POLITECNICO DI TORINO

MASTER THESIS

# Damage Thresholds for Monitored Historical Structures

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*A thesis submitted in fulfillment of the requirements for the degree of Masters in Civil Engineering*

*in the*

Department of Civil and Structural Engineering

*"Thanks to my professors, today I can analyze and handle hundreds of problems on any topic without feeling very stressed, which is how a good civil engineer should be."*

Mohamad Dabdoub

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# *Abstract*

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The purpose of this study is to update the material properties of the structural elements of the Sanctuary of Vicoforte by the mean of model updating in order to use the updated model to increase the environmental and operational variations and noise rejection capability of model based damage identification algorithms. Finite element model updating has recently arisen as an issue of high importance on the design, construction, maintenance of structures in civil engineering. Model updating is the process of updating mass and stiffness matrices of the desired finite element model that has been already monitored. It is divided into two main families, deterministic and iterative approaches. In this study, an iterative approach has been used for determining the results.
The updating method used is particle swarm optimization which is part of the nature-inspired methods that consists also of,for instance, genetic algorithm. The updating procedure was based on the experimental results estimated in 2016 by the mean of the structural health monitoring sensing system, where natural frequencies and modal parameters have been acquired. Nevertheless, the structure has been modeled three-dimensionally using Autocad and analyzed with DIANA FEA software. Both results, experimental and numerical (analytical), have been correlated using modal assurance criterion (MAC) and a cost function that takes into account the difference between the results in order later update the chosen structural elements in the Sanctuary. As it is stated previously, results are iterated up to reach acceptable values of the difference between numerical and experimental values. In our study, the initial configuration of the material properties shows that the eigenvalues and eigenvectors are close to the experimental results, although the natural frequencies are different from the measured values. As a result, it was found that also fine-tuning could be a good estimation as the results between the experimental and numerical showed almost a consistent relation. Moreover, after updating iteratively the mechanical properties of the structural elements, the eigenanalysis showed an agreement with the experimental data.
As a conclusion, the numerical model that has been updated can be furtherly studied as the model is showing acceptable results compared to the measured one. These studies that can be carried out on the model could be the effect of temperature on the dynamic behavior of the Sanctuary, also the effect of the soil on the structure as a function of the degree of saturation.

**Keywords**: Finite Element Modeling, Model Updating, Particle Swarm Optimization, Fine-tuning, Eigenvalue Analysis.

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# List of Symbols

| | |
|---|---|
| $d$ | distance |
| $\omega$ | Angular Frequency |
| $f$ | Natural Frequency |
| $\psi$ | Modal Vector |
| $\phi$ | Mode Shape |
| K | Stiffness Matrix |
| M | Mass Matrix |
| $\phi_r$ | r-th mode shape |
| d.o.f | Degree of Freedom |
| MAC | Modal Assurance Criterion |
| FRF | Frequency Response Function |
| FE | Finite Element |
| SVM | Support Vector Machine |
| LST | Land Surface Temperature |

*Dedicated to my family*

# Chapter 1

# Introduction

## 1.1 Introduction

Finite element model updating has come out recently as it is concerned with the correction of the finite element models in many different fields, specifically engineering. Finite element method is widely used to model the dynamics of structures as it is considered as a robust tool for providing accurate results, according to Zienkiewicz and Taylor, it is the most appropriate and realistic method that may deal with large complex structures [1].
But however, inaccuracies will arise due to the problems that will encounter the modeling procedure. A three commonly errors which may give rise to inaccuracy in the numerical results are model structure errors where it occurs when there is uncertainty concerning the governing physical equations, model parameter errors due to the inappropriate boundary conditions and inaccurate assumptions, and model order errors which would arise in the discretization of complex systems [2]. These inaccuracies can be realized when comparing between predicted and measured results, then general improvement can be done based on the experimental test results although, it should be mentioned that, they are not taken without errors.
Many model updating methods have been proposed, but all seek to correct the inaccurate parameters in the model so that an agreement is reached between predictions and test results. Model updating in dynamics aims to achieve that the mass, stiffness and damping parameters in the updated model to be physically meaningful. According to J.E. Mottershead [2], the methods also can be divided based on the type of the measured data and the model parameters that are updated. Where such data are sometimes in form of frequency response function (FRF) or natural frequencies and mode shapes. In addition to that, Mottershead and Friswell, have considered that the choice of the parameters for model updating is a crucial step where these parameters are chosen for correcting uncertainty in the model [3].
All what had been mentioned state that, the problem of model updating can be described in two equations; the first one is that observation equals to reality and the observation errors/noise, and the second equation about model which equals to reality and discrepancy of the model. The model updating tries to minimize difference between the observed results and the numerical model. As it is stated previously, many methods have been developed for the purpose of solving the problem of inaccuracy, where some of these methods were found decades ago but they are still being proposed to solve this problem. Methods can be divided into two main categories/methodologies in structural dynamics: the direct methods and the iterative methods. The usage of these two families will be briefly presented in the following sections.

## 1.2 Direct Methods

### 1.2.1 Advantages and Disadvantages

Direct methods are proposed for updating parameters such as natural frequencies using mass and stiffness matrices, such methods have the capability to reproduce the measured data exactly, and thus they are called as representational methods. However, such methods don't require iterations which are considered as a great advantage that may eliminate divergence and excessive computation. But due to the fact that there will be measurement inaccuracies in numerical data and measurement noise in experimental data, they are unlikely to be equal. This means that we should have very high quality measurements, otherwise analysis may be flawed [3].
Another problem is the mode shapes that must be expanded to the size of the finite element model, which will then introduce errors in the data required by the updating algorithm due to the errors in the model itself. Even though, Mottershead considered an alternative, which is the reduction of the finite element model to the measured degrees of freedom, but this would also lead to error localisation and damage detection problems because of the reduced model which would have a change in matrices due to the inadequate modelling [2][3].
In the direct method, updated mass and stiffness matrices are meant to be physically less meaningful because the methods are unable to keep connectivity of nodes and so the updated matrices are usually fully populated.

### 1.2.2 Updating Approaches

Direct method that is also called representation models target to match some reference data which is usually consist of incomplete set of eigenvalues and eigenvectors derived from measurements. In literature, different methods have been introduced such as;

- Lagrange Multiplier Methods
- Matrix Mixing Methods
- Inverse Eigenvalues Methods
- Methods from Control Theory

Lagrange multiplier method is an optimization method that tries to minimize an objective function that is subjected to constraints; such method considers three main quantities experimental modal data, and numerical mass and stiffness matrices. The measured eigenvectors are updated so they are orthogonal with respect to the mass matrix, then an updated stiffness matrix is estimated that will be related to the experimental modal data.
Matrix mixing method assumes that all the vibration modes are measured at all d.o.f and so mass and stiffness matrices can be constructed directly. This method has two main difficulties, first that the measured modes are less than the number of d.o.f and also the response of the structure is measured in specific points of the structure. Second, the expansion of the experimental mode shapes.
Inverse eigenvalues method tends to reproduce a number of measured modes exactly, where it has been adapted from the control theory. It is also called pole placement, if the eigenvalues are used.

## 1.3 Iterative Methods

### 1.3.1 Advantages and Disadvantages

Iterative methods modify the finite element model parameters incrementally, while maintaining desirable properties these parameters will be physically meaningful, they are also called local methods. The correlation between the measured and analytical model is determined by penalty functions which are generally non-linear functions, and thus the problems has to be linearized and optimized iteratively. However, both measured and analytical data can be weighted, a feature accommodate engineering intuition.
There are three major problems when relating analytical estimates and experimental data. First, modes must be paired correctly and not always sorting the frequencies, for instance, in ascending order is sufficient. Another problem when pairing, experimental measurements are not taken accurately, usually because the force excitation or the accelerometer is placed close to a node of a particular mode shape.
Second, the difference in the mass distribution of the experimental and actual structure and this means that the mode shapes should be scaled, this can be done using modal scale factor (MSF). Third problem is related to the absence of the damping in the theoretical model which requires either a real mode shape to be extracted from measured complex FRF data or the updating algorithm must be able to overcome such data[3].

### 1.3.2 Updating Approaches

Iterative models are mathematical based methods taken from theories, fitting the need of model updating. These methods can be divided into three families;

- Sensitivity Based Methods
- Optimization Methods
- Bayesian/Monte Carlo Approach

Sensitivity methods is one of the most successful and popular techniques for model updating. It has been applied to large and complex structures; the sensitivity method updating approach is as a non-linear least square minimization problem which is solved by iterations of linear approximation [4].
Optimization is a mean of finding the best solution to a desired problem. Mathematically, it involves finding the minimum and maximum of a function that can be constrained by additional functions that are related to specific physical quantities [5]. There are many optimization methods that can be used for model updating, where these methods can be nature-inspired algorithms like genetic algorithms, particle-swarm method, simulated annealing, and evolutionary strategies, or response surface method or gradient based method.
Bayesian method is a method that is based on Bayes' theorem, that describes the probability of an event that depends on a prior knowledge of the conditions related to that specific event. In structural dynamics of Bayesian theory has been used for identification of parameters and detection of damages in steel structures as in the case of Wu and Li, for example.

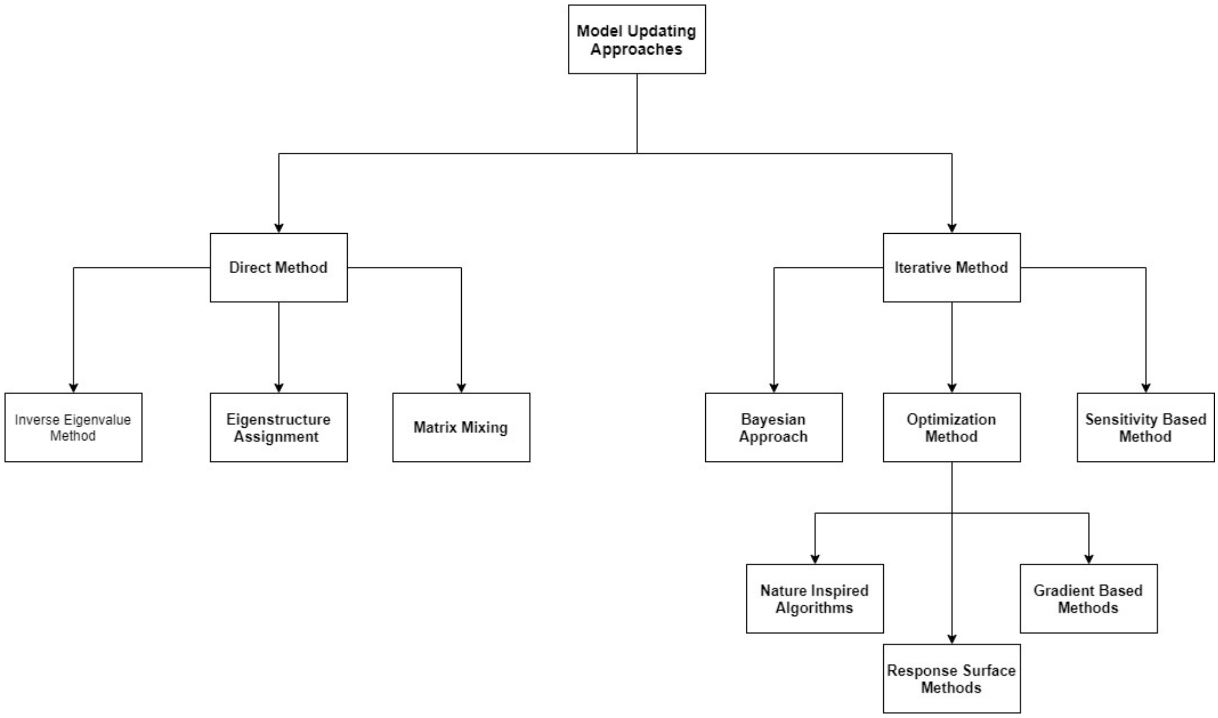



FIGURE 1.1: Model Updating Approaches

## 1.4 Overview of the Thesis

Chapter two describes the case study that is called the Sanctuary of Vicorforte which is a church. The history of the church is described from the time been constructed with the interventions that has been done for specific parts. In addition to that, the geometrical elements that represent the body of the church are presented part by part. The finite element model (mechanical model) that is constructed using DIANA FEA software is illustrated with material properties considered for the elements of the church.
Chapter three provides information about the eigenvectors and eigenvalues in their initial configuration. Thus, these results are considered as the numerical data i.e. the analytical one which then will be used for the model updating.
In the next chapter, chapter four, experimental data are presented considering the measurement tools used to take such data i.e. monitoring procedure used for detecting damages and extracting information. However, the chosen model updating method is described, particle swarm optimization method has been used among the other updating methods, chosen method usually used to generate highly quality solutions to optimization problems where it relies on the positions and the velocity of the particles. Finally, in this chapter, model assurance criterion (MAC) values are computed for the purpose of validation of the modes considered.
Chapter five concludes the thesis report as it represents the conclusion. It discusses the results obtained from the updating procedure, problems encountered during the project and recommendations.

# Chapter 2

# Case Study: Sanctuary of Vicoforte

Historical structures are considered as the city characters that give a sense of community generation by generation through its history. These structures are witnesses on the happened events overtime in the city, they reflect conflicts, wars, traditions, and the economic condition of the city as well. Preserving these old buildings is important and has many benefits, specifically with respect to tourism, culture and environment. In this chapter, historical description of Sanctuary of Vicoforte will be presented. Then, physical and geometric properties will be described. Finally, the construction of the finite element model will be illustrated (mechanical model) through DIANA FEA software.

## 2.1 Historical Description

Everything has started in the fifteenth century when the sanctuary contained a paint of Madonna and Child. Around 1590 the image of the Virgin has been struck by a hunter, and according to legendries, she began to bleed. The huntsman began to collect money in order to repair the damage and expiate his sin.
Later the first brick was formally introduced in the $7^{th}$ of July 1596, but has stopped later in the 1630 due to the death of the Duca Carlo Emanuale I and due to the economic and social problems. Construction restarted in the 1672 under the guide of monks and around the $16^{th}$ century the main lobby, lateral and the dome of S.Bernardo were completed and it was 18 meters height including the arches.
In 1701, the architect Francesco Gallo has been charged the construction activities who built the great elliptical dome which has major and minor diameters of 36 and 25 meters, respectively. As it is mentioned, Gallo was required to remove the scaffolding himself, as nobody thought that a structure of this type would be able to stand on its own.
In the second half of the $19^{th}$ century, the temple was recognized as an important mark, declared as a national monument from the Royal decree in the $15^{th}$ of November 1880. The main internal façade, dome, and the bell towers have been adjusted and arranged. Inauguration of the work was made in the $23^{rd}$ August 1891 with the presence of the king Re Umberto I.
The administration of the church, after one century, started extraordinary maintenance of operas, in 1982-1984; they have started with the maintenance of ground, foundation and the drainage system. In 1982-1986, the restoration activities have started for the painting and steel elements have been added into the drum.

FIGURE 2.1: Sanctuary of Vicoforte

## 2.2 Physical Description

The Sanctuary of Vicoforte is a complex stunning masonry structure that is known with it world's largest oval dome, has encountered several problems over centuries which lead to some structural problems. Unfortunately the sanctuary is threatened with unpleasant fractures and damages due to ageing, degradation of material and other significant problems. Great efforts have been made for the repair and maintenance of the sanctuary which required a better understanding of the behavior of the structure and the material properties of the elements composing the structure.
In the $13^{th}$ international Brick and Block Masonry conference, series of non-destructive testing was made on the structure [6]. These tests are radiation thermometer, electromagnetic radar, impact echo scanner, concrete test hammer, scratch tester, Windsor pin system, and electromagnetic induction scanner, for the purpose of determination of the deterioration on the Sanctuary of Vicoforte.
The value of the sanctuary prohibits the coring testing or any other destructive testing process, thus non-destructive testing had been useful instead. Tests showed that, there are severe states of delamination of stone finishing; researchers recommended that some measurements should be taken. However, they found that there is an agreement between thicknesses of main dome and vault with respect to those measured previously in the 1976 by Eng. Bernasconi. In addition to that, they are expecting that the dome of the sanctuary seems to be vulnerable to earthquakes. Also, there was a good correlation among the compressive strength for the bricks and mortar that had been estimated by Scratch Tester and Windsor Pin System and Scratched width and penetration resistance.
As it has been stated previously, the sanctuary of Vicoforte is a masonry structure composed with different elements. In the following sections, geometrical elements will be illustrated showing the cracks that have been mentioned in literature, if available. Then, the material properties of the elements will be presented.
The Sanctuary of Vicoforte is made of different sectors and halls i.e. in the ground floor which has an area of around 2900-3000 $m^2$ that is consist of the main lobby, and other sectors that will be shown in the figures below. The first floor (directly over

the ground floor) is raised by a group of columns where still the main lobby can be seen. These two mentioned floors, both together, are the base of the drum, internal and external dome, and the lantern. However, there are four bell towers placed on the corners of the basement. Finally, the soil that is underneath the structure is composed of two main types of soil clay and marl. In this part, the elements forming the sanctuary will be illustrated, mentioning the problems and cracks that each element has according to literature.

- Soil
  As shown in the figure 2.2, the soil is made up of two layers clay and marl. The soil depth that has been considered in this study is about 15 meters.

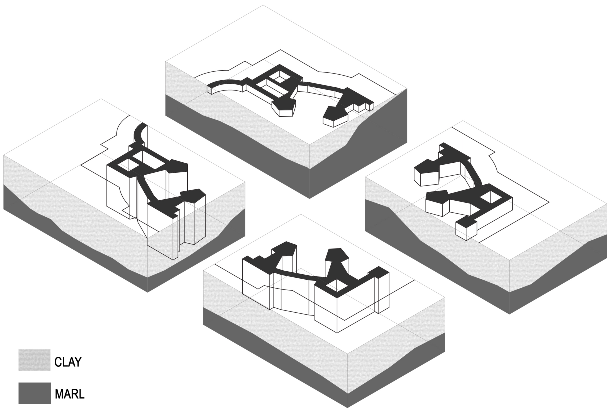



FIGURE 2.2: Soil

- Foundation
  The height of the foundation is about 3.3 meters, where it is made up of masonry material composition. The foundation of the Sanctuary of Vicoforte follows the shape as in the figure 2.3 where it follows the shape of the ground floor.

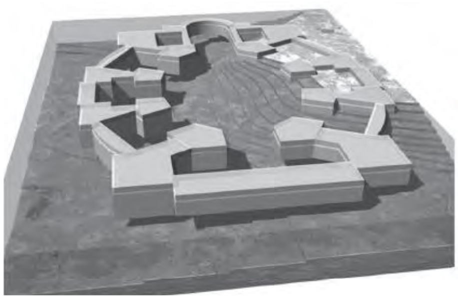


FIGURE 2.3: Foundation

In the analyses that had been held before showed a settlement in the foundation which has affected the other elements by causing cracks.

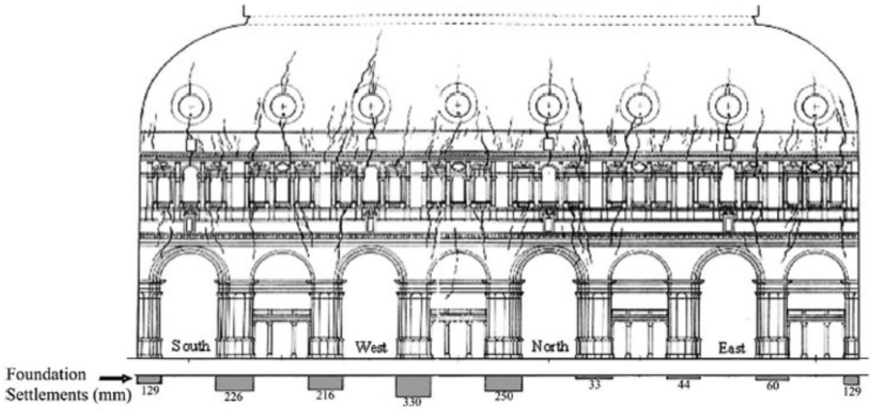


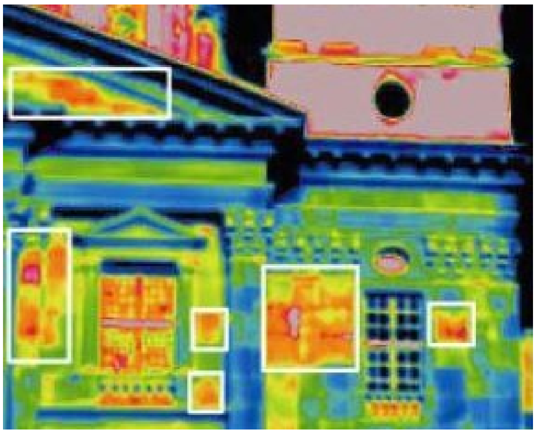

FIGURE 2.4: Foundation Settlement

- Main Lobby
  The main lobby is surrounded by 8 large arched doors each of about 15 meters height. In the figure 2.5 it can be seen a statue that had been placed in the middle of the lobby, and the pavement is made off tiles.


FIGURE 2.5: Main Lobby

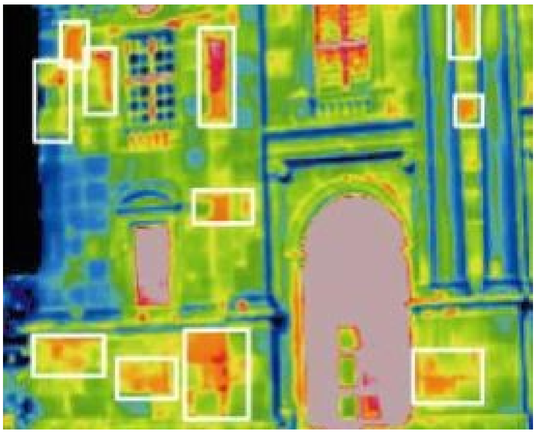
But this astonishing view doesn't show the real problems that has been discovered by the Japanese team where they detected a defects like delamination and water leakage in both south and west sides. These defects had been discovered using radiation thermometer and the Japanese team considered these problems as very dangerous where they have recommended for safety measurements to take place for solving these problems. The defects are shown in the figures below [6].
Figure 2.6 shows the delamination of fresco painting in both the south and west sides, where they are highlighted in the rectangular boxes.

(A) South Side



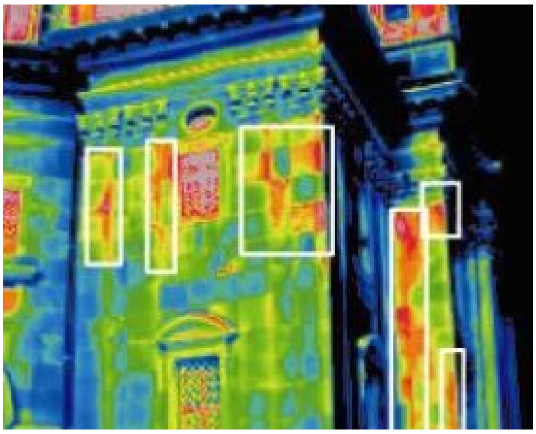
(B) Thermal South Side

(C) South Side 2



(D) Thermal South Side 2

(E) West Side



(F) Thermal West Side

FIGURE 2.6: Delamination of Stone Finishing

- Dome

  The Sanctuary of Vicoforte consists of two domes, the internal and the external dome. The internal dome is made up of masonry where it is located over the drum, while the external dome is made up of wood beams (both in tangential and radial directions of the dome) and copper shells. Many studies had been held considering the internal dome in order to estimate the natural frequency and other constitutive parameters in order to account for the damages, but also other studies targeted the detection of cracks and reinforcements inside the dome[1]. In addition to that, thermal images shows the delamination in the fresco painting from the inner sides of the dome as well, specifically near windows. The thickness of the main dome varies from 110 to 130 cm and 120 to 133 cm in south and east directions, respectively.

  Electromagnetic Radar and electromagnetic induction scanner had been applied in order to detect the presence of the reinforcement. A three sets of iron rings are embedded at the base of the main dome by Eng. Gallo as shown in 2.7 , and in 1987 post-tension steel ties inserted at the level of the drum. The total length of the ties is 104 meter, it was detected using the impact echo scanner test.

  However, during and after construction of the Sanctuary of Vicoforte plastic deformations of the dome has occur, where fracture developed, material started to separate and turns into blocks, slippage began and the discontinuous deformation begins due to many reasons including dead load, differential settlement, temperature stress, and also chemical degradation.

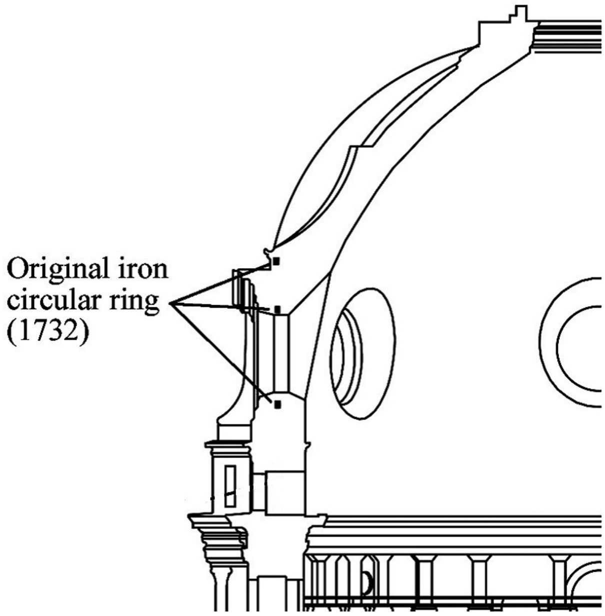



FIGURE 2.7: Position of Reinforcement

- Other Elements

  Due to the lack of information about the other elements in the structure of Vicoforte, the rest of the elements will be introduced as figures so that readers would have an idea about the upcoming tasks that had been done. These other elements are the drum (elliptical volume placed on the basement), buttresses

[1]Note that, no studies had been held considering the external dome

(elements that are attached to the drum), bell towers (towers in figure 2.1), and lantern. As it is stated before, in 1987, the university of Politecnico di Torino inserted post-tension steel bars into the drum due to the fact that there are quite a lot of cracks in this element.

FIGURE 2.8: Buttress

## 2.3 Mechanical Model

Historical Structures as the Sanctuary of Vicoforte are important where they represent the history of a country in a specific era, this makes such structures a landmark for tourists and as a result an income for the country. So the preserve of these structures is a paramount.
The analysis of these historical structures represents a challenge due to it's complexity more than that of the modern constructions. The uncertainty surrounding the materials that has been used in construction, and the other tasks that happened during the lifetime of the structure. It is important to mention again the destructive testing such as cores or other type of tests (compression tests) is prohibited in, most of the cases, due to the value that the structure represents. And thus, any intervention or retrofitting of the structure should be hidden from the visitor eyes'.
This requires a sophisticated and robust tools in order to predict a good match of the results of the analysis for these historical structures. In this part, a finite element software has been used for modeling of the Sanctuary of Vicoforte. DIANA is a unique program that allows the possibility of analysing masonry structures in detail or as a whole, under standard or extreme loading such as earthquakes.
Nowadays finite element method has become one of the most universally used method in analysis as it gives accepted results. In structure design, it leads to the construction of a discrete systems of matrix equations to represent the mass and stiffness effects of a continuous structure. These matrices are usually symmetric and banded. There is no restriction is placed upon the geometrical complexity of the structure because both matrices i.e. stiffness and mass matrices are assembled from the contributions of the individual finite elements with simple shapes. These small simple shapes possess mathematical formula that represents the geometrical shape of the structure. The structure is divided into discrete volumes and surfaces that are called elements. The element boundaries are defined when the nodal points are

connected by a unique polynomial curve or surface. Usually, elements are of displacement types where the polynomial description are related to internal, element displacements to the displacements of the nodes. This process is generally known as shape function interpolation.

Shape functions are used to express both the coordinates and the displacement of an internal point in terms of values at the nodes. For instance, if the coordinates of a point are denoted be (x,y,z) and the displacements by (u,v,w), then

$$x = \sum_{j=1}^{r} N_j x_j \tag{2.1}$$

and

$$u = \sum_{j=1}^{r} N_j u_j \tag{2.2}$$

where is the $x_j$ coordinate of the jth node and $u_j$ is the displacement of this node. Similar expressions can be written for the co-ordinates y and z and the displacements v and w. And $N_j$ is the shape function corresponding to the jth node which depends on the local coordinates. As this procedure goes on, there will be the formulation of the system of equations which is a basic step in the FEM. And finally, solution of these system of equations which will be a global solution, once these equations have been solved then we will have a meaningful and interpretable results.
As a general form, mass and stiffness can be expressed as

$$m = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} N^T \rho N.det(J) d\xi_1 d\xi_2 d\xi_3 \tag{2.3}$$

$$k = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} B^T DB.det(J) d\xi_1 d\xi_2 d\xi_3 \tag{2.4}$$

Where $\rho$ represents the mass density, D is the elasticity matrix, N is the matrix of the shape functions, and B is the matrix of the shape function derivatives. However, the J is the Jacobian matrix that defines the relation between local and global frames.
In the Euler one dimensional beam, the equations 2.3 and 2.4 can be written as following;

$$m = \rho A \int_{-1}^{1} N^T N (\frac{dx}{d\xi_1}) d\xi_1 \tag{2.5}$$

$$k = EI \int_{-1}^{1} B^T B (\frac{dx}{d\xi_1}) d\xi_1 \tag{2.6}$$

where B consists of the terms which are the second derivatives of the shape function, with respect to x, EI is the bending rigidity, and A is the area.
Obviously, the element matrices are symmetric, and that the terms depend directly upon the physical quantities such as Young's modulus, mass density, area, second moment of area, and the physical dimensions of the structures. The mass and stiffness matrices can be obtained directly from energy considerations such that the shape functions and their derivatives represent the distribution of displacements and strains (or rotations) respectively.
The finite element model is assembled from contributions acquired from the individual elements. At nodes where a number of individual elements meet of different types as in our model, the motion experienced at each of the element nodal degrees

of freedom in turn must be identical if the model doesn't undergo separation. Constraints are tie elements together, and result in individual element mass and stiffness terms being added to the mass and stiffness terms of other elements at nodes that will be shared with other elements at each degree of freedom in turn. The overall mass and stiffness matrices are generally sparsely populated and the degree to which the matrices are banded can often be significantly affected by the arrangement and ordering (numbering) of the degrees of freedom in the assembled system of equations.
All these steps that have been mentioned are done behind the scenes, users are only modeling the structure geometrically and assign the necessary parameters that fit their needs. In this part of the chapter, the modeling of the Sanctuary of Vicoforte is described. Modeling of a structure is usually consist of these main steps;

- Drawing of the geometry
  The study of the Sanctuary of Vicoforte, that compromises the modeling and analysis, was performed using a 3D model that has been drawn first in AutoCad before exporting to the FEA software DIANA. The whole elements of the structure were modeled with solid elements except the steel elements that are located in the drum. However, a large volume of soil has been considered in the model due to the fact that later, sensitivity analysis will be done. A global view of the model is shown in the figure below; It has to be mentioned that,

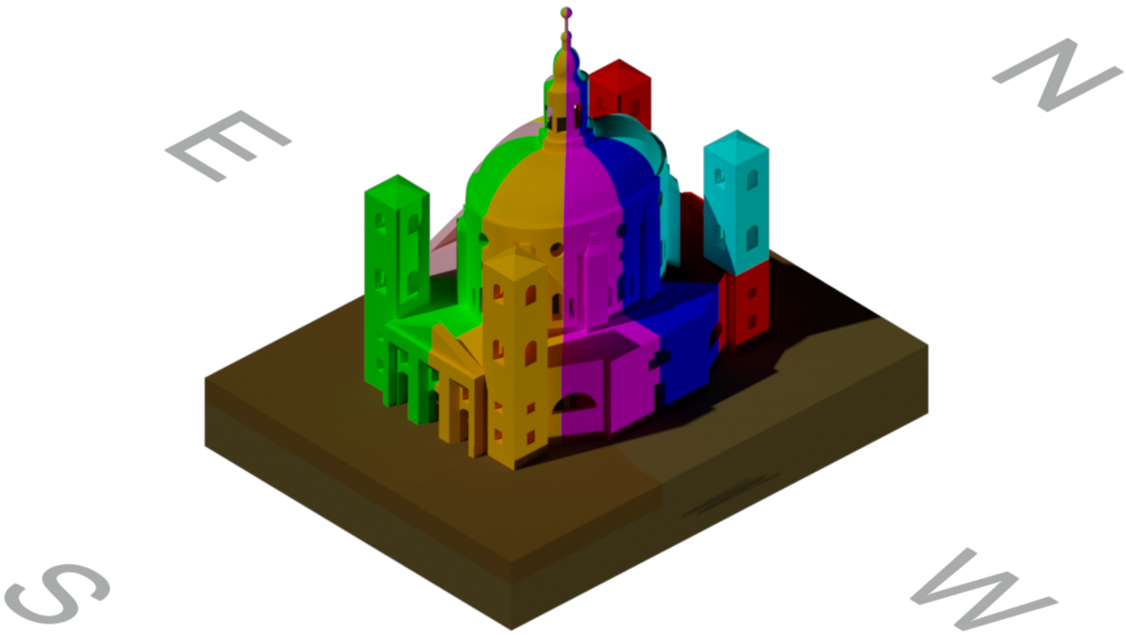



FIGURE 2.9: 3D Model-Autocad

  the reference system that is used in the modeling is as following: x direction is from south to north of the Church (yellow to blue), the y direction is from left to right (green to yellow), and the z is the elevation of the church).
  The structural elements such as main-body, drum and others were exported to the Diana software by the mean of IGES extension, that is a common extension between DIANA and AUTOCAD. Figure 2.11 shows the window that is used normally to define the element class of an element and the corresponding

material. The element class that has been considered in the study is the solid elements.

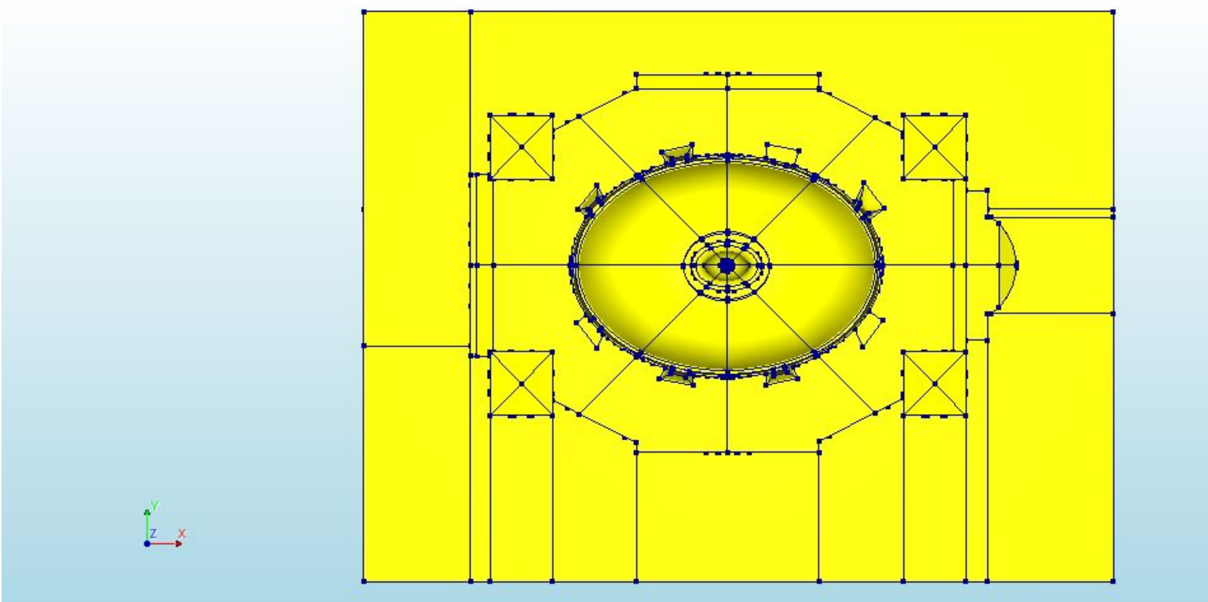



FIGURE 2.10: Reference System

- Material assignation
  The main structural elements of this historical structure, Sanctuary of Vicoforte, consist mainly of masonry material. The initial material properties selected for the analysis are given in the table 2.1.Although these values are taken from a calibrated model, still due to the purpose of this project another values are going to be estimated. The constitutive law that was considered in the analysis is the linear elastic one, thus three values will be considered which are the young modulus, Poisson ratio $v$ and the density of the material.

| Element | Young modulus $E$ (GPa) | Poisson Ratio $v$ | Density (Kg/m$^3$) |
|---|---|---|---|
| Clay | 0.75 | 0.35 | 1900 |
| Silt | 5.6 | 0.35 | 2100 |
| Foundation | 2 | 0.35 | 1800 |
| Main-Body | 2 | 0.35 | 1800 |
| Towers | 4.5 | 0.35 | 1800 |
| Buttresses | 5.5 | 0.30 | 1700 |
| Drum | 2.3 | 0.35 | 1700 |
| Dome | 5.5 | 0.35 | 1800 |
| Lantern | 5.6 | 0.35 | 1800 |

TABLE 2.1: Material Properties

Note that when assigning the material parameters to the elements, it has been considered that the soil is exactly like the other elements and thus normal geotechnical/soil parameters like porosity has not been considered.
Another element is the external dome that is composed of the following materials: copper, and wood. The copper layer is of thickness 1 cm, and the wood layer of thickness 2 cm. However, the external dome is also composed of 44

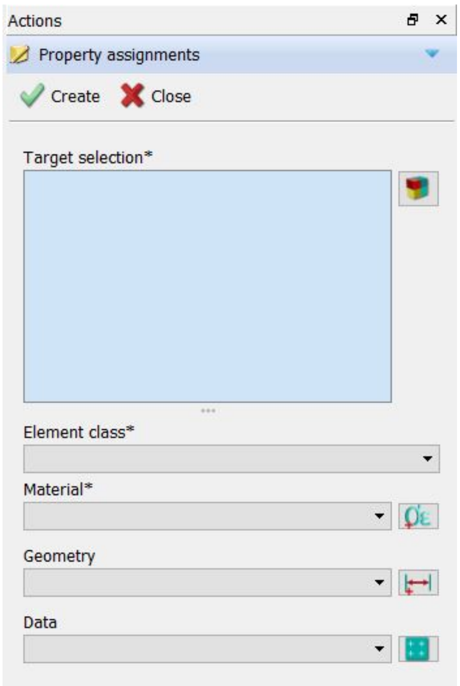



FIGURE 2.11: DIANA Environment- Properties Assignment

wood beams, each of 23x8cm and 5 columns 15x15cm that intersects with the internal dome.The external dome has been designed as a shell element, where the layer of the copper modelled to be overlaying over the wood shell.
Copper material properties:

- Young Modulus E = 117 GPa
- Poisson Ratio v = 0.25
- $\rho$ = 8940 kg/$m^3$

In addition to that, when modeling the wood material, it has been assumed an equivalent mass density that compromise the wood beams and the shell. The mass of the wood beams are estimated, then it is added to the shell's one in order to account for the presence of the wood beams. Wood material properties:

- Young Modulus E = 8.1 GPa
- Poisson Ratio v = 0.25
- $\rho_{equivalent}$ = 651 kg/$m^3$

Moreover the steel elements that are inside the drum, were given 210 GPa as a young modulus, Poisson ratio of 0.3 and mass density of 7800 Kg/$m^3$. As the elastic constitutive model is considered in our project, just these three parameters are going to be assigned to the material section in the figure 2.11.

- Mesh assignment
  Sanctuary of Vicoforte is a complex structure that needs a bit of care when dealing with its mesh and its element size. In this model, the size of element that has been used is in the range of 0.5 to 1.5 meters, and the mesher type is hexa and quad elements. The total number of elements created in the model are more than 265000 elements as it is shown in the figure 2.12.
  When dealing with solid elements in DIANA software, different solid elements

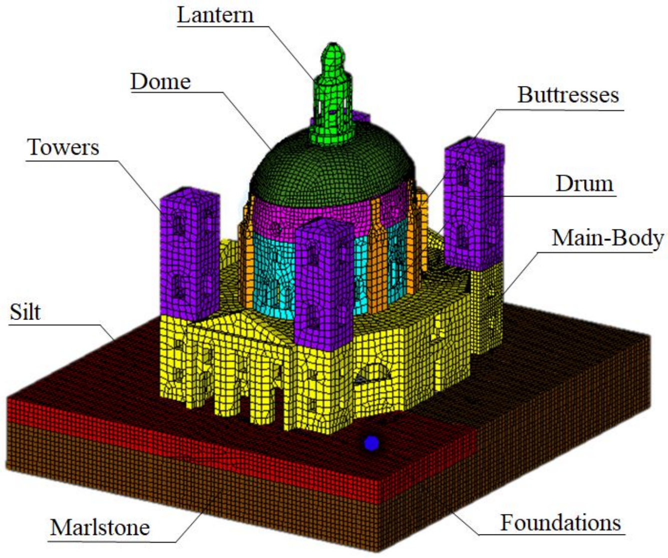



FIGURE 2.12: Generated Mesh

types are assembled to the model. These solid elements depend upon the shape of the structural element, and the size of mesh assigned. The elements that were used by DIANA are the following; HX24L, PY15L, Q20SH, T15SH, TE12L, and TP18L. The differences among these elements are the shape, sides, nodes and order[**cite**].

- TE12L-tetrahedron, 3 sides, and 4 nodes: TE12L element is a four-noded, three-side isoparametric solid tetrahedron element, that is based on linear interpolation and numerical integration. The polynomials for the translations $u_{xyz}$ can be expressed as

$$u_i(\xi, \eta, \xi) = a_0 + a_1\xi + a_2\eta + a_3\zeta \tag{2.7}$$

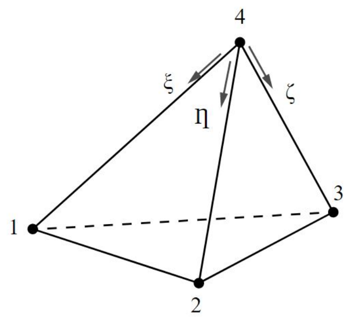



FIGURE 2.13: ELement Type: TE12L

- PY15L-pyramid, 5 nodes: PY15L is a five-noded isoparametric solid pyramid element based on linear interpolation and numerical integration. The polynomials can be expressed as

$$u_1(\xi, \eta, \xi) = \frac{1}{8}(1-\xi)(1-\eta)(1-\zeta) \tag{2.8}$$

$$u_2(\xi, \eta, \xi) = \frac{1}{8}(1+\xi)(1-\eta)(1-\zeta) \tag{2.9}$$

$$u_3(\xi, \eta, \xi) = \frac{1}{8}(1+\xi)(1+\eta)(1-\zeta) \tag{2.10}$$

$$u_4(\xi, \eta, \xi) = \frac{1}{8}(1-\xi)(1+\eta)(1-\zeta) \tag{2.11}$$

$$u_5(\xi, \eta, \xi) = \frac{1}{2}(1+\zeta) \tag{2.12}$$

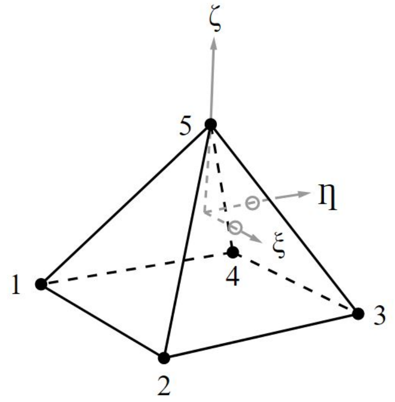



FIGURE 2.14: ELement Type: PY15L

A pyramid element approximates these upcoming strain and stress distribution over the element volume. The strain $\epsilon_{xx}$ and stress $\sigma_{xx}$ are constant in the x direction and they also vary linearly in both y and z direction. The strain $\epsilon_{yy}$ and stress $\sigma_{yy}$ are constant in y direction and they both vary linearly in the x and z direction. The strain $\epsilon_{zz}$ and stress $\sigma_{zz}$ are constant in z direction and they also vary linearly in x and y direction.

– TP18L-wedge, 6 nodes: TP18L is a six-noded isoparametric solid wedge element that is based on linear area interpolation in the triangular domain and a linear isoparametric interpolation in the $\zeta$ direction. The polynomials for the translations $u_{xyz}$ can be expressed as

$$u_i(\xi, \eta, \zeta) = a_0 + a_1\xi + a_2\eta + a_3\zeta + a_4\xi\zeta + a_5\eta\zeta \tag{2.13}$$

These polynomials yield a constant strain and stress distribution over the element volume.

– HX24L-brick, 8 nodes: is an eight-noded isoparametric solid brick element. It is based on linear interpolation and Gauss integration. The polynomials for the translations $u_{xyz}$ can be expressed as

$$u_i(\xi, \eta, \zeta) = a_0 + a_1\xi + a_2\eta + a_3\zeta + a_4\xi\eta + a_5\eta\zeta + a_6\zeta\xi + a_7\xi\eta\zeta \tag{2.14}$$

A rectangular brick element approximates the strain and stress distribution over the element volume. The strain $\epsilon_{xx}$ and stress $\sigma_{xx}$ are constant

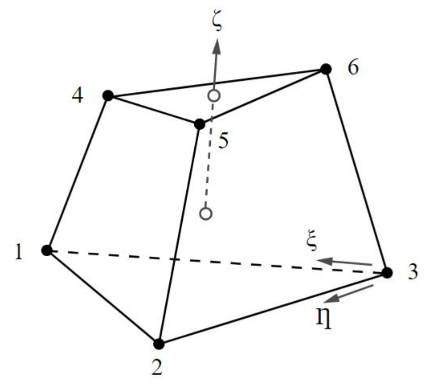



FIGURE 2.15: ELement Type: TP18L

in x direction and they vary linearly in the y and z direction. The strain $\epsilon_{yy}$ and stress $\sigma_{yy}$ are constant in y direction and also they vary linearly in x and z direction. The strain $\epsilon_{zz}$ and stress $\sigma_{zz}$ are constant in z direction and vary linearly in both the x and y direction.

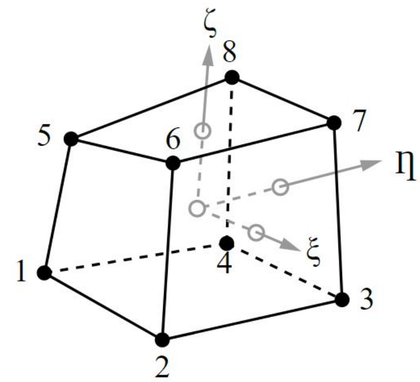



FIGURE 2.16: ELement Type: HX24L

– Q20SH is a four node quadrilateral isoparametric curved shell element. In the figure 2.17, the desired element that is going to be meshed is selected first, and as a solid element the shape is going to be meshed, rather than meshing just the edges or the faces. Then, the element size is selected, and as it is been stated before, the sizes selected are ranging between 0.5 and 1.5 meters. Finally, the default mesher type is the one chosen at the very first step when defining the project as a new project. In our study the default mesher is the Quad and Hexa type mesher types.

- Boundary condition assignation
  Boundary conditions are important for the solution of the boundary value where the latter it is estimated as a system of differential equations that need to be solved. In this model the boundary condition has been assigned to the bottom face of the soil, where it has been pinned in the translation directions (T1,T2,T3) as it is shown in the figure 2.19. In addition to that, the model has been fixed in the plane direction (X,Y).

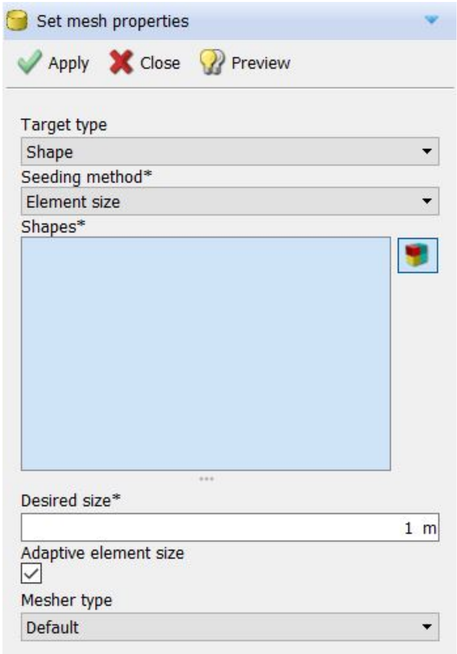



FIGURE 2.17: DIANA Environment- Mesh Assignment

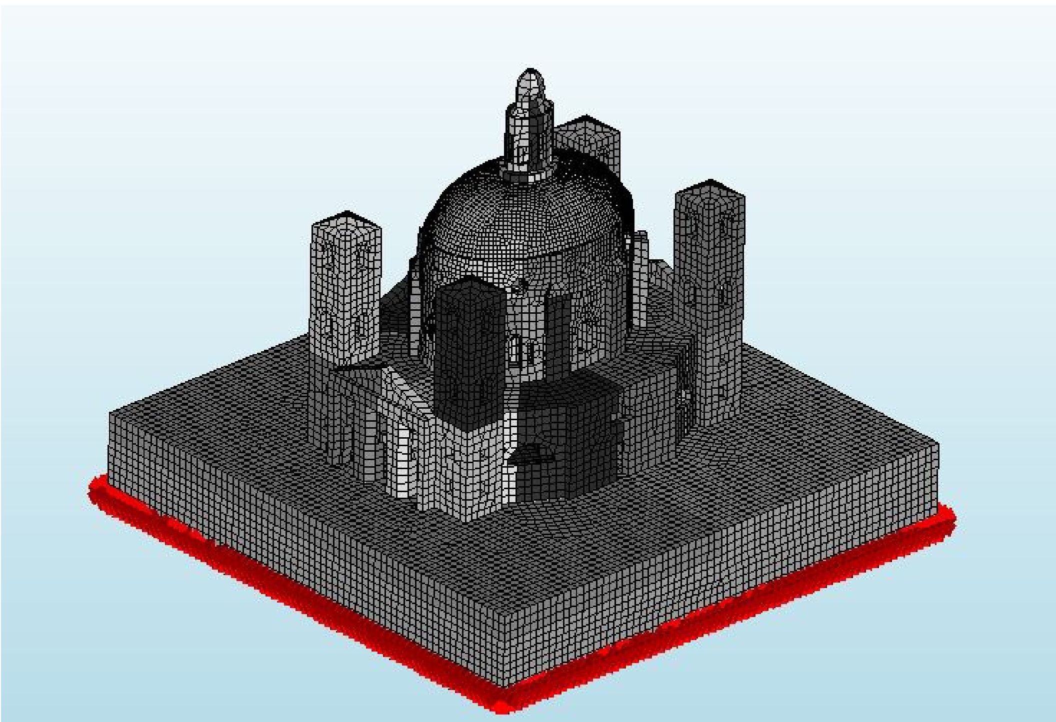


FIGURE 2.18: Boundary Condition Assignment

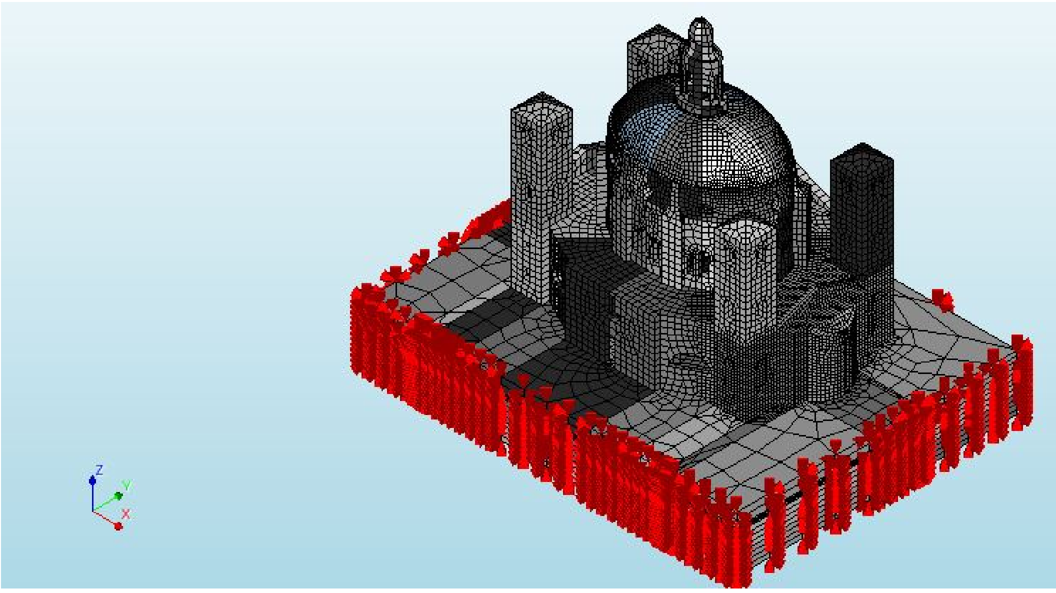


FIGURE 2.19: Boundary Condition Assignment-Along Vertical faces

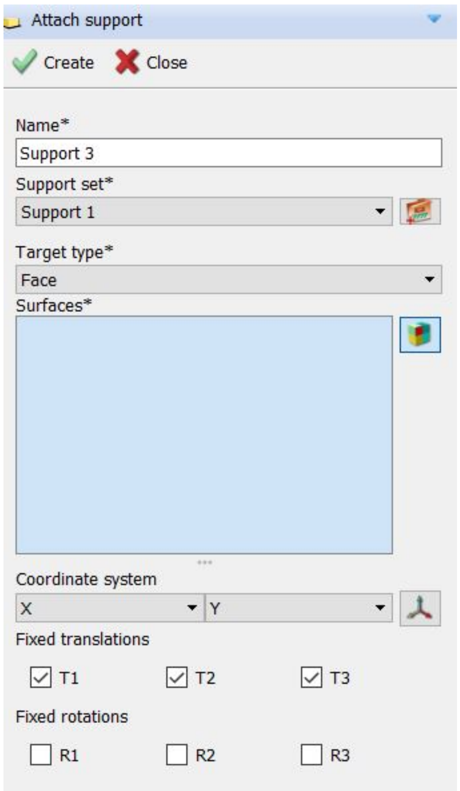



FIGURE 2.20: DIANA Environment - Support Assignment

- Load definition
  The parameters that are going to be updated in this project is the young modulus based on the values of the natural frequency of both the numerical and the experimental model in addition to the mode shapes, and thus just the dead weight has been considered as a global load set while modeling and running the analysis for the Sanctuary of Vicoforte.

# Chapter 3

# Eigenvalue Analysis

The very usual first step in dynamic analysis is the estimation of the natural frequencies and mode shapes of the structure. These results will identify the behavior of the structure when subjected to dynamic loading. Natural frequencies and mode shapes are function of the structural properties, material properties and boundary conditions. There are many reasons for computing these dynamic parameters, one of these reasons is to compare numerical results to that of the experimental one if the structure been monitored. Design decisions can thus be made by using natural frequencies and mode shapes. And the question to be asked always: Does the desired design modification cause an increase in dynamic response ?
In this chapter, the eigenvalue analysis procedure in DIANA is described and then the results of this analysis is presented with the impact of the soil volume on the results of the natural frequencies (1st actual modes) i.e. sensitivity analysis.

## 3.1 Overview of the Eigenvalue Analysis

The solution of the equation of motion for natural frequencies and normal mode requires a special reduced form of the equation of motion. If there is no damping and applied loading the equation of motion will be in the following form;

$$[M]\{u''\} + [K]\{u\} = 0 \tag{3.1}$$

where M is a the mass matrix, and K is the stiffness matrix. However the equation 3.1 represents the equation of motion for undamped free vibration and in order to solve this equation, it has to be estimated a harmonic motion where;

$$\{u\} = \{\phi\} sin\omega t \tag{3.2}$$

where $\{\phi\}$ is the eigenvector or the mode shape and w is the angular natural frequency.
In addition to the importance use of the harmonic form numerically, it has also a physical meaning where it means that the degrees of freedom of the vibrating structure move synchronous pattern. And the structural configuration does not change its basic shape during motion, but its amplitude.
Substituting the equation 3.2 in the equation 3.1 will result in;

$$-\omega^2[M]\{\phi\} sin\omega t + [K]\{\phi\} sin\omega t = 0 \tag{3.3}$$

which would be after simplification:

$$([K] - \omega^2[M])\{\phi\} = 0 \tag{3.4}$$

The latter equation is called eigenequation, where it has this form;

$$[A - \lambda I]X = 0 \tag{3.5}$$

where A is the square matrix, $\lambda$ is the eigenvalues, I is the identity matrix, and X is the eigenvector. The eigenequation is written in terms of K, $\lambda$, and M as shown in the equation 3.4 with $\omega^2 = \lambda$. There are two possible solution form for the equation 3.4:
First, if det ([K] -$\omega^2$[M]) $\neq 0$, the only possible solution is

$$\{\phi\} = 0 \tag{3.6}$$

This solution does not provide any meaningful information, except that there is no motion and so it is considered as a trivial solution.
Second, if if det ([K] -$\omega^2$[M]) = 0, in this case there a non-trivial solution($\{\phi\} \neq 0$) that can be obtained for

$$([K] - \omega^2[M])\{\phi\} = 0 \tag{3.7}$$

The determinant is zero only at a set of discrete eigenvalues $\lambda_i$ or ${\omega_i}^2$. There is an eigenvector $\{\phi_i\}$ which satisfies equation 3.7 and corresponds to each eigenvalue. And then it can rewritten in the following form

$$[K - \omega_i^2[M]]\{\phi_i\} = 0 \tag{3.8}$$

i= 1,2,3...

The number of eigenvalues and eigenvectors is equal to the number of degrees of freedom (d.o.f) that have mass or the number of dynamic d.o.f. Each eigenvalue and eigenvector define a free vibration mode of the structure, where the i-th natural frequency equals to the following

$$f_i = \omega_i / 2\pi \tag{3.9}$$

## 3.2 Eigenvalue Results

A similar description of the solution of the equation 3.7 has been presented in the DIANA documentation for the generalized eigenvalue problem. In DIANA there are two way to solve the eigenvalue problem, the Arnoldi method and the FEAST method. Both methods calculate all eigenpairs based on the user definition.
Arnoldi method have three possible ways of solving the problem which are the parallel direct sparse solver as a default, sparse Cholesky based solution method, and out of core solution algorithm. DIANA calculate the natural frequencies in an ascending order and at most n eigenfrequencies can be estimated, where n is the dimension of the system matrix, which is the number of equations in the problem.
The FEAST method is based on calculating a user defined vibration modes within a range using the Intel MKL Extended Eigensolver where the initial number of eigenvalues are going to be find in the range between the lower and upper limits.
In the file.out, the standard output file resulted from the analysis, the following general information are included: the natural frequencies, eigenmodes in terms of displacements, the relative errors, generalized mass matrix and participation factors.

### 3.2.1 Initial Configuration

Global natural frequencies can be presented using DIANA, where it can provide as much as the user wants number of eigenvalues, as it has been stated previously. In this section, the initial results of the eigenvalues are described where it was considered the 1st mode based on the results of the sensors and previous researches.
The figure 3.1 shows the eigen frequency of the 1st natural mode of the structure with a bending of X direction with a frequency of 2.23 Hz with a maximum displacement at the level of the lantern.
It should be mentioned that, DIANA calls the coordinates as displacements as they are normalized with respect to the maximum values and this is the reason why the "displacements" shown are with a large values.

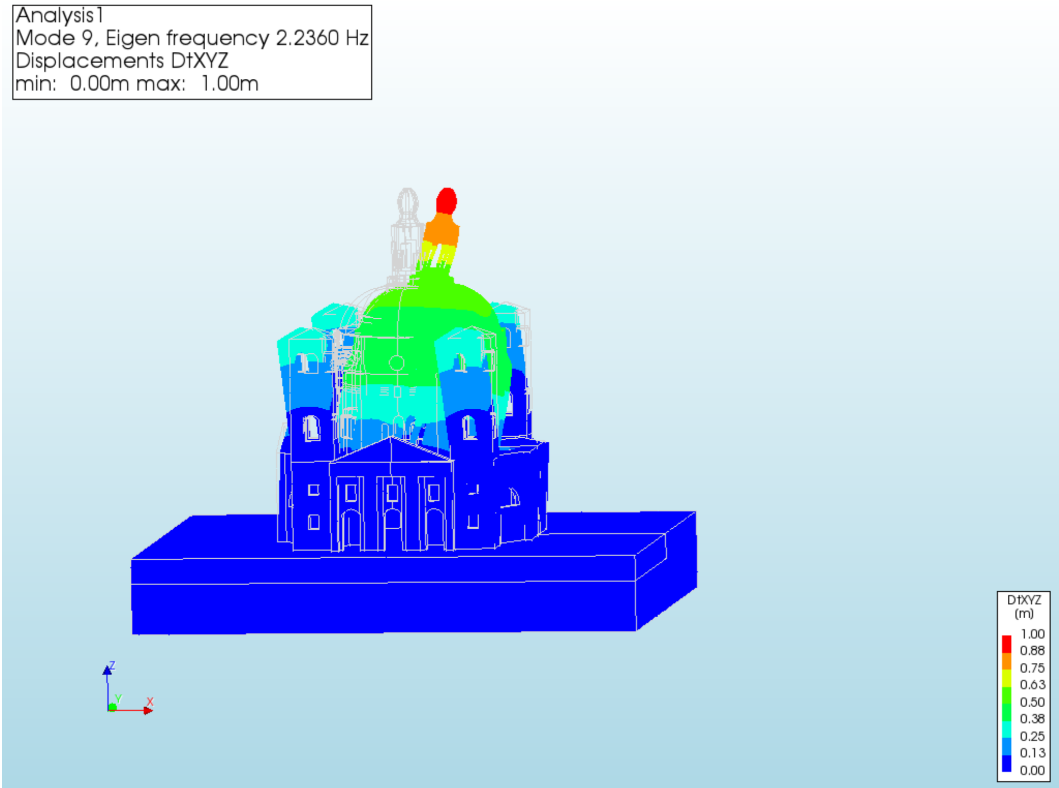



FIGURE 3.1: 1st Mode-Bending X

Figure 3.2 the natural frequency is 2.48 Hz where it represents the bending of the structure in the Y direction, as in the previous figure the most element that is affected is the lantern where it has also the maximum displacement at its level. Torsional mode of the Sanctuary of Vicoforte is 3.42 Hz, the displacement is mainly concentrated at the level of the dome and the drum. However, figure 3.3 shows that the top part of the basement is influenced with the torsional mode. Basement and soil are less influenced compared to the other elements of the structure.

Nevertheless, DIANA always write the following general information resulting from eigenvalue analysis: eigenmodes, relative errors, generalized masses, participation factors, direction dependent participation factor, effective masses, modal masses, equivalent masses and transformation factors.

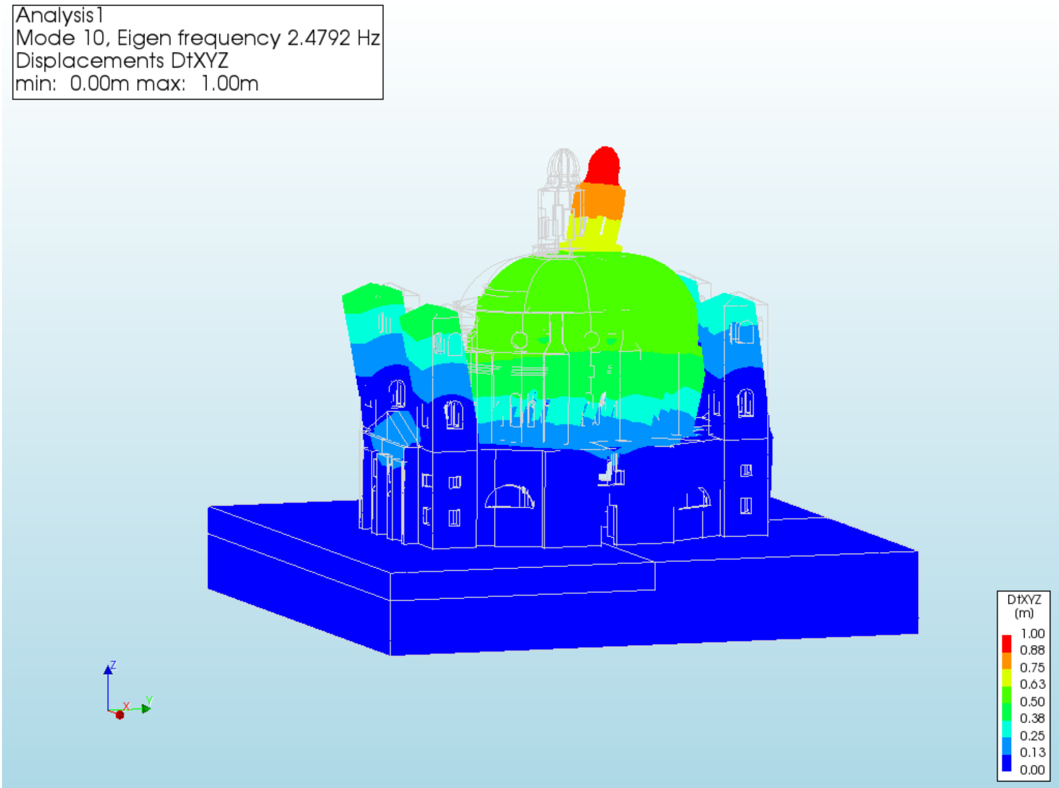



FIGURE 3.2: 1st Mode-Bending Y

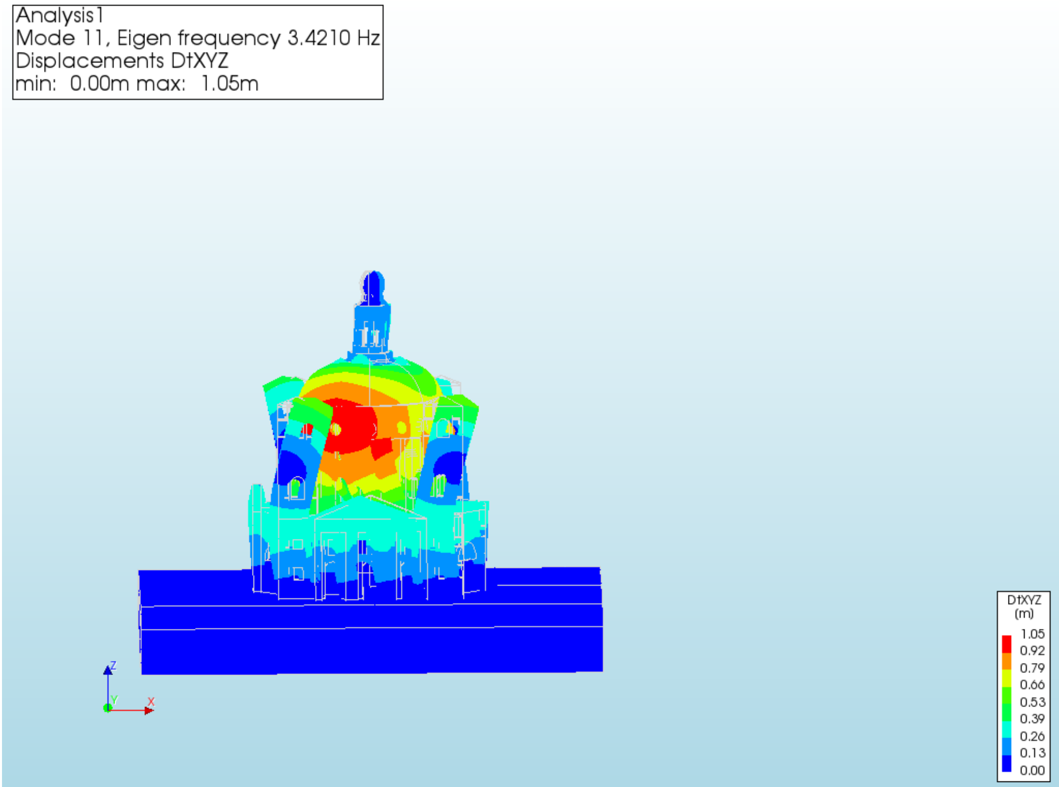



FIGURE 3.3: 1st Mode-Torsional

- Eigenmodes: The user can specify the eigenmodes in terms of coordinates which is called displacement in DIANA. The coordinates can be in the form of total displacement where DIANA normalizes the eigenmodes in such a way that the largest translation displacement component has a value of 1. Another way it could be the matrix normalized displacement, Diana normalizes the displacements with respect to a matrix, where this matrix would be the mass matrix for a free vibration eigenvalue analysis, the identity matrix for the standard eigenvalue analysis, or the geometric stress-stiffness matrix for a linearized buckling analysis.Last way can be the participation vectors which is the weighted eigenmodes.

- Relative errors: The error of each approximation of the eigenvalues and eigenmodes $\lambda$ and $\phi$ and determined as following for each eigenpair (i).

$$\epsilon_i = \frac{||K\phi_i - \lambda_i M\phi_i||}{||K\phi_i||} \tag{3.10}$$

- Generalized masses: In eigenvalue analysis DIANA determines the corresponding generalized masses $m_{ii}$:

$$m_{ii} = \phi_i^T M\phi_i \tag{3.11}$$

  With the eigenvectors normalized such that $m_{ii}$= 1

- Participation factors: DIANA determines participation factors for each calculated frequency based on the following equation;

$$\phi_{p.i} = \gamma_i \phi_i \tag{3.12}$$

  The sum of all participation factors is a unit vector i.e. a unit displacement of each d.o.f.

- Direction dependent participation factor: It is determined for the three directions X,Y, and Z for the translation and rotational d.o.f.

$$\Gamma_{tXi} = \frac{I_{tXi}}{m_i i} \tag{3.13}$$

$$\Gamma_{rXi} = \frac{I_{rXi}}{m_i i} \tag{3.14}$$

  Same equations can be applied for the other two directions Y and Z. $I_t$ are the coefficient vectors for each translational d.o.f, and $I_r$ are the coefficient vectors for each rotational d.o.f according to the following equation;

$$I_i = \phi_i^T Mr \tag{3.15}$$

  Where r is the influence vector which represents the displacements resulting from a static unit ground displacement in the direction of the corresponding translational or rotational degree of freedom.

- Effective masses: The software determines the corresponding effective masses $m_{eff,i}$ for the translational d.o.f in global X,Y, and Z directions.

$$m_{eff.tx.i} = \frac{I_{tXi}^2}{m_{ii}} \tag{3.16}$$

It is the same equation for the other two direction Y and Z.

- Modal mass: for each calculated frequency, modal mass $m_{mod.ii}$ is computed through the following equation;

$$m_{mod.ii} = \phi_i^T M \phi_i \tag{3.17}$$

With the eigenvectors $\phi_i$ normalized such that the largest translation displacement component has a value of 1. Note that if no translation displacement component exists, the modal mass will be set zero for that frequency.

- Equivalent mass: the direction dependent equivalent masses $m_{eq,i}$ for the translational d.o.f in global X,Y and Z directions are calculated using the following equation for X, where same equation can be applied for other directions;

$$m_{eq,i} = \phi_i^T M r_x \tag{3.18}$$

Where r is the influence vector which represents the displacements resulting from a static unit ground displacement in the direction of the corresponding translational or rotational degree of freedom. With the eigenvectors $\phi_i$ normalized such that the largest translation displacement component has a value of 1. Note that if no translation displacement component exists, the equivalent mass will be set zero for that frequency.

- Transformation mass: DIANA determines the corresponding direction dependent transformation factors by

$$\Gamma_{trXi} = \frac{m_{eqX,i}}{m_{mod.ii}} \tag{3.19}$$

Where $m_{eq.i}$ is the equivalent mass and $m_{mod.ii}$ is the modal mass. Note that if no translation displacement component exists, the transformation factor will be set zero for that frequency.

### 3.2.2 Sensitivity Analysis

Sensitivity analysis is a method that describes how a quantities/elements/variables are influenced based on a change on some properties or input variables. In other words, sensitivity analysis is a simulation method, which would give an idea about the importance of the input variables on the results.
Our study is mainly highlighting the volume to be considered in the analysis as in reality the volume of the soil is infinite, so this study tries to find a good compromise of the volume that can be considered in the analysis as there is no change on the static or dynamic behavior of the structure. The criteria of this study is based on the addition soil volumes in the plane directions (x,y), randomly and manually.
In the first sensitivity model, soil volumes has been added in the X-direction with an addition of 30%, where the initial length of the soil i.e. the first model is 100 meters and 30 meters are added in both sides, 15 meters each.
In the second sensitivity model, soil volumes has been subtracted in the X-direction with a percentage of 30%, with the subtraction of the 30% from the initial length it would be 70 meters.

The third and fourth models are similar to the latter two models, but the third and fourth models represent the Y-direction.

| Model | Addition/Subtraction Percentage (%) | Rate of Change of $f_{nat}$ (%) |
|---|---|---|
| First | +30 | 0.06 |
| | | 0.01 |
| | | 0.05 |
| Second | -30 | 0.15 |
| | | 0.04 |
| | | 0.07 |
| Third | +30 | 0.04 |
| | | 0.01 |
| | | 0.05 |
| Fourth | -30 | 0.02 |
| | | 0.56 |
| | | 0.32 |

TABLE 3.1: Sensitivity Models

The table 3.1 shows the different models that has been used while simulating the sensitivity analysis.
The change in the natural frequencies in the three main modes are shown in the table in percentages. It can be noticed that the changes is negligible and soil in its linear elastic behavior is not affecting the dynamic behavior of the Sanctuary of Vicoforte. Thus, the values of the natural frequencies (eigenvalues) which are going to be used in the model updating are those that has been estimated with the initial configuration of the soil.
The results are also graphed as in the figure 3.4, where the figure shows three different linear graphs. F1 is the first natural frequency that represents the bending in X-direction, F2 is the second natural frequency that represents the bending in Y-direction, and F3 is the torsional frequency. It is apparent from the graph that the values of the frequencies remained the same as the first assumed volume of soil.

Nevertheless, the change in differential settlement under the structure has been checked for each models. Differential settlement as a terminology is the change in settlements between two points in the same foundation, that may cause structural damages and relative movements among parts of buildings. The differential settlement has been checked between two foundations, one in the clay part and the other in the marl part. The vertical displacement for more than 20 different nodes are averaged into one value that represents the vertical settlement for the desired foundation, and same has been done for the other foundation, as in the equation 3.20. The impact of the soil addition or subtraction was monitored and the results are shown in the figure 3.5.

$$Settlement = |V1 - V2| \tag{3.20}$$

As a result, the soil has no impact on the results of the Sanctuary of Vicoforte both in terms of dynamic parameters and differential settlement. The model that has been used when analyzing the structure is the linear elastic model. This doesn't mean that it wouldn't have any influence when dealing with non-linear analysis. However, the initial configuration of soil volume is considered to be the one to continue with our analysis.

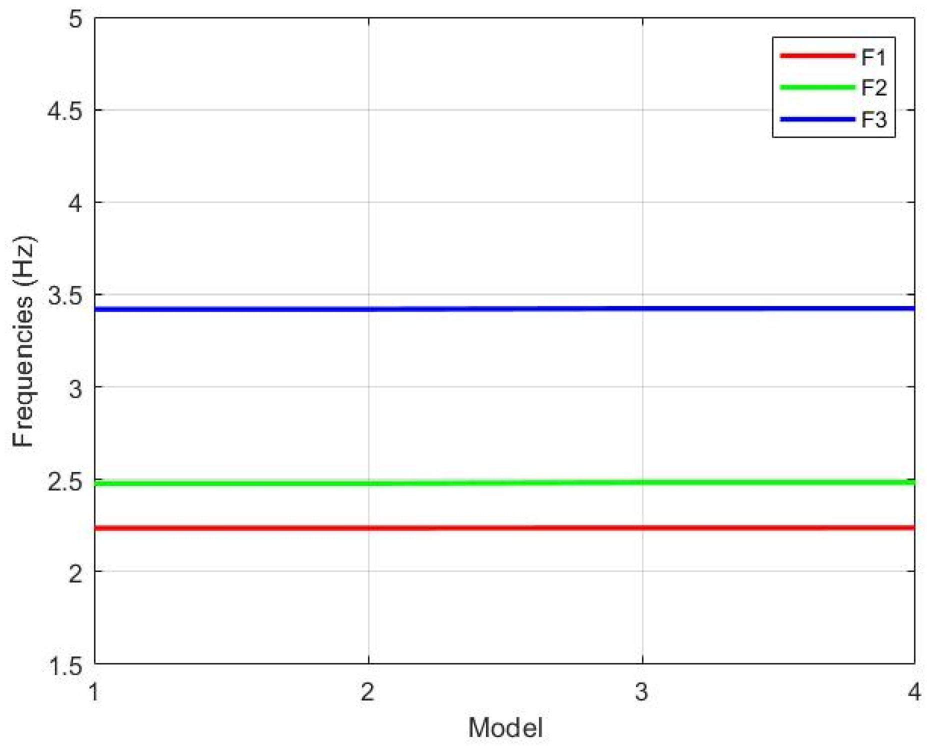



FIGURE 3.4: Sensitivity Analysis-Frequencies

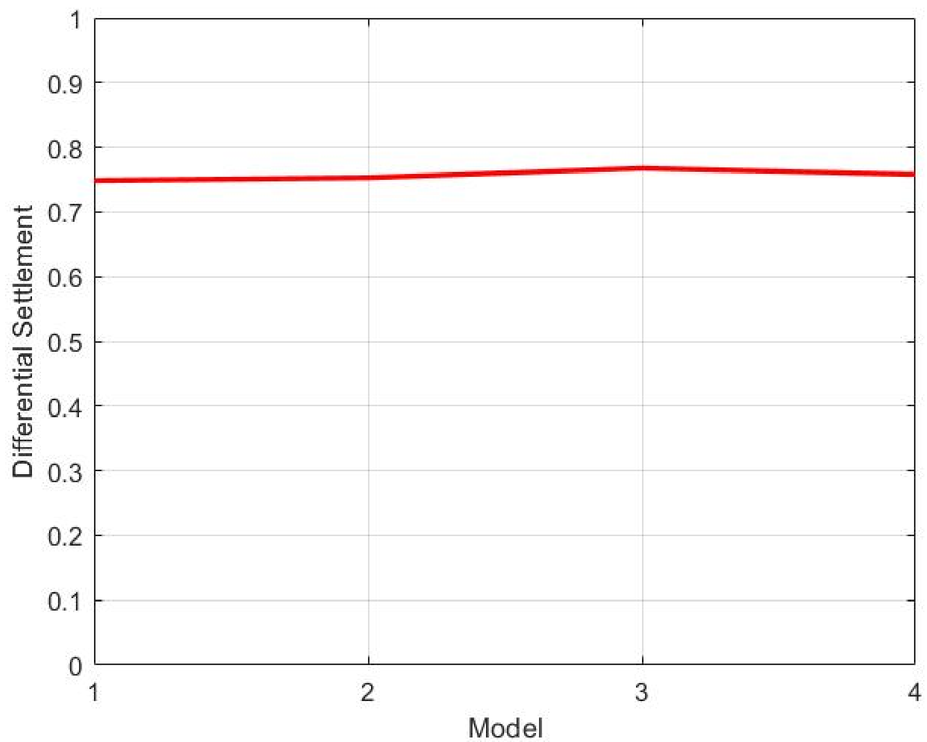



FIGURE 3.5: Sensitivity Analysis-Differential Settlement

Moreover, the natural frequency estimated from DIANA FEA are acquired where fifteen natural frequencies has been estimated and are shown in the table below[1];

| Mode | Natural Frequency ($Hz$) |
|---|---|
| 1 | 1.65 |
| 2 | 1.68 |
| 3 | 1.74 |
| 4 | 1.82 |
| 5 | 1.83 |
| 6 | 1.87 |
| 7 | 1.88 |
| 8 | 1.89 |
| 9 | 2.23 |
| 10 | 2.47 |
| 11 | 3.41 |
| 12 | 3.89 |
| 14 | 4.01 |
| 15 | 4.51 |

TABLE 3.2: Natural Frequencies

[1]The output results that are mentioned in the section "Initial configuration" will be reported in the Appendices

# Chapter 4

# Model Updating

Finite element results, such as natural frequencies and mode shapes, are often called when there are differences with the experimental results. Model updating is concerned with solving such problems by correcting the finite element models. In Chapter 1 an overview of the theory of model updating, usages and types, presented briefly. In this chapter, model updating is implemented on the case study using Particle Swarm Optimization method which is illustrated firstly. Then a correlation criterion, modal assurance criterion MAC, is discussed. And as a final part, the application of implementation of PSO and its result is presented.

## 4.1 Particle Swarm Optimization Theory

Particle swarm optimization (PSO) is a mathematical model that optimizes a problem/function iteratively, it tries to improve solutions by estimating the best solution in each iteration taking into account given measure of quality or constraints. PSO shares many similarities with the nature inspired optimization methods where the system is initialized with a population of random solutions, then it searches for the optimal solution by updating generations. PSO was firstly proposed by Kennedy and Eberhart in the 1995 where they state that the method was discovered through simulation of a simplified social model [7]. A number of scientists interpreted the movement of organisms in a bird flock or fish school. They were interested in finding out the rules that make large number of birds to flock synchronously, often birds change direction suddenly, sometimes they scatter, regroup, etc. Models are heavily relying in the inter-distance between birds, and thus the synchrony of flocking behavior was thought to be a function of birds' efforts to maintain an optimum distance between themselves.
Indeed, this logic doesn't fit all creatures such as flocks, schools, herds, or even human being. The hypothesis that is considered as a fundamental to the development of particle swarm optimization (PSO) is that creatures can profit from the discoveries and previous experience of all other members for e.g. fish schooling [8].
Mathematically, PSO solves a function by having a population of random solutions, while these particles moves in the search space, the best local solution will be then known. The latter solution started to be updated iteratively based on position "$x_i$" and velocity "$v_i$" values up to reach a global best solution. It can be noticeable that, this optimization method comprises a very simple concept where it can be implemented in a few lines of computer codes. It requires only primitive mathematical operators where it is computationally in expensive in terms of memory requirements and speed.
Every iteration, each particle changes its position according to the new velocity as shown in the following equations:

$$v_i^{t+1} = w.v_i^t + c_1.r_1(xBest_i^t - x_i^t) + c_2.r_2(gBest_i^t - x_i^t) \tag{4.1}$$

$$x_i^{t+1} = x_i^t + v_i^t.t \tag{4.2}$$

Where $xBest$ and $gBest$ are the best local particle and global best particle solutions, respectively. However, w is denoted to the inertia weight where usually is chosen as a unit, $c_1$ and $c_2$ are two positive constants where they represent the personal and global learning coefficients, respectively. Also, $r_1$ and $r_2$ are two random parameters range between [0,1]. Usually maximum and minimum velocity values are also defined and with the initial the particles that are distributed randomly, this encourages the search in all possible locations.

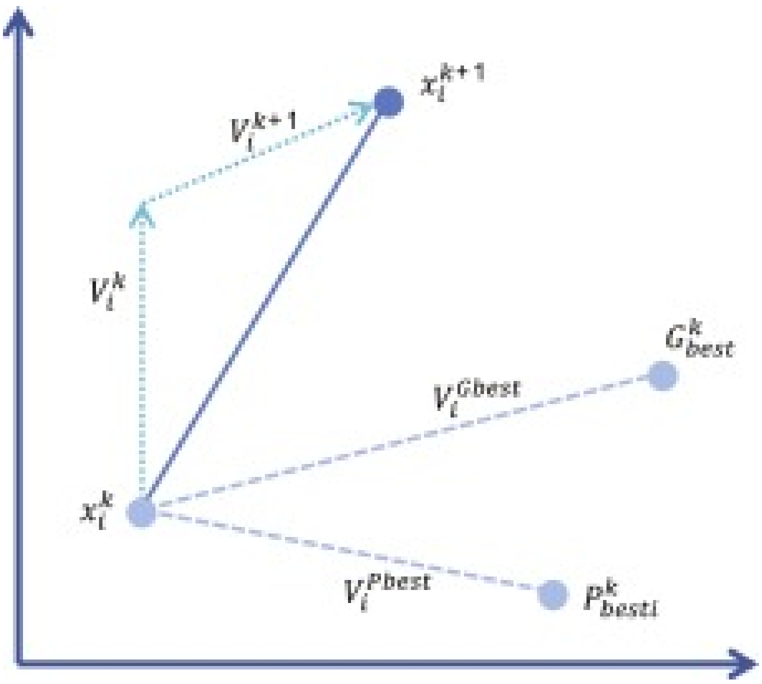



FIGURE 4.1: Movement of the Particle(i) in the iteration k and k+1

In the figure 4.1 a two-dimensional representation of one particle, 'i', movement between two positions. It can be observed how the particle best position, Pbest, and the group best position, Gbest, influence the velocity of the particle at the next iteration. Nevertheless, the stochastic properties of the algorithm allow for solution variability to guarantee the solution space exploitation.
Thus, it is noticeable that Particle Swarm Optimization method has many advantages. According to Kwang Y. Lee and Jong-Bae Park, PSO has the following advantages [10]:

- Is a derivative-free method like other heuristic models
- Easy to implement when compared to other optimization models
- Has limited number of parameters
- Can generate high-quality solutions within shorter calculation time and stable convergence characteristics than other stochastic methods

According Kwang Y. Lee and Jong-Bae Park the major drawback of the PSO method is that it lacks a solid mathematical foundation just like other heuristic models. However, PSO is less accurate than other optimization methods due to the fact that there is still dependency on initial point and parameters, difficulty in finding their optimal design parameters, and the stochastic characteristic of the final outputs [9].

### Algorithm Improvement

The processing of the optimization method that's been used in this study, Particle swarm optimization, is all based on the parameters efficiency in optimizing the desired problem. This part gives a list of literature researches done by scientists about the list of good choices of the parameters for various problems.
As it stated before the solutions are particles with a random position. The direction of the particle is then gradually change, to move to another best position. It should be mentioned that, small changes in PSO can cause a dramatic changes in the finding of the last solution. Such dramatic changes can be almost correlated with the parameters defined. Starting with the population size, which is widely known that it affects the performance of the optimization process.According to the recent studies done by the Polish Academy of Sciences [10], they have considered eight PSO variants, where each has been tested with 15 different population sizes, ranging from 3 to 1000. The 15 different algorithms has been chosen among different disciplines from economics to physics. The idea is not to compare functions and algorithms, but it is to find the best compromise of the swarm size. They have found that the classical choice of 20-50 population size, is frequently inadequate except for uni-dimensional problems. They have highlighted that, in case of no hint of which population size should be used for a specific PSO variant, [70-100] particles is the safest choice.

However, another important parameter is the inertia weight which would also affects the convergence of the solution. It plays an important role in the process of providing balance between exploration and exploitation process. In addition to that, it determines the contribution rate of a particle's previous velocity to its velocity at the current time step. The very first illustration of PSO, presented by Kennedy and Eberhart, has not inertia weight. Later in 1998 was the first attempt of inertia weight estimation, as it facilitates a global search. Several researches had been done targeting the value of the inertia weight that may increase the capability of PSO.
Eberhart and Shi [11] proposed a Random Inertia weight strategy (equation 4.3) and they found that this method increases the convergence of PSO in the early iterations of the algorithm. It is found that Inertia weight from 0.9 to 0.4 provides the excellent results.

$$w = 0.5 + \frac{Rand()}{2} \tag{4.3}$$

Global-Local Best Inertia Weight [11], Inertia weight is based on the function of the local and global best of the particles in each generation (equation 4.4). The value of inertia weight "w" is not considered as constant or even as a linearly decreasing value. To overcome the weakness of premature convergence to local minimum, Adaptive Inertia Weight strategy [11] is proposed to improve its searching capability (equation 4.5. It controls the population diversity by adaptive adjustment of Inertia Weight.

$$w_i = (1.1 - \frac{gbest_i}{(pbest_i})) \quad (4.4)$$

$$w_i(t+1) = w(0) + (w(n_t) - w(0))\frac{e^{m_i t} - 1}{e^{m_i t} + 1} \quad (4.5)$$

$$m_i(t) = \frac{gbest - current}{gbest + current} \quad (4.6)$$

Another method was introduced by Fayek et al. [11], simulated annealing for optimizing the Inertia Weight (equation 4.7). The method gave much better convergence speed. Chen et al. [11] present two Natural Exponent Inertia Weight strategies which are based on the basic idea of Decreasing Inertia weights (equation 4.10). The presented revolutionary methods converge, Natural Exponent Inertia Weight Strategy, faster than linear one during the early stage of the search process and provide better results for complex optimization problems (equations 4.8 and 4.9).

$$w_k = w_{min} + (w_{max} - w_{min}) * \lambda^{k-1} \quad (4.7)$$

$$w(t) = w_{min} + (w_{max} - w_{min})e^{-\frac{t}{\frac{MAXIT}{10}}} \quad (4.8)$$

$$w(t) = w_{min} + (w_{max} - w_{min})e^{-[\frac{t}{\frac{MAXIT}{4}}]^2} \quad (4.9)$$

$$w_k = w_{max} - \frac{w_{max} - w_{min}}{MAXIT} * k \quad (4.10)$$

Segmoid Increasing Inertia weight has been introduced by Malik et al.[11].The function has contributed in getting minimum fitness function while linearly increasing the interia weight that gave a quik convergence ability. Equations 4.11 and 4.12 represents the Sigmoid Increasing Inertia Weight and Sigmoid decreasing Inertia Weight, respectively

$$w_k = \frac{w_{start} - w_{end}}{1 + e^{u*(k-n*gen)}} + w_{end} \quad (4.11)$$

$$w_k = \frac{w_{start} - w_{end}}{1 + e^{-u*(k-n*gen)}} + w_{end} \quad (4.12)$$

$$u = 10^{(log(gen)-2)} \quad (4.13)$$

Oscillating Inertia Weight [11]provides periodically alternates between global and local search-spaces and results shows that it is a competitive approach and outperform particularly in terms of convergence speed (equation 4.14).

$$w_t = \frac{w_{max} + w_{min}}{2} + \frac{w_{max} - w_{min}}{2}cos(\frac{2\pi t}{T}) \quad (4.14)$$

Another proposed method is the combination of PSO and logarithm decreasing inertia weight with Chaos mutation operator. This method was proposed by Gao et. al.[11], where in this method the convergence speed is improved, and the Chaos mutation gives the ability to jump out of the local optima. Nevertheless, to overcome the premature convergence and later period oscillatory occurrences of the standard PSO, Gao et al.[11] proposed an exponent decreasing inertia weight and a stochastic mutation to have an improved PSO.
Moreover, another dynamic decrease method have been proposed in literature considering a damping factor that ranges between 0 and 1. In that study, particle swarm

optimization for endurance time excitation functions is tested with different values of the damping factors.

$$w = w_{damp} * w^{i-1} \tag{4.15}$$

However, PSO has been used for testing the sphere equation with different inertia weight. The form of the inertia weight used was as in the equation 4.15, with w = 1 and $w_{damp}$ 0.99, 0.95, 0.90, and 0.8. Also, in the study for the endurance time excitation functions the same value was found as the proper value for a better convergence. Particle swarm optimization parameters had been under investigations for the structural design purposes, as in the research paper of Ruben Perez and Kamran Behdinan [12]. They have also tested the inertia weight parameter, that can fit the civil engineering problems. According to their studies, dynamic decrease method presented a faster convergence. Dynamic decrease method was compared to fixed value of inertia, and linear variation inertia weight as in the equation 4.10. The results are shown in the figure 4.2.

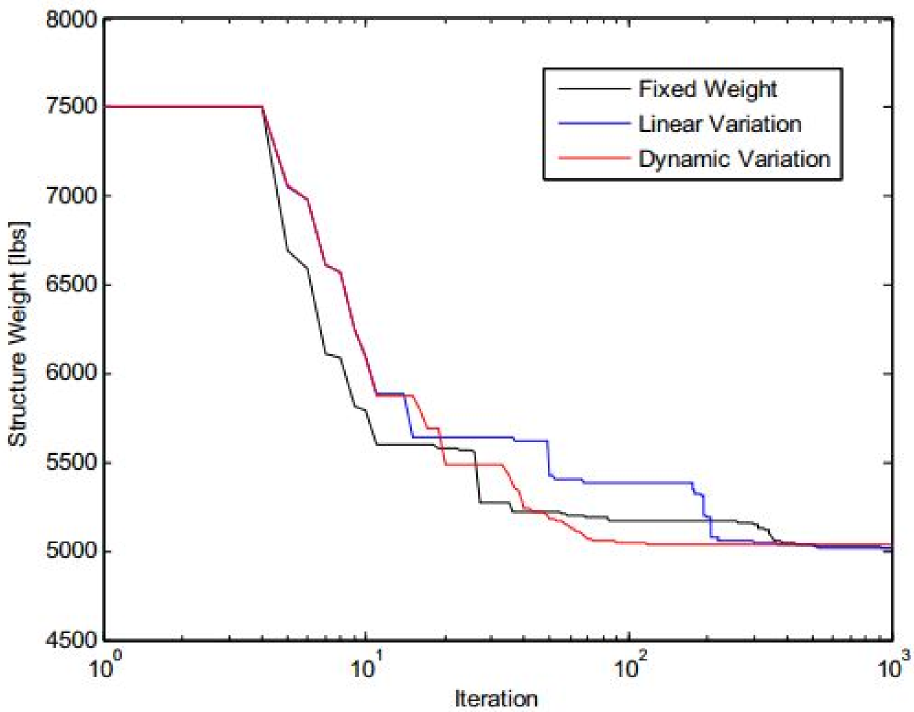



FIGURE 4.2: Inertia Weight Comparison

On the other hand, learning coefficient are also parameters affect the convergence of the optimization process, they are also called social and cognitive parameters. Always questions arise asking which values of social and cognitive parameters guarantee the desired convergence. An analysis of the effect of the different parameter settings was made to determine the sensitivity in the overall optimization procedure. In the figure 4.3 structural weight has been determined using PSO with 1000 iterations, fixed inertia weight and different social ($c_2$) and cognitive values ($c_1$) [12].

Figure 4.3 shows the effect of the variation of the social and cognitive values assignment on the convergence of the function to the global optimal value. Firstly, $c_1 = 0$ $c_2 = 3$, the algorithm converges to the local optimum within few iterations (first ten iterations) where then all the particles in the swarm converge rapidly to

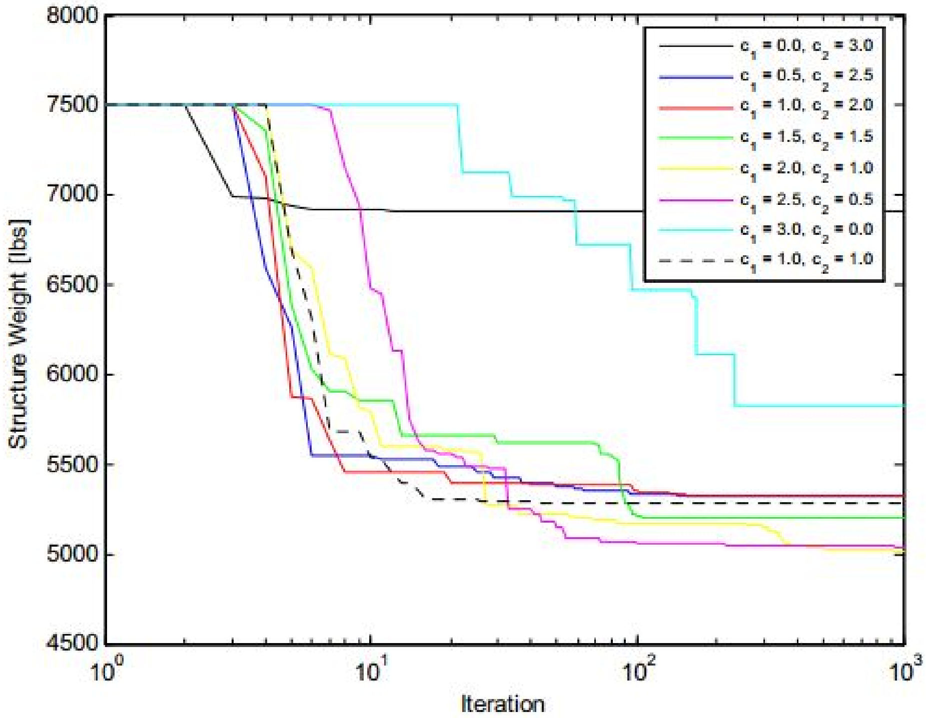



FIGURE 4.3: Social and Cognitive Variation Effect

the best initial optimum found before (local best). However, it is obvious that if the values of the $c_1$ and $c_2$ lowered, better solutions are found requiring less number of iterations for convergence, as for instance in the case of $c_1 = 2$ $c_2 = 1$ and $c_1 = 2.5$ $c_2 = 0.5$. At latter mentioned values, the algorithm provides the best convergence speed. This is due to the fact that the individuals concentrate more in their search making the swarm go toward the best global solution. The case of $c_1 = 3$ $c_2 = 0$ where local exploration over the global one, this case has its limit as it requires a huge number of iterations to find the solution, and also to no common solution that is not even the global optimum solution.
Nevertheless, based on Mathwork website [12] it is suggested that, the number of iterations has to be 200 * Number of variable (nvar) initiated. Also, the swarm size to be the minimum of the following interval (100, 10*nvar).
In our case study, one parameter was updated and this means that the number of

| Parameters | Value |
|---|---|
| Number of Variable | 1 |
| Swarm size | 10 |
| Iterations | 200 |
| Cognitive Parameter $c_1$ | 2.5 |
| Social Parameter $c_2$ | 0.5 |
| Inertia Weight w | 0.95 |
| Damping Factor $w_{damp}$ | 0.975 |

TABLE 4.1: Particle Swarm Optimization Parameters

variable is equal to one, as a result of this a 10 swarm size are initialized due to the fact that the analysis of this complex structure may cost a lot in terms of time. However, the maximum iterations that are going to be considered are 200*1 iterations. Dynamic inertia weight method is used in the updating process where the initial inertia weight used is 0.95 and damping parameter $w_{damp} = 0.975$. Also cognitive parameter "$c_1$" is equal to 2.5, and social parameter "$c_2$" is equal to 0.5, as they are recommended for the civil engineering use.

## 4.2 Model Updating

As it is stated in the beginning of this chapter and chapter 1, model updating is a method that improve the results of the finite element model based on the test results. In this section, a brief presentation of the structural health monitoring criterion used in the Sanctuary of Vicoforte is presented with its experimental results. Then, correlation criterion MAC is illustrated starting with its definition and how it is linked to the objective function. As a final step, implementation of PSO is described with the results of the model updating.

### 4.2.1 Experimental Results

In civil engineering discipline constructing new structures is not the only context, but also preserving old structures is a necessity, this means that the overall health of old structures should be always monitored and checked. Structural health monitoring (SHM) is a process of implementing a strategy for damage detection for engineering structures such as bridges and buildings. It involves the application of sensors such as accelerometers, thermometers, wire gauges, load cells and crack meters. These sensors are continuously recording and processing to extract damage-sensitive features to determine the current state of system health. Long term SHM, the output is updated periodically where it gives information about the ability of the structure to function considering any problem such as aging and degradation. In the figure below the usual process flow that is usually followed for the SHM 4.4;

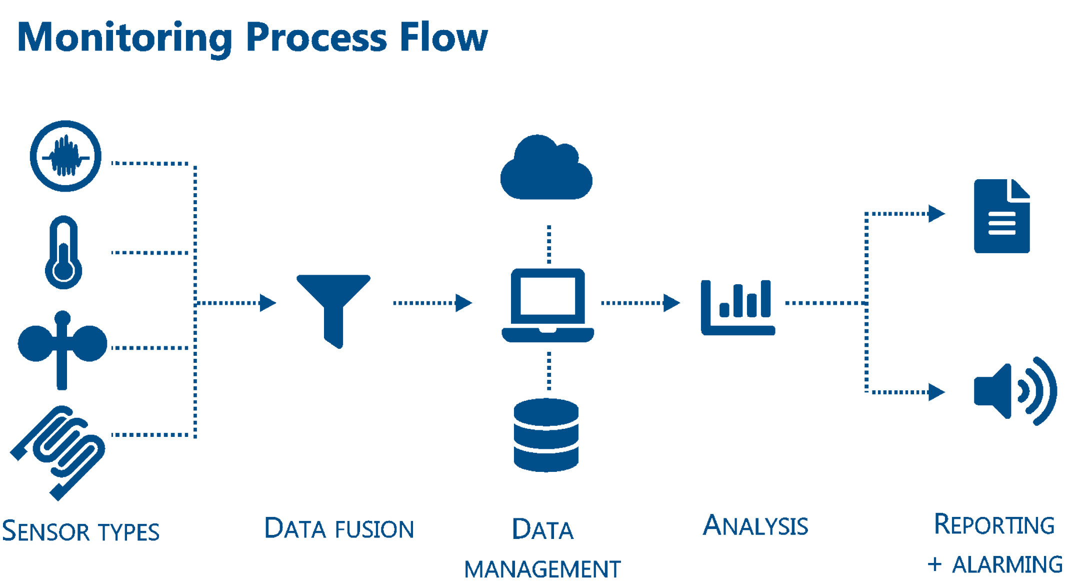



FIGURE 4.4: Process Flow SHM

Sanctuary of Vicoforte has been equipped with a permanent static and dynamic monitoring system, which over years have recorded long series of data that is useful for determining important outputs such as mode shape and natural frequencies [13]. In 1983, the first static monitoring instrument applied to the structure to check the evolution of the cracks, and this has been followed by several upgrades up to 2004 where a group of static monitor sensors were installed such as sensors for strain, stresses, crack width and instruments that acquire measurements of environmental conditions, as shown in the figure 4.5.

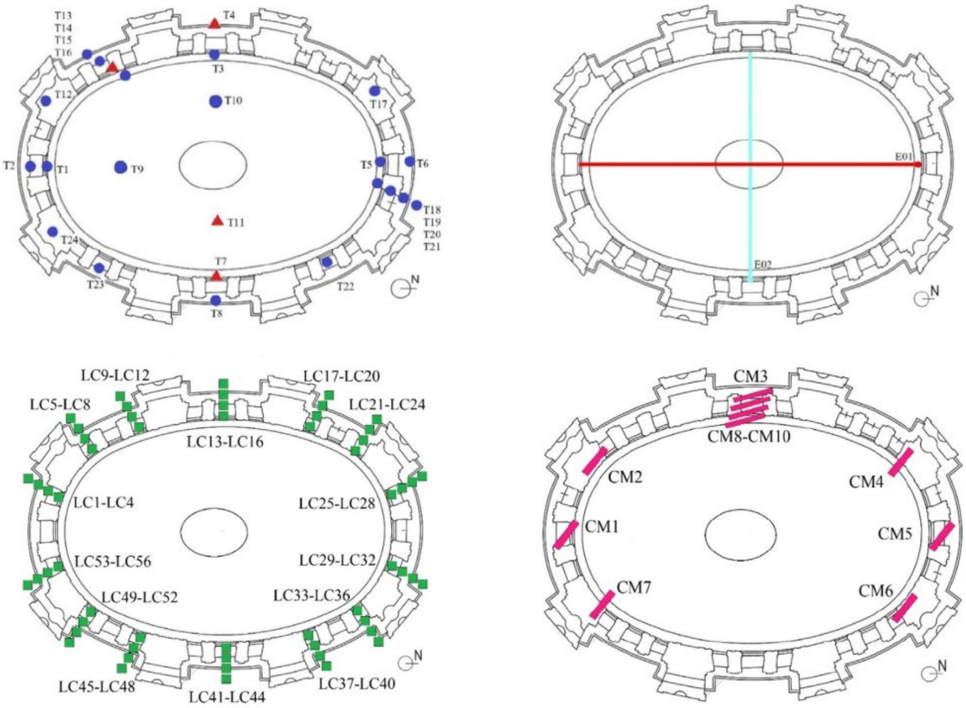



FIGURE 4.5: Layout of Static Monitoring sensors

However, dynamic monitoring system was installed to have a global observation of the structural behavior of the church where 12 piezoelectric acclerometers has been installed. The recorded accelerations are continuously processed to extract the modal parameters using modal identification procedure. The location of the accelerometers is shown in the figure 4.6.

The first step is to collect the field data such as the data acquired from the static monitoring system and the frequencies that is obtained by the dynamic monitoring system. Before correlation analysis is done, a crucial step is to detect the dependency between variables by scatter plotting. There will be a huge data that need to be managed and studied and this done by the mean of Machine learning. According to SHM literature Support Vector Machine SVM regression model is the most used in this field. Such regression models it's very first step is to clean the data i.e. the outliers in order later extract the desired data.

It can be said that mentioned monitoring campaigns were not the first (2008), where another vibration based monitoring techniques were used to study the dynamic behavior of the Sanctuary (2017). The natural frequencies that had been found are shown in the table below [14];

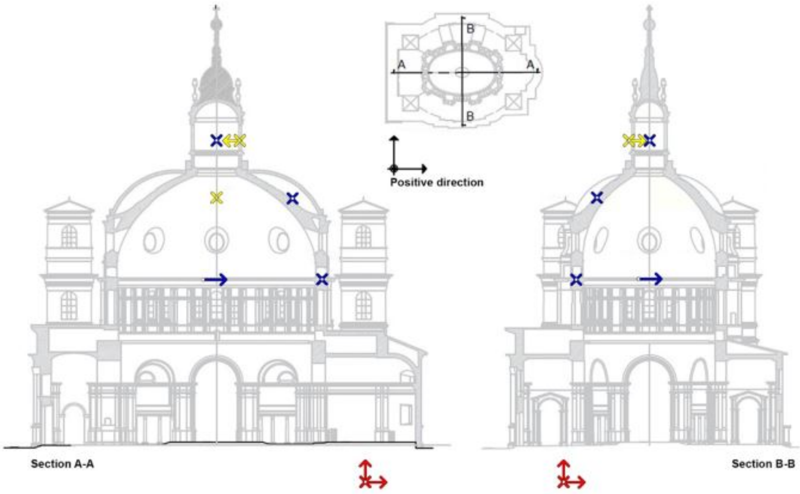



FIGURE 4.6: Location of the Accelerometers

| Frequencies identified Recently ($Hz$) | Frequencies identified in 2008 ($Hz$) | Mode Classification |
|---|---|---|
| 1.92 | 1.99 | First bending Y |
| 2.09 | 2.08 | First bending X |
| 2.83 | 2.86 | First torsional |

TABLE 4.2: Identified Frequencies from SHM

It is observable that the values of the natural frequencies observed in both years differ slightly.

Six different sensors each with a specific position as shown in the figure 4.7 has been used for model updating. The eigenmodes acquired are three, one for each frequency, with eight rows. The position of the sensors based on the reference system considered in the case study (2.10). The positions are reported in the table 4.3. Also

| POS | X (m) | Y (m) | Z (m) |
|---|---|---|---|
| POS1 | 35.25122 | 20.0055 | 57.94207 |
| POS2 | 31.65122 | 22.7555 | 57.94207 |
| POS3 | 31.65122 | 30.0055 | 46.94207 |
| POS4 | 45.95122 | 20.0055 | 46.94207 |
| POS5 | 51.45122 | 20.0055 | 32.24207 |
| POS6 | 31.65122 | 33.4555 | 32.24207 |

TABLE 4.3: Sensor's Position

the experimental eigenmodes are reported in the following table;

### 4.2.2 Correlation Criterion

An important requirement in design is to be able to compare between experimental results for the desired structure with the predicted results. In finite element modeling, it is important to compare results in order to assess the improvement in the modelled response. Problems may arise because of the large number of degrees

| Position | Direction | $\phi_1$ | $\phi_2$ | $\phi_3$ |
|---|---|---|---|---|
| POS1 | Ux | 0.284730515 | 1 | 0.201210957 |
| POS3 | Ux | -0.018782565 | 0.907856559 | -0.596536107 |
| POS6 | Ux | -0.018607864 | 0.737601596 | -0.584559741 |
| POS1 | Uy | 0.981500183 | -0.511783323 | 0.490996922 |
| POS2 | Uy | 1 | -0.312724047 | 0.03576581 |
| POS3 | Uy | 0.905219431 | -0.110738596 | 0.164901962 |
| POS4 | Uy | 0.69216886 | -0.096221011 | 1 |
| POS5 | Uy | 0.49609157 | -0.037308496 | 0.980219743 |

TABLE 4.4: Experimental Eigenmodes

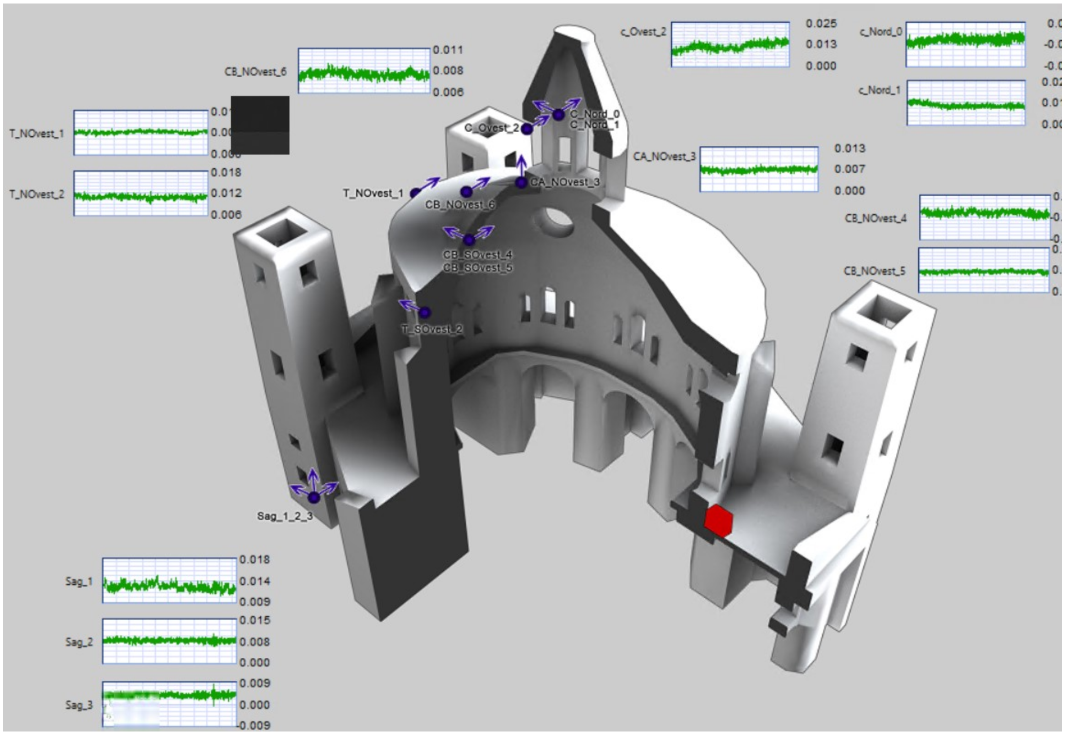



FIGURE 4.7: Position of Sensors

of freedom in the numerical mode; the limited number of sensors used to measure the response of the structure; and modelling inaccuracies. In this part, a correlation method that is used to compare results is used and is called modal assurance criterion.

Modal assurance criterion [15] is a statistical index that is sensitive to large variations in modal shape, and relatively it is not sensitive to the small differences. This means that it is a good statistic indicator and a degree of consistency. Modal assurance criterion (MAC) is a measure of consistency between estimates of modal vector. The modal vectors from a finite element analysis can be compared with the experimental modal vectors. The modal assurance criterion is to be defined as a scalar constant relating modal vectors based on the following equation [13];

$$MAC_{cdr} = \frac{\mid \sum_{q=1}^{N_o} \psi_{cqr} \psi^*_{dqr} \mid^2}{\sum_{q=1}^{N_o} \psi_{cqr} \psi^*_{cqr} \sum_{q=1}^{N_o} \psi_{dqr} \psi^*_{dqr}} \tag{4.16}$$

It is easy to apply and does not require an estimate of the system matrices. It is bounded between 0 and 1, with 1 indicating fully consistent mode shapes. It can only indicate consistency and does not indicate validity or orthogonality. A value near 0 indicates that the modes are not consistent that can for the following reasons:

- The system is non stationary. Such case occurs in non linear case where two different sets of data have been acquired at different time or excitation.
- Noise on the reference modal vector.
- The modal parameter estimation is invalid.

In contrary, if the modal assurance criterion MAC has a value of one, this is an indication that the modal vectors are consistent. However, this doesn't mean that a value of one is a correct value. Modal vectors are consistent for the following reasons;

- Modal vectors have been incompletely measured. Such situations occur when few response stations have been included in the experimental testing of the modal vector.
- Modal vectors are resulted from force excitation.
- Modal vectors are free of noise

Modal assurance criterion can be applied in many different ways where it can be used also to validate or correlate experimental modal vectors with respect to analytical modal vector(eigenmodes).
Most of the potential uses of the MAC are well known, beside the comparison and correlation with the experimental results, but a few more uses that makes this correlation criterion a popular technique; a lot of researches in literature considered this fact and some uses are mentioned as follows:

- Validation of experimental modal models
- Correlation with analytical results
- Correlation with operating response vectors
- Mapping matrix between analytical and experimental modal models
- Modal vector error analysis
- Modal vector averaging
- Experimental modal vector completion and/or expansion
- Damage detection
- Optimal sensor placement

### 4.2.3 Fine Tuning

Fine tuning as a definition is the process of fitting some observations by adjusting some parameters precisely. In our study, fine tuning was applied to the parameters after checking the relation between the experimental and the numerical results. The relation between the experimental and the numerical results seemed to be consistent as a ratio. As for the first pair of natural frequencies, the ratio between both experimental and numerical was equal to 0.8648 while the ratio of the second pair was equal to 0.8472 and finally the third pair was equal to 0.8325. It is apparent that, the values of the ratios seem to be consistent and this means that tuning a constant that is in common between the experimental and the numerical will give an improvement in the final results.
The constant value has been estimated as the following;

$$\beta_{min} = 0.99 * min((\frac{f_{exp1}}{f_{num1}})^2, (\frac{f_{exp2}}{f_{num2}})^2, (\frac{f_{exp3}}{f_{num3}})^2) \tag{4.17}$$

$$\beta_{min} = 1.01 * max((\frac{f_{exp1}}{f_{num1}})^2, (\frac{f_{exp2}}{f_{num2}})^2, (\frac{f_{exp3}}{f_{num3}})^2) \tag{4.18}$$

The lower boundary of beta is less than the minimum of the squared ratio between the natural frequencies (experimental and numerical), while the upper boundary is greater than the maximum of the squared ratio. As a result the beta value will be ranging between a value of 0.67 and a value of 0.77.
Initial values of the young modulus showed a good results as well when computing the modal assurance criterion, but a high values of the natural frequencies as it was stated before. The results are tabulated below;

| Modes | MAC |
|---|---|
| Mode 1 | 0.9608 |
| Mode 2 | 0.85 |
| Mode 3 | 0.92 |

TABLE 4.5: Initial Values of MAC

The MAC values are considerably high, this means that fine tuning could be a good approach to reach a good agreement of the natural frequencies. Studies and experiments done on the Sanctuary of Vicoforte showed that the natural frequency is totally dependent on the slender elements such as basement and drum. However, it is clear that the natural frequencies with the initial configuration of the young modulus shows that the structure is stiff with assigned parameters and as a result the young moduli need to be reduced in order to match the natural frequencies. But as our goal is to perform a fine tuning calibration to improve the results, especially after the significant match between the numerical model with the initial parameters and the experimental results the beta value will be an amplification factor that will reduce the young modulus matrix that will be assigned iteratively in the software DIANA, in order to find the solution.

### 4.2.4 Implementation of PSO

Particle swarm optimization is a population based optimization approach inspired by nature habits such as bird flocks and fish school. PSO, the potential solution is called particle which will be the local optimum particle in the search space up to find the global best solution. All starts with initialization of number of particle in the search space, with a position with a value of position "x" that is bounded between the lower and upper limits of the search space. The initial velocities for all the initialized particles is zero. Based on the initialized values, cost function is then is computed. All solutions of all initialized particles will be compared and the local optimum solution will be chosen as the current global optimal solution.

In the next step, velocity will be updated based on the constants of the particle swarm optimization approach; $c_1$ and $c_2$ and $w$ as in the equation 4.1. Where these constants have been defined in the section of "Particle Swarm Optimization Theory". The updated velocity is also bounded between a value of maximum and minimum allowable velocities. After that, the position "x" is updated based on the value of the updated velocity as in the equation 4.2. This step is iterated according to the defined number of iterations, and positions are compared and the optimum value will be denoted as the global best solution.

For the case study, the initialized populations are a constant value called beta which will be multiplied with all the young moduli of all the structural elements of the structure such as silt, marl stone, basement, drum, buttresses, lantern, external dome that is made of copper and wood. These values of young modulus, for each population, are printed in a python file that will be read by DIANA FEA which will later run the analysis. The results of the analysis are also printed on a text file, that will be read by python. Then, cost function is computed, and the smaller solution is denoted to the local best solution, as the minimal value represent the optimum solution. Cost function (J) comprises two terms, one related to the natural frequencies (global), and another term is the MAC that takes into account the eigenmodes; as shown in the equation below:

$$J = \sum \frac{|f_{exp} - f_{num}|}{f_{exp}} + \sum |1 - MAC| \tag{4.19}$$

Figure 4.8 describes the different steps illustrated in the beginning of this section. The idea behind optimizing a constant is due to the fact that the ratio between the experimental and the numerical natural frequency is almost equal. This means that, it is enough to tune this parameter so it is easy to reach our target result. However, it is expected that the optimal value will be around the average of the boundaries of the beta value.

### 4.2.5 Results

As we have started with a calibrated model, the modal assurance criterion values MAC were already high and greater than or equal 85 percent. Thus, the change in the cost function will target almost only the natural frequencies variation when calibration is processing. It is expected that the MAC values will remain the same, even though the model is being calibrated. However as the values of the natural frequencies been normalized in the cost function equation, it is obvious that the

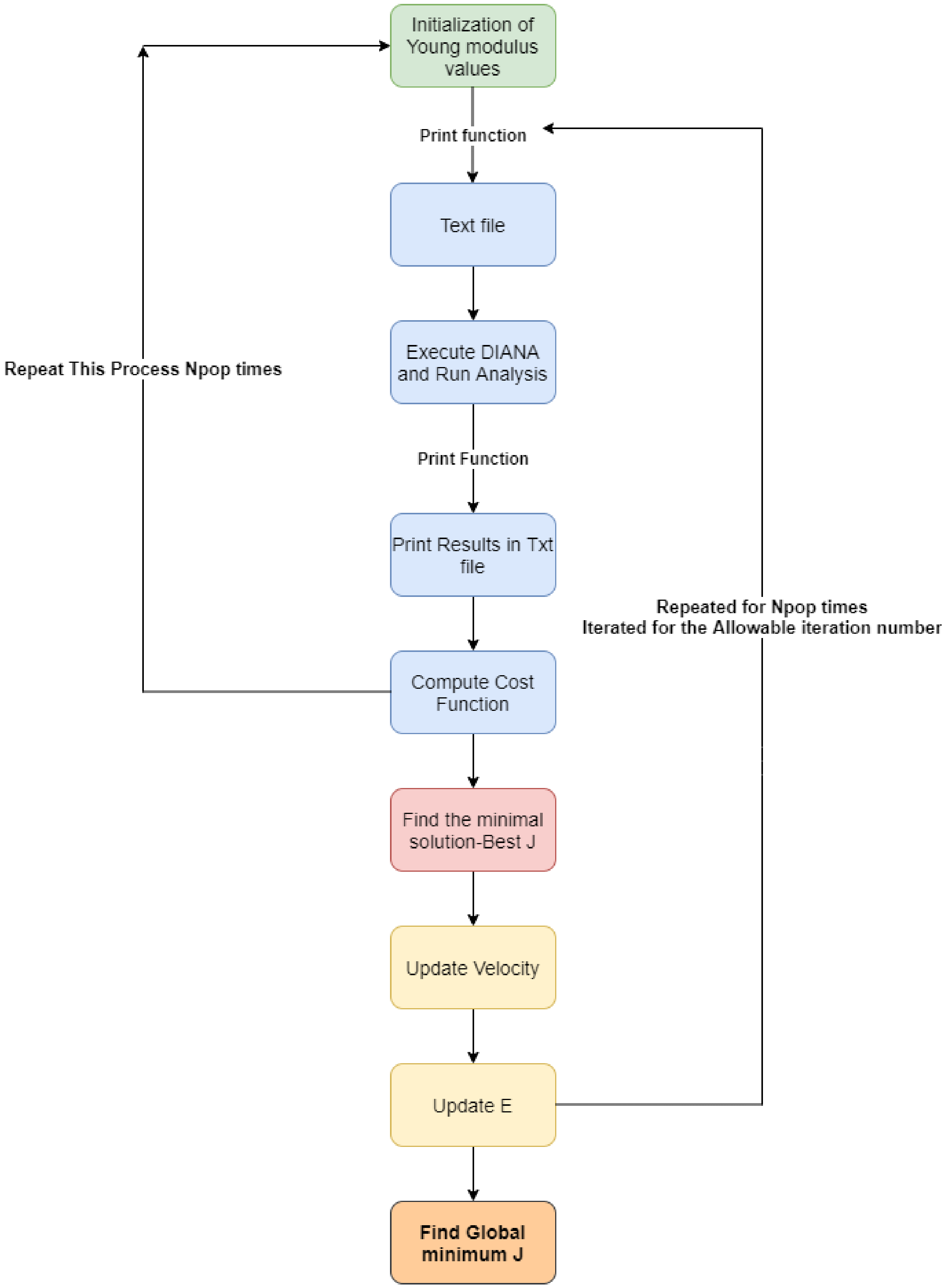



FIGURE 4.8: Flowchart

variation and the decrease in the cost function won't be significant as in case calibration started from the very beginning. The figure 4.9 shows how speedy was the convergence to the solution, where after almost 12 or 13 iteration the solution has been reached. It has to be mentioned that, any values of calibration could be a good results as the goal is to make a fine tuning.

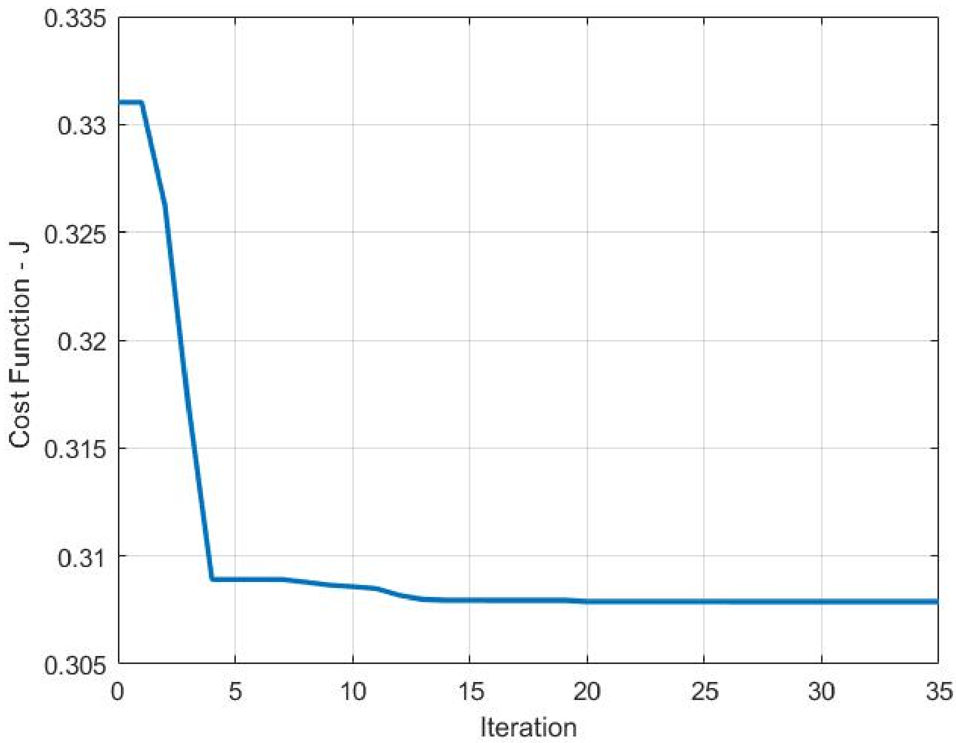



FIGURE 4.9: Cost Function Optimization

| Element | Initial Young Modulus (GPa) | Calibrated Young Modulus(GPa) |
|---|---|---|
| Silt | 0.75 | 0.53 |
| Marl Stone | 5.6 | 3.99 |
| Foundation | 2 | 1.42 |
| Basement | 2 | 1.42 |
| Drum | 2.3 | 1.63 |
| Buttresses | 5.5 | 3.91 |
| Dome | 5.6 | 3.99 |
| Lantern | 5.6 | 3.99 |
| Towers | 4.5 | 3.20 |
| Wood | 8.1 | 5.77 |

TABLE 4.6: Calibrated Young Modulus

The natural frequencies significantly decreased from the initial numerical model with the very first assigned young moduli. The new natural frequencies are still different but with a hundredth decimal as for instance the first pair of frequencies are 1.88 and 1.92, the second 2.08 and 2.09, and the third pair are 2.88 and 2.83. The new values of the natural frequencies are shown in the figures 4.10, 4.11, and 4.12,

as beta value converged to a value of 0.71.
However, as it is been said before the initial model had a high values of MAC and it was expected that the MAC values are not going to change a lot as they are already with a significant physical meaning. The MAC matrix after the fine tuning is as the following;

$$MAC = \begin{bmatrix} 0.96 & 0.12 & 0.35 \\ 0.008 & 0.86 & 0.06 \\ 0.17 & 0.19 & 0.91 \end{bmatrix}$$

Table 4.6 shows the new values of the young modulus after calibration the model. The new values of the young moduli just gives another hint that the initial configuration of the values were overestimating the stiffness of the Sanctuary, as the new values now decreased significantly with a value of almost 30 %.

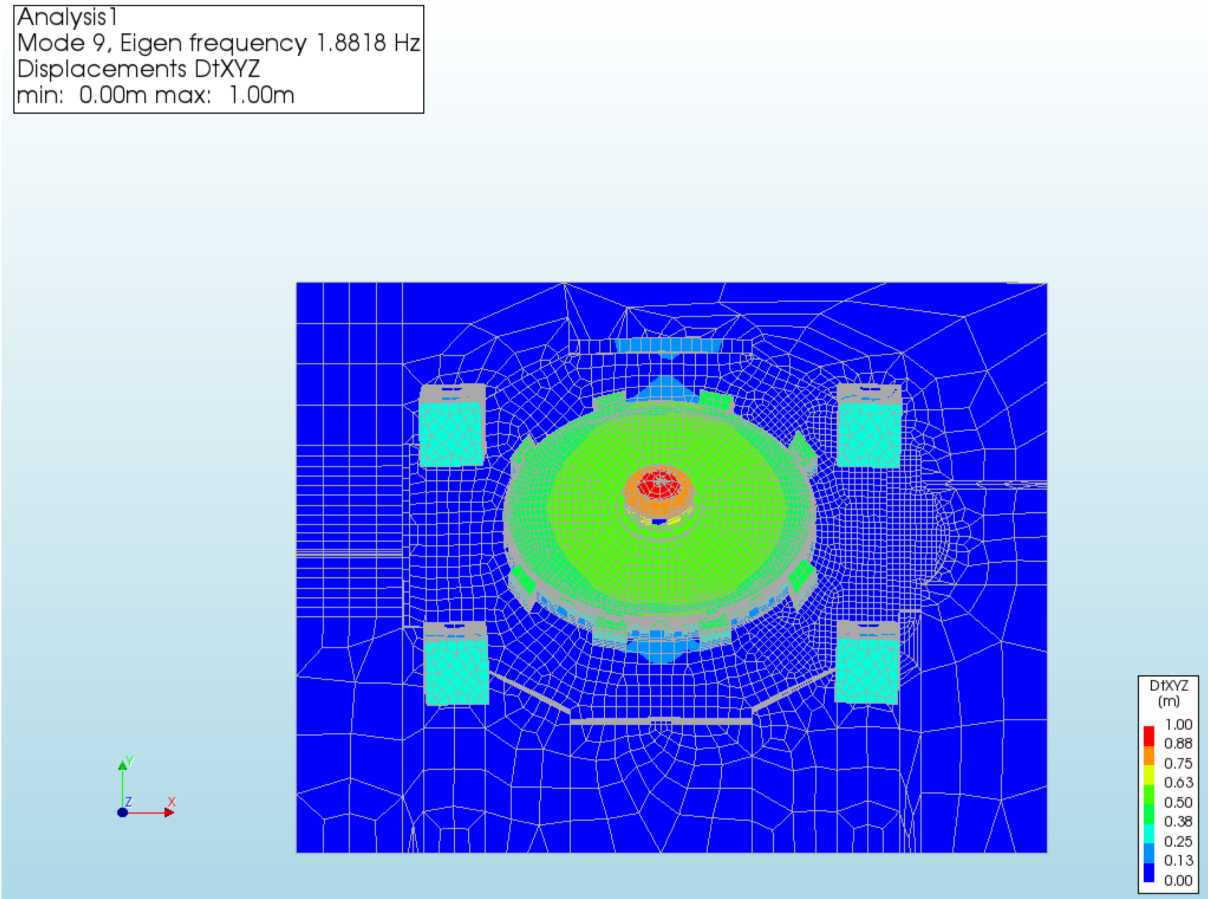



FIGURE 4.10: 1st Calibrated Mode

Figures 4.13,4.14,4.15 and 4.16 are the results of the linear static analysis done by DIANA, as it is significant the displacements in Z-direction which is normal since it is the direction of the gravitational forces or in other words the self-weight of the structure. Moreover, the figures 4.13,4.14,4.15, and 4.16 are the results of the linear elastic analysis due to the self-weight of the structure.

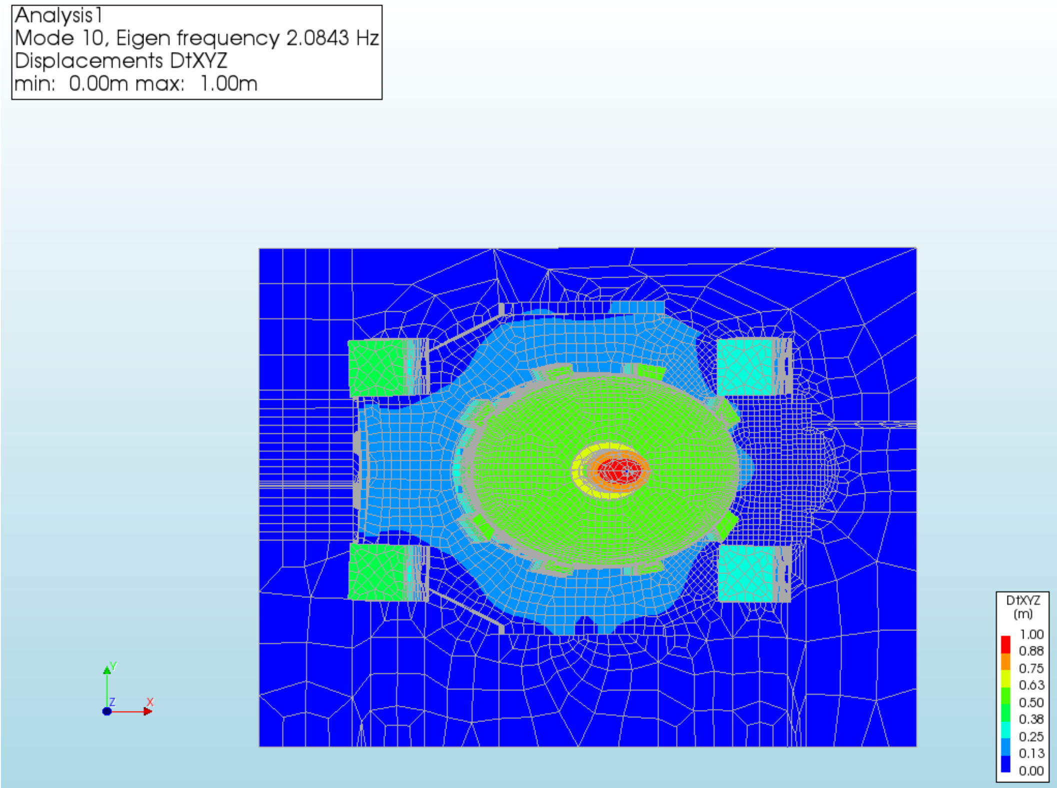



FIGURE 4.11: 2nd Calibrated Mode

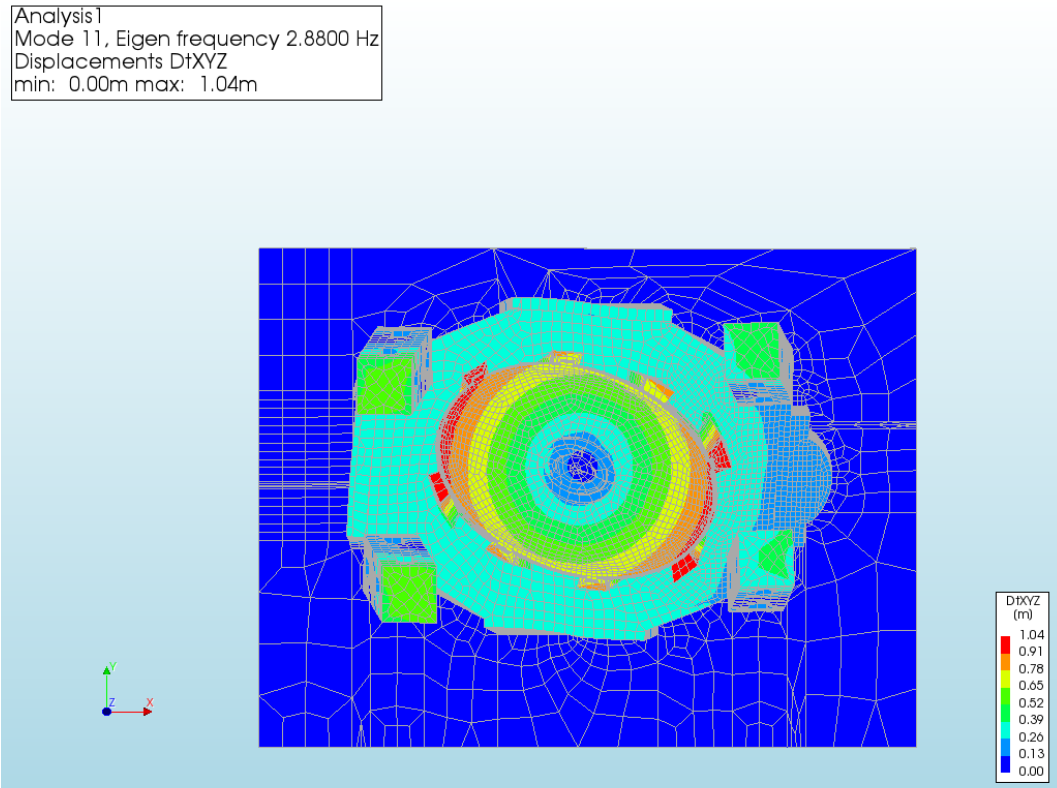



FIGURE 4.12: 3rd Calibrated Mode

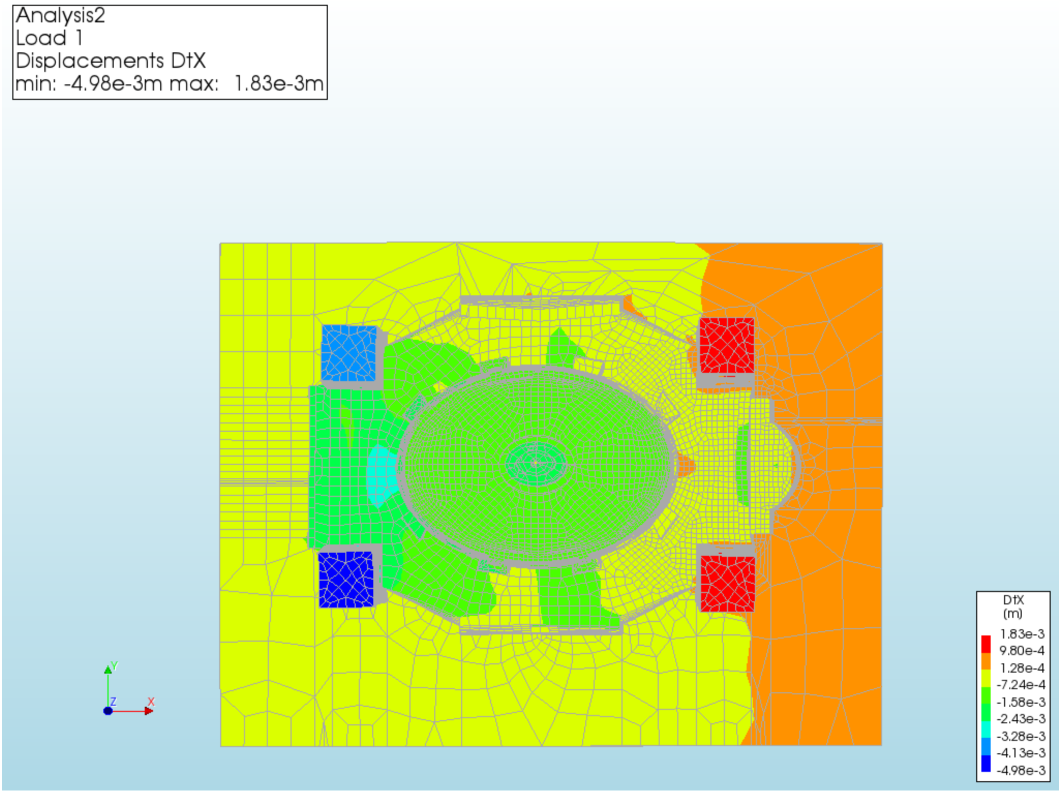



FIGURE 4.13: Linear Elastic Analysis Results-Displacement X direction

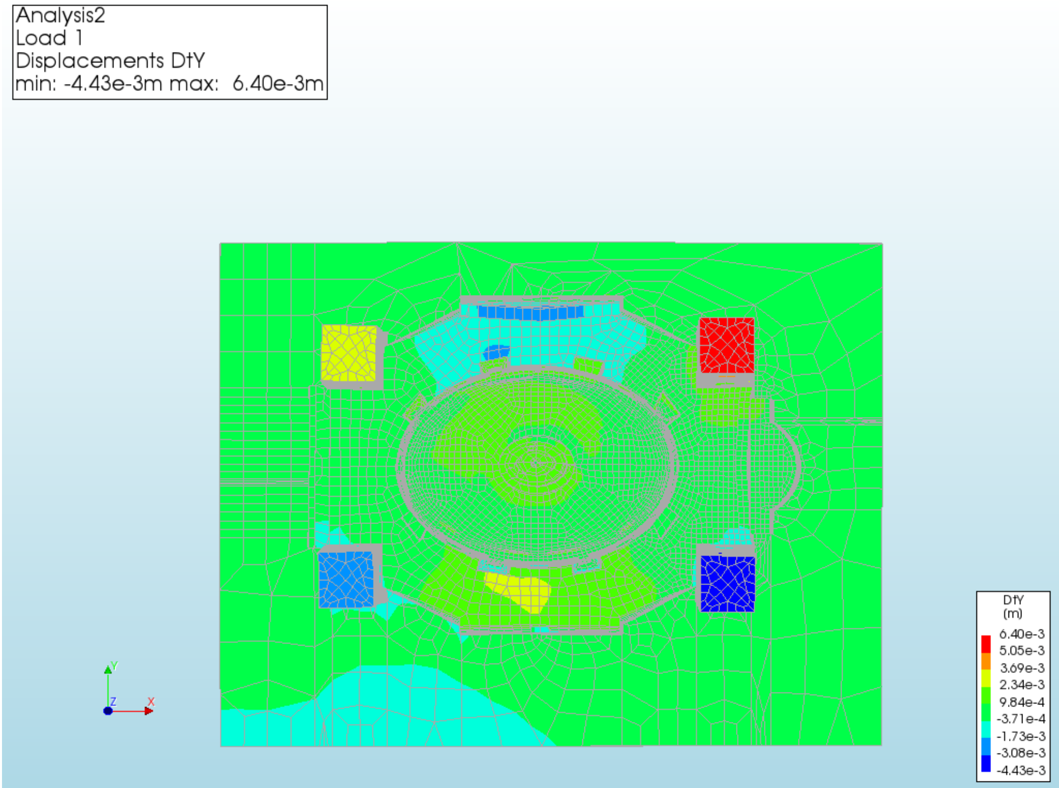



FIGURE 4.14: Linear Elastic Analysis Results-Displacement Y direction

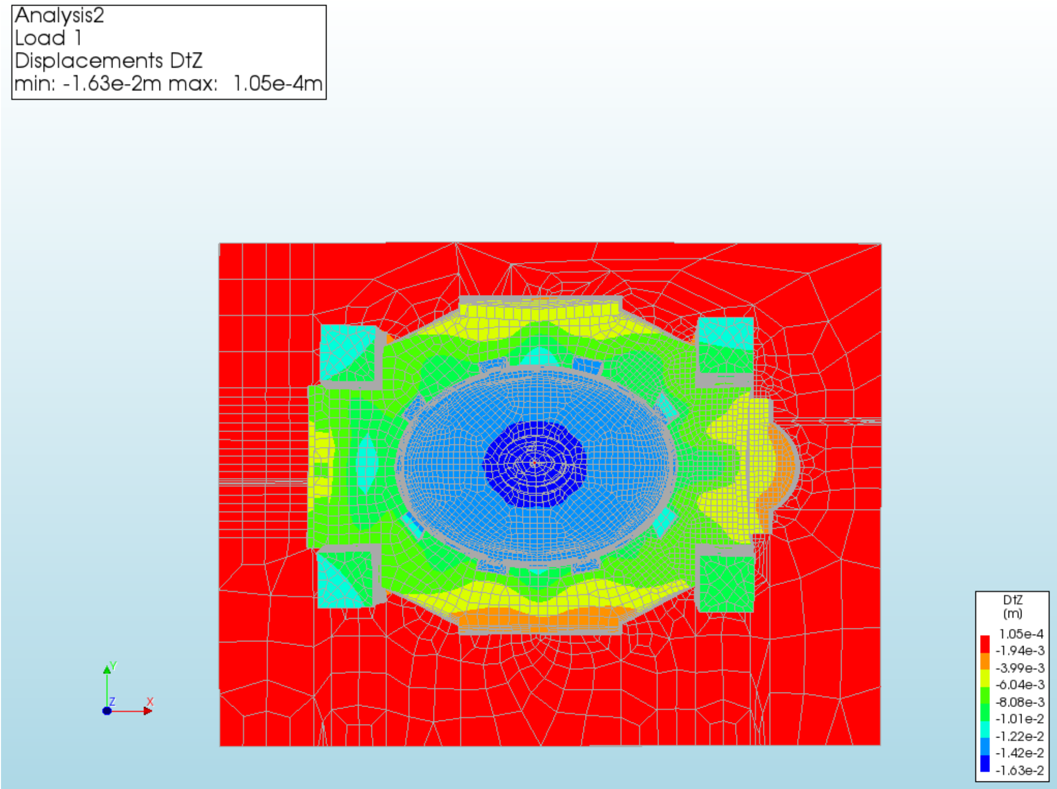



FIGURE 4.15: Linear Elastic Analysis Results-Displacement Z direction

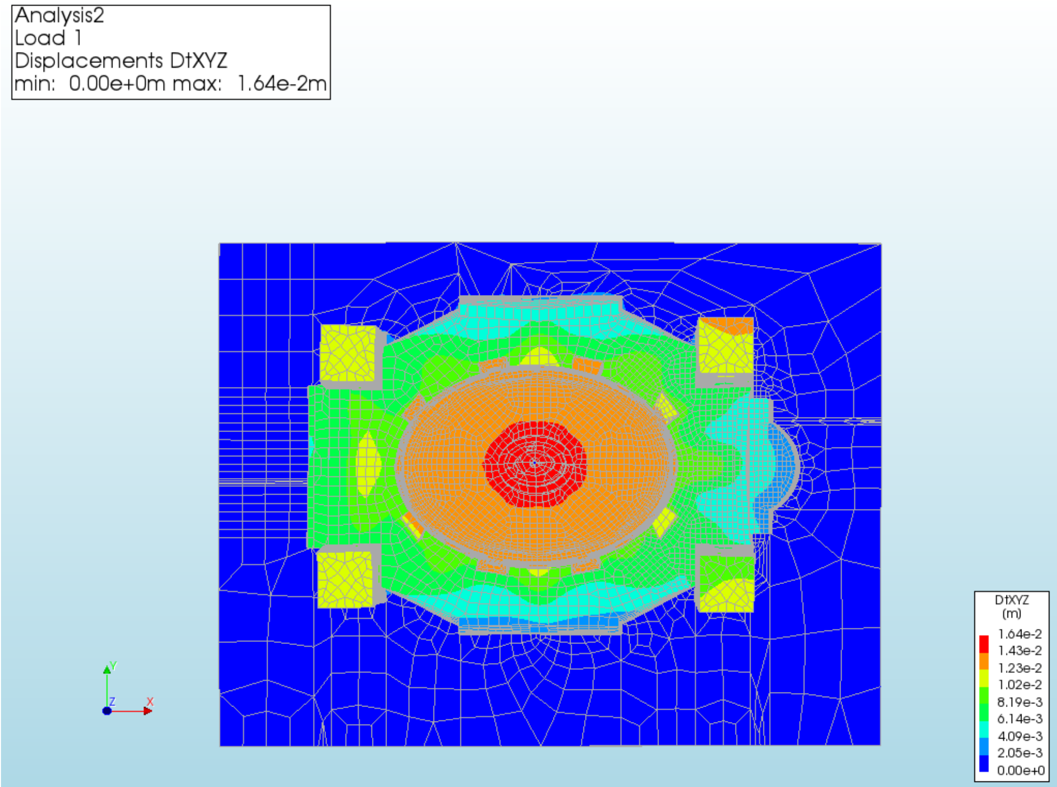



FIGURE 4.16: Linear Elastic Analysis Results-Displacement XYZ direction

# Chapter 5

# Conclusion

Historical structures and landmarks are well-known property in the Italian Culture. Preserving these structures is representing a challenge for both academic in terms of study and for technical engineer in terms of the retrofitting applications. In our study, we have passed through a one of the most known churches in the world as it has the largest oval dome that has a great history that started in the 1400's. The Sanctuary of Vicoforte has been under studies for almost thirty years. Non-destructive testing has shown that the structure is having a critical damages in terms of delamination, cracks, and other matters. However, studies showed that a large value of settlement has been experienced by the structure. The studies and drawings has showed the configuration of the soil that is composed of two main layers: the silt and marl stone. The configuration of the soil shows a significant slope in the cross section of the soil, going deeply into this fact this may later affect the behavior of the structure.

## 5.1 Summary

Everything has started with the 3D modelling of the Sanctuary of Vicoforte, where it has been firstly modeled and modified using AutoCad and then exported to a finite element analysis software called DIANA FEA. The structural elements of the Sanctuary has been modeled as a solid elements, except for the roof of the dome that has been chosen to be modeled as a shell element. The structure is mainly made of masonry material (except the roof of the dome which is made of wood and copper). The consecutive model that has been chosen in this study is the linear elastic model that is composed of three parameters: the young's modulus, Poisson ratio and the mass density. After assigning the material properties to the structure, discretization and meshing has been generated with an element size that ranges between 0.5 and 1.5 meters.
Eigenvalue analysis was made where in this study the natural frequencies and the eigenmodes were targeted for the purpose of making model updating. The initial configuration of the material properties showed a good results in terms of the modal assurance criterion, but however it showed a high values of natural frequencies compared to those of the experimental one. This meant that, the young's modulus parameters are kind of overestimated.
Model Updating is the process of updating the mass and stiffness matrices in order to match the measured behavior of the structure experimentally. Ratios of the numerical natural frequencies and the experimental natural frequencies showed that the three ratios are almost constant. This meant that also fine tuning could be a good approach to update the parameters. In which all the material properties were targeted to be updated and modified to match the experimental results.

The experimental results were obtained from a structural health monitoring sensing system. The SHM system consists of a static and dynamic monitoring plan, where it targeted different types of results i.e. environmental, thermal and also natural frequencies and modal coordinates.
In our case study, Particle Swarm Optimization method was used to optimize the cost function that consists of the modal assurance criterion values and the normalized difference of the natural frequencies between the experimental and the numerical results. The parameters chosen for the PSO resulted in the speedy convergence of the optimization process was firstly found from different studies that were carried out for the civil engineering purposes. It was expected that the convergence of our cost function will be fast, due to the fact that we are already having a very high value of modal assurance criterion values MAC. The results showed a good agreement compared to the experimental results.

## 5.2 Recommendations and Future Studies

The study performed on the study targeted the improvement of the mechanical parameters of the almost the whole structural elements of the Sanctuary except for those that have almost no uncertainties in their values such as copper and steel. As it has shown previously, the fine-tuning method has brought acceptable results in terms of natural frequencies and modal coordinates. Such 3D model and studies could be useful for further studies that can be done on the model for assessing and identifying unpredictable behaviors.
The structural health monitoring plan that is used for the Sanctuary of Vicoforte is a relevant database as it studies different aspects including climatic, geological, geophysical and other important phenomena. Recent studies have shown that different parameters concerning the structural behaviour of soil and structures can be extracted by satellite such as temperature of the soil and the masonry micro-elements, also a quantification of the water in the soil.
Collected parameters could be a valuable inputs to study the effect of their variations on the dynamic behavior of the Sanctuary. Such studies could be useful due to the fact that there are quite high uncertainties.
The decoupling between the acquired parameters and the validated constructed model in our case study might help in understanding some global dynamic behavior of the structure. As a result, this would help in getting a better understanding and attain more accurate predictions.

# Appendix A

The following appendix aims to show the different steps that was used for modeling using the DIANA FEA software. In addition to that, some codes that was used are reported as it could help clarify problems in programming.

- New Project

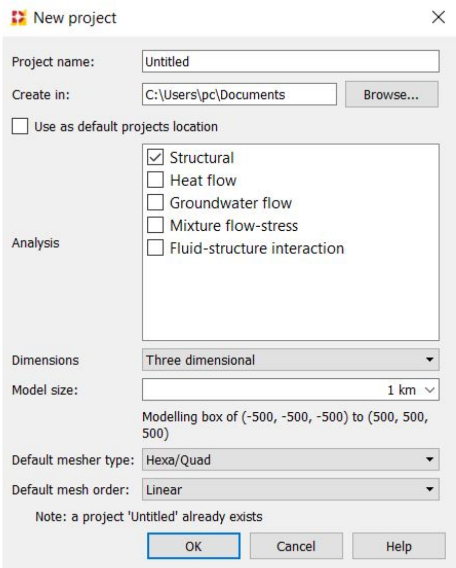



FIGURE A.1: New Project

- Import Cad File
  It should be mentioned that the file that has to be imported from Autocad has

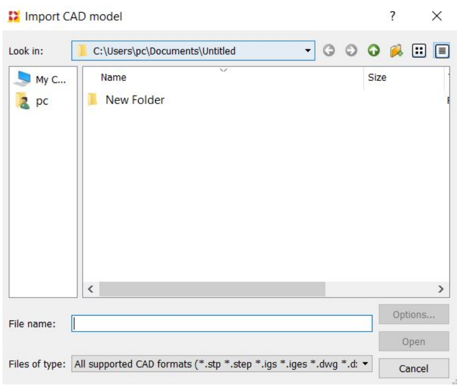



FIGURE A.2: Import CAD File

to be in the form of **FILE.IGES**, unless the user wants to use the IFC files.

- Material Definition

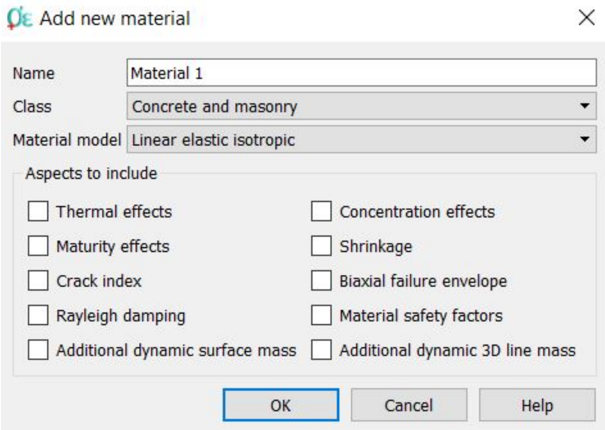



FIGURE A.3: Material Properties

- Properties Assignment

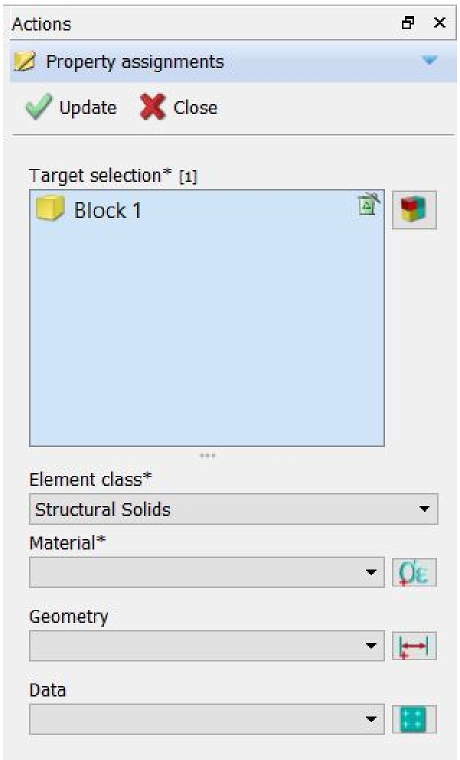



FIGURE A.4: Properties Assignment

- Meshing Assignment

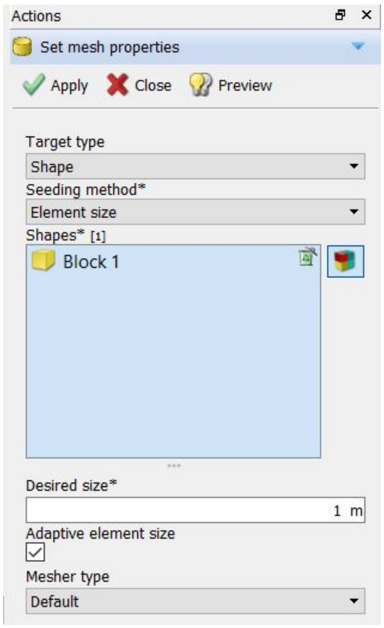



FIGURE A.5: Meshing Assignment

- Attaching Supports

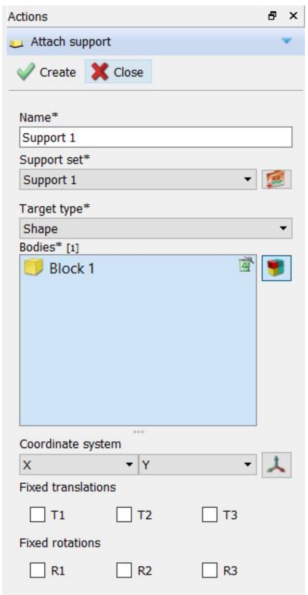



FIGURE A.6: Attach Supports

- Global Load Definition

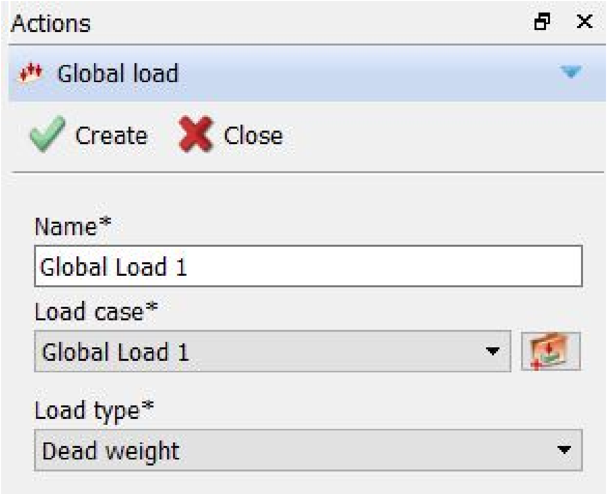



FIGURE A.7: Global Load Definition

The definition and the assignment of the different mentioned steps concludes the inputs of the FEM model. It would be possible now, to generate the mesh using the DIANA environment using the **GENERATE MESH** button.
As a recommendation, it would be better to import the elements of the structure separately and perform the steps each time in particular the generation of the mesh for two main reasons to identify the errors if exists, and less computational time.

- Eigenvalue Analysis

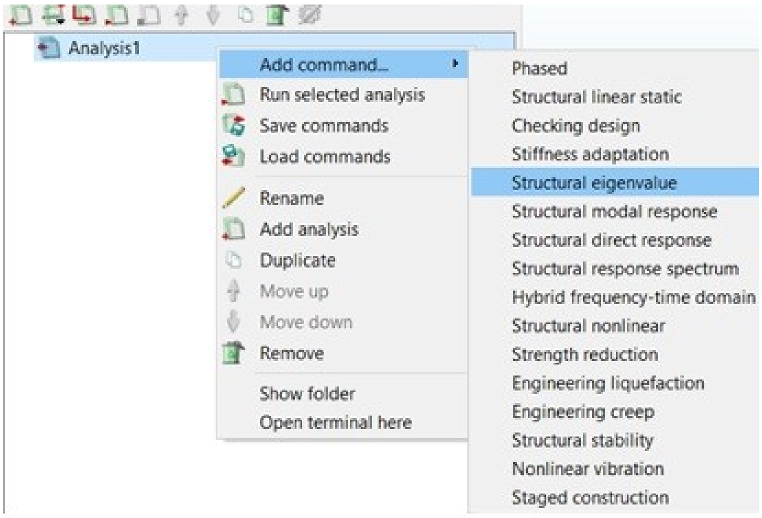



FIGURE A.8: Eigenvalue Analysis

However, in the upcoming parts of this appendix some useful python codes are presented, these codes has been also used in this study.

- DIANA Environment
openProject( "C:/Users/pc/xxxx/xxxx/Model.dpf" )
setParameter( "MATERIAL", "ELEMENT", "LINEAR/ELASTI/YOUNG", )
**"Definition of the young's modulus for ELEMENT"**
runSolver( [] )
**"It runs the analysis you have defined, if more than one analysis is defined it is then required to add the analysis name inside the rectangular parenthesis."**
showView( "RESULT" )
saveProject( )
closeProject( )

- Writing inside a text file or a python file can be using the following commands:
content1 = open("test.txt", "w+")
content1.write(content)
content1.close()
Where test.txt is a text file the user wants to define. Knowing that, DIANA software reads just python file, so user have to change the txt extension in ".py" extension.

- Executing DIANA FEA software using python could be possible by importing the "subprocess" library.
import subprocess
subprocess.call(['C:\ Program Files \ Diana 10.3\ \ bin\ \ DianaIE.exe', 'test.py'])

- File reading using python, here the reading of the natural frequency will be mentioned as an example; Taking into account the needed indentations.
linenumber1 = 288
with open(filename, 'r') as filehandle:
currentline1 = 1
for line1 in filehandle:
if currentline1 == linenumber1:
break
currentline1 += 1

  line1 = line1.split()
Fnat1 = float(line1[1])

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