EXPERIMENTS

In the interest of assessing the seismic three dimensional effects (such as torsion) and non-linear response of reinforced concrete buildings, Commissariat à l'Energie Atomique (CEA) and Electricité de France (EDF) has launched in 2008 the "SMART-2008" international project (*Seismic design and best-estimate Methods Assessment for Reinforced concrete buildings subjected to Torsion and non-linear effects*). A reduced scaled model (scale of 1/4th) of a nuclear reinforced concrete building was tested on the AZALEE shaking table at Commissariat à l'Energie Atomique (CEA Saclay, France). In the present study, Phase 1B of the SMART-2008 project has been studied. The objectives of the Phase 1B are to investigate the efficiency of the model in the non-linear range through the comparison with the experimental results and to adjust the model in order to match the experimental response of the specimen under different seismic loadings. The primary objective of this study is to obtain a valid and adequate model that can simulate the experimental response of the specimen. For this reason, two models were generated. In the first model, the effect of shaking table was ignored and the base of the specimen was considered as fixed. In the second model, the shaking table was also included in the model. In order to check adequacy of the model, first experimentally obtained modal properties that is modal frequencies were compared with numerical ones. Then, displacement time histories and response spectra computed at different points on the third floor were compared.

3.1. Structural Properties

The specimen is a three story shear wall structure with, 1.25 m, 1.2 m and 1.2 m story heights. The geometrical properties of the specimen and the shaking table representation are given in Fig. 3.1. Response parameters (accelerations, displacements) were computed at points A, B, C and D (each corner of the specimen) at third floor level. The locations of these points are shown in Fig. 3.1.b. and their coordinates are given in Table 3.1. Compressive and tensile strength of the concrete, elasticity modulus of concrete and Poisson’s ratio are given in Table 3.2.



(a) *(b)*

Fiure 3.1. AZALEE Shaking Table and the model building (a) and its plan (b) (RAPPORT DM2S, 2007)

Table 3.1. Location of study points shown in Figure 3.1.b.

Point	**X(m)**	**Y(m)**
A	0	0
B	3	0
C	3	1
D	0	2.5

Table 3.2. Materials characteristics

f_{cj} (MPa)	f_{tj} (MPa)	E_c (MPa)	ν_c	ν_s
30	2.4	32000	0.2	0.3

The steel reinforcement has been defined according to the European design codes (EC2). Steel reinforcement FeE500-3 is used in details and its yielding stress is 500 MPa. To reproduce the structural and additional masses of the real structure; additional loads were applied on the slab at each level. The total weight of the specimen was estimated at about 44.29 tons (RAPPORT DM2S, 2007). Additional masses on the floor levels are given accordingly; 11.60 t, 12.00 t, 10.25 t at floor levels from first to third one, respectively. The average density of the reinforced concrete of the structure was taken as 2460 kg/m^3 based on the SMART 2008 Phase 2 report (RAPPORT DM2S, 2007).

3.3. Experimental Program

Three real and 10 synthetic accelerograms were applied to the specimen in the experimental phase. The details of the accelerogram sets are given in Table 3.3. and Fig. 3.2. The earthquake ground motions were applied in both orthogonal and horizontal directions.

Table 3.3. Real and synthetic accelerogram sets

No	Real Earthquakes		Mag.	Dist.	Acc .(g)
1	REA1	UMBRO-MARCH(AS)	5.2	23	0.05
2	REA2	MANJIL(AS)	4.4	14	0.05
3	REA3	UMBRO-MARCHIGIANO	5.9	81.4	0.05
Synthetic Earthquakes					
4-13	Derived according to the response spectrum and scaled from 0.1 g to 1.0 g				

The specimen was a reproduction of a typical nuclear building sub-component at a scale of ¼. Thus, some assumptions were made to perform the experiments. In order to keep the same acceleration (gravity load cannot be changed) as well as the same material properties, the scaling of ¼ of the structure's dimension implies to scale the mass by 1/16 and the time by ½. The other scaling factors of parameters are given in Table 3.4.

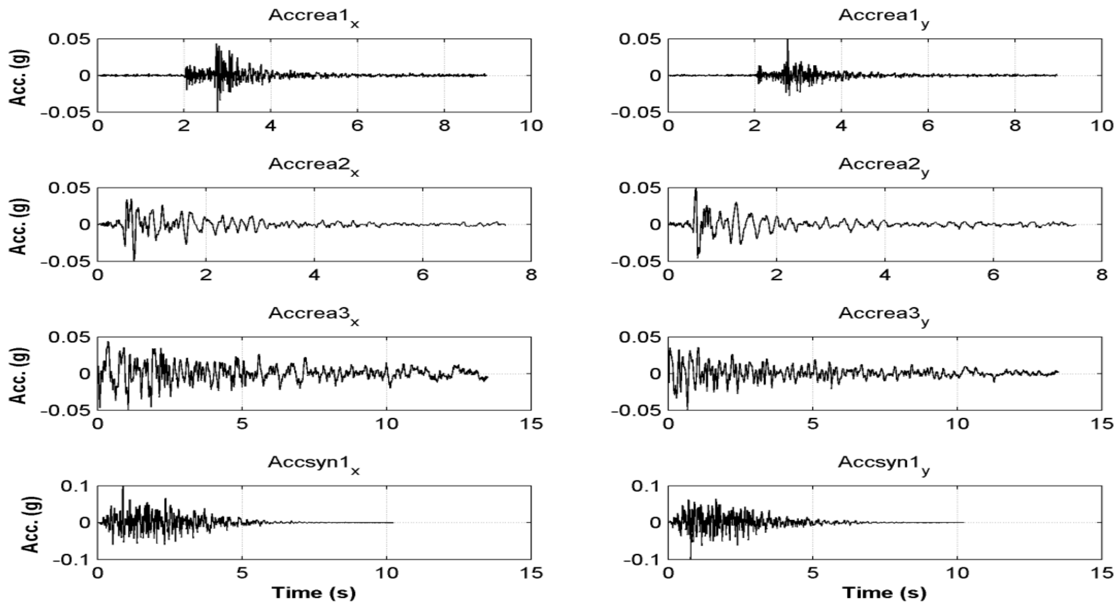


Figure 3.2. Ground motion data used in the experiments

Table 3.4. Scaling factors of the parameters

	Scaling factor
Length (m)	4= (λ)
Mass (kg)	16=(λ^2)
Time (sec)	2=($\lambda^{1/2}$)
Acceleration (g*)	1
Stress (MPa)	1
Frequency (Hz)	0.5
Force (N)	16
Steel reinforcement area (m^2)	16
* 1 g = 9.81 m/s^2	

3.4. Shaking Table

The Azalée shaking table can be considered as a rigid block with a total mass of 25 tons fixed to eight hydraulic jacks (4 in the horizontal direction and 4 in the vertical direction). The actuators controlling the horizontal motion of the table are located at 1.02 m below the upper face of the shaking table, while the center of gravity is 0.60 m below this level. All the jacks are active systems, which means that they are controlled during the experiment. Based on earlier experiences, it has been observed that shaking table has a flexibility that could affect the response of the specimen. The spring constant value of 215 MN/m could be used for each vertical jack to simulate the foundation- shaking table connection. The centers of gravity of the table and the model are given in Table 3.4. The position of the specimen on the shaking table is shown in Fig. 3.5.

Table 3.5. Center of gravity for the system coordinates presented in Fig. 3.1.

	x_g (m)	y_g (m)
Table	1.50	0.94
Model	1.28	0.92

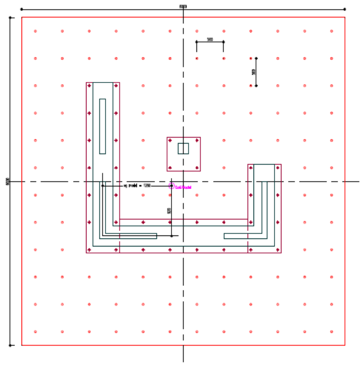


Figure 3.4. Position of the specimen on the shaking table

Total mass of the structure is equal to 68,212 kg (specimen + shaking table).

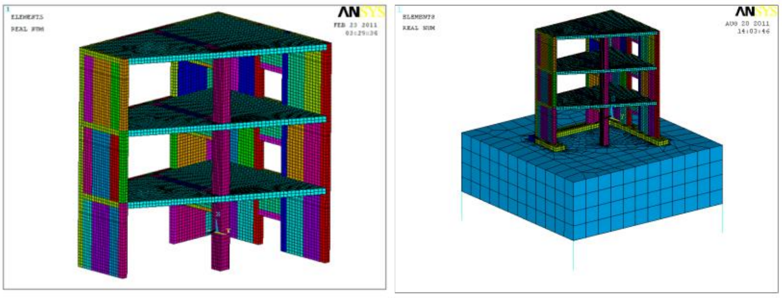
3.5. Element Types Used in the Analysis

Three–dimensional–modeling approach was chosen for analyzing the specimen. The element type chosen for this purpose is SOLID 65 (3-D Reinforced concrete element). It was preferred for modeling of the concrete solids with or without reinforcing bars. Element specifications are explained in detail in ANSYS manual. The element is defined by an eight node solid having three translational degrees of freedom at each node. Up to three different rebar specifications may be defined. Reinforcement in concrete can be added to the model by the “Smeared” approach for SOLID 65 or using the LINK 8, three dimensional truss elements. The most important aspect of this element is the treatment of nonlinear material properties. The concrete is capable of cracking (in three orthogonal directions), crushing, plastic deformation, and creep.

The rebar is capable of tension and compression, but not shear. They are also capable of plastic deformation and creep (ANSYS R 12.0). In the numerical model vertical rods supporting the shaking table were included and assigned a stiffness to capture the measured vertical frequencies. For thsese rods, a spring element, COMBIN14, was used. COMBIN14 has longitudinal or torsional capability in one-, two-, or three-dimensional applications. The longitudinal spring-damper option is a uniaxial tension-compression element with up to three degrees of freedom at each node: translations in the nodal x, y, and z directions. The elastic constant of each spring element was taken as K=215MN/m (in accordance with the experimentally measured response during previous tests) in the numerical computations.

3.6. Material Properties

Material properties summarized in Table 2 were used in the analytical model. All concrete sections were modeled using MKIN and CONCRETE from ANYSY library. For MKIN (Multi linear kinematic hardening) rate-depended plasticity is used . CONCRETE is a defined material model in ANSYS for Willam – Warnke material model. For this material type open shear transfer coefficient, 0.2 and closed shear transfer coefficient, 0.8, are used. Uniaxial cracking stress is taken as 2.4 MPa. The finite element models of the specimen with and without shaking table are shown in Fig. 3.5.



(a) (b)

Figure 3.5. Finite Element Models of the Specimen; a) Fixed-base, b) with Shaking Table

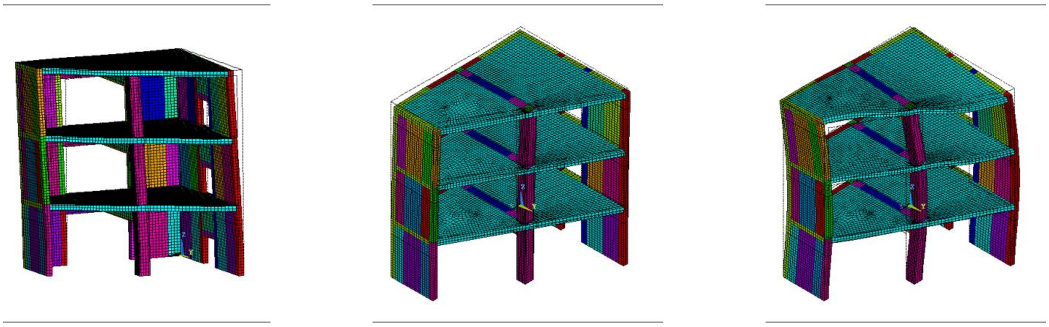
4. RESULTS OF ANALYSES

The primary objective of the analyses was to obtain a valid and adequate model that can simulate the experimental response of the specimen. For this reason, two models were generated. In the first model, the effect of shaking table was ignored and the base of the specimen was considered as fixed. In the second model, the shaking table was also included in the model. In order to check adequacy of the model, first experimentally obtained modal properties that is modal frequencies were compared with numerical ones. Then, displacement time histories and response spectra computed at different points on the third floor as marked in Fig. 3.1. were compared.

4.1. Modal analyses

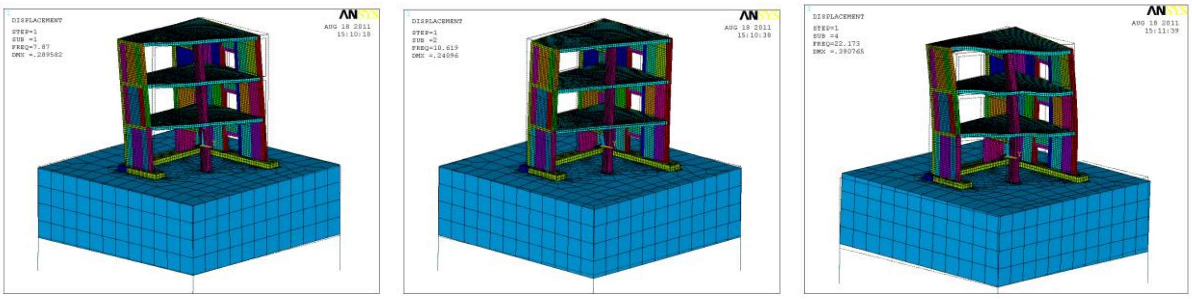
Modal analyses were performed to obtain the frequencies from the two models developed. The first three mode shapes are given in Figs. 4.1. and 4.2. for the case of fixed base and shaking table, respectively. Modal frequencies of the specimen were measured and reported during the experimental phase. The frequencies and periods obtained from analyses are compared with the experimental ones in Tables 4.1. and 4.2. respectively.

As can be seen from the results the fixed based model is more rigid thus yields larger frequency values as compared to the experimental ones. Considering the high stiffness of the shaking table, the finite element representing the shaking table were assumed to remain elastic and almost infinitely rigid. The total mass of the shaking table was uniformly distributed to these finite elements. It appears that the modal properties obtained from the model with shaking table are much closer to measured ones. The oscillation of the specimen causes vertical displacements on the shaking table and results in significant reductions of the corresponding natural frequencies of the system (shaking table + specimen).



Mode 1: F=9.23 (Hz) Mode 2: F=15.93 (Hz) Mode 3: F=32.76 (Hz)

Figure 4.1. First three modes of the specimen calculated for the fixed base model



Mode 1: F=7.87 (Hz) Mode 2: F=10.62(Hz) Mode 3: F=22.17 (Hz)

Fiure 4.2. First three modes of the specimen calculated for the model with shaking table

Table 4.1. Comparisons of Frequencies obtained from Models with Experimental results

Mode	Frequency (Hz)		
	Experimental	Model with shaking table	Model with fixed base
Mode 1	6.24	7.87	9.23
Mode 2	7.86	10.62	15.93
Mode 3	15.00	16.61	32.76

Table 4.2. Comparison of periods

	Experimental –T(s)	Model with shaking table-T (s)	Model with fixed base-T (s)
Mode 1	0.16	0.13	0.11
Mode 2	0.13	0.09	0.06
Mode 3	0.07	0.06	0.031

4.2. Time history analyses

As mentioned before, at first we assumed that the model is fixed at base and performed time history analyses. Then we modeled the shaking table and repeated the analyses. Considering the high stiffness of the shaking table, the finite element representing the shaking table were assumed to remain elastic and almost infinitely rigid. The total mass of the shaking table was uniformly distributed to these finite elements. The results in terms of displacements and response spectra at points A, B, C and D in the third floor for given ground motions calculated for both models. Low excitations are influenced more from noise. At larger excitation levels, the match between the measured and calculated response improves such that a better representation on the experimental behavior is achieved. Fig. 4.3. presents the comparison of the displacement time histories with the experimental results for ground motions having Peak Ground Acceleration of 0.7 g. The time step in the acceleration data was 0.025 second and time duration for each run was approximately 6 seconds.

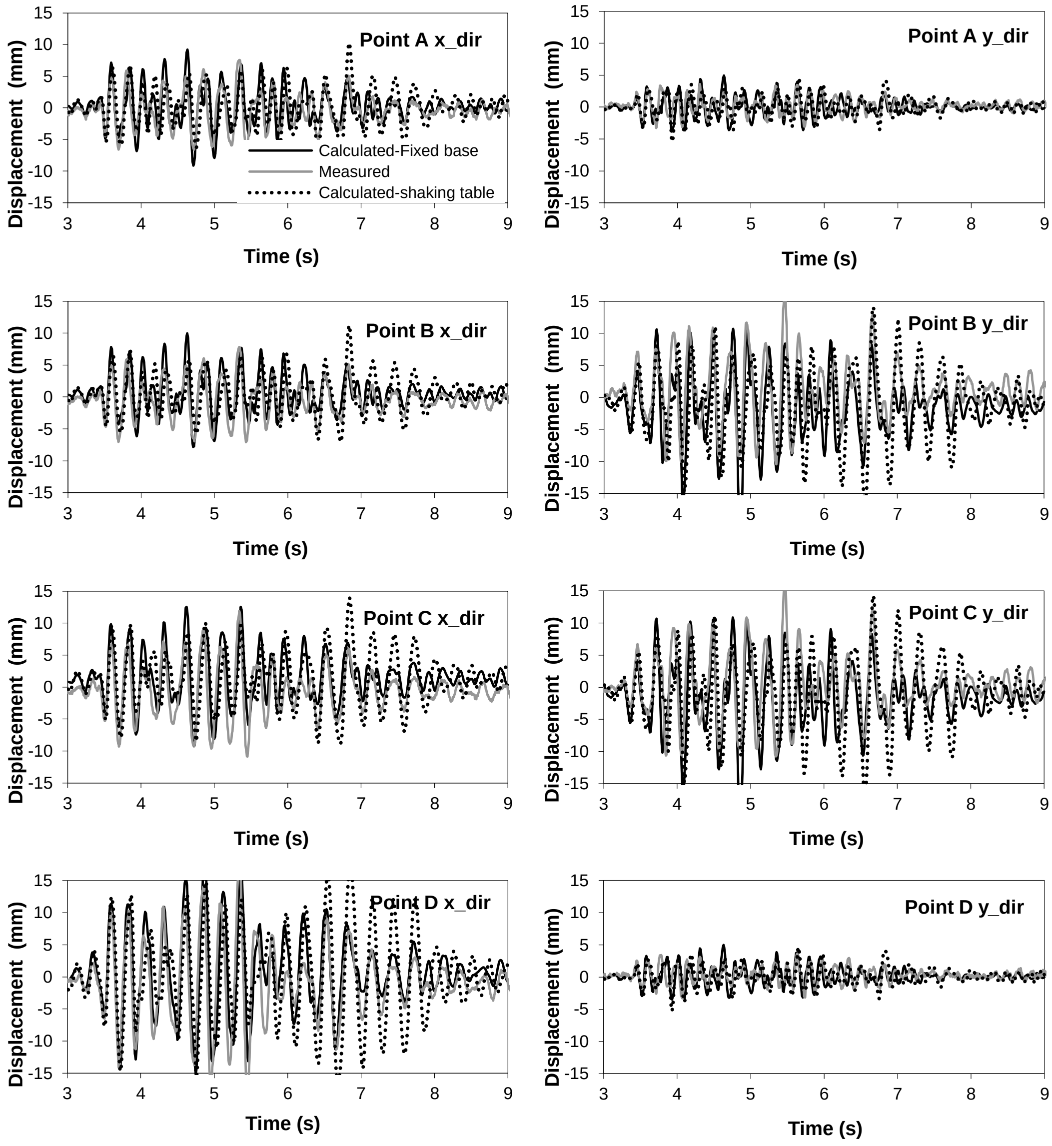


Figure 4.3. The comparison of displacements of Points A, B, C and D for experimental data, fixed base and shaking calculated table data for third floor (PGA=0.7 g, damping ratio=2%)

The comparison of calculated and measured displacements of the third floor for 0.7 g reveals that the fixed-base and shaking table model is able to adequately yield the experimental results. Displacements calculated for the model with shaking table appear to overestimate the experimental results due to a more flexible system as compared to the fixed base model. The magnitude of displacement changes depending on the location due to torsional behavior of the structure. Experimental and analytical results are in phase yielding better agreement especially at point A that has relatively less torsional response. The match is not as good at other points where analytical results generally yielding smaller displacements. The difference between trend of displacements at points A, B, C and D is due to torsional behavior of the structure. Also it is to be noted that, the maximum values of displacement in numerical and experimental results are in the same frequency. Comparing the maximum values of displacements in x- and y- directions for each excitations, it was observed that in x-direction the trend is not regular; both models generally underestimate the displacements at smaller excitations (PGA<0.4g) but overestimate it at larger excitations. Although shaking table model yields better estimates, in certain cases fixed base model gives closer results to the experimental values. Higher displacement values occurs at points C and D in the x direction. At points B and C, motion in the y direction is dominant. For analyzing the performance of the structure in earthquakes and assessing the peak response of building to earthquake, the response spectrum plot considering the damping ratio as

5% for each point at the 3rd floor were generated. The results were compared with the experimental results. In Fig. 4.4. the response spectra for accsyn 0.7 g is given. These comparisons reveal unsatisfactory results obtained from numerical analyses. Due to stiffer nature of the numerical fixed base model experimental spectra are underestimated. Additionally, frequency content and spectral values are not adequately predicted. It is observable that, except point D, the maximum value of accelerations of numerical model occurs in y-direction. The maximum spectral acceleration is 12.49 g corresponding to frequency of 6.69 Hz at point B, y-direction for Run7. Similar to fixed-base model, except point D, the maximum value of accelerations of numerical model occurs in y-direction. For Run 7 we can observe that, the maximum spectral acceleration value is 10.10 g corresponding to the frequency of 12.71 Hz at point D, x-direction. Experimental spectra are overestimated at the low seismic tests and underestimated at the high seismic tests.

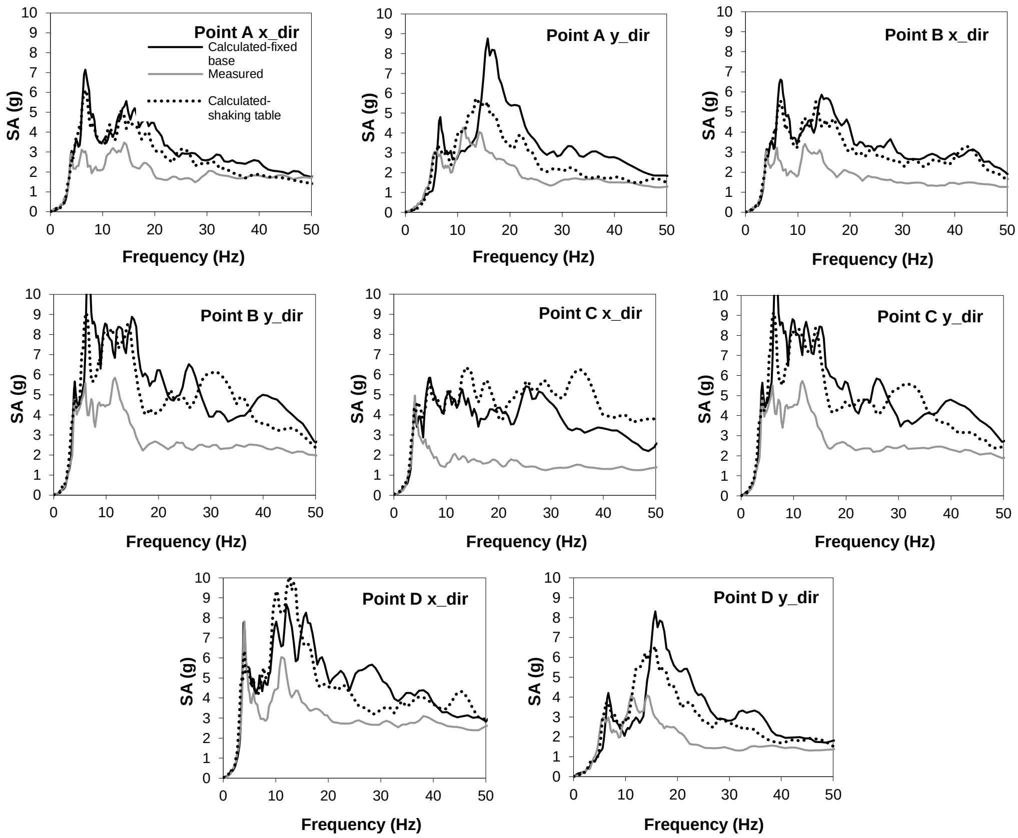


Figure 4.4. The comparison of Spectra at Points A,B,C and D for experimental data, fixed base and shaking table calculated data for third floor (PGA=0.7g, damping ratio=5

5. CONCLUSIONS

The model building was tested under a set of bi-directional synthetic and real ground motions that have varying intensities, peak ground accelerations ranging from 0.1g to 1g. Displacements and accelerations measured at different locations on the plan at third story were compared with the numerically computed values in order to check the validity of the FEM that has been obtained in ANSYS ver.12.1. Simulations based on the fixed-base model showed that experimentally measured displacements were captured with reasonable accuracy despite deviations from the modal frequencies and spectral accelerations. A more flexible model including the shaking table yielded better estimates of accelerations and frequencies but overestimates of displacements were obtained. Although both models captured the torsional behavior adequately, neither was adequate to simulate all experimental results. Modeling of the specimen-table interaction which is believed to be affected by the specimen properties, needs more investigations. In addition to this, experimental data needs to be further examined for consistency. Comparing the modal analyses results indicated that, the results achieved from analyzing the shaking-table model is much more closer to the experimentally obtained results. Comparing the displacements and accelerations depicted that, the maximum value of displacements ratio and accelerations of numerical model occurs in y-direction.

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