

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**APPLICATION OF OPTIMIZATION BASED
FINITE ELEMENT MODEL UPDATING
METHOD ON 3D PRINTED MODEL
STRUCTURES**

by

Mohammed Kashama GUZUNZA

August, 2020

İZMİR

**APPLICATION OF OPTIMIZATION BASED
FINITE ELEMENT MODEL UPDATING
METHOD ON 3D PRINTED MODEL
STRUCTURES**

**A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Master of Science
in Civil Engineering, Structure Program**

**by
Mohammed Kashama GUZUNZA**

August, 2020

İZMİR

M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**APPLICATION OF OPTIMIZATION BASED FINITE ELEMENT MODEL UPDATING METHOD ON 3D PRINTED MODEL STRUCTURES**” completed by **MOHAMMED KASHAMA GUZUNZA** under supervision of **PROF. DR. ÖZGÜR ÖZÇELİK** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ACKNOWLEDGMENTS

I would first like to thank my supervisor Prof. Dr. Özgür ÖZÇELİK who gave me a force and believed in me during this work. During the preparation of this work, he ensured that this work was authentic and whenever I needed his help, the door of his office was widely open to welcome me and guide me.

I would like to thank the Turkish scholarship program which gave me the opportunity to do my Master of Science and with all the support throughout my stay in Turkey.

I would like to thank and acknowledge my friends Civil Engineers, (M.Sc) Umut YÜCEL, and (M.Sc) Özgür GIRGIN for their support and assistance during the experimentally measured data, it was not easy to finalize this of work. I would like to thank my friend Mechanical Engineer (M.Sc) Alif DIAMBU for getting me the upper hand of this work during the conception stages.

Finally, I would like to express my gratefulness to my parents and all the Congolese students of Izmir for their unwavering support during my years of study, and especially during the preparation of this thesis.

Mohammed Kashama GUZUNZA

APPLICATION OF OPTIMIZATION BASED FINITE ELEMENT MODEL UPDATING METHOD ON 3D PRINTED MODEL STRUCTURES

ABSTRACT

Nowadays the study of dynamic behavior of complex structures has become a trend. Model updating is one of the tools developed for verifying the accuracy of finite element models. In this research, the method for computing model updating on the finite element model and the experimental modal analysis of structural systems is developed. The case study considered in this work is a 3D printed structure that was modelled as a two-story shear building system with an irregular torsion. A preliminary numerical model of this two-story shear building system is developed by using SAP2000 and the experimental modal parameters data are collected at the laboratory by ambient vibration and white noise test, then are modelled by ARTeMIS pro. The identification method developed in this study is based on numerical techniques for the identification of systems in the time domain. The results obtained from the numerical model and experimental model were uploaded to FEMtools software to improve the match between the dynamic properties of the analysis model and the experimentally estimated modal data for updating the numerical model. After updating, it was found that some material parameters (Such as Young modulus and density) were optimized.

Keywords: 3D printed, finite element model updating, sensitivity analysis, system identification, irregular torsion

OPTİMİZASYON TABANLI SONLU ELEMANLAR MODELİ GÜNCELLEMESİ YÖNTEMİNİN 3 BOYUTLU BASKI KULLANILARAK YAPILAN MODELLERE UYGULANMASI

ÖZ

Günümüzde karmaşık yapıların dinamik davranışlarının incelenmesi bir eğilim haline gelmiştir. Model güncelleme, sonlu eleman modellerinin doğruluğunu doğrulamak için geliştirilen araçlardan biridir. Bu çalışmada, sonlu elemanlar modelinde model güncelleme ve yapısal sistemlerin deneysel modal analizi için yöntem geliştirilmiştir. Bu çalışmada ele alınan vaka çalışması, düzensiz burulma ile iki katlı bir kesme yapı sistemi olarak modellenmiş 3D baskılı bir yapıdır. SAP2000 kullanılarak bu iki katlı kesme yapı sisteminin bir ön sayısal modeli geliştirilmiş ve deneysel modal parametre verileri laboratuarda ortam titreşimi ve beyaz gürültü testi ile toplanmış, daha sonra ARTeMIS pro tarafından modellenmiştir. Bu çalışmada geliştirilen tanımlama yöntemi, zaman alanındaki sistemlerin tanımlanması için sayısal tekniklere dayanmaktadır. Sayısal model ve deneysel modelden elde edilen sonuçlar, analiz modelinin dinamik özellikleri ile sayısal modelin güncellenmesine yönelik deneysel olarak tahmin edilen modal veriler arasındaki uyumu geliştirmek için FEMtools yazılımına yüklenmiştir. Güncellemeden sonra bazı malzeme parametrelerinin (Young modülü ve yoğunluk gibi) optimize edildiği bulundu.

Anahtar kelimeler: 3D baskılı, sonlu elemanlar model güncellemesi, duyarlılık analizi, sistem tanımlama, düzensiz burulma

CONTENTS

	Page
M.Sc THESIS EXAMINATION RESULT FORM.....	ii
ACKNOWLEDGMENTS	iii
ABSTRACT.....	iv
ÖZ	v
LIST OF FIGURES	x
LIST OF TABLES	xii
CHAPTER ONE-INTRODUCTION	1
1.1 Description of the project.....	2
1.1 Use software.....	4
1.2 Aims of work	4
1.3 Thesis contributions	5
1.4 Thesis layout	5
CHAPTER TWO-THEORY	6
2.1 Finite element (FE) method.....	6
2.1.1 FE overview	6
2.1.2 Finite element method applications.....	7
2.2 Finite element model updating method.....	8
2.2.1 Finite element model updating overview	8
2.2.2 Finite element model updating problem.....	8
2.2.3 Aspects of the model to be updated	9
2.2.4 Femtools updating	9
2.2.5 Sensitivity-based parameter estimation.....	10

2.3	Optimization	12
2.3.1	Overview of optimization.....	12
2.3.2	Femtools optimization.....	12
2.4	Selected parameters.....	13
CHAPTER THREE-SPECIMEN DESIGNS AND PRELIMINARY WORK ..		14
3.1	Preliminary test specimen.....	14
3.2	3D Printed	15
3.2.1	Acrylonitrile Butadiene Styrene (ABS) and its Features	15
3.2.2	Geometry properties	16
3.2.3	Material properties	17
3.2.4	Printed model	18
CHAPTER FOUR-DYNAMICS ANALYSIS		20
4.1	Introduction.....	20
4.2	Analysis of unsymmetric building with ground motion	20
4.2.1	Analysis and results.....	21
CHAPTER FIVE-LABORATORY STUDIES OR EXPERIMENTAL MODELLING		26
5.1	Data acquisition.....	28
5.1.1	LabVIEW software	28
5.1.2	Permanent sensors	29
5.2	Detrending & filtering of signal.....	31
5.2.1	Detrending	31
5.2.2	Filtering	31

5.3 Operational Modal Analyses (OMA)	32
5.3.1 Enhanced frequency domain decomposition (EFDD)	32
5.3.2 Stochastic subspace identification method (SSI)	33
5.3.3 Why EFDD and SSI are used as a technique for deducting frequencies and modes instead of another method	35
5.3.4 Difference between EFDD and SSI	35
5.3.5 Which method is more reliable in what sense?	36
5.4 Modal Assurance Criteria (MAC)	36
5.5 Ambient vibration	37
5.5.1 Measurement of ambient vibration responses	37
5.5.2 Detrending & filtering of an ambient vibration signal	37
5.5.3 EFDD method for ambient vibration	38
5.5.4 SSI method for ambient vibration	39
5.5.5 Comparison of EFDD and SSI by ambient test	41
5.6 White Noise (WN) vibration test	42
5.6.1 Measurement of white noise responses	42
5.6.2 Detrending & filtering of WN	43
5.6.3 EFDD method for white noise	43
5.7 Conclusion and discussion	45
CHAPTER SIX-NUMERICAL MODELLING & UPDATING	48
6.1 Introduction	48
6.2 Problem description	48
6.3 Numerical model (Initial Finite Element model)	49
6.4 Comparison of Numerical models	51
6.5 Finite Element Model Updating (FEMU) Studies	52
6.5.1 Mode shapes pairs and comparison	52
6.5.2 Numerical results	55
CHAPTER SEVEN-CONCLUSIONS	61

REFERENCES..... 63



LIST OF FIGURES

	Page
Figure 1.1 Perspective of the structure	2
Figure 1.2 Schema of FE model updating method for a structure	3
Figure 3.1 Conception of a structure by SOLIDWORKS.....	14
Figure 3.2 (a) Rolling of ABS, (b) 3D printer machine	16
Figure 3.3 Geometrical properties: (a) perspective view; (b) top view; (c) side view	17
Figure 3.4 Perspective view of 3D printed structure.....	19
Figure 4.1 (a) view plan of structure (b) side view of structure.....	21
Figure 5.1 PCB Piezotronics set.....	27
Figure 5.2 The flow chart of the Experimental study	27
Figure 5.3 Structure with accelerometers.....	28
Figure 5.4 Structure with accelerometers on the shaking table	29
Figure 5.5 Disposition of sensors on the base floor	30
Figure 5.6 Disposition of sensors on the 1st base floor	30
Figure 5.7 Disposition of sensors on the 2nd floor	30
Figure 5.8 MATLAB _ filtering of an ambient vibration signal.....	38
Figure 5.9 Spectral density singular values graph using ambient vibration data by SSI	39
Figure 5.10 Stability diagram and estimation modal properties using ambient vibration data by SSI method	40
Figure 5.11 MAC diagram of EFDD and SSI method of ambient vibration	42
Figure 5.12 MATLAB _ filtering of white noise signal	43
Figure 5.13 Singular values of spectral densities analyses and estimation of white noise by EFDD method	44
Figure 5.14 Stability diagram and estimation modal properties using WN data by SSI method.....	45
Figure 5.15 1st mode; couple mode obtained from EFFD method, by ARTeMIS....	46
Figure 5.16 2nd mode; torsional mode obtained from the SSI method, by ARTeMIS	46

Figure 5.17 3rd mode shape: lateral mode obtained from the SSI method, by ARTeMIS	47
Figure 6.1 Initial Finite element model from SAP2000.....	49
Figure 6.2 1st mode: 1st transversal mode of SAP2000 model	50
Figure 6.3 3rd mode: 2nd torsional mode of SAP2000 model	51
Figure 6.4 5th mode: 3rd transversal mode of SAP2000 mode	51
Figure 6.5 Mode shape pairs of 1st mode of FEM and 2nd mode of EMA.....	53
Figure 6.6 Mode shape pairs of 2nd mode of FEM and 3rd mode of EMA	53
Figure 6.7 Mode shape pairs of 3rd mode of FEM and 5th mode of EMA.....	54
Figure 6.8 MAC diagram of an analytical and experimental model before updating	55
Figure 6.9 MAC diagram of an analytical and experimental model after updating ..	56
Figure 6.10 MAC diagram of an analytical and experimental model before updating	57
Figure 6.11 MAC diagram of an analytical and experimental model after updating	57
Figure 6.12 MAC diagram of an analytical and experimental model before updating	59
Figure 6.13 MAC diagram of an analytical and experimental model after updating	59

LIST OF TABLES

	Page
Table 3.1 Table of ABS's properties.....	18
Table 4.1 Eigenvalues, frequencies and mode shapes found by dynamic analysis ...	25
Table 4.2 Frequencies and mode shapes found by dynamic analysis	25
Table 5.1 Table of frequencies and mode shapes obtained from the ambient test by EFDD method.....	39
Table 5.2 Table of frequencies and mode shapes obtained from the ambient test by SSI method	40
Table 5.3 Table of comparison of results from EFFD & SSI method using for ambient vibration.....	41
Table 5.5 Table of frequencies and mode shapes obtained from WN test by EFDD method	44
Table 5.6 Table of frequencies and mode shapes obtained from white noise test by SSI method	45
Table 5.7 Table of summarized frequencies experimental method by WN.....	47
Table 6.1 Modal parameters from the initial FE model for all modes.....	50
Table 6.2 comparison of frequencies from dynamic analysis and SAP2000.....	52
Table 6.3 Comparison of the modal parameters obtained by numerically and experimentally method	54
Table 6.4 Table of Comparison estimated modal parameters between analytical and experimental results.....	56
Table 6.5 Table of updated parameters	56
Table 6.6 Table of Comparison estimated modal parameters between analytical and experimental results.....	58
Table 6.6 Table of updated parameter.....	58
Table 6.7 Table of Comparison estimated modal parameters between analytical and experimental results.....	60
Table 6.8 Table of updated parameter.....	60

CHAPTER ONE

INTRODUCTION

One of the engineering challenges is to understand natural phenomena, analyze systems, and use results found as needed, based on scientifically approved processes. These processes consist of measuring, designing mathematical models to explain and describe these systems, and finally verifying the validity of these models.

Infrastructure age over time and there is a need to examine the integrity of these structures without necessarily obstructing the operation of the system. System identification is a technique that can be used in tracking the changes in structure parameters, identified from vibrational signatures of the structural system. (Shiradhonkar & Shrikhande, 2011)

This thesis deals with 3D printed structures which are needed to know about materials that should have different chemical or physical properties.

The finite element method is used in a several fields to solve and analyze complex problems that other empirical methods could not solve. Although it is difficult to fully represent the model by the finite elements due, for example, to the complex behavior of geometries, boundary conditions, and properties of materials. The results obtained enable reliable decisions to be made. (Girardi et al., 2019)

The finite element model updating consists of the establishment of an objective function that measures the difference between the analytical model and the experimental model for optimizing structure parameters using mode shapes and natural frequencies.

FE model updating is a combination of two methods, Finite element method, and updating. The first consists of subdividing large problems into smaller problems that are easier to solve and the second consists of updating the initial model either by adding or correcting some information.

FEMU is a technique designed to calibrate the FE model (Represented as an initial model) based on experimental dynamic data to obtain an updated model.

This thesis does not assume the reader is familiar with the field of finite element model, but it is going to develop the topic of finite element model updating which is a method for performing structures.

1.1 Description of the project

Studying the finite element model updating (FEMU) method on 3D printed structure needs firstly a good Conception, and then it must be designed by a computer tool. Before printing, the sketched model should be adjusted to all conditions of a test device, so that the sample is fixed on the device without losing its characteristics.

This work was modelled as a building system with two-story and a part of a shell on the top with the intention of producing an irregular torsion. The material used is ABS (Acrylonitrile Butadiene Styrene) because of its most versatile materials to learn a good specimen's frequencies. A model is a frame divided by two symmetrical stories with 4 circular columns separated with a plate slab (See figure 1.1).



Figure 1.1 Perspective of the structure (Personal archive, 2019)

The experimental method is a real method which its processing required a lot of steps for reaching to the results. An important task is to perform vibration tests to accurately evaluate their dynamic features such as mode shape, frequencies, and damping coefficients. This work was carried out by white noise and ambient vibration tests that were accomplished to obtain the modal parameters of the frame structures. ARTeMIS pro Software was used for predicting dynamic characteristics of the structure which were estimated by operation modal analysis techniques. Extracted parameters were used to calibrate the numerical model of the structure.

The numerical model also called the initial model was deducted by SAP2000. This computer program is a finite element program that allows us to compute the frequencies and corresponding mode shapes of the model.

FEMtools software was used to improve the match between the dynamic properties of an initial FE model and test data, in the end, to make an updating model. In addition, FEMtools is a set of tools used for structural design based on applied loads and required structural behavior. Moreover, it also processes design constraints and calculates optimal design parameters for the component or assembly in question (FEMtools, 2017). Figure 1.2 shows the summary of all steps in the FEMU method.

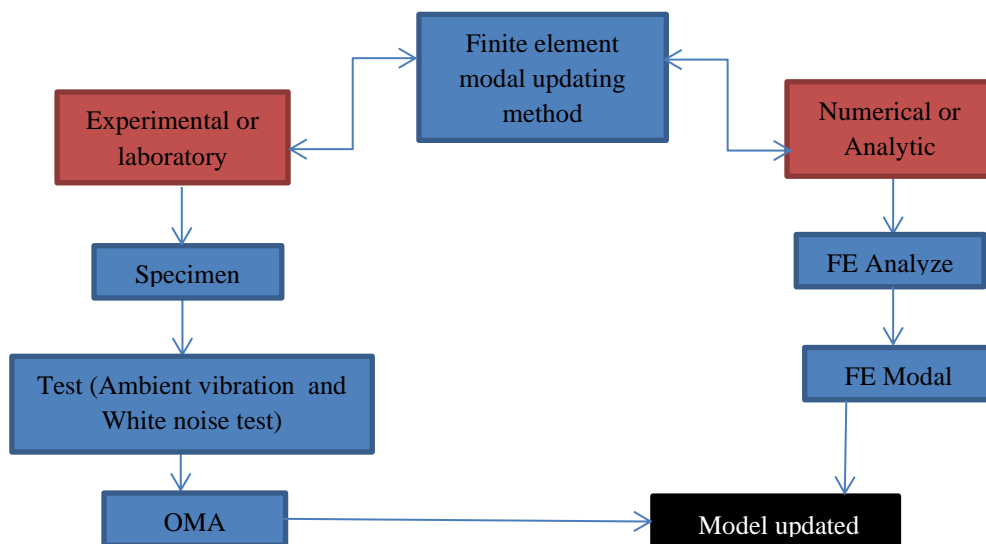


Figure 1.2 Schema of FE model updating method for a structure

1.1 Use software

In this work, studying finite element model updating method was executed minimally by 6 different kinds of software, according to their objection:

For conception & design;

- **SAP2000:** It was used for choosing the model that can behave as an irregular torsional and verifying the predicted model whether it is compatible or not.

- **SOLIDWORKS:** It was used for designing and giving features of structures.

For analysis;

- **SAP2000:** It was used for predicting the FE model as the initial model or numerical model. The modal response (Mode shapes and natural frequencies) was also deducted.

For testing;

- **LabVIEW:** It was used for collecting data from different tests such as white noise and ambient vibration for transferring data to the computer and finally to get the numerical data.

- **ARTeMIS MODAL pro:** It was used for predicting the natural frequencies and modes shapes about the experimental modal analysis.

For updating

- **FEMtools:** It was used for improving the match between the dynamic properties of an initial structure and the experimentally estimated modal data than updating.

1.2 Aims of work

The purpose of this work was based on comprehension of the Finite element model updating method applied to 3D printed specimen that will be used for dynamic response analysis. In addition, one of the main aims is to provide the match of the real model and testing model to create an updated and optimized model after knowing the discrepancy between these two models.

1.3 Thesis contributions

This work is a contribution to the science of civil engineering, which intends to study a structural model and an understanding of the system between an analytical and real model with an irregular torsion. The researcher will be able to provide an updated model of the different types of structures (Such as concrete, steel, wood, etc.) using system identification. In this work, plastic has been used as a material and has the same interaction applicable to all other material structures. The updated FE model of this structure obtained can be used for another research.

1.4 Thesis layout

This thesis is based on a research project and is divided into six chapters.

In the first part, goals, problems, and objectives are clearly expressed.

In the second chapter, theories on the FE model updating method and the examination of preferred modelling approaches are introduced.

In the third chapter, the study demonstrates how all the preliminary work was done.

In the fourth chapter, the main purpose is to study the dynamic analysis of structure performed by mathematical evidence.

In the fifth chapter, experimental work with different modelling approaches and all stages of testing has been shown.

In the sixth, the finite element structural model was made. Numerical analyses, the results of the finite element model updated method and the optimization were presented.

the seventh chapter detailed the discussion and conclusion of this study.

CHAPTER TWO

THEORY

Our project is one of the parts of the new trend of the civil engineering world. In engineering, the use of experimental data to determine a dynamic model allows for the modal analysis of systems. This method is used in the process of designing the control techniques necessary to achieve the desired dynamic behavior and to predict the system's response to external excitements. Any action begins with understanding the behavior of the dynamic system before conception.

2.1 Finite element (FE) method

2.1.1 FE overview

The FE method is a numerical approximation implement for the study of physical systems with complex analytical solutions. It is based on approximate solutions of partial integrals and differential equations governing physical phenomena, by partitioning the field of study into several small entities.

The finite element name comes from these small entities. It is based on assumptions such as linearity of parameters, variation according to polynomial functions, or considering certain parameters as constant. Its importance in engineering studies provides that most natural phenomena are complex. (Jonsson & Johnson, 2007).

Models that are simple and have got large elements are quickly calculated, but models with too many systems contain numerical errors that lead the FE model necessary for the physical interpretation of the results.

Complex modelling with fine resolutions can produce more realistic results in the cost of increasing time computation. An optimal model produces exact results with minimal computation time. If the results found are not matched with the expected results, i.e. the finite element model probably presents a problem where these results should not be approved or trusted.

2.1.2 Finite element method applications

FE method is a tool that is used in several engineering fields and numerous FE analysis software exists for civil engineering, automotive industries, and aeronautical. In structural analysis, finite element analysis (FEA) demands three steps, pre-processing, finite element calculation, and post-processing. Nowadays, there are several FE software that are marketed and specialized for the treatment of each of these stages.

2.1.2.1 Structural analysis

The finite element method is a stronger method for structural analyzes, allowing complex structures to be studied by subdividing them into small pieces, allowing all responses of the parent structure to be evaluated. To date, there are several efficient finite element analysis (FEA) software available to facilitate calculation. To better understand the specific structural details, a detailed analysis is required.

In majority cases, elastic linear analysis is often used for the computation of structural behavior. Dynamic structural analysis studies the behavior of temporal variants of a structure. Several iterations over time can be used to find the accuracy of the available computing power. In the automotive and aerospace sector, structural dynamics are widespread, but they are not the case for structural FEA because most structures are designed to withstand temporal variations without significant movement or deformation.

The characteristic natural frequencies (Eigenvalues) and mode shapes (Eigenvectors) of a structure are interesting because they define the vibration behavior of the structure.

2.2 Finite Element Model updating method

2.2.1 Finite element model updating overview

Finite element model updating is not an old tool in this domain, it emerged around the 1990s as a tool to correct hypotheses that are not valid on models using vibration test data. A FE model updating method is used to estimate a FE model and also to compare targeted output responses with those from experimental data.

Almost unlimited input parameters are iterated until target responses are more accurate. For convergence of models, many iterations may be necessary, and models should be simplified as much as possible, the calculation time is reduced for each iteration. The Enhanced Finite element model can still be used for structural evaluation. the design and maintenance of civil engineering structures require that modeling be well done and improved.

In order for the FE model to be able to replicate natural frequencies and well-measured mode shapes, the FE model updating slightly updates the rigidity and global mass matrices in one step, although the structural connectivity of the resulting FE model is not maintained. Because of the mode shape data and the need for a result that must be significant, this, as well as the application of finite element model updating, is requested.

In studying the behavior of structures, sometimes the differences between the predicted and measured data are significant, especially in the case of vibration studies. FE model updating is therefore used to reduce these measurement deviations and allows for better accuracy at each subsequent step.

2.2.2 Finite Element Model Updating Problem

Finite element models, although they are useful for analyzing models, are limited by the fact that their results are only close to the real system without completely reproducing it. To complement this shortfall, prototyping is used to improve the result to better reproduce the actual system.

2.2.3 Aspects of the model to be updated

This is an important step to determine which characteristics of the initial model are incorrect or uncertainly modeled (Bartilson et al, 2019). System-identification involves the development of mathematical approximations set up in a complex system whose characteristics or order are unknown and must be determined.

In the FE models concerned, there are a variety of structural parameters that can be updated. They can vary from geometric properties to material properties. The geometric properties of this structure are clear and clean. The structure has a well-defined thickness, from which geometrically it does not represent a design failure.

However, printing a 3D model as an exact structure is a difficult procedure due to the inaccuracy of certain properties. The specimen was printed with 50% voids but it is a little difficult to know exactly how much the material is filled. During printing, the materials also underwent heating which also could modify a density of the structure. Going from these two hypotheses, it has been deduced that the parameters that can be updated are the *Young's modulus (E)* and *the density (ρ)*.

2.2.4 FEMtools updating

The FEMtools updating is part of the FEMtools software which deals with the problem of updating to calibrate the FE model. In FEMtools Model Updating, built-in utilities and methods are used to better match test data with target data. Updating methods use sensitivity coefficients to iteratively update certain physical properties of models such as rigidity, to improve the correlation between the target and simulated values (FEMtools,2017).

FEMtools works as a mathematical tool for performing an updating, provides the same approaches as other computer programs but the demarche is not the same, each software has personally kind of approaches and interaction can use.

2.2.4.1 Normal modal analysis

To make a dynamic study of a system, the formulation of a mathematical model taking into account the inherent properties of the system such as damping factor, natural frequency, and mode shapes is necessary. The mathematical model formulated is called modal data and the process for determining these dynamic properties is called Modal analysis.

$$([K]-\omega^2[M])\{\psi\}=0 \quad (2.1)$$

[M] Structural mass matrix

[K] Structural stiffness matrix

{ ψ } Modes shapes

ω Natural frequency

FEMtools uses a Lanczos method for solving this equation.

The Lanczos method is well known for the application of structural vibration by its ability to extract eigenvalue using a minimum number of iterations. It extracts a given number of the lowest eigenvalues from the system.

The real eigenvalue analysis problems have solutions that are called normal modes. Modal frequencies are the eigenvalues with zero damping and mode shapes are valued because they depend on the materials, geometry, and boundary conditions of the structure.

2.2.5 Sensitivity-Based Parameter Estimation

In the updating procedure, sensitivity analysis, which determines the change rate of response values with respect to changes in model properties, is required. In other words, sensitivity analysis allows us to have an idea of how the change of parameters influences the structural responses of the model.

The functional relationship between structural parameters and modal characteristics is expressed in terms of expansion of the Taylor series limited to the linear term. It can be written as follows:

$$\{ Re \} = \{ Ra \} + [S] (\{ Pu \} - \{ Po \}) \quad (2.2)$$

Where:

$\{ Ra \}$ Vector containing the predicted system responses for a given state

$\{ Re \}$ Vector containing the reference system responses (Experimental data).

$\{ Pu \}$ Vector containing the updated parameter values

$\{ Po \}$ The parameter values.

[S] Sensitivity matrix.

Equation (2.2) is often under-determined and its resolution is done utilizing a pseudo-inverse or least squares, Bayesian techniques (Weighted least squares), according to weighting coefficients, which are used to weight the modal components corresponding to their importance and amount of noise, are added or not.

To improve stability, FEMtools use the normalized sensitivity matrix is with the Bayesian parameter estimator.

The use of weighting coefficients on parameters and responses is included in the Bayesian parameter estimation expression. The difference between the test data and the initial model predictions is solved by minimizing the weighted error E expressed by this relationship:

$$E = \{\Delta R\}^t [C_R] \{\Delta R\} + \{\Delta P\}^t [C_P] \{\Delta P\} \quad (2.3)$$

[C_R] Is a diagonal weighting matrix expressing the confidence in the test data

[C_P] Represents a diagonal weighting matrix expressing the confidence in the model parameters.

2.3 Optimization

2.3.1 Overview of Optimization

In mathematics, optimization is a technique that consists of analyzing, modeling, and solving a real function numerically or analytically according to the integer or real variables with the aim of minimizing or maximizing it on a set. Optimization is particularly useful when applied to finite elements. A non-linear function of the input parameters (The residual) is thus established. A FE model may be aware of optimization by minimizing the objective function, which includes the residual function of the response with the optional regularization of duration.

2.3.2 FEMtools Optimization

FEMtools Optimization aims to optimize the performance of structures using FE models. As such, the reliability of the optimization results depends on the reliability of the FE models, i.e. if the FE model is not a reliable representation of the real structure, the optimization results will not provide a real structure that works optimally. The results will represent an optimally behaving model, not an optimally behaving structure. In case the reliability of the FE-models is too low, they will have to be improved or updated before starting the optimization. (FEMtools, 2017).

The suggested way to handle the design problem is to build the FE-models, perform the validation tests, and update the models if required before starting the optimization. In short:

Simulate > Validate > Update > Optimize.

FEMtools Optimization provides tools for:

- ***Sensitivity analysis:*** It is the part of optimization that analyzes how changing of parameters can influence the responses.
- ***Size optimization:*** Study the optimization of component parameters such as cross-section and thickness.

- **General non-linear optimization:** It deals with the problem of solving arbitrary non-linear optimization problems.
- **Topology optimization:** Create new designs with a layout optimized for a given load.

2.4 Selected Parameters

This method requires the update of a certain parameter, hence in this study, the parameters selected for the update are mass density (ρ) and Young (E) module, then the results of the sensitivity analysis are considered optimized results.

CHAPTER THREE

SPECIMEN DESIGNS AND PRELIMINARY WORK

3.1 Preliminary Test specimen

At the conception stage, structural design of a two-story frame structure was tested in SAP2000 for dynamic behavior. The frame structure was designed as a model working under irregular torsion. After conception, the model was gotten to SAP2000 software to verify if the sought features are found. After verification and discussion, it was decided to conduct the study using a 3D printed model structure. The model was designed in SOLIDWORKS Software (See figure 3.1) and ABS (Acrylonitrile Butadiene Styrene) plastic filled in 50% is chosen as material according to its mechanical properties.

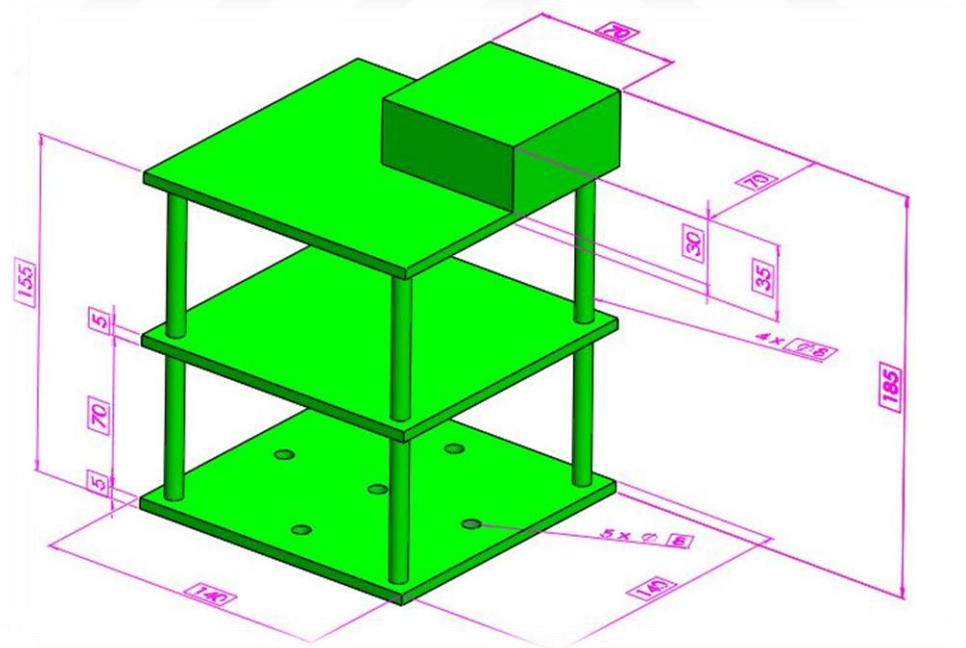


Figure 3.1 Conception of a structure by SOLIDWORKS

3.2 3D Printed

After designing SOLIDWORKS software, the specimen was brought in a special 3D printer for printing out the model that was needed. The ABS (Acrylonitrile butadiene styrene) filled in 50% materials according to its mechanical properties. See figure 3.1 for the conception of the 3D model. In this work, SOLIDWORKS Software was used as a conception program to design the frame then printed it out with a special printer as structure.

After designing by SOLIDWORKS software, the specimen was brought in a 3D printer for printing out the model that was needed.

3.2.1 Acrylonitrile Butadiene Styrene (ABS) and its Features

Acrylonitrile Butadiene Styrene is generally better known by the abbreviation ABS (see Figure 3.2) is an opaque thermoplastic more commonly found in the field of engineering and several sectors such as consumer products, electronic boxes, automotive parts, piping agreements, toys, etc... This material is also used in injection molding applications.

Its good market price, excellent mechanical properties, dimensional stability, chemical resistance, and maneuverability that make it easy to machine by manufacturers, Acrylonitrile Butadiene Styrene (ABS) is counted among the most popular plastics in the engineering sector.

ABS, although widely used, is not biodegradable. PLA plastic is therefore a competitor of ABS particularly during this century when pollution and plastic waste represent a universal threat. The great advantage of ABS is its ability to be recycled more than once without losing its mechanical properties.



(a)



(b)

Figure 3.2 (a) Rolling of ABS, (b) 3D printer machine (Omnexus.specialchem, 2019)

3.2.2 Geometry properties

This 3D printed structure is modelled as a two-story shear building system with a small shell on top is shown in figure 3.3(a). The structure comprises of 2 squared slabs of 14x14 cm, 0.5 cm of thickness supported by 4 circular columns 0.8 cm of diameter. Then a small shell over the upper story, it has a 3.5 cm of thickness, a squared of 7x7 cm. the height under the floor of all story is 7 cm then the total high of the frame is 18.5 cm. the structure is bolted with the same plate mention above (14x14x0.5) cm. (Illustrate in figure 3.3)

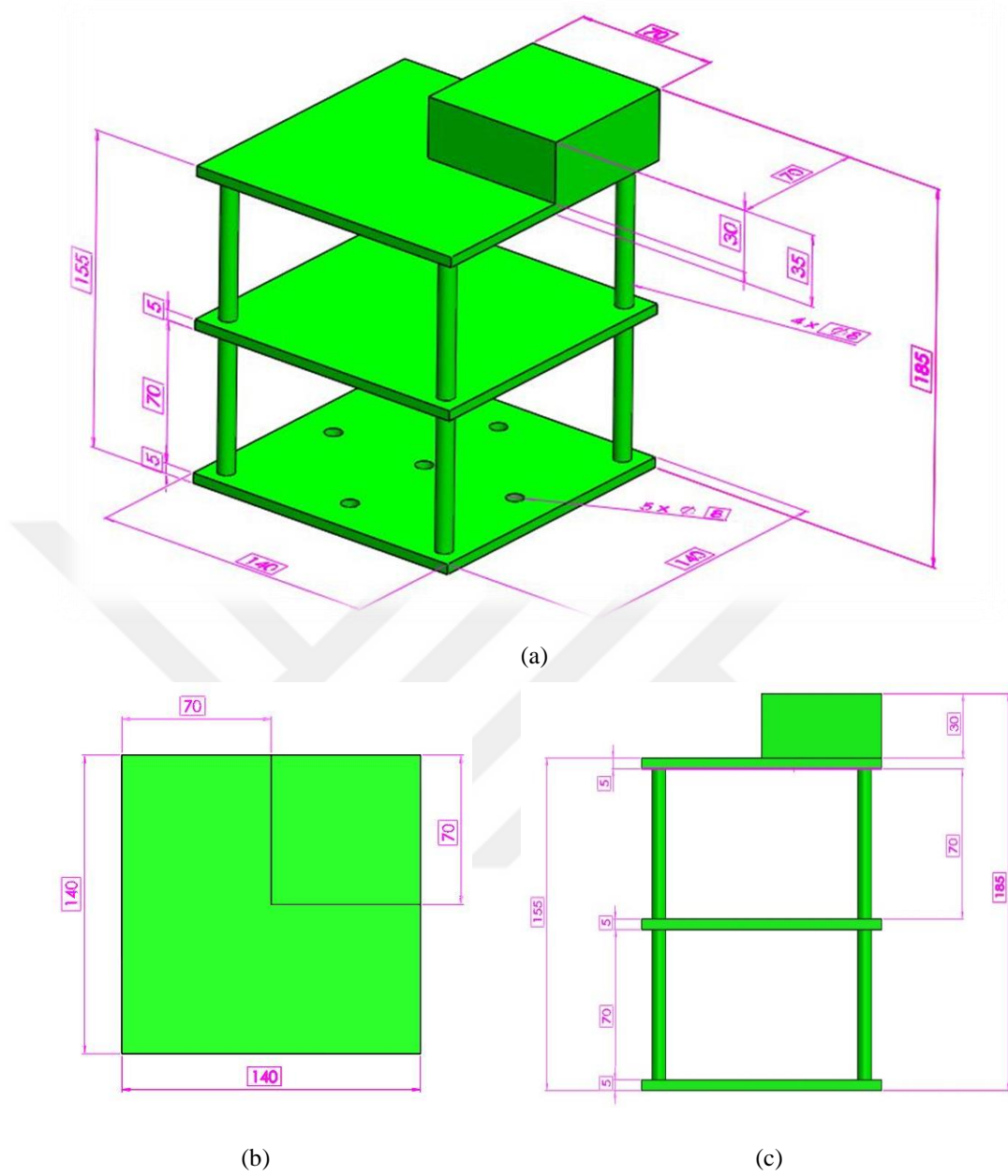


Figure 3.3 Geometrical properties: (a) perspective view; (b) top view; (c) side view

3.2.3 Material properties

Due to its many physical properties (See Table 3.1), ABS is an ideal material for diverse engineering applications. The stress-strain relationship is defined in the structural FEA based on the properties of the material used.

Table 3.1 table of ABS's properties (Matweb Material Property Data, 2019)

physical Properties	Metric	English
Density	1.01 - 1.20 g/cc	0.0365 - 0.0434 lb/in ³
water Absorption	0.250 - 1.00 %	0.250 - 1.00 %
Moisture Absorption at Equilibrium	0.000 - 0.210 %	0.000 - 0.210 %
Water Absorption at Saturation	0.300 - 1.03 %	0.300 - 1.03 %
Linear Mold Shrinkage, Transverse	0.00300 - 0.00800 cm/cm	0.00300 - 0.00800 in/in
Melt Flow	0.100 - 35.0 g/10 min	0.100 - 35.0 g/10 min
Mechanical Properties	Metric	English
Hardness, Rockwell R	68.0 – 118	68.0 – 118
Tensile Strength, Ultimate	22.1 - 49.0 MPa	3210 - 7110 psi
Tensile Strength, Yield	13.0 - 65.0 MPa	1890 - 9430 psi
Flexural Modulus	1.90 - 2.80 GPa	276 - 406 ksi
Modulus of Elasticity	1.00 - 2.65 GPa	145 - 384 ksi
Thermal Properties	Metric	English
CTE, linear	40.0 - 110 $\mu\text{m}/\text{m}\cdot\text{C}$	22.2 - 61.1 $\mu\text{in}/\text{in}\cdot\text{F}$
CTE, linear, Transverse to Flow	87.0 - 98.0 $\mu\text{m}/\text{m}\cdot\text{C}$	48.3 - 54.4 $\mu\text{in}/\text{in}\cdot\text{F}$
Thermal Conductivity	0.150 - 0.200 W/m-K	1.04 - 1.39 BTU-in/hr-ft ² - °F

One of the most commonly used properties of materials in FEA is isotropy (Direction-independent properties). This material property is an assumption. In real behavior, materials are anisotropic which is to say their properties are direction dependent. In this study, isotropic material properties are used.

3.2.4 Printed model

The model was printed as it was designed to achieve a two-level frame structure with a shell above (See in figure 3.4). The printed model is reserved to be submitted to the vibration test at the end of deducing the dynamic characteristics of the structure.

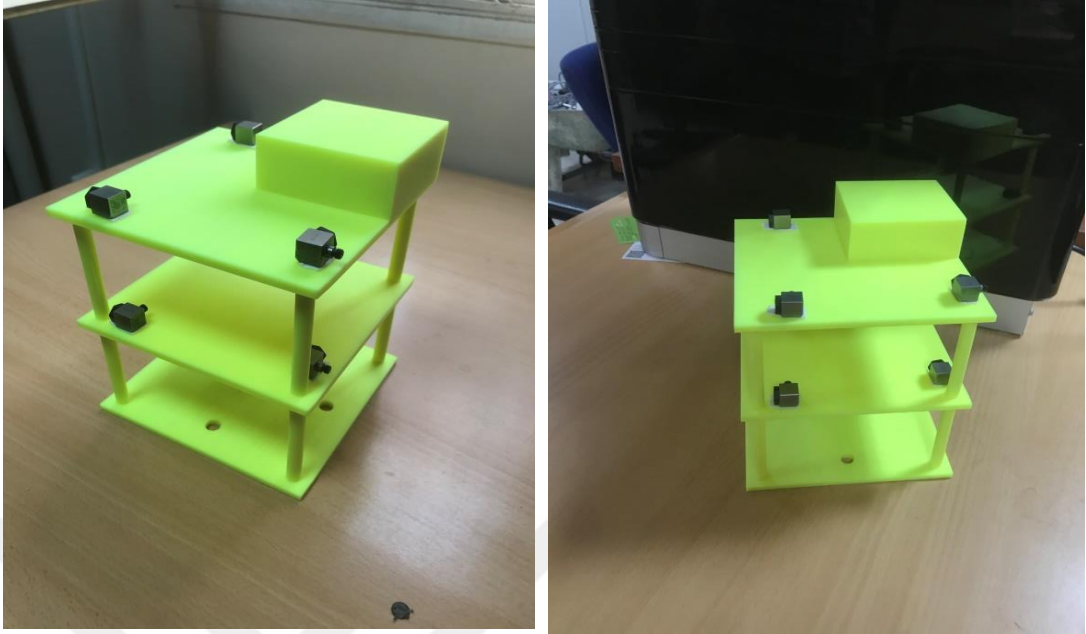


Figure 3.4 Perspective view of 3D printed structure (Personal archive, 2019)

CHAPTER FOUR

DYNAMICS ANALYSIS

4.1 Introduction

This section presents a short introduction to the dynamics of structures. He will be between other questions here of the equation of motion of buildings and parameters which composes it. Because the buildings that will be used in this research are composed of frames, the discussion thus focuses only on the discrete systems. It is important to mention that it is also possible to make a dynamic analysis of a building using a continuous system.

this analysis is carried out by the equation of motion of the system, presents a mathematical study of a building with an eccentric. so as to reveal the parameters governing the behavior of this type of building in the direction perpendicular to the retrenchment.

In the dynamic analysis of three-dimensional structures, it is not appropriate to assign a direction to a mode shape that may include components of all the directions.

4.2 Analysis of unsymmetric building with ground motion

Consider the idealized two-story building shown in figure 4.1, the motion of the plate mass will be described by three DOFs in each level defined at the Centre of mass of the roof: translation u_x in the x-direction, translation u_y in the y-direction and torsional rotation u_θ about the vertical axis.

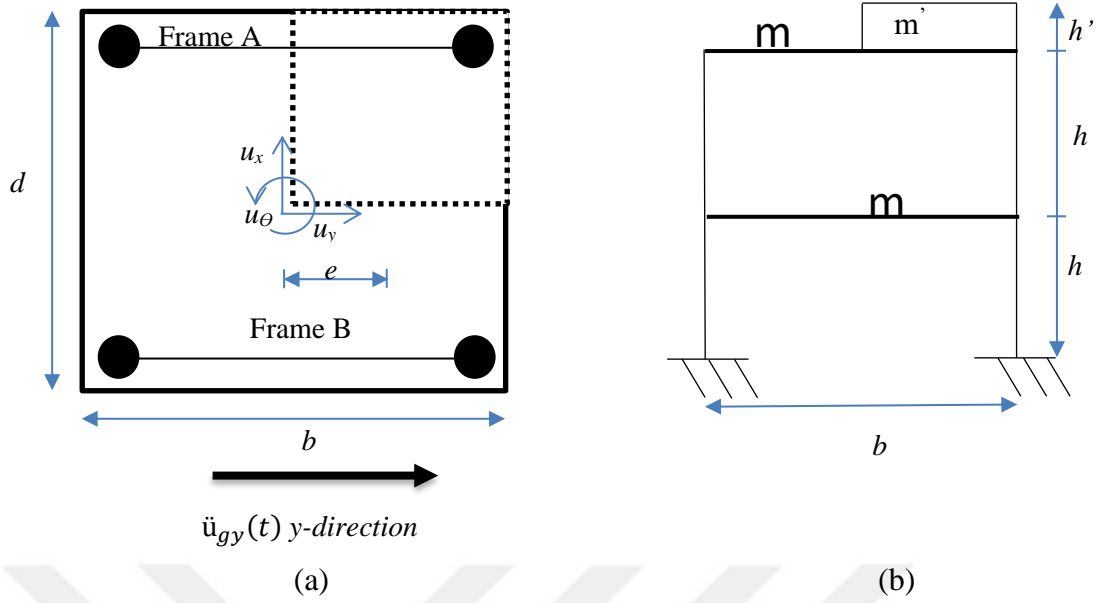


Figure 4.1 (a) view plan of structure (b) side view of structure

4.2.1 Analysis and results

It is subjected the ground motion $u_{gy}''(t)$ in the y-direction, the behavior of the building in x-direction is completely independent of behavior in the y and z directions. For this reason, behavior in the x direction will now be neglected. Therefore, the force in the lateral x-direction DOFs is zero.

The governing equation of motion in this case is:

$$\begin{bmatrix} M & 0 \\ 0 & I_o \end{bmatrix} \begin{Bmatrix} \ddot{u}_y \\ \ddot{u}_\theta \end{Bmatrix} + \begin{bmatrix} k_{yy} & k_{y\theta} \\ k_{y\theta} & k_{\theta\theta} \end{bmatrix} \begin{Bmatrix} u_y \\ u_\theta \end{Bmatrix} = - \begin{bmatrix} M & 0 \\ 0 & I_o \end{bmatrix} \begin{Bmatrix} 1 \\ 0 \end{Bmatrix} \ddot{u}_{gy}(t) \quad (4.1)$$

U_y , and U_θ correspond to the vectors of translations according to y axis and the rotation by z-axis and $\ddot{U}_{gy}(t)$ is the acceleration of the ground by y-axis. All translations and rotations are calculated by the report that caused the system. Here, the system studied has only two floors, which means all the matrices listed above are 2x2 and all vectors of 2x1 dimensions. Therefore, the mass and stiffness matrices are 4x4 dimensions. M corresponds to the mass matrices containing the mass of each floor according to the x and y directions, I_o corresponds to the matrix from the polar inertia

of the floors of each of the floors, K_{ij} , to the rigidity matrix according to y or z axes, ij indices referring to directions and 0 is a null matrix.

The stiffness matrix of the system is

$$K = \begin{bmatrix} k_{yy} & k_{y\theta} \\ k_{y\theta} & k_{\theta\theta} \end{bmatrix} \quad (4.2)$$

Where:

$$k_{yy} = \sum_i k_{yi} \quad k_{y\theta} = \sum_i e k_{yi} \quad k_{\theta\theta} = \sum_i e^2 k_{yi} \quad (4.3)$$

Equation (4.2) becomes
$$K = 2 \begin{bmatrix} k_{yi} & k_{y\theta} \\ e k_{yi} & e^2 k_{yi} \end{bmatrix} \quad (4.4)$$

e corresponds to the eccentricity between the center of a floor mass and the origin.

- Let compute the stiffness matrix of the frame

In this case, we have 3 degree of freedom, the stiffness matrix of frame A and B in the y-direction are determined by:

- we consider $k_y = k_{yA} = k_{yB}$, all frames are directed in the y-direction

$$K_y = \frac{12EI_c}{h^3} \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \quad (4.5)$$

where
$$k_j = \sum_{j=1} 12 \frac{EI_c}{h^3} \quad (4.6)$$

- Young modulus of ABS $E= 1.9$ GPa

- Column $d = 0.8$ cm, $h = 70$ cm $I_c = \frac{\pi d^4}{64} = 2.10 \cdot 10^{-10}$ m⁴
- Eccentricity $e = 35$ cm, $e = 0.035$ m, $e^2 = 0.00123$ m

$$k_1 = k_2 = 2 * \frac{12EI_c}{h^3}$$

$$K_y = \begin{bmatrix} 2 * \frac{12EI_c}{h^3} + 2 * \frac{12EI_c}{h^3} & -2 * \frac{12EI_c}{h^3} \\ -2 * \frac{12EI_c}{h^3} & 2 * \frac{12EI_c}{h^3} \end{bmatrix}$$

$$K_y = \frac{12EI_c}{h^3} \begin{bmatrix} 2 & -1 \\ -1 & 1 \end{bmatrix}$$

$$K_y = \frac{24 * 1.9 * 10^9 * 2.01 * 10^{-10}}{343 * 10^{-6}} \begin{bmatrix} 2 & -1 \\ -1 & 1 \end{bmatrix}$$

$$k_y = 26695 \begin{bmatrix} 2 & -1 \\ -1 & 1 \end{bmatrix}$$

$$k_y = \begin{bmatrix} 53390 & -26695 \\ -26695 & 26695 \end{bmatrix}$$

- $k_{y\theta} = ek_y$

$$k_{y\theta} = 0.035 * 26695 \begin{bmatrix} 2 & -1 \\ -1 & 1 \end{bmatrix}$$

$$k_{y\theta} = \begin{bmatrix} 1868.65 & -934.33 \\ -934.33 & 934.33 \end{bmatrix}$$

- $k_{\theta\theta} = e^2 k_y$

$$k_{\theta\theta} = 0.00123 * 26695 \begin{bmatrix} 2 & -1 \\ -1 & 1 \end{bmatrix}$$

$$k_{\theta\theta} = \begin{bmatrix} 65.66 & -32.83 \\ -32.83 & 32.83 \end{bmatrix}$$

The stiffness matrix of all system is given by:

$$K = 2 * 10^4 \begin{bmatrix} 5.3390 & 2.6695 & 0.1869 & -0.0934 \\ -2.6695 & 2.6695 & -0.0934 & 0.0934 \\ 0.1869 & -0.0934 & 0.0066 & -0.0033 \\ -0.0934 & 0.0934 & -0.0033 & 0.0033 \end{bmatrix}$$

- The mass matrix

$$M = \begin{bmatrix} m & 0 \\ 0 & I_{oj} \end{bmatrix}$$

Where $m = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}$ and $I_{oj} = \begin{bmatrix} \frac{m_1(b^2+d^2)}{12} & 0 \\ 0 & \frac{m_2(b^2+d^2)}{12} \end{bmatrix}$

- ABS density $\rho = 1050 \text{ kg/m}^3$

- Square $b = 0.14 \text{ m}$ and $d = 0.14 \text{ m}$

$$m_1 = (0.14 * 0.14 * 0.005) * 1050 = 0.103 \text{ kg}$$

$$m_2 = (0.07 * 0.07 * 0.005) * 1050 + 0.103 = 0.283 \text{ kg}$$

Thus, the mass matrix of the system is:

$$M = \begin{bmatrix} 0.1030 & 0 & 0 & 0 \\ 0 & 0.2830 & 0 & 0 \\ & SYM & 0.0003 & 0 \\ & & 0 & 0.0009 \end{bmatrix}$$

Let compute the eigenvalues and eigenvectors to determine the natural frequencies and modes shapes of the structure

$$\text{Det} |(K - \lambda M)| = 0 \quad \text{where} \quad \omega = \sqrt{\lambda} \quad (4.7)$$

The eigenvalues problem was solved to find the natural frequencies ω_n and modes shapes Φ_n as detailed in the table 4.1 and 4.2.

$$\lambda_1 = 0.9216; \lambda_2 = 1211.04; \lambda_3 = 117854.89; \lambda_4 = 1563000.04$$

$$\omega_1 = 9.6 \text{ Hz}; \omega_2 = 34.8 \text{ Hz}; \omega_3 = 343.3 \text{ Hz}; \omega_4 = 1250.2 \text{ Hz}$$

Table 4.1 Eigenvalues, frequencies and mode shapes found by dynamic analysis

Eigenvalues Λ	Mode #	n=1	n=2	n=3	n=4	Frequencies (Hz)
$\lambda_1 = \mathbf{0.9216}$	1	-0.5065	-0.9313	14.4548	26.5807	9.60
$\lambda_2 = \mathbf{1211.04}$	2	1.5412	-0.3061	-43.9880	8.7345	34.80
$\lambda_3 = \mathbf{117854.89}$	3	0.8316	1.5235	8.8265	16.2439	343.30
$\lambda_4 = \mathbf{1563000.04}$	4	-2.5269	0.5014	-26.8213	5.3458	1250.20

Table 4.2 Frequencies and mode shapes found by dynamic analysis

#	MODE	Frequency Cycle/sec (Hz)
1	1 st torsional	9.60
2	2 nd torsional	34.8
3	1 st vertical	343.3
4	2 nd vertical	1250.2

CHAPTER FIVE

LABORATORY STUDIES OR EXPERIMENTAL MODELLING

This project is part of the new trend in the world of civil engineering. In engineering applications, a dynamic model of a mechanical system determined from experimental data can be utilized to execute modal analysis of the system, to predict the response of the system to assess external actions, and in the design process of control strategies necessary to achieve desired dynamic behavior.

PCB Piezotronics is an American company that designs and manufactures sensors for dynamic measurement of physical dimensions such as vibration, motion for monitoring, shock, acceleration, and testing applications. (PCB Piezotronics Inc,2019).

In this study, the PCB Piezotronics set (See in Figure 5.1) was used to collect the data from the structure to transfer to a computer that uses LabVIEW as software for performing the experimental model. For each Test, approximately 10 minutes of long data with a sampling rate of 500 Hz were collected. After collecting data, filtering and detrending of the dynamic data was performed in MATLAB (MATLAB, 2017). After, modal parameter estimation was conducted by using modal analysis software ARTeMIS (ARTEMIS, 2016). The application of these data was used for identifying the modal parameters of the structure and for studying dynamic features of the specimen.

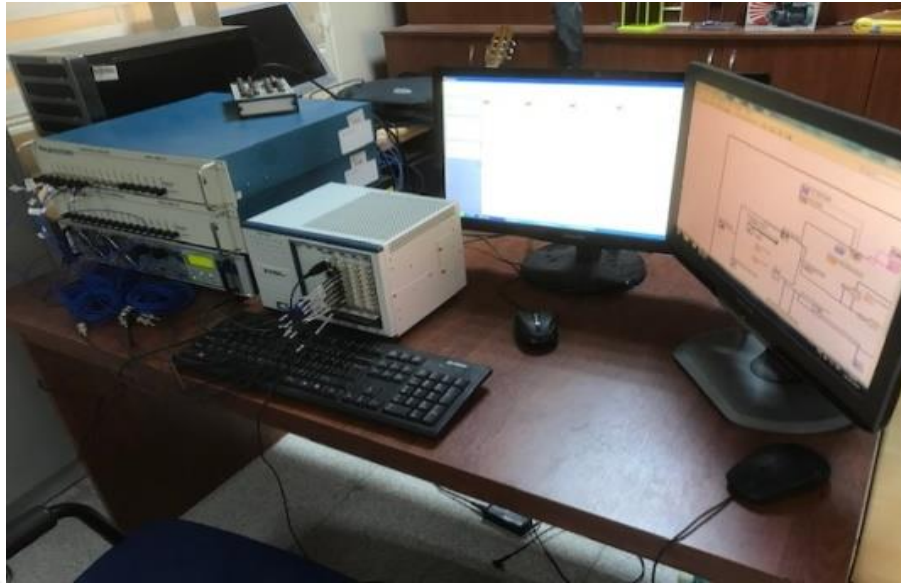


Figure 5.1 PCB Piezotronics set (Personal archive,2019)

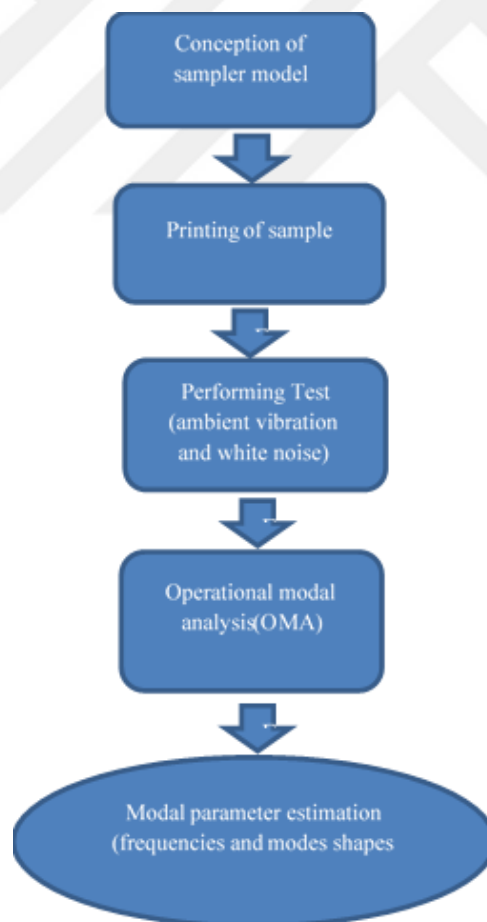


Figure 5.2 The flow chart of the Experimental study

5.1 Data acquisition

5.1.1 LabVIEW software

LabVIEW is a software used in the engineering sector for tests, measurements, and controls with a fast possibility to reach hardware and data information.

LabVIEW is typically used for the signal sampling process that measures actual physical values and converts them to numerical values that can be manipulated by a computer. In addition, it is also used for instrument control by connecting a device to a computer and taking measurements on various operating systems.

In this work, data are collected from ambient test and shaking table test (Shown in figure 5.3), they are transferred into a computer program to convert signals to numeric values before using in other software.

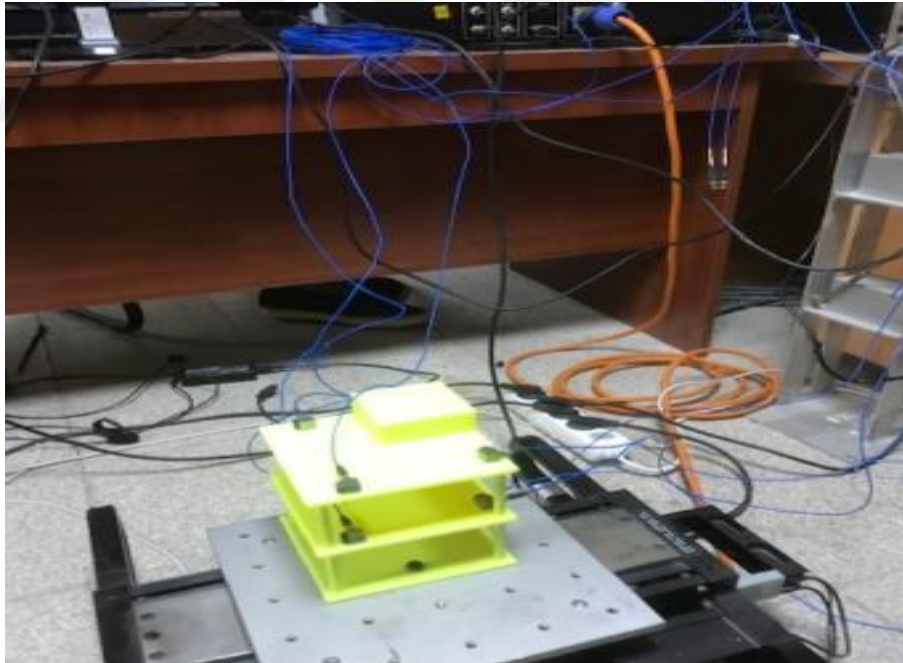


Figure 5.3 Structure with accelerometers (Personal archive, 2019)

5.1.2 Permanent sensors

The analysis of the frame structure was done by installing sensors near the columns. The sensors used are accelerometers that are capable of measuring the acceleration, learning the modal frequency, and modal shapes of the specimen. Seven accelerometers were used to measure ambient vibration and white noise test.

Each accelerometer was placed close to the columns, three sensors were used in both the first and second story, see in figure 5.4. One of them is located in the base of the center. On every story, 2 accelerometers were located in + X direction, one in the -Y direction. These dispositions were determined according to the measurement of the torsion (See figure 5.5 to figure 5.7).

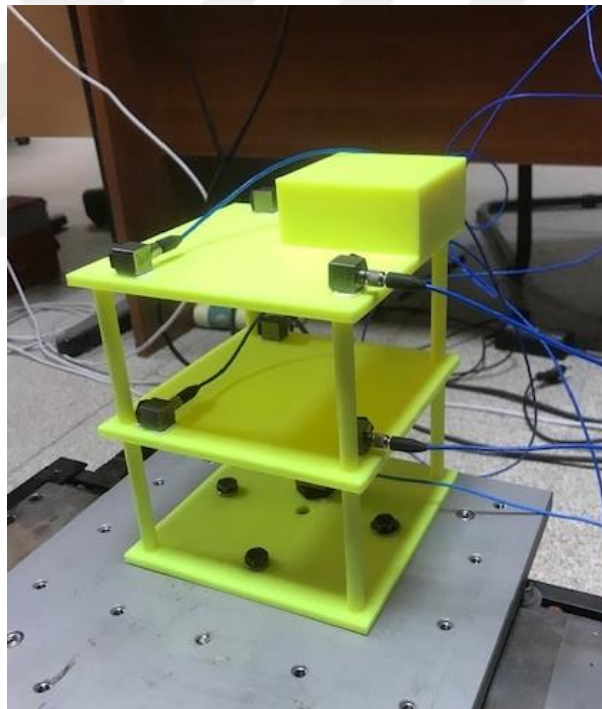


Figure 5.4 Structure with accelerometers on the shaking table (Personal archive, 2019)

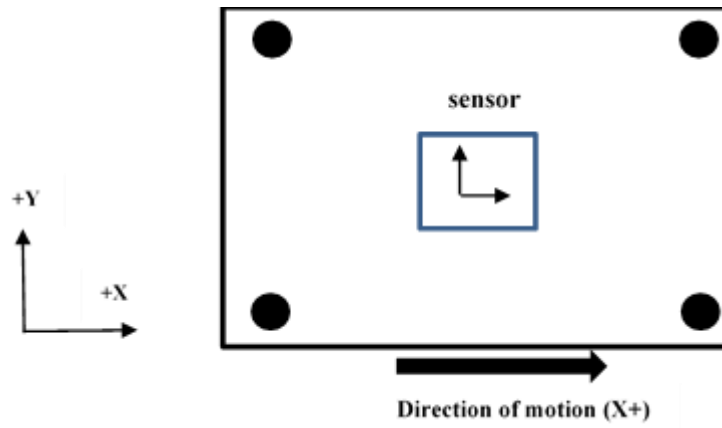


Figure 5.5 Disposition of sensors on the base floor

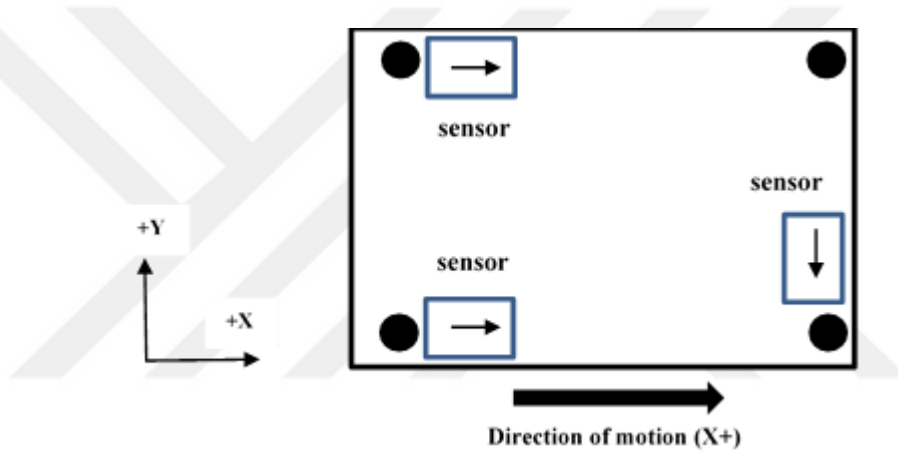


Figure 5.6 Disposition of sensors on the 1st base floor

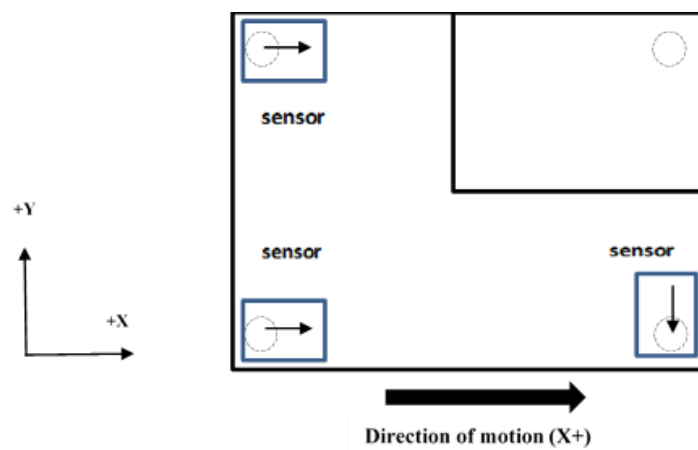


Figure 5.7 Disposition of sensors on the 2nd floor

This type of accelerometer is a small device, it has a good frequency response over a large frequency band. It has $\sim 1,000$ mV/g (102 mV/(m/s²)) sensitivity, acceleration measurement ranges of ± 5 g (± 49 m/s²) peak, a frequency ranges of 0.05 to 3000 Hz, a weight 7.5 gm.

Cables with a 50 Ohms resistivity are used for connecting accelerometers to the portable data acquisition system. The data were transmitted to a computer where LabView software is installed. (PCB piezotronics Inc., 2019).

5.2 Detrending & filtering of signal

5.2.1 Detrending

For this study, the detrend function built into MATLAB was used. In cases where the data contains several columns, this function allows us to focus on the fluctuation of the data according to the trend. The detrend function subtracts the average or the best-fit line, talking about the least-squares. A linear trend generally indicates an increase or decrease in data depending on the slope of the curve. A sudden shift can be caused by the movement of sensors, for example. In some studies, the use of trends may not provide successful results. Thus, whether to use or remove trends will depend largely on the intended results (MATLAB, 2017).

5.2.2 Filtering

Filtering is the process of removing or separating the unwanted part of a signal. Filters are techniques used in data processing to mitigate or eliminate fluctuations in data at a certain frequency.

Filtering has been used in this study specifically to remove or extract part of a signal, and this has been accomplished by using MATLAB software.

5.3 Operational Modal Analyses (OMA)

Operational Modal Analysis (OMA) is the domain of engineering that evaluates the modal properties of vibrating systems, either under ambient conditions or normal operating conditions. It is very useful for modal analysis in several structural engineering sectors through its appropriate methods. The target is to create a correlation between the physical properties of the system derived from real measurements and the dynamic characteristic of a numerical model (Brincker et al, 2015).

In OMA, depending on frequency or time domain, there are two methods of identification, such as Stochastic Subspace Identification (SSI) in the time domain and Enhanced Frequency Domain Decomposition (EFDD) in the frequency domain. Both methods are more effective with multi-input data. They describe two different kinds of identification, but they clearly present what is counted as a common trend in all methods.

Several methods for identifying modal parameters exist. EFDD and SSI were used in this present work for extracting dynamic characteristics of the frame structure by ARTeMIS software.

5.3.1 Enhanced frequency domain decomposition (EFDD)

EFDD is an extension of the Frequency Domain Decomposition (FDD) method which is easy to use. In EFDD, the modes are simply selected by locating the peaks in the singular value decomposition plots (SVD) computed from the spectral density spectrum of the responses.

In EFDD method, the power spectral density function (PSD) at a single degree of freedom (SDOF), which is located around a peak of resonance, when using the inverse discrete Fourier transform (IDFT), this function is taken back to the time domain. The natural frequency is achieved by determining the number of zero-crossing as a time

function and damping by the logarithmic decrement of the corresponding SDOF normalized autocorrelation function (Jacobsen et al, 2006).

In the EFDD method, instead of selecting the peaks in the power spectral density (PSD) functions, spectral matrices are created using these functions estimated only by the output data and decomposition into singular values (SVD) is applied to these matrices. In cases where the function that excites the system is broadband, the system has low damping values (Engineering structures are an example of low damping systems) and the closure modes are perpendicular to each other, each value is the self-power spectral density (Auto-PSD) corresponding to a single mode of the system. If the above conditions are not met, the results obtained are sufficiently precise. The mode forms of the system are obtained from singular vectors.

In EFDD, the relation between measured output and unknown input is shown in Equation 4.1 below (Bendat & Piersol, 2010).

Equation (5.1) indicates the complex conjugate and transpose of the expression, respectively.

$$[G_{yy}(j\omega)] = [H(j\omega)]^* [G_{xx}(j\omega)] [H(j\omega)]^T \quad (5.1)$$

$G_{xx}(j\omega)$ = Matrix of Input signal power spectral density function

$G_{yy}(j\omega)$ = Matrix of Output signal PSD function

$H(j\omega)$ = Frequency Response Function (FRF) matrix

“*” Denotes complex conjugate and “T” denotes transpose

5.3.2 Stochastic subspace identification method (SSI)

The SSI is an output-only temporal domain technique that works directly with the temporal data without requiring the conversation of the data in spectra or correlation. This method is suitably peculiar to identifying operational modal parameters, but it is

somewhat difficult to provide a detailed explanation in civil engineering. (Van Overschee & DeMoor, 1996; Peeters & DeRoeck, 1999).

The SSI method identifies the state-space matrices using robust numerical techniques such as QR factoring, singular value decomposition (SVD), and least squares. SVD is used for noise rejection so that QR factorization results in a significant reduction in data. SSI is considered to be the most powerful and precise methods systems identification methods applicable in several structural civil engineering projects successfully under operational conditions. (Hermans et al, 1999).

The vibration of structures can be defined as a linear dynamic system and can be expressed as:

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = F(t) \quad (5.2)$$

where:

M = Mass matrix

C = Damping matrix

K = Stiffness matrix

$\ddot{X}(t)$ = Time dependent acceleration vector

$\dot{X}(t)$ = Time dependent velocity vector

$X(t)$ = Time dependent displacement vector

$F(t)$ = The excitation forces

The Equation (5.2) will not be immediately used in SSI methods, then it will be transformed into this form:

$$x_{k+1} = Ax_k + w_k \quad (5.3)$$

$$y_k = Cx_k + v_k$$

This equation is called the discrete-time stochastic state-space model (Peeters & DeRoeck, 1999), Where:

A = State matrix

C = Observation matrix

x_k = Discrete-time state vector

y_k = Output vector

5.3.3 Why EFDD and SSI are used as a technique for deducting frequencies and modes instead of another method

The answer to this question is not only due to the computer program ARTeMIS which uses these two technical methods, but both techniques work in the time domain.

In addition, in EFDD, the damping is obtained by the logarithmic decrement of the corresponding single degree of freedom normalized autocorrelation function and the natural frequency by determining the number of zero-crossing as a function of time.

According to the SSI method, it is very effective because it requires no cross-correlation function or output measurement spectra. Another method uses reliable numerical techniques such as QR-factorization and SVD in the process of defining modal parameters.

5.3.4 Difference between EFDD and SSI

In enhanced frequency domain decomposition, the power spectral density function (PSD) at a single degree of freedom (SDOF), identified in the vicinity of a resonance peak, this function is returned to the time domain when using the inverse discrete Fourier transform (IDFT). The stochastic identification of the subspace (SSI) is a time-domain method that does not require the estimation of the spectral density functions which is not the case in the EFDD method. Thus, problems such as spectral leaks do not occur in the SSI method. Since the estimation of the model is not based on any Fourier transformation in the frequency domain, no leak is introduced and there is no unpredictable overvaluation of the damping. The SSI method is a parametric method that allows the creation of stabilization diagrams to differentiate physical modes from non-physical modes.

5.3.5 Which method is more reliable in what sense?

SSI techniques are precise and powerful modal analysis techniques available and provide more detail on the responses. Therefore, the technique works entirely with a time-domain which does not require estimation of the spectral density functions. Its identification is based on data measured instead of covariance. It is clear that the method works straightly with temporal data without converting them in correlation or matrix spectral data.

5.4 Modal Assurance Criteria (MAC)

The MAC is among the strong used and precise to correlate two sets of mode shapes. The MAC value is used to determine the similarity between two different mode shapes. MAC function is used to measure the harmony between modal vectors (Allemang and Brown, 1982). The formula used in the calculation of the MAC is displayed as;

$$\text{MAC}(\phi_{A,k}, \phi_{B,j}) = \frac{(\phi_{A,k}^T \phi_{B,j})^2}{(\phi_{A,k}^T \phi_{A,k})(\phi_{B,j}^T \phi_{B,j})} \quad (5.3)$$

Where;

$\phi_{A,k}$ Is the k th mode of data set A and

$\phi_{B,j}$ Is the j th mode of the data set B.

In equation (5.3), the calculation gives values between 0 and 1. The value obtained after the calculation if approaching 1, it shows that the similarity between the two modes considered is high. The value obtained from the calculation if it approaches 0, it indicates that the similarity between the two modes considered is weak.

5.5 Ambient vibration

5.5.1 Measurement of ambient vibration responses

The analysis of ambient vibrations for the deduction of natural frequencies and mode forms is an interesting topic in control studies and structural monitoring to illustrate the linear nature of structures. (Ivanovic et al. 1999).

Acceleration measurements of ambient vibrations obtained from accelerometers that are installed and used to measure frequencies. Dynamic data for 3D printed structure is crucial to understand the influence of parameters such as stiffness, overall mass, and mass distribution on the modal parameters of the structure (Mode shapes, frequencies, and damping).

At ambient excitation, it is difficult to determine the calculations of frequency response function (FRF) or the impulse response function (IRF) because the input force is not estimated in an ambient vibration test. Thus, a modal identification technique is necessary to process the output data only.

5.5.2 Detrending & filtering of an ambient vibration signal

Before performing a modal analysis, collected data have to undergo a detrending and filtering. Filtering processing techniques are tools that allow fluctuations to be made in the high frequencies of data less intense or to remove periodic trends of a specific frequency of data.

The data were collected from ambient vibration were filtered as shown in figure 5.8.

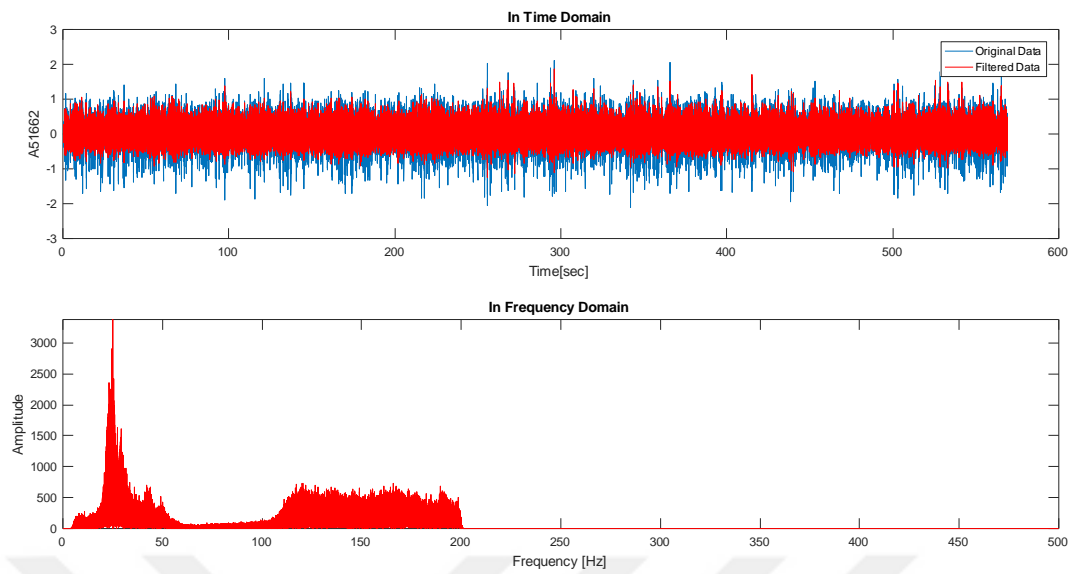


Figure 5.8 MATLAB _ filtering of an ambient vibration signal

5.5.3 EFDD method for ambient vibration

the theoretical background of the EFDD technique was detailed in the previous section, thus the mode shapes and frequencies were obtained using EFDD technique presented in table 5.1 below. The spectral density singular values graph of the lateral dominant modes found by EFDD in the frequency domain from the ambient test is shown in Figure 5.9.

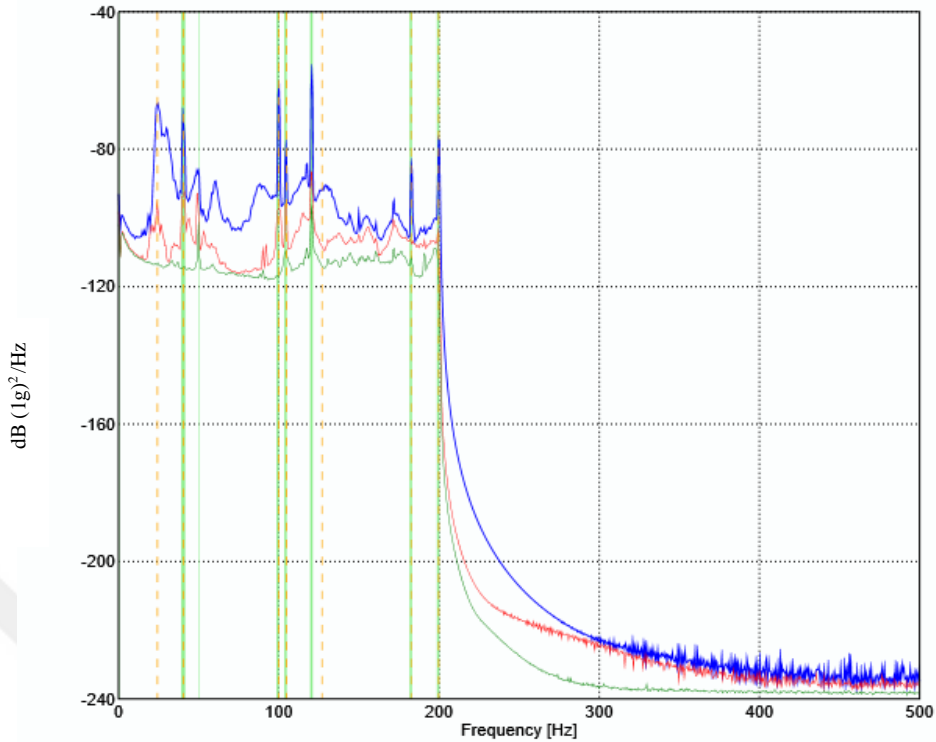


Figure 5.9 Spectral density singular values graph using ambient vibration data by SSI

Values of dominant modes found by EFDD in the frequency domain from the ambient test are detailed in table 5.1

Table 5.1 Table of frequencies and mode shapes obtained from the ambient test by EFDD method

MODE #	Frequency [Hz]	Complexity [%]
1	29.310	0.446
2	89.955	0.345
3	117.317	83.406
4	129.089	4.378

5.5.4 SSI method for ambient vibration

In the previous section, the SSI method was presented then the dominant modes and frequencies obtained from the ambient test by using the SSI method, are shown in the stabilization diagram (See in Figure 5.10).

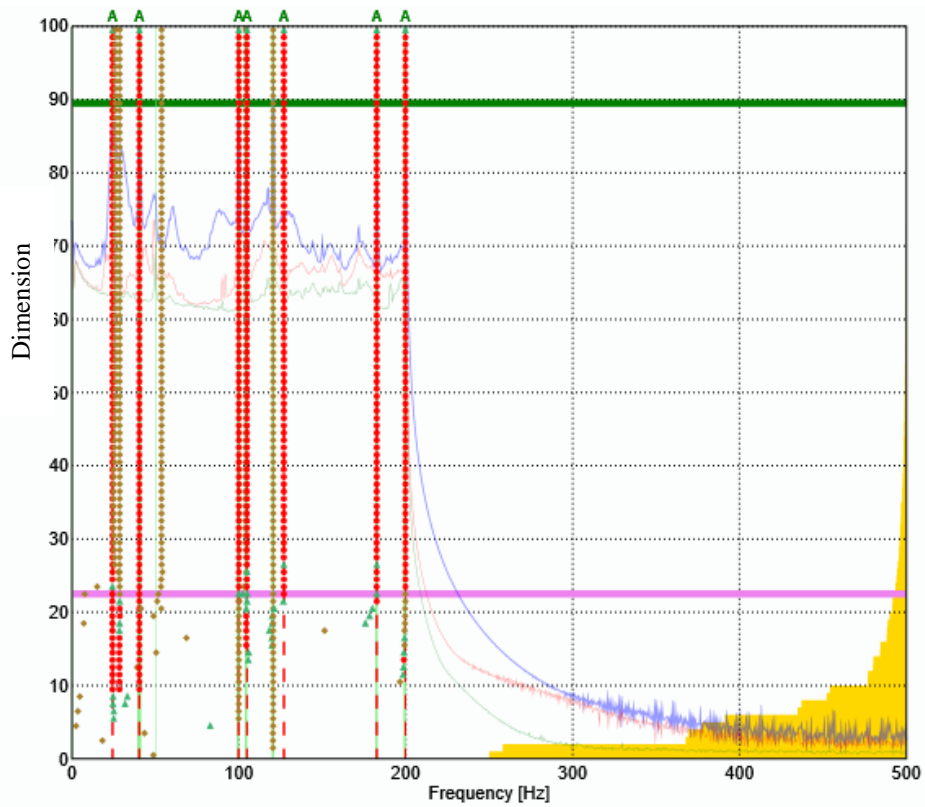


Figure 5.10 Stability diagram and estimation modal properties using ambient vibration data by SSI method

Considered modes and frequencies found by SSI technique from the ambient test are detailed in table 5.2

Table 5.2 Table of frequencies and mode shapes obtained from the ambient test by SSI method

MODE #	Frequency [Hz]	Damping [%]	Complexity [%]
1	24.238	1.065	6.376
2	40.31	0.296	2.399
3	99.906	0.206	0.458
4	104.834	0.819	45.161
5	126.924	3.861	37.305
6	182.556	0.798	73.568
7	199.761	0.167	0.143

5.5.5 Comparison of EFDD and SSI by ambient test

The comparison of frequencies and mode shapes obtained from ambient vibration using EFDD and SSI methods are presented in table 5.3 and the given MAC values are calculated between the modes found by SSI and EFDD methods.

Table 5.3 Table of comparison of results from EFFD & SSI method using for ambient vibration

MODE #	EFDD		SSI		Diff. (Hz)	MAC (%)
	Mode	Freq. [Hz]	Mode	Freq. [Hz]		
1 st transversal	1	29.310	1	24.902	4.398	39.90
2 nd transversal	2	89.955	3	99.906	-9.951	72.70
3 rd transversal	4	129.089	5	126.924	2.165	89.60

The torsion mode was not found by the EFDD method but by the SSI method it was found, so it means ambient vibration is not a favorable or preferable test for finding a torsional modal for this type of frame structures.

In the MAC graphic (See in figure 5.11) gives the possibility to show how the discrepancies exist between these given modes from these two methods. Only 3 modes are shown to be compatible.

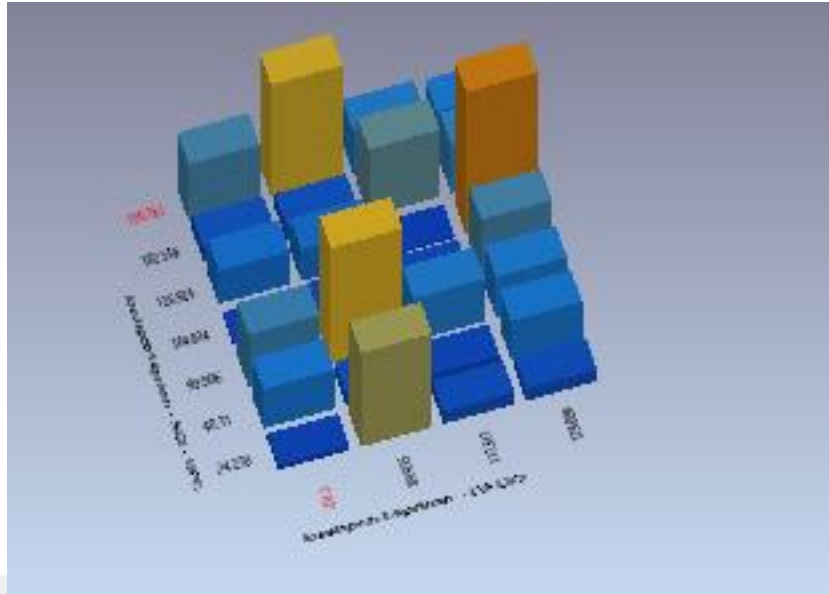


Figure 5.11 MAC diagram of EFDD and SSI method of ambient vibration

5.6 White Noise (WN) vibration test

5.6.1 Measurement of white noise responses

White noise (WN) test is usually executed by shaking table. When This table produces a periodic wave, it is called sinus and when it produces the random waves it is called white noise.

In this work, to performing modal parameters and mode shapes, it was found by shaking the table for getting WN signals that can be transformed into numerical values for learning the modal characteristics of the structure. Computing frequencies were between 0-300 Hz. Approximately 10 minutes were collected during the shaking of the table. The direction of motion was + X direction. It was using 7 uni-axial accelerometers, as shown in figure 6. The uniaxial accelerometers have ~1,000 mV/g (102 mV/m/s²) sensitivity, a frequency range of 0.05 to 3000 Hz, acceleration measurement range of ± 5 g (± 49 m/s²) peak, a weight 7.5 gm, a broadband resolution 0.00005 g RMS (Root mean square).

5.6.2 Detrending & filtering of WN

After collecting the shaking table signal, data were transferred to LabVIEW software to transform the signal into digital data, then based on the numerical values. The numerical values that are gotten, they should remove a strange value by a detrending and filtering process to get the clean signal that was needed as shown in figure 5.12.

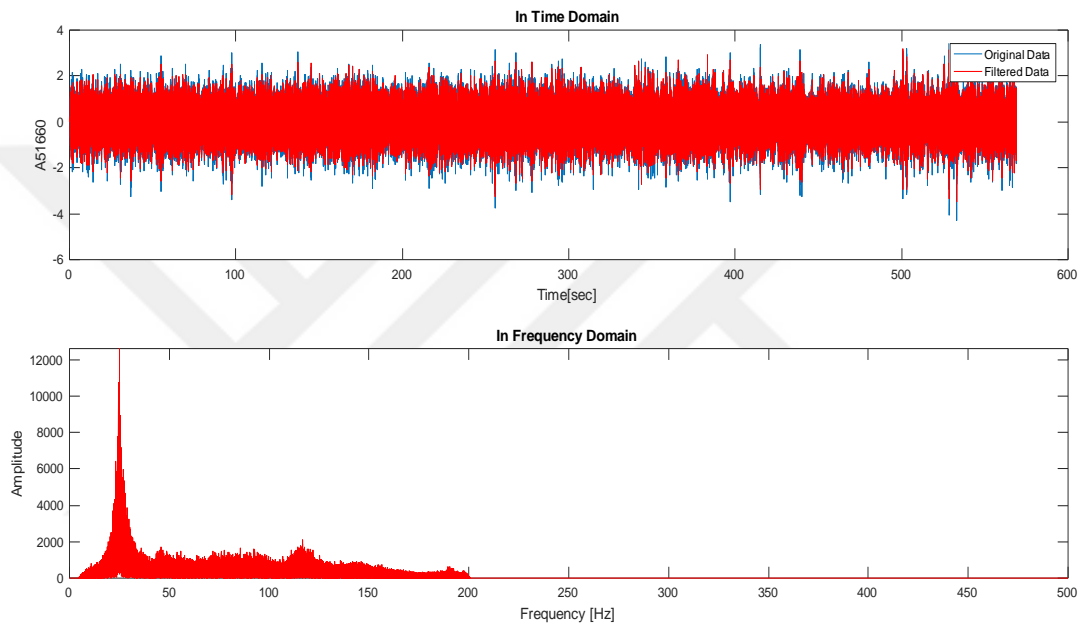


Figure 5.12 MATLAB _ filtering of white noise signal

5.6.3 EFDD method for white noise

The modes and frequencies obtained by the EFDD processing technique for white noise are presented. Similarly, the spectral density singular values graph of the lateral dominant modes found by EFDD in the frequency domain from the white noise test is shown in Figure 5.13.

The values of dominant modes found by EFDD in the frequency domain from the WN test are detailed in table 5.5.

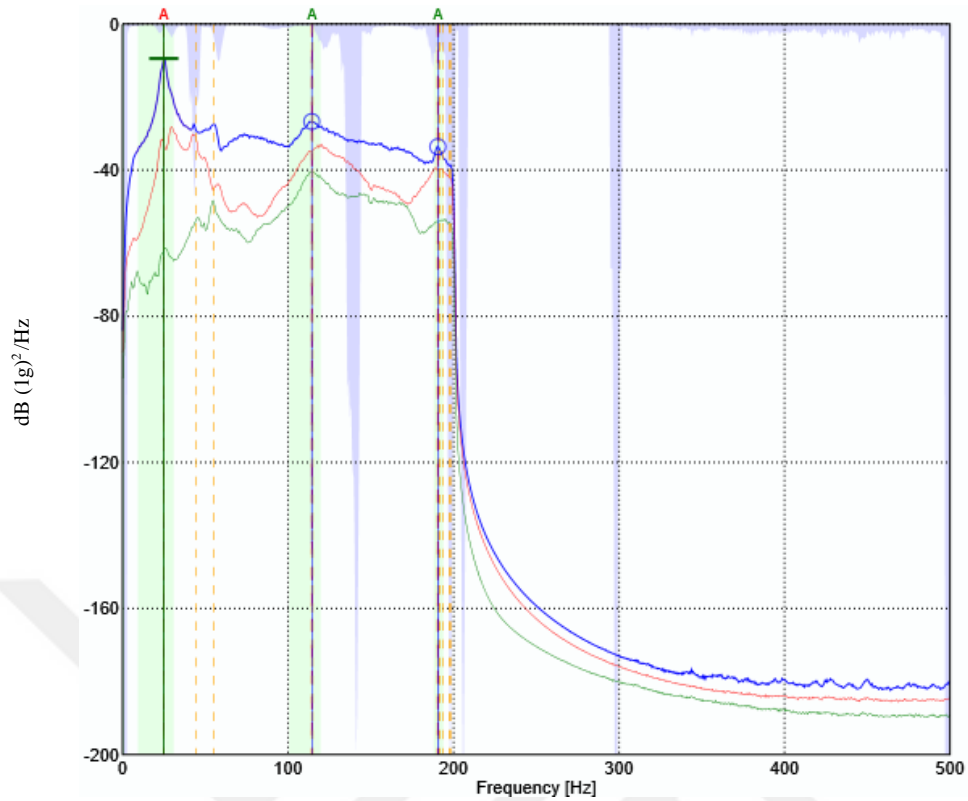


Figure 5.13 Singular values of spectral densities analyses and estimation of white noise by EFDD method

Table 5.5 Table of frequencies and mode shapes obtained from WN test by EFDD method

MODE #	Frequency [Hz]	Complexity [%]
1 st trans.	24.854	18.155
2 nd trans.	114.460	62.063
1 st torsion & trans	190.576	62.274

5.6.4 SSI method of white noise test

The stabilization diagram of the considered modes found by the SSI technique from the WN test is shown in Figure 5.14. All considered mode shapes and frequencies found by the same method from the WN test are detailed in table 5.6.

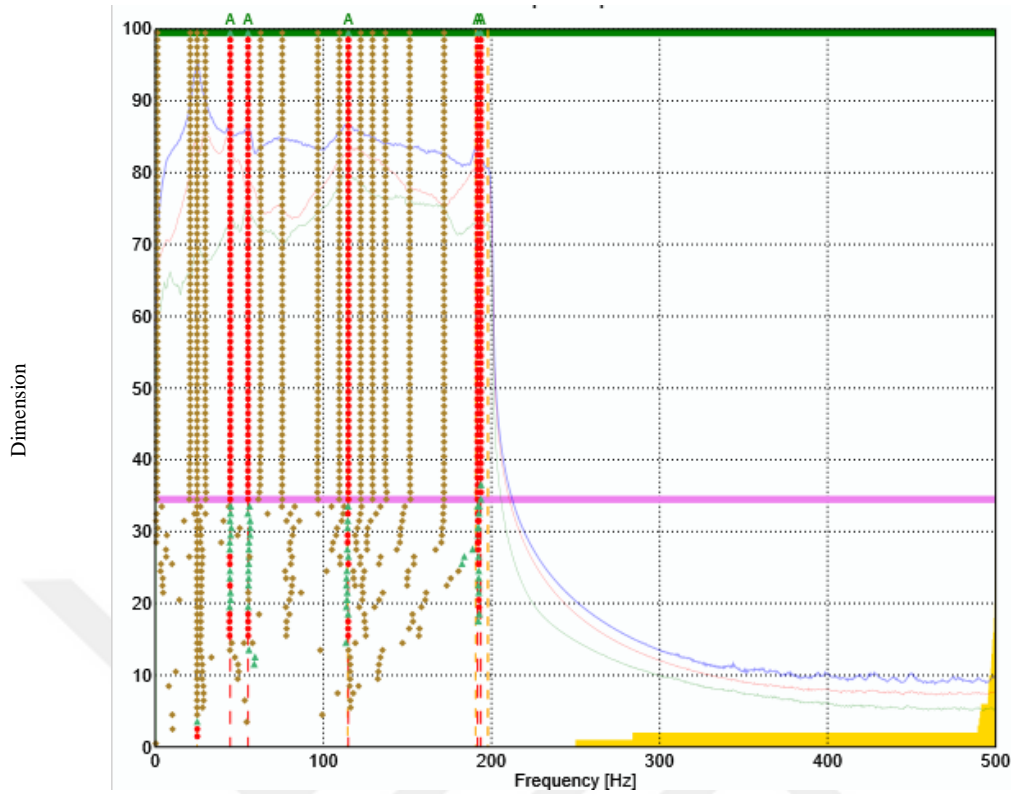


Figure 5.14 Stability diagram and estimation modal properties using WN data by SSI method

Table 5.6 Table of frequencies and mode shapes obtained from white noise test by SSI method

MODE #	Frequency [Hz]	Damping [%]	Complexity [%]
1 torsion	44.537	0.871	10.803
1 st trans.	55.156	2.757	17.340
2 nd trans.	114.843	4.216	16.219
3 rd trans.	191.711	1.495	56.627
Tors. & trans	193.642	0.871	81.700

5.7 Conclusion and discussion

In this case, the ambient vibration test could not give a good frequency for the torsional modal. Therefore, the WN vibration test results (1st mode from EFDD, 2nd, and 3rd modes from the SSI method) were used to obtain the model parameters for performing the analysis model to merge with the experimental model. Mode shapes

estimated by EFDD method is presented in Figure 5.15 and those that are estimated by SSI are presented in Figure 5.16 and Figure 5.17

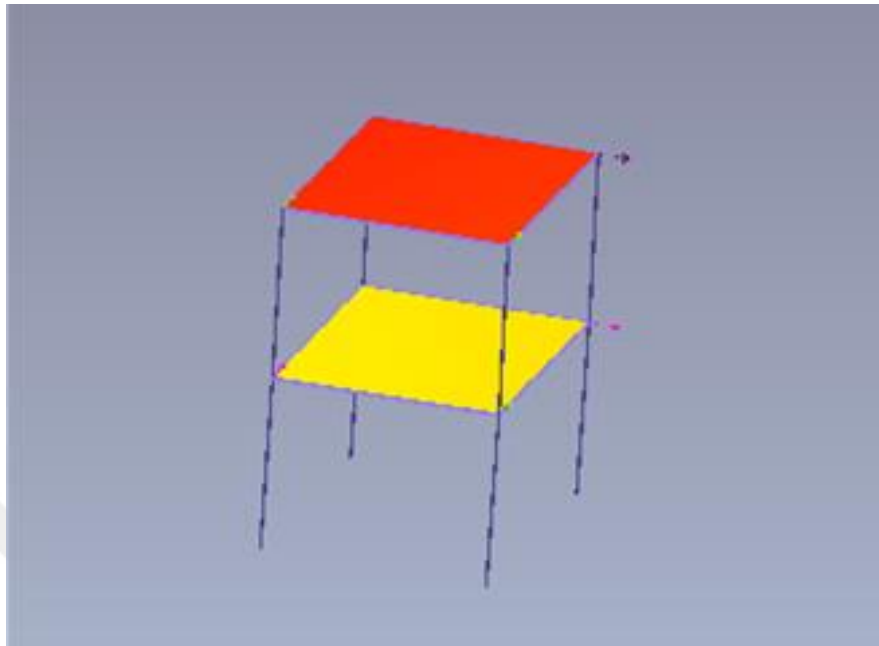


Figure 5.15 1st mode; couple mode obtained from EFFD method, by ARTeMIS (24.854 Hz)

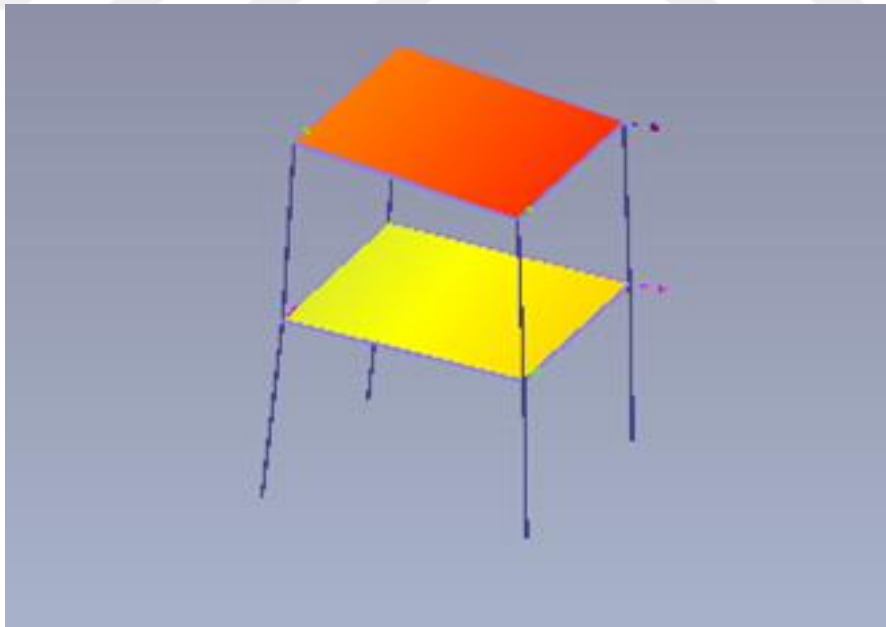


Figure 5.16 2nd mode; torsional mode obtained from the SSI method, by ARTeMIS (44.537 Hz)

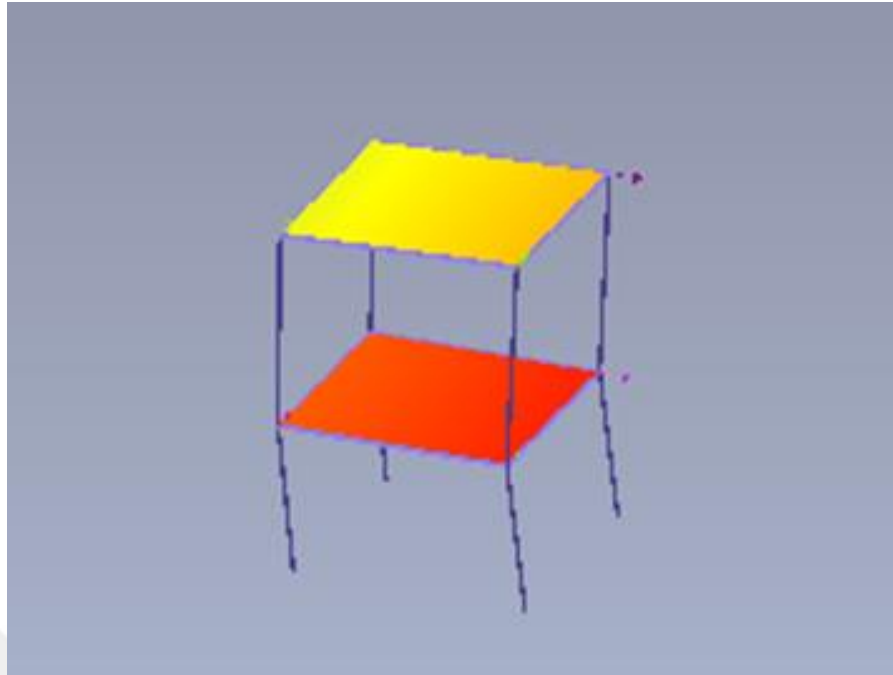


Figure 5.17 3rd mode shape: lateral mode obtained from the SSI method, by ARTeMIS (114.843 Hz)

Only 3 modes are considered in the experimental method. Therefore, experimentally obtained natural vibration frequencies for the 1st, 2nd, and 3rd modes are 24.854Hz, 44.537Hz, and 114.843Hz, respectively presented in table 5.7. These modes were obtained from two different methods, these modes are then compared with those of the numerical method.

Table 5.7 Table of summarized frequencies experimental method by WN

MODE #	EMA (EFDD & SSI)	
	Mode	Freq. [Hz]
1 st transversal	1	24.854
1 st torsion	2	44.537
2 nd transversal	4	114.843

CHAPTER SIX

NUMERICAL MODELLING & UPDATING

6.1 Introduction

In this section, the main objective is to present a numerical model as an initial model which would be matched with the real at end calibrating this initial model to become an updated model.

To make a finite element (FE) analysis there is a need to use a tool that can help in the computation of the modal parameters. FE modeling was carried out in SAP2000 software to learn the characteristics of the modal structure. This software is an effective civil engineering software in several different cases in the design and analysis of various structural systems. It has the ability to analyze, model, design, and optimize simple and complex systems, from 2D to 3D, from simple geometry to complex geometry in a convenient manner.

6.2 Problem description

During the model proposal, a preliminary study was carried out in terms of an irregular torsion structure. Torsional mode needs to be seen under the vibration load. This preliminary work was performed by SAP2000 to verify whether the needed model is done or not. After this step of verification, then the FE model (Or initial FE model) was performed to learn modal parameters of the model by SAP2000 software again; see in figure 6.1. This initial FE model is a model that is predicted to be for matching with the real measured model that also should be updated is the one to be updating.

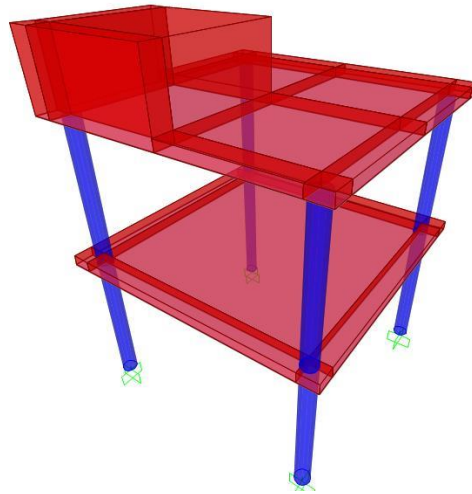


Figure 6.1 Initial Finite element model from SAP2000

6.3 Numerical model (Initial Finite Element model)

FE is one of the popular structural analysis tools used for numerical model prediction. However, building a precise and reliable FE model is a somewhat difficult exercise due to the inaccuracy of certain mechanical properties. For example, it is difficult to determine the exact quantity that a body is filled.

Therefore, it is important to make realistic assumptions in numerical modeling in order to represent the true global behavior of the structural system. (Ozcelik et al., 2018).

The analytical study of this work considered to be the initial model was done by the finite element analysis (FEA) method using SAP2000 software. Modal analysis of this structure has been made and the resulting modal parameters are taken into account. Several modes have been obtained but only 3 modes are considered for this study. The frequency values of the frame structure that was obtained from the FE model are presented in Table 6.1.

Table 6.1. Modal parameters from the initial FE model for all modes

#	MODE	Frequency Cycle/sec
1	1 st torsional	23.689
2	1 st transversal	25.737
3	2 nd torsional	34.939
4	2 nd transversal	98.702
5	3 rd transversal	99.763
6	3 rd torsional	105.227
7	1 st vertical	125.288
8	2 nd vertical	151.699
9	3 rd vertical	250.661
10	4 th vertical	279.972
11	5 th vertical	341.184
12	6 th vertical	642.379

The numerical modal parameters were obtained by using the modal analysis of the initial numerical model processed by SAP2000, only the results of 1st, 3th, and 5th modes correspond to the modes extracted from the laboratory measurements, are used and shown from Figure 6.2 to Figure 6.4. Natural frequencies of 1st transversal mode is 25.737 Hz, for the 2nd torsional mode is 34.939 Hz and for 3rd transversal mode 99.702 Hz were obtained for the 2nd, 3rd, and 5th modes, respectively.

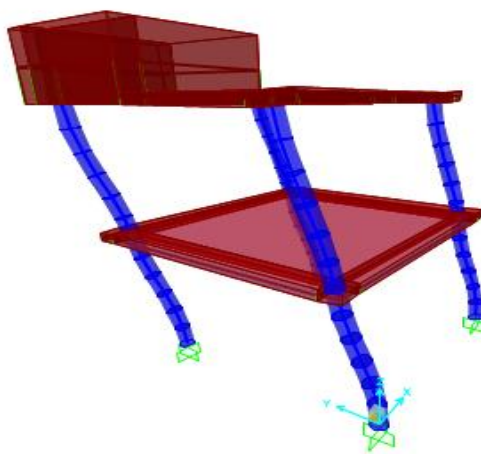


Figure 6.2 1st mode: 1st transversal mode of SAP2000 model

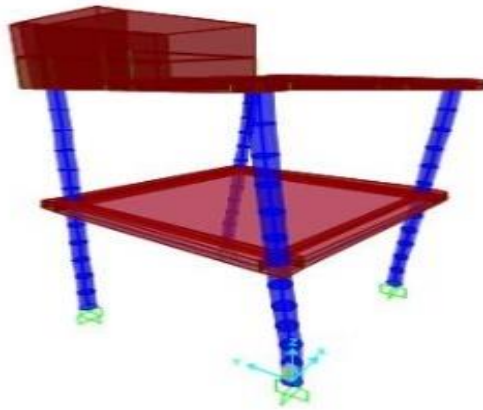


Figure 6.3 3rd mode: 2nd torsional mode of SAP2000 model

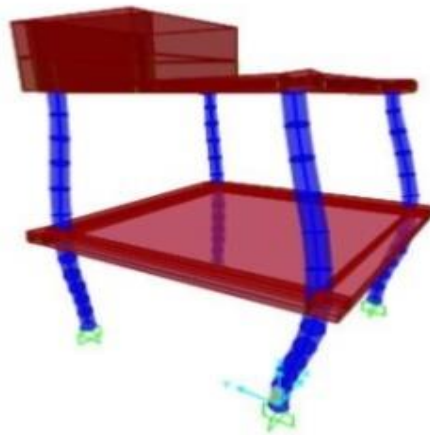


Figure 6.4 5th mode: 3rd transversal mode of SAP2000 mode

6.4 Comparison of Numerical models

In this section, the main purpose is to compare the numerical model of the dynamic analysis performed by mathematical evidence with the analysis performed by SAP2000 software to verify these two tools and to ensure that the calculations made by the software are safe.

The results of dynamic analysis have been developed above in the chapter four (4) are detailed in the table 6.2.

Table 6.2 comparison of frequencies from dynamic analysis and SAP2000

MODE #	Dynamic analysis		SAP2000	
	<i>Mode</i>	<i>Freq. [Hz]</i>	<i>Mode</i>	<i>Freq. [Hz]</i>
1 st trans.-torsional	1	9.60	1	23.68
2 nd torsional	2	34.80	3	34.93
1 st vertical	3	343.30	11	341.18
2 nd vertical	4	1250.2	-	-

6.5 Finite Element Model Updating (FEMU) Studies

FEMU method is an updated technique that produces more accurate results because the studies are based on measured data compared with those of the analytical analysis.

This study was done by FEMtools (FEMtools, 2017) model updating software was used to improve the match between the dynamic properties of an initial FEM and test data. FEMtools calculates optimal design parameters for the components based on design constraints, action loads, and required structural behavior.

6.5.1 Mode shapes pairs and comparison

Before making a comparison between the experimental and analytical models, the models must be well matched and adapted to provide a good updated model. It has been assumed that models are perfectly adapted as shown from Figure 6.5 to figure 6.7. This helps to understand the differences between these two methods. FEMtools software can also be used to identify and compare the different modes, i.e. modes that match very well between the experimental and numerical models by giving MAC values presented in Table 6.3.

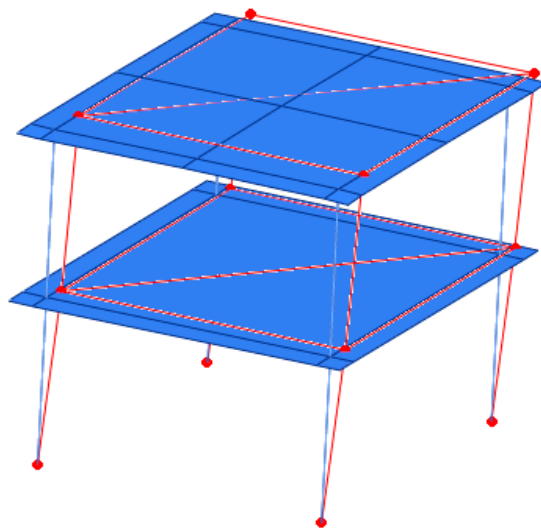
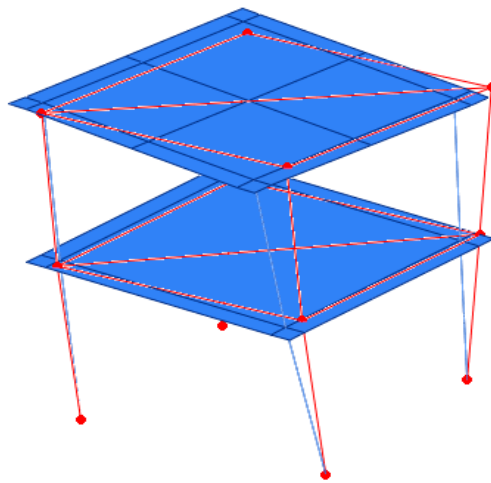


Figure 6.5 Mode shape pairs of 1st mode of FEM and 2nd mode of EMA



1

Figure 6.6 Mode shape pairs of 2nd mode of FEM and 3rd mode of EMA

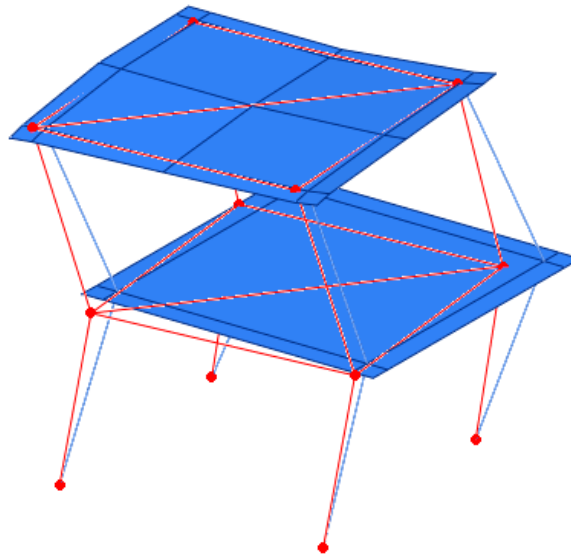


Figure 6.7 Mode shape pairs of 3rd mode of FEM and 5th mode of EMA

Table 6.3 Comparison of the modal parameters obtained by numerically and experimentally method

MODE #	FEA		EMA		Diff. (%)	MAC (%)
	Mode	Freq. [Hz]	Mode	Freq. [Hz]		
1	2	25.73	1	24.90	3.28	64.6
2	3	34.94	2	44.53	-24.13	49.5
3	5	99.76	4	114.26	-13.55	38.8

Before computing FEM, sensitivity analysis has to be carried out on the frame to determine which elements had the most effect on the estimation of the modal parameters, and these elements are then updated to calibrate the model. The analysis of effective optimization and sensitivity requires that gradient information for stress and objective functions be analytically calculated. FEMtools has an internal sensitivity module that plays the role of providing gradient information for responses and parameters. In this way, processing times are reduced, and the possibility of errors is minimized in the update process using fewer elements.

6.5.2 Numerical results

To improve the match between the dynamic properties of an initial FE model and test data the same software was used.

- **1st case: Young's modulus (E) and mass density (ρ) were selected as update parameters**

In this first case, the MAC diagram of experimental mode shape and analytical mode shape before updating and after updating are seen in figure 6.8 and figure 6.9, respectively. The MAC values comparison of three different experimental and three analytical models are shown in Table 6.4.

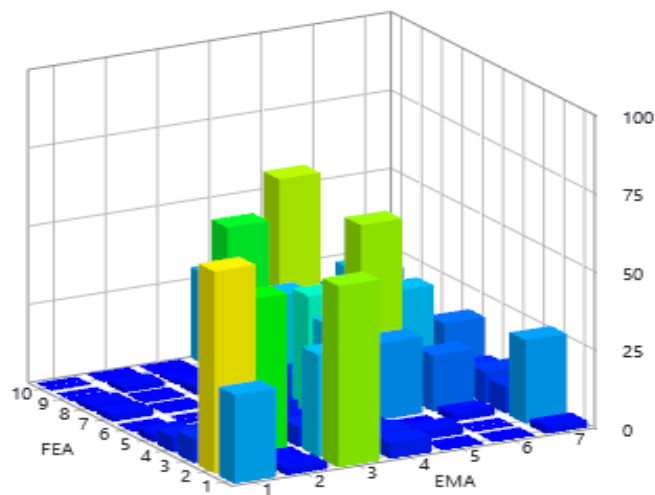


Figure 6.8 MAC diagram of an analytical and experimental model before updating

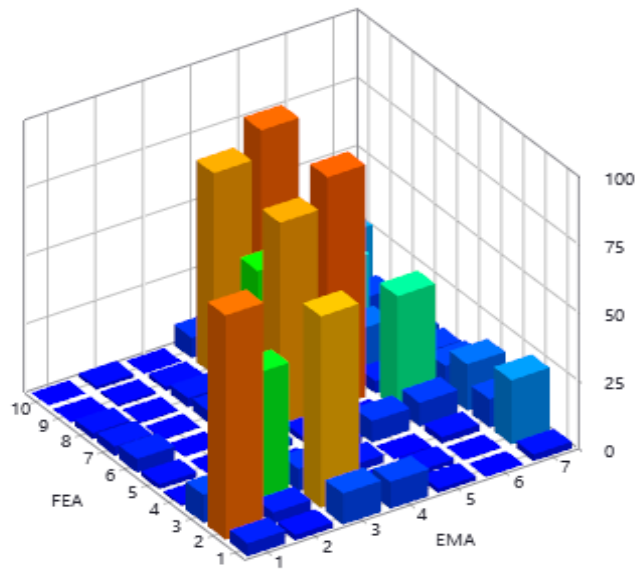


Figure 6.9 MAC diagram of an analytical and experimental model after updating

Table 6.4 Table of Comparison estimated modal parameters between analytical and experimental results

MODE #	FEA (Numerical modal)		EMA (Experimental modal) Freq. [Hz]	Diff. (%) Freq Before updating	Diff. (%) Freq After updating	MAC (%) Before updating	MAC (%) After updating
	Before updating Freq. [Hz]	After Updating Freq. [Hz]					
1-2	25.73	24.95	24.90	3.28	0.20	64.60	70.40
2-3	34.94	44.16	44.53	-24.13	-0.83	49.50	62.50
3-5	99.74	115.87	114.74	-13.55	1.41	38.80	68.10

The concept of model updating is made to adapt the values of the chosen parameters to understate a reference correlation coefficient. After updating, the obtained values of updated parameters are presented in Table 6.5.

Table 6.5. Table of updated parameters

#	Level	Type	Old	Actual	Difference (%)
1	GLOBAL	E	1.01972E+01	2.02733E+01	9.88132E+01
2	GLOBAL	RHO	1.01892E-09	2.20828E-09	1.16727E+02

- **2nd case: Only mass density (ρ) were selected as update parameter**

In this case, the MAC diagram of experimental mode shape and analytical mode shape before updating and after updating are seen in figure 6.10 and figure 6.11, respectively. The MAC values comparison of three different modes are shown in Table 6.6.

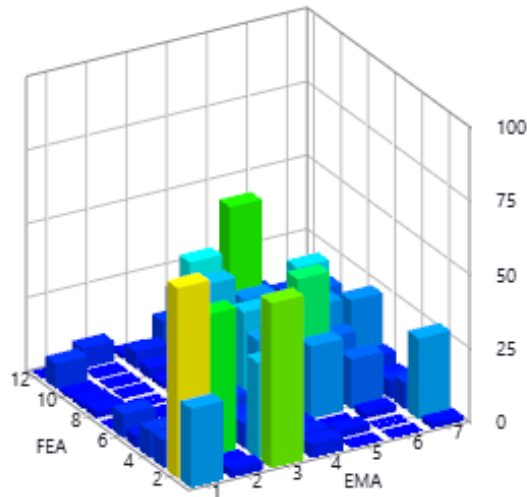


Figure 6.10 MAC diagram of an analytical and experimental model before updating

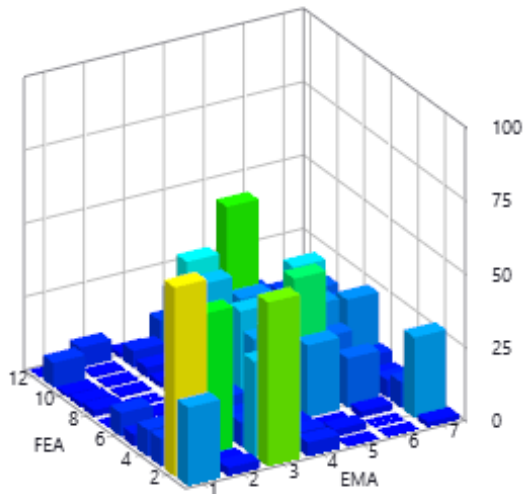


Figure 6.11 MAC diagram of an analytical and experimental model after updating

Table 6.6 Table of Comparison estimated modal parameters between analytical and experimental results

MODE #	FEA (Numerical modal)		EMA (Experimental modal) Freq. [Hz]	Diff. (%) Freq	Diff. (%) Freq	MAC (%)	MAC (%)
	Before updating Freq. [Hz]	After Updating Freq. [Hz]		Before updating	After updating	Before updating	After updating
1-2	25.73	24.84	24.90	3.28	-0.26	64.60	64.50
2-3	34.94	43.93	44.53	-24.13	-1.37	49.50	48.50
3-5	99.74	115.66	114.74	-13.55	1.23	38.80	32.90

Mass density (ρ) was used as an update parameter then after updating, the obtained value of this parameter is presented in Table 6.6.

Table 6.6. Table of updated parameter

#	Level	Type	Old	Actual	Difference (%)
2	GLOBAL	RHO	1.01892E-09	9.29900E-10	-8.73678E+00

- **3rd case: Only Young's modulus (E) was selected as update parameter**

In this case, the MAC diagram of experimental mode shape and analytical mode shape before updating and after updating are seen in figure 6.12 and figure 6.13, respectively. The MAC values comparison of three different modes are shown in Table 6.6.

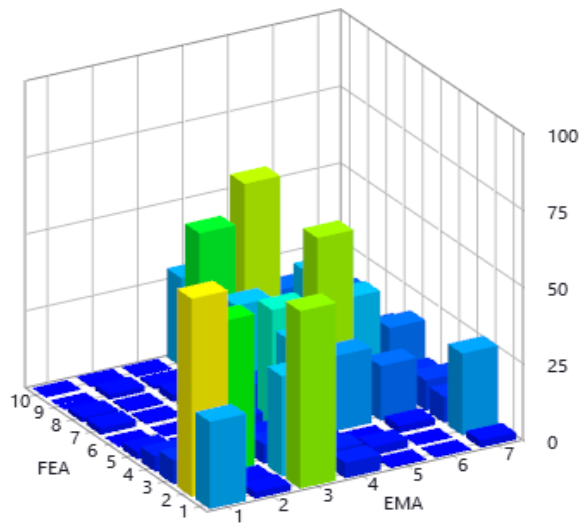


Figure 6.12 MAC diagram of an analytical and experimental model before updating

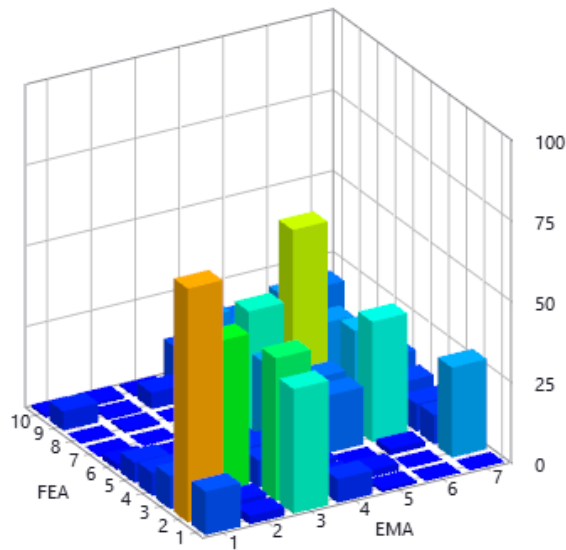


Figure 6.13 MAC diagram of an analytical and experimental model after updating

Table 6.7 Table of Comparison estimated modal parameters between analytical and experimental results

MODE #	FEA (Numerical modal)		EMA (Experimental modal) Freq. [Hz]	Diff. (%) Freq	Diff. (%) Freq	MAC (%)	MAC (%)
	Before updating Freq. [Hz]	After Updating Freq. [Hz]		Before updating	After updating	Before updating	After updating
1-2	25.73	27.51	24.90	3.28	8.76	64.60	72.40
2-3	34.94	40.99	44.53	-24.13	-7.95	49.50	48.30
3-5	99.74	98.72	114.74	-13.55	1.23	38.80	61.10

Young's modulus (E) was used as an update parameter then after updating, the obtained value of this parameter is presented in Table 6.8.

Table 6.8. Table of updated parameter

#	Level	Type	Old	Actual	Difference (%)
1	GLOBAL	E	1.01972E+01	9.58085E+00	-6.04397E+00

CHAPTER SEVEN

CONCLUSIONS

The project is based on a Finite element model updating (FEMU). The implementation of FEMU in this study is a process that begins from the design of the model to the updating of results. This procedure may also be applied to other types of structures.

The model is a two-story frame structure made of ABS material. The frame was manufactured as a structure yielding an irregular torsion mode. Its geometry has been designed so that the structure is not inconsistent during test execution. Material properties and element section data must be known.

Two tests were performed on this frame, white noise, and ambient vibration. Data collected on frame structure was processed and filtered using MATLAB. The ARTEMIS software based on the EFDD and SSI methods was used to deduce modal characteristics. Seven modes were found in the software, but only three (3) were considered, such as 1st transversal mode; the 2nd twist mode, and the 2nd transversal with the frequencies 24,854Hz, 44,537Hz, and 114,843Hz, respectively.

The FE model was executed by using SAP2000. The mesh, geometry, and element types are well defined in this FE model. Material properties data are compiled to facilitate the update of the FE model. During the FE modeling phase, the modal parameters found are compared only to the frequency and mode shapes found in the white noise. Because in this work, the ambient vibration test didn't give a good model of torsion. Hence the frequencies found according to the three modes compared with the modes found of the test result are 25.737 Hz, 34.939 Hz, 99.763 Hz, respectively.

The purpose of this thesis is to identify the modal parameters of this structure and to create a calibrated FE model of reference by the Finite element model updating method.

Modal characteristics were well identified from the tests mentioned above, which allowed the initial model produced by the analytical method to be calibrated.

The FE model updating method was based on sensitivity. Sensitivity studies were performed to determine which elements most affect modal parameters and which elements are ineffective. In addition, these studies were carried out to identify the parameters that will be updated because the structure contains many of the elements.

Young modulus and density were selected as parameters. After the process of updating these parameters, the values of these parameters have been increased. Therefore, this change means that the numerical model is calibrated.



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