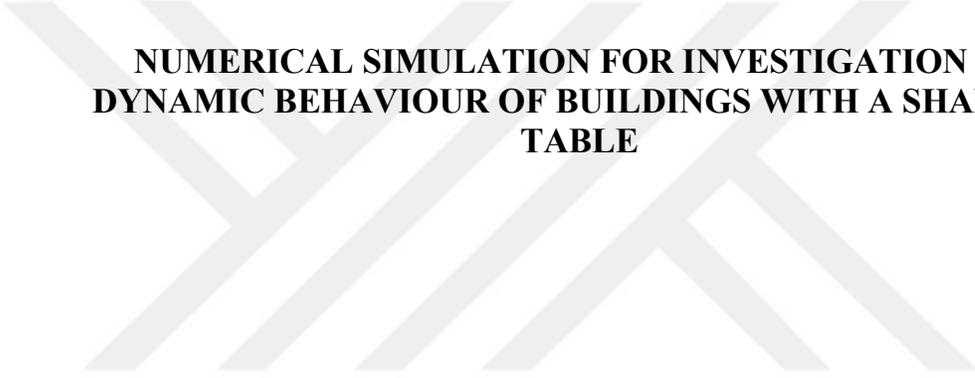**THE REPUBLIC OF TURKEY**
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

NUMERICAL SIMULATION FOR INVESTIGATION OF DYNAMIC BEHAVIOUR OF BUILDINGS WITH A SHAKING TABLE

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I devoted this research to Iraq.

We ask God Almighty to help us serve our country and the people of our homeland.

December, 2017

Hudhaifa Mohammed ABDULGHAFOOR

TABLE OF CONTENTS

LIST OF SYMBOLS

FL	Loading Frequency
f	Natural frequency
L	Load
Ms.	Mode Shape
i	Number of Loading
j	Number of Mode
an	Acceleration
D	Displacement
Dr.	Drift
σ	Equivalent stress
γ	Equivalent strain
E	Modulus of elasticity
K	Stiffness
M	Structural mass
C	Damping
v	velocities
t	Time

LIST OF ABBREVIATIONS

1-D	One Dimension
2-D	Two Dimension
3-D	Three Dimension
DOF	Degrees of Freedom
FEA	Finite Element Analysis
FEM	Finite Element Method
Fi-Mj	Harmonic Load

LIST OF FIGURES

Page

LIST OF TABLES

xvi

ABSTRACT

NUMERICAL SIMULATION FOR INVESTIGATION OF DYNAMIC BEHAVIOUR OF BUILDINGS WITH A SHAKING TABLE

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MSc. Thesis

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Shaking table test of a structure has a vital role in the understanding of the dynamic behavior of the structure. In conjunction with the shaking table, a seismic simulation of the building, bridge, and underground structures can be conducted up to the collapse stage.

Traditionally, engineers have used laboratory test to investigate the structural behavior of building products and systems which are subjected to the effect of dynamic loads such as wind and earthquake loads and to develop appropriate design rules. Laboratory tests were also used to develop new building systems.

However, laboratory testing has time-consuming and expensive effects so that numerical analysis can be included to optimize or minimize these effects. In this study, three-dimensional finite element analyses of a shaking table (substructure) model and models of some types of buildings (superstructures) were conducted together using the ANSYS program. In the finite element analysis, a hexahedral mesh including approximately 1.9 million degrees of freedom was used. For the motion of the shaking table linear contact elements were taken into consideration. The constructed models were linearly analyzed under various dynamic loadings including harmonic and earthquake loads which were carried out as displacement-controlled loading. The results are given to find out displacements, accelerations and overall strength at different points of the substructures and superstructures and to determine the collapse styles or failure mechanisms.

ÖZET

SARSMA TABLASI İLE BİNALARIN DİNAMİK DAVRANIŞININ İNCELENMESİ İÇİN SAYISAL BENZETİM

Hudhaifa Mohammed ABDULGHAFOOR

İnşaat Mühendisliği Anabilim Dalı

Yüksek Lisans Tezi

Danışman: Doç. Dr. Serkan BEKIROĞLU

Bir yapının sarma tablası ile testi, yapının dinamik davranışının anlaşılmasında çok önemli bir role sahiptir. Sarsma tablası ile birlikte, bina, köprü ve yer altı yapılarının sismik benzetimi o yapıların göçme anına kadar devam ettirilebilir.

Genellikle mühendisler, laboratuvar testini rüzgâr veya deprem yüklerine maruz kalan yapıların veya yapı sistemlerinin yapısal davranışını incelemek ve uygun tasarım kurallarını geliştirmek için kullandılar. Laboratuvar testleri ayrıca yeni bina sistemleri geliştirmek için kullanıldı.

Öte yandan, laboratuvar testi zaman alıcı ve pahalıdır, öyleki, sayısal analiz bu etkileri en aza indirmek veya eniyilemek için dikkate alınabilir. Bu çalışmada, ANSYS programı kullanılarak bir sarsma tablası (alt yapı) ve bazı yapı tiplerinin (üst yapılar) modellerinin üç boyutlu sonlu elemanlar analizi yapılmıştır. Sonlu elemanlar analizinde, yaklaşık 1,9 milyon serbestlik derecesini içeren altı yüzeyli katı elemanlar ağı kullanılmıştır. Sarsma tablasının hareketi için doğrusal temas elemanları dikkate alınmıştır. Oluşturulmuş modeller, yerdeğiştirme kontrollü yükleme olarak harmonik ve deprem yüklerini içeren çeşitli dinamik yükler altında doğrusal olarak analiz edilmiştir. Alt yapıların ve üst yapıların farklı noktalardaki yer değiştirmeleri, ivmelenmeleri ve toplam dayanımını bulmak ve göçme halleri belirlemek için sonuçlar sunulmaktadır.

Anahtar kelimeler: Sonlu elemanlar analizi, ANSYS programı, sarsma tablası, harmonik yükleme, dinamik yükleme.

CHAPTER 1

INTRODUCTION

1.1 Literature Review

1.1.1 Numerical Modelling and Analysis of Structures

Finite Element Analysis is a numerical method used to simulation and analysis the behavior of structures and building under several of conditions. It is an advanced engineering approach that is used in the design and to substitute experimental testing. It was generated from the need of solving complex and structural analysis problems in Civil, Mechanical and Aerospace engineering. In a structural simulation, Finite element method helps in creating stiffness and strength imaginations. It also helps to reduce material weight and its cost of the structures. Finite element permits for detailed imaginations and marks the distribution of stresses and strains inside the body of a structure. Although the development of Finite element software it is still sophisticated tool meant for professional engineers with the training and education necessary to accurately interpret the results [1].

Many of modern finite element packages include specialized components such as structural, mechanical, fluid, thermal, and electromagnetic working environments. Finite element modeling allows entire designs to be constructed, simplify and optimize before the design is manufactured. This robust design technique has significantly improved both the standard of engineering designs and the methodology of the design process in many practical applications. The use of finite element analysis has significantly reduced the time to take products from concept to the production line [2]. Now day engineers must take advantage of the creating of faster generation of personal computers for the analysis and design of engineering product with a precision level of accuracy. The accurate solution of complex structural problems has been the aim of some generations of engineers and scientists. The aim has been achieved to a broad range, by using experimental, analytical (exact) or numerical (approximation) techniques, or any

combination of the three. The general applicability of the finite element method makes it a powerful and global technique for a wide range of engineering problems. Therefore some computer program packages have been developed for the solution of a difference of structural and solid mechanics problems. Among more widely used packages are ANSYS, NASTRAN, ADINA, LS-DYNA, MARC, SAP, COSMOS, ABAQUS, NISA [3]. Each finite element program package consists of three parts:

- programs for preparation and control of the initial data,
- programs for the solution of the finite element problem,
- programs for processing of the results.

In this thesis, a numerical study on the simulation of the shaking table behavior subjected to cyclic loading will be carried out through the use 3-D (solid) finite element models using ANSYS program.

1.1.2 Dynamic Analysis of Building

It's known in the recent years, that the high-rise buildings play a "crucial roles in modern cities. Firstly, tall buildings can efficiently be used to meet the requirements of modern society and solve the problem of limitation of construction site resources. Nowadays high-rise buildings get higher and higher, with more and more complex and individual plan and elevation, such as multi-tower buildings. Therefore, irregularities and complexities are developed during the structural design of buildings, which have imparted great challenges to structural engineers since their structural behaviors are difficult to estimate and analyze. Although the fundamental progress has been made in computer software for structure analysis these years, it is still hard to predict the seismic performance analytically and view the dynamic response of a building. Under this situation, it is essential to investigate the dynamic properties of actual structures and discuss the validity of the computation [4].

The Calculation of three-dimensional dynamic effects on buildings is a challenge for structural engineering, especially for non – linear behavior under earthquake effects. The numerical Modeling of these types of buildings needs much more care to produce acceptable results. Despite the developing computer technology and creation of many numerical models, there are still defects in modeling because of the assumptions made in the numerical models for material and seismic excitation estimation [5]. Most of the numerical models should be confirmed through comparisons with experimental test

results. Many experimental techniques can be used to test the dynamic behavior and response of structures to verify their seismic performance. One of these tests is the shaking table which is the most likely experiment type developed in the last four decades. A shaking table is a platform for structural test models or building components with a wide range of simulated ground motions, including reproductions of recorded earthquakes time-histories. Therefore, the shaking table tests give good results for earthquake simulations [6].

The shaking table test is one of the most effective tools to study the dynamic performance of complex structures, and it is a relevant and useful method to help structural engineers get a better investigation and visualize about the dynamic behavior and dynamic response of the buildings [7]. Not only can engineers study the damage mechanism, the failure pattern and the dynamic response of the structure, but also weak positions in the structure can be obtained. The building such as unique and complex structure system which are far from the limitation of interrelated codes should be first studied through the experiment on dynamic behavior to examine the structural response, the weak positions and crack pattern under loads of different levels and to help the designer's engineers improve the scheme [8]. The dynamic response of a building structure depends on its dynamic characteristics of input ground motions. Nowadays, after comparison with experiment is carried out the static and dynamic properties of structures can be approximately obtained using computer software. Advance analysis method based on Finite Element method is the best suited to simulate the complex structures in three dimensions' model [9].

In this research, a shaking table model with a prototype of the building is modeling and simulated using ANSYS workbench software, including the structural system characteristics, model material selection, similitude relationship and simplification of the model design [10]. By using numerical analyses (modal and dynamic analyses) the dynamic property, mode shapes, acceleration and displacement responses of the model structure are investigated and make comparisons of the results in different cases of analyses with different loads and boundary conditions.

1.1.3 Analytical and Numerical Studies

Review of numerical methods for static and dynamic analyses of the structures buildings returns to the 1960's. Because the low speed and capacity of computers, researchers were forced to use simplified methods and hand calculations in the design of structures [11]. With the advancement of technology of computers, after the 1960's, a significant amount of analytical and experimental research, achieved all through the world, using commercial software based on finite element methods. Many types of research, found much practical information on the dynamic response of buildings structural systems. The most general method that is used for simulating the behavior of structure buildings using modeling and simulation is finite element method [12]. A finite element method is a powerful tool for the analysis of structures, including three-dimensional and nonlinear analysis. The FEM of analysis is capable of observing 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). Researchers have used a finite element modeling approach to simulate the experimental measurements [12]. FE modeling represents the overall behavior of the Structures. The global behavior of the Structures elements using an FE model should be compared using an experimental investigation to modify the parameters needed for the model [13].

Finite element analysis of structures can be divided into two divisions. In the first division, researchers try to develop their finite element formulations and models and then they later assess the reliability of the proposed models by comparing with experimental data [14]. In the second division, researchers also try to use already developed and available advanced finite element software packages such as ANSYS and ABAQUS. The study conducted in this thesis focuses on the use of 3-D finite element models present in ANSYS. Literature survey will focus on the use of finite element programs to model shaking table with superstructure buildings [15].

Saeideh Nazirzadeh, Ahmet Yakut (2012) used a numerical method to simulation of shaking table model with three-story RC shear wall. They used two type of models one with shaking table and other with a fixed base, and the models have been tested using model and transient analyses with ANSYS. Moreover, the results are compared with experimental ones [16]. Tian Chunyu, Xiao, Zhang and Cao Jinzhe (2012) performed a dynamic elastic and plastic time-history analysis on the prototype structure of Shanghai Tower, and the results were carried out by SAP2000 and ABAQUS, and the results are

compared with experimental results [17]. The error was within 10%. Chengqine Liu, Kaiqiang Ma, and Ying Zhou (2017) used finite element model to simulate the high-rise Diagrid Tube structure, the model and time –history analyses were carried out, and the numerical results show a good agreement with shaking table test [18]. Qingyuan Dong worked with numerical simulation of full-scale five-story building base Isolated by a system of lead-rubber bearing (LRBs) and cross line bearing (CLBs) was performed. The structure was subjected to some ground motions using the E-Defense shaking table, the behavior of LRBs, the response of the building, vertical loads, and acceleration are discussed [19]. Hiroyuki, Tomoshi, Takuzo, and Makoto (2015) detailed finite element analysis of a full-scale four-story steel frame structure, subjected to earthquake loads using E-Simulator. E-simulator is a finite element analysis software developed to accurately simulate structural behavior up to collapse by using a fine mesh of solid elements. The four-story frame was tested at the largest shaking table facility, E-Defense. The local buckling behavior at the top and bottom of the columns in the first story and a story mechanism were simulated. Analysis results indicated that the first-story drift response for the consecutive 100% excitation after 60% excitation was slightly smaller than that for single 100% excitation [20]. Wensheng LU and Xilin LU used new assumption by applied the multi-rigid block model to analyze several multi-tower buildings, and the theoretical dynamic behavior was compared with shaking table test results. The error between the results of testing and the theoretical ones are within 10%-30%. Hence the results of shaking table testing are satisfactory [21].

Other researchers like Roberto Nascimbene (2015) concerned a fiber-based finite elements model of a half-scale 3D reinforced concrete frame tested under dynamic loads. The numerical tool that was employed in the prediction of the shaking table response of the specimen was verified against experimental data [22]. X. Wang and T.C. Hutchinson presented the numerical simulation of the 5-story building which was being tested on the UCSD NEES shaking table. The numerical data are presented and compared with measured results [23].

1.1.4 Experimental Studies

Many shaking table tests have been performed to evaluate the inelastic seismic response of structures, and dynamic behaver of the building was proposed. Jingjiang et al. (2007) performed earthquake simulator test of an RC frame –wall model and compared the analytical and experimental results, and presented conclusion related to seismic design

and damage evaluation of RC structures [24]. 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 [25]. Palermo and Vecchio (2002) studied the behavior of three-dimensional reinforced concrete shear walls under cyclic displacements [26].

(Lee HS et al. 2007). Several previous studies by the authors were conducted to investigate the dynamic response of the three individual building models having different layouts of the vertical earthquake-resistant elements in the lower soft stories [27]. 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 fiber and a beam model) and two resolutions. In the USA and Japan shaking table tests for full-scale seven-story RC wall structures and six-story RC wall frame buildings respectively were performed by using large shaking table schemes (implicit and explicit, respectively) by J.Mazars et al. (2004) [28]. Ile et al. (2004) compared numerical and experimental results of the U-shaped walls subjected to lateral cyclic loadings applying the refined shell model [29].

The effect of torsion and the seismic behavior of a lightly reinforced wall model under bi-directional loading were studied by Ile and Reynoaurd (2003). (Spatial and time discretization, modeling and damping mechanism and materials constitutive relations) to analysis the non-linear behavior of the structures following different design philosophies [30]. (Kotronis et al. 2005) Two structures, considering the "multitude" 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, to test the ability of the proposed numerical tools. They also conducted dynamic shaking table tests on AZALEE shaking table [31].

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 a sequence of ground motions [32]. Dynamic interaction between the shaking table and the structure has been studied by Le Maoult et al. (2010) [33]. They demonstrate that most of the interaction for AZALEE shaking table is due to the platform deformation during the tests. Hiroyuki, Tomoshi, and Makoto performed a dynamic analysis of four-story frame and tested at the largest shaking table facility E-Defense in 2007 [34]. Wensheng LU and Xilin LU studied the tests of several scaled high-rise building models on shaking table, the multi-rigid block model has been applied to analyze several multi-tower buildings,

6

and the numerical dynamic results were compared with test results, the error between them are within 10%-30%. Hence the results of shaking table testing are satisfactory [35].

1.2 Objective of the Thesis

In this study, the objective is to investigate dynamic behavior of a shaking table linear model with buildings (superstructures) under a set of dynamic loading including harmonic loadings with various frequencies and earthquake loadings in one directional and two directional lateral motion by using 3-D finite element analysis within ANSYS program. Therefore, first of all, free vibration analyses for a shaking table with/without superstructure are done to finding a valid and adequate range of frequencies that can be considered to get responses of the shaking under harmonic loading. Secondly, a reference earthquake is chosen to determine the behavior of the shaking table with different superstructures.

In summary, the covered issues of this thesis can mainly be articulated as follows:

- Simulation of a shaking table with superstructure building is carried out using finite element model.
- Mode shapes and natural frequencies of superstructure models within the fixed base and within the are obtained to determine the range of frequencies to be applied for harmonic loading.
- Results of displacement and acceleration at a different point on the shaking table and top story of building in the lateral perpendicular directions, that is, X and Z, are compared to evaluate the response of the shaking table and superstructure.
- Expectations about the collapse styles and failure mechanism for the shaking table are determined to find critical points on the shaking table.
- Stress and strain results of the shaking table and superstructures under dynamic loadings such as harmonic loadings and the reference earthquake loading are compared.
- Drift on the top story of superstructures is also given to get a response of superstructures under the dynamic.

1.3 Hypothesis

In this study, 3-D finite element modeling of a shaking table and different superstructure buildings are considered using ANSYS program. The two type of analyses are used so that modal analysis is executed to obtain mode shapes and natural frequencies, and dynamic analysis to obtain displacements and accelerations, stress, strain and drift at different points on the models. By the way, the models are simulated under a set of dynamic loadings including harmonic loadings and earthquake loading within one lateral direction or two lateral directions to determine the dynamic behavior of the shaking table with different types of building. In this study the analyses are assumed liner, therefore; the materials properties and contact are considered liner and the damping ratio and gravity is ignored for models on which harmonic loads act.

GENERAL INFORMATION

2.1 Finite Element Method

Finite element analysis (FEA) is a numerical technique tool which used to find approximate solutions of engineering field problems by dividing a domain into several smaller finite subdomains, which each act as individual elements over which algebraic equations are applied, and an approximate solution is given using the finite difference methods. The results from each finite element are then reassembled, and different types of analysis can be run to solve any number of complicated engineering problems using this method and powerful solver [36].

Finite element is quite accepted in almost all engineering departments. The method is often used as a substitutional to the experimental test method set out in many standards. The technique is based on the approximate solution to any complex engineering problem can be reached by subdividing the structure/component into smaller finite elements. The Finite Element Model (FEM) is analyzed with an inherently higher accuracy than would otherwise be possible using traditional hand analyses, since the actual shape, load, and constraints, as well as material property combinations, can be specified with much higher accuracy than that used in classical hand calculations.

2.1.1 Stages of Finite Element Analysis

- (A) Pre-processing, in this, proses the analyst develops a finite element mesh of the geometry and applies material properties, boundary conditions and loads.
- (B) The solution, in this proses the program derives the governing matrix equations (stiffness x displacement = load) from the model and solves for the displacements, strains, and stresses. This is the case in implicit code applications. Moreover, explicit codes can be used, especially for high strain rate engineering problems [37].

- (C) Post-processing, in this, proses the analyst obtains results usually in the form of deformed shapes, contour plots, etc. which help to check the validity of the solution[37].

2.1.2 How the FEM Works

To epitomize in generally how the finite element method works we list main steps of the finite element solution procedure below.

1. Discretize the problem. The first step is to discretize a solution area into small finite elements. Moreover, in the preprocessor program, the mesh element is typically created.

2. Interpolation functions.in the second step the Interpolation functions are used to interpolate the field variables through the element. Frequently, polynomials are used as interpolation functions. The degree of the polynomial function based on the nodes number which assigned to the element.

3. Define properties of the element. The matrix equation for the finite element should be determined which connect to the nodes values of the unknown function to other variables. For this job various approaches can be used; the most suitable are the variation approach and the Galerkin method [38].

4. Assemble equations of the element. To find the global equation system for the full solution field, we should collect all the element equations. Also, local element equations for all elements used for discretization are assembled.

5. Find the solution of the global equation system. The finite element global equation system is generally dispersed, symmetric and positive definite. The solution can be obtained by using the direct and iterative methods. The nodal values of the examine function are generated as a result of the solution.

6. Calculate supplemental results. In many statuses, we need to compute additional parameters. As an example, in mechanical problems, stress and strain are of advantage in addition to displacements, which are calculated after the solution of the global equation system.

2.1.3 Type of Finite Element

In the finite element method, there are three types of element (a) one-dimensional element, (b) Two-dimensional element, and (c) Three-dimensional element.

Table 2.1 Finite element type

Type of element	Model Name	Finite element
1 –D	Bar/Truss Beam Tube/Pipe	
2-D	Plate/shell	
3- D	Solid	
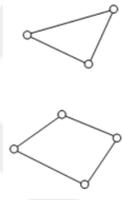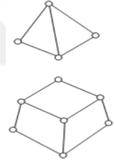
Finite element applications supply many engineering parameters such as (Stress/strain, deformation, natural frequencies, etc.) about a structured system which cannot be determined by using classical analysis methods. It is possible to produce a simulation of any design and to determine its real behavior under nearly any imaginable environments, thus giving the concept to be repeated before to the creation of the design. Once a model has been developed the analysis helps in estimate the feasibility of the new design as well as problem shooting failed designs already in the market and finding solutions without the need to prototype and waste time and money [39].

2.1.4 The Benefits and Applications of Finite Element

- Linear and non-linear analysis of structure in static and dynamic states and bulking analysis.
- Various types of boundary conditions can be used in finite element method.

11

- By this method, we can work with Material, various and inhomogeneity without much difficulty.
- In this method, any loading can be applied.
- Analyses and simulate of contact between parts and composition.
- Analyses of welded and bolted connections.
- Analysis Fatigue and fracture of structures.
- Can be make sub-modeling to study a local part of a vast model.
- Implemented higher order elements with relative ease.
- Analysis of steel and reinforced concrete buildings and frames.
- Analyses of structures subjected to fire.

Finite element analysis has significant advantages when compared to the other numerical analysis methodologies. It is mighty and applicable to many engineering problems such as dynamic, static analysis for both linear and non-linear problems and displacements, stress, the strain of structural systems, heat transfer and magnetic fields. Also, for individual elements, different material properties can be incorporated. One of the most critical advantages of finite element analysis is that there are no limitations concerning the geometry or boundary conditions. Different types of geometry and boundary conditions can be accommodated comfortably. In addition to these properties, it is easy to modify the problem and increase the accuracy of the results while usually only at the expense of computational efficiency [40].

2.2 Computational Modelling Using the FEM Software's

Through the last years, the development of numerical methods and more powerful computers has been a leading factor for the scientific research. At the same time, the finite element method has become a widely used for researchers and engineers. New advances in computational software have made possible to solve more physical and complex problems such as static, dynamic, heat flow, electromagnetics, and coupled problems. Nowadays many commercial software packages use the finite element method because of the benefits mentioned above. ANSYS, ALGOR, ABAQUS, COSMOS/M and SAP2000 are some of the well-known commercial software packages that are based on finite element analysis. That is to say that the finite element analysis has a wide range of usage and is conveniently available for engineers and researchers [41].

In this study 3-D, finite element analyses are considered by using ANSYS programs which were used in the field of structural dynamics. Figure 2.1 shows the computational modeling Processes using FEM.
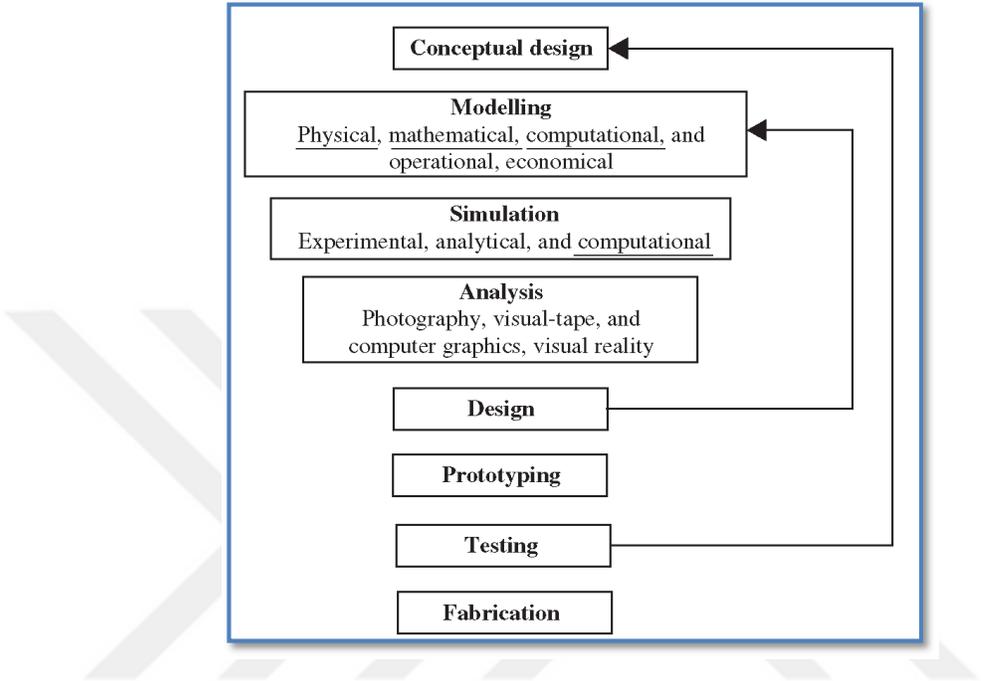
Figure 2.1 FEM computation diagram [5].

2.2.1 ANSYS Workbench Software Package

ANSYS program is engineering simulation software that used dependability to the performance of the product under the real-world environments for all the existing physical phenomena. During the last years, much research work has been in the field of numerical modeling which enable engineers today to perform simulations near to reality. The researcher who uses ANSYS can run simulations for linear and nonlinear problems in engineering where structural nonlinearities may occur due to run nonlinear material behavior, large deformations or contact boundary conditions [42].

Engineers use simulation software, like ANSYS software and its combinations, to perform several types of analysis; such as structural, dynamic, static, thermal, modal, and buckling for both linear and non-linear fields. The calculated finite element analysis results let to optimize designs, by making changes and then quickly repeating the different analyses. Combining simulation software early in the design process will help reduce the

need for costly prototypes and late-stage design changes as well as improve product performance, immortality, and safety.

The finite element method used in ANSYS display an agreement approach to modeling and simulation a Complex structure system. The procedure of computational modeling using the finite element in general consists of six steps:

1- Modelling of the geometry:

Geometric modeling is the performance of physical matter on computers, allowing both reactive and automatic analysis of design, and the transfer of design in a form adequate for industrialization. In ANSYS the geometry can be generated from either of the following options: (1) from within Workbench using design modeler (2) From a CAD system supported by the workbench. There are three types of geometric model, Wireframe modeling, Surface modeling, and Solid Modeling. In this study uses three-dimension solid model to perform finite element analysis (stress, strain, acceleration, and displacement) [43].

2- Specification of material property:

The material property input can be edited to the engineering data module of structural analysis toolbox. In this module, different material definitions can be used as mentioned above. After the material name is defined, the properties such as density, elasticity, plasticity, etc. are given by the user. By using engineering data in ANSYS, we can select a different material for the simulation and define the linear and non-linear material properties for each component of the multibody system.

3- Meshing:

Meshing is the operation in which the geometry of model is spatially discretized into elements and nodes. This mesh over with material properties is used to perform the stiffness and mass distribution of the structure mathematically. The model automatically meshes for further process. The element size by default is determined based on various factors including body curvature, the overall model size, the complexity of the feature and the proximity of other topologies. When required, the mesh size is checked up to four times (eight times for an assembly) till a successful mesh is achieved.in this study hexahedral mesh type was using in the models.

4- Definition of Contact:

One important thing when dealing with multipart geometries is contact between part elements. Contact properties between each part/member of a structure should be well defined in ANSYS. Contact properties can be assigned by using the contact menu in the mechanical module. Contact between the parts can be defined as bonded, no separation, frictionless, frictional or rough. Choosing the correct type of contact is vital regarding simulating the physical problem realistically.

5- Specification of boundary conditions and loading:

ANSYS Workbench makes possible to simulate different boundary conditions and loads, through its support options. In the mechanical program, a support can be assigned to a point, edge or surface. Also, support displacements can be defined from these options. Displacement can be assigned with different values for each step and in a different direction so that the cyclic displacement can easily be defined, and through load options, we can assign to a point, edge or surface different type of loadings such as force, pressure, moment and others.

6- Solve the model and Review the results:

The analysis type determines the results available for the user to examine after Solution. The result in the mechanical application section lists various results available for post-processing.

2.2.2 Dynamic Analysis of Structures Using Numerical Methods

The dynamic analysis can be defined as the response analysis of structures subjected to dynamic loadings like earthquake, wind and vibration loads. The dynamic response of a building structure based on its dynamic properties and characters of input loads. Dynamic analysis can be performed to obtain, mode shape, displacements, acceleration and time history results. In the last years, the development of the structural design system of building and due to increasing demands for better performance of structures, engineers must have better dynamic testing and analysis tools than in the past. The dynamic behavior of the structure needs to be understood and, subsequently, an accurate dynamic model needs to be developed. Analyses of the dynamic behavior of the structure with such a model can reduce development cost and test effort [44]. Moreover, due to the discretization process of a continuous structure with finite elements the following equation of motion can be derived:

$$M \cdot \ddot{u} + C \cdot \dot{u} + K \cdot u = f(t) \qquad\qquad (1)$$

Where M denotes the structural mass, C denotes damping and K denote the structural mass stiffness matrices. The vectors of nodal accelerations, velocities, and displacements are ü, û and u respectively. F (t) is the vector of applied forces. Dynamical equilibrium is obtained if equation (1) holds for all times t.

All problems in structural dynamics can be formulated based on the above equation of motion (1). A classification is obtained by taking different representations for the time-varying applied forces. For this classification Figure, 2.2 presents a diagram where several analysis types of structural dynamics are listed according to the representation of the applied load [44].
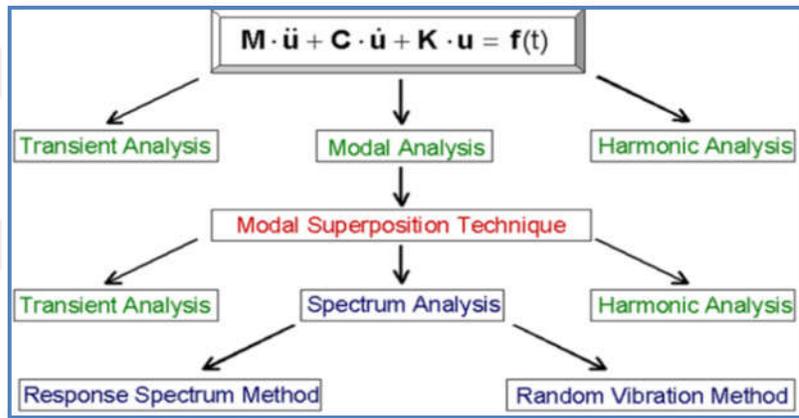
Figure 2.2 Classification of problems in structural dynamics [5].

In the following sections, we briefly describe the different analysis types mentioned in the above Figure 2.2. We also discuss present solution algorithms of ANSYS and describe practical applications for each type of dynamic analysis.

2.2.2.1 Modal Analysis

A modal analysis is used to determine the vibration characteristics of a structure while it is being designed. Hence, the goal of a modal analysis is determining the natural frequencies and mode shapes. The right-hand side of the equation of motion (1) is considered to be zero, f(t)= 0. A modal analysis can also be taken as a basis for other more detailed dynamic analyses such as a transient dynamic analysis, a harmonic analysis or even a spectrum analysis based on the modal superposition technique. The modal analysis is a linear analysis. Any nonlinearity which may have been specified by the user is ignored [44].

2.2.2.2 Transient Dynamic Analysis

A transient dynamic analysis is a technique which is used to determine the time history dynamic response of a structure to arbitrary forces varying in time. On the right-hand side of equation (1) any function for the load vector may be specified, i.e. $f(t) = f(t)$. This type of analysis yields the displacement, strain, and stress and force time history response of a structure to any combination of transient or harmonic loads. To obtain a solution for the equation of motion (1) time integration has to be performed. In the literature, several time integration algorithms are discussed in detail [44].

They can be broadly classified into implicit and explicit methods. Considering the stability of these two types of integration methods, we notice that implicit methods are usually unconditionally stable which means that different time step sizes can be chosen without any limitations originating from the method itself [44].

2.3 Dynamic Analysis of Structure on Shaking Table

The development of high-rise buildings design led to complexity and irregularity of structure system. An accurate investigation of their seismic performance is thus necessary to verify the safety of these buildings. In the recent years, much fundamental progress has been made in the development and use of computer-based procedures for seismic analysis of structures. However, it is still hard to accurately predict the seismic performance of a given structure due to the variation between analysis model and real structure. Therefore, it is essential to investigate the dynamic properties of actual structures and discuss the validity of computation.

Dynamic characteristics and responses of the model structures such as acceleration and displacement under different dynamic loads were obtained through analysis and test [45]. Dynamic testing can be classified into three types, i.e., shaking table test, vibration generator test, and free vibration test as shown in Table 2.2.

Table 2.2 Dynamic tests

Test	External force	Results
Shaking table	harmonic or random wave	Elastic resonance curve Time history response
Vibration generator	harmonic wave	Resonance curve
Free vibration	İnitial movement	Time history of free vibration

2.3.1 Operation of Shaking Tables

Shaking table test is an experimental approach used to assure the validity of the theoretical estimation of the response of the structure with the exact dynamic characteristics thus to develop the safety margin of design for the structure. Shaking table is a mechanical device that is used to test any structures under seismic or other types of dynamic loading such wind, vibration, and random load [46]. If the shaking table is designed primarily to test civil structure under seismic loading, then it is also called earthquake simulator. Usually, test model is developed to understand the effects of different parameters and process that leads to failure of the prototype at a real time. If the test model is performed under gravitational field of the earth, then it is subjected to the shaking table test, whereas if the model tests are performed under the higher gravitational field, then it is subjected to the centrifugal test. [46]. In the shaking table test, the specimens are placed on the table, and it is fixed by a mechanical fastener or artificial soil compacted on the table. Then the structure will experience a shaking process at specific frequency values until a specific time limit set by the operator.

The earthquake simulator or shaking table has a wide range of applications such as:

1- Models of buildings or structure in a given scale, subjected to an actual earthquake.
2- Models of power supply or industrial buildings under specific dynamic loading conditions.
3- Mechanical equipment and transportation facilities test.
4- Mechanical testing and development of dampers for power transmission lines.

Shaking table model testing is adopted to investigate the seismic performance of the building structure. The use of shaking table model tests in civil engineering began in 1980. The introduced and discussed the principles of structural model based on the similitude theory, shake table are a necessary testing facility for the development of earthquake resistant techniques. The shaking table is a platform excited with hydraulic actuators to simulate different types of periodic and random motions, such as artificial earthquakes and another dynamic testing. The shaking table test is the only experimental technique available for direct simulation of inertia forces which can be used to simulate different types of motion such as a recorded earthquake, ground motions, sine sweeps, etc. Shake table tests results enhance further the understanding of the behavior of structures and calibration of various numerical tools used for analysis.

2.3.2 Shaking Table Test Producer:

1. Description of the building structure
2. selection the Materials of model
3. Model scaling factor
4. Model design and construction
5. Test program and instruments
6. Experimental results
7. Compare with experimental and numerical analysis results.

2.3.3 The Main Purposes of Shaking Table Test are:

1- To check the free vibrating modes, and the corresponding frequencies and damping ratios of the structural model after different earthquake intensity.

2- To study the seismic responses of accelerations, displacements, and strains.

3- To determine the structural crack positions and the weak points, to verify or find the collapse styles and failure mechanism.

4- To assess the safety reliability of main structures under different earthquake intensity, to verify the rationality and effectiveness of various earthquake-resistant countermeasures.

5- Provide data to validate/calibrate analytical models.

6- Validate design/construction concepts and details.

NUMERICAL MODELS

In this study, models of three type of buildings on shaking table are modeled and simulated under a set of harmonic loadings and an earthquake loading using ANSYS program. The first model was a single story-single bay reinforced concrete (RC) building on shaking table which was supposed to both a set of harmonic loadings and earthquake loadings, respectively. All dynamic loadings were considered to act in one-direction then in two-directions firstly. When an earthquake loading acted in the two-directional, two components of the earthquake loading are considered so that each component acted in a separate direction. The second model was the two story-single bay RC building on shaking table which was just supposed to an earthquake loading acting in one direction and two-direction like in the first example, respectively. The third model was the three-story RC shear wall building on shaking table which was just supposed to an earthquake loading acting in one direction and two-direction like in the second example, respectively. In the examples except for the second one, before applying dynamic loadings, the modal analysis was executed. In this study, the linear analysis is used, and the damping ratio and gravity load are ignored for all models under harmonic loadings.

3.1 Analysis of Model of Single Story-Single Bay RC Building on Shaking Table with an Axial Harmonic Loading

3.1.1 Finite Element Modelling

Modeling and analysis of a single story-single bay RC building on shaking table were performed with ANSYS program in this thesis. ANSYS program is an advanced software package that aims to model the interaction of different disciplines such as physics,

structural, vibration, fluid dynamics, heat transfer and electromagnetic for engineers. ANSYS program has various analysis systems provided in its toolbox, and dynamic analysis is one of them that suited to the finite element analysis study performed in this thesis. This tool has the capability of performing linear and nonlinear analysis, detection of contacts automatically and simplifies the parametric analysis; the solid elements were used with hexahedral mesh including total 98934

Elements, 481328 nodes, and approximately 1.9 million degrees of freedom. The surface-to-surface contact elements were taken into consideration by using some types of contact such as bonded, and no separation. The geometry modeling is shown in Figure 3.1, and modeling details are described as below.

3.1.1.1 Geometric Properties

Three dimensional-modeling approaches were chosen. The geometry of model was created by using ANSYS program, which consisted of a shaking table (Substructure) model and model of the single story-single bay RC building (Superstructure). A shaking table model which had a dimension of 4m by 4 m and bearing capacity of 50 tons, acceleration up to 4.5g for 20 tons and speed up to 1m/sec. The geometry of shaking table was divided into three steel frame layers such as bottom, middle, and top layers and top cover plate as shown in Figure 3.1. The middle layer of shaking table was sliding over bottom layer by cars in the Z-direction, and the top layer was sliding over middle layer in the X-direction by cars. The central section of steel frames consisted of I-section profiles. These frames had contacted each other with cars. In the superstructure each column had dimensions 0.3x0.2x3 m for width, height, and length, respectively, each beam had 0.3x0.2x3 m, slab had 3x3x0.1 m, and bottom base had 3.5x3.5x0.15m for width, length, and thickness as shown in Figure 3.1.
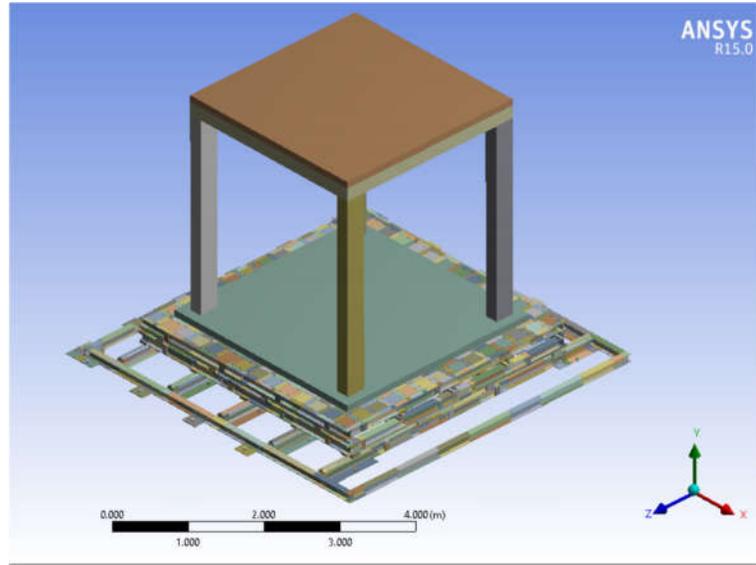
Figure 3.1 Geometry of a model of the single story-single bay RC building
on the shaking table

3.1.1.2 Definition of Materials Properties

Material properties of the model are defined in Table 3.1. The shaking table is made of
steel and the building reinforced concrete.

Table 3.1 Materials properties of model of single-storey building on shaking table

Member	Material	Mass (Ton)	Density (kN/m³)	Young's Modulus (MPa)	Poisson's Ratio	Compressive Strength (MPa)	Tensile Strength (MPa)
Shaking Table	Steel	5.50	76.98	2.00E+05	0.3	250	460
Building	Concrete	8.10	24.6	32000	0.2	40	5

3.1.1.3 Meshing of Model

After simplifying the geometry of the model, the mesh is created by using ANSYS
program. In order to get more accurate results, a hexahedral mesh is used in this model,
including total 98934 elements, 481328 nodes, and approximately 1.9 million degrees of
freedom as shown in Figure 3.2.
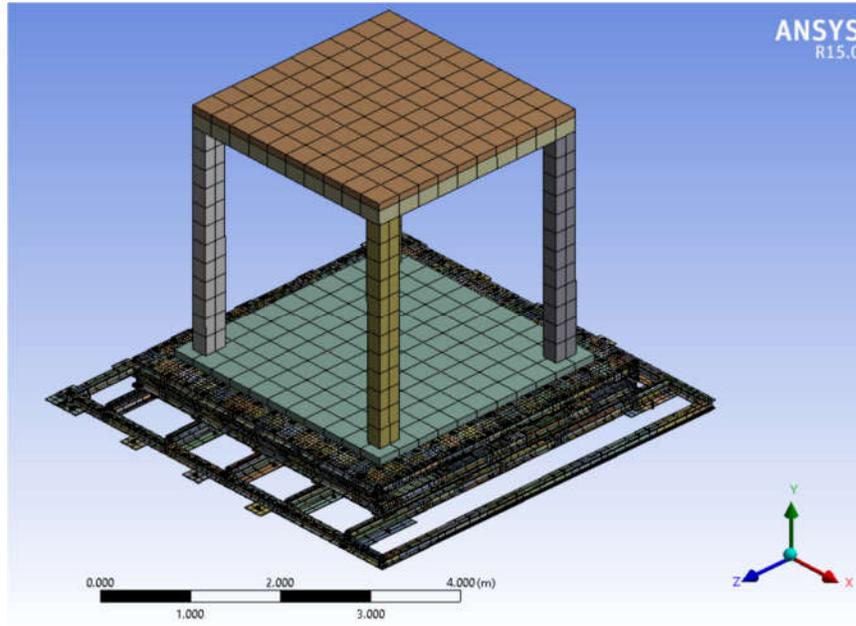
Figure 3.2 Mesh of model of the single story-single bay RC building on the shaking table

3.1.1.4 Definition of Contact

One important issue when dealing with multipart geometries is to handle contacts between parts. Contact properties between each part/member of a structure should be well defined in ANSYS. Contact properties can be assigned by using the contact menu in the mechanical module. Contact between the parts can be defined as bonded, no separation, frictionless, frictional or rough. Choosing the correct type of contact is vital regarding simulating the physical problem realistically. In this model surface to surface, contact is created by using some types of contact such as:

- Bounded: No penetration, no separation and no sliding between contact faces are allowed. The contact type was applied to between top cover plate and the top layer of the steel frame, bottom layer of the steel frame and anchor plates flanges I-section profiles included in the steel frames and side plates, cars, and the steel frames.
- No separation: There are similar motion abilities to bounded contact except frictionless sliding along contact faces. The contact type was implemented between cars and sliding line faces to give the ability of a shaking table to slide in two directions.

23

3.1.1.5 Boundary Conditions

When the dynamic behavior of the shaking table model and the building is simulated, there are two types of boundary conditions are used:

- Fixed support: is deployed on the bottom surface of the shaking table which provides to fix the motion of the model within all directions in applied surfaces.
- Frictionless support: is deployed on the side face of the cover plate and the side face of the top flange to prevent motion of the top layer of the steel frame in the X-direction as shown in Figure 3.3. This support definition was applied when one-directional shaking was considered. Otherwise, it was not applied.
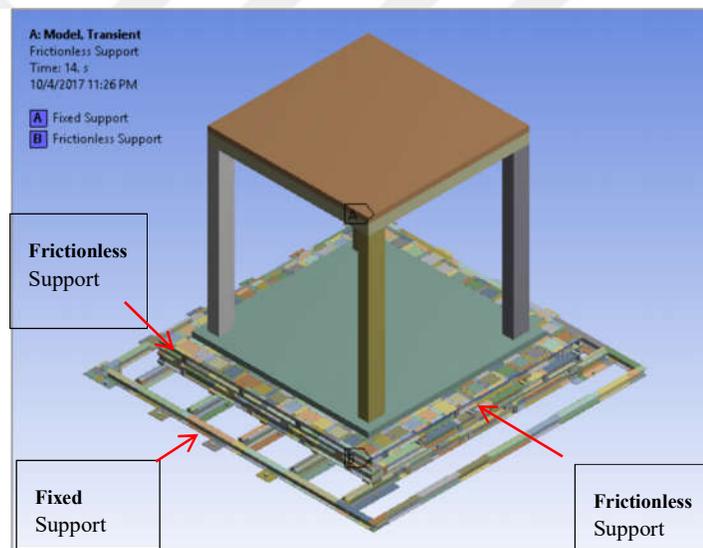
Figure 3.3 Arrangement of the boundary conditions of model of the single story-single bay RC building on the shaking table

3.1.1.6 Definition of an Axial Harmonic Loading

A set of harmonic loads with different frequencies was applied in Z-direction on middle frame layer of a shaking table model. These harmonic loads were developed according to the frequencies of first-three modes of the building (superstructure) as shown in the modal analysis (or free-vibration analysis). Moreover, the frequencies and the produced harmonic loads based on the frequencies were given in Table 3.2, Table 3.3, and Table 3.4. Moreover, they are graphed in Figure 3.4, Figure 3.5, and Figure 3.6, respectively. Three group of harmonic loading, each of which includes six different loads, are presented

so that the loads in each group could produce by scaling the frequency of the related mode of the building. Here, to give a name to the loads, an abbreviation "FL-Mj" was used, where "FL" means the frequency of loading, "i" denotes the number of loading, "M" means mode, and "j" denotes the number of modes. When the load frequency is calculated, a series of scales such as 0.010, 0.025, 0.050, 0.075, 0.100, and 0.125 are used by multiplying these scales with the frequency of the related mode of the building. For example, a load frequency FL1-M1 is calculated as 0.01*7.08 Hz=0.0708 Hz.

Table 3.2 Harmonic loads for first mode (mode-1)

The frequency of the first mode of the building. 7.08 Hz											
FL1-M1=0.0708Hz		FL2-M1= 0.177 Hz		FL3-M1=0.35 Hz		FL4-M1= 0.53 Hz		FL5-M1= 0.7 Hz		FL6-M1=0.89 Hz	
Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)
0	0	0	0	0	0	0	0	0	0	0	0
3.5	0.2	1.4	0.2	0.7	0.2	0.5	0.2	0.35	0.2	0.28	0.2
7	0	2.8	0	1.4	0	1	0	0.7	0	0.56	0
10.5	-0.2	4.2	-0.2	2.1	-0.2	1.5	-0.2	1.05	-0.2	0.84	-0.2
14	0	5.6	0	2.8	0	2	0	1.4	0	1.12	0
17.5	0.2	7	0.2	3.5	0.2	2.5	0.2	1.75	0.2	1.4	0.2
21	0	8.4	0	4.2	0	3	0	2.1	0	1.68	0
24.5	-0.2	9.8	-0.2	4.9	-0.2	3.5	-0.2	2.45	-0.2	1.96	-0.2
28	0	11.2	0	5.6	0	4	0	2.8	0	2.24	0
31.5	0.2	12.6	0.2	6.3	0.2	4.5	0.2	3.15	0.2	2.52	0.2
35	0	14	0	7	0	5	0	3.5	0	2.8	0
38.5	-0.2	15.4	-0.2	7.7	-0.2	5.5	-0.2	3.85	-0.2	3.08	-0.2
42	0	16.8	0	8.4	0	6	0	4.2	0	3.36	0

Table 3.3 Harmonic loads for second mode (mode-2)

The frequency of the second mode of the building. 10.14 Hz											
FL1-M2 = 0.1Hz		FL2-M2 = 0.25 Hz		FL3-M2 = 0.5 Hz		FL4-M2 = 0.76 Hz		FL5-M2 = 1 Hz		FL6-M2 = 1.26 Hz	
Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)
0	0	0	0	0	0	0	0	0	0	0	0
2.5	0.2	1	0.2	0.5	0.2	0.3	0.2	0.25	0.2	0.2	0.2
5	0	2	0	1	0	0.6	0	0.5	0	0.4	0
7.5	-0.2	3	-0.2	1.5	-0.2	0.9	-0.2	0.75	-0.2	0.6	-0.2
10	0	4	0	2	0	1.2	0	1	0	0.8	0
12.5	0.2	5	0.2	2.5	0.2	1.5	0.2	1.25	0.2	1	0.2
15	0	6	0	3	0	1.8	0	1.5	0	1.2	0
17.5	-0.2	7	-0.2	3.5	-0.2	2.1	-0.2	1.75	-0.2	1.4	-0.2
20	0	8	0	4	0	2.4	0	2	0	1.6	0
22.5	0.2	9	0.2	4.5	0.2	2.7	0.2	2.25	0.2	1.8	0.2
25	0	10	0	5	0	3	0	2.5	0	2	0
27.5	-0.2	11	-0.2	5.5	-0.2	3.3	-0.2	2.75	-0.2	2.2	-0.2
30	0	12	0	6	0	3.6	0	3	0	2.4	0

Table 3.4 Harmonic loads for third mode (mode-3)

The frequency of the third mode of the building. 12.75 Hz											
FL1-M3 = 0.127 Hz		FL2-M3 = 0.3 Hz		FL3-M3 = 0.63 Hz		FL4-M3 = 0.95 Hz		FL5-M3 = 1.27 Hz		FL6-M3 = 1.6 Hz	
Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)
0	0	0	0	0	0	0	0	0	0	0	0
2	0.2	0.8	0.2	0.4	0.2	0.25	0.2	0.2	0.2	0.15	0.2
4	0	1.6	0	0.8	0	0.5	0	0.4	0	0.3	0
6	-0.2	2.4	-0.2	1.2	-0.2	0.75	-0.2	0.6	-0.2	0.45	-0.2
8	0	3.2	0	1.6	0	1	0	0.8	0	0.6	0
10	0.2	4	0.2	2	0.2	1.25	0.2	1	0.2	0.75	0.2
12	0	4.8	0	2.4	0	1.5	0	1.2	0	0.9	0
14	-0.2	5.6	-0.2	2.8	-0.2	1.75	-0.2	1.4	-0.2	1.05	-0.2
16	0	6.4	0	3.2	0	2	0	1.6	0	1.2	0
18	0.2	7.2	0.2	3.6	0.2	2.25	0.2	1.8	0.2	1.35	0.2
20	0	8	0	4	0	2.5	0	2	0	1.5	0
22	-0.2	8.8	-0.2	4.4	-0.2	2.75	-0.2	2.2	-0.2	1.65	-0.2
24	0	9.6	0	4.8	0	3	0	2.4	0	1.8	0
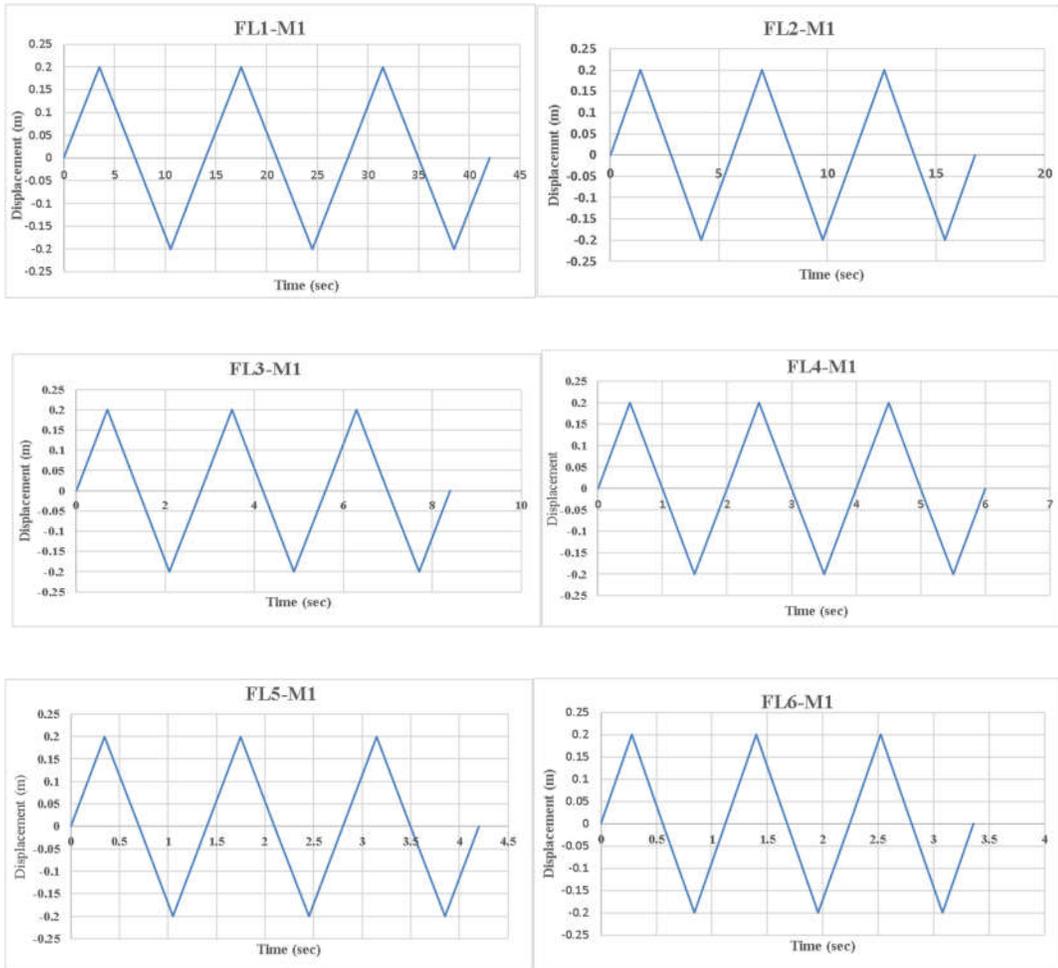
Figure 3.4 Harmonic loads frequencies of the first mode (mode-1)
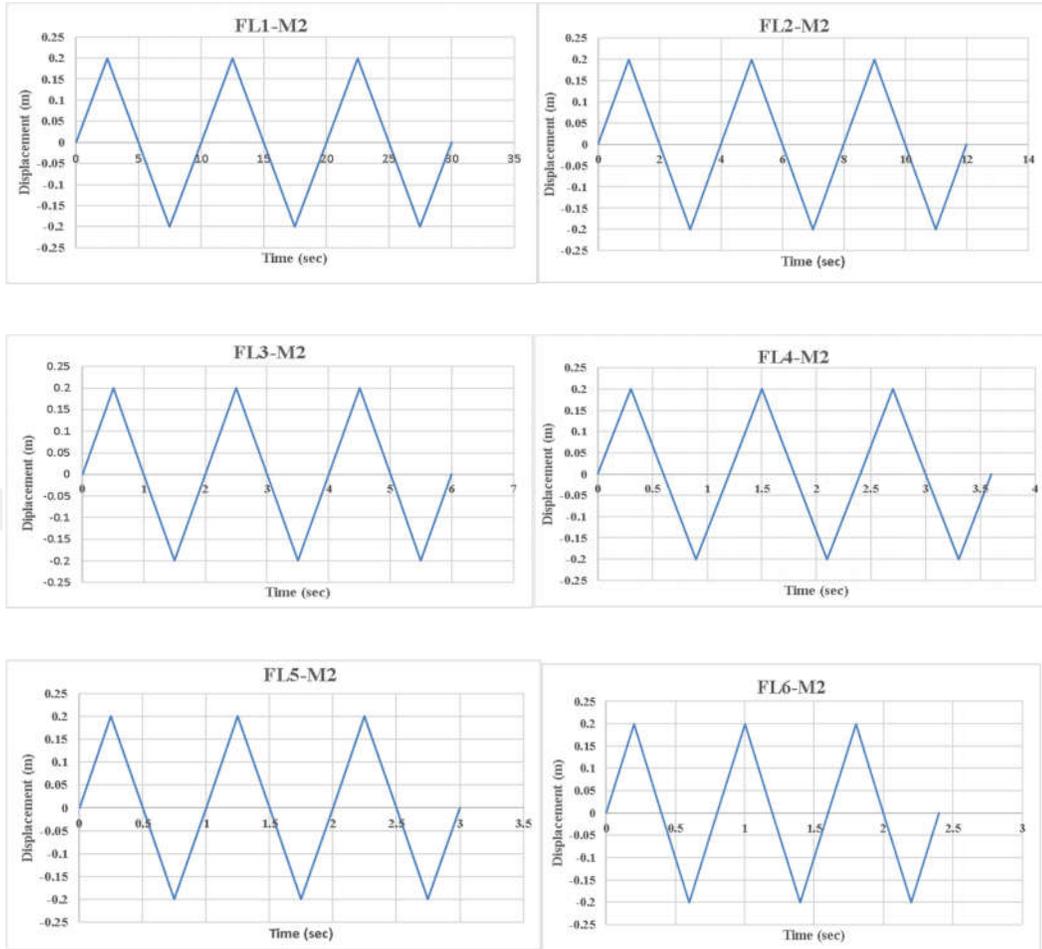
Figure 3.5 Harmonic loads frequencies of the second mode (mode-2)
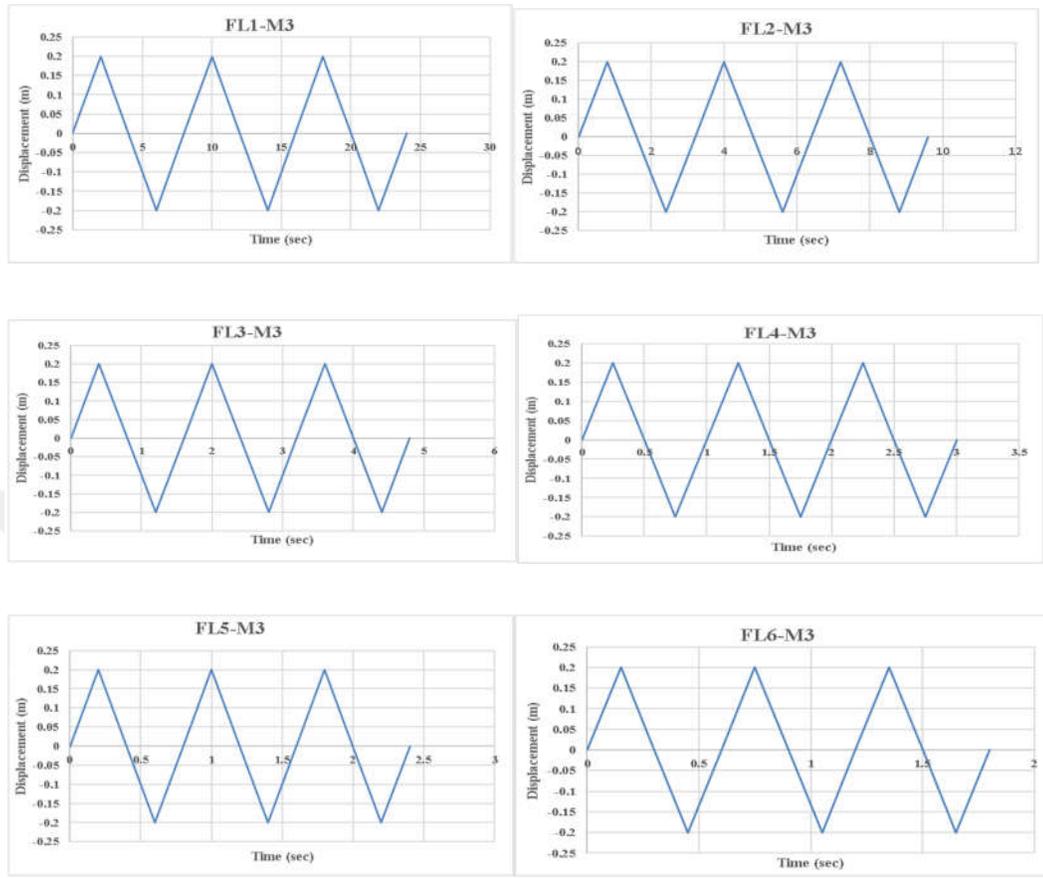
Figure 3.6 Harmonic loads frequencies of the third mode (mode-3)
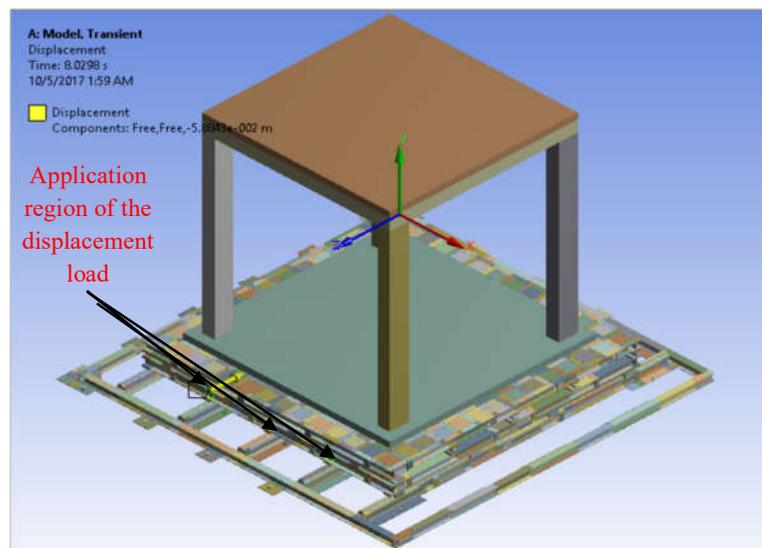
Figure 3.7 Application of an axial harmonic load to the model of the single story-single bay RC building on the shaking table in the Z-direction

3.1.2 Analysis Procedures

Model of the single story RC building on shaking table was performed using ANSYS program to understand the dynamic behavior of the model under the dynamic loads. In this thesis, the parametric studies are used to test the versatility of a model and to identify the importance of the variables in the models.

Therefore, the model is run and tested under a set of the harmonic loads through a set of run analyses. The main idea of the analysis is to obtain a valid and adequate model that can use in the simulation of the structure, and determine the dynamic characteristics of the structure under different loads with different frequency. For this reason, two types of analyzes were running, modal analysis and dynamic analysis. In the modal analysis, frequencies and modes shape of the whole system and sub-systems were separately obtained. Displacement, acceleration, stress, and strain were obtained under the harmonic loadings, and their results were compared.

3.1.2.1 Modal Analysis

Modal analysis was performed to obtain the natural frequencies of three models developed. In the first model, the effect of a shaking table was ignored, and the fixed base is considered for the superstructure. In the second model, a shaking table was included in the model. In the third model, a shaking table was running standalone without an effect of the building. First, three mode shapes are extracted from each model, and the frequencies are compared as shown in Table 3.5.

Table 3.5 Comparisons of frequencies obtained from modal analysis

Mode	Frequency (Hz)		
	Model of Single-story building on shaking table	Model of Single-story building with fixed base	Model of Shaking Table
Mode 1	8.65	7.08	132.19
Mode 2	10.55	10.14	148.43
Mode 3	36.55	12.75	150.02

Three modes of these models are shown in Figure 3.8, Figure 3.9 and Figure 3.10, respectively.
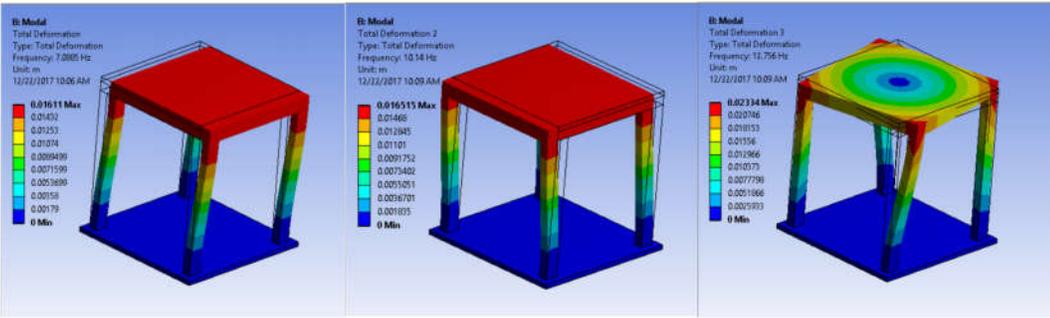
Mode 1: F=7.08 Hz   Mode 2: F=10.14 Hz   Mode 3: F=12.76 Hz

Figure 3.8 First three modes of the model of the single-storey building with fixed base
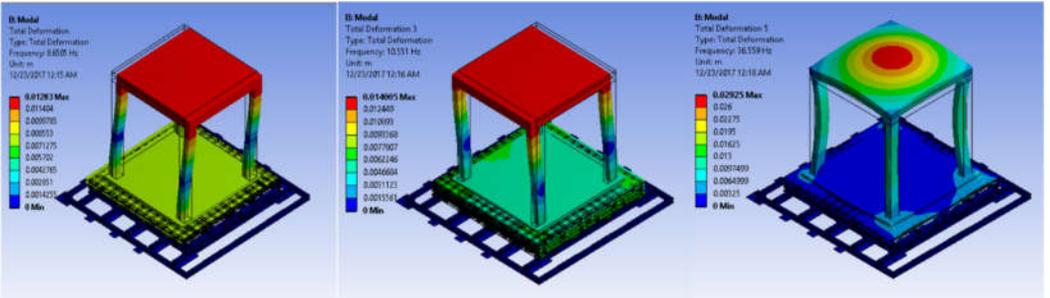
Mode 1: F=8.65 Hz   Mode 2: F=10.55 Hz   Mode 3: F=36.55 Hz

Figure 3.9 First three modes of the model of the single-storey building on shaking table
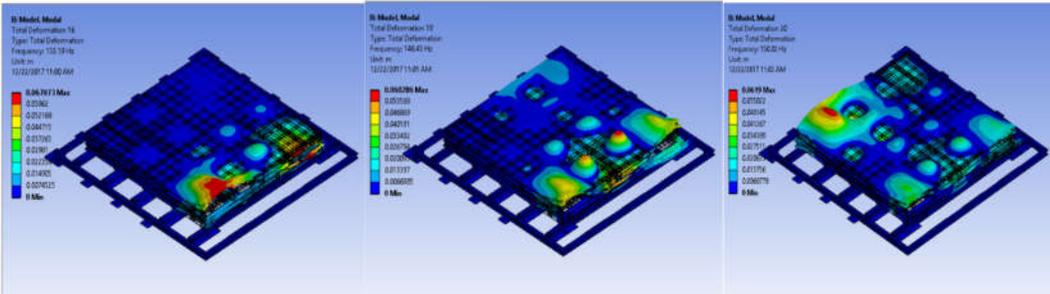
Mode 1: F=132.19Hz   Mode 2: F=148.43Hz   Mode 3: F=150.02Hz

Figure 3.10 First three modes of the model of the shaking table

As can be seen in Table 3.5, while translational modes are compared, the fixed based model is flexible than the shaking table based model so that the shaking table based model yields larger frequency value, that is, the model including shaking table appears stiffer than the fixed based model. There is another observation in Figure 3.8 and Figure 3.9, which is that top floor of the superstructure and shaking table move opposite direction in the translational modes of the shaking table based model. However, to see rigid body mode in the shaking table based model is not expected and it has not been observed in the similar comparison of the fixed based model and shaking table based model in the paper [47] where the building had not base plate.

As seen in Figure 3.10 the shaking table has rigid body modes which are not translational or torsional. First three modes from the fixed based model were selected and used to develop a set of harmonic loads with different frequencies to test the structure system.

3.1.2.2 Dynamic Analysis

In the next step, a linear dynamic analysis was done, and the results such as displacement, acceleration, stress, strain, and drift were obtained using ANSYS program. This type of analysis is used to determine the dynamic response of structures under the action of any general time-dependent loads.

The models such as the single story single bay RC building on shaking table system was investigated under a set of different harmonic loads with various frequencies in the Z-direction. The harmonic loads are produced under the title "An Axial Harmonic Load" before and were developed according to first three modes of the building structure. Six harmonic loads were produced for each mode, but some of them seemed unacceptable in linear behavior, that is, they would create nonlinear deformation. Therefore, 6, 5, and 4 produced harmonic loads were considered for the first, second, and third mode, respectively so that there were 15 feasible harmonic loads. These harmonic loads are applied to the model through a set of run analyses in one direction of the shaking table.

3.1.3 Comparison of the Results and Discussion

After the linear dynamic analysis of the model is run, and ANSYS program obtains the results. The essential dynamic characters such as displacement, acceleration, stress, strain, and drift are taken on a shaking table and on the top floor of a single story building

for a set of run-model which subjected to a set of harmonic loads in the Z-direction. The analysis results for the model are compared to verify the accuracy of the results and understand the dynamic performance of the structure.

3.1.3.1 Acceleration Results

Acceleration results were taken for 15 run-models with various frequencies. Maximum acceleration results of the single story-single bay building on a shaking table with different run-models are given in Table 3.7.

Table 3.6 Maximum acceleration results for model of single story-single bay RC building on shaking table with axial harmonic loads

Mode frequency	Run-Model	Harmonic load Frequency (Hz)	Maximum Acceleration on top floor of building (m/sec^2)	Maximum acceleration on shaking table (m/sec^2)	Softining ratio*
Mode 1=7.08 Hz	Model-1	0.07	0.06	0.06	1.00
	Model-2	0.18	0.40	0.40	1.00
	Model-3	0.35	1.60	1.62	0.99
	Model-4	0.53	12.20	15.13	0.81
	Model-5	0.70	14.08	18.21	0.77
	Model-6	0.84	15.19	16.11	0.94
Mode 2=10.14 Hz	Model-1	0.10	0.13	0.13	1.00
	Model-2	0.25	0.79	0.79	1.00
	Model-3	0.50	12.20	16.11	0.76
	Model-4	0.76	13.38	15.97	0.84
	Model-5	1.00	16.33	22.56	0.72
Mode 3=12.75 Hz	Model-1	0.13	0.20	0.20	1.00
	Model-2	0.30	1.23	1.24	0.99
	Model-3	0.63	10.93	11.84	0.92
	Model-4	0.95	22.56	48.70	0.46
* Softining ratio : ratio of acceleration on top floor of building to acceleration on shaking table.					

As seen Table 3.6, it can be observed that the acceleration values are increased with increasing frequency of harmonic load. Moreover, the acceleration values on the shaking table are higher than the values on the top floor of the building. When it is looked in detail, up to a frequency of harmonic load 0.30 Hz, acceleration on the top floor and the shaking table are the same, that is, rigid body motion it seemed. The rigid body motion corresponds to Model-1 and Model-2 for all modes. After the frequency of harmonic load 0.30 Hz, relative motion starts in all models for all modes, which can be seen when looked to softening ratio (ratio of acceleration of top floor of the building to the acceleration of the shaking table) in Table 3.7. When the frequency of harmonic load increase, softening

ratio for relative motion shows nonlinear behavior, that is, there is not any particular tendency. Maximum accelerations of the top floor of a single story-single bay building and the shaking table are given for the harmonic loads classified according to mode frequencies in Figure 3.11 and Figure 3.12, respectively.
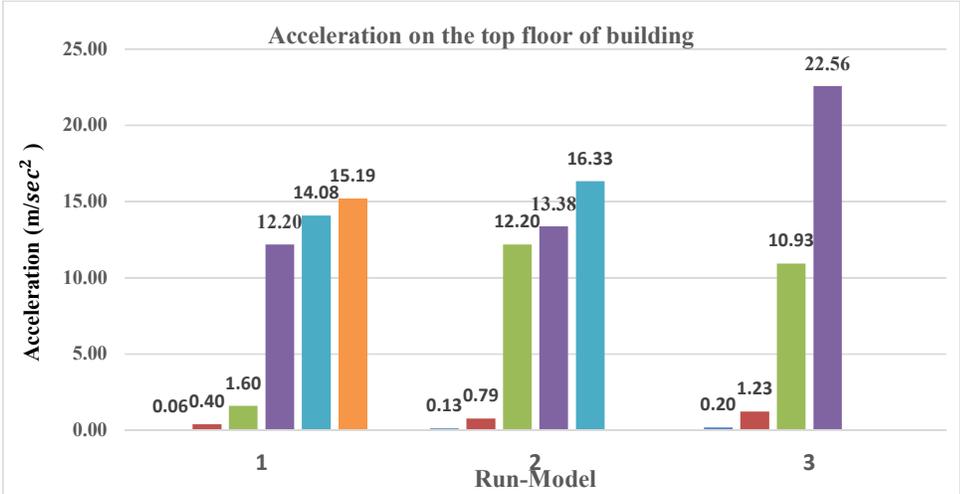
Figure 3.11 Maximum accelerations on the top floor of a single story-single bay building under harmonic loads

Figure 3.12 Maximum accelerations on the shaking table under harmonic loads

As seen in Figure 3.11, maximum acceleration dramatically increases for all modes when the relative motion just occurs. Maximum acceleration in Mode 3 for Model 4 reaches 22.56 m/sec² (2.29 g). As seen in Figure 3.12, the same behavior for maximum

acceleration with that in Figure 3.11 is observed. Maximum acceleration in Mode 3 for Model 4 reaches 48.70 m/sec² (4.96 g). Maximum accelerations of the top floor of a single story-single bay building and the shaking table versus frequencies of harmonic loads are given in Figure 3.13 and 3.14, respectively.

Figure 3.13 Maximum accelerations on the top floor of a single story-single bay building versus frequencies of harmonic loads
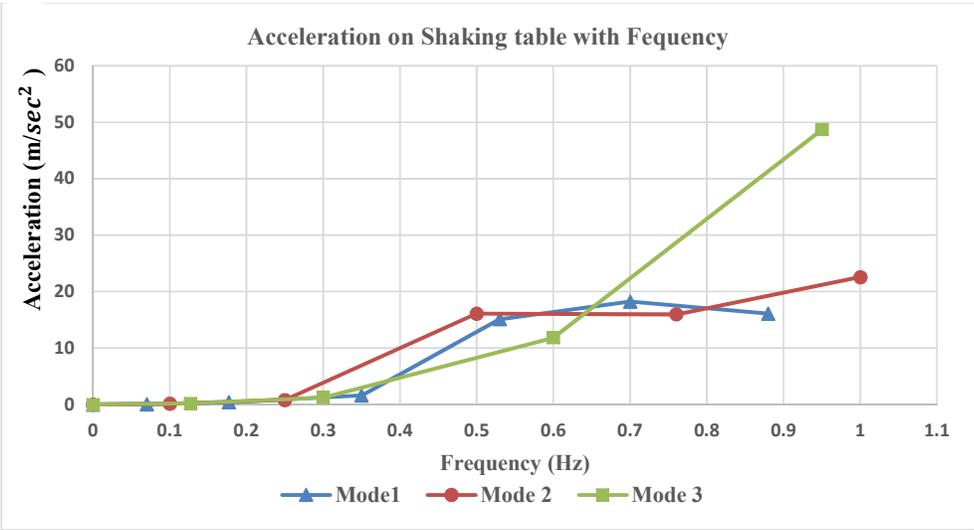
Fig. 3.14 Maximum accelerations on the shaking table model versus frequencies of harmonic loads

As seen in Figure 3.13, there are three strict regions of developing acceleration for all modes. In the first region, tendencies of increasing part of accelerations for all modes are so slow up to approximately 0.3 Hz, but they are exactly same. In the second region,

similar dramatic tendencies of increasing of accelerations for all modes are going to develop up to approximately 0.55 Hz. However, while the tendency of the third mode is going to increase in the same manner of the second region, tendencies of the first and second modes show slow development than those in the second region.

As seen in Figure 3.14, similar observations are shown like in Figure 3.13. However, there is one exception which is that in the third region tendency of the third mode is going to sharply increase comparing to that of the third mode in the second region. Accelerations on the top floor of the building versus time for the first, the second, and the third modes are shown in Figure 3.15, Figure 3.16, and Figure 3.17, respectively.
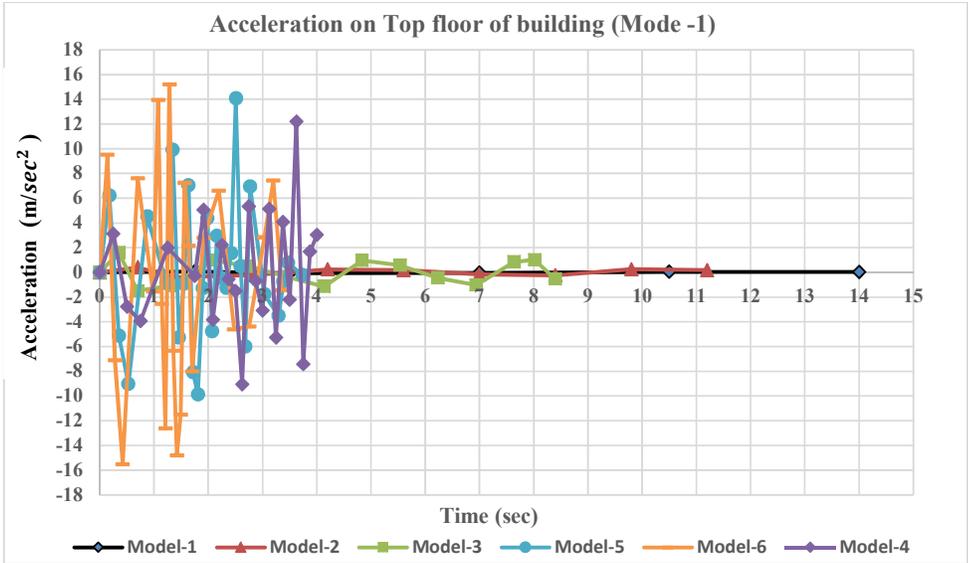
Figure 3.15 Accelerations response on top floor of a single story-single bay building for the first mode
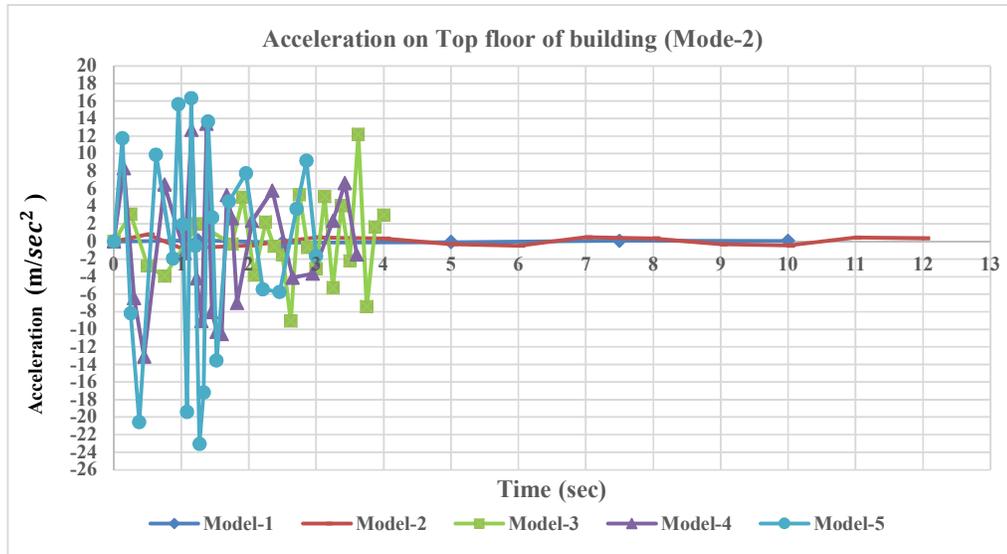
Figure 3.16 Accelerations response on top floor of a single story-single bay building for the second mode
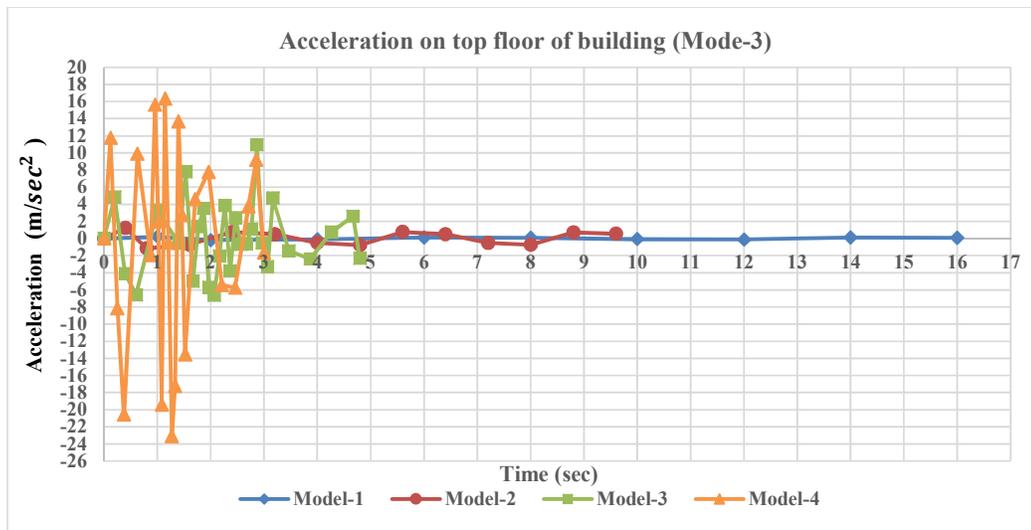
Figure 3.17 Accelerations response on top floor of a single story-single bay building for the third mode

As seen in Figure 3.15, Figure 3.16, and Figure 3.17, it is seen that the amplitudes of acceleration of the models increase with frequencies of the harmonic loads. Behaviors of maximum accelerations versus frequencies are similar to those of amplitudes of accelerations in time.

3.1.3.2 Displacement Results

Maximum displacements were taken on the top floor and bottom base of a single story-single bay building in the Z-direction. Maximum displacements on the top floor and bottom base of the building and drift for 15 run-models are given in Table 3.7, where the drift is denoted as deference of displacement between the top floor and upper floor of the building.

Table 3.7 Maximum displacement results and drift for model of single story- single bay building on shaking table with axial harmonic loads

Mode frequency	Run-Model	Harmonic load Frequency (Hz)	Maximum displacement on top floor of building (m)	Maximum displacement on base of building (m)	Drift
Mode 1=7.08 Hz	Model-1	0.07	0.2001	0.20000	0.00002
	Model-2	0.18	0.2004	0.20002	0.00013
	Model-3	0.35	0.2016	0.20006	0.00052
	Model-4	0.53	0.2031	0.20024	0.00095
	Model-5	0.70	0.2060	0.20037	0.00186
	Model-6	0.84	0.2087	0.20041	0.00285
Mode 2=10.14 Hz	Model-1	0.10	0.2001	0.20001	0.00004
	Model-2	0.25	0.2008	0.20003	0.00026
	Model-3	0.50	0.2031	0.20012	0.00099
	Model-4	0.76	0.2078	0.20033	0.00248
	Model-5	1.00	0.2104	0.20045	0.00332
Mode 3=12.75 Hz	Model-1	0.13	0.2002	0.20001	0.00006
	Model-2	0.30	0.2013	0.20005	0.00040
	Model-3	0.63	0.2047	0.20019	0.00150
	Model-4	0.95	0.2104	0.20045	0.00332

As seen in Table 3.7, the displacement values are slowly increased with increasing frequency of harmonic load for all modes. Moreover, the drifts in all cases seem less than 0.01 [47]. Therefore, it can be said that the building (superstructure) is in the level of linearity for all cases. Moreover, another point that the maximum displacement results approximately are the similar to input displacement. Maximum displacement and drift on the top floor of a single story-single bay building versus frequencies of harmonic loads are given in Figure 3.18 and Figure 3.19 respectively.

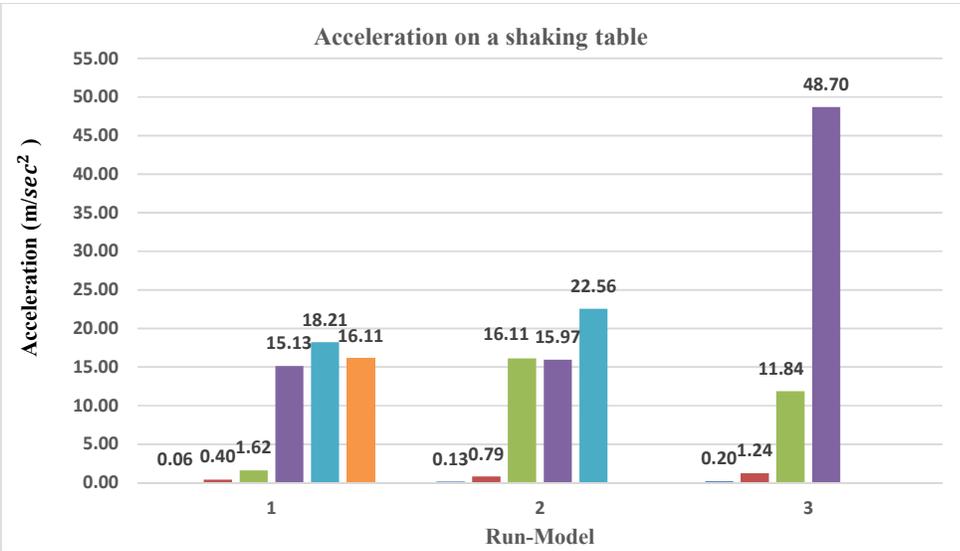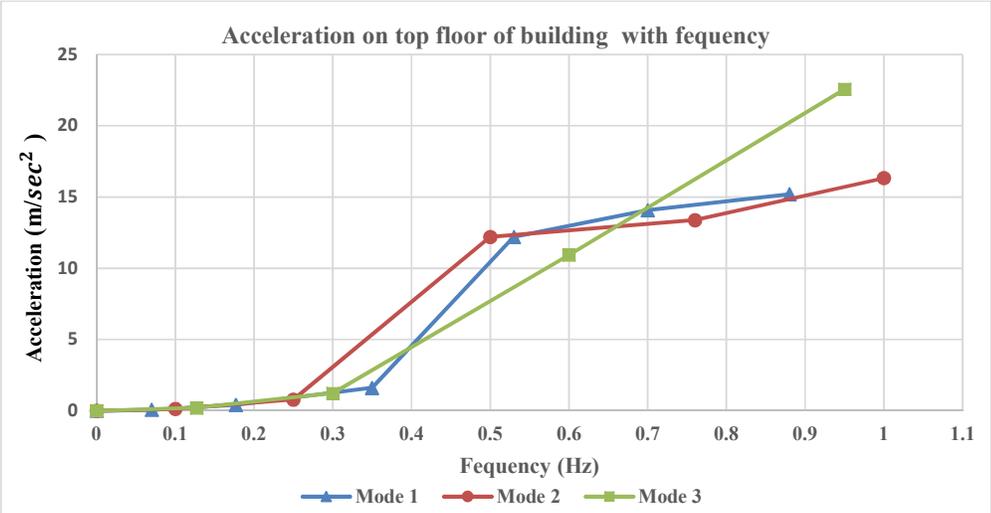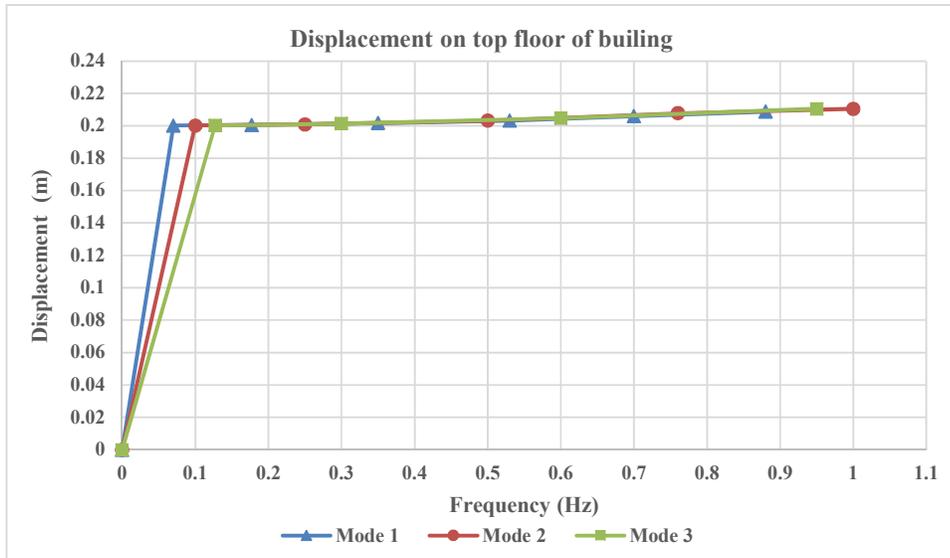Figure 3.18 maximum displacement on the top floor of a single story-single bay building versus frequency
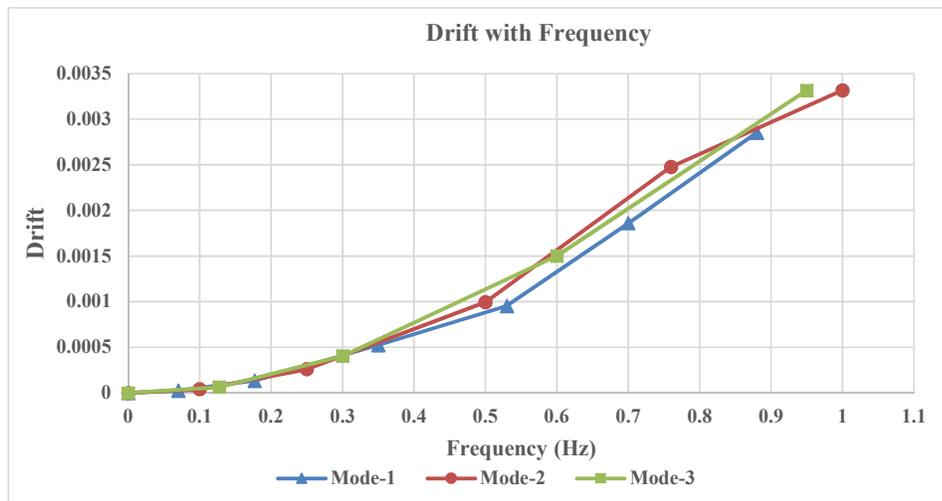
Figure 3.19 maximum drift on the top floor of a single story-single bay building versus frequency

As seen in Figure 3.18, displacement of the top floor of the building does not develop so much. As seen in Figure 319, there are two regions of developing the drift for three modes. It can be observed in the first region that the tendencies of increasing of drift curves are parabolic up to 0.3 Hz, then the tendencies keep going approximately as linear in the second region.

3.1.3.3 Stress and Strain Results

To check the overall strengths of the superstructure and the shaking table and to determine the weakness positions, the maximum equivalent stress and strain for the shaking table and the superstructure were separately obtained for 15 run- models which are subjected to a set of harmonic loads. Maximum equivalent stress and strain for different run-models are given in Table 3.8.

Table 3.8 Maximum equivalent stress and strain for model of single storey single bay building on shaking table with axial harmonic loads

Mode frequency	Run-Model	Harmonic load Frequency (Hz)	Maximum equivalent Stress on building (Mpa)	Maximum equivalent Stress on shaking table (Mpa)	Maximum equivalent Strain on building (m/m)	Maximum equivalent Strain on shaking table (m/m)
Mode 1=7.08 Hz	Model-1	0.07	0.02	0.14	0.000001	0.000001
	Model-2	0.18	0.04	0.21	0.000002	0.000001
	Model-3	0.35	0.74	4.11	0.000037	0.000021
	Model-4	0.53	10.75	57.00	0.000534	0.000294
	Model-5	0.70	7.76	77.99	0.000386	0.000444
	Model-6	0.84	8.18	71.93	0.000407	0.000409
Mode 2=10.14 Hz	Model-1	0.10	0.09	0.27	3.72E-09	0.000001
	Model-2	0.25	0.05	0.49	0.0000045	0.000003
	Model-3	0.50	8.18	71.93	0.000407	0.000409
	Model-4	0.76	7.31	68.85	0.000364	0.000392
	Model-5	1.00	8.81	96.35	0.000439	0.000549
Mode 3=12.75 Hz	Model-1	0.13	0.02	0.08	0.000001	0.000000
	Model-2	0.30	0.16	0.85	0.000008	0.000004
	Model-3	0.63	4.46	22.65	0.000221	0.000117
	Model-4	0.95	8.81	96.35	0.000439	0.000549

As seen in Table 3.8, it can be observed that the maximum equivalent stress and strain values are increased with increasing frequencies of the harmonic load. Moreover, the maximum equivalent stress and strain values on the shaking table are higher than the values of the building. Another important point is that stress created by the set of harmonic loads is in the linear material level of the shaking table and the superstructure. The maximum equivalent stress of the building and the shaking table versus frequencies of harmonic loads are given in Figure 3.20, and Figure 3.21, respectively.
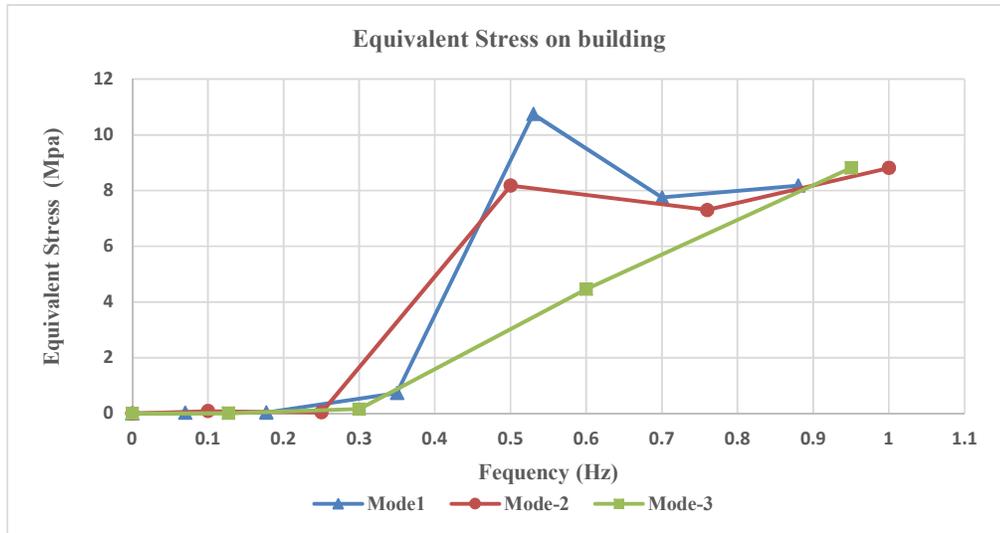
Figure 3.20 Maximum equivalent stress on a single story single bay building versus frequency
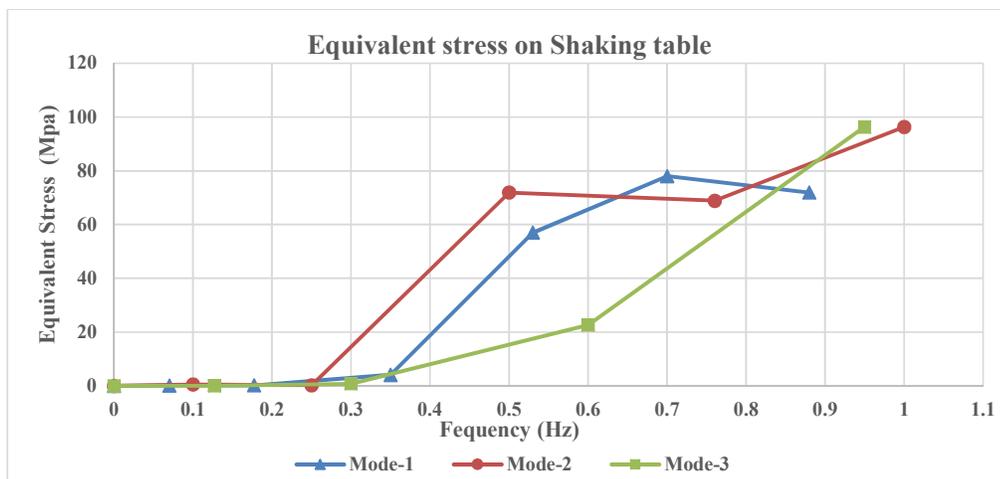
Figure 3.21 Maximum equivalent stress on the shaking table model versus frequency

As seen in Figure 3.20 and Figure 3.21, respectively, there are two strict regions of developing the maximum equivalent stresses of the building and the shaking table for all modes. In the first region, the tendencies of increasing of equivalent stress for all modes up to approximately 0.3 Hz are so slow and exactly have the same values. However, in the second region, the tendency of the maximum equivalent stress for each mode changes differently. Therefore, characters of the maximum equivalent stress of the building and the shaking table change nonlinearly according to frequencies of the harmonic loads.

3.2 Analysis of Model of Single Storey-Single Bay R.C Building on Shaking Table with Biaxial Harmonic Loadings

The same model (shaking table and a single story-single bay building model) is used with the same geometry, material properties, contact, and mesh. This model is run and simulated under a set of harmonic loads, this harmonic loads which developed according to the natural frequency of the building structure are defined in the two directions, Z- and X-directions in two cases. In the first case the harmonic loads are applied in two directions with phase, and in the second case, the harmonic loads are applied at the same time without phase. The boundary conditions are defined as fixed support on the bottom frame layer of a shaking table.

3.2.1 Definition of Biaxial Harmonic Loads with Phase

In this case, five run-models are performed to verify the behavior of the model under circular dynamic load. Where the harmonic loads are defined in two directions; in the Z-direction a set of harmonic loads are applied which developed according to the first mode (frequency=7.08 Hz) as shown in Table 3.9 and Figure 3.22. Moreover, in the X-direction, a set of harmonic loads are applied with a phase which developed according to the second mode (frequency=10.14) as shown in Tables 3.10 and Figure 3.23.

Table 3.9 Biaxial harmonic loads in Z-direction (Fi-Mj-Z)

The frequency of the first mode of the building. 7.08 Hz									
FL1-M1=0.0708Hz		FL2-M1= 0.177 Hz		FL3-M1=0.35 Hz		FL4-M1= 0.53 Hz		FL5-M1= 0.7 Hz	
Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)
0	0	0	0	0	0	0	0	0	0
3.5	0.2	1.4	0.2	0.7	0.2	0.5	0.2	0.35	0.2
7	0	2.8	0	1.4	0	1	0	0.7	0
10.5	-0.2	4.2	-0.2	2.1	-0.2	1.5	-0.2	1.05	-0.2
14	0	5.6	0	2.8	0	2	0	1.4	0
17.5	0.2	7	0.2	3.5	0.2	2.5	0.2	1.75	0.2
21	0	8.4	0	4.2	0	3	0	2.1	0
24.5	-0.2	9.8	-0.2	4.9	-0.2	3.5	-0.2	2.45	-0.2
28	0	11.2	0	5.6	0	4	0	2.8	0
31.5	0.2	12.6	0.2	6.3	0.2	4.5	0.2	3.15	0.2
35	0	14	0	7	0	5	0	3.5	0
38.5	-0.2	15.4	-0.2	7.7	-0.2	5.5	-0.2	3.85	-0.2
42	0	16.8	0	8.4	0	6	0	4.2	0

Fig 3.22 Biaxial harmonic loads in the Z-direction without phase

Table 3.10 Biaxial harmonic loads with phase-in the X-direction (Fi-Mj-X)

The frequency of the second mode of the building. 10.14 Hz									
FL1-M2 = 0.1 Hz		FL2-M2 = 0.25 Hz		FL3-M2 = 0.5 Hz		FL4-M2 = 0.76 Hz		FL5-M2 = 1 Hz	
Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)
0	0	0	0	0	0	0	0	0	0
2.5	0	1	0	0.5	0	0.3	0	0.25	0
5	0.2	2	0.2	1	0.2	0.6	0.2	0.5	0.2
7.5	0	3	0	1.5	0	0.9	0	0.75	0
10	-0.2	4	-0.2	2	-0.2	1.2	-0.2	1	-0.2
12.5	0	5	0	2.5	0	1.5	0	1.25	0
15	0.2	6	0.2	3	0.2	1.8	0.2	1.5	0.2
17.5	0	7	0	3.5	0	2.1	0	1.75	0
20	-0.2	8	-0.2	4	-0.2	2.4	-0.2	2	-0.2
22.5	0	9	0	4.5	0	2.7	0	2.25	0
25	0.2	10	0.2	5	0.2	3	0.2	2.5	0.2
27.5	0	11	0	5.5	0	3.3	0	2.75	0
30	-0.2	12	-0.2	6	-0.2	3.6	-0.2	3	-0.2
32.5	0	13	0	6.5	0	3.9	0	3.25	0

42
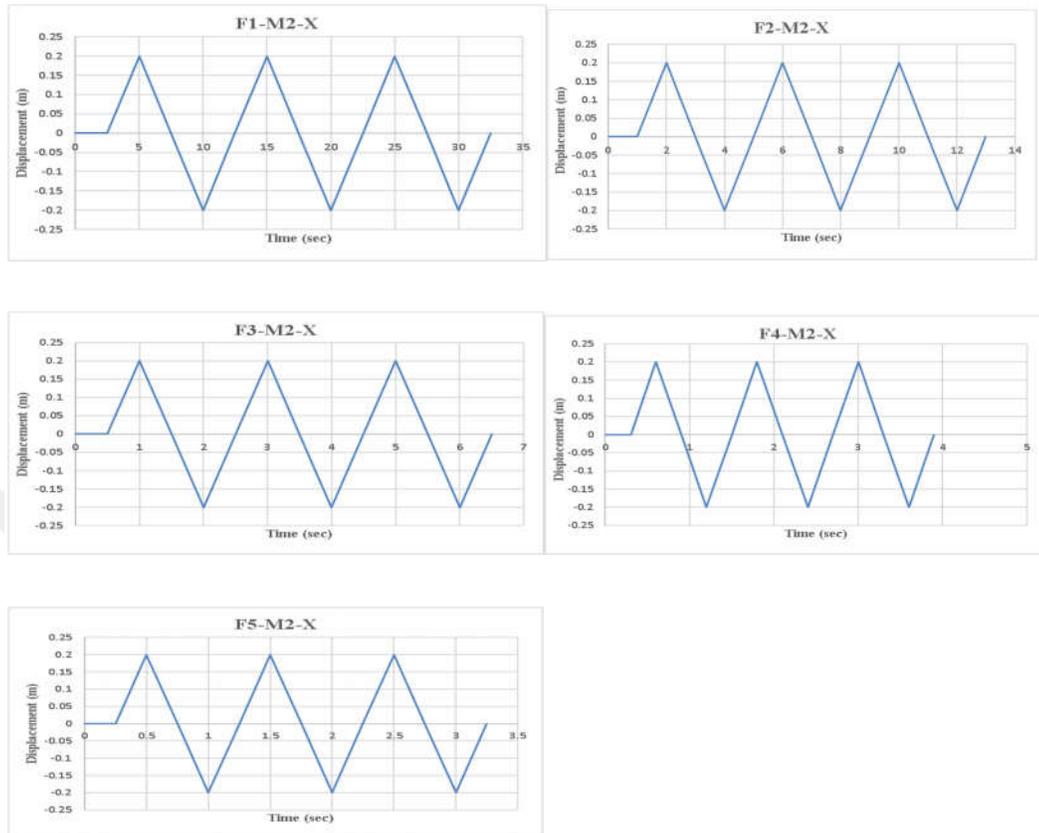
Figure 3.23 Biaxial harmonic loads in the X-direction with phase

Figure 24 given the application of harmonic loads where applied in two directions, in the Z-direction the harmonic loads applied in the middle plane of the shaking table and the X-direction the harmonic loads applied in the top plane of the shaking table.
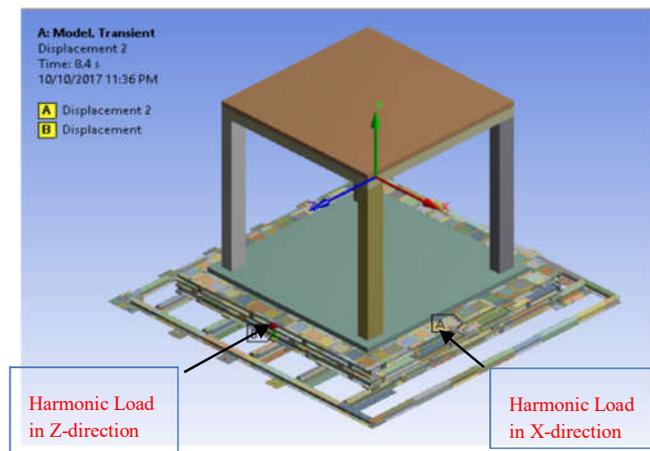

Figure 3.24 Application of Biaxial harmonic loads on model of single story-single bay building on shaking table in the Z and X directions

3.2.2 Comparison the Results and Discussion

In this case, results such as displacement, acceleration, stress, and strain are obtained for five run-models subjected to a set of harmonic loads in two directions with phase. Comparison results of acceleration, displacement, and drift on the top floor of the building and the shaking table in the Z and X directions are given in Table 3.11.

Table 3.11 Displacement, acceleration and drift results of model of single story-single bay building on shaking table under biaxial harmonic loads

Run-Model	Frequency of harmonic load (Hz)		Max acceleration on top floor of building (m/Sec^2)		Max. acceleration on the shaking table (m/sec^2)		Max.displacement on top floor of building (m)		Max.drift on top floor of building	
	Z	X	Z	X	Z	X	Z	X	Z	X
Model-1	0.07	0.10	0.28	0.33	0.28	0.38	0.177	0.176	0.00008	0.0003
Model-2	0.18	0.25	2.26	2.52	2.81	3.23	0.178	0.193	0.00048	0.0003
Model-3	0.35	0.50	4.80	10.64	7.12	16.76	0.190	0.186	0.00013	0.0001
Model-4	0.53	0.76	6.17	11.09	7.47	30.12	0.175	0.184	0.00051	0.0021
Model-5	0.70	1.00	11.13	14.33	11.80	11.10	0.164	0.189	0.00028	0.0006

As seen Table 3.11, the maximum acceleration values are increased with increasing frequencies of harmonic loads. The maximum acceleration values on shaking table are higher than the maximum acceleration on the top floor of building in two directions. Moreover, the acceleration values in the X-direction are higher than the accelerations in the Z-direction since applied load frequencies in the X-direction are higher than those of in the Z-direction. Maximum accelerations in the Z-direction and X-direction on the top floor of a single story-single bay building and shaking table under biaxial harmonic loads are given in Figure 3.25 and Figure 3.26, respectively.
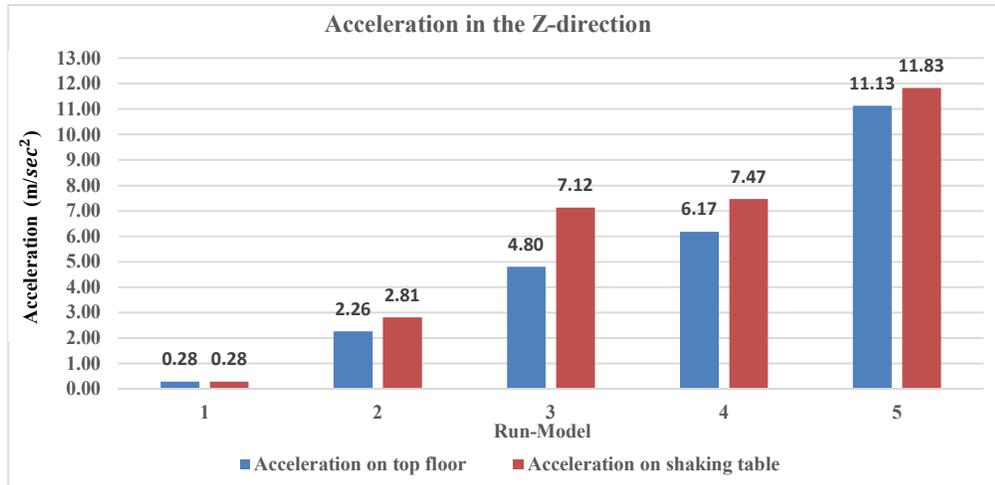
Figure 3.25 Maximum acceleration on top floor of a single story building and shaking table model under biaxial harmonic loads in the Z-direction

Fig 3.26 Maximum acceleration on top floor of a single story-single bay building and shaking table under biaxial harmonic load in the X direction

As seen in Figure 3.25 and Figure 3.26, maximum accelerations in the Z-direction and X-direction are increased smoothly, and the highest value is in run-model five which reaches 11.8 m/sec² and 30.12 m/sec² respectively. Furthermore, maximum acceleration on the top floor of building and shaking table versus frequencies of harmonic loads in the Z-direction and X-direction are given in Figure 3.27 and Figure 3.28, respectively.

Figure 3.27 Maximum acceleration for model of single storey building on shaking table under biaxial harmonic loads versus frequency in the Z-direction
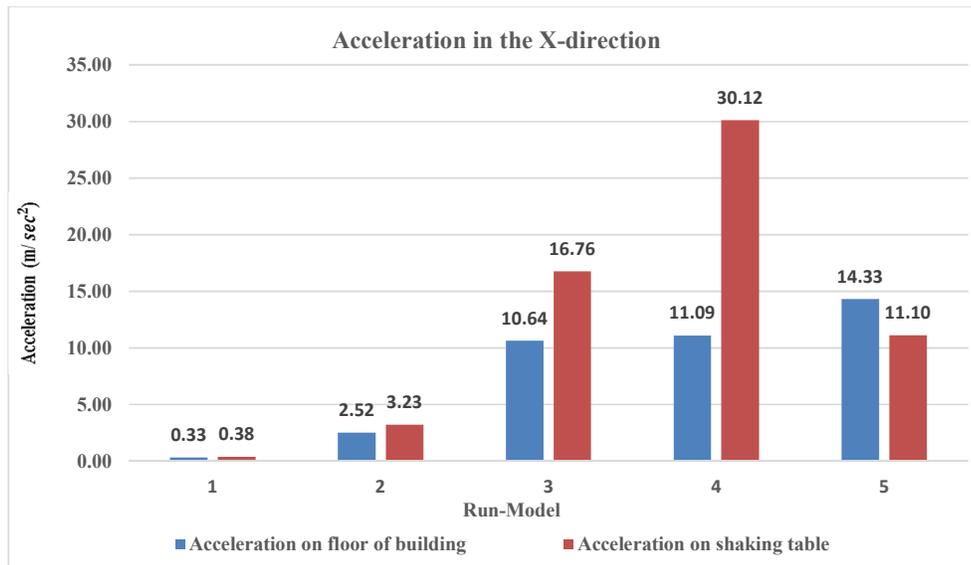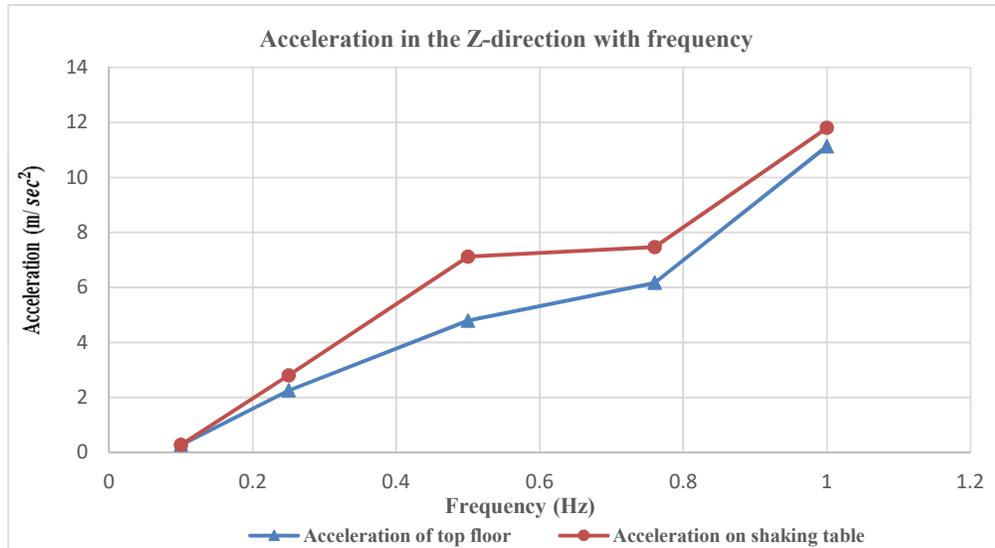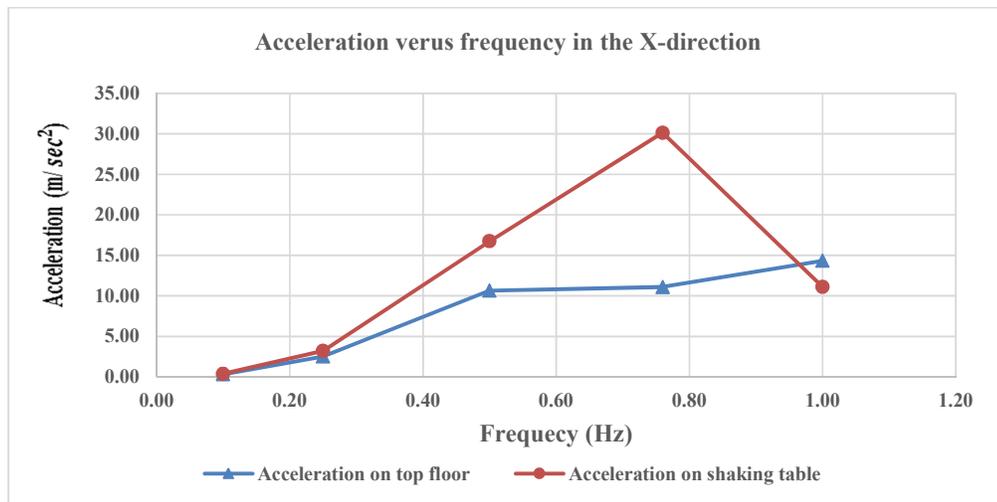

Figure 3.28 Maximum acceleration for model of single story building on shaking table under biaxial harmonic loads versus frequency in the X-direction

As seen in Figure 3.27, maximum acceleration of the shaking table has a trend increasing in frequency, while that of the top floor slows an increasing trend up to 0.5 Hz. However, between 0.5 Hz and 0.75 Hz acceleration response of the shaking table is stationary while that of the top floor keeps going with a slow increasing tendency compared to the tendency in the range of 0.1-0.5 Hz. After 0.75 Hz, the tendency of maximum acceleration of the top floor and the shaking table is approximately same. As seen in Figure 3.28, the behavior of maximum acceleration of the top floor and shaking in the X-

46

direction up to 0.5 Hz is seen in the Z-direction up to 0.75 Hz. However, after 0.75 Hz tendency of the maximum acceleration of the top floor starts to decrease and reaches the less value than that of the shaking table while the maximum acceleration of the shaking table follows slow increasing tendency. Maximum displacements on the top floor and base of a single story-single bay building in the Z and X directions are described in Figure 3.29 and Figure 3.30, respectively.

Figure 3.29. Maximum displacement of the top floor and base of a single story-single bay building under biaxial harmonic loads in the Z-direction
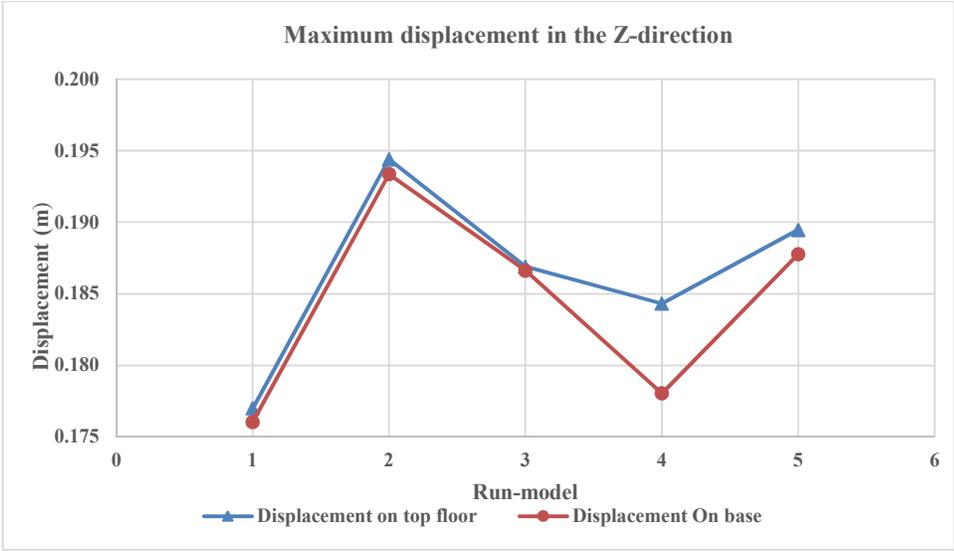

Figure 3.30 Maximum displacement of the top floor and base of a single story-single bay building under biaxial harmonic loads in the X-direction

As seen in Figure 3.29 and Figure 3.30, the tendencies of maximum displacement on top floor and base of the building are developed similarly in the Z and X-direction. Moreover, the highest value of displacement is measured in run-model 2 in the Z-direction and run-model 3 in the X-direction. Maximum drifts on the top floor of a single story-single bay building in the Z and X-direction are given in in Figure 3.31.
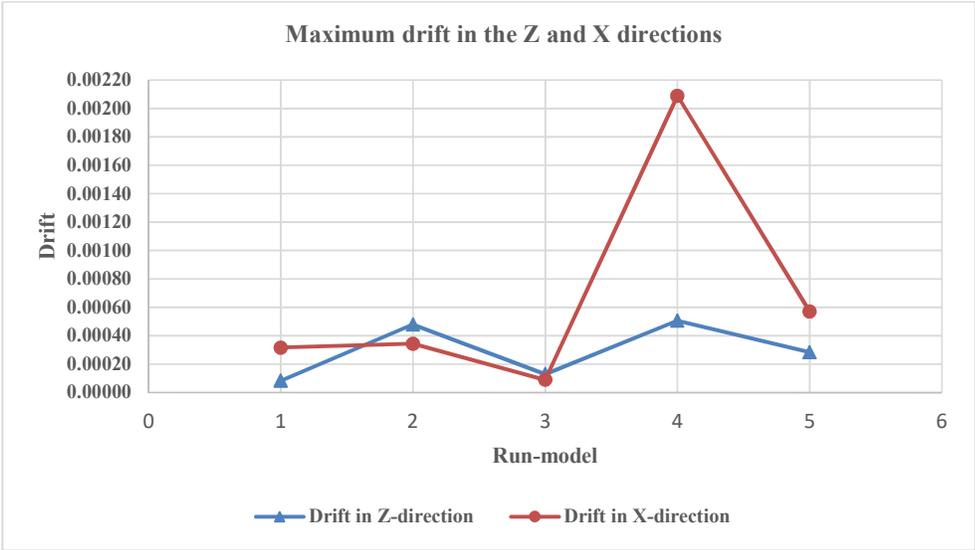

Figure 3.31 Maximum drift on the top floor of a single storey building under biaxial harmonic loads with phase in the Z and X-direction

As seen in Figure 3.31, Maximum drifts in all models seem less than 0.01 [47], which can be limit of linear deformation for reinforced concrete buildings. Therefore, it can be said that the building (superstructure) is in the level of linearity for all cases. Maximum equivalent stress and strain for different run-models are given in Table 3.12.

Table 3.12 Maximum equivalent stress and strain for model of a single story building on shaking table under biaxial harmonic loads

Run-Model	Frequency of harmonic load (Hz)		Max.equivalent stress of building (Mpa)	Max.equivalent stress of shaking table (Mpa)	Max.equivalent strain of building (m/m)	Max.equivalent strain of shaking table (m/m)
	Z	X				
Model-1	0.07	0.10	1.66	8.9	0.00005	0.00006
Model-2	0.18	0.25	14.79	78.9	0.00047	0.00053
Model-3	0.35	0.50	7.62	181.7	0.00025	0.00104
Model-4	0.53	0.76	5.09	244.8	0.00026	0.00142
Model-5	0.70	1.00	33.82	185.0	0.00107	0.00161

As seen in Table 3.12, the maximum equivalent stress and strain are increased with increasing frequencies of the harmonic load. Moreover, the equivalent stress and strain on shaking table seemed higher than the values of the building. For more explanation, the maximum equivalent stress of the building and shaking table are given in Figure 3.32 classified according to run-models.
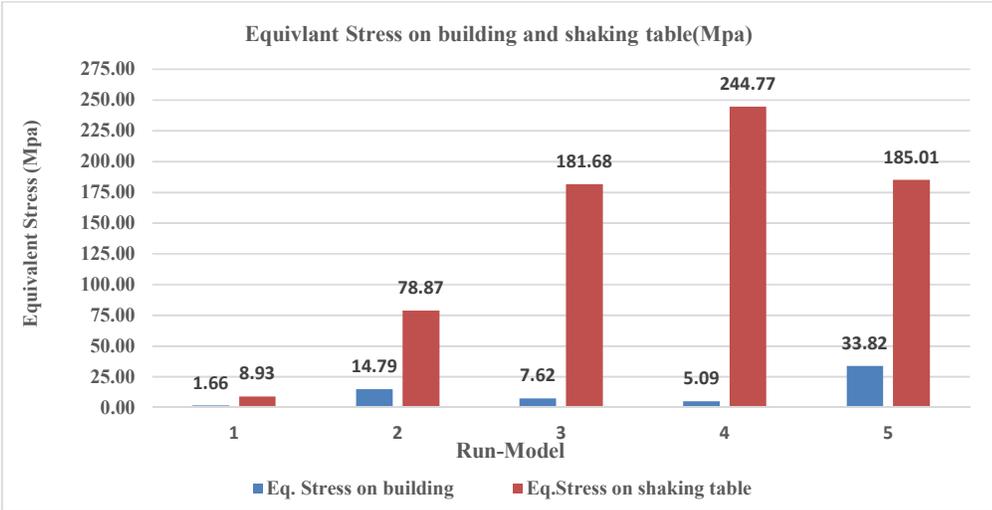

Figure 3.32 Maximum equivalent stress of a single story-single bay building under biaxial harmonic loads

As seen in Figure 3.32, the maximum equivalent stress of building and shaking table have variable behavior for all run-models. Moreover, the highest equivalent stress of building is measured in run-model 5 reaches 33.82 MPa, and the highest equivalent stress of shaking table is measured in run-model 4 reaches 244.77 MPa. Figure 3.33, shown the maximum equivalent stress of a single story-single bay building and shaking table versus frequencies of harmonic loads.

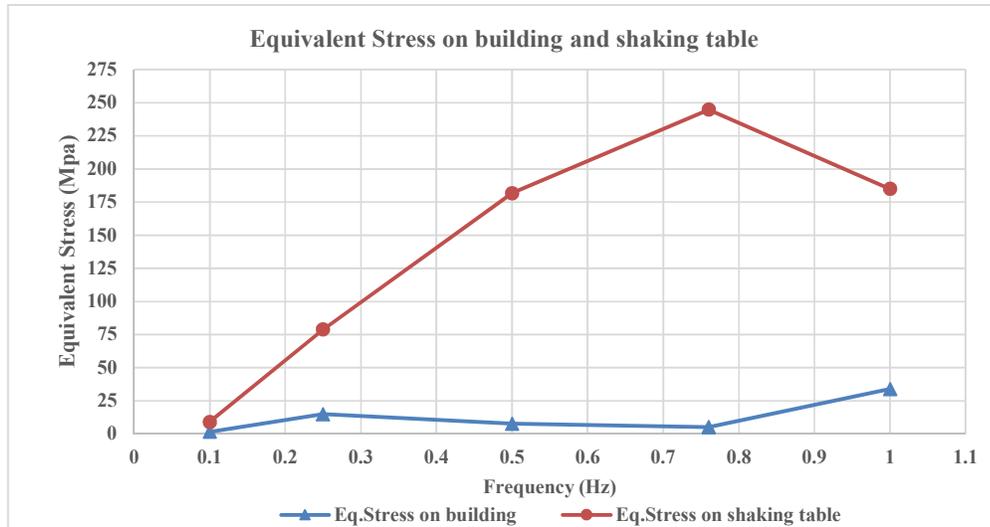**Equivalent Stress on building and shaking table**

Figure 3.33 Maximum equivalent stress of a single story-single bay building versus frequencies of harmonic loads

As seen in Figure 3.33, the maximum equivalent stress of the shaking table has a trend increasing with frequency up to 0.75 Hz, while that of the top floor slows a fluctuated trend through all loadings. However, after 0.75 Hz equivalent stress of the shaking table decreases.

3.2.3 Definition of Biaxial Harmonic Loads without Phase

In this case, five run-models are performed to verify the behavior of the shaking table and superstructure under two directional dynamic loads. The harmonic loads are defined without a phase in two directions simultaneously. A set of harmonic loads which is developed according to the frequency of mode-1 as shown in Table 3.13 and Figure 3.34. Moreover, a different set of harmonic loads which is developed according to the frequency of mode-2, as shown in Tables 3.14 and Figure 3.35 are applied in the Z-direction and X-direction, respectively.

Table 3.13 Biaxial harmonic loads without phase in the Z-direction (Fi-Mj)

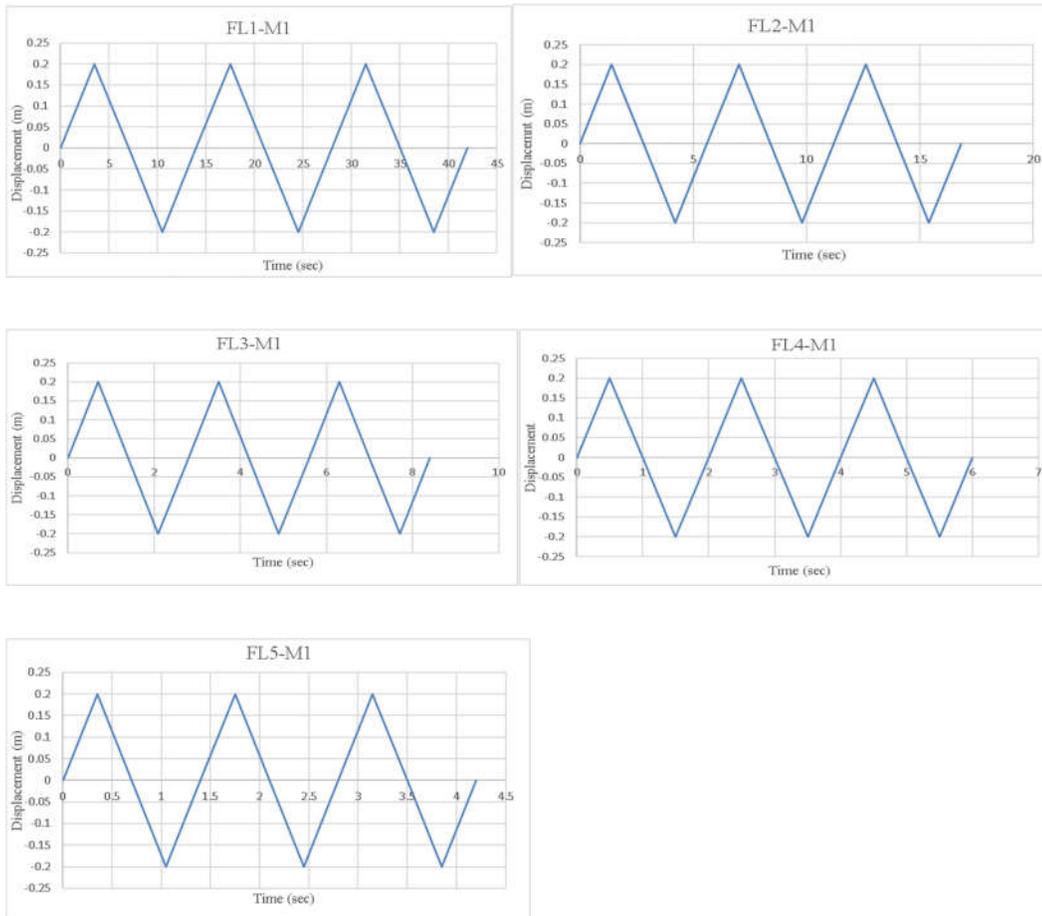| The frequency of the first mode of the building. 7.08 Hz									
FL1-M1=0.0708Hz		FL2-M1= 0.177 Hz		FL3-M1=0.35 Hz		FL4-M1= 0.53 Hz		FL5-M1= 0.7 Hz	
Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)
0	0	0	0	0	0	0	0	0	0
3.5	0.2	1.4	0.2	0.7	0.2	0.5	0.2	0.35	0.2
7	0	2.8	0	1.4	0	1	0	0.7	0
10.5	-0.2	4.2	-0.2	2.1	-0.2	1.5	-0.2	1.05	-0.2
14	0	5.6	0	2.8	0	2	0	1.4	0
17.5	0.2	7	0.2	3.5	0.2	2.5	0.2	1.75	0.2
21	0	8.4	0	4.2	0	3	0	2.1	0
24.5	-0.2	9.8	-0.2	4.9	-0.2	3.5	-0.2	2.45	-0.2
28	0	11.2	0	5.6	0	4	0	2.8	0
31.5	0.2	12.6	0.2	6.3	0.2	4.5	0.2	3.15	0.2
35	0	14	0	7	0	5	0	3.5	0
38.5	-0.2	15.4	-0.2	7.7	-0.2	5.5	-0.2	3.85	-0.2
42	0	16.8	0	8.4	0	6	0	4.2	0

Figure 3.34 Biaxial harmonic loads in the Z- directions without phase

Table 3.14 Biaxial harmonic loads without phase in the X-direction (Fi-Mj)

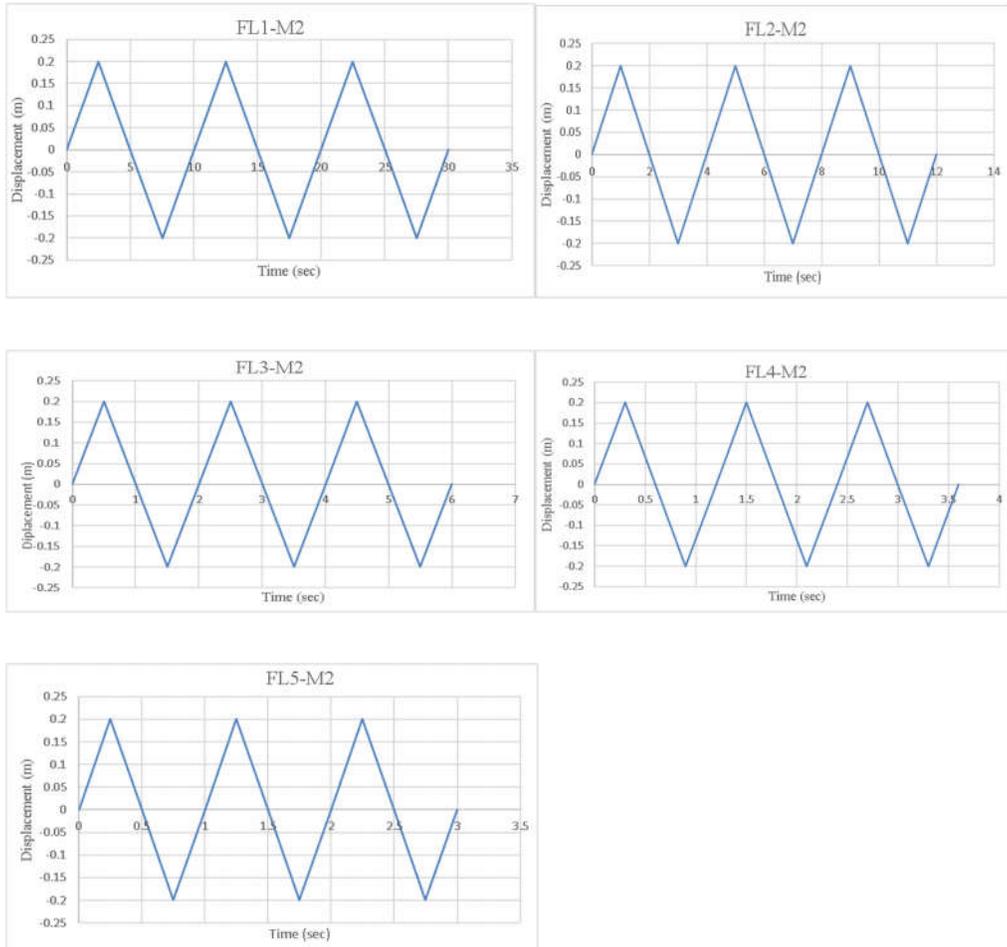| The frequency of the second mode of the building. 10.14 Hz									
FL1-M2 = 0.1 Hz		FL2-M2 = 0.25 Hz		FL3-M2 = 0.5 Hz		FL4-M2 = 0.76 Hz		FL5-M2 = 1 Hz	
Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)	Time (sec)	Displacement (m)
0	0	0	0	0	0	0	0	0	0
2.5	0.2	1	0.2	0.5	0.2	0.3	0.2	0.25	0.2
5	0	2	0	1	0	0.6	0	0.5	0
7.5	-0.2	3	-0.2	1.5	-0.2	0.9	-0.2	0.75	-0.2
10	0	4	0	2	0	1.2	0	1	0
12.5	0.2	5	0.2	2.5	0.2	1.5	0.2	1.25	0.2
15	0	6	0	3	0	1.8	0	1.5	0
17.5	-0.2	7	-0.2	3.5	-0.2	2.1	-0.2	1.75	-0.2
20	0	8	0	4	0	2.4	0	2	0
22.5	0.2	9	0.2	4.5	0.2	2.7	0.2	2.25	0.2
25	0	10	0	5	0	3	0	2.5	0
27.5	-0.2	11	-0.2	5.5	-0.2	3.3	-0.2	2.75	-0.2
30	0	12	0	6	0	3.6	0	3	0

Figure 3.35 Biaxial harmonic loads in the X- directions without phase

3.2.4 Comparison the Results and Discussion

In this case, the analysis parameters such as displacement, acceleration, stress, strain, and drift are obtained. Maximum acceleration on the top floor of a single story-single bay building and the shaking table in the Z and X directions are described in Figure 3.36 and Figure 3.37 respectively.
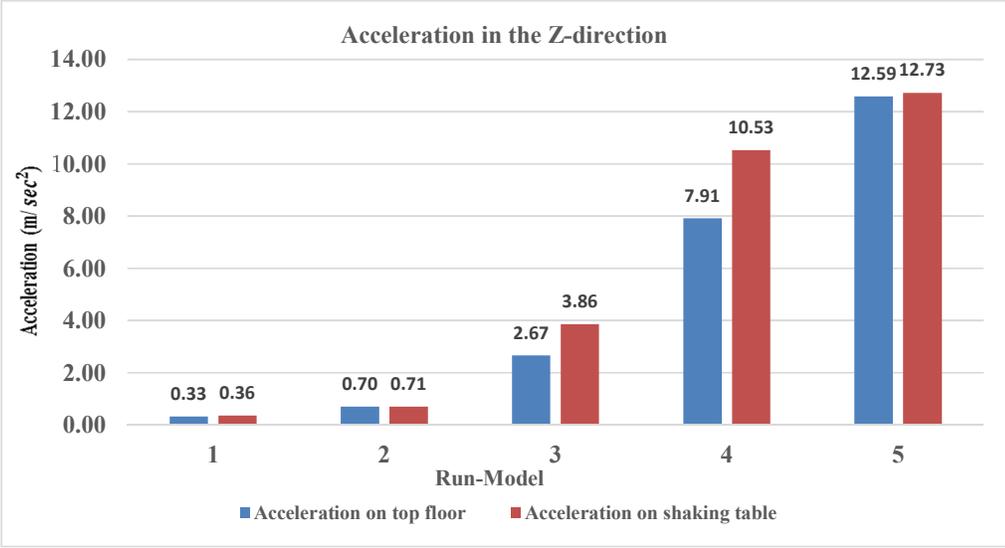

Figure 3.36 Maximum acceleration on the top floor of a single story-single bay building and the shaking table in the Z-direction
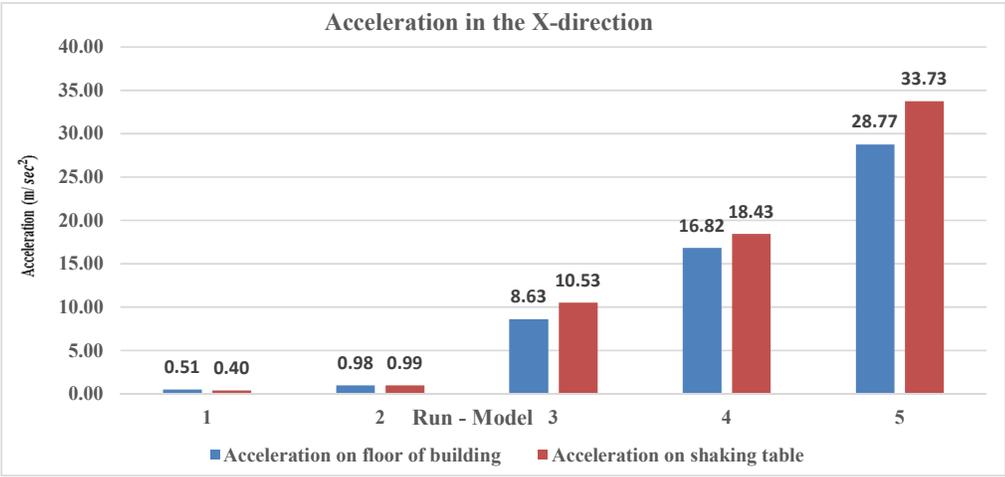

Figure 3.37 Maximum acceleration on the top floor a single storey-single bay building and on the shaking table in the X-direction

As seen in Figure 3.36 and Figure 3.37, the maximum acceleration values of shaking table are higher than values on the top floor of building for all models, where the highest acceleration value in the Z and X direction in model 5 reaches 12.73 m/sec² and 33.73 m/sec², respectively. Maximum acceleration versus frequencies of harmonic loads in the Z and X directions are given in Figure 3.38 and Figure 3.39 respectively.
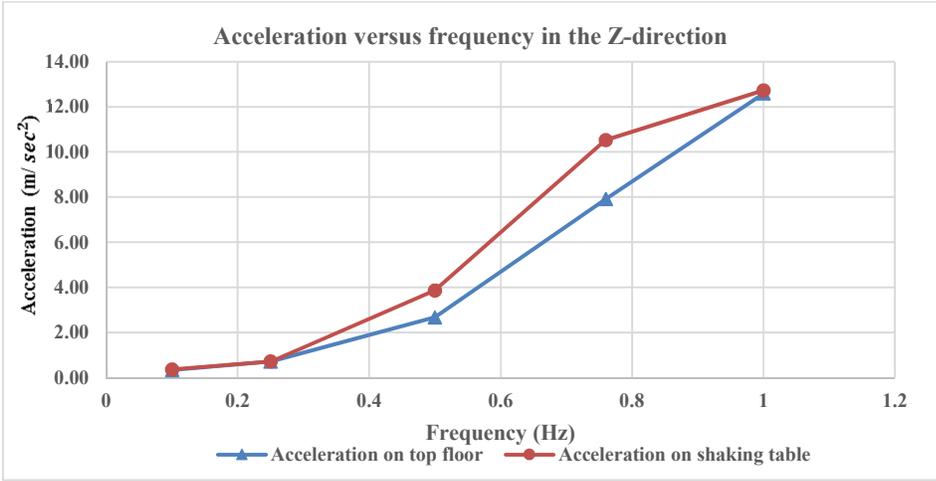

Figure 3.38 Acceleration on the top floor of a single story-single bay building and shaking table versus frequency in the Z-direction
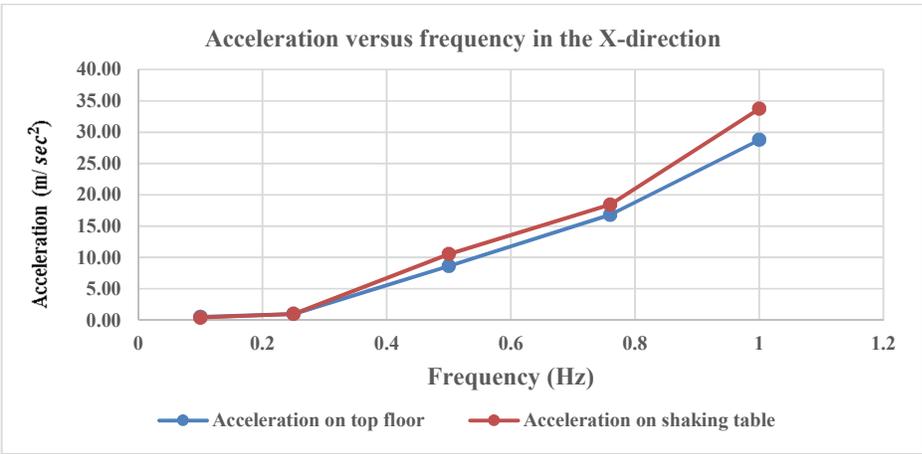

Figure 3.39 Acceleration on the top floor of a single story-single bay building and shaking table versus frequency in the X-direction

As seen in Figure 3.38, maximum acceleration of the shaking table has a trend increasing in frequency, while that on the top floor slows an increasing trend up to 0.5 Hz. Between 0.5 Hz and 0.75 Hz, tendencies of acceleration have steeper increasing than those in the range of 0.1-0.5 Hz. for the top floor and shaking table. After 0.75 Hz, the tendency of

increasing of acceleration on the top floor is continued to increase in the same behavior while the tendency of increasing of acceleration on shaking table is going to be slow up to 1 Hz. As seen in Figure 3.39, maximum acceleration values in the X-direction are increased in similar behavior on the top floor and shaking table. Maximum displacement on the top floor and bottom base of a single story-single bay building in the Z and X directions for five run-models are given in Figure 3.40 and Figure 3.41 respectively.
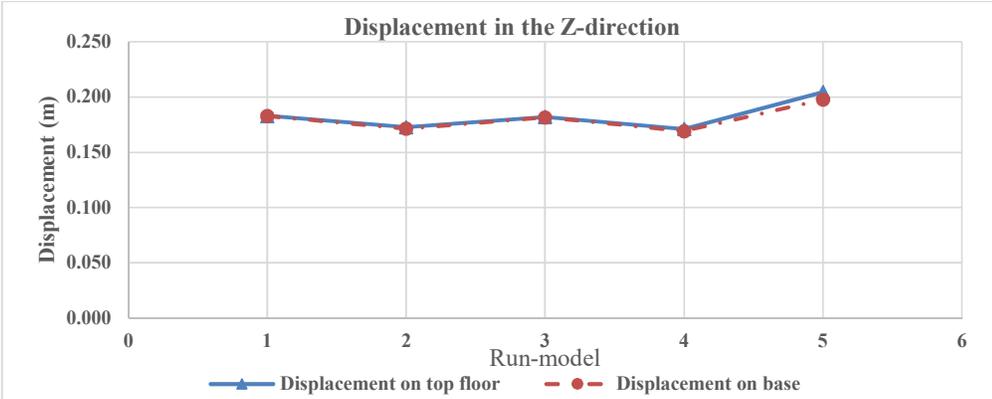

Figure 3.40 Maximum displacement on top floor and base of a single story-single bay building under harmonic loads in the Z-direction without phase
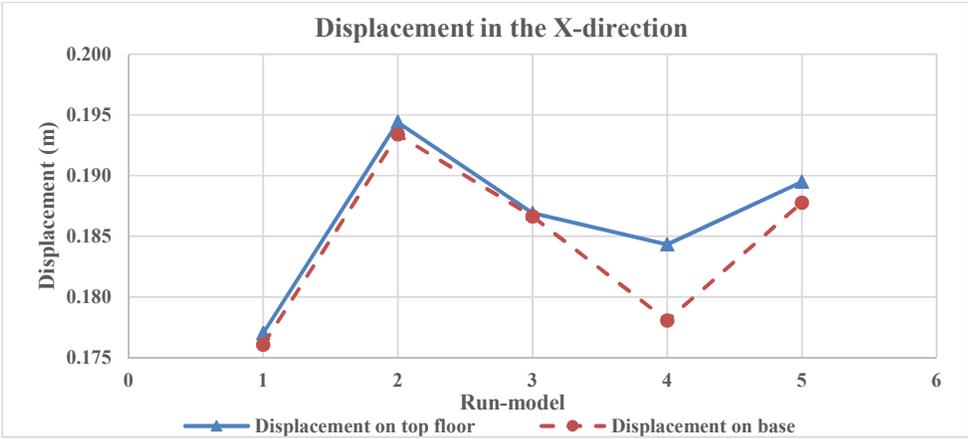

Figure 3.41 Maximum displacement of a single storey-single bay building in the X-direction under harmonic loads without phase

As seen in Figure 3.40 and Figure 3.41, the tendencies of maximum displacement on top floor and base of the building are developed similarly in the Z and X-direction. Moreover, the highest value of displacement is measured in run-model 5 with Z-direction and in run-model 2 in the X-direction. Moreover, the maximum difference between displacement on

55

the top floor and bottom base occurs in model 4. The maximum drift of the top floor of a single storey-single bay building in the Z and X-direction are given in the Figure 3.42.
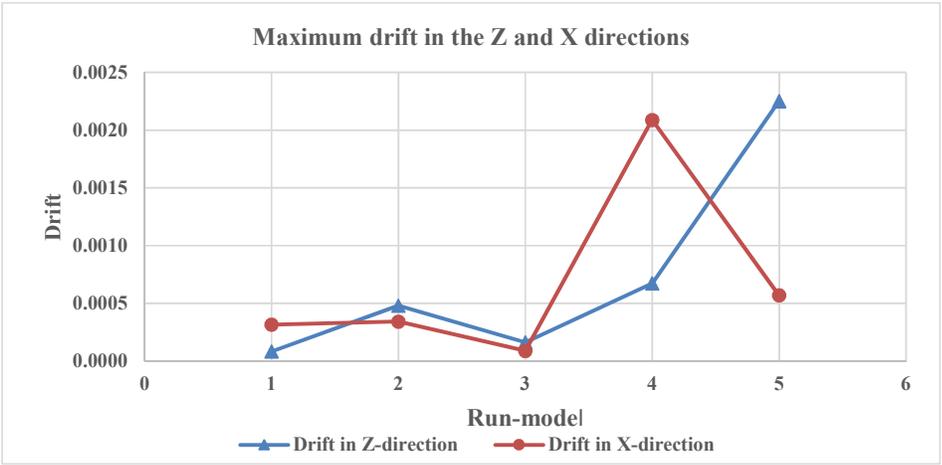

Figure 3.42 Maximum drift on top floor of a single storey-single bay building under biaxial harmonic loads without phase

As seen in Figure 3.42, maximum drift on the top floor of the building is measured in model 5 in the Z-direction and model 4 in the X-direction. Moreover, the maximum drifts in all models seem less than 0.01 [47], which can be limit of linear deformation for reinforced concrete buildings. Therefore, it can be said that the building (superstructure) is in the level of linearity for all cases. The maximum equivalent stress of a single story-single bay building and a shaking table under biaxial harmonic loads without phase is described in Figure 3.43.
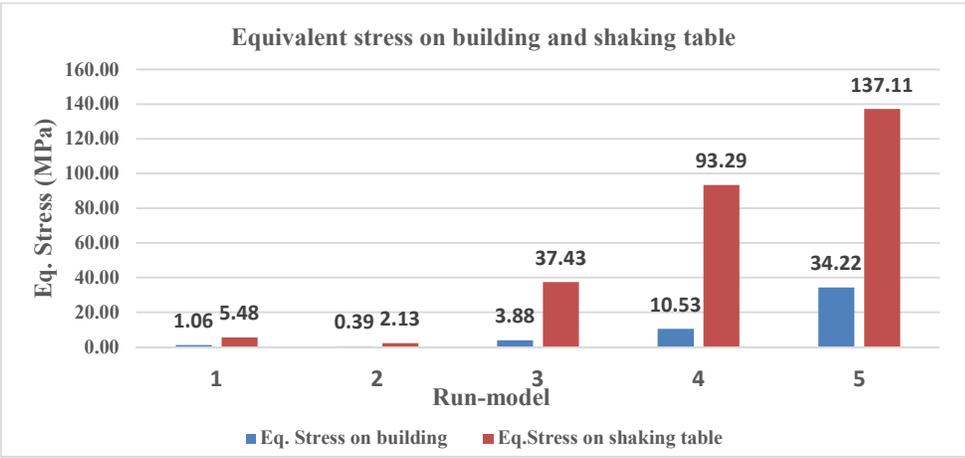

Figure 3.43 Maximum equivalent stress of a single story-single bay building and shaking table under biaxial harmonic load without phase

As seen in Figure 3.43, maximum equivalent stress on a single story building and a shaking table are increased with increasing frequency of harmonic loads. Moreover, the equivalent stress values of shaking table seem higher than the values of building for all run-models, and the highest value is measured in run-model five which reaches 137 MPa on shaking table. Maximum equivalent stress value for all models are less than the maximum stress capacity of materials, which means the model specifies the acceptable results. The maximum equivalent stress of building and shaking table versus frequency of harmonic loads is given in Figure 3.44.
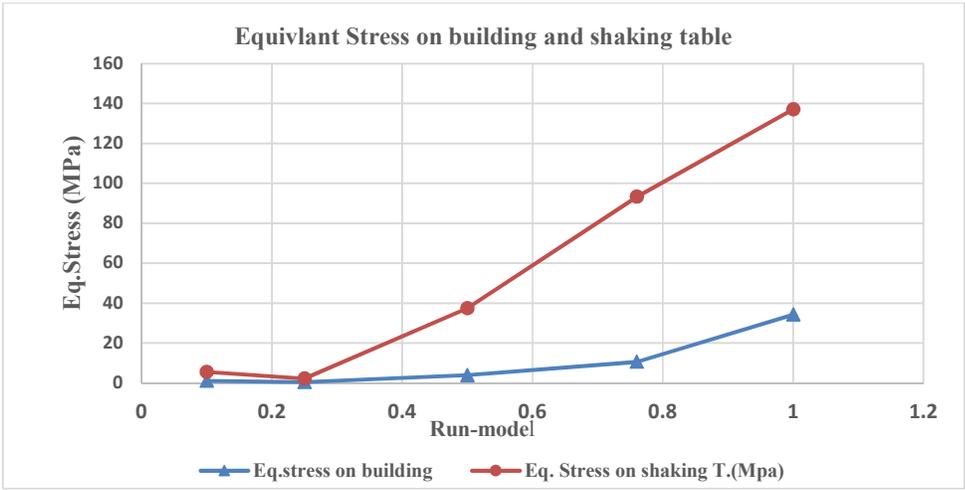

Figure 3.44 Maximum equivalent stress of a single story-single bay building and a shaking table versus frequency of harmonic load

As seen in Figure 3.44, maximum equivalent stress values are developed in two regions according to frequencies of harmonic loads. In the first region, the tendency of increasing part of equivalent stress is so slow up to approximately 0.25 Hz. In the second region different dramatic tendencies of increasing of equivalent stress are going to developed, where the increase in the equivalent stress of shaking table is developed higher than the equivalent stress of building, and the highest value of equivalent stress occurs in the frequency of 1.00 Hz.

3.3 Analysis of Model of Single Storey-Single Bay R.C Building on Shaking Table Model Under Earthquake Load

This analysis aims to determine the response of the shaking table model with the building under earthquake load. Therefore, displacement loading induced by earthquake acceleration is applied to the shaking table. The loading is a part of earthquake record taken from Northridge earthquake 1994 data set. The displacement loading is defined in two cases, in the first case an axial displacement loading is applied in the Z –direction, and in the second case, biaxial displacement loading is simultaneously applied in the Z and X- direction.

3.3.1 Definition of an Axial Displacement Loading

The displacement loading is applied on the middle plane of the shaking table model in the Z-direction which is shown in Figure 3.45.
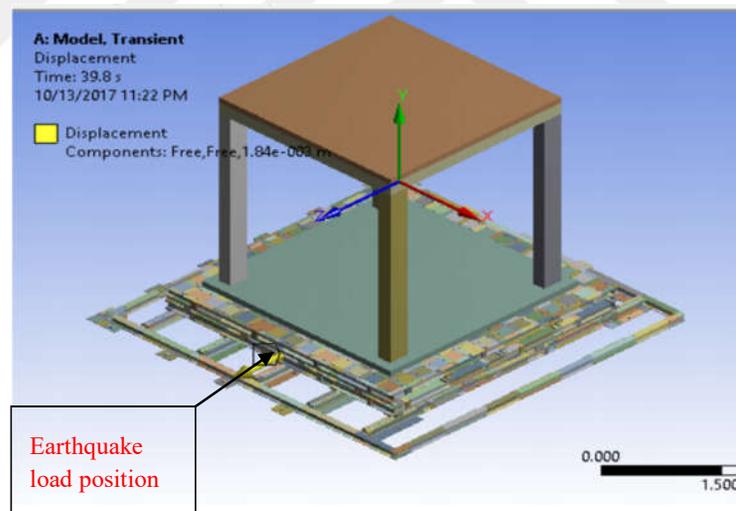

Figure 3.45 Application of an axial displacement loading on model of single story-single bay R.C building on a shaking table

Displacement loading form Northridge earthquake load which has a peak ground acceleration 1.7 g is defined with less time step than original one to decrease computational time. The displacement loading and the earthquake acceleration are constructed with 250-time steps which are shown in Figure 3.46 and Figure 3.47, respectively.
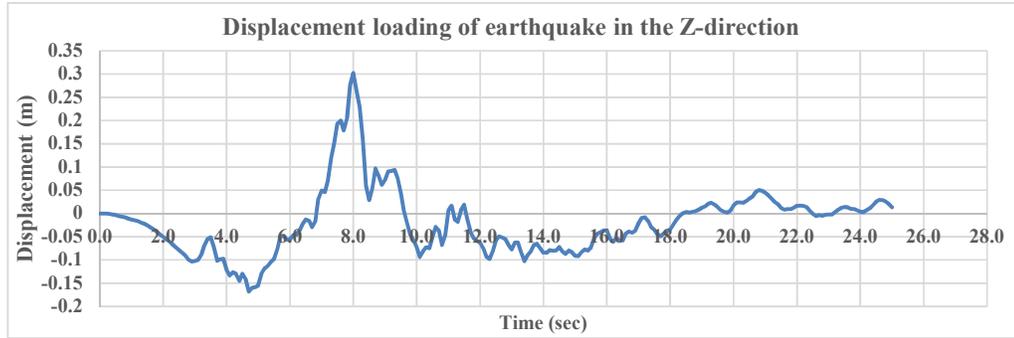
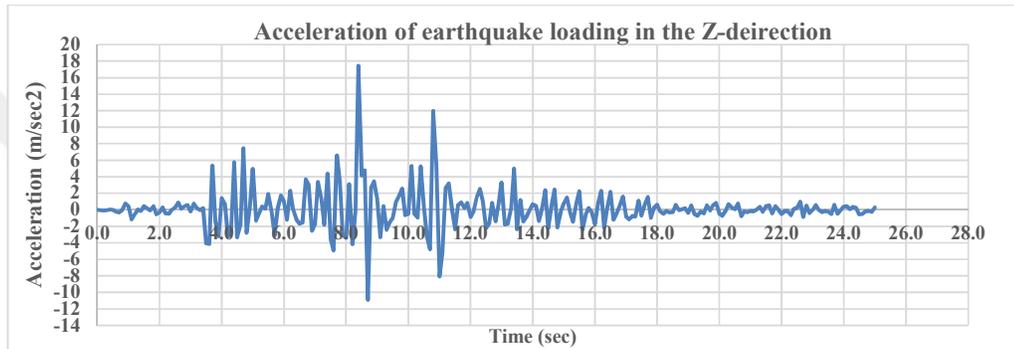Figure 3.46 Displacement loading of earthquake in the Z-direction

Figure 3.47 Acceleration of earthquake loading in the Z-direction

3.3.2 Comparison of the Results and discussion

The results such as displacement, acceleration, stress, strain, and drift are obtained by using ANSYS program. The results of the shaking table model with single story-single bay building under an axial earthquake load are given in Table 3.15.

Table 3.15 Results for model of single story-single bay building on shaking table under an axial earthquake load

Location	Max. acceleration on top floor (m/sec^2)	Max. equivalent Stress (Mpa)	Max. equivalent Strain (m/m)	Max. displacement on top floor (m)	Drift
Building	18	10.65	0.000048	0.301	0.001
Shaking table	14.5	14	0.00012	0.298	

As seen in Table 3.15, maximum acceleration value on the top floor of the building is higher than the acceleration on shaking table. Therefore, the system has relative motion. The maximum equivalent stress and strain of the shaking table are seemed higher than the value of the building, and the model is still in the linear elastic range. Moreover, maximum displacement on the top floor was higher than on bottom base. The maximum drift is less than 0.01 therefor; the building is still in the linear range. The acceleration

response versus time on the shaking table and the top floor of the single story-single bay building is given in Figure 3.48 and Figure 3.49, respectively.
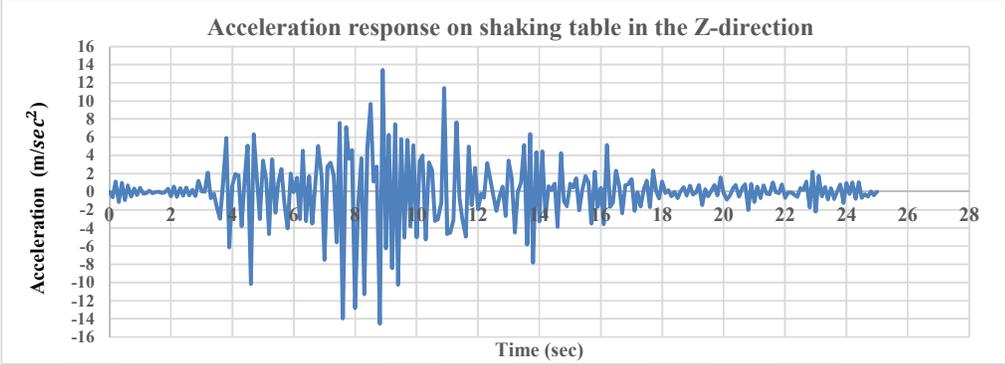

Figure 3.48 Acceleration response on the shaking table with single-storey building under an axial earthquake load
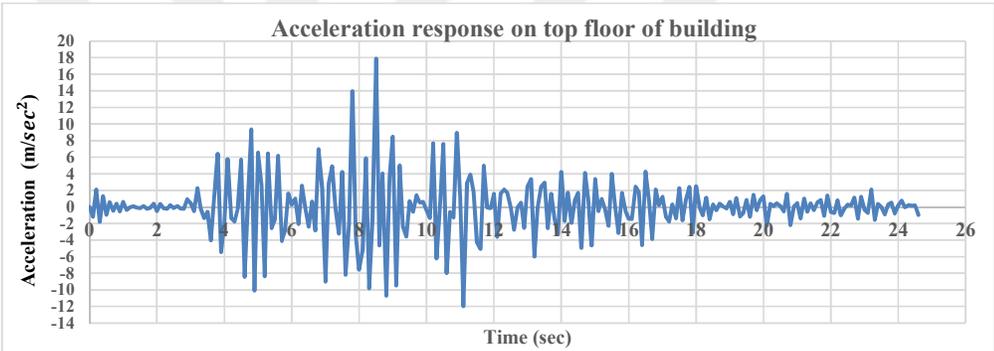

Figure 3.49 Acceleration response on top floor of single story building under an axial earthquake loading

As seen in Figure 3.48, the acceleration response on the shaking table has a similar response to acceleration of input earthquake load. Moreover, in the Figure 3.49, the amplitudes of acceleration on the top floor of the building which is slow up to 4 seconds for a time of analysis are started to increase, then the amplitude is going to be a higher increase, and the maximum amplitude of acceleration reaches to 18 m/sec^2. The displacement response on the shaking table and on the top floor of building versus time is given in Figure 3.50 and Figure 3.51, respectively.
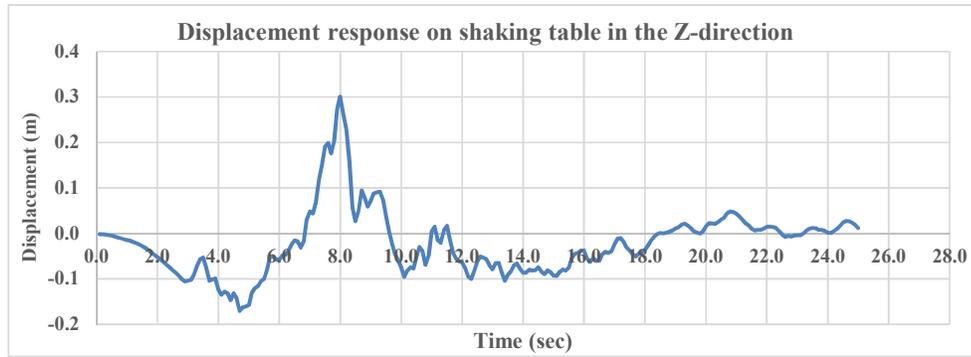
Figure 3.50 Displacement response on the shaking table under axial earthquake load
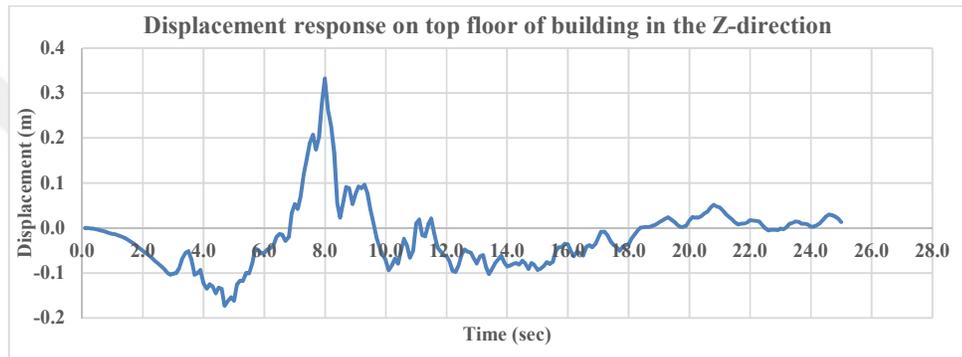

Figure 3.51 Displacement response on top floor of a single story-single bay building under axial earthquake load

As seen in Figure 3.50, the displacement response on the shaking table has a similar behavior when compare with input displacement of earthquake load. Moreover, in the Figure 3.51, the displacement response on the top floor of the building has little deference than displacement response on shaking table where the maximum displacement reaches to 0.33m.

3.3.3 Definition of Biaxial Earthquake Loads of Model of Single-Storey Single Bay Building on Shaking Table

In this analysis, the displacement loadings are applied on a shaking table within two directions. The first displacement loading is applied in the Z-direction in middle plane of a shaking table and the second displacement loading is applied in the X-direction in the top plane of a shaking table. The application of biaxial displacement loadings on shaking table is shown in the Figure 3.52.
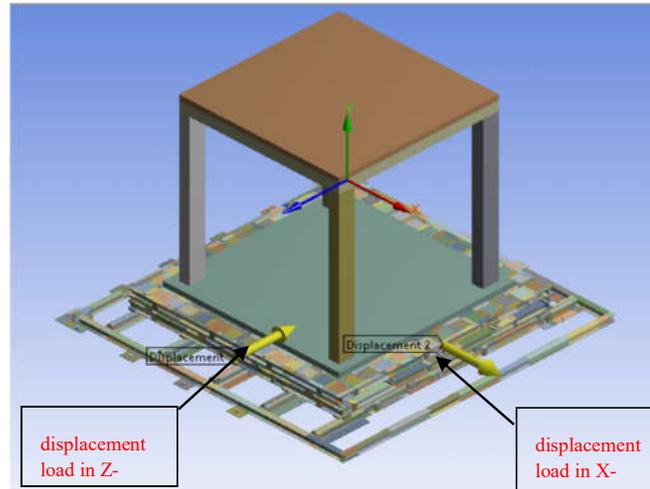
Figure 3.52 Application of biaxial earthquake loads on model of single story-single bay RC building table on shaking table

The displacement loadings which applied in the Z and X-direction respectively are given in Figure 3.53 and Figure 3.54.
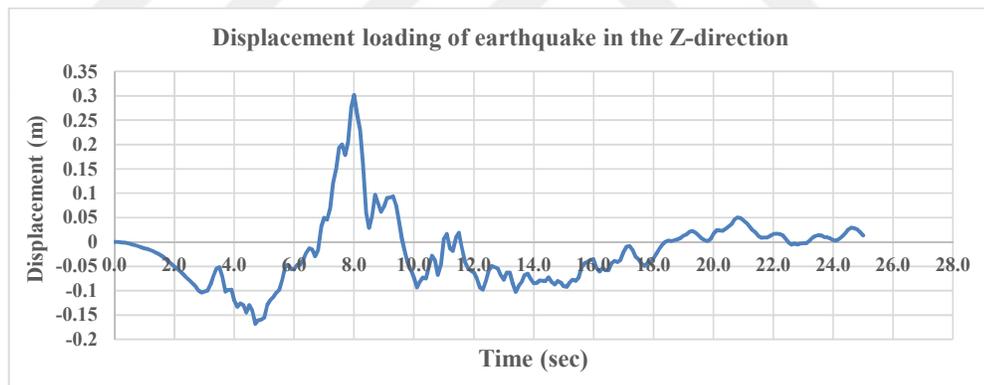

Figure 3.53 Displacement loading of earthquake in the Z-direction
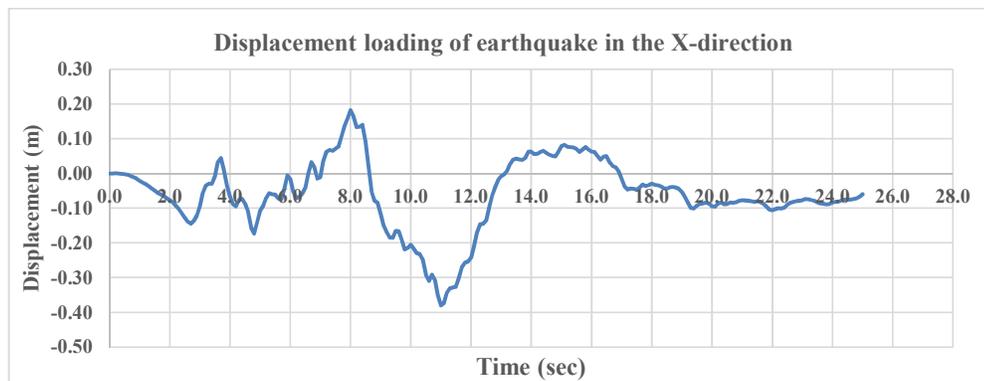

Figure 3.54 Displacement loading of earthquake in the X-direction

Moreover, the acceleration of earthquake loadings in the Z and X directions which have peak ground acceleration approximately 1.7 g, and 0.9 g, respectively are shown in Figure 3.55 and Figure 3.56, below.
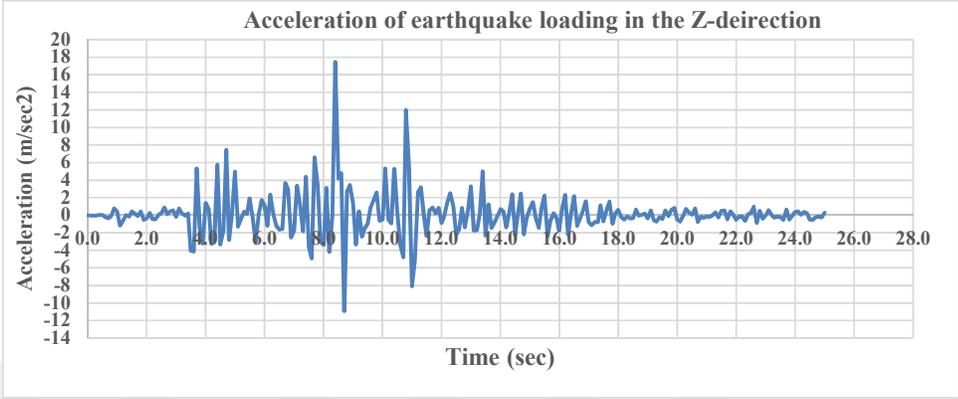

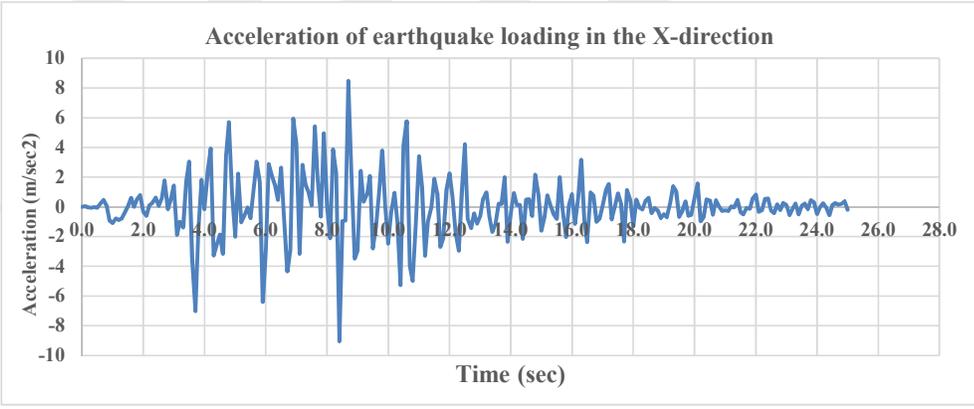Figure 3.55 Acceleration of earthquake loadings in the Z-direction

Figure 3.56 Acceleration of earthquake loading in the X-directions

3.3.4 Comparison of the Results and discussion

The results such as displacement, acceleration, stress, strain, and drift are obtained, and the results are compared as shown in Table 3.16

Table 3.16 Results for model of single story-single bay building on shaking table under biaxial earthquake loads

Location	Direction	Max. acceleration (m/ sec^2)	Max. equaivalent Stress (Mpa)	Max. equaivalent Strain (m/m)	Max. displacement on top floor (m)	Drift
Building	Z	17.70	312.0	0.00006	0.3670	0.01265
	X	11.47			0.3930	0.02029
Shaking table	Z	14.50	533.0	0.00007	0.3240	
	X	13.80			0.3240	

As seen in Table 3.16, maximum acceleration values on the top floor of the building are higher than values on shaking table. Moreover, maximum acceleration values in the Z-direction are higher than values in the X-direction. Maximum equivalent stress and strain values seem on shaking table higher than on building. The maximum drift on the top floor in the Z direction is higher than the drift in the X direction. The acceleration response on the shaking table and on the top floor of building in the Z and X direction are given in Figure 3.57, Figure 3.58, Figure 3.59 and Figure 3.60, respectively.
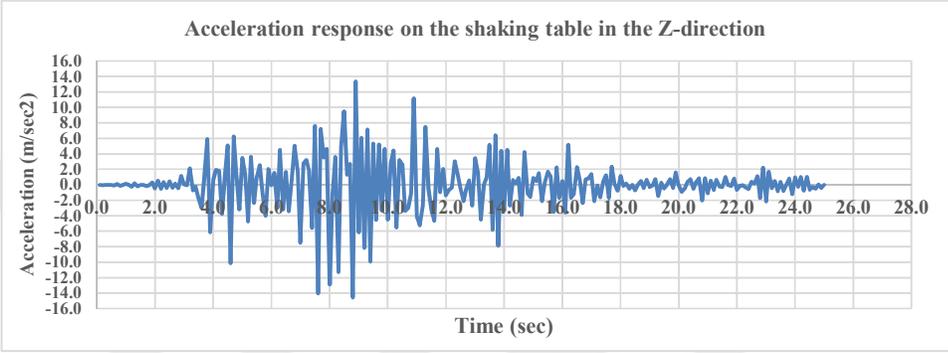

Figure 3.57 Acceleration response on the shaking table model with single storey building in the Z direction
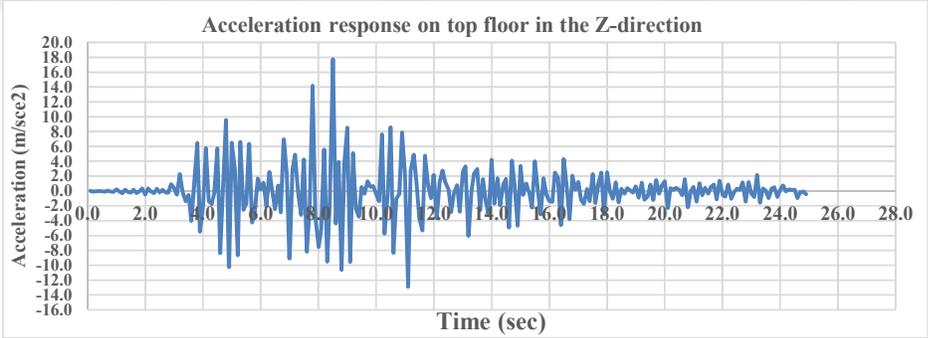

Figure 3.58 Acceleration response on top floor of single storey building on shaking table model in the Z direction
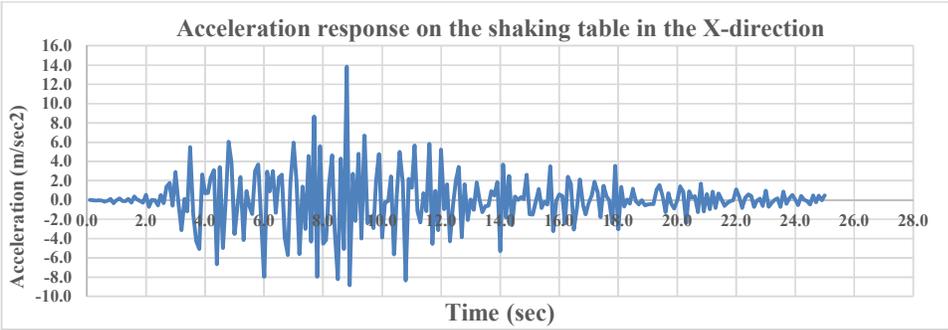

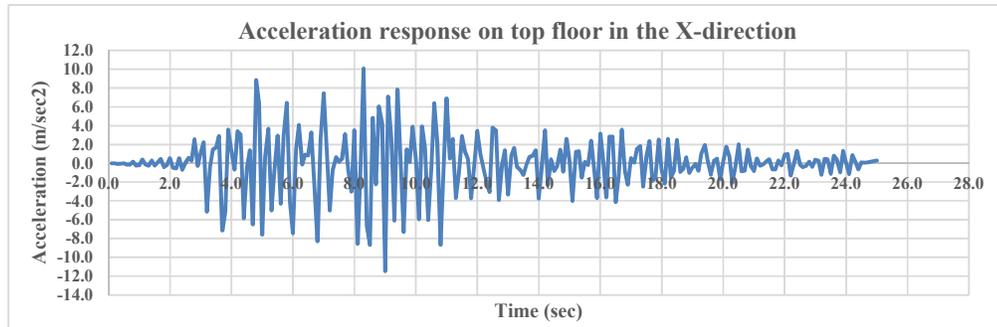Figure 3.59 Acceleration response on the shaking table in the X direction

Figure 3.60 Acceleration response on top floor of single story building on shaking table model in the X direction under biaxial earthquake loads

As seen in the Figure 3.57 and Figure 3.58, the acceleration response on the shaking table in the Z and X directions have similar behaviors with the acceleration of input earthquake loadings which applied in the Z and X direction respectively. As seen in Figure 3.59 and Figure 3.60, The amplitude of acceleration on the top floor of the building is increased with time where the maximum amplitude in the Z and X directions reach to 17.7 m/sec² and 14.5 m/sec². The displacement response on the shaking table and on the top floor of building in the Z and X directions are given in Figure 3.61, Figure 3.62, Figure 3.63 and Figure 3.64, respectively.
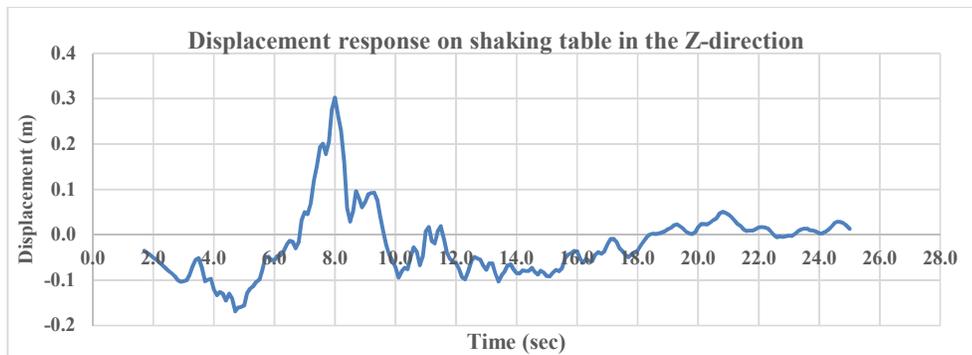

Figure 3.61 Displacement response of the shaking table model with single storey building in the Z direction
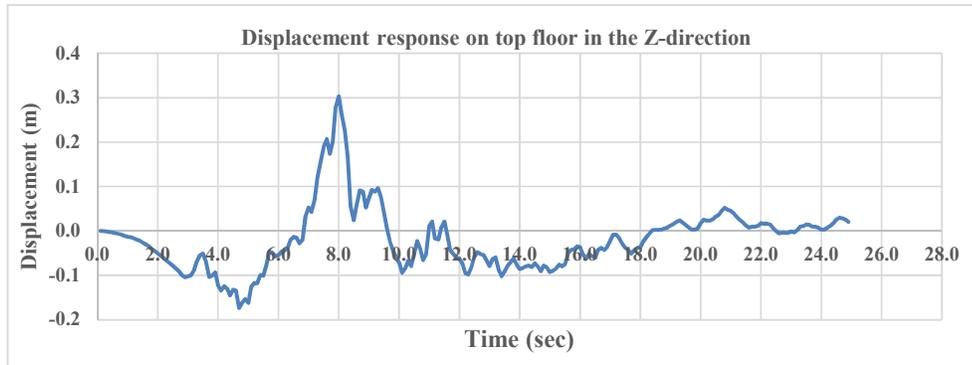
Figure 3.62 Displacement response on top floor of single storey building on shaking
table model in the Z-direction
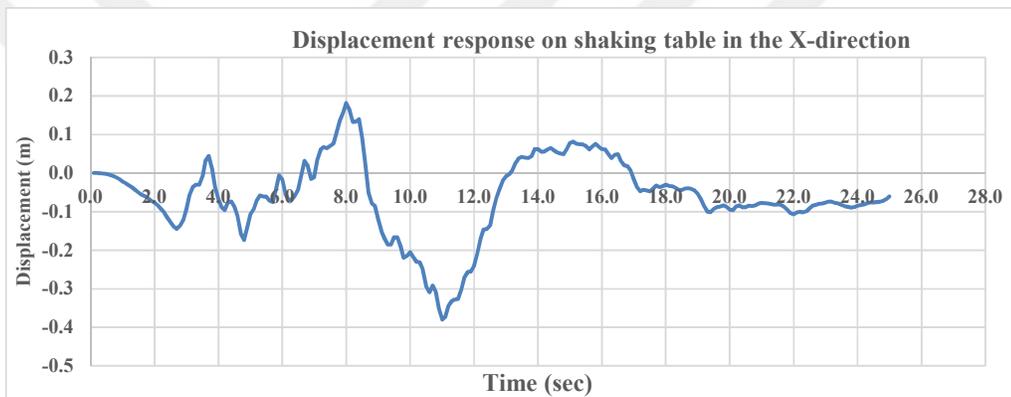
Figure 3.63 Displacement response on the shaking table model with single storey
building in the X direction

Figure 3.64 Displacement response on top floor of single storey building on shaking
table model in the X direction

As seen in Figure 3.61 and Figure 3.62, the displacement response on the shaking table
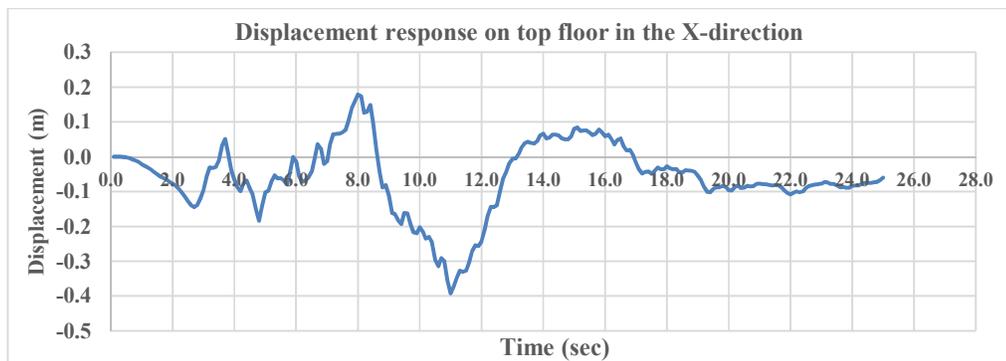has a similar behavior when compare with input displacement of earthquake loads. As
seen in Figure 3.63 and Figure 3.64, the displacement on the top floor of building in the
Z and X directions seems developing so small.

3.4 Numerical Analysis of Model of Two Storey-Single Bay RC Building on

Shaking Table Under Earthquake Loadings

In this analysis, two-story reinforced concrete building was modeled and simulated with a shaking table by using ANSYS program to check the performance of a shaking table with a different model of the building and different mass under earthquake loadings. The superstructure of the building has a dimension of 3.5 by 3.5 m width and length, and 3 m height for each story and have approximately 40 tons' mass. The dynamic analyses are run in two cases, in the first case the displacement loading is applied in one direction Z-direction, and in the second case, the displacement loadings are applied in two directions Z and X directions. The geometry of shaking table model with two-story single bay building is given in Figure 3.65
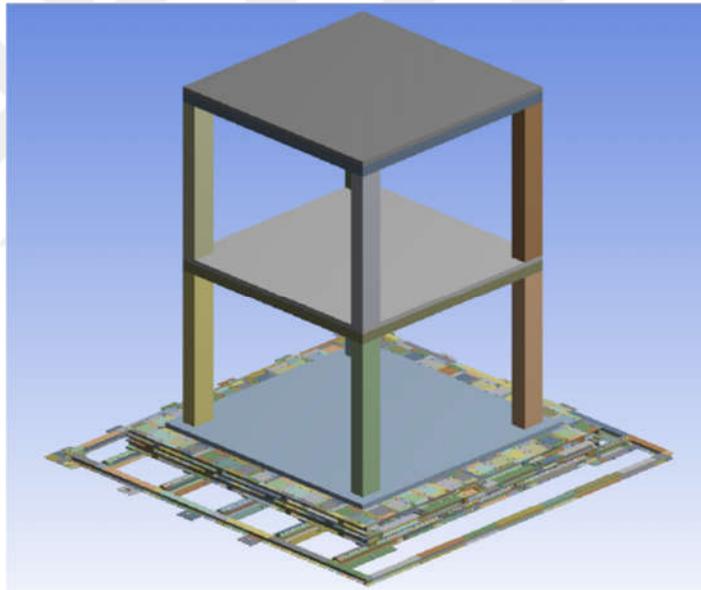

Figure 3.65 Geometry of model of two story-single bay R.C building on shaking table

The materials properties for a shaking table which consist of steel and a two-story building which consist of reinforced concrete are given in Table 3.17 below.

Table 3.17 Materials properties of model of two-story building on shaking table

Member	Material	Mass (ton)	Density (KN/m³)	Young's Modulus (Mpa)	Poisson's Ratio	Compressive Strength (Mpa)	Tensile Strength (Mpa)
Shaking Table	Steel	5.50	76.98	2.00E+05	0.3	250	460
Building	Concrete	40.00	60.6	32000	0.2	40	5

After simplifying the geometry of the shaking table model with the two-storey building. The mesh is generated for the model by using mesh control/ sizing, multizone and mapping face to get hexahedral mesh for all parts of the model as shown in Figure 3.66.
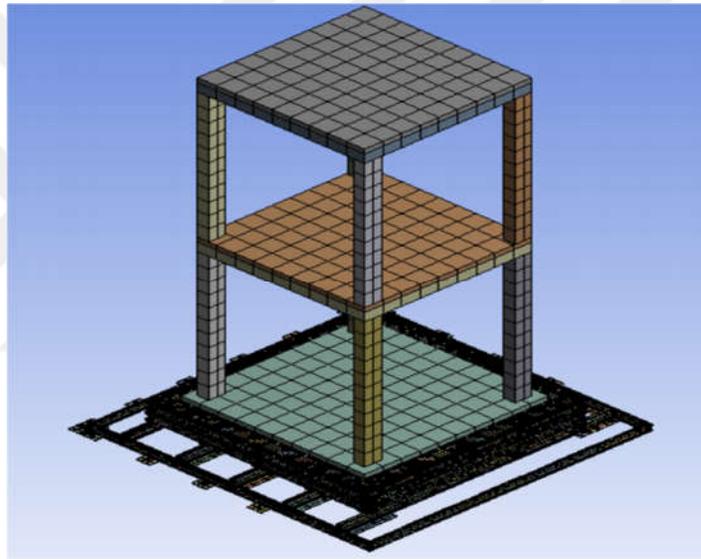
Figure 3.66 Mesh of model of two story-single bay R.C building on shaking table

3.4.1 Dynamic Analysis of Model with an Axial Earthquake Load

In this case, a displacement load is applied in the Z-direction in middle plane of the shaking table model. The dynamic analysis is run using ANSYS program and the result of displacement, and acceleration is calculated on the shaking table, first floor, and second floor respectively, and the stress and strain are calculated separately of the shaking table and the building. The displacement loading and the earthquake acceleration is constructed with 250-time steps which are shown in Figure 3.67 and Figure 3.68, respectively.
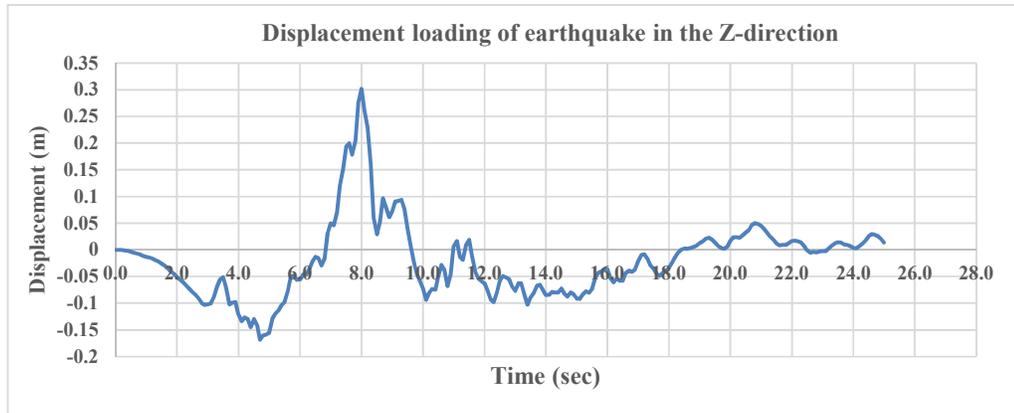
Figure 3.67 Axial displacement loading applied to the model of two storey-single bay RC building on shaking table in the Z-direction

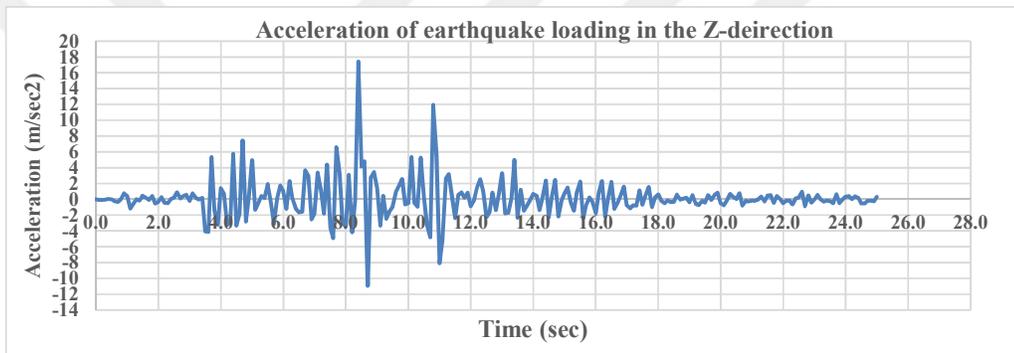Figure 3.68 Acceleration of earthquake loading applied to the model of two-storey building on shaking table in the Z-direction

The application of the earthquake load which applied in the middle plane of the shaking table was given in Figure 3.69, below.
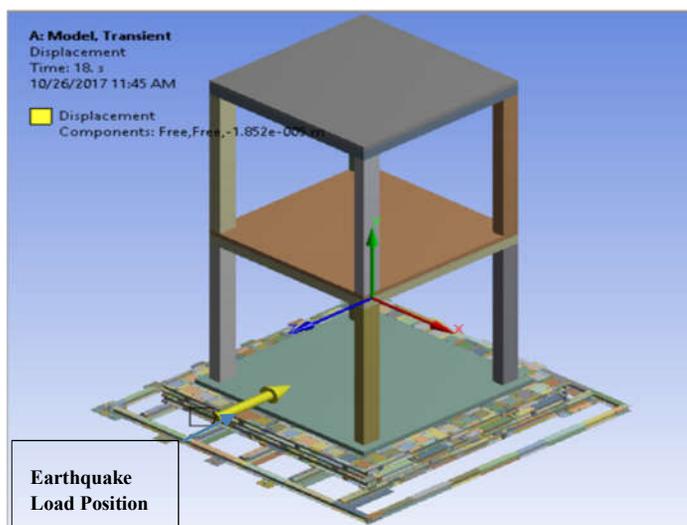

Figure 3.69 Application of an axial earthquake load of model of two-storey building on shaking table in the Z-direction

3.4.2 Comparison of the Results and Discussion

The analysis parameters such as displacement, acceleration, and drift are calculated on the shaking table, first floor and second floor of the building and the equivalent stress and strain are calculated separately of shaking table and building. The comparison of results is given in Table 3.18.

Table 3.18 Comparison of the results of model of two-story building on shaking table under axial earthquake load

Location	Acceleration (m/sec^2)	Equivalent Stress (Mpa)	Equivalent Strain (m/m)	Displacement (m)	Drift
Second floor of building	23.10	5.60	0.000188	0.3620	0.0083
First floor of building	14.90	5.60	0.000188	0.3372	0.0065
Shaking Table	14.56	196	0.000984	0.3178	

As seen in Table 3.18, the maximum acceleration values are increased with increasing the height of building where the maximum acceleration measured on the second floor. The maximum equivalent stress and strain of shaking table are higher than the values of building due to the effect of building on shaking table. Moreover, values of the maximum displacement and drift are measured on the second floor of the building where the maximum drift value reaches to 0.0163 m. The acceleration response versus time on the shaking table is given in Figure 3.70 and Figure 3.71, respectively.
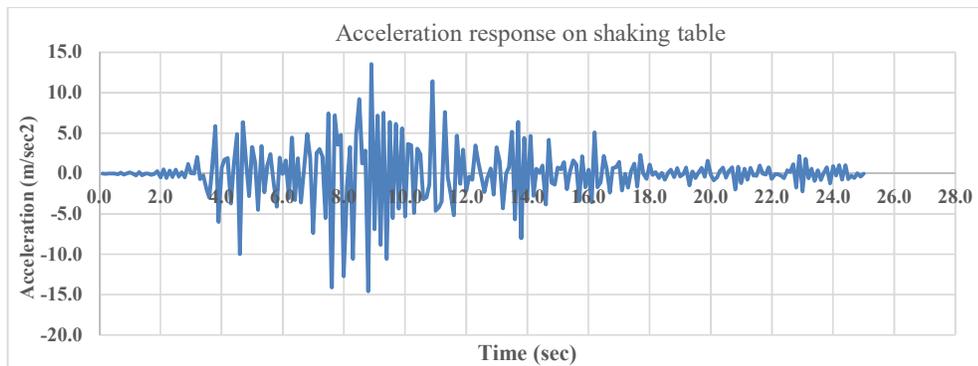

Figure 3.70 Acceleration response on the shaking table model with two-story building

Figure 3.71 Acceleration response on the second floor of two-story building on shaking table model

As seen in Figure 3.70, the acceleration response on the shaking table has the same behavior with the acceleration of earthquake loading. Moreover, from Figure 3.71, the acceleration response on the second floor of building increasing higher than acceleration response on shaking table. The displacement response on shaking table and on the second floor of the building is given in Figure 3.72 and Figure 3.73, respectively.
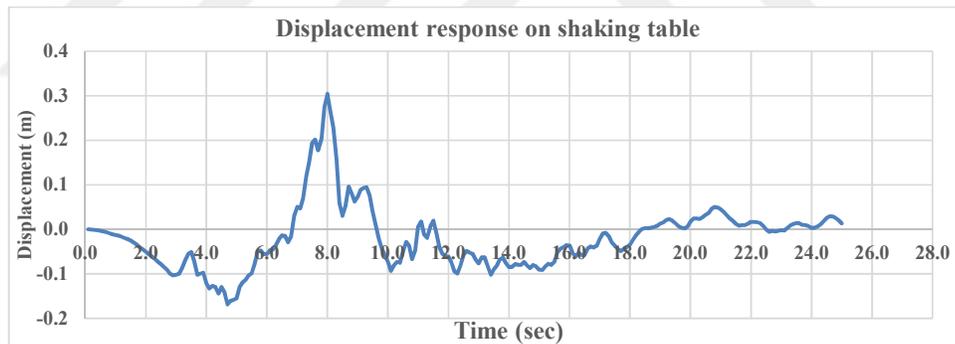
Figure 3.72 Displacement response on the shaking table model with two-story building under axial earthquake load
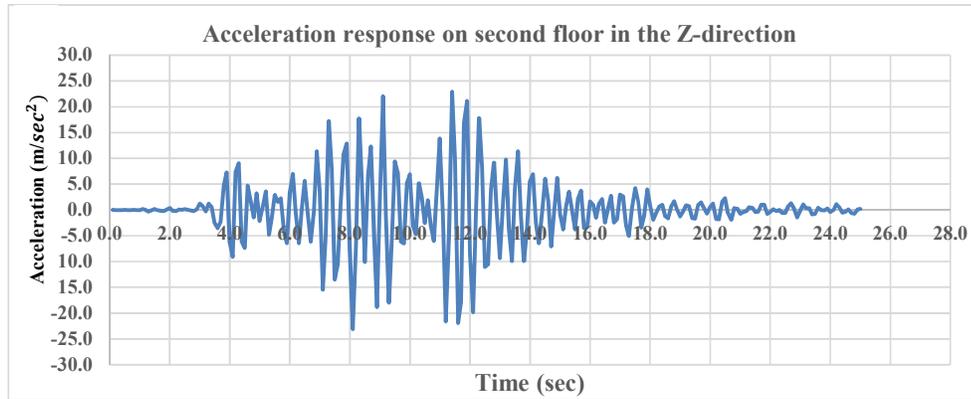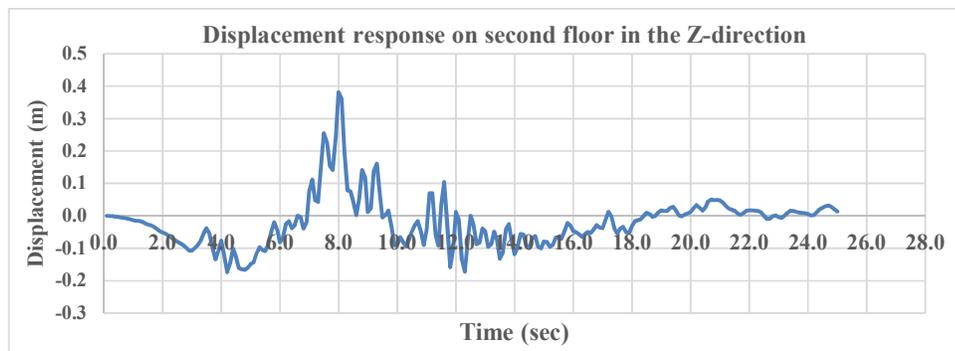

Figure 3.73 Displacement response on the second floor of two-storey building on shaking table model under axial earthquake loading

71

As seen in Figure 3.72, the displacement response on the shaking table has a similar behavior with a displacement of earthquake loading. Therefore, we have good, acceptable results. As seen in Figure 3.73, the displacement response on the second floor is developed higher than displacement response on shaking table where the maximum amplitude is calculated on 8 seconds for the time of analysis. The distribution of displacement and acceleration and drift along the floor level are given in the Figure 3.74.

(a)

(b)

(c)
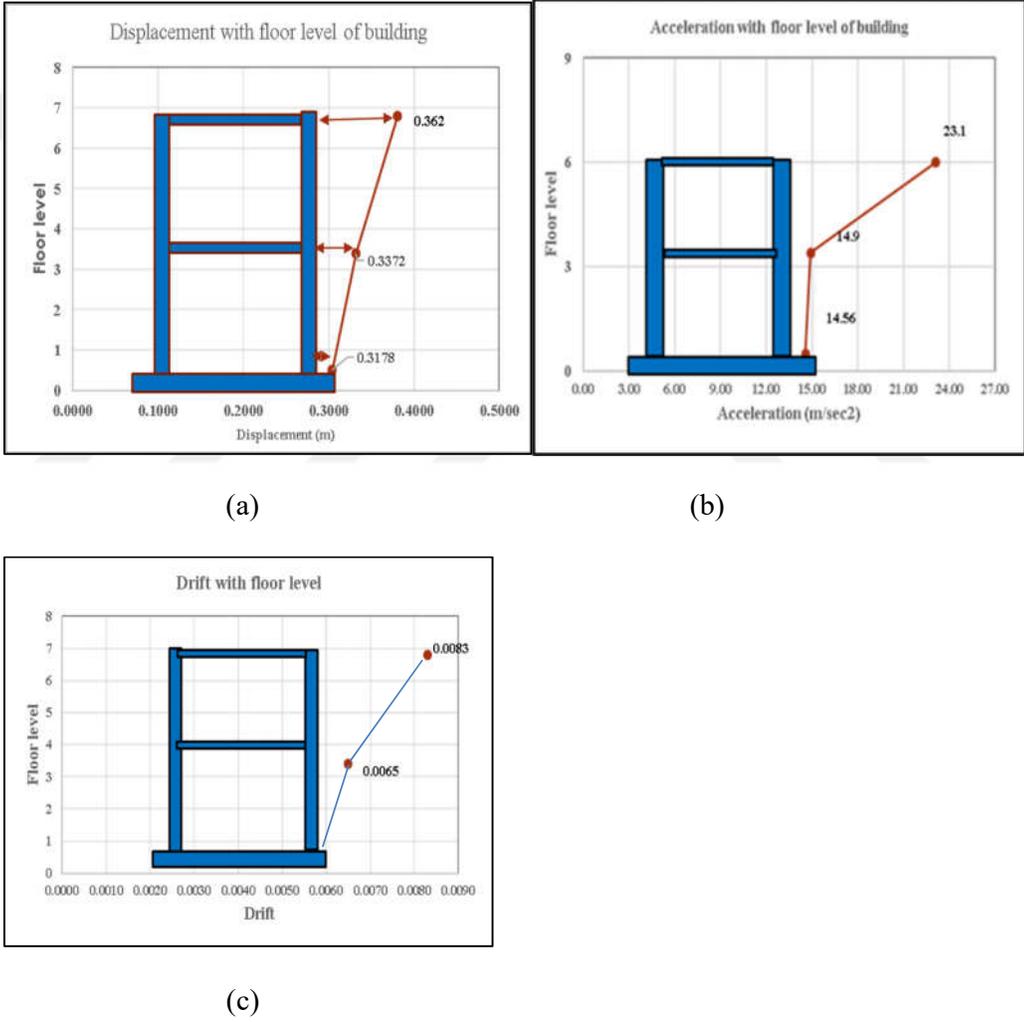
Figure 3.74, Distribution of displacement, acceleration and drift along floor level for model of two-storey building on shaking table

3.4.3 Dynamic Analysis of Model of Two Storey-Single Bay R.C Building on Shaking Table Under Biaxial Earthquake Loads

In this analysis, two directional displacement loadings are applied to the shaking table model with a two-story building. The first loading which applied on middle plane of shaking table in the Z-direction and at the same time the second loading which applied on the top plane of shaking table in the X-direction. The biaxial displacement loadings in the Z and X direction are given in Figure 3.75 and Figure 3.76 respectively.
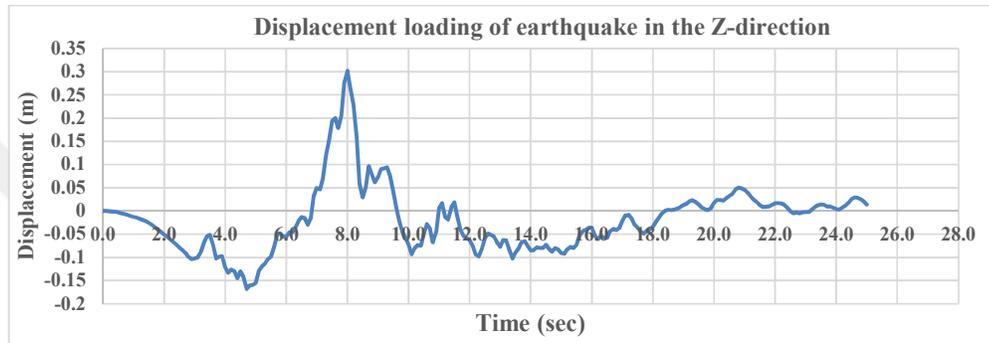
Figure 3.75 Displacement loading applied to the model of two-story building on shaking table in the Z-direction
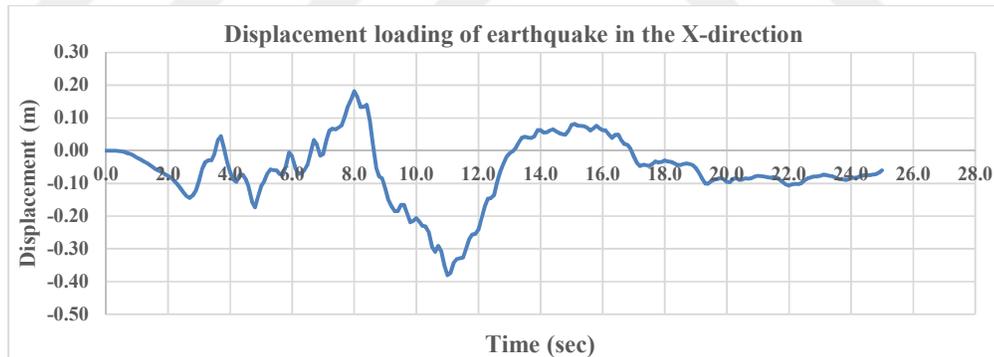
Figure 3.76 Displacement loading applied to the model of two-story building on shaking table in the X-direction

Moreover, the acceleration of earthquake loadings in the Z and X directions which have peak ground acceleration approximately 1.7 g, and 0.9 g, respectively are shown in Figure 3.77 and Figure 3.78, below.

Figure 3.77 Acceleration of earthquake loading applied to the model of two-story building on shaking table in the Z-direction

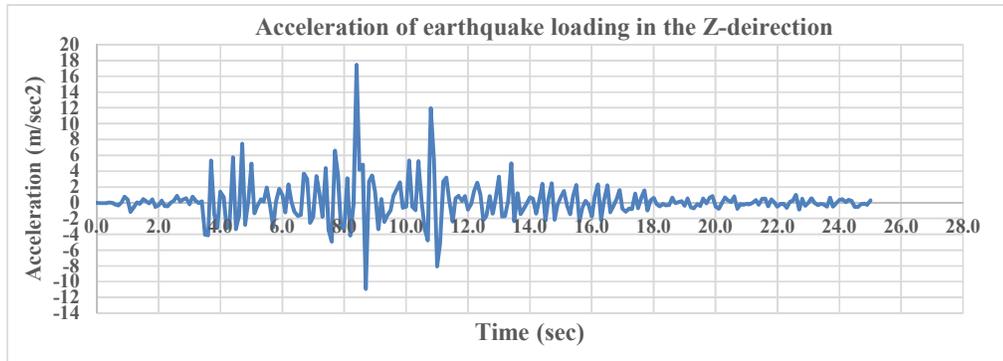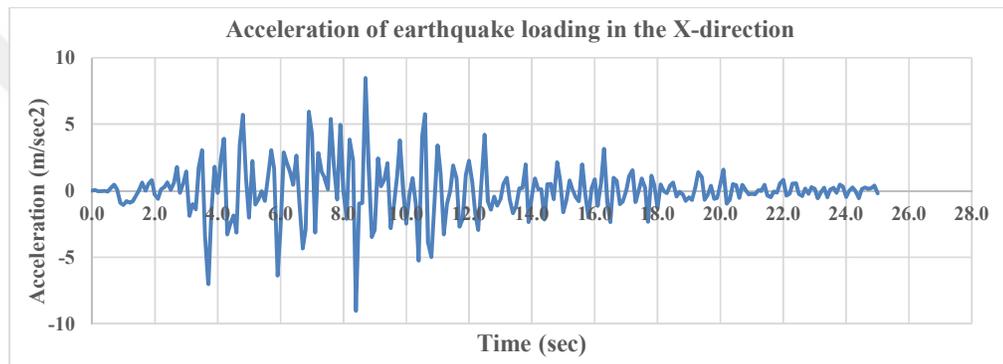Figure 3.78 Acceleration of earthquake loading applied to the model of two-story building on shaking table in the X-direction

The position of the two earthquake loads which applied in middle plane in the Z-direction and top plane in the X-direction of a shaking table was given in Figure 3.79.
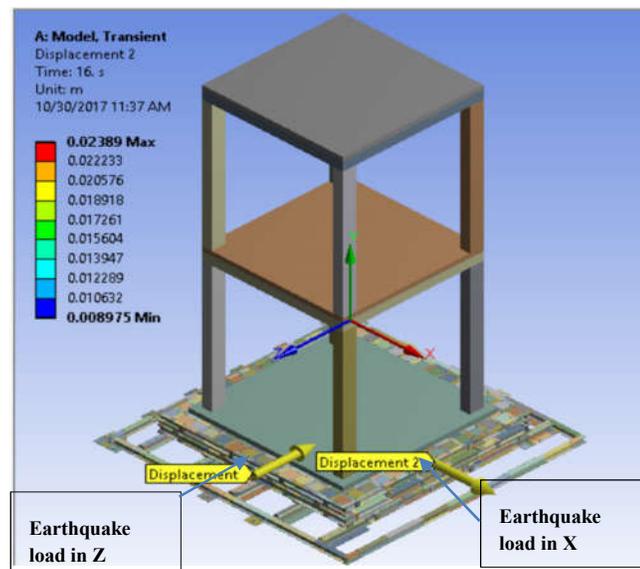

Figure 3.79 Application of biaxial displacement loadings on the model of two-story building on shaking table

74

3.4.4 Comparison of the Results and Discussion

The analysis aimed to create and study more loading conditions that would be present the shaking table model. Therefore, the maximum analysis results such as displacement, acceleration, and drift are obtained for the model under two directional earthquake loadings. The comparison of results which measured at different locations on the model in the Z and X directions are given in Table 3.19.

Table 3.19 Comparison results of model of two-story building on shaking table under biaxial earthquake loads

Location	Acceleration (m/sec^2)		Displacement on floors of building (m)		Drift	
	Z	X	Z	X	Z	X
Second floor of building	25.32	16.57	0.381	0.439	0.0205	0.0173
Firest floor of building	15.00	11.97	0.347	0.410	0.0264	0.0176
Shaking table	14.37	14.25	0.304	0.381		

As seen in Table 3.19, the maximum acceleration values are calculated on the second floor of building in two directions, and the acceleration values in the Z direction are higher than in the X direction. The maximum displacement value is calculated on the second floor in the X-direction while the maximum drift is calculated on the first floor in the Z-direction. The acceleration response on the shaking table in the Z and X direction are given in Figure 3.80 and Figure 3.81, respectively.
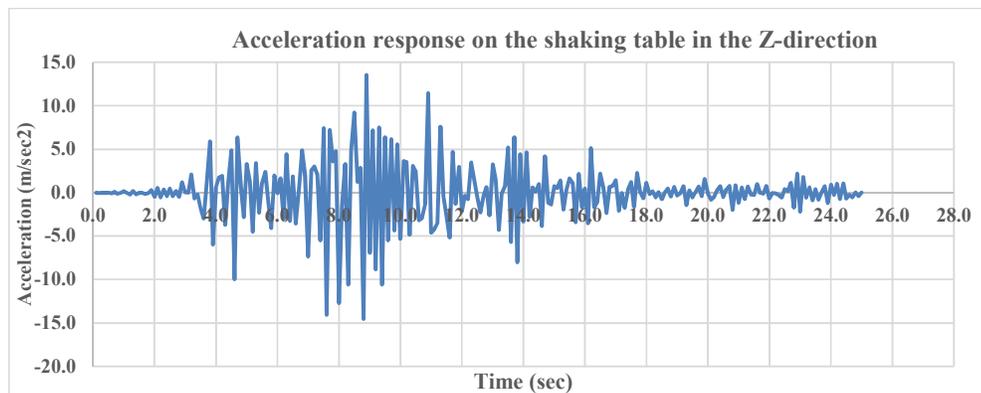
Figure 3.80 Acceleration response on the shaking table model with two-storey building in the Z-direction
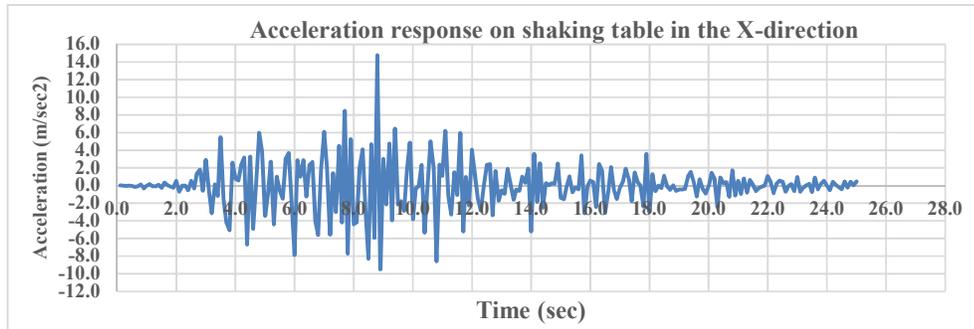
Figure 3.81 Acceleration response on the shaking table model with two-storey building in the X-direction

As seen in Figure 3.80 and Figure 3.81, the amplitudes of acceleration on the shaking table is developed with time, and the maximum amplitude values are seemed higher than the peak acceleration values of earthquake loadings in two directions but with the same behaviors. The displacement response versus time on the shaking table in the Z and X directions are given in Figure 3.82 and Figure 3.83, respectively.
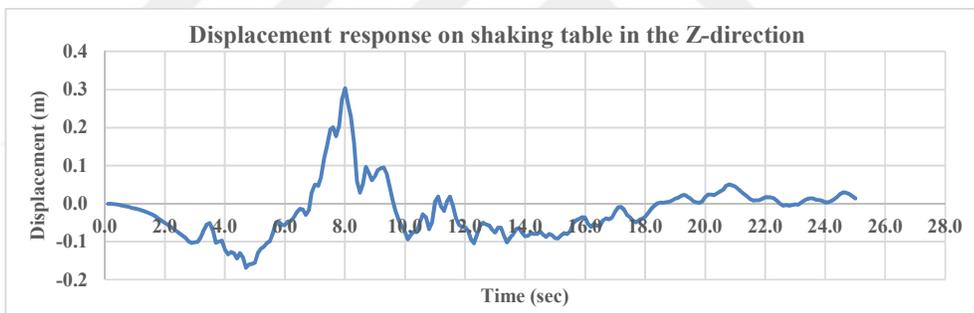
Figure 3.82 Displacement response on the shaking table model with two-storey building in the Z direction
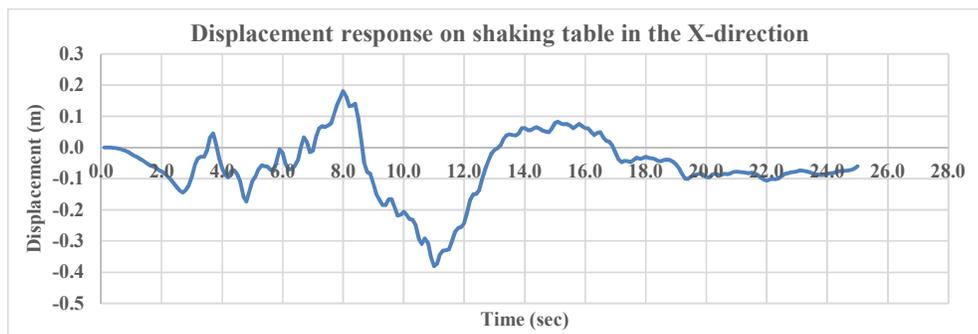
Figure 3.83 Displacement response on the shaking table mode with two-storey building in the X direction

As seen in Figure 3.82 and Figure 3.83, the displacement response which measured on the shaking table is increased with time. Furthermore, can be noted from results that the displacement responses in the Z and X directions have similar behaviors when compared

with input displacement of earthquake loadings. The distribution of displacement and acceleration and drift along the floor level are given in the Figure 3.84 and Figure 3.85.

(a)

(b)

(c)
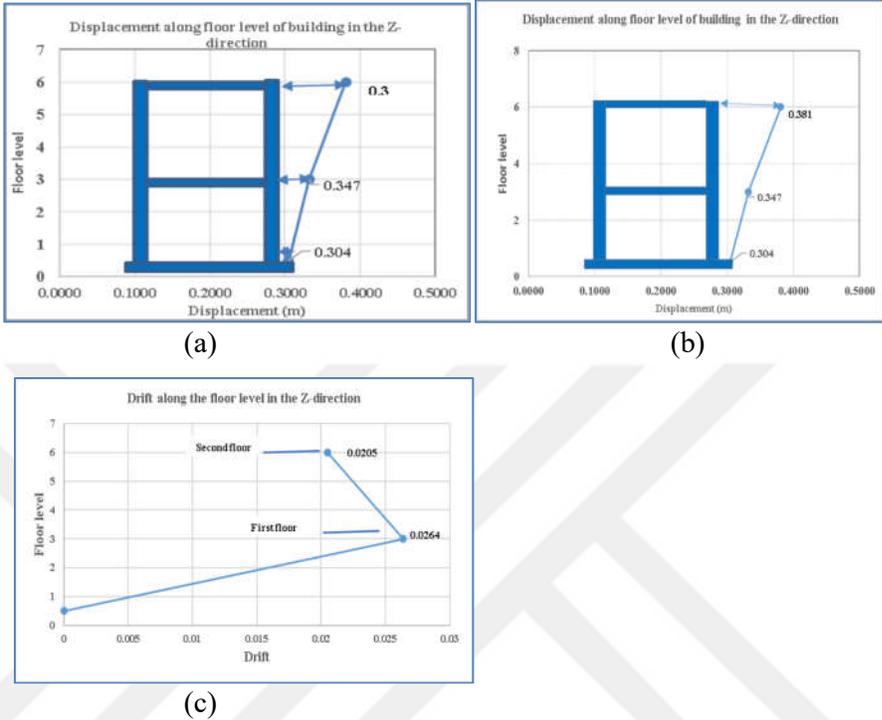
Figure 3.84 Displacement, acceleration and drift along floor level in the Z-direction

(a)

(b)

(c)
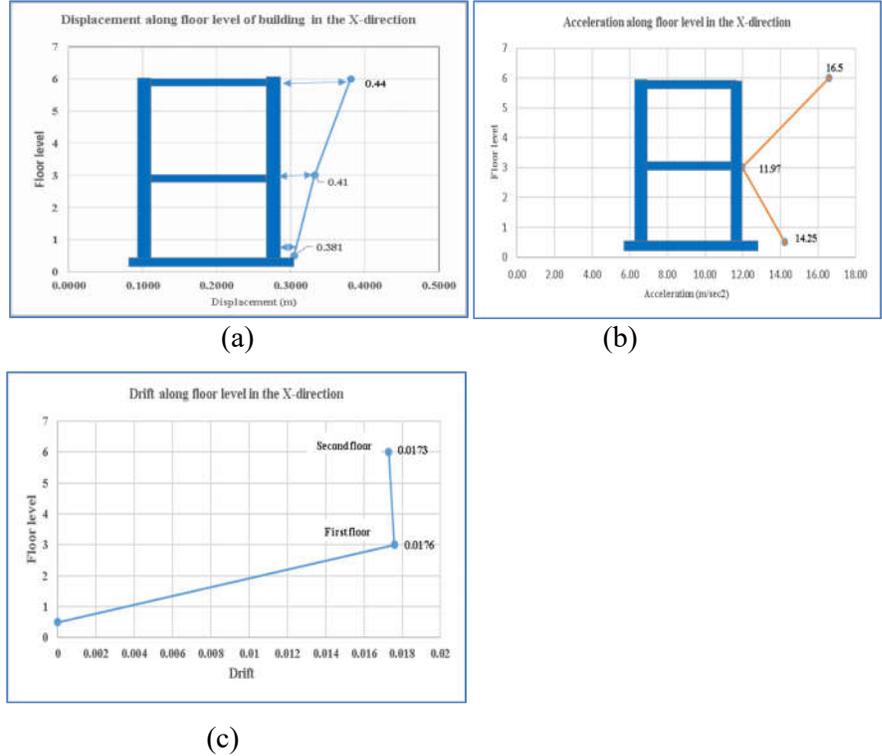
Figure 3.85 Displacement, acceleration, and drift along floor level in the X-direction

77

3.5 Numerical Analysis of Model of Three Storey Shear Wall RC Building on Shaking Table Under Earthquake Loads

The three-dimensional finite element is used for modeling and analysis of the shaking table with three-story RC shear wall building which investigated under displacement loading in one direction and two directions. The model has been tested under two types of analyses, modal analysis, and dynamic analysis. The outstanding results such as displacement, acceleration, frequency, stress, strain, and drift are obtained on the building and shaking table by using ANSYS program.

3.5.1 Geometric of Modeling

The geometry of the model of three-story shear wall RC building on shaking table is created by using ANSYS program. The shear wall building consists of the three-story reinforced concrete building. It is composed of three walls forming a U shape, a column and a beam dividing the slab into two parts. The height of the floor levels is, accordingly 1.25 m, 2.45m, and 3.65 m from the basement. The thickness of the slab is 10 cm. Moreover, the geometrical model and Plane view of the three-story shear wall building shown in Figure 3.86 and Figure 3.87, respectively.
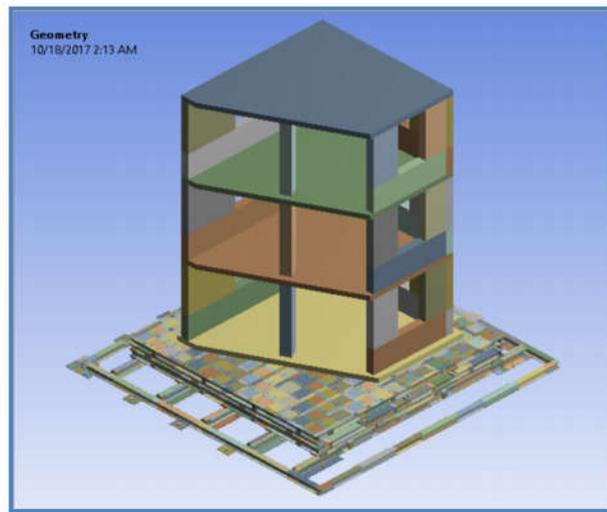
Figure 3.86 Geometry for model of three-storey shear wall RC building on shaking table
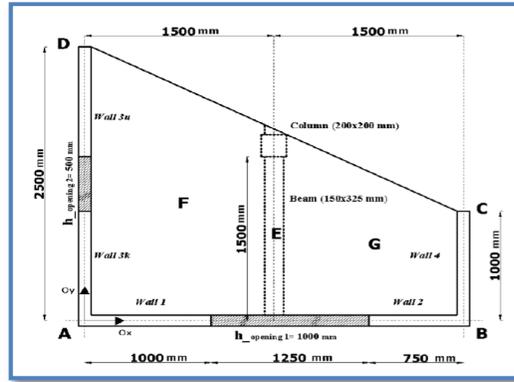
Figure 3.87 Plane view of model of three-storey shear wall RC building

3.5.2 Definition of Materials Properties

The materials properties of the model can be edited by using engineering data with ANSYS program. In this model two different materials are defined, steel and reinforced concrete and the properties such as density, young modulus, strength, and poisons ratio are defined as shown in Table 3.20.

Table 3.20 Materials properties of model of the three-story shear wall RC building on shaking table

Member	Material	Mass (ton)	Density (KN/m^3)	Young's Modulus (Mpa)	Poisson's Ratio	Compressive Strength (Mpa	Tensile Strength (Mpa)
Shaking Table	Steel	5.50	76.98	2.00E+05	0.3	250	460
Building	Concrete	44.30	66.4	32000	0.2	40	5

3.5.3 Meshing of Model

ANSYS program provides meshing module that allows mesh generation of a drawn structure. The purpose of meshing in a numerical simulation is to discretize a continuous domain, which contains an infinite number of points, as a finite number of regions. Meshing module enables the user to generate meshing automatically or manually with different level of precision. After simplifying the geometry of model the mesh was generated by using mesh tools (sizing, multizone and mapping face). The hexahedral mesh is used to get more accurate results as shown in Figure 3.88.
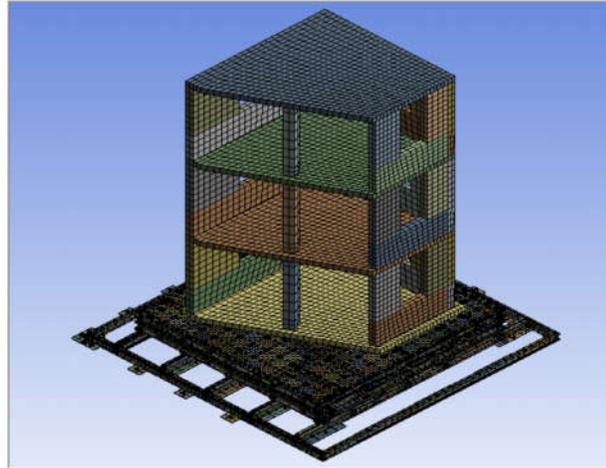
Figure 3.88 Mesh for model of three-storey shear wall RC building on shaking table

3.5.4 Analysis Procedures

To perform the dynamic behavior of the shaking table model and superstructure with different applied loads and boundary conditions, therefore two type of analyses are generated using ANSYS program. Modal analysis and dynamic analysis and the results of natural frequency, displacement, acceleration, stress, strain, and drift are calculated.

3.5.4.1 Modal Analysis

The modal analysis is performed to obtain the natural frequencies of two models, in the first model, the effect of shaking table was ignored, and the base of the shear wall building was considered as fixed. In the second model, the shaking table was included with the building. The first three mode shapes for each model are calculated as shown in Figure 3.89 and Figure 3.90 respectively. The first three mode frequencies are obtained from analyses and compared with results of a previous study [16], as shown in Table 3.21.

Mode 1: F=8.26 Hz   Mode 2: F=14.8 Hz   Mode 3: F=26.44 Hz

Figure 3.89 First three modes for model of three-storey shear walls R.C building with fixed base
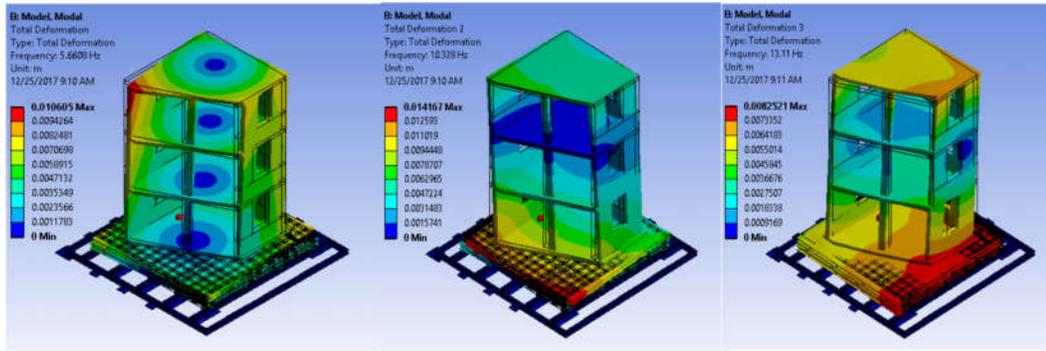
| Mode 1: F=5.66 Hz | Mode 2: F= 10.32 Hz | Mode 3: F= 13.11 Hz |

Figure 3.90 First three modes for model of three-storey shear wall RC building on shaking table

Table 3.21 Comparisons of frequencies for model of three-story shear wall RC building on shaking table

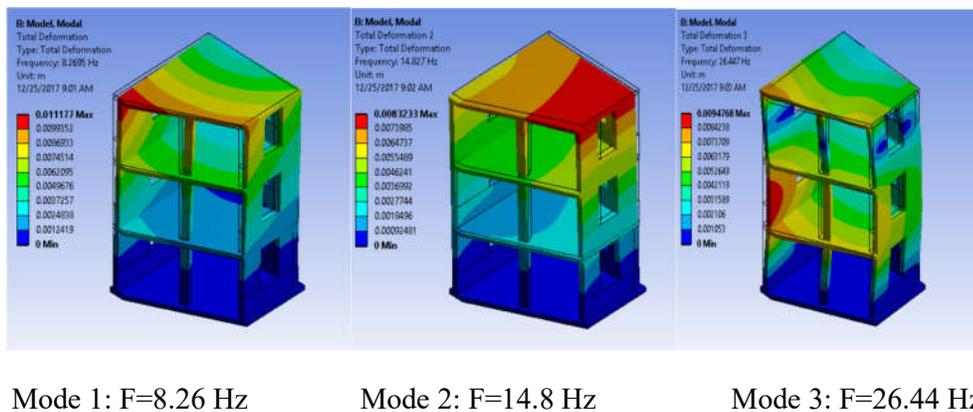| Mode	Frequency (Hz)			
	Model of three-storey shear wall building with fixed base	Model of three-storey shear wall building on shaking table	Model of three-storey shear wall building with fixed base from literature[16]	Experimental results for model of three-storey shear wall building on shaking table from literature [16]
Mode 1	8.26	5.66	9.2	6.24
Mode 2	14.8	10.32	15.9	7.86
Mode 3	26.44	13.11	32.7	15

As seen in the Table 3.21, the fixed based model was more rigid thus yields larger frequency values as compared with shaking table base model, and the shaking table base model appeared more flexibility that could affect the response of the superstructure. Moreover, the frequencies that obtained from a model with a shaking table were much closer to experimental results which in the previous study [16].

3.5.4.2 Dynamic Analysis of Model with an Axial Earthquake Load

The dynamic analysis is run on a shaking table with three-story shear wall building which subjected to one-directional displacement loading in the Z-direction. The displacement and acceleration of earthquake loading in the Z-direction are given in Figure 3.91 and Figure 3.92, respectively.
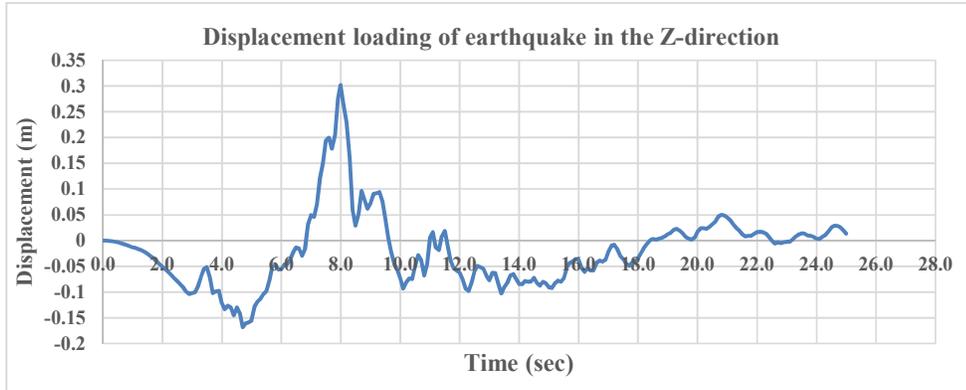
Figure 3.91 Displacement loading applied to model of three-storey shear wall RC building on shaking table in the Z-direction

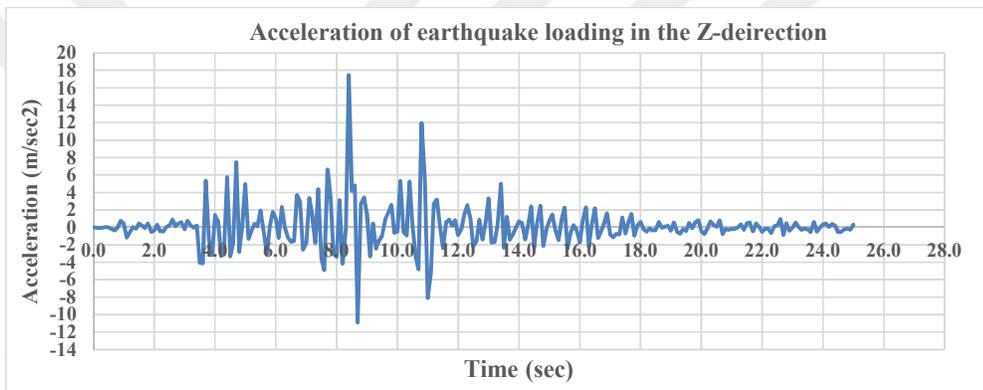Figure 3.92 Acceleration of earthquake loading which applied to model of three-storey shear wall RC building on shaking table in the Z-direction

The application of an axial displacement loading which applied on shaking table with three-story shear wall RC building is given in Figure 3.93.
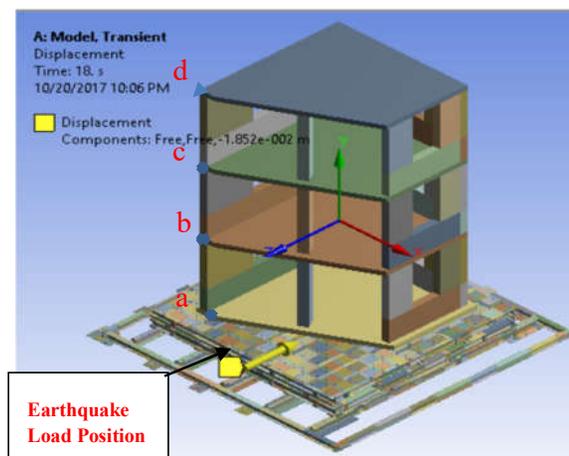

Figure 3.93 Application of an axial earthquake load on model of three-storey shear wall RC building on shaking table

After the dynamic analysis is run the results of displacement, acceleration, and drift are taken on the shaking table, first floor, second floor and third floor of the shear wall building, where the results are taken at points a, b, c, and d respectively. Moreover, the results of equivalent stress and strain which calculated Separately of the shaking table and building are compared in the Table 3.22.

Table 3.22 Comparison results for model of three-story shear wall building on shaking table under axial earthquake load

Location	Max. acceleration (m/sec^2)	Max. equaivalent Stress (Mpa)	Max. equaivalent Strain (m/m)	Max.Displacement on top floor (m)	Drift
Third floor of building	16.81	14.00	5.09E-05	0.33470	0.00588
Second floor of building	14.60	14.00	5.09E-05	0.32500	0.00545
Firest floor of building	13.90	14.00	5.09E-05	0.31600	0.00970
Shaking table	13.80	115.00	5.75E-04	0.3000	

As seen in Table 3.22, the maximum acceleration values are increased gradually with increasing the height of the building where the highest acceleration value is measured on the third floor of the shear wall building. The maximum equivalent stress and strain seem on the shaking table higher than on the building. Moreover, the maximum displacements are increased with increasing the height of the building, and the highest displacement is measured on the third floor of the building. The maximum drift values of the building are seemed small, that is, the building still in the linear range. The acceleration response on the shaking table and the third floor of the three-story shear wall RC building are given in Figure 3.94 and Figure 3.95, respectively.

Figure 3.94 Acceleration response on the shaking table model with three-storey shear wall RC building

Figure 3.95 Acceleration response on the third floor of three-storey shear wall building on shaking table

As seen in Figure 3.94 and Figure 3.95, the amplitudes of acceleration are increased with time, and the acceleration response on the shaking table have similar behavior of acceleration of earthquake loading. The displacement response on shaking table and on the third floor of the building is given in Figure 3.96 and Figure 3.97, respectively.
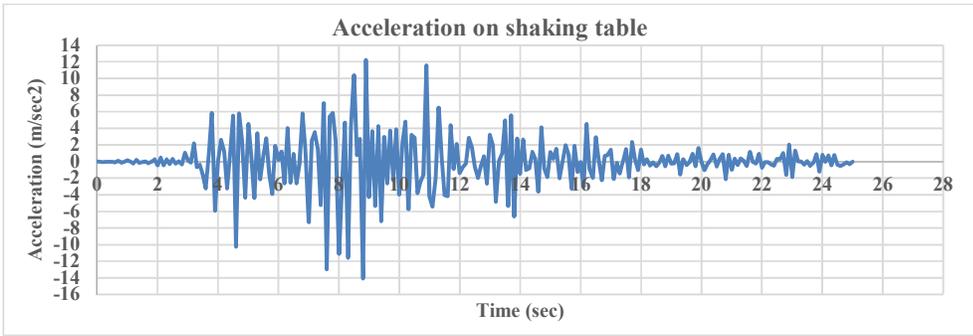

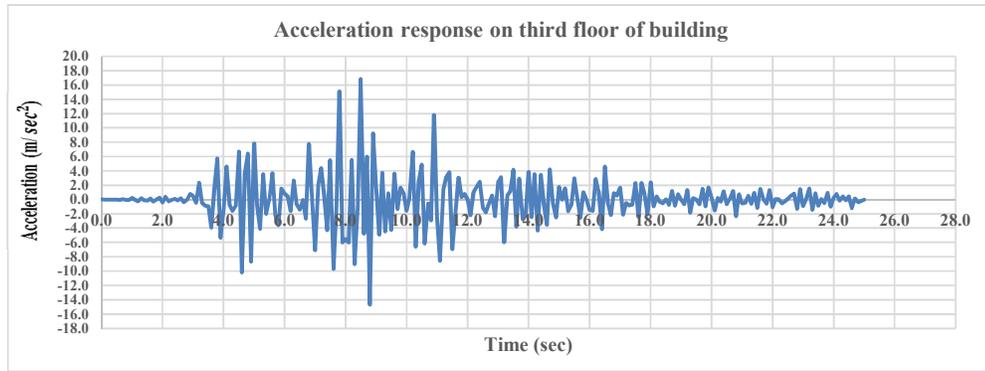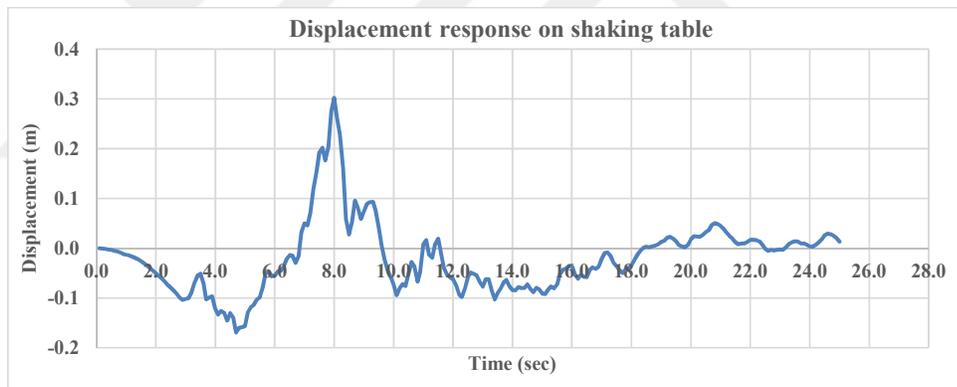Figure 3.96 Displacement response on the shaking table model with three-story shear wall RC building
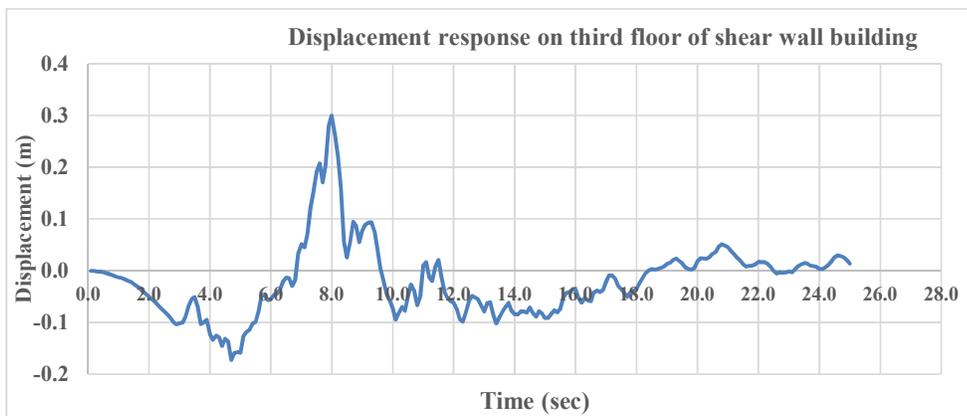
Figure 3.97 Displacement response on the third floor of three-story shear wall RC building on shaking table

From Figure 3.96, the displacement response on the shaking table have the same behavior when compared with input displacement of the earthquake load, that is, the analysis has good agreement results. As seen in Figure 3.97, the displacement response on third-floor dose does not develop so much. The distribution of displacement, acceleration and drift along the floor level are given in the Figure 3.98,

(a)

(b)

(c)
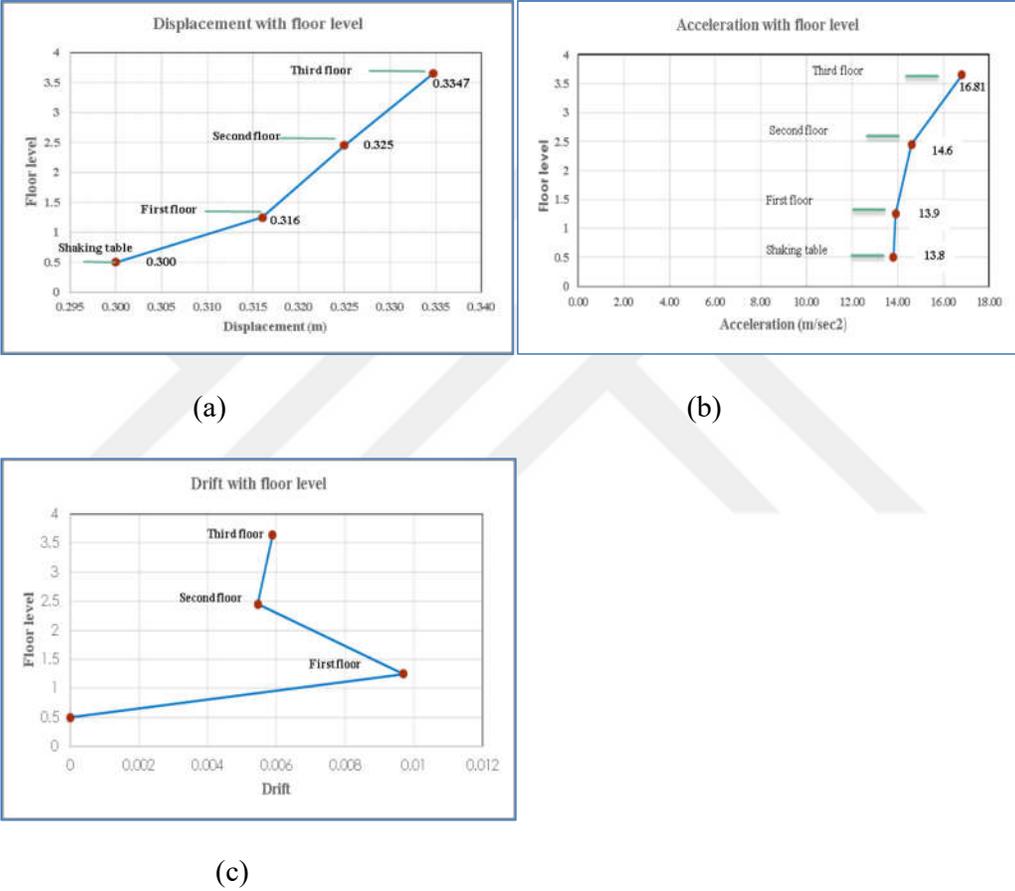
Figure 3.98, Distribution of displacement, acceleration, and drift along floor level for model of three-story shear wall building on shaking table

3.5.4.3 Dynamic Analysis of Model with Biaxial Earthquake Load

In this analysis, the model of a shaking table with three-story shear wall building is subjected to two directional displacement loadings. The first displacement load is applied in the middle plane of a shaking table in the Z-direction and in the same time the second displacement load is applied in the top plane of a shaking table in the X-direction. The displacement loadings in the Z and X directions are given in Figure 3.99 and Figure 3.100, respectively.
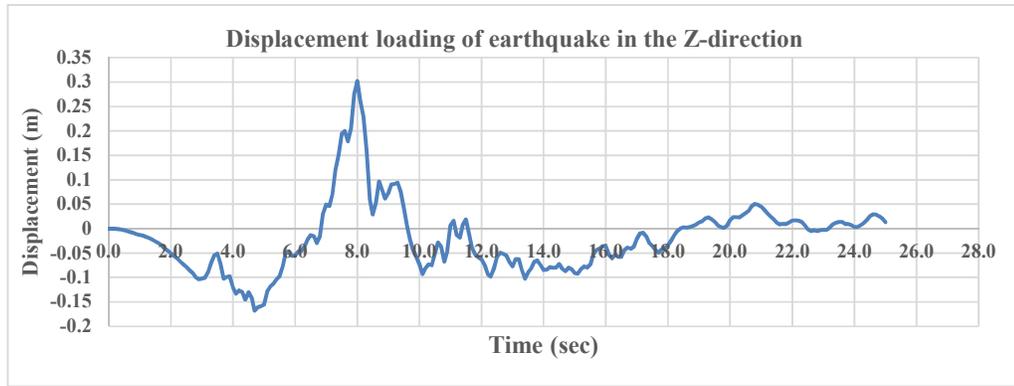
Figure 3.99 Displacement loading applied to model of three-story shear wall RC building on shaking table in the Z-direction
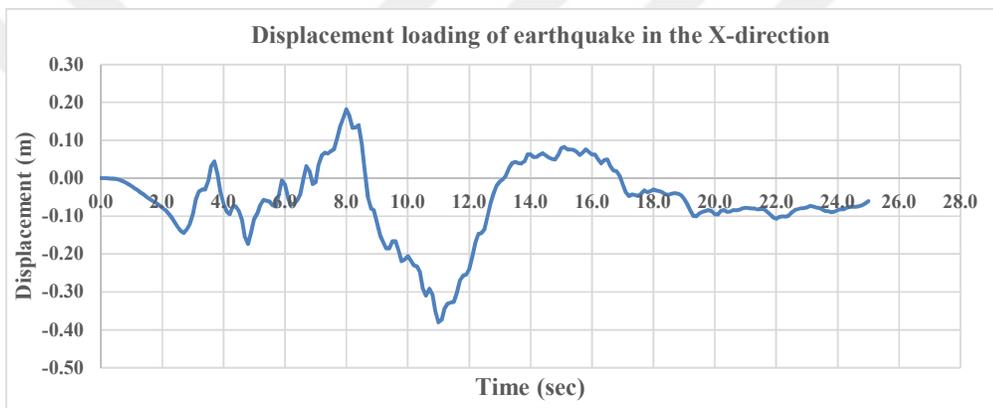
Figure 3.100 Displacement loading applied to model of three-story shear wall RC building on shaking table in the X-direction

Moreover, the acceleration of earthquake loadings in the Z and X directions are shown in Figure 3.101 and Figure 3.102, respectively.
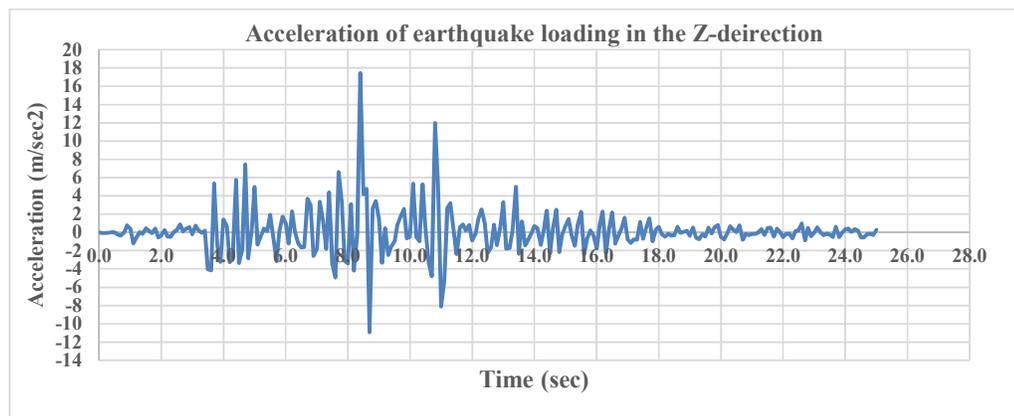
Figure 3.101 Acceleration of earthquake loading applied to model of three-storey shear wall building on shaking table in the Z-direction
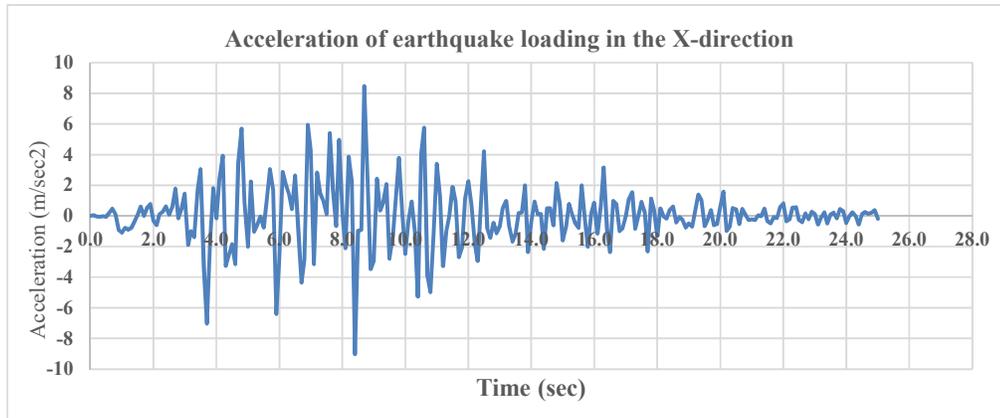
Figure 3.102 Acceleration of earthquake loading applied to model of three-storey shear wall building on shaking table in the X-direction

The application of biaxial displacement loadings on shaking table model with three-story shear wall RC building is given in Figure 3.103.
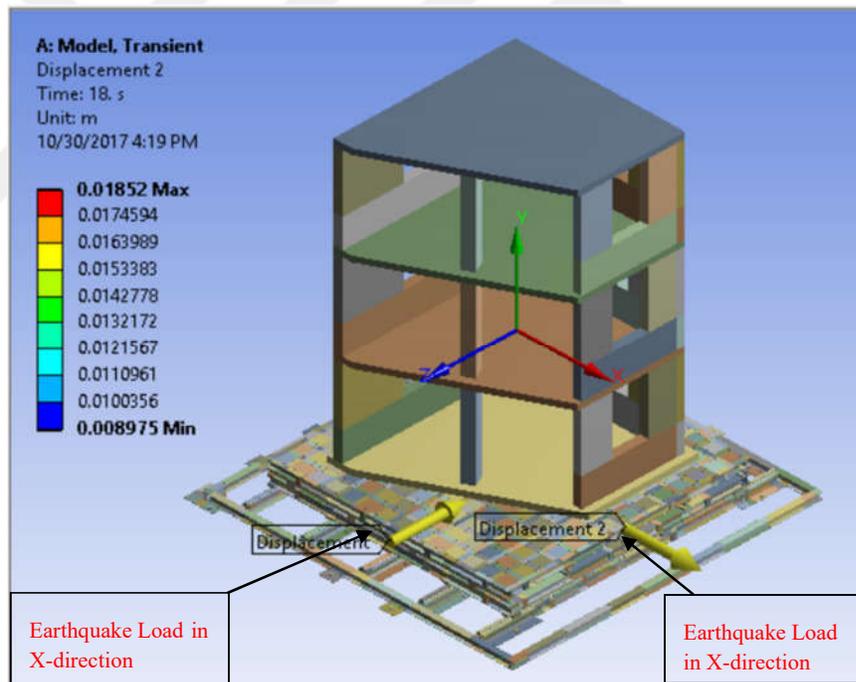
Figure 3.103 Application of biaxial displacement loadings applied on model of three-story shear wall building on shaking table

The dynamic analysis is run by using ANSYS program. Results of the analysis such as displacement, acceleration, and drift are calculated on a shaking table, first floor, second floor and on the third floor of shear wall building. Moreover, results of equivalent stress and strain which are calculated separately on shaking table and building. The comparison of results is given in the Table 3.23.

87

Table 3.23 Comparison results for model of three-story shear wall building under
biaxial earthquake loads

Location	Acceleration (m/sec^2)		Displacement on floors of building (m)		Drift	
	Z	X	Z	X	Z	X
Third floor of building	22.40	13.70	0.3250	0.390	0.00509	0.00606
Second floor of building	21.75	10.00	0.3166	0.380	0.00582	0.00182
Firest floor of building	21.30	12.14	0.3070	0.377	0.00424	0.00061
Shaking table	17.70	15.40	0.3000	0.376		

As seen in Table 3.23, the maximum acceleration values in the Z direction are increased
gradually with increasing the height of building while the accelerations in the X direction
have a different manner in each story of the building. Moreover, the highest acceleration
value in the Z direction is measured on the third floor of the building, and the highest
acceleration value in the X direction is measured on shaking table. In the other hand, the
highest value of displacement is measured on the third floor of shear wall building in the
X direction, and the drift values are seemed small, that is, the building still in linear elastic
range. The acceleration response on the shaking table in the Z and X direction are given
in Figure 3.104 and Figure 3.105, respectively
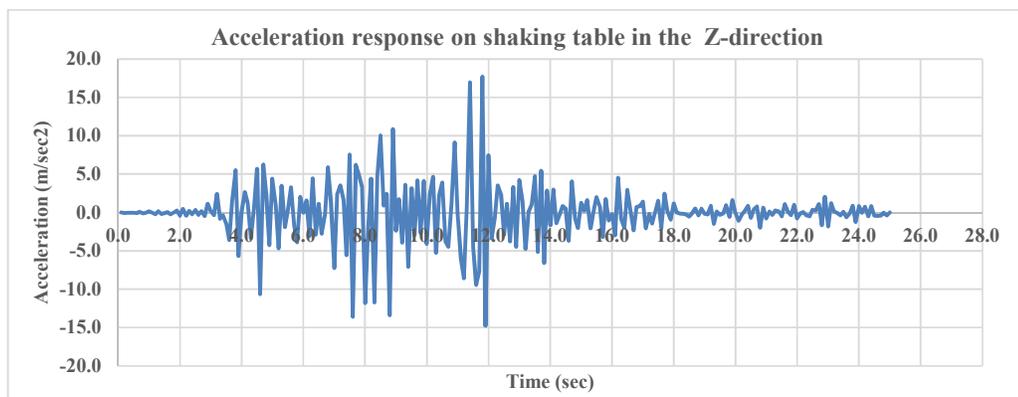
Figure 3.104 Acceleration response on shaking table model with three-storey shear wall
building in the Z-direction
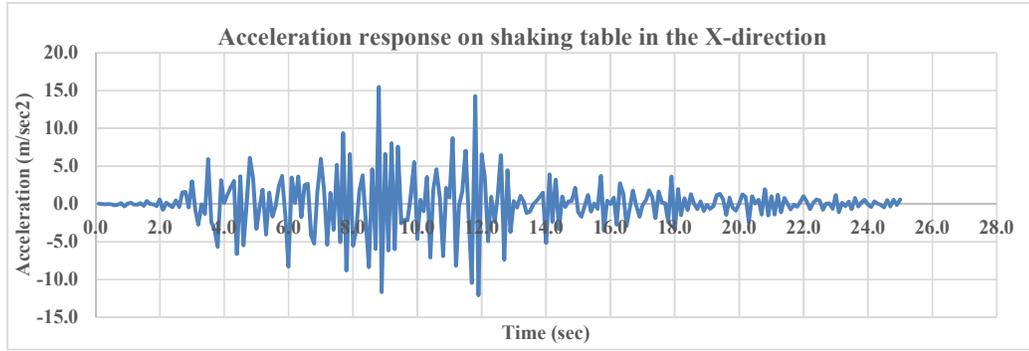
Figure 3.105 Acceleration response on the shaking table model with three-storey shear wall building in the X-direction

As seen in Figure 3.104 and Figure 3.105, the amplitudes of acceleration of model increasing with time, and the accelerations response on the shaking table have the similar behavior when compared with the acceleration of earthquake loadings in two directions.

The displacement response on the shaking table in the Z and X directions are given in Figure 3.106 and Figure 3.107, respectively.
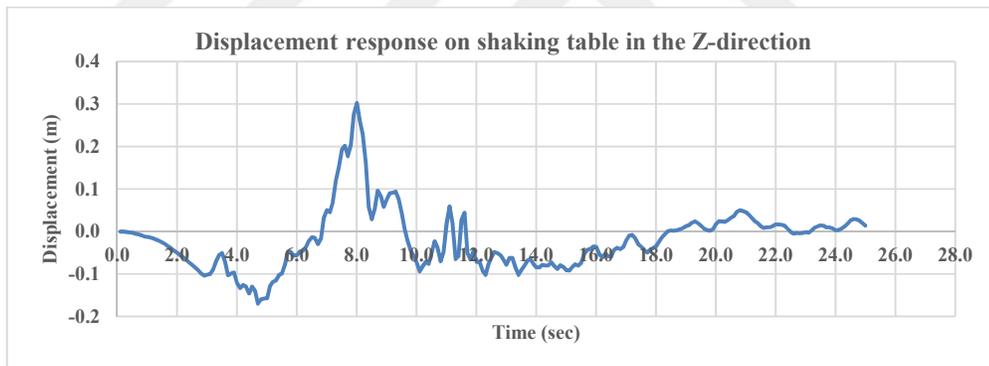
Figure 3.106 Displacement response on the shaking table model with three-storey shear wall building in the Z-direction
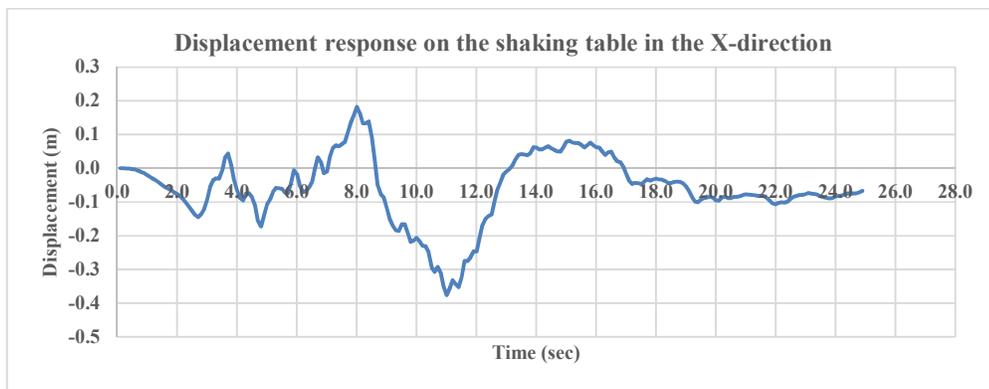
Figure 3.107 Displacement response on the shaking table model with three-storey shear wall building in the X-direction

As seen in Figure 3.106 and Figure 3.107, the displacement response on the shaking table has the same behavior when compared with input displacement response of earthquake loadings in the Z and X directions. The distribution of displacement, acceleration and drift along floor level are given in the Figure 3.108 and Figure 3.109, respectively.
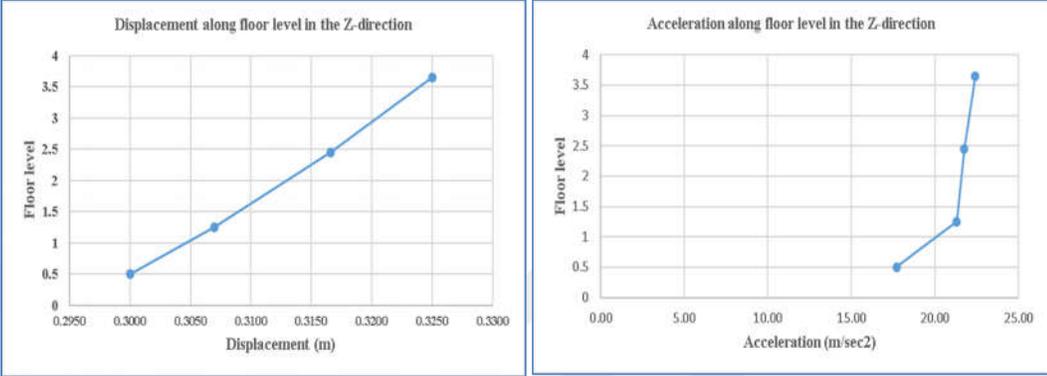
(a)

(b)
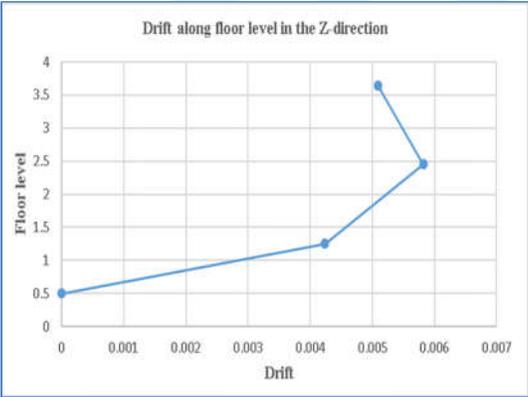
(c)

Figure 3.108 Displacement, acceleration, and drift along floor level in the Z-direction
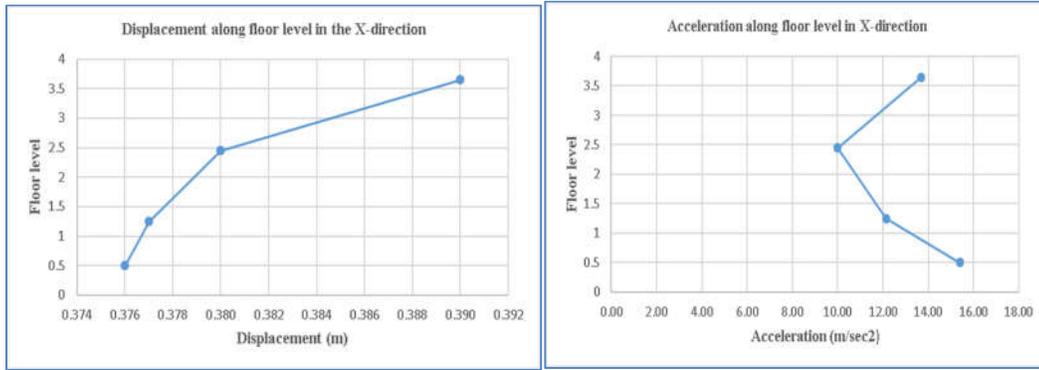
(a)

(b)
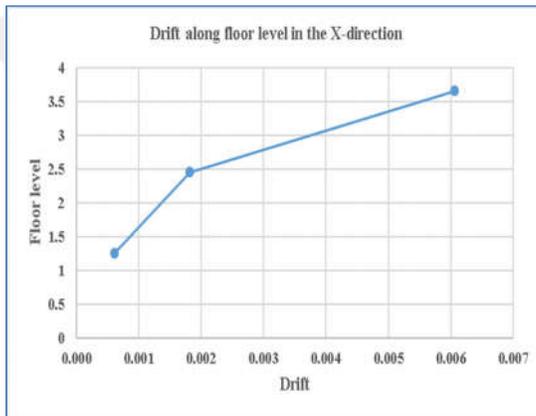
(c)

Figure 3.109 Displacement, acceleration, and drift along floor level in the X-direction

4. CONCLUSIONS

In this study, models with different types of building structures on shaking table are modeled and simulated numerically by using ANSYS program. Moreover, the models are tested under a set of dynamic loadings including harmonic loads and earthquake loadings.

In summary, the following conclusions could be obtained:

1. In the first part of the thesis, the modal analysis was run for two models, shaking table model with single story-single bay building and for shaking table model with the three-storey shear wall RC building. The natural frequencies are obtained and compared to these models and from the results can be observed the following points:

- For the single-storey building, the model including shaking table appears stiffer than the fixed based model. So that, the shaking table based model yields larger frequency values.

- The shaking table model alone has stiff modes which are out of the plane.

- For the three-storey shear wall building, the fixed based model is seemed stiffer than shaking table base model so that it yields higher frequency value than that of the fixed based model.

2. The second part of the study was to solve the two-structure system (shaking table and building) subjected to set of harmonic loads which developed according to natural frequencies of building structure and study the variations of the dynamic parameters (displacement, acceleration, and stress) with the frequency. From the results can be observed the following points:

- The analysis parameters values such as acceleration, displacement, and stress increase with the increasing frequency of harmonic loads.

- After the frequency of harmonic load is 0.30 Hz, relative motion starts in all models for all modes

- The drifts in all cases seem less than 0.01 which can be limit of linear deformation for reinforced concrete buildings. Therefore, it can be said that the building (superstructure) is in the level of linearity for all cases.

- In the shaking table model with the single-storey building, the results have conformity since the results such as for shaking table analysis have similar behavior with the data of displacement and acceleration for the harmonic loads.

- In two directions harmonic loads the highest values of acceleration and displacement are measured in X-direction.

- According to specifications properties of shaking table, the dynamic response of model gets acceptable values at some exciting range of frequencies.

3. The third part of this study was to understand the performance of shaking table model with building under earthquake loadings,

- It can be observed that the displacement and acceleration response on the top floor of building had the same behavior when compared with displacement and acceleration for input earthquake loadings

- The dynamic parameters such as (displacement, acceleration, and drift) Which measured on models get large values under two direction earthquake loadings than one direction earthquake load.

- In model under biaxial earthquake loads, the highest results of acceleration values are measured in Z-directions that mean structure system response is dominant in the Z direction.

- The analysis showed no sign of damage in models and kept in elastic range all the time.

REFERENCES

[1]   Klaus, J.B., (2014). " Finite element analysis is an art to predict the future, the second edition ", Printed and distributed by K.J. Bathe, Watertown, MA, 1:1-22.

[2]   Karadeli, J.N., (2010). Advanced Computational Methods and Solutions in Civil and Structural Engineering, Ph.D. Thesis, Coventry University, (1): 2-12.

[3]   Barkanov, E., (2001). Introduction to the finite element method, Institute of Materials and Structures, Master Thesis, Faculty of Civil Engineering. Riga Technical University, Riga, (1): 5-25.

[4]   Akansel, V.H., (2011). The fragility of a shear wall building with torsional irregularity, Master Thesis in Civil Engineering, Middle East Technical University, 37-55.

[5]   Karadelis, J.N., (2000), "A Numerical Model for the Computation of Concrete Pavement Moduli", A Non-destructive Testing and Assessment Method. NDT&E International. 33 (2): 77-84.

[6]   Karadelis, J.N., (2010) "Reliability Pointers for Modal Parameter Identification of Precast Concrete Terraces", Computers, and Concrete, An International Journal, 65-87.

[7]   Zhang, H., & Li, H.N., (2012). "Shaking table test and dynamic response analysis of reinforced concrete structure," Dalian University of Technology, P. R. China, 15 WCEE Lisboa.

[8]   Brazão, J.M., (2008). Dynamic analyses of structures in shaking tables, Master Thesis in Civil Engineering, Characterization of the Instituto Superior Técnico Shaking Table, 5-16.

[9]   Ningfen, S., Xilin L., Ying Z., Kun D., Wensheng L., (2001). "Shaking Table Model Test of a Super High-rise Building" National Natural Science Foundation of China (NSFC), 1-10.

[10]   Shen, D. and Lu, X., (2008). " Shaking table Test and Analysis on Seismic Behavior of Steel-Concrete Hybrid Structure for High Rise Buildings", The 14th World Conference on Earthquake Engineering, Beijing, China, 12-16.

[11]   Khan, F.R. and Sbarounis, J.A., (1964). "Interaction of Shear Walls and Frames," ASCE Journal of Structural, Division 90:3, 285-335.

[12]   Kwak, H.G. and Kim D.Y., (2004). "FE analysis of RC shear walls subjected to monotonic loading", Magazine of Concrete Research 56:7, 387-403.

[13]   Ile, N. and Reynouard, J.M., (2004). "Seismic behavior of R/C walls subjected to multi-directional seismic loading," 13th World Conference on Earthquake Engineering, 3243.

[14]   Ile, N. and Reynouard, J.M., (2008). " Lightly reinforced walls subjected to seismic excitations," Interpretation of CAMUS 2000-1 and 2000-2 dynamic tests. Journal of Earthquake Engineering 12:1, 91-114.

[15]   Galal, K. and ElSokkary, H., (2008). Advancement in the modeling of RC shear walls. 14th World Conference on Earthquake Engineering, Beijing, China.

[16]   Saeideh, N., Vasile, H. A., &Yakut, A., (2012). "Numerical Simulation of Shaking Table Test of an RC Shear Wall Structure with Torsional Irregularity",15 Wcee Lisboa.

 [17]   Tian, C., Xiao, C., Zhang, H., and Jinzhe, C., (2012) " Shaking Table and Seismic Evaluation of Shanghai Tower High-Rise", International Journal of Buildings. September, (3):221-228.

[18]   Liu, C., Kaiqiang, M., Xiaodan, W., Guangjie, H., Weixing, S., Zhou, Y., (2016). " Shaking Table Test and Time-History analysis of High-rise Diagrid Tube Structure", Research Article, Tongji University, Shanghai, China, 61(2), PP. 300-312.

[19]   Dong, Q., (2011). Numerical Simulation of Shaking Table Tests of a Full-Scale Building Seismically Isolated with Lead-Rubber Bearings, Master of Engineering, Division of Architectural and Structural Design, Japan, 1-4.

[20]   Tagawa, H., Tomoshi, M., and Ohsaki, M., (2015). " Detailed Finite element analysis of full-scale four-story steel frame structure subjected to consecutive ground motions," 4 (1): 65-73.

[21]   Lu, W. and Lu, X., (2000). " Seismic Model Test and Analysis of Multi-Tower High-Rise Buildings", 12WCEE, 1-8.

[22]   Nascimento, R., (2015). Numerical Model of Reinforced Concrete Building. Earthquake analysis and Experimental Validation, European Centre for Training and Research in Earthquake Engineering, Via Ferrata, 1, 27100, Pavia, Italy, 59(4): 521–530.

 [23]   Wang, X. and Hutchinson, T.C., (2011). "Shaking Table Testing and Numerical Simulation of Raised Access Floor-Computer Rack Systems in a full-scale five-story Building," Department of Structural Engineering, University of California, CA 92093-0085; PH (858): 822-0058.

[24]   Jingjiang, S., Tao, W., and Hu, Q., (2007). "Earthquake simulator tests and associated study of a 1/6-scale nine-story RC model", Journal of Earthquake Engineering and Engineering Vibration 6 (3): 281-288.

[25]   Kim, Y. and Kabeyasawa, T., (2002). " Shaking table test on eccentric pilots wall-frames to collapse," Part 1, Response behavior on the reinforced concrete specimen. The 11th Japan Earthquake Engineering Symposium.

[26]   Palermo, D. and Vecchio, F.J., (2002). "Behavior of Three-Dimensional Reinforced Concrete Shear Walls". ACI Structural Journal. 99-S9.

[27]   Lee, H.S. and Ko, D.W., (2007). Seismic response characteristics of high-rise RC wall buildings having different irregularities in lower stories, Engineering Structures 2 (29): 3149-3167.

[28]   Mazars, J., Ragueneau, F., Casaux, G.A. and Kotronis, P., (2004). "Numerical modeling for earthquake engineering: The case of lightly RC structural walls". International Journal for Numerical and analytical methods in Geomechanics (28):7-8, 857-874.

[29]   Ile, N. and Reynouard, J.M., (2004). "Seismic behavior of R/C walls subjected to multi-directional seismic loading". 13th World Conference on Earthquake Engineering, 32-43.

[30]   Ile, N. and Reynouard, J.M., (2003). "Lightly reinforced walls subjected to multi-directional seismic excitations", Interpretation of CAMUS 2000-1 dynamic tests. Journal of Earthquake Technology (40):2-4, 117-135.

[31]   Kotronis, P. Ragueneau, F. and Mazars, J., (2005). A simplified modeling strategy for R/C walls satisfying PS92 and EC8 design, Engineering Structures 8 (27): 1197-1208.

[32]   Kazaz İ., Yakut A. and Gülkan P., (2006). " Numerical simulation of dynamic shear walls tests", A benchmark study. Computers and Structures 84,549-562.

[33]   Le, A. and Queval, J.C., (2010). Advances in Performance-Based Earthquake Engineering. ISBN: 978-90-481-8745-4, 4 (13): 431-440.

[34]   Hiroyuki, T.,Tomoshi, M. Takuzo, Y. Masayuki, K. and Makoto, O., (2015). Detailed finite element analysis of a full-scale four-story steel frame structure subjected to consecutive ground motions. National research institute for earth science and disaster prevention. Miki, 673-0515, Japan.

[35]   Lu, W. and Lu, X., 2000, Seismic model test and analysis of multi-tower high rise buildings.

[36]   Bathe, K.J., and Wilson, E.L., (1976). "Numerical Methods in Finite Element Analysis". Prentice-Hall, Inc.

[37]   Nikishkov, G.P., (2004). Introduction to the finite element method, University of Aizu, Aizu-Wakamatsu, 965-8580.

[38]   Stephen, H. and Mago, N., (2010). "Finite element analysis, what is it and how can it help your company", NAFEMS Registered Analyst.

[39]   David, H.V., (2004). "Fundamentals of finite element analysis", International edition ISBN 0-07-112231-1, copyright © 2004- McGraw-Hill companies.Inc. 1-27.

[40]   Olivier, D.W., (2004). Finite Element Method and engineering design and rapid prototyping, Massachusetts Institute of Technology. 16 (810) :682.

[41]   Mahendran, M., (2007). Applications of Finite Element Analysis in Structural Engineering, Faculty of Built Environment and Engineering, Queensland University of Technology, Australia.

[42]   Lopez, A., Sebastian, R., and Jose, M.F., (2015). Three-dimensional cardiac computational modeling: methods, features, and applications, Biomedical Engineering OnLine201514:35.

[43]   Adriana Ionescu, Madalina Calbureanu, Mihai Negru., (2013). " Static and dynamic simulation in the seismic behavior of a building structure using ANSYS program", International Journal of mechanics. Issue 3, Volume 7, 2013.

[44]   Wang, E. and Nelson, T., (2001). "Structural Dynamic Capabilities of ANSYS", CADFEM Gmbh, Munich, Germany.

[45]   Farqaleet, A. and Islamia, J.M., (2016). " Dynamic Analysis of Multi-storey RCC Building", A Central University, New Delhi. © August 2016 (IJIRT) ISSN: 2349-6002.

[46]   BAIRRAO, R. and Carlos, T.V., (2000). " Shaking Table Testing of Civil Engineering structures- The Lnec 3D Simulator Experience", 12WCEE-2000.

[47]   Hudhaifa Mohammed, H.A., BEKİROĞLU, S., (2017). " Numerical Simulation of a Building on Shaking Table", IATS'17 International Advanced Technologies Symposium, Elaziğ, Turkey.

[48]   Yönetmlik, B.H., (2007). Deprem Bölgelerinde Yapılacak, Resmi Gazete: 26454: 127.

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