QATAR UNIVERSITY

COLLEGE OF ENGINEERING

OPERATIONAL MODEL ANALYSIS AND FINITE ELEMENT MODEL UPDATE USING AMBIENT VIBRATION DATA FOR AL-SINYAR TOWER

BY

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ABSTRACT

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Title: Operational Model Analysis and Finite Element Model Update using Ambient Vibration Data for Al-Sinyar Tower

Supervisor ofThesis: Dr. Mohammed Farouk Mohammed Hussein.

Buildings in Qatar rely on minimum structural code requirements implemented by design consultants' offices. Qatar 2030 vision considers increasing of structures' sustainability and serviceability as a high priority, which require testing structures under real full scale modeling.

The process of monitoring structures' behavior over time for aerospace, civil and mechanical engineering infrastructure is referred to as structural health monitoring (SHM). In Qatar, most high-rise building stability design is based on wind loading. According to Uniform Building Code3 1997 (UBC1997) which classifies seismic zones on a scale of zero to four, Qatar's seismic classification on the scale is zero which is the minimum seismic risk value. Qatar Meteorological data on wind speeds enabled analysis of extreme winds to be undertaken in structural designs.

This study aims to identify dynamic properties of the structural by using wired and wireless accelerometers in order to assess structural performance to update Finite Element Model (FEM). By updating FEM, engineers are enabled to support clients to make quick and correct decisions in extreme emergency situations in the case of boundary conditions changes and loads such as seismic vibration and wind pressure changes, during a structure's life. The objective of this research is to apply and evaluate a single output-only procedure on a reinforced concrete tower building, *Al Sinyar Tower*, which consists of 2B+G+52 floors in Al Dafna Area in Qatar, with a total built up area of 74,747 sqm and is the tallest residential building in Qatar with a total height of 230 m . A Finite Element model using Sap2000 program was used to model and analyze building values in order to compare results with the real test results. The different forms of response data from ambient vibration were scrutinized to evaluate structure performance. Mode shapes, natural frequencies, modal damping ratios were studied, while the results of tests carried under ambient conditions were used to update the Finite Element model based on modules of elasticity, density and also connections fixity.

The thesis concluded that wired sensors are not practical to use for low frequencies measurements in high rise buildings and that it is tremendously challenging and difficult to deal with more than 1000 meter long cables, especially with a very sensitive devices. Frequencies values from wired sensors could not been captured, whereas wireless connection provided more reasonable values. Ambient vibration results based on as-built environment provided higher frequency values in comparison to FEM because the stiffness provided by cladding, façade and walls eventually increased the system's stiffness, which cannot be revealed in FEM based on structural drawings only. The foremost concept of Model Updating is to have an ideal simulation of structure that can represent real structure behavior. The Final Updated model results founded satisfactory according to modal assurance criterion (MAC) value with 98.9% and frequency deference errors average of 7.6%.

DEDICATION

This thesis is dedicated to a number of people, without whom it might not have been completed, and to whom I am deeply indebted. To my parents and parents-in-law who supported me in every day of my journey and were always a source of love and encouragement. To my dear wife who remains willing to engage practically and emotionally in supporting my work and igniting my commitment. It is also dedicated to special friends and colleagues who were tremendously and continuously supportive. For them I extend my deepest gratitude.

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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

Strength, Safety and durability of complex structure such as towers and bridges play a very important role to societies economic and owners perspectives. In high rise buildings, it is very important to ensure adequate stiffness to resist lateral forces induced by wind or seismic or blast effects. These forces can develop high stresses and produce a sway movement or vibration that can cause a discomfort to the occupants. Concrete shear walls and columns which have high in plane stiffness with the floor contribution will act as a diaphragm in each floor that will displaced in its horizontal plan as rigid body (Figure 1). A structure is undergoing free vibration when it is disrupted from its static equilibrium position and then allowed to vibrate without external dynamic excitation. Analytical solution of equation of motion is usually not possible if the excitation applied forces or ground acceleration varies arbitrary with time and the system of the load applied is nonlinear. When we design a structure against earthquake and wind, one of the most recommended methods by design specifications is “response spectrum analysis” (Freeman, Nicoletti, & Tyrell, 1975) in which rather than time history analysis, maximum responses are estimated by this method. As structures aging and deteriorating over time due to creeping and shrinkage of concrete, the durability and structure serviceability have become a highly researched area (Baiant, 1975). Therefore, structure deteriorations need a repair and maintenance when needed. Building repaired at early stage will reduce cost of maintenance (Figure 2 and 3).

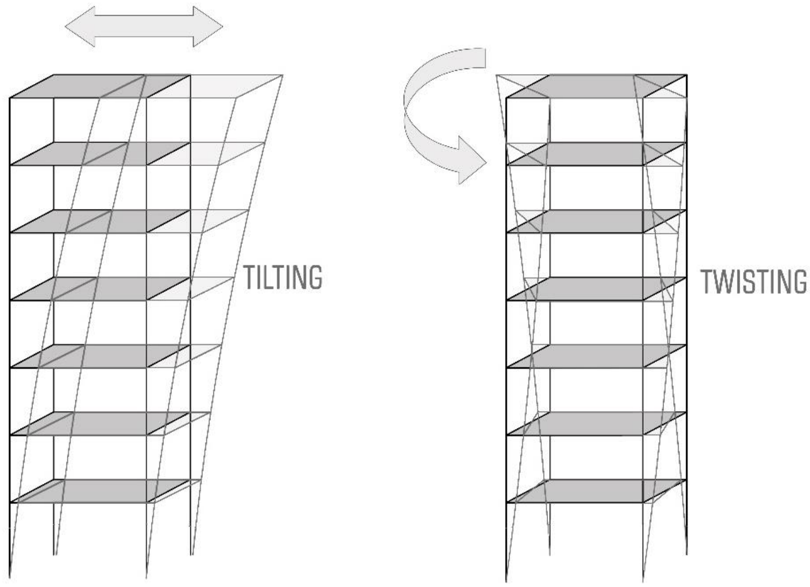


Figure 1. Diaphragms produce rigid body. ("World of Anti-Vibration Engineering.,")

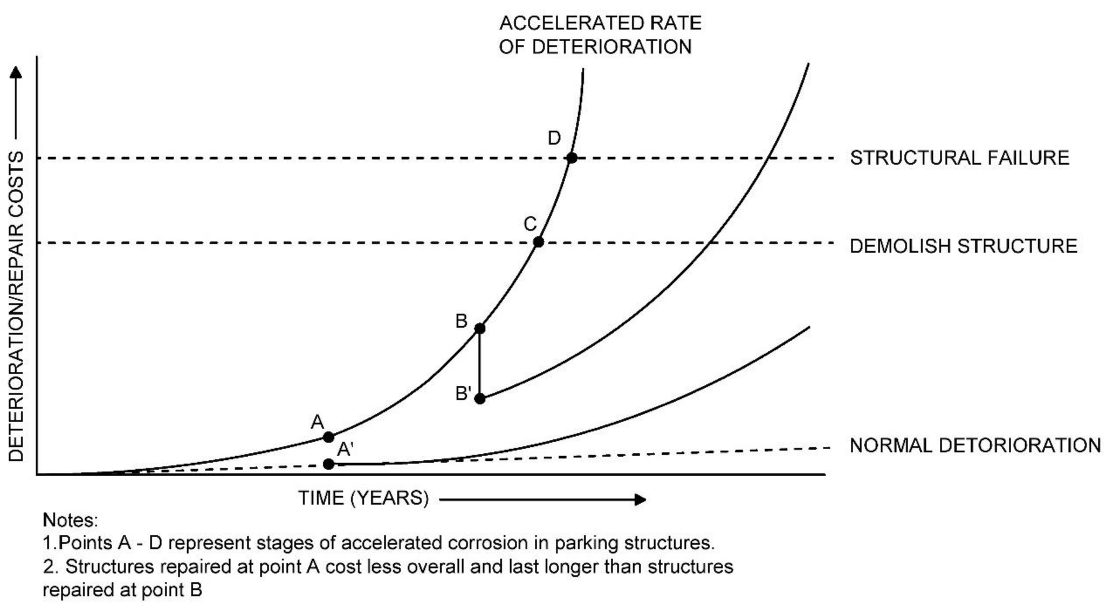


Figure 2. Point A – D characterize stage of acceleration of corrosion ("Effective repair and maintenance strategies for parking structures," 2015)

Figure 3. Concrete cracks deterioration. *(Baiant, 1975).*

1.1 Modal Analysis in Structure Vibration

To study structure vibration and analyze structure response to obtain modes, frequencies and modal parameters, engineers use two main methods: a theoretical sequence; and modal response sequence. The theoretical sequence for vibration analysis is demonstrated in (Figure 4) which clarifies the progress of a typical vibration analysis through three stages. In general, the analysis begins with the specification of the physical attributes of the structure, typically in terms of its damping properties, stiffness and mass, which are attributed to the spatial model. Subsequently, an analytical modal analysis is performed on the spatial model in which the behavior of the structure is denoted as a group of vibration modes, or otherwise, the modal model. The latter is, by definition, a group of natural frequencies with their analogous modal damping factors and mode shapes. The numerous ways in which natural vibration could occur in the structure are always described by this solution. The next phase reveals information about the excitation conditions. Obviously, this will be determined not only by the structure characteristics but also by the magnitude and nature of the exposed excitation and thus countless solutions of this kind will be available. Nevertheless, it is favorable to proffer a study of the reaction of the structure to a 'standard' excitation and to refer to this analysis as the *response model*. A unit-amplitude sinusoidal force (Kuroiwa, 1967) that is applied to the structure at every point independently and at each frequency within the indicated range might be a standard excitation. Consequently, the response model will comprise a group of Frequency Response Functions (FRFs) that should be determined over the pertinent frequency range (Ewins, 1984).

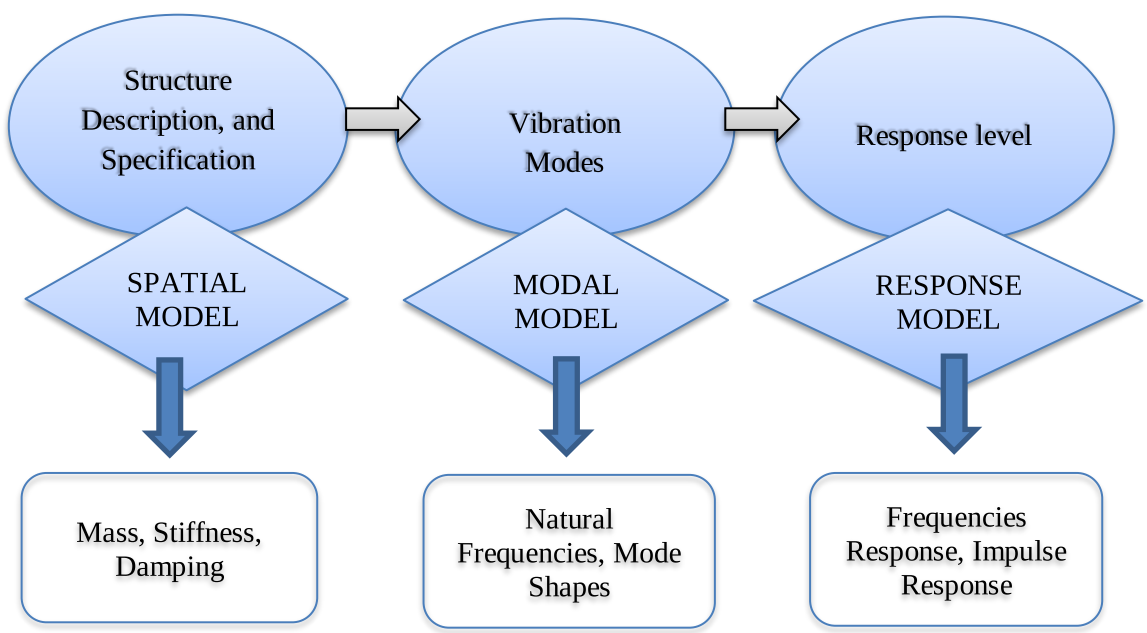


Figure 4. Theoretical sequence of Vibration Analysis.

Through this thesis study, attention will be focused on the three phases and forms of model – *spatial*, *modal* and *response* – then it is crucial to comprehend their mutuality as it is upon this property that the modal testing principles are originated. It is also viable to advance from the spatial model via the analysis of the response. As can be concluded from (Figure 4), an analysis could be undertaken reversely. Modal and spatial properties can be deduced. This, otherwise defined as the vibration analysis 'experimental route', is presented in (Figure 5).

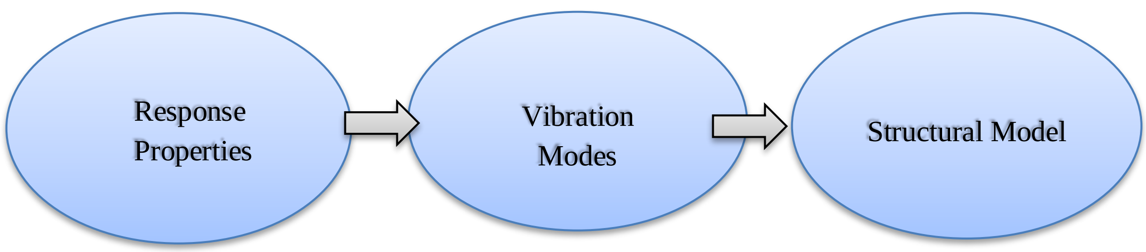


Figure 5. Modal Response Sequence (Operational Model Analysis (OMA))

1.2 Excitation in Model Analysis.

There are four categories of testing scheme: Single Input Single Output (SISO), Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO) and Multiple Input Multiple Output (MIMO). The subject of this study focuses on output-only modal tests which are of the MIMO type since there are assumptions made about the input. (Gul & Catbas, 2008). This paper, referring to peak picking method, uses the information that the dimension of (Frequency Response Function-FRF) becomes very high as it is approaching the same natural frequencies of the structure. Frequency response function expresses the tower or bridge response due to excitation force as a function of frequency (Brincker, Zhang, & Andersen) demonstrates the modal parameters of the structures such as damping, stiffness and resonance frequency situation with output data. FRF method can be categorized as time-domain and frequency-domain. Ren & Zong, 2004 state that the spectral density of ambient vibration of structure is used as another method of FRFs. (Frequency Domain Decomposition-FDD) has been used for ambient investigation to mitigate the frequency output from FRF by using the Singular Value Decomposition -SVD of the output spectrum matrix. This method also called Complex Mode Indicator Function - CMIF (Catbas et al.; Peeters & De Roeck, 2001).

In spite of the dissimilarities in terms of excitation, the same three steps involved in the typical input-output testing make up the output-only modal testing:

- Tests planning and execution: this phase involves defining the experimental setup (cable paths, attachment of sensors, sensor layout, measurement chain, etc.) as well as the data gathering parameters (sampling frequency, duration of records).

- Data analysis and the modal parameters identification: this stage encompasses validating and pre-treating (decimation, filtering, etc.) the collected data, performing several signal processing operations (e.g. for the computation of random decrement functions, PSD functions, transmissibility functions, correlation functions, etc.), besides estimating the modal parameters.

- Finally, Validation of the estimates of modal parameters.

In this field of research, three different tests used to identify the behavior of structure depending on the way of excitation used. Those types illustrated briefly below (Figure 6). The type of vibration forces demand according to the parameters that the research need to identify.

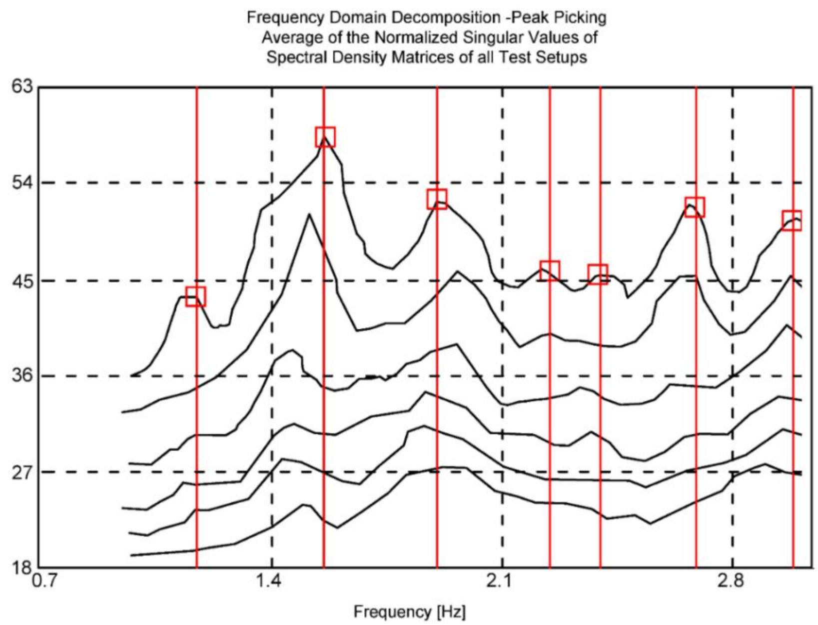


Figure 6. FRF and FDD - Peak Picking

1.2.1 Forced Vibration

Excitation of known force by a designed excitation machine such as hummers or mass shakers gives frequencies of interest and the Structure characteristics in any direction horizontally or vertically. The type of forces provided contains liner mass which is a liner force of steady state or eccentric mass that import sinusoidal force. This type of structure test should be in a closed environment in order to operate this kind of forcing and usually. Also, the size of structure must be modelled properly to have an accurate approximation of data analysis and results (Peeters & De Roeck, 2001).

1.2.2 Ambient vibration

This type of test is related to the unknown excitation of forces that are not under control. Data collection from the structure will give an estimate of the dynamics characteristic of structure and the main parameters. Excitation forces can be from sources like wind, seismic earthquakes, pedestrians and any activities that case vibrations of structure. This type of assessment is related to structures with lack of data and information and engineers use this type of test widely in real structure analysis because of the non-linearity systems exhibited in the real structure (Ivanovic, Trifunac, & Todorovska, 2000).

1.2.3 Free Vibration

Tests that contains an initial input that will impact a structure to introduce a change in an initial static equilibrium. The response is disrupted from the allowable freely movement of structure with no external force applied to structure during this free vibration. System will lose energy because of damping properties of the structure and the energy will decay. It is difficult to apply this test in a large structure and full-scale structures. However, modelling and testing will give a good indication of behavior of damping and frequency properties of the real structure (Mottershead, Friswell, Ng, & Brandon, 1996).

Inaccuracies associated with model setting and discretization result in modal parameter estimates that are, predominating, not completely reliable. Consequently, a numerical model does not usually represent the structure’s actual dynamic behavior; hence a correction is necessary to increase its reliability and proximity to the experimental observations. The correction is established according to the evaluation of the link between numerical and experimental modal properties' estimates as well as a guided model modification, with the aim of predicting the structure's dynamic behavior more reliably after the update. The model validation or otherwise, calibration guarantees increased accuracy in predicting the structure's vibration response to different stimuli and further reliability in evaluating the impacts of perilous natural or artificial events. Damage detection is one more typical use of the updated model (Teughels & De Roeck, 2004).

The estimated modal parameters help in forecasting the impacts of structural modifications as well as assessing several solutions for the vibration issue without going through the expensive costs usually accompanying actual interferences. Supposing that the structural modifications are adequately slight, a linear sensitivity analysis facilitates identifying the structure's most sensitive parts for applying the structural modification and solving the vibration issue. SHM and Damage detection are relevant fields of use of the identified modal parameters.

1.3 Experimental Modal Analysis (EMA)

Supposing that a structure's dynamic behavior can be seen as a group of modes, each one categorized by some parameters such as mode shape, damping ratio or natural frequency. This parameters values vary depending on boundary conditions, material properties and geometry which can be identified by Experimental Modal Analysis (EMA) using measurements of the vibration response and the applied force. Over the past few decades, ground-breaking inventive methods for understanding and controlling vibrations, design optimization as well as structures' performance and health state assessment have been provided by the system identification principles and the modal parameters' experimental estimation (Rainieri & Fabbrocino, 2014). Although the rapid evolution in computing technologies besides the Finite Element (FE) technique have made outstanding analysis tools accessible to the technical community, the innovation and advancement of high-performance materials and the structures' growing complexity have demanded powerful tools to validate and aid the numerical analyses. In this framework, identifying modal properties experimentally undeniably assists professionals to obtain in-depth physical perception about a structure's dynamic behavior and to differentiate between errors caused by discretization and those created by incorrect modeling assumptions. There are many examples of an EMA tests such as Impact Testing by measuring multiple inputs and their corresponding values from single row of Frequency Response Function (FRF) matrix. This impact inputs usually by using roving hammer (Figure 7) or also shaker test by using shaker device to measure multiple outputs and their equivalent values from single columns of FRF matrix (Figure 8) (Schwarz & Richardson, 1999).

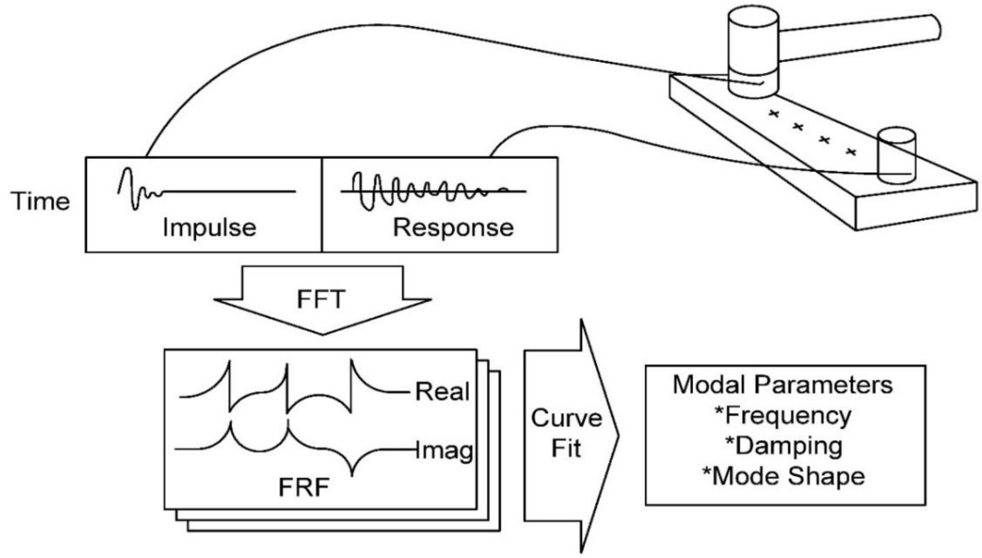


Figure 7. Roving hammer Test.

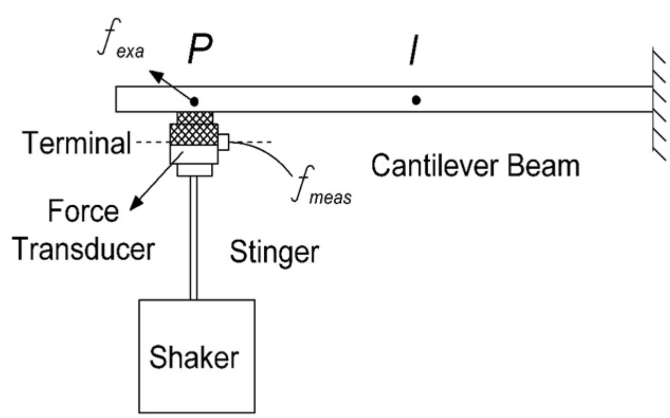


Figure 8. Shaker device Test.

Laboratory studies were conducted in many research papers to demonstrate the efficiency of the methodology. Researchers apply an excitation in a lab model and study the impact of these loads. This methodology can be extended to a complex and compound experiment structure.

Steel grid is usually used in many lab structure material studies (Figure 9) and the main purposes are to confirm the EMA methods, to discover novel technologies, and to standardize applications that can then be conducted on complex structures such as towers and bridges. The structure is generally designed to have the dynamic characteristics of bridges. The bridges sizes and dimensions vary from paper to paper such as (Burkett, 2005; Gul & Catbas, 2010). Put the most important thing is that researchers provide a comparison between lab test and finite element modeling by using software. Before applying force to study the impact and ambient vibration assessment a Finite Element method (FE) (Figure 10) was prepared to model steel grid in order to calculate the dynamic properties of the structure.

Figure 9. Steel gird testing (Gul & Catbas,2010).

Then, impact tests were conducted to confirm the ambient vibration results. The model bridges were excited by an impact hammer with random excitation on the structure generated by gradual hits in the model at different locations simultaneously. Then the acceleration data where taken by using the accelerometers sensors.

The analysis as mentioned before for all researchers was planned to be carried out until 150 Hz the preliminary (FE) model (Figure 10) after designing the models of bridges also shows that 0–150 Hz frequency range will be sufficient to obtain the modes exists on the model. The unscaled function were adjusted by an averaged data to mitigate problems when reaching the stage of FFT process. For example, leakage and miscorrelation of points (Fladung & Rost, 1997). After this iteration, the unscaled functions where used to FRF by taking FFT. This FRF data where used in CMIF and the CMIF curves where obtained for impact excitation and ambient tests. Plotting CMIF after RD mitigation where give an indicator of steady and smooth plotting in a very good correlation with a smaller amount of noise which give a clear resonance peaks. After that; researchers selected the peaks using CMIF curves. Then the damping ratio, natural frequency values, and mode shapes where obtained by FRFs. (Figure 10).

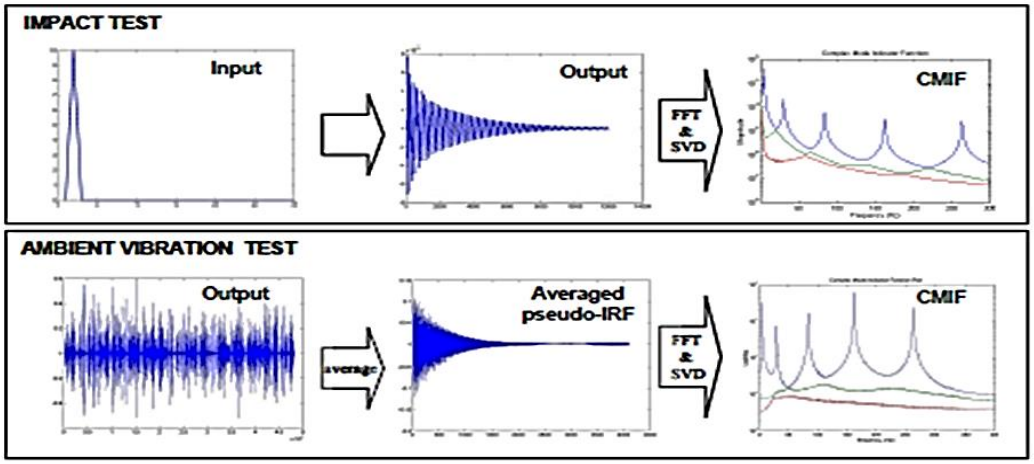


Figure 10: Reponses from impact and ambient tests (Burkett, 2005)

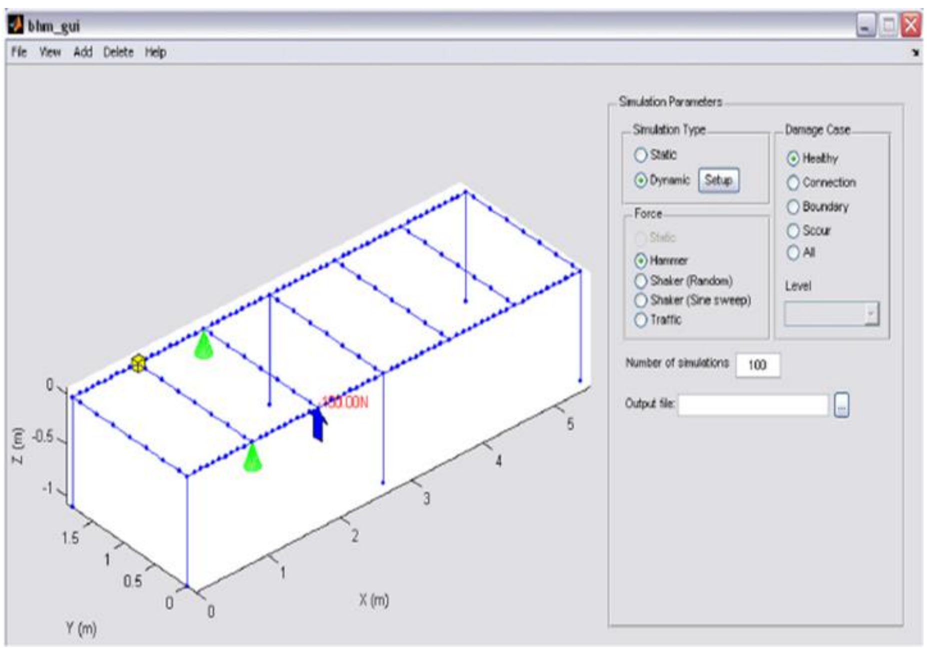


Figure 11. Finite element model for steel grid (Burkett, 2005).

Results of the FE model shows higher values more than experimental models, this happened because of the factor of safety with the known input in designs codes for real life structure. Noting that; Impact and ambient are a quick method that can supply us a good indications and results.

1.4 Operational Modal Analysis (OMA).

Basically, OMA is the modal testing method through which the structure's modal parameters could be experimentally estimated based solely on dynamic response measurements. The idea behind this procedure is to exploit the freely available natural excitation caused by ambient forces along with operational loads such as wind or earth quick to substitute simulated excitation. Accordingly, instead of being regarded as disturbance, they facilitate large structures' dynamic identification. Since this method prerequisite nothing other than the structure's vibration response measurements in operational conditions, while being exposed to the ambient excitation, OMA is also called "output-only modal analysis" or "ambient vibration modal identification". OMA is tremendously appreciated in the civil engineering field, since tests are fast and inexpensive, besides creating no interference with the structure's normal use. Additionally, the structure's actual behavior in its operative conditions is well represented by the identified modal parameters, since it uses natural excitation instead of artificial one. From research papers studied in this knowledge area, researchers and engineers apply methods of operational modeling to study structure health monitoring (SHM) and also to update finite element model from practical measurement collected from building under natural ambient vibration (Chang, Flatau, & Liu, 2003) (Park, Sohn, Farrar, & Inman, 2003).

Damping ratios of the structure when applying a forced impact and ambient tests are in good correlation where the values founded are smooth and reasonable and that correlation happened because of the mitigation for modes. The frequency varies among experimental approaches in research papers, however a comparison between (FE) and (impact and ambient) provide by each researcher (Michel, Guéguen, El Arem, Mazars, & Kotronis, 2010). The proposed method for unknown inputs perform accurate values of frequency and mode shape that is correlated with the results. Resolution of the FE model shows higher values more than experimental models, this happened because of the accelerometers absorption of energy and this issue will be mitigated in real life structure as a factor of safety with the known input case. Impact and ambient are a quick method that can supply us a good indications and results.

Experimental modal parameter identification and the data input and output were set in (Table 1) for 5 modes as an example of approaching the system frequency by impact and ambient method. This data is generally identified by methods for identification unknown modal properties of a system. Relationships between the experimental and numerical approaches for modal limitation have been addressed and in (Table 1) there is a good indication of the coloration between the data sets.

Table 1

Comparison of data output steel grid from different papers in (Laboratory Modeling, FE Modeling)

Grid/Deck Model Test Results By Korhan (Ciloglu, 2006)				**Steel Grid Model Test Results By Mustafa (Gul & Catbas, 2008)**				**Steel Stringer Bridge Modal Test By Catbas (Catbas Et Al.)**			
MODE	Impact (Hz)	Ambient (Hz)	% diff	MODE	Impact (Hz)	Ambie nt (Hz)	% diff	MODE	Impac t (Hz)	Ambie nt (Hz)	% diff
1	5.04	5.05	0.19	1	22.37	22.38	0.04	1	1.64	1.69	3.04
2	7.8	7.8	0	2	22.70	27.03	19.07	2	1.9	1.86	-2.10
3	17.84	17.97	0.72	3	33.38	33.44	0.18	3	3.69	3.7	0.27
4	22.29	22.44	0.67	4	40.91	40.96	0.12	4	4.86	4.97	2.26
5	28.09	28.59	1.78	5	64.93	64.88	-0.07	5	5.33	5.28	-0.93

Researches provided an understanding about model dynamic testing by using software as finite elements modals with all known data of the structure as computerized simulations. Then, comparing this data with a model of the same structure in lab with an excitation of known forces using necessary calibration and mitigation to simulate actual structures, after those comparing results with another test using unknown forces excitation on the same modal. Therefore, after those three tests, a full-scale testing were shown in (Table 1) a collection of date that give a proven truth about structural performance without known of the energy of excitation and the stiffness of structure. This evaluation gives a way to use it as advanced assessment of structural condition, detection of damage, dynamic performance and structure health monitoring with an unknown stiffness and unknown excitation in real structures construction quality, validation of design assumptions, and also as lessons for future design and construction of similar structures.

Furthermore, as the vibration response arises from modes, that are mainly properties of the structure, enormous vibration responses are yielded by magnifying loads at resonant frequencies, which can cause damage or discomfort. Identifying modal parameters regularly as well as analyzing their variation can aid the structural performance and integrity assessment. Thus, lately, the attention of civil engineers has been more concentrated on the opportunities which Operational Modal Analysis (OMA) provides.

Kaynardağ & Soyoz, 2017 , represent a model study for 26 floor building in Istanbul constructed based on design drawings and updated to optimize the actual mode shapes and frequencies of the building. Results present that frequency from ambient test were less than frequencies obtained from FE model and the updated FE model had an Error percentage of 1.5%.

FE modeling and ambient vibration tests were used to test two towers commercial building in Shenzhen city (Zhou, 2008) and the dynamic characters and natural frequency of the buildings have been obtained and results from the updated model shows a percentage error of 1.8%. It can be realized that the stiffness of the structure is larger, if we compare it with FE model by 1.7 times. This increase in stiffness provided by wall, façade and other facilities

Brincker, Ventura, & Andersen (2003) , demonstrate the possibility to use ambient vibration as a modal identification technique to modify and improve FE model on fifteen story building. Author present a behavior study for two high-rise building located in Vancouver. Modes shape, Natural frequencies and damping were determined experimentally and analytically using FE. Frequencies for ambient vibration value is

0.68Hz and for Finite element model is 0.402 Hz for both testes.

From this paper and as shown in table 1 before, the period values obtained from FE modeling are larger than ambient vibration and this because of the assumption during FE modeling such as moment of inertia were assumed to be constant however its varies in columns weak axis. Furthermore, the density and stiffness parameters for the building seem that it was overestimated. This conclusion from author perspective highlight our assumption that FE model will give us a lower frequency as stiffness provided by cladding, façade and walls eventually will increase system stiffness that cannot be reflected in FE modeling based on structure drawings only.

As features of SHM expanded in last few years, engineers decided to design sensors to measure more than the structure behavior. Such as wind characteristics, guest factor, wind spectrum, turbulence intensity and also concrete settlement (Xua, 2000). This paper studies the wind characteristics and structure deformation in Typhoon York building located in Hong Kong - 69 stories reinforced concrete -. The validation of structure properties in this research allow the author to evaluate the response of the structure during earthquake. Displacement and deformation where measured from two university as the following table (Table 2).

Table 2

Typhoon York behavior study from two university (Hong Kong, Tsing Hua)

Hong Kong Polytechnic University,			
Ambient Test	Lateral	Longitudinal	Torsional
Frequency	0.170 Hz	0.201 Hz	0.280 Hz
Damping	1.07%	0.99%	1.36%
Tsing Hua University			
Ambient Test	Lateral	Longitudinal	Torsional
Frequency	0.178	0.210	0.298
Damping	1.02%	0.96%	0.78%
FE Model			
Frequency	0.186	0.201	0.370

Frequency Domain Decomposition (FDD), Random Decrement Technique (RDT) and Basic Frequency Domain (BFD) where used to identify the structure behavior in (Lorenzo, Mercerat, d'Avila, Bertrand, & Deschamps, 2015) these three methods are techniques in Operational Modal Analysis (OMA) depending on ambient vibration testing. The authors in this paper present results from FE and ambient vibration in tall building that have 22 story Reinforced concrete - located in Nice, and results error were less than 2%.

1.5 Modal Analysis Preliminary Concepts

In order to elucidate the comprehensive context of the notions demonstrated in this research and to set some terminology, an introductory discourse about systems and signals is undeniably worthwhile. The indispensable cultural background prerequisite to approach the discussion of OMA is obliquely defined by the summarized concepts about structural dynamics, signals and systems.

A signal, by definition, is any physical quantity that is dependent on a single or numerous independent variables and linked to data of interest. An input signal is converted into an output signal by a system. Significant information about a system could be revealed through plotting the response to a certain stimulus. For example, analyzing a building's swinging (output signal) due to wind load, which can be considered an input signal, supports and facilitates the study of the modal specification of the structure. Problems in engineering are typically classified as forward problems; they intend to approximate the response of a certain system to a particular input. Nevertheless, the focus of this research is on another type known as inverse problems, where neither the system characteristics nor the input are unknown but the output is known. Specifically, this study examines the identification of the system characteristics given the output signal (besides several assumptions regarding the input). (Rainieri & Fabbrocino, 2014)

Noise is a term that denotes any unsought signal that overlays the desired signal. The noise amount in a signal is measured by the Signal-To-Noise Ratio (SNR), in decibels (dB) as follows:

$$SNR = 20\log\left(\frac{A_s}{A_n}\right) \qquad \text{Equation 1.5.1}$$

where A_s stands for the signal amplitude and A_n refers to the noise amplitude, both expressed in the same units. When the value of signal-to-noise ratio is small, the desired signal can become indiscernible. Hence, proper data gathering approaches should be implemented to diminish the noise level that inescapably impacts measurements. (Johnson, 2006).

Generally, structure's dynamics can be defined and expressed in terms of its stiffness, mass and damping properties, or in terms of the properties of its vibration (mode shapes, damping ratios and natural frequencies) or, otherwise, in terms of its response to a particular stimulus.

1.5.1 Frequency Response Function (FRF)

A frequency response function expresses the structural response to an applied excitation as a function of frequency. When a structure is subjected to any excitation, the period of the response will be different than that of the excitation. The phase variation among the response and the excitation will be different according to frequency. The characteristics of the structure that explain its response to excitation as the function of frequency is the Frequency Response Function H(f) define as the proportion of the compound spectrum of the response to the compound spectrum of the excitation (Figure 12) (Gentile; Lorenzo et al.; Rainieri, Fabbrocino, Cosenza, & Manfredi).

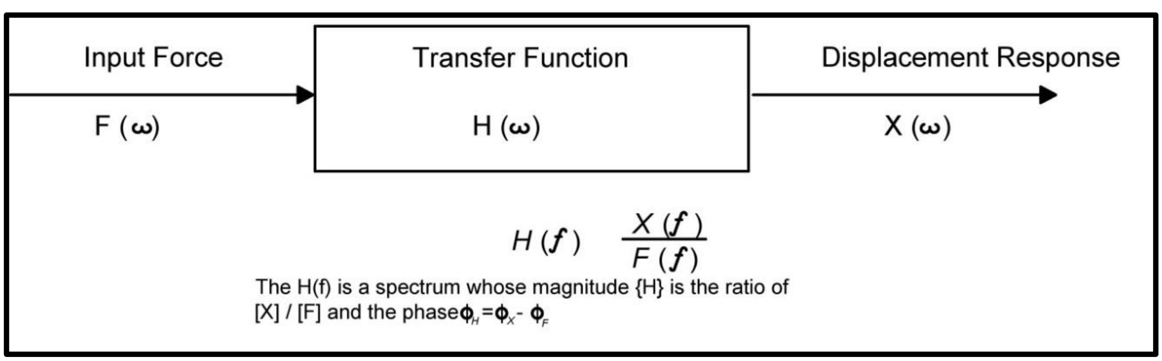


Figure 12. FRF Spectrum

1.5.2 Frequency-Domain Decomposition FDD

The Frequency Domain Decomposition (FDD) method is identified for operational modal analysis of structures, used as the modal data in a system for structural health monitoring (Brincker, Andersen, & Jacobsen) it is a basic technique that is very easy to use. Only choose the modes by locate the peaks in the Singular value decomposition (SVD) plots of responses .As the FDD technique is based on using a single frequency line it can predict frequencies and mode shapes and as well enable damping evaluation.

1.5.3 Signal Processing and data sampling:

Fast Fourier Transform (FFT) converts a uniformly tested time waveform signal to corresponding Digital Fourier Transform (DFT). It is worth to mention that sampling time domain shall be calculated based on frequency range of building that need to be captured before starting test experiment. As FFT assumes sampling time contains of N uniformly spaced in time domain related to the following equation:

$$\mathrm{T} = \mathrm{N} \times \mathrm{delta\ t} \qquad \text{Equation 1.5.1}$$

Digital Fourier Transform (DFT) the DFT contains (N/2) evenly spread out data of composite (phases and magnitudes) resolution or time spaces between frequency denoted as delta frequency as the following equation

$$\text{Delta f} = 1/T \text{ (in Hz)} \qquad \text{Equation 1.5.2}$$

This equation represents a sampling length window of T corresponding to resolution of delta f set that need to be measured.

1.6 Operational Model Analysis - Practical Application

1.6.1 Structure Health Monitoring (SHM)

(SHM) promises a new technology to test and analyze the behavior of structure mode excited by any load that cause the structure to deform. This technology will provide an important information for engineers to study the ductility and durability of structure (Abdelrazaq,2010). It is a development of mathematical models to characterize behavior of unknown forces and data by means of experimental data. The best practice now a day is a dynamic testing for condition assessment and damage identification of existing structures. A structure will act as rigid body when dynamic analysis treats forces motion. Structural Health Monitoring consists of sensors such as accelerometers displacement transducers that have to be installed in the structure to collect all data, thus data will be transmitted to a computer of server to analyze them with a software in order to approach an assessment strategy for the structure depending on their mode shapes and the behavior during the excitation of loads. This methodology called ambient vibration resting where the data required such as forces excitation or stiffness of the structure are not available. (Birtharia & Jain, 2015)

SHM is classified into two groups:

1- Short-term monitoring in short time as temporal inspection of structures

2- Long-term monitoring for a long period or continuous investigation of structures.

While long-term monitoring is applied in highly important structures such as cable bridges, plants, high-rise buildings and nuclear power, it is also necessary to apply short-term monitoring for complex building structures such as towers. Maintenance activities should achieve numerous stages of tests and inspection periodically. Temporal inspection sensors usually installed at structure to identify structure behavior in various level of periodically inspections where the most concern values obtained is damping, natural frequency and mode shapes.

Burj Khalifa in Dubai is a good example of a tower with SHM scheme. A dozen of sensors distributed along the height of the tallest building in the world (Abdelrazaq,2010) in order to measure by time ambient vibration impact and also temperature changes effect on structures elements.

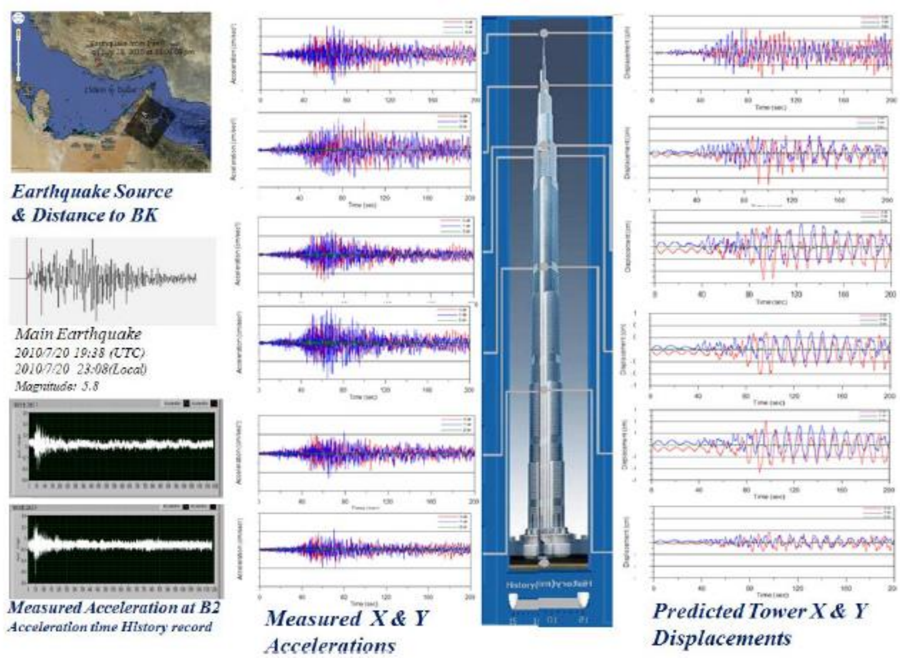


Figure 13. Sample of measured acceleration at all levels of Khalefa Tower (Abdelrazaq)

1.6.2 Damaged detection methodology

According to the examination of the variations in the modal properties estimations, the foremost downside of damage detection procedures is associated to the impact of environmental, operational factors and boundary conditions on the estimates. The structure's integrity can be evaluated, theoretically, by comparing the subsequent estimates of modal parameter with the reference estimates. Over the past decades, the techniques of structure damage assessment based on vibration have been successfully developed so that they not only identify the damage presence, but moreover quantify and localize it. Comprehensive reviews about these methods are presented in literature. (Doebling, Farrar, Prime, & Shevitz, 1996; Farrar & Worden, 2012; Park et al., 2003)

One more pertinent constraint to the widespread use of these damage detection methods was the absence of completely automated techniques for estimating the monitored structure's modal parameters.

Researches and recent papers –cited in this literate review - present a methodology to analyze and assists real life application structures using data collection from ambient vibration tests and laboratory testing by combining Complex Mode Indicator Function (CMIF) method and Random Decrement (RD) method, develop an estimation of location and identification monitoring and controlling system of damage of an existing structure during structure life time. Damage discovery is an extremely critical aspect of SHM. Damage detection in the circumstance of SHM can utilize a collection of strong and practical damage detection methodologies to classify, trace, and compute damage or changes in apparent performance. Also, it can enhance and build a world class expertise with a full-scale modeling of behavior dynamics of structure with its corresponding mode shape. This kind of analysis will give an indication of structure stiffness and energy loss depending on the response and the change of mode shape in a function of time. Exploring elements behavior from the mode shape of a structure such as shear wall and columns behavior under forces and lateral excitation, will give engineers a full vision on how the building elements react with the excitation and whether there are any serious drifting of displacement that need to be calibrated. Hence, this method will work as a mitigation plan before disaster may happen. Using the theoretical background design and the situation existing in life time of structure mode shapes will aid engineers to improve the structural design methodology, particularly in controlling sway-drifting and longtime deflection.

The unscaled flexibility matrix is used to establish deflection profiles of the laboratory experiment structure for healthy and damaged situation such as in this research paper (Fladung & Rost, 1997). However, in towers and tall buildings, the design complexity is being overcome by the availability and advances in programming and structural analysis tools as the minimum code requirement still controls the design that yet have to be validated in full scale. In this case, real value can be optimized with ambient vibration measured because modeling in lab will be a time consuming to get a reasonable accurate measurement as in real life structure.

Structural Health Monitoring systems use a network of sensors (accelerometers) connected to an input data analyzer to monitor and measure response spectrum and dynamic parameters of the building. When the Input data from ambient vibration and other climate factors response parameters exceed updated finite element model design values, the system will alarm warning signals. As the updated model, that has incorporated data and information, system will routinely interrogate data and simulate building response spectrum during and after damaging event. In this stage of testing, the system will capture response deference and will provide detail, detect, localize, and analyze damage in structure. (Figure 14)

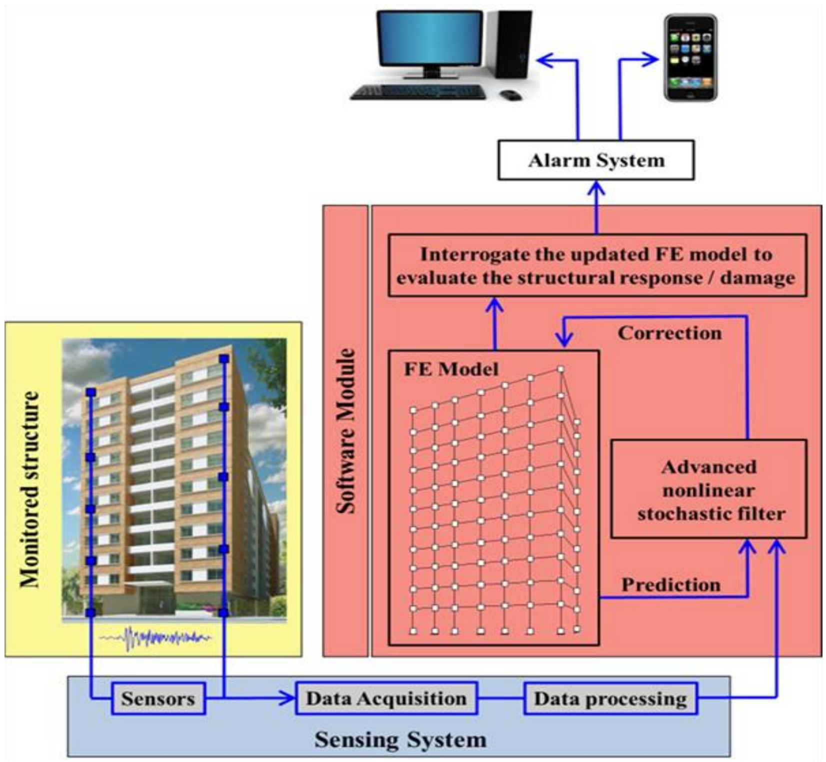


Figure 14. SHM and Damaged detection system

("Model-based System for Rapid Post-disaster Health Monitoring and Damage Detection of Civil Infrastructure," 2015)

1.6.3 Historical Building health Assessment

Architectural Heritage Conservation is a cultural necessity that has been a central concern in the cultural background of humankind, arising from buildings' historical value. Modern societies view ancient buildings as icons of culture and diversity and strongly believe that their existence should be eternal. However, this demand poses high difficulties to everyone since deterioration is instinctive to life. Bell towers, masonry towers and historical religious buildings are examples of the most endangered erections because of their age, slenderness, monumental height and the presence of significant dead loads that make them extremely susceptible to dynamic forces. Particularly, the preservation of historical masonry towers and the evaluation of their structural safety have become exceptionally critical, possibly due to the several tragic collapses recorded in Europe, including the abrupt collapse of Italy's Civic Tower, collapse of the bell tower of St. Magdalena church in Germany in 1992 and the collapse of the Campanile, in 1902 in San Marco Square, Venice. (Binda, Gatti, Mangano, Poggi, & Landriani, 1992; Lionello et al.) More recent examples of dramatic deteriorations include renowned structures such as Venice's St. Stefano bell-tower and the Civic Tower in the Italian city of Vicenza (Valluzzi, Da Porto, & Modena, 2003).

Cities in Europe are characterized by a high density of historical, globally renowned edifices. The majority of these buildings are still functional, but demanding regular maintenance. Basically, the notion behind vibration-based health assessment, which was founded in the late 1970s, supposes that the irreversible modifications in modal are a consequence of structural damage. Actually, dynamic theory of structures asserts that the existence of any damage impacts the structure's stiffness damping, resulting in a diverse vibration response.

Figure 15.a. Cathedral of Monza (Modena et al., 2004), 15.b. Trabzon, Turkey (Bayraktar, Türker, Sevım, Altunişik, & Yildirim, 2009), 15.c. University of Coimbra (Modena, Lourenco, & Roca, 2004)

For structures, FE model must offer an advanced diagnosis level since it could be applied in structural safety evaluation under service loads, prediction of the structure's performance under extraordinary loads (for instance, earthquakes) and simulation of the impacts of repair interventions or structural changes. Whatever the case may be, a numerical model should be corrected or validated using previous acquaintance.

Thus, in such interdisciplinary structural health evaluation approach, permanent vibration monitoring must not only be merely introduced but must be regarded as a vital solution. In reality, due to the numerous benefits of ambient dynamic monitoring, it seems to be the perfect method to procedurally complement the tests carried out to evaluate historic buildings' structural safety. More precisely, vibration monitoring is the only approach to acquire worthwhile data (in terms of modal parameters) on the structure's inclusive dynamic behavior, providing an accurate and effective model validation preceding its application in upcoming numerical analysis.

Regardless of this, a protocol regarding long-term dynamic monitoring for civil or historic structures does not exist yet neither in the national code nor the international codes or other manuals. Hence, because of the extreme challenges that face long-term vibration monitoring which demand considering a variety of factors, codes and references are a serious necessity, particularly for historic infrastructures and structures because of their inherent complexity.

Nonetheless, it is worth mentioning that long-term dynamic monitoring of cultural heritage structures and historic buildings is a relatively new subject that is rarely completely investigated in literature. (Binda et al., 1992; Lionello et al.; Valluzzi et al., 2003) Particularly, a close agreement between experimental and theoretical modal parameters was achieved for comparatively low values of the model Young's modulus in the highly impaired tower regions.

Moreover, the vibration-based model updating, done through two different methods, resulted in steady structural parameters (distribution of Young's modulus in the masonry) which are in good match with the double flat-jack tests results.

Because of the good relationship between theoretical and experimental models, the modified model seems to be sufficient to deliver trustworthy forecasts to evaluate the tower's structural health, which is principally important bearing in mind the vastly inhomogeneous materials (cycloptic concrete and stones) that make up the tower itself. Dynamic tests are typically repeated by researchers after the strengthening so as to examine the relationship between the changes in the structure's modal parameters and the repair. As the cracks have advanced gradually throughout the years, a material's potential time-dependent behavior can be assumed due to the weighty dead load, besides wind actions and temperature variations (Modena et al., 2004).

1.6.4 Updating FEM model During Construction stages

As operational model analysis and structure health monitoring structure have received a tremendous attention those days due to the possibility of identifying structure dynamic properties using the ambient vibration forces, structure engineers assume input signal as a noise to drawback a methodology to capture peaks in input spectrum to evaluate structure modes and natural frequencies.

There is no doubt that finite element method (FEM) using advanced modeling software is the dominating analysis strategy in most of designs consultant's offices. However, structure design engineer has to accept various simplifications and assumptions based on minimum code requirements of the real construction in geometry, masses, stiffness, elasticity, loads, and other limitations during the stage of design. This is actually happened because the level of details to get the exact structure simulation will take an extensive amount of efforts, time and expenditures. For that reason, it's significant to monitor, control and analyze calculation during construction stage by implementing on-site measurements. This step will make sure that the simplification and assumption during design stage will not disrupt building response criteria. And also, to update and validate structure design during construction planning.

Response by ambient vibration will primarily respond in natural building frequency and fundamental modes (Zhou, 1999). This hypothesis might be established by many case studies, for example (Chintalapudi et al.; Wu & Li, 2007). Consequently, to know fundamental frequency does not need destruction or costly dynamic testing process but still it offers a valid technique aimed to check assumptions and simplifications during design. Abdelrazaq,2010, as tower shape is not symmetrical per floor and also the difference between center of gravity and stiffness center. It's very important to track building movements as this tower is the highest structure in the world any minor movements different than design in any level of the building will facilitate a major consequence later on.

Monitoring building response during construction implemented in many towers like Shanghai Tower, Ruihua Tower, and Di wang Tower and Canton Tower. Engineers consider monitoring the response for both scenarios, during construction phase and also for a long-time period to do the regular maintenance and damage deduction analysis (Chang et al., 2003; Ko & Ni, 2005; Moyo, Brownjohn, Suresh, & Tjin, 2005; Ni, Xia, Liao, & Ko, 2009; Park et al., 2003)

1.7 Motivation and Focus of the Thesis

Skyscrapers are nowadays omnipresent in the skylines of wealthy modern metropolises. Within the past few decades, these soaring buildings have reserved positions in the most Arabian Gulf cities such as Doha, Kuwait, Dubai, Riyadh, Abu Dhabi and Jeddah. Yet it is undeniable that the dizzying heights of skyscrapers predominantly denote mankind’s profound desire to declare technological force, power, progress, and wealth, in addition to mirroring countries’ prominent positions on the international political and economic stages. The commercial rivalry that created the skyscrapers in Doha was mainly concerned with national branding and image-making, reflecting the city's modernity and development.

Qatar Projects have expanded a lot and the number of high-rise buildings and complex structures are increasing. Government in alignment with its corporate strategy that outlines its direction and the operational procedures which need to be followed in order to achieve the Qatar 2030 mission and vision.. These visions focus not only on the upgrade and maintenance of existing national assets, but also on the development of major new building projects across Qatar.

Literature and research regarding vibration analysis of Doha towers is undeniably lacking. In an attempt to fill this gap, this study scrutinizes the behavior of - *Sinyar Tower*, in which studies and test results caused by ambient conditions and wind conditions were used to find out structure modal parameters to validate and update structure finite element modal according to structure design specification and structure drawings. The purpose is to study dynamic properties of the structural system with output OMA techniques by using wired and wireless accelerometers in order to update finite element model (FEM). By updating FEM, engineers are enabled to support clients to make quick and correct decisions in extreme emergency situations in the case of boundary conditions and excitation changes, during a structure's service. This evaluation gives a way to use it as advanced assessment of structural condition. Mode shapes, natural frequencies, modal damping ratios were studied, while the results of tests carried under ambient conditions and wind conditions were used to update the Finite Element model. Thesis concluded that FEM updating is important as values from full-scale testing provides higher frequency values in comparison to design. This mainly because of design codes factor of safety and also the stiffness provided by cladding, façade and walls eventually increased the system's stiffness, which cannot be revealed in FE modeling based on structural design only. Furthermore; wired sensors are not practical for high rise building.

Figure 16: Sinyar Tower 1/3

Figure 17. Sinyar Tower 2/3

Figure 18. Sinyar Tower 3/3

CHAPTER 2: FINITE ELEMENT MODEL (FEM)

2.1 Model Description – Al- Sinyar Tower

High rise buildings in general are considered as one of the important factors that affect the economy of the country and showing the power. Furthermore, generate office space, living space on a smaller piece of (mostly expensive) land. Improvements in economy, jobs, trade can be achieved through those projects.

Concrete building is ideal in Arabian gulf because of the concrete resources availability in the local markets and also the availability of qualified concrete structure engineering, this study focusing on Al-Sinyar Tower that contain 2B+G+52 floor used mainly for residential and hospitality as Hilton hotel apartments in Al Dafna Doha / Qatar. Al-Sinyar Tower has a total area of 74,747 sqm. With a total of 340 service apartments, and 7 Passenger/customers elevators and it’s the highest residential tower in Qatar.

2.1.1 Location of the Tower

Al Dafna is a seaside region in Doha/Qatar located on west Bay. As the huge number of skyscrapers in this area it considered as one of the greatest prominent regions. Since 1980s, Qatar government focused in Al Dafna to develop and create a business region district. This start with a huge land renovation along Al Dafna coastline.in 1990s dozens of skyscrapers have risen in this district and recently this area becoming a new center to Doha. (Figure 21)

Figure 19. Al Dafna/Qatar

2.1.2 Structure Specification

The structure arrangement contains flat slab (reinforced concrete with drop panel to transfer loads to beams. Central core walls, boundary columns mounting the floor concrete system and boundary beams. This is the main Skelton of Al Sinyar structure, columns and core walls were introduced with different sizes along the tower height to reduce structure dead loads and also to control story drifts (Table 3).

Table 3

Tower area and floors

Total Plot Land Area	3,394.00 SQ.M	Height: To Tip	230 m / 755 ft
Average Floor Area	1,288.04 SQ.M	Floors Above Ground	53
Total building Area	19,907.32 SQ.M	number of Apartments	340

2.1.3 Tower Design Aspects and Techniques:

The Construction and Design of high rise buildings involve two main aspects: safety and severability. As in any building structure self-weight loads increase vertical with respect to building height and lateral loads large effect coming from horizontal wind-load. Tower behavior under the lateral loading distribution work as cantilever fixed at the ground (Figure 22) Wind uniform distribution growth in quadratic manner with the elevation which gives uniform larger base-moment. High-rise building designers design buildings to be able to absorb the lateral loading and to transfer resulting moment throw building lateral elements system into foundation.

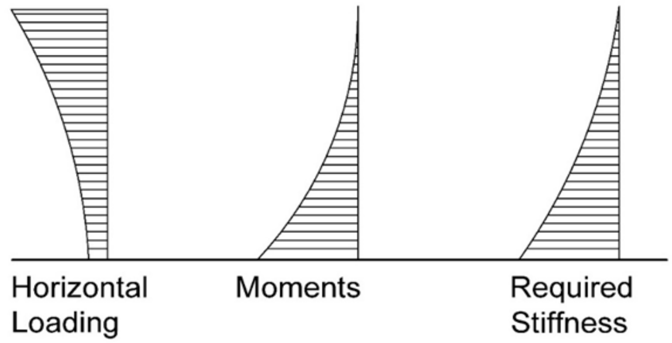


Figure 20. Moment and Horizontal loading disruption

The most effective way to achieve this by vertical walls this is the most popular way used in tower designs in Qatar. Though, with the consideration of tensile stresses concrete walls designers use building self-weight to minimize tensile stresses by slabs, beams. Etc. to increase compressive stresses. Al-Sinyar Tower façade transfers wind load to slabs that works as diaphragms. Its worth to mention here that slabs system in Al-Sinyar are flat slabs with a drop beams without any posttension tendons. However most of towers in Doha used Posttension slabs to decrease structure self-weight as steel tendons provide more compression stresses into concrete slabs and increase steel tension stresses.

The horizontal load from wind working as a distributed load on the facade, which transfers the load to the slabs that works as diaphragms to delivers lateral shear loading too the vertical system (Figure 23). The shear forces in the diaphragms occur mainly in the concrete because of its in-plane stiffness.

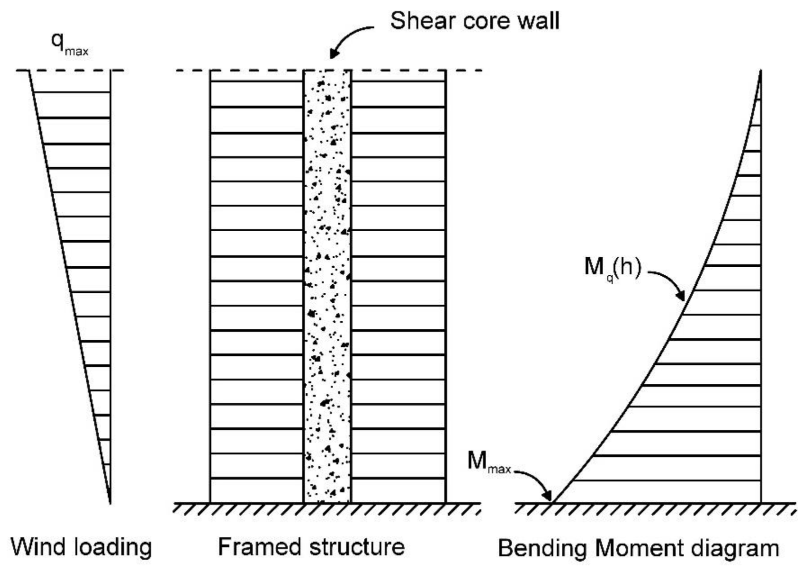


Figure 21. Tower shear core under wind loading

2.1.4 Tower layout

The building has 52 stories, and two basements underground. Concrete core walls and columns continuous along the height of the building. The structure layout plan with its double symmetry where tremendously effective for lateral load resistance. Structure has no outrigger trusses walls, and no column transfer girders. As the structure behavior under wind load can be seen as a cantilever beam fixed at the ground, Walls are structurally linked and contribute in resisting sway deflection (Figure). Walls and columns sizes reduced when going higher to reduce the total gravity loads. Coupled-bearing walls where used as their ability to absorb lateral loading to transmit moment from building to foundation. Stresses caused by tensile stresses from walls where treated with self-weight flat slab placed on walls to introduce compressive stress. Floor-to-floor height is typically the same for all levels expect lobby and mechanical floor. Floor Height equal 3.5 meter and the Tower flooring system typically framed with 300mm thick reinforced concrete flat slab surrounded with boundary beams with two sizes (1.20x0.45 m) and (1.00 x0.45 m). It is worth to mention that tower still under construction stage and progress of work approximately reached 90% as the contractor work in finishing and façade elements installation. (Figure 22)

Figure 22. Floor 52 during Construction stage

2.1.5 Modules elasticity used in FEM

As consultant design aspects to use ACI code 318-08 (metric) and ASCE7-05 to design and analyze structure members, the modulus of elasticity has been calculated based on the following equations: -

- For normal weight concrete with a density of 2300 kg/m^3, ACI Section gives the modulus of elasticity as

$E_c = 4700\sqrt{f_c'}\ Mpa$ Equation 2.1.5.1

- But ACI Committee 363 [3-8] proposed the following equation for high-strength concretes (50 Mpa and more)

$E_c = 3320\sqrt{f_c'} + 6895\ \ Mpa$ Equation 2.1.5.2

2.1.6 Tower Concrete grades and specifications

Grade of concrete is indicated as C50/20 in which 50 is the cube strength of concrete in N/mm2 and 20 is the nominal maximum size of the aggregate in mm as per code BD 5328.

The following table shows concrete grade distribution (Table 4).

Table 4

Concrete Grade distribution

For suspended slabs & beams
Cement - ordinary Portland cement (OPC)
Grade – From B2 to L20 is C50
From L20 to Roof C45
For Wall
Cement - ordinary Portland cement (OPC)
Grade – From Raft to L10 is C70
From L10 to L25 C60
From L25 to Roof C50
For Columns
Cement - ordinary Portland cement (OPC)
Grade – From Raft to L20 is C70
From L20 to L30 C60
From L30 to Roof C50

2.1.7 Reinforcement strength for structure elements

Reinforcement high yield stress = 460 N/mm2.

A summary of concrete grade and strength can be demonstrated in the following (Figure 25).

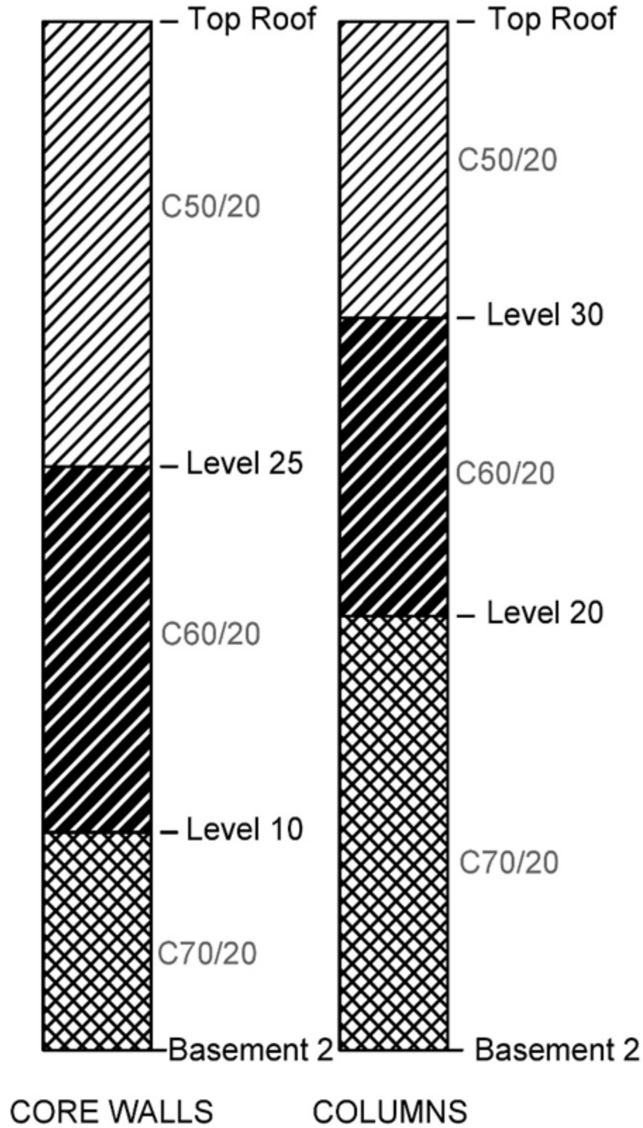


Figure 23. Summary of concrete grad and strength

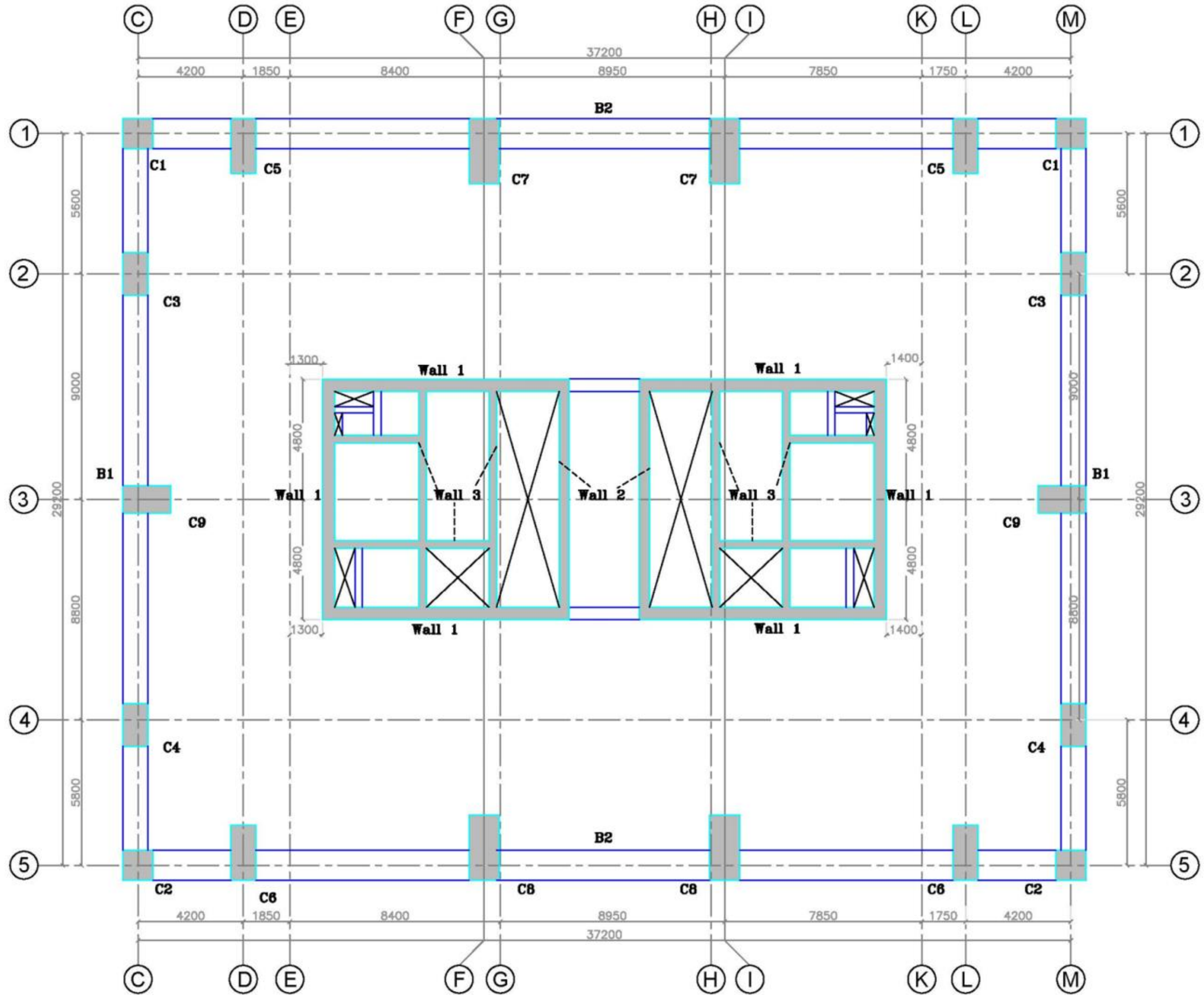


Figure 24. Structural Layout

2.2 FE Modeling Process for Al Sinyar Tower

Finite element method (FEM) uses many elements in any continuum analyzing. As the number of used elements increases, the time and effort required to prepare the relevant and necessary data and interpret the results increases. Meshing is performed to discrete the geometry created into small pieces called elements the rationale behind this to divide (meshed) a body or a problem domain into small elements or cells using a set of grids or nodes, the solution within an element can be approximated by simple functions. In the building industry, the use of advanced finite element tools has not only allowed the introduction of innovative and efficient building products, but also the development of accurate design methods.

SAP2000 model was used in this thesis. This program represents objects as a physical structure member by using graphical interface. It is a user-friendly program that provide users drawing tools to draw structure members, assigning properties and load to the members to fully define an FE Model (Figure 27).

When running Program analysis, program automatically renovates objects to elements according to certain meshing criteria defined by user in order to facilitate analysis to create a traditional FE model. The impact of analysis will be represented in model geometry as deformation shape. Sap2000 have the following terminology:

- Static and dynamic analysis
- Dynamic seismic analysis and static pushover analysis
- Linear and nonlinear analysis

2.2.1 Model Geometry

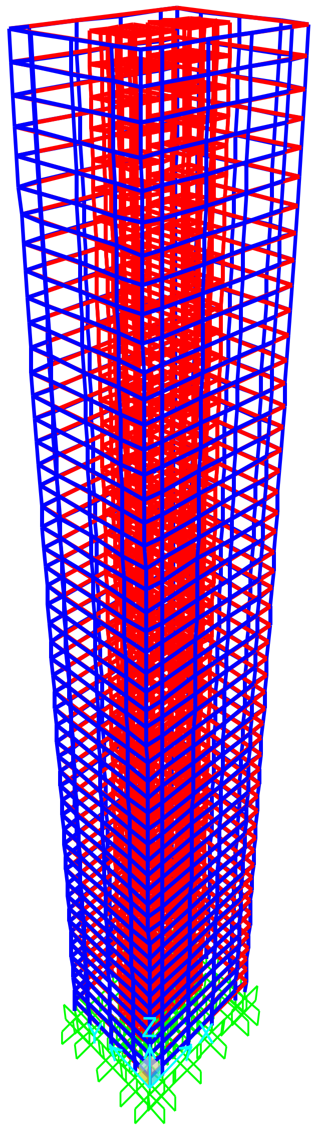


Figure 25. FEM MODEL

SAP2000 Model of Al Sinyar Tower contain all components that effect mass, forces, strength, dynamic, deflection and also stiffness of building. Building effective elements consists of beams, slabs, walls and columns. However, the foundations were considered as fixed because this research considers dynamic analysis of superstructure elements and the deformation of foundation is not captured here.

Referring to Chapter 2: Building Description, building FE Model introduced tower structure arrangement according to design drawings and specification taking in consideration all loads cases and wind load parameters.

The structure is divided, discretized, into a finite number of discrete components. Characteristics of elements and their behavior their nodal transpositions and responses can be quantified by finite function shapes. In order to capture the exact movement of elements in tower, structure drawings measurements where used taking in consideration thickness, distances and location of members to obtain accurate result.

2.2.2 Model Assumptions

As any program in FE modelling the following assumption were introduce in order to obtain reasonable values and comparing values with real test by sensors:

1- Beams connection Pin-Pin – and this assumption will be discussed during model updating.

2- Walls and Columns Connection Fix-Fix

3- All the structure dimensions for beam + Column + Slab + Core taken from structure drawings and the arrangement dimension in excel sheet shown in appendix.

4- All material properties for the concrete were taken from structure drawings and the arrangement also in Excel sheet attached

5- Dead load and live load taken from structure general notes: - DL: 6.5 KN and LL: 2.5 KN.

6- Mass source considered structure elements + Load patterns with Multipliers: DL =1 and LL = 0.25

7- Base connection is fixed

8- A linear elastic behavior is assumed for Reinforced Concrete material, appropriate under the assumption of small strains. Taken as typical properties for Reinforced Concrete

2.2.3 Material properties of structure

This section provides material property information for materials used in model.

Table 5

Material Properties - Steel Data

Material	Fy KN/m2	Fu KN/m2
A992Fy50	3.45E+05	4.48E+05

Table 6

Material Properties Concrete Data

Material	Fc KN/m2
C40/50	4.00E+04
C45/55	4.50E+04
C50/60	5.00E+04
C60/75	6.00E+04
C70/85	7.00E+04

2.2.4 Section properties

This section provides section property information for objects used in the model, as per structural drawings.

Table 7

Frame Section Properties

Section Name	Material	width	depth	Area	I33	I22
		m	m	m2	m4	m4
B0.3x0.5	C45/55	0.500	0.300	0.150	0.003	0.001
B0.4x0.7	C50/60	0.700	0.400	0.280	0.011	0.004
B1.0x0.45	C50/60	0.450	1.000	0.450	0.008	0.038
B1.2x0.45	C50/60	0.450	1.200	0.540	0.009	0.065
C0.6x1.4 (C50)	C50/60	1.400	0.600	0.840	0.137	0.025
C0.6x1.9 (C50)	C50/60	1.900	0.600	1.140	0.343	0.034
C0.7x0.8 (C50)	C50/60	0.800	0.700	0.560	0.030	0.023
C0.8x1.6 (C60)	C60/75	1.600	0.800	1.280	0.273	0.068
C0.8x2.1 (C60)	C60/75	1.200	0.800	0.960	0.115	0.051
C0.8x2.3 (C50)	C50/60	2.300	0.800	1.840	0.811	0.098
C0.9x0.9 (C60)	C60/75	0.900	0.900	0.810	0.055	0.055
C0.9x1.6 (C70)	C70/85	1.600	0.900	1.440	0.307	0.097
C0.9X2.5 (C60)	C60/75	2.500	0.900	2.250	1.172	0.152
C1.0x1.7 (C70)	C70/85	1.700	1.000	1.700	0.409	0.142
C1.0x2.1 (C70)	C70/85	2.100	1.000	2.100	0.772	0.175
C1.0x2.3 (C70)	C70/85	2.300	1.000	2.300	1.014	0.192
C1.1x1.1 (C70)	C70/85	1.100	1.100	1.210	0.122	0.122
C1.1x2.6 (C70)	C70/85	2.600	1.100	2.860	1.611	0.288
C1.2x1.2 (C70)	C70/85	1.200	1.200	1.440	0.173	0.173
C1.2x2.6 (C70)	C70/85	2.600	1.200	3.120	1.758	0.374
C1.7x0.6 (C50)	C50/60	0.600	1.700	1.020	0.031	0.246
C1.9X0.7 (C60)	C60/75	1.900	0.700	1.330	0.400	0.054
C1.9x0.9 (C70)	C70/85	0.900	1.900	1.710	0.115	0.514
C1.9x1.1 (C70)	C70/85	1.100	1.900	2.090	0.211	0.629

Table 8

Area Section Properties

Section	Material	Thickness	Bend Thick
		m	m
SLAB(0.3)	C45/55	0.3	0.3
Wall300	C50/60	0.3	0.3
Wall300 (60)	C70/85	0.3	0.3
Wall300 (C70)	C70/85	0.3	0.3
Wall400 (C70)	C70/85	0.4	0.4
Wall450 (C60)	C60/75	0.45	0.45
Wall500 (C70)	C70/85	0.5	0.5
Wall600 (C70)	C70/85	0.6	0.6

2.2.5 Defining elements of FEM

In the models with the element type walls, the feature floor diaphragm is used to simulate a slab. The floor diaphragm works as a rigid link where each node in each story are linked to a master node located in or close to the stories' center of mass. The nodes linked to the master node are called slave nodes. The stiffness of the diaphragms are close to infinitely stiff, to simulate a slab transferring the lateral loads to the vertical elements. The diaphragms only transfers axial force and no out-of-plane shear or bending. For the meshed models there is no need for floor diaphragms since the slab is meshed with plate elements and have stiffness, both in-plane and out-of-plane bending, and connects all nodes in the plane. This provides stiffness in-plane and the load can be transferred to the vertical elements. A general modelling feature that is unchanged for all models are the connections between the columns and all beams except those running between the two cores. These connections are modelled as hinged in order to avoid statically indeterminate load distribution. This Model is a three dimensional, Liner and Isotropic. The X, Z, Y axes represent N-E and S-E and vertical direction respectively.

2.2.6 Procedure of solution using SAP2000 Program

SAP2000 is a broad-purpose finite element software which carries out the linear or nonlinear, dynamic or static analysis of structural systems. In addition, it is a potent design tool for designing structures based on ACI and AISC building codes as well as AASHTO specifications. These characteristics and countless more make this program the most advanced in structural analysis. The GUI, or graphic user interface, in SAP2000 is used to design, model, display and analyze the structure properties, geometry and analysis results. There are three stages in the analysis procedure:

1. Pre-processing. This phase is for building the model and adding the desired restrictions and loads, specifying the geometry, defining material properties and element type and Meshing, or dividing the object into small elements.

2. Solving. In this stage, the algebraic equations system which represents physical system are assembled and solved.

3. Post-processing, where the manipulation of numerical results is facilitated, either in graphical form or in the form of tables and lists.

AL Sinyar Tower was modelled using frame and plane elements. While the floors and the shear walls were modelled by the plane elements, the beams were modelled by the frame elements, and 4522 frames, 35053 joints, and 41068 plane elements were used to model the whole structure. It is assumed that all degrees of freedom under the building’s base are fixed.

2.3 Mode Shapes and Natural Frequencies

Two types of modal analysis in SAP2000 that can be used for dynamic analysis. Eigenvector analysis and Ritz-vector analysis. Eigenvector analysis provides the undamped mode shapes with free vibration in order to get natural modes. However Ritz-vector analysis need a set of load dependent ritz vectors in order to get good results. In this research Eigenvector analysis where chosen. Eigenvector analysis use the following equation to solve eigenvalue problem:

$$[\,K - \Omega^2 M\,]\Phi = 0 \qquad \text{Equation 2.3.1}$$

where K is the stiffness Matrix, M is Mass Matrix, Ω^2 is the diagonal Matrix and Φ the eigenvectors mode shapes matrix. After running the model analysis in SAP2000, the first 10 modes are demonstrated in (Figure 28).

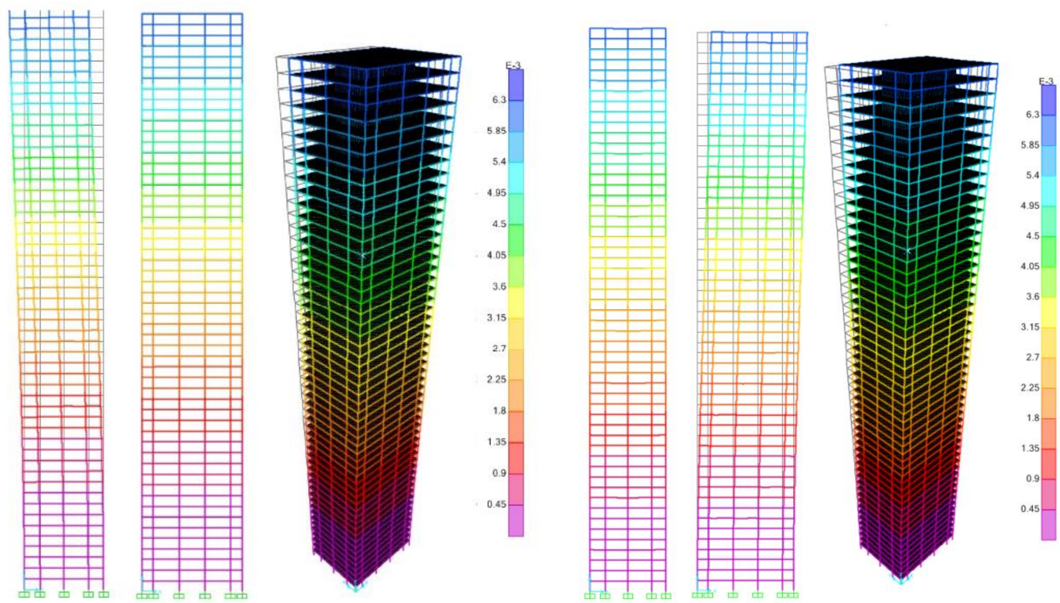
2.4 Elements Meshing

In order to have appropriate meshing, several trials were done using different mesh sizes. Eventually, a selective criteria of meshing were chosen in order to have a convergence and to ensure that changes in frequency values are less than 0.0001Hz. Meshing size of different elements are shown as following (Table 9):

Table 9

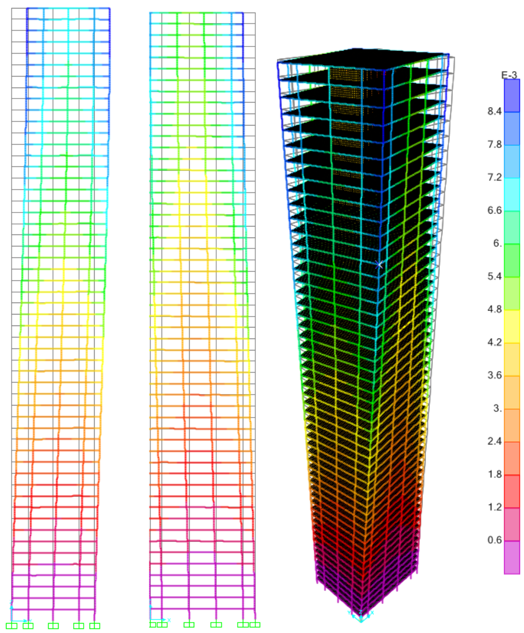
Element Meshing Size

Element	Meshing size
Slab	0.5m
Wall	0.3m
Column	0.5m
Beam	0.5m

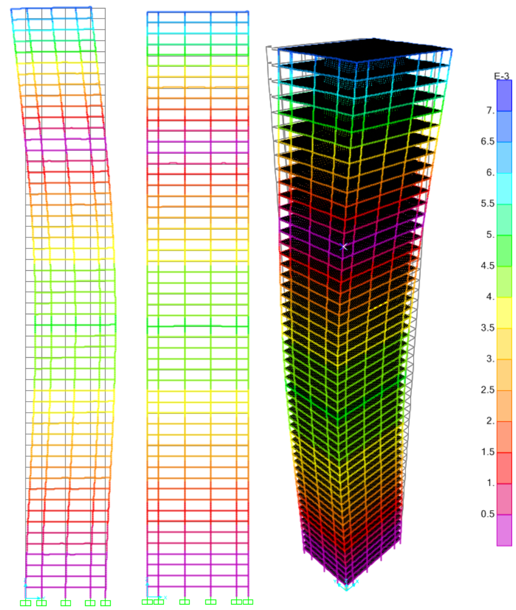


a) MODE 1: 0.1504 *b)* MODE 2: 0.2062

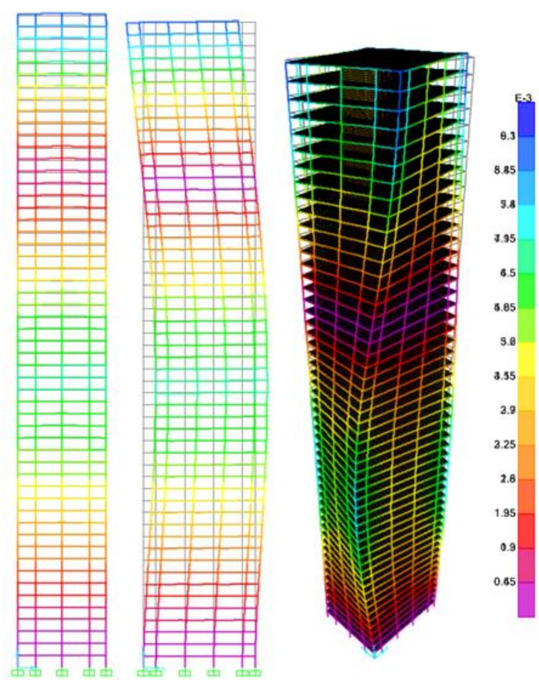
*continued



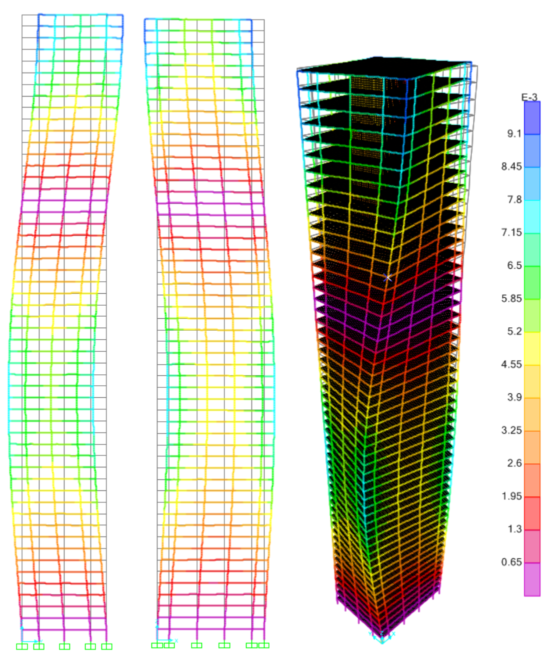
c) MODE 3: 0.4724



d) MODE 4: 0.6059

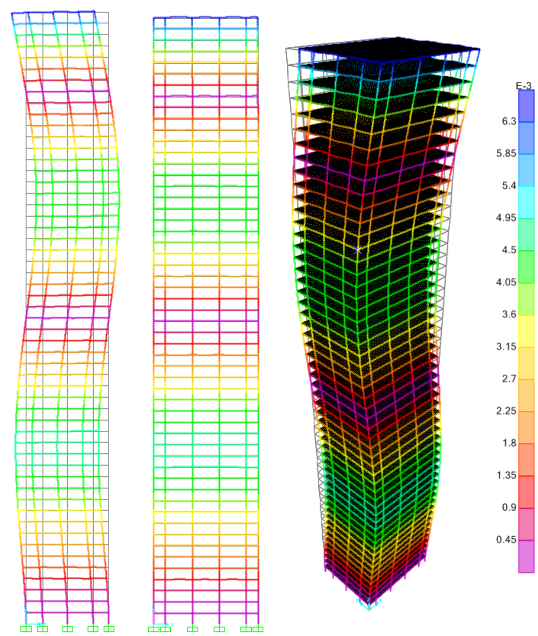


e) MODE 5: 0.7501

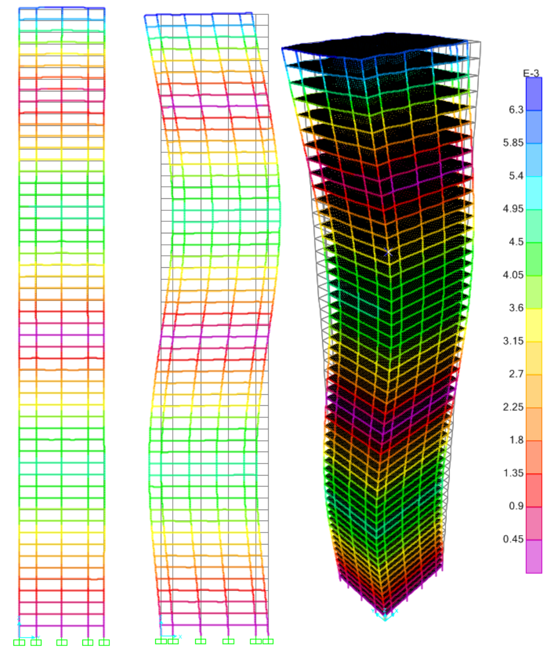


f) *MODE 6: 1.2939*

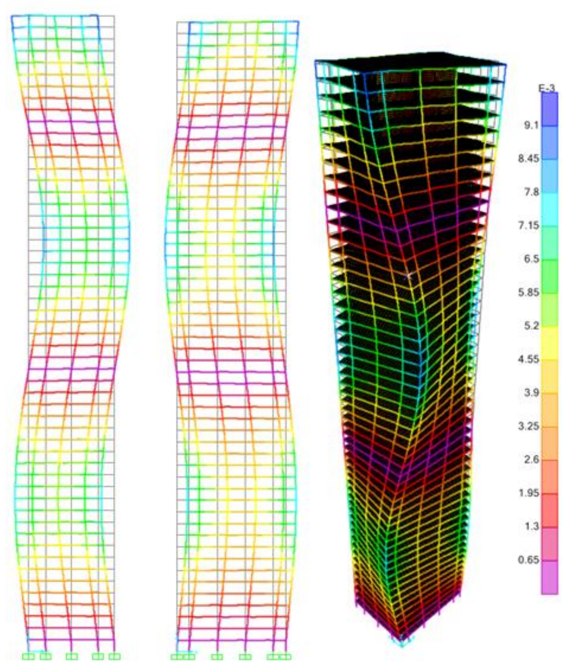
*continued



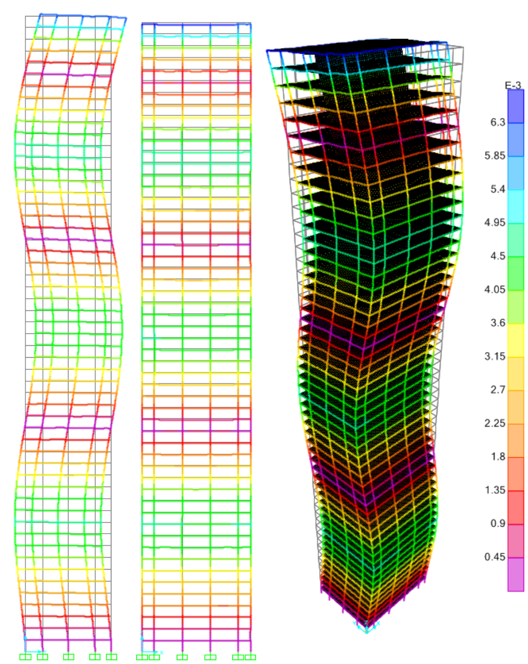
g) MODE 7: 1.4357



h) MODE 8: 1.6165



i) MODE 9: 2.2104



j) MODE 10: 2.6090

Figure 26. FEM MODES

Natural frequency from FEM are listed in the following table (Table 9) and a comparison with experimental full scale test will be discussed in CHAPTER 4.

Table 10

Natural Frequencies for each mode

MODE	Frequency
1	0.1504
2	0.2062
3	0.47245
4	0.6059
5	0.7501
6	1.2939
7	1.4357
8	1.6165
9	2.2104
10	2.6090

CHAPTER 3: AMBIENT VIBRATION TEST

3.1 Introduction

In an ambient modal analysis test, the key components are the structure being investigated, a data acquisition device, a number of motion sensors and a data processing system to extract the modal information from the obtained data. Regarding the transducers, any sensor's function is to transform a physical quantity into an electrical one, usually voltage. Afterwards, the voltage is transmitted, for digitization, to the data acquisition hardware. The foremost benefit of ambient vibration testing is that, in order to evaluate the dynamic characteristics of a structure, no "artificial" excitation has to be introduced. A natural source such as wind dynamically excites the structure continuously. These naturally occurring "loads", along with proper data analysis tools and instrumentation, can be exploited to determine dynamic characteristics of an enormous structure such as SYNIAR TOWER. In this chapter, Operational Modal Analysis (OMA) method was used to conduct a full-scale vibration test of the structure under ambient vibrations using wired sensors and wireless sensors. Ambient vibration testing's main objective was to evaluate the dynamic characteristics of *Al- Syniar Tower*. The relevant modal parameters were to the torsional and lateral natural periods along with their mode shapes. The aim was to record the structure's first ten modes and natural periods as first ten modes represent structure behavior in low frequency range.

3.2 Selection of the Measurement Scheme

The first essential step for an effective modal identification is high-quality measurements. If noise entirely corrupts measurements, any OMA method is unsuccessful. Low-quality measurements can be due to an improper selection of measurement hardware or sensors, but they can as well be the consequence of incorrect wiring. In reality, various measurement schemes can usually be adopted for a given selection of the sensors and measurement hardware. The gathering of high-quality data relies heavily on the adoption of the associated specifications for the whole analog signal path besides the selection of the most suitable cabling scheme. Nowadays, the market provides versatile data collection systems, permitting diverse wiring configurations.

If such schemes can easily be applied in the instance of commercial systems, attention is required whenever an own measurement system is developed a programmable hardware or when data acquisition systems come from different manufacturers. In both instances, the proper wiring is often in the user's full responsibility.

An exhaustive analysis of noise control techniques and cabling schemes is out of the scope of this research, but a general illustration about them can still offer valuable suggestions to refrain from common errors in performing measurement. The herein stated guidelines cannot substitute an in-depth analysis of specifications and documents accompanying measurement systems and sensors for the determination of the proper wiring scheme, but they can undeniably help the inexpert user in the choice of the measurement scheme and chain. As wireless sensors is very expensive, first test were implemented by using wires sensors and all this steps will be discussed in wires sensors testing.

3.3 Transducers

Obtaining electrical signals from physical quantities is the role of transducers. For example, motion transducers translate velocity, displacement or acceleration into voltage that is proportional to the considered physical quantity's magnitude. Civil Structures' dynamic response can be measured by numerous types of sensors available in the market. Piezoelectric sensors translate the mechanical quantity into an electrical one. Due to piezoelectricity, positive and negative ions mount up onto the crystals opposite surfaces when a force is applied to the crystal.

The accumulated charge amount is directly proportional to the magnitude of the applied force. In piezoelectric accelerometers the crystal is coupled to a mass. At the accelerometer's base, the application of an input acceleration leads to a deformation of the crystal due to the inertia force of the mass. An electric charge proportional to the deformation is generated by the piezoelectric material. The structure's limited frequency range and low amplitude of motion under test direct the selection towards high-sensitivity accelerometers like those employed for seismic networks. Nevertheless, parameters other than sensitivity and frequency band should also be taken into consideration. In order to appropriately choose the sensors and use them for a particular application, sensor specifications must be carefully studied. Precisely, it is worth remarking that some sensor features, such as sensitivity or dynamic range, might depend on frequency. Accordingly, a sensor could show better properties in a particular frequency band and worse features elsewhere. This condition should be taken into consideration when selecting a sensor. In this research, two test were implemented by using wires and also wireless sensors.

3.3.1 Test using Wired Transducers

The selection of the cable type as well as the connection with the terminals impacts the measurements quality. Cable selection were studied deeply before testing by wires sensors. To transfer the analog signals to the data collection system from the sensors

As a first step to test sensors connectivity a mockup test were implemented in lab by using Coaxial cables. For piezoelectric accelerometers, coaxial cables are often used, which are extremely inexpensive cables but are the most susceptible to electrical noise exposure; For force balance accelerometers, cables involving several individually shielded twisted pairs are used, and although these are weighty and costly but are the least subjected to collect noise from the surroundings.

DT9857E modules were used which have a high-accuracy dynamic signal analyzer with 16 IEPE inputs or two stimulus waveform output channels RG58/U, 50 OHM, with Shield low noise Coaxial Cable were used to connect sensors with the module. (Figure 29). For Piezoelectric accelerometers (PCB 393b04) 10 V/g sensitivity and 0.5 g peak acceleration with (0.1 to 200 Hz)

Figure 27: Wired sensors , accessories and cable termenation

Another critical aspect is the assembly of the wires with the terminals, because an improper connection promotes the intervention of electrical noise. In this viewpoint as our observation during lab testing, certain attention has to be concentrated on good shield termination, preventing ground current flows within the shield. This can be achieved through connecting the shield to the ground at a single end only. Directions for cable connections offered by data acquisition system and sensor manufacturers must be taken seriously. In order to test long coaxial cables, a mockup test were conducted on a model steel stadium in lab to check if the data transmitted throw the cable would suffer losses once increasing cable length. Raw data were in a good quality and ready for analysis (Figure 30)

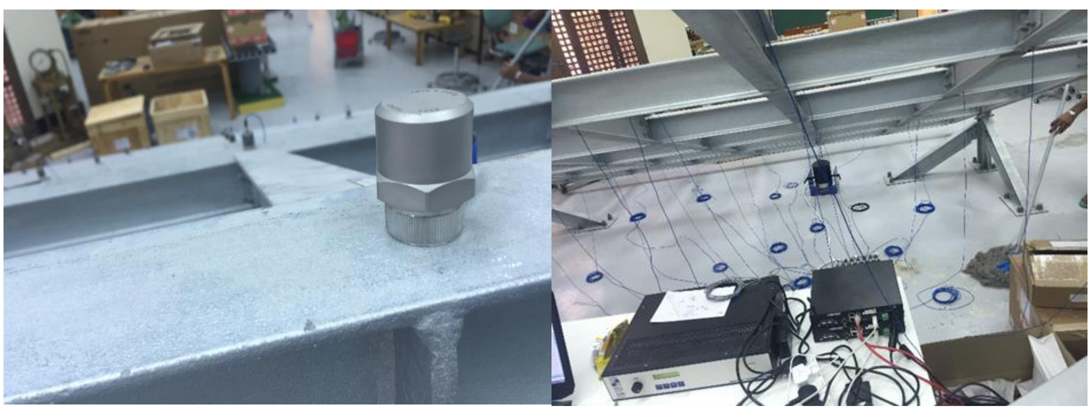


Figure 28: Validation test for wires sensors

In fact, results from lab testing were satisfying however results from Syniar tower were disappointing due to the following:

- The picked up signal contains of high range of noise. The acquired signal which carrying this amount of noise stands against implement OMA techniques effectively.
- Sensor frequency range from 0.1 up to 200 Hz. As SYNIAR tower consist of 52 floor sensors failed to capture low frequencies below 0.5 Hz.
- Distances between sensors and modules were more than 50 m, especially for sensor in 48th floor, a huge noise effect signals carried by the cables.
- Practically, it's hard to deal with more than 1000 meter cables especially with a very sensitive device.

3.3.2 Test using Wireless Transducers

In the last decade, considerable efforts were put into the improvement of wireless sensor networks for health monitoring and structural testing. This field earned an increasing interest of the scientific and professional community, and has experienced an unprecedented development. Due to the affordable cost and the option to join multiple sensors in the same wireless node, this technology gained a commercial success (Lynch & Loh, 2006).

Despite the abundance of wireless sensing solutions available today, providing attractive attributes such as the reduction of installation time and costs linked to the cables use, they have not entirely substituted wired systems. The time synchronization of the channels is the major benefit of wired systems over wireless sensor network. Concurrent sampling, actually, guarantees the phase consistency among all the measurement channels, avoiding errors in the computation of cross-spectral and cross correlation density functions. In wireless sensor networks, time synchronization demands particular solutions whereas it is a normal task when wired sensors and a single data acquisition system are adopted. Each node in wireless sensor networks has its own ADC. Accordingly, an external time base providing a time reference is required for the time synchronization of the different ADCs. Recently; TROMINO used for the operational modal analysis of structures to such as the Eiffel tower, and Golden Gate Bridge in San Francisco. In this project, TROMINO use 3 channels connected to 3 orthogonal electrodynamics with selectable gain for vibration tremor acquisition. (Figure 31)

Figure 29: wireless Sensors Setup – TROMINO-

3.4 Sensor Installation

The selection of the sensor layout relies on the modal identification test objectives, the number of available sensors, and the required data about the mode shapes, which may bring about altered requirements in terms of sensors' spatial density. Literature on the optimization of sensor location is abundant. Yet, the adopted criteria and optimization techniques highly influence the results acquired from the application of those methods, resulting in various possible layouts. Hence, although those techniques can aid the definition of the test layout, a specific amount of physical insight besides cautious planning by the test engineer still play an essential role in the definition of test layouts that are capable of maximizing the modes' observability and the amount of data obtained from the sensors.

When some theoretical information regarding the mode shapes exists, a successful sensor layout can be achieved by setting up the sensors in a set of points. Mode shapes were taken from FEM in sap2000 in order to locate sensors in the Anti-nodes of the mode shape.

Accordingly from FEM model of SYNIAR tower which provides us first mode equal 0.15 Hz that means sampling window shall be 1/0.15 which is equal of 7 second per each window time frame as a minimum value in order to have a good resolution of frequency. However as TROMINO sensor capable to carry smaller window time frame, a 1/128 seconds where chosen to have higher resolution in this project test. And Data was collected for a period of 90 minutes at a rate of 128 sample per second. In order to have a constant measurement and a reasonable data collection, first and last 10 minutes were removed from the analysis. The location of sensors were in opposite corners in each instrumented floor. And the first reference sensor were placed in the first floor (Figure 32).

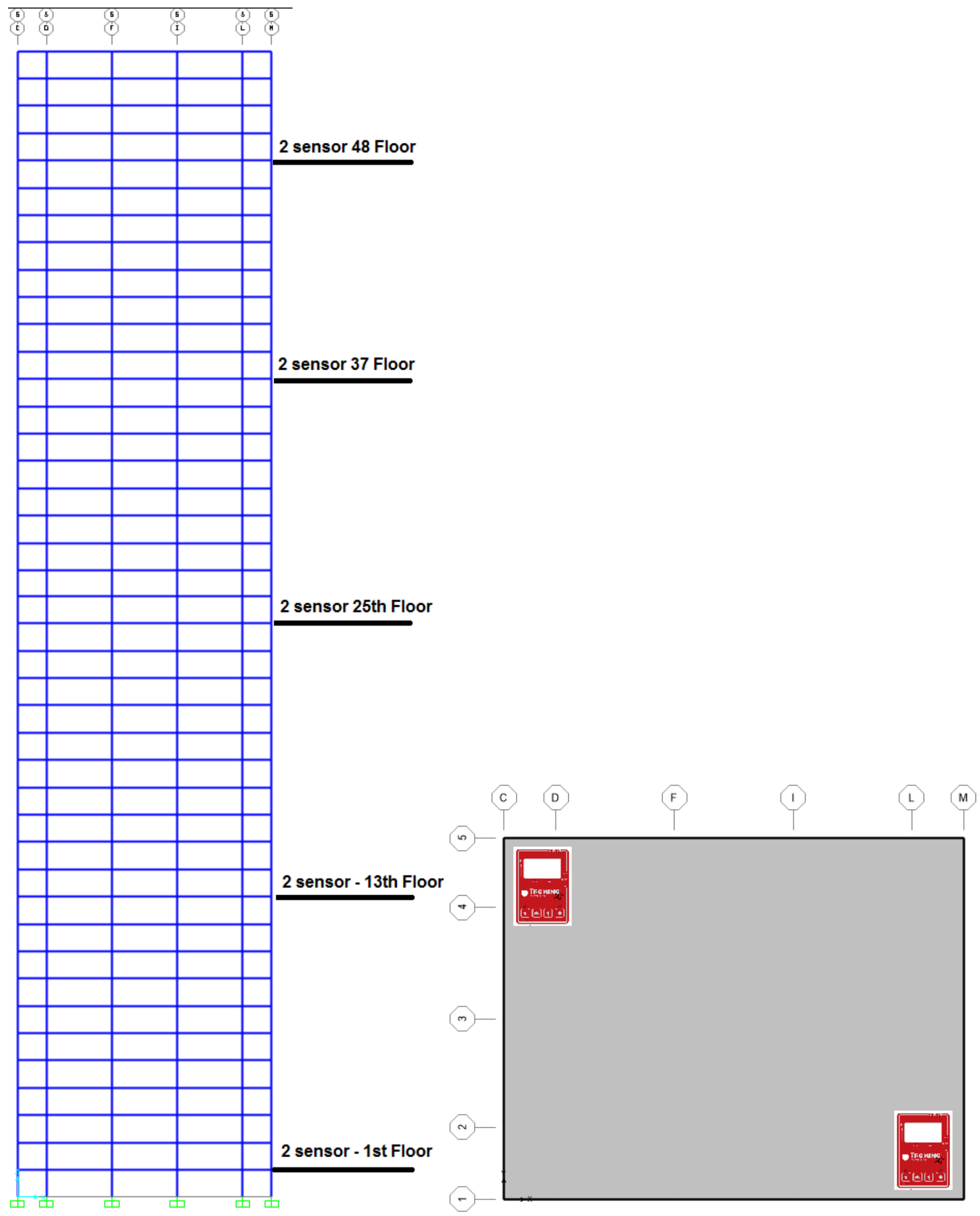


Figure 30: sensors location

3.5 OMA using ME 'Scope

ME 'Scope designed to capture and analyze vibration and modal dynamic identification. Modular design allows users to create a 3D modal and this 3D modal interact with the data sets input to create deflection shapes and mode shapes by using multichannel time and frequency domains acquired during structure operation. To analyze cross-channel functions like Frequency Response Functions or cross-spectrum. A measurement sets used as an input data from acceleration sensor – TROMINO- used in Al- Syniar Tower. Active channels of data sets have to be simultaneously acquired. In ME 'scope all data sets represented as channel spreadsheet with a Degree of freedoms which will be discussed later on. And all data sets shall be saved as an Acquisition file. After setting out data sets a mode shape shall be animated as a response of vibration on 3D mode1.

3.6 Model Identification

First ten modes were considered in this study from the Model identification outcomes for SYNIAR TOWER using TORMONO sensors along with ME 'Scope program.. as discussed previously. And the model assurance criterion (MAC) used to compare results between FEM and ambient vibration test. As an example; (Figure 33) displays sensors ambient vibration data from 48th floor that were located in corner.

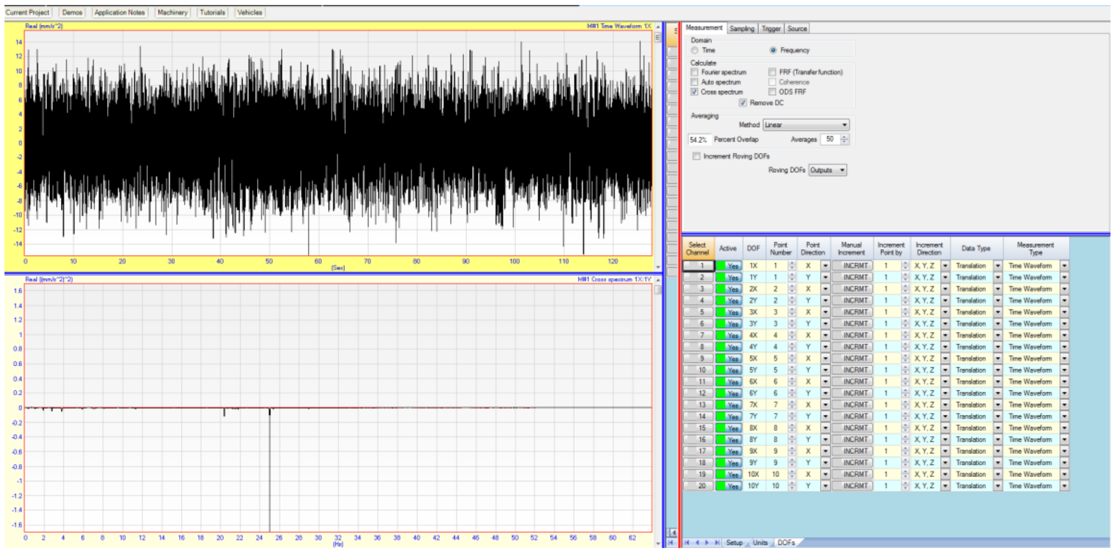


Figure 31: Acquisition Window Showing the Sampling Tab

(Figure 34) shows the cross power spectral density and peaks represent natural frequencies of SYNIAR TOWER. From this figure it is observed that the first 10 Modes contribute in low frequencies and as expected from FEM model. Once power spectral density have been calculated throw ME 'Scope, damping identification of the structure is performed.

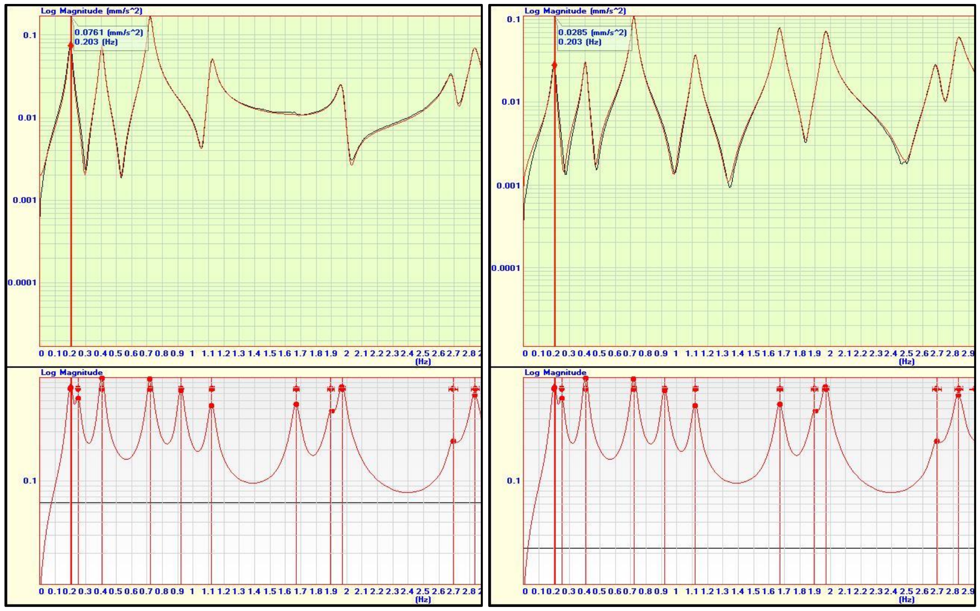
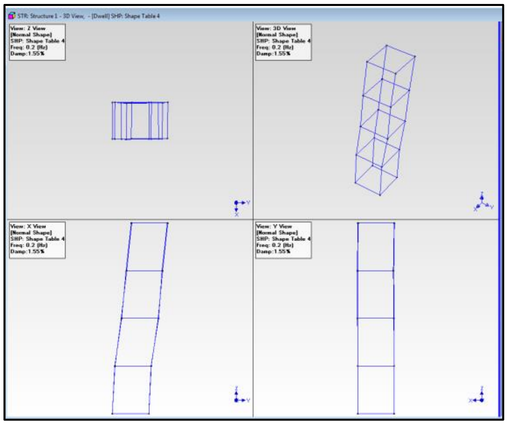
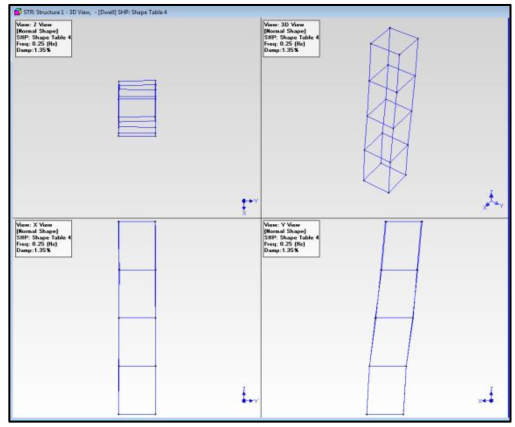


Figure 32: Cross Power Spectral Density of two Modes .

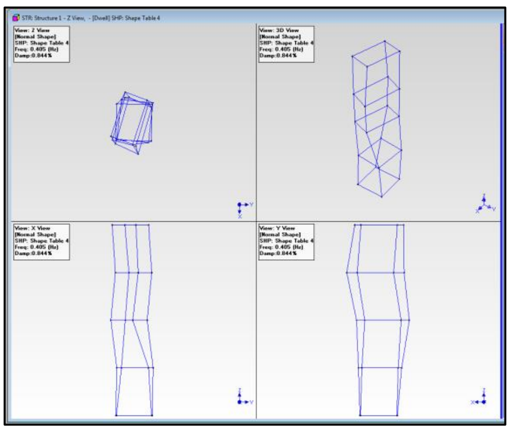
In order to simplify the visualization of mode shapes in ME 'Scope, A graphical tool were used to represent the structure with corresponding mode shapes as following; (Figure 35)



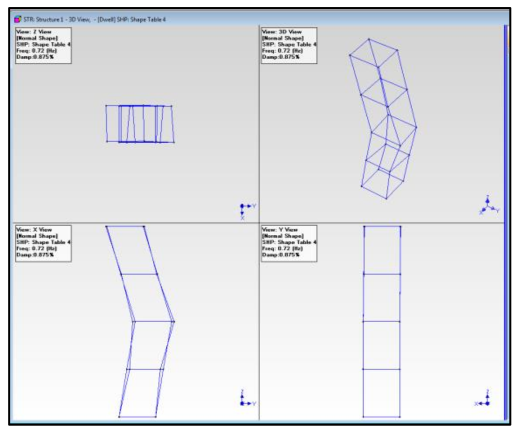
a) MODE 1: 0.200 Hz



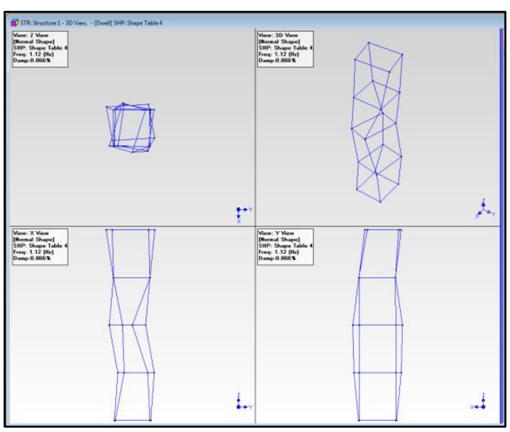
b) MODE 2: 0.250 Hz



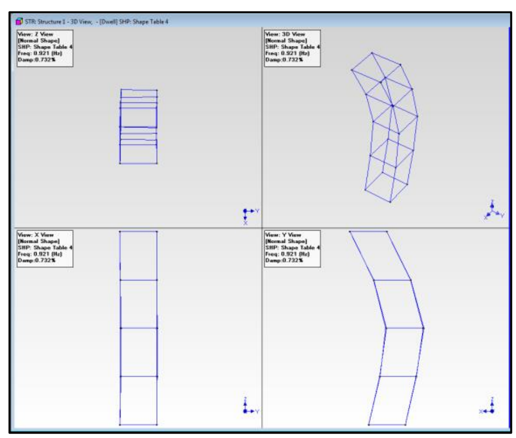
c) MODE 3: 0.405 Hz



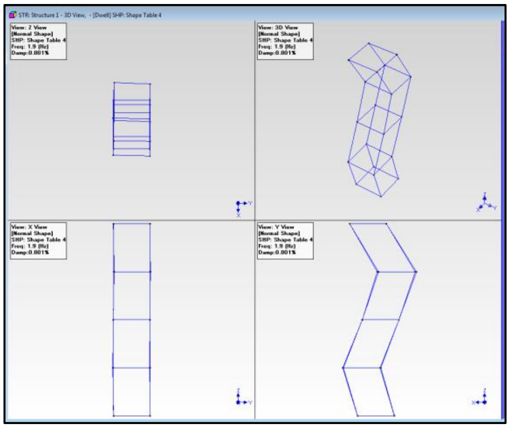
d) MODE 4: 0.720 Hz

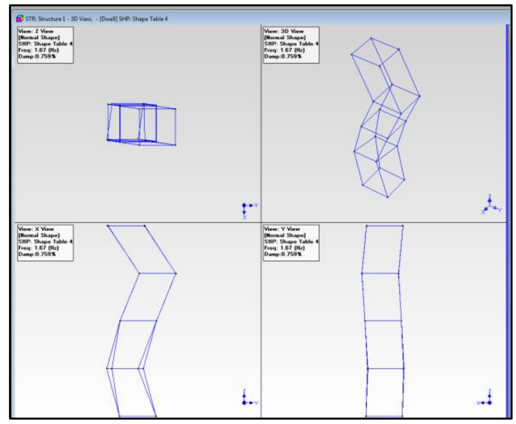


e) MODE 5: 0.921 Hz



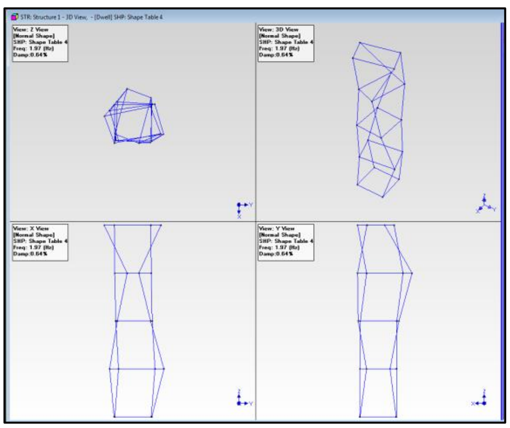
f) MODE 6: 1.120 Hz

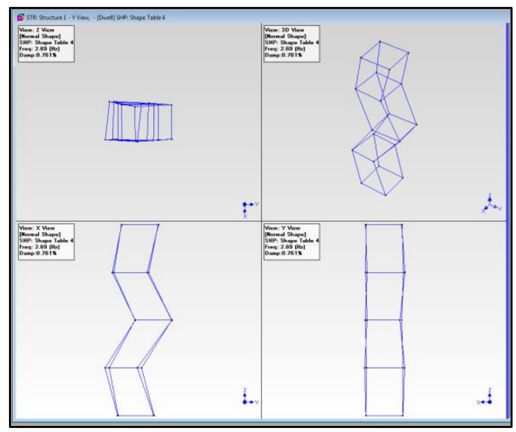




g) MODE 7: 1.670 Hz

h) MODE 8: 1.900 Hz





g) MODE 9: 1.970 Hz

h) MODE 10: 2.690 Hz

Figure 33: First 10 Mode Shape from Me'Scope .

Table 10

Natural Frequencies and Damping ratios for each mode from Experimental Test

Frequency (Hz)	Damping (%)
0.200	1.550
0.250	1.350
0.405	0.844
0.720	0.875
0.921	0.732
1.120	0.866
1.670	0.759
1.900	0.801
1.970	0.640
2.690	0.761

Results from Me Scope in (Table 10) provides 10 mode shapes along with structure damping ratios and the following section will discuss a comparison between FE Model and Experimental obtained from structure in site condition.

3.7 Comparison between FEM and Experimental Values

The Ambient – output only- modal identification results proposed a valuable information about dynamic characteristics for Al-Sinyar Tower. The first 10 natural frequencies along with mode shapes were captured. This experimental values will develop a base line in order to an update model that will be studied in e detail later in this study. Table 11, shows Comparison between frequencies obtained from Experimental and FEM Values

Table 11

Comparison between frequencies obtained from Experimental and FEM Values

MODE	Model (FEM) Hz	Experimental Frequency Hz	Error %
1	0.1504	0.2000	4.96
2	0.2062	0.2500	4.38
3	0.4724	0.4050	6.745
4	0.6059	0.7200	11.41
5	0.7501	0.9210	17.09
6	1.2939	1.1200	17.39
7	1.4357	1.6700	23.43
8	1.6165	1.9000	28.35
9	2.2104	1.9700	24.04
10	2.6090	2.6900	8.1

Model assurance criterion (MAC) main purpose to mathematically compare modes shapes results for the same model but from different analysis techniques. It is usually used as a quality assurance indicator for experimental comparisons .MAC value range from 0 to 1. When the two mode are too similar, MAC value will be closed to 1. And when two mode shapes are orthogonal, MAC value will be closed to 0.

$$MAC(i,j) = \frac{\left|\emptyset_i^T \hat{\emptyset}_j\right|^2}{\left|\emptyset_i^T \emptyset_i\right|\left|\emptyset_j^T \hat{\emptyset}_j\right|} \qquad \text{Equation 3.7.1}$$

Where $\hat{\emptyset}_j$ is the measure of j th mode and $\emptyset_i$ is the corresponding analytical solution of mode shape.

The values that were measured from FEM and experimental model analyzed by MAC in order to check modes fittings. (Figure 36) shows that MAC values is acceptable and modes in both experimental and FEM in good colorations.

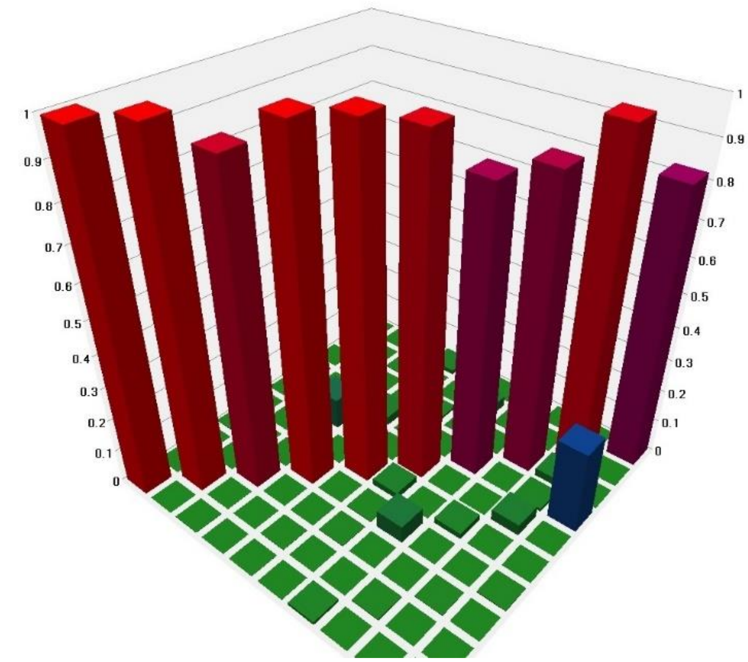


Figure 34: MAC values (FEM / Experemental)

The diagonal matrix of MAC shows that the correlation is not good with mode 7 and mode 8. And the correlation between all modes reaching 90% only. This means that an updated model is needed in order to obtain a better correlation.

CHAPTER 4: MODEL UPDATING

4.1 Introduction

Model updating relies on changes of certain structure parameters in order to have a closely matching values that were obtained by FEM. This depend on performing some adjustments in FEM to minimize corresponding differences between experimental ambient testing and numerical structure design. In this chapter; a study will be considered mainly to optimize parameters such as the modules of Elasticity, Density and fixity release of structural elements and how it will effect FEM dynamic values such as frequencies mode shapes to give an understanding of parameters that will effect model to have a better reflection of experimental response values obtained from ambient vibration testing. However, structure design engineer has to accept various simplifications and assumptions based on minimum code requirements of the real construction in geometry, masses, stiffness, elasticity, loads, and other limitations during the stage of creation design model in finite element model.

Three FEM updating techniques were used in this research by updating Modules of Elasticity, Density and also combination of both parameters along with partial fixity releases in order to have a final model update that represent experimental model with fairly values. Accordingly MAC ratio were studied per each model update to check mode shape coloration between update modes and experimental modes.

4.2 Optimizing of Density

In this optimization; a modification of material density of concrete was considered as the frequency is increasing while density is decreasing according to the following percentage of reduction. The density of concrete is a measurement of concrete's solidity. The density of concrete of normal weight is about 2,400 kg per cubic meter. And the following table shows that in order to minimize frequency errors for the first 10 Mode, density of concrete have to decrease 58 percent. These values were obtained by analyzing model with the following density values (27000 kg, 20000 kg, 15000 kg and 14000 kg). (Table 12)

Table 12

optimization values – Density parameter

Concrete Density as structure specification (FEM)	Concrete Density Optimization value	Percentage of Optimization
24000 kg per meter	14000 kg per meter	- 58.00%

After updating density parameter, the following natural frequency were obtained. (Table 13)

Table 13

Comparison between frequencies obtained from Experimental and FEM Update- Density parameter

MODE	Model Update (Density Parameter)	Experimental Frequency	Error %
1	0.2009	0.2000	0.45
2	0.2555	0.2500	2.20
3	0.5232	0.4050	29.19
4	0.7535	0.7200	4.65
5	0.9877	0.9210	7.24
6	1.3288	1.1200	18.64
7	1.8112	1.6700	8.46
8	2.0745	1.9000	9.18
9	2.2532	1.9700	14.38
10	2.9422	2.6900	9.38

The values that were measured from- FEM Updated by Density Parameter and experimental model, analyzed by MAC in order to check modes fittings. (Figure 37) shows that MAC values is increasing more than the values of MAC analysis in FEM model discussed earlier.

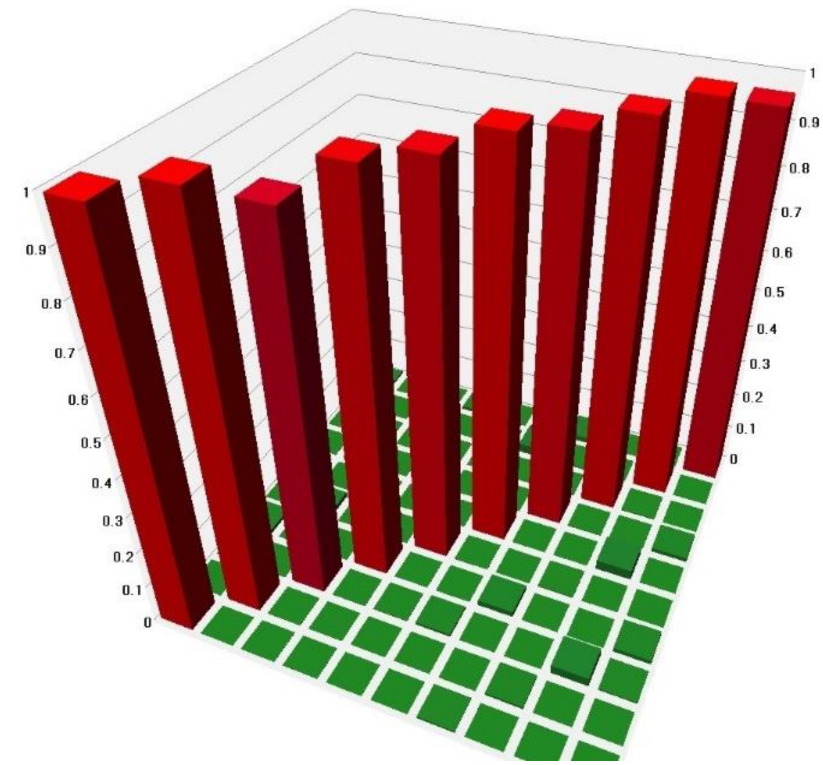


Figure 35: MAC values (FEM Update by Density Parameter/ Experimental)

4.3 Optimizing of Modules of Elasticity

In this optimization; a modification of Modules of Elasticity were considered as the frequency is increasing while density is Modules of Elasticity increase according to the following percentage of increment:

Table 14

optimization values – - Elasticity parameter

Material	**Modules of Elasticity as structure specification (FEM) $/m^2$**	**Modules of Elasticity Optimization value kN/m^2**	**Percentage of Optimization**
C40/50	3.50E+07	5.95E+07	58%
C45/55	3.60E+07	6.12E+07	58%
C50/60	3.70E+07	6.29E+07	58%
C60/75	3.90E+07	6.63E+07	58%
C70/85	4.10E+07	6.97E+07	58%

Modules of elasticity values in FEM model taken from structure drawings and general specification for Al Sinyar Tower . After updating Modules of Elasticity parameter the following natural frequency were obtained. (Table15)

Table 15

Comparison between frequencies obtained from Experimental and FEM Update-Elasticity parameter

MODE	Model Update (Elasticity Parameter)	Experimental Frequency	Error %
1	0.1961	0.2000	1.95
2	0.2588	0.2500	3.52
3	0.5010	0.4050	23.70
4	0.7550	0.7200	4.86
5	0.9780	0.9210	6.19
6	1.3170	1.1200	17.59
7	1.7920	1.6700	7.31
8	2.0866	1.9000	9.82
9	2.2321	1.9700	13.30
10	2.8785	2.6900	7.01

And the MAC values as following (Figure 38)

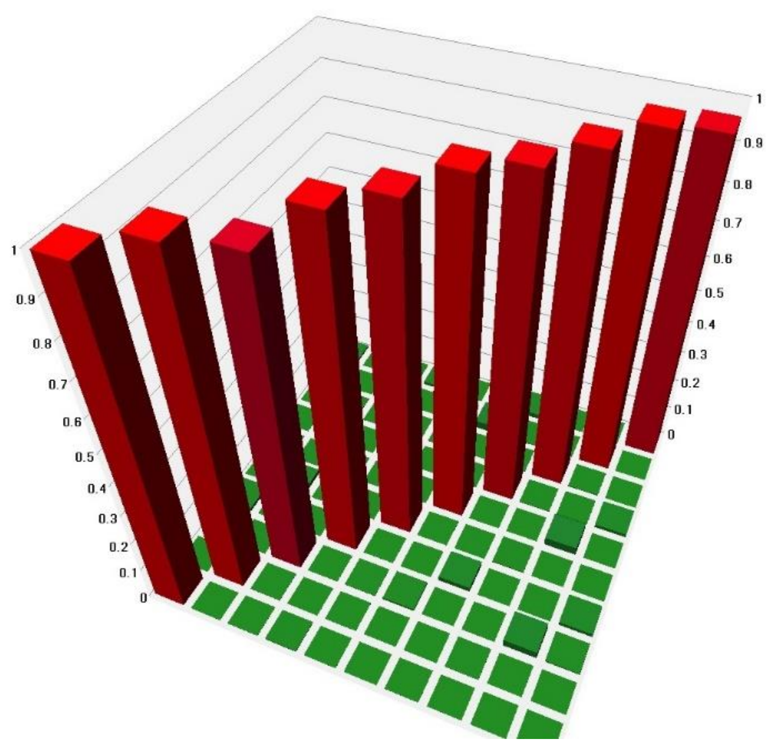


Figure 36: MAC values (FEM Update by Elasticity Parameter/ Experimental)

4.4 Final Model Update

From previous optimization torsional modes 3, 6 and 9 natural frequencies have a high Error percentage. As this thesis main scope is to update FEM model in order to best fit experimental model a deep investigation in SAP2000 Manual take place and after many iteration the main controlling of torsion is related to end frame fixity, partial releases.

Going back to our assumption that columns beams connection is pin, it is an assumption that codes and consultant office based their calculation. As cracked section analysis concept is to let steel carry a full tensile loading and release moments throw pin connection. However during structure service the connection between beam and columns is partially fixed and this allow moment to be transferred to column and the behavior of building act as a full frame during ambient vibration. And this is a valid point that can be consider as a reason also to have a stiffer structure in reality more than Finite Element model structure.

From this point a partial releases of torsion and moment were released as 50% and the following optimization were considered:

Table 16

optimization values – Final Model Update 1/2

Material	Modules of Elasticity as structure specification (FEM) KN/m2	Modules of Elasticity Optimization value KN/m2	Percentage of Optimization
C40/50	3.50E+07	4.39E+07	+ 22.00%
C45/55	3.60E+07	4.51E+07	+ 22.00%
C50/60	3.70E+07	4.76E+07	+ 22.00%
C60/75	3.90E+07	5.00E+07	+ 22.00%
C70/85	4.10E+07	4.39E+07	+ 22.00%

Table 17

optimization values – Final Model Update 2/2

Concrete Density as structure specification (FEM)	Concrete Density Optimization value	Percentage of Optimization
24000 kg per meter	18720 kg per meter	- 22.00%

After this final iteration torsion modes were updated and this final updated Model is satisfactory based on Error percent and Mac Values as below (Table18) (Figure 39)

Table 18

Comparison between frequencies obtained from Experimental and Final Model update

MODE	Model FINAL Update	Experimental Frequency	Error %
1	0.1865	0.2000	6.75
2	0.2434	0.2500	2.64
3	0.4713	0.4050	16.37
4	0.7350	0.7200	2.08
5	0.9730	0.9210	5.65
6	1.2758	1.1200	13.91
7	1.7559	1.6700	5.14
8	2.0142	1.9000	6.01
9	2.1841	1.9700	10.87
10	2.8891	2.6900	7.40

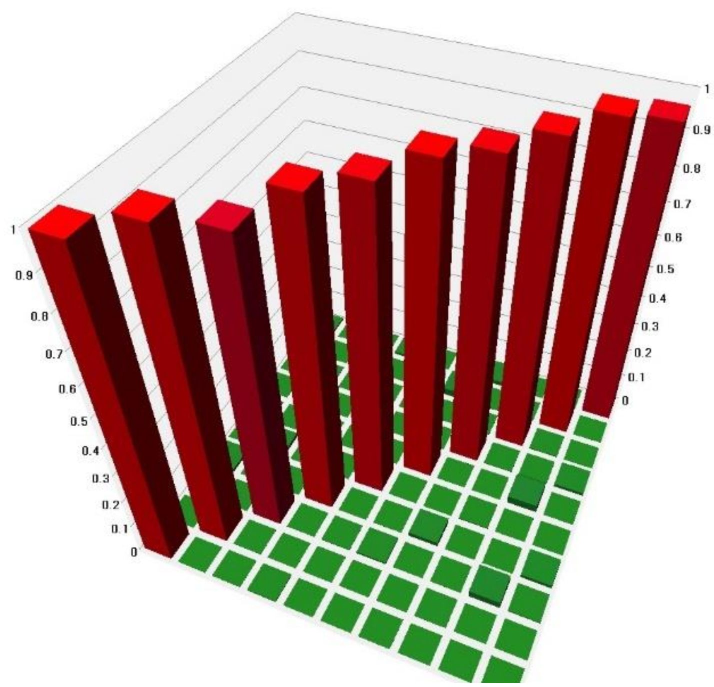


Figure 37: MAC values (Final Model Update/ Experimental)

CHAPTER 5: CONCLUSIONS AND RECOMMENDATION

This study focus on ambient vibration testing on the SYNIAR TOWER, a 52-story high building which consists of 2B+G+52 floors in Al Dafna Area in Qatar, with a total built up area of 74,747 sqm. Testing was conducted to determine structure modal characteristics which include natural periods, damping ratios and mode shapes by using ME'SCOPE program. Results from analyzing this building by ambient vibration testing were compared to FE modeling in SAP2000 that were modeled using structure drawings and specifications from consultant office. Ambient test were conducted by using wires and wireless sensors and the following conclusion can be drawn from this study:

1- Distances between sensors and modules were more than 50 m, especially for sensor in 48th floor. So Practically, it's hard to deal with more than 1000 meter cables especially with a very sensitive device

2- Ambient vibration results based on As-built environment provided higher frequencies values in comparison to FEM because the stiffness provided by cladding, façade and walls eventually increased the system's stiffness, which cannot be revealed in FE modeling based on structural drawings only.

3- This first 10 modes and corresponding mode shapes were determine from ambient test and the fundamental frequency of the building was 0.2 Hz

4- The stiffness impact of non-structure elements were found to be important factor to minimize the differences between experimental and analytical natural frequencies and mode shapes.

5- Results from model updating shows that structure was sensitive to the following

a. Young's Modulus for the reinforced concrete.

b. Materials Density for columns and walls.

c. Fixity connection between columns and beams.

6- Initial model analysis through SAP2000 was implemented by using structural drawings and the first natural periods obtained are 65% less than natural periods that were obtained from ambient test.

7- Final updated model were satisfactory according to modal assurance criterion (MAC) and frequency deferent errors.

8- Model updating main concept to have an ideal simulation of structure that can represent real structure behavior and optimized values of deferent parameters can exceed limitation in order to obtain sufficient results that can represent structure experimental behavior.

Due to the limitation time of this test in site and the complexity of structure geometry that include structure and non-structure elements, further investigation is needed to study structure design of high-rise building and the effect of non-liner behavior of concrete cracked sections and load disruptions throw beams , columns and walls.

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APPENDICES

Appendix A: Columns Elements Arrangement

Column Arrangement

Floor	C1	C2	C3	C4	C5	C6	C7	C8	C9
G	1200x1200	1200x1200	1000x1700	1000x1700	100x2300	100x2300	1200x2600	1200x2600	1900x1100
1	1200x1200	1200x1200	1000x1700	1000x1700	100x2300	100x2300	1200x2600	1200x2600	1900x1100
2	1200x1200	1200x1200	1000x1700	1000x1700	100x2300	100x2300	1200x2600	1200x2600	1900x1100
3	1200x1200	1200x1200	1000x1700	1000x1700	100x2300	100x2300	1200x2600	1200x2600	1900x1100
4	1200x1200	1200x1200	1000x1700	1000x1700	100x2300	100x2300	1200x2600	1200x2600	1900x1100
5	1200x1200	1200x1200	1000x1700	1000x1700	100x2300	100x2300	1200x2600	1200x2600	1900x1100
6	1200x1200	1200x1200	1000x1700	1000x1700	100x2300	100x2300	1200x2600	1200x2600	1900x1100
7	1200x1200	1200x1200	1000x1700	1000x1700	100x2300	100x2300	1200x2600	1200x2600	1900x1100
8	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
9	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
10	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
11	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
12	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
13	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900

14	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
15	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
16	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
17	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
18	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
19	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
20	1100x1100	1100x1100	900x1600	900x1600	1000x2100	1000x2100	1100x2600	1100x2600	1900x900
21	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
22	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
23	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
24	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
25	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
26	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
27	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
28	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
29	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
30	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
31	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
32	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
33	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
34	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700
35	900x900	900x900	800x1600	800x1600	800x2100	800x2100	900x2500	900x2500	1900x700

36	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
37	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
38	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
39	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
40	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
41	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
42	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
43	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
44	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
45	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
46	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
47	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
48	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
49	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
50	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
51	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
52	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600
ROOF	700x800	700x800	600x1400	600x1400	600x1900	600x1900	800x2300	800x2300	1700x600

Appendix B : Shape Matrix

Experimental Model Test Model										
	SHAPE1	SHAPE2	SHAPE3	SHAPE4	SHAPE5	SHAPE6	SHAPE7	SHAPE8	SHAPE9	SHAPE10
1X:2X	5.00E-06	3.20E-04	-2.11E-04	1.61E-05	1.94E-03	-4.91E-04	2.75E-05	3.00E-03	-1.35E-03	2.95E-05
1Y:2X	5.97E-05	-8.35E-06	3.30E-04	1.36E-04	2.71E-05	6.55E-04	2.06E-04	-1.26E-04	1.90E-03	1.29E-04
2X:2X	5.02E-06	3.96E-04	2.57E-04	9.38E-06	2.07E-03	5.77E-04	1.37E-05	3.11E-03	1.72E-03	3.80E-06
2Y:2X	7.09E-05	7.50E-05	-3.47E-04	1.50E-04	1.38E-04	-7.09E-04	2.29E-04	1.55E-04	-2.00E-03	1.64E-04
3X:2X	3.19E-05	2.86E-03	-2.58E-03	9.61E-05	1.63E-02	-5.37E-03	1.35E-04	1.80E-02	-1.10E-02	9.80E-05
3Y:2X	4.66E-04	-1.75E-04	3.62E-03	1.44E-03	-1.35E-03	7.62E-03	1.52E-03	-2.24E-03	1.63E-02	5.22E-04
4X:2X	8.99E-06	2.91E-03	2.72E-03	3.66E-05	1.62E-02	5.88E-03	3.30E-05	1.74E-02	1.30E-02	-2.88E-05
4Y:2X	4.33E-04	3.09E-05	-3.24E-03	1.34E-03	2.87E-04	-6.76E-03	1.48E-03	3.51E-04	-1.44E-02	6.27E-04
5X:2X	7.11E-05	9.05E-03	-6.74E-03	1.33E-04	2.63E-02	-7.51E-03	-1.91E-05	-2.87E-03	3.97E-03	-1.15E-04
5Y:2X	1.22E-03	-3.70E-04	8.72E-03	2.22E-03	-1.53E-03	9.92E-03	-7.62E-06	5.51E-04	-5.08E-03	-5.31E-04
6X:2X	-5.58E-06	8.12E-03	6.35E-03	2.86E-05	2.33E-02	7.39E-03	-8.75E-06	-1.95E-03	-3.75E-03	3.38E-05
6Y:2X	1.32E-03	9.26E-05	-8.87E-03	2.35E-03	2.97E-04	-9.93E-03	-2.27E-05	-6.38E-04	5.20E-03	-7.10E-04
7X:2X	8.30E-05	1.24E-02	-8.30E-03	3.27E-05	7.64E-03	-5.75E-04	-1.29E-04	-1.88E-02	1.20E-02	7.46E-05
7Y:2X	1.91E-03	-5.88E-04	1.22E-02	7.15E-04	-4.42E-04	9.24E-04	-1.88E-03	2.47E-03	-1.83E-02	2.52E-04
8X:2X	-3.99E-05	1.37E-02	9.54E-03	-7.99E-06	8.47E-03	8.12E-04	-3.33E-05	-1.88E-02	-1.48E-02	-2.82E-05
8Y:2X	1.74E-03	1.09E-04	-1.04E-02	6.45E-04	-2.02E-04	-8.00E-04	-1.73E-03	-6.17E-04	1.54E-02	3.45E-04
9X:2X	4.94E-06	1.63E-02	-9.86E-03	-2.34E-05	-2.02E-02	7.44E-03	5.08E-05	9.58E-03	-8.70E-03	-2.80E-05
9Y:2X	2.56E-03	-1.78E-04	1.37E-02	-1.94E-03	8.15E-04	-1.05E-02	9.16E-04	-1.08E-03	1.26E-02	1.54E-05
10X:2X	-1.02E-04	1.77E-02	1.12E-02	8.87E-06	-2.15E-02	-8.64E-03	-1.82E-05	9.47E-03	1.05E-02	1.98E-05
10Y:2X	2.49E-03	3.89E-04	-1.29E-02	-1.83E-03	-5.85E-04	9.78E-03	9.34E-04	6.57E-04	-1.15E-02	-4.88E-05

Finite Element Model

	SHAPE1	SHAPE2	SHAPE3	SHAPE4	SHAPE5	SHAPE6	SHAPE7	SHAPE8	SHAPE9	SHAPE10
1X:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1Y:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2X:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2Y:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3X:2X	1.23E-06	9.00E-04	-1.50E-04	-1.60E-06	3.00E-03	-5.31E-03	-1.80E-05	-4.20E-03	-1.14E-02	1.70E-05
3Y:2X	-8.00E-04	-4.16E-07	2.34E-04	-2.60E-03	-5.50E-06	8.29E-03	-4.20E-03	1.80E-05	1.86E-02	-4.40E-03
4X:2X	-2.40E-07	9.00E-04	1.82E-04	-2.90E-06	3.20E-03	3.57E-03	-3.80E-06	-4.30E-03	8.26E-03	-4.00E-05
4Y:2X	-8.00E-04	2.00E-06	-2.46E-04	-2.60E-03	1.59E-05	-6.68E-03	-4.10E-03	-3.10E-05	-1.50E-02	-4.50E-03
5X:2X	4.35E-06	2.50E-03	-1.83E-03	-1.30E-06	4.40E-03	-7.42E-03	-2.60E-05	-1.90E-03	4.13E-03	2.00E-06
5Y:2X	-2.40E-03	1.80E-06	2.57E-03	-4.50E-03	-3.02E-06	1.08E-02	-2.50E-03	-2.00E-05	-5.83E-03	3.00E-03
6X:2X	1.00E-06	2.50E-03	1.93E-03	1.02E-06	4.40E-03	4.48E-03	2.00E-05	-1.90E-03	-2.40E-03	5.00E-05
6Y:2X	-2.40E-03	5.00E-06	-2.30E-03	-4.50E-03	8.77E-06	-9.86E-03	-2.40E-03	2.00E-05	5.41E-03	3.00E-03
7X:2X	7.95E-06	4.10E-03	-4.45E-03	-5.80E-06	1.20E-03	-5.68E-04	-7.00E-06	4.40E-03	1.25E-02	2.00E-05
7Y:2X	-4.10E-03	4.00E-06	6.19E-03	-1.70E-03	1.05E-05	1.01E-03	4.10E-03	-5.00E-04	-2.10E-02	7.00E-05
8X:2X	1.09E-06	4.10E-03	4.51E-03	9.80E-06	1.20E-03	4.92E-04	3.00E-05	4.50E-03	-9.40E-03	5.00E-05
8Y:2X	-4.10E-03	7.00E-06	-6.30E-03	-1.60E-03	-1.37E-05	-7.90E-04	4.20E-03	6.00E-05	1.60E-02	-2.00E-04
9X:2X	1.97E-05	5.50E-03	-5.89E-03	-1.35E-05	-4.00E-03	7.36E-03	2.50E-05	-2.20E-03	-9.06E-03	-1.60E-05
9Y:2X	-5.60E-03	6.60E-06	8.66E-03	4.00E-03	2.38E-05	-1.14E-02	-1.80E-03	-5.20E-05	1.45E-02	-2.00E-04
10X:2X	5.46E-06	5.50E-03	6.39E-03	-1.35E-05	-4.00E-03	-5.24E-03	-3.58E-05	-2.30E-03	6.70E-03	1.40E-05
10Y:2X	-5.60E-03	7.70E-06	-7.38E-03	4.00E-03	-2.74E-05	9.68E-03	-1.90E-03	-5.10E-05	-1.20E-02	-2.00E-04

Model Update by optimizing Density

	SHAPE1	SHAPE2	SHAPE3	SHAPE4	SHAPE5	SHAPE6	SHAPE7	SHAPE8	SHAPE9	SHAPE10
1X:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1Y:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2X:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2Y:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3X:2X	1.93E-06	1.30E-03	-2.27E-03	-2.00E-06	4.30E-03	-5.34E-03	2.50E-05	-5.70E-03	-1.09E-02	-2.30E-05
3Y:2X	-1.20E-03	-3.90E-07	3.19E-03	-3.80E-03	-6.90E-06	7.58E-03	-5.50E-03	2.50E-05	1.62E-02	-5.90E-03
4X:2X	-2.40E-07	1.30E-03	2.39E-03	-3.00E-06	4.30E-03	5.85E-03	-5.00E-05	-5.70E-03	1.29E-02	-5.00E-05
4Y:2X	-8.00E-04	4.10E-06	-2.85E-03	-3.80E-03	2.20E-05	-6.73E-03	-5.50E-03	-4.20E-05	-1.43E-02	-6.00E-03
5X:2X	6.20E-06	3.50E-03	-5.93E-03	-2.17E-06	5.80E-03	-7.47E-03	-2.00E-05	-5.00E-05	3.95E-03	8.00E-05
5Y:2X	-3.40E-03	2.80E-06	7.67E-03	-5.90E-03	-3.02E-06	9.87E-03	-9.00E-04	-4.00E-05	-5.05E-03	5.70E-03
6X:2X	1.70E-06	3.50E-03	5.59E-03	2.00E-06	5.80E-03	7.35E-03	4.00E-05	2.40E-05	-3.73E-03	8.00E-05
6Y:2X	-3.40E-03	7.70E-06	-7.81E-03	-5.90E-03	9.60E-06	-9.88E-03	-8.00E-04	5.00E-05	5.17E-03	5.80E-03
7X:2X	1.09E-05	5.70E-03	-3.92E-03	-1.24E-05	1.10E-03	-5.72E-04	-1.00E-05	5.90E-03	1.19E-02	2.00E-05
7Y:2X	-5.70E-03	4.66E-05	5.45E-03	-1.60E-03	1.50E-05	9.19E-04	5.90E-03	-5.00E-05	-1.82E-02	-3.50E-03
8X:2X	4.30E-06	5.70E-03	3.97E-03	1.24E-05	1.00E-03	8.08E-04	2.80E-05	6.00E-03	-1.47E-02	7.50E-05
8Y:2X	-5.70E-03	9.60E-06	-5.54E-03	-1.60E-03	-2.00E-05	-7.96E-04	6.00E-03	6.00E-05	1.53E-02	-3.60E-03
9X:2X	1.50E-05	7.50E-03	-8.68E-03	-1.90E-05	-5.90E-03	6.62E-03	3.70E-05	-2.90E-03	-7.74E-03	-2.00E-05
9Y:2X	-7.60E-03	9.60E-06	1.21E-02	6.00E-03	3.00E-05	-9.35E-03	-2.40E-03	7.00E-05	1.12E-02	-3.00E-04
10X:2X	6.60E-06	7.50E-03	9.86E-03	-1.90E-05	-6.00E-03	-7.69E-03	-5.00E-05	-3.00E-03	9.35E-03	2.00E-05
10Y:2X	-7.60E-03	1.20E-05	-1.14E-02	6.10E-03	-3.50E-05	8.70E-03	-2.50E-03	-7.00E-05	-1.02E-02	-2.00E-04

Model Update by optimizing elasticity										
	SHAPE1	SHAPE2	SHAPE3	SHAPE4	SHAPE5	SHAPE6	SHAPE7	SHAPE8	SHAPE9	SHAPE10
1X:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1Y:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2X:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2Y:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3X:2X	1.20E-06	9.00E-04	-2.72E-03	-2.08E-06	4.48E-03	-6.41E-03	2.40E-05	-5.47E-03	-1.31E-02	-2.21E-05
3Y:2X	-8.00E-04	-4.10E-07	3.82E-03	-3.96E-03	-7.19E-06	9.10E-03	-5.28E-03	2.40E-05	1.95E-02	-5.66E-03
4X:2X	-2.70E-07	1.35E-03	2.87E-03	-3.13E-06	4.48E-03	7.02E-03	-4.80E-05	-5.47E-03	1.55E-02	-4.80E-05
4Y:2X	-8.00E-04	2.80E-06	-3.42E-03	-3.96E-03	2.29E-05	-8.07E-03	-5.28E-03	-4.03E-05	-1.72E-02	-5.76E-03
5X:2X	4.00E-06	2.50E-03	-7.12E-03	-2.26E-06	6.04E-03	-8.97E-03	-1.92E-05	-4.80E-05	4.74E-03	7.68E-05
5Y:2X	-2.40E-03	1.80E-06	9.21E-03	-6.15E-03	-3.15E-06	1.18E-02	-8.64E-04	-3.84E-05	-6.07E-03	5.47E-03
6X:2X	1.00E-06	2.50E-03	6.71E-03	2.08E-06	6.04E-03	8.82E-03	3.84E-05	2.30E-05	-4.48E-03	7.68E-05
6Y:2X	-2.40E-03	5.00E-06	-9.37E-03	-6.15E-03	1.00E-05	-1.19E-02	-7.68E-04	4.80E-05	6.21E-03	5.57E-03
7X:2X	7.00E-06	3.90E-03	-4.70E-03	-1.29E-05	1.15E-03	-6.87E-04	-9.60E-06	5.66E-03	1.43E-02	1.92E-05
7Y:2X	-3.80E-03	4.50E-06	6.54E-03	-1.67E-03	1.56E-05	1.10E-03	5.66E-03	-4.80E-05	-2.19E-02	-3.36E-03
8X:2X	2.00E-06	3.90E-03	4.76E-03	1.29E-05	1.04E-03	9.70E-04	2.69E-05	5.76E-03	-1.77E-02	7.20E-05
8Y:2X	-3.80E-03	6.92E-06	-6.65E-03	-1.67E-03	-2.08E-05	-9.55E-04	5.76E-03	5.76E-05	1.84E-02	-3.46E-03
9X:2X	1.00E-05	5.50E-03	-1.04E-02	-1.98E-05	-6.15E-03	7.95E-03	3.55E-05	-2.78E-03	-9.29E-03	-1.92E-05
9Y:2X	-5.60E-03	6.30E-06	1.45E-02	6.25E-03	3.13E-05	-1.12E-02	-2.30E-03	6.72E-05	1.35E-02	-2.88E-04
10X:2X	5.00E-06	5.50E-03	1.18E-02	-1.98E-05	-6.25E-03	-9.23E-03	-4.80E-05	-2.88E-03	1.12E-02	1.92E-05
10Y:2X	-5.60E-03	7.00E-06	-1.36E-02	6.35E-03	-3.65E-05	1.04E-02	-2.40E-03	-6.72E-05	-1.23E-02	-1.92E-04

Model Update - Final Revision

	SHAPE1	SHAPE2	SHAPE3	SHAPE4	SHAPE5	SHAPE6	SHAPE7	SHAPE8	SHAPE9	SHAPE10
1X:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1Y:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2X:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2Y:2X	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3X:2X	1.20E-06	9.00E-04	-2.72E-03	-2.08E-06	4.48E-03	-6.41E-03	2.40E-05	-5.47E-03	-1.31E-02	-2.21E-05
3Y:2X	-8.00E-04	-4.10E-07	3.82E-03	-3.96E-03	-7.19E-06	9.10E-03	-5.28E-03	2.40E-05	1.95E-02	-5.66E-03
4X:2X	-2.70E-07	1.35E-03	2.87E-03	-3.13E-06	4.48E-03	7.02E-03	-4.80E-05	-5.47E-03	1.55E-02	-4.80E-05
4Y:2X	-8.00E-04	2.80E-06	-3.42E-03	-3.96E-03	2.29E-05	-8.07E-03	-5.28E-03	-4.03E-05	-1.72E-02	-5.76E-03
5X:2X	4.00E-06	2.50E-03	-7.12E-03	-2.26E-06	6.04E-03	-8.97E-03	-1.92E-05	-4.80E-05	4.74E-03	7.68E-05
5Y:2X	-2.40E-03	1.80E-06	9.21E-03	-6.15E-03	-3.15E-06	1.18E-02	-8.64E-04	-3.84E-05	-6.07E-03	5.47E-03
6X:2X	1.00E-06	2.50E-03	6.71E-03	2.08E-06	6.04E-03	8.82E-03	3.84E-05	2.30E-05	-4.48E-03	7.68E-05
6Y:2X	-2.40E-03	5.00E-06	-9.37E-03	-6.15E-03	1.00E-05	-1.19E-02	-7.68E-04	4.80E-05	6.21E-03	5.57E-03
7X:2X	7.00E-06	3.90E-03	-4.70E-03	-1.29E-05	1.15E-03	-6.87E-04	-9.60E-06	5.66E-03	1.43E-02	1.92E-05
7Y:2X	-3.80E-03	4.50E-06	6.54E-03	-1.67E-03	1.56E-05	1.10E-03	5.66E-03	-4.80E-05	-2.19E-02	-3.36E-03
8X:2X	2.00E-06	3.90E-03	4.76E-03	1.29E-05	1.04E-03	9.70E-04	2.69E-05	5.76E-03	-1.77E-02	7.20E-05
8Y:2X	-3.80E-03	6.92E-06	-6.65E-03	-1.67E-03	-2.08E-05	-9.55E-04	5.76E-03	5.76E-05	1.84E-02	-3.46E-03
9X:2X	1.00E-05	5.50E-03	-1.04E-02	-1.98E-05	-6.15E-03	7.95E-03	3.55E-05	-2.78E-03	-9.29E-03	-1.92E-05
9Y:2X	-5.60E-03	6.30E-06	1.45E-02	6.25E-03	3.13E-05	-1.12E-02	-2.30E-03	6.72E-05	1.35E-02	-2.88E-04
10X:2X	5.00E-06	5.50E-03	1.18E-02	-1.98E-05	-6.25E-03	-9.23E-03	-4.80E-05	-2.88E-03	1.12E-02	1.92E-05
10Y:2X	-5.60E-03	7.00E-06	-1.36E-02	6.35E-03	-3.65E-05	1.04E-02	-2.40E-03	-6.72E-05	-1.23E-02	-1.92E-04