UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF OPTIMIZED DAMAGE PREDICTION METHOD FOR HEALTH MONITORING OF ULTRA HIGH PERFORMANCE FIBER-REINFORCED CONCRETE COMMUNICATION TOWER

SARAH JABBAR GATEA

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By

SARAH JABBAR GATEA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

DEVELOPMENT OF OPTIMIZED DAMAGE PREDICTION METHOD FOR HEALTH MONITORING OF ULTRA HIGH PERFORMANCE FIBER-REINFORCED CONCRETE COMMUNICATION TOWER

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June 2018

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The requirement for communication towers increases due to the growing demand for power supply and telecommunication services. Recently, many attempts have been exerted to monitor the tower to ensure its excellent performance during operation. The capability of the tower to detect, localize, and quantify structural damage is the most important factor in maintaining excellent performance, reliability, and cost-effectiveness and ensuring its stability and integrity. The dynamic analysis of tall slender towers is commonly performed in the frequency domain. However, the recorded frequencies can be noisy, random, unstable, and with skewed data. The damage, due to uncontrolled noise reciprocating motion in the machines or broadband noise from wind or other sources, is identified based on frequency testing in an operator. Therefore, this study aims to develop a new health monitoring system for communication towers based on AdaBoost, Bagging, and RUSBoost algorithms as hybrid algorithm, which can predict the damage by using noisy, random, unstable, and skewed frequency data with high accuracy.

For this purpose, a UHPFRC tower with 30-m height is considered, and the finite element model (FEM) of the tower is developed. The modal frequencies of the tower are evaluated under various conditions of damage in concrete and connection in different parts of the tower by using finite element simulation. The results are used to develop the hybrid learning algorithm based on the AdaBoost, Bagging, and RUSBoost methods to predict the damage in the tower based on dynamic frequency domain. Therefore, 78 damage scenarios have been simulated by using finite element software to generate the frequency of the UHPFRC communication tower with various types of damage. The damage scenarios consist of losing bolts and vertical and horizontal cracks. The frequency before and after damage was set as input training

data, whereas the damage types and locations are set as output data (damage index). The verification results indicate that all the structural defects were predicted with high accuracy by the developed hybrid algorithm in cases of healthy and damaged structures. The full-scale UHPFRC communication tower is experimentally tested for dynamic frequencies to verify the numerical analysis results. The frequency response of the tower structure was obtained by exciting with an impact hammer at various points, and the acceleration of the tower structure was gathered through three accelerometer sensors attached at the top, middle, and bottom parts of the structure. Damaging the full-scale tower is not practical; thus, two different parts of the tower segments and their connections (1-2 and 2-3) are considered and tested experimentally with and without damage to validate the capability of the developed hybrid algorithm to detect damage. A dynamic actuator was used to cause damage in the tower segments by applying vibration force.

In addition, a simple procedure is proposed to determine the optimal solution and predict the correlation factor and the frequency of the damaged communication tower by using the particle swarm optimization (PSO) method. This technique avoids the exhaustive traditional trial-and-error procedure to obtain the coefficient of the correlation factor of frequency for the damaged communication tower by conducting several analyses. The new assessments on the capability of the indicator to detect and quantify the defects are performed. For this purpose, the FEM is implemented to model three communication towers with a height of 15, 30, and 45m to develop the frequency correlation factor. The verification results indicate that the PSO technique can develop a correlation factor with acceptable accuracy to predict the damage.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KAEDAH RAMALAN KEROSAKAN OPTIMUM UNTUK PEMANTAUAN KESIHATAN MENARA KOMUNIKASI MENGGUNAKAN FIBER KONKRIT BERTETULANG BERPRESTASI TINGGI

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Seiring dengan kemajuan dalam bidang telekomunikasi dan juga penyiaran, keperluan untuk menyediakan menara komunikasi turut menunjukkan peningkatan. Sehingga kini, beberapa penyelidikan telah dijalankan untuk memantau menara komunikasi bagi memastikan prestasi yang optimum semasa operasi. Keupayaan untuk mengesan, menempatkan dan mengira kuantiti kerosakan struktur merupakan faktor utama untuk mengekalkan prestasi, kebolehpercayaan, keberkesanan kos serta memastikan kestabilan dan integriti menara telekomunikasi. Analisis dinamik terhadap menara tinggi langsing biasanya dijalankan dalam frekuensi domain. Walau bagaimanapun, frekuensi yang direkodkan boleh menjadi bising, rawak, tidak stabil, dan dengan data yang condong. Kerosakan tersebut yang disebabkan oleh pergerakan hingar yang tidak terkawal dalam mesin atau bunyi jalur lebar dari angin atau sumber lain, dikenalpasti berdasarkan ujian frekuensi dalam pengendali.

Oleh yang demikian, matlamat utama penyelidikan ini dijalankan adalah membangunkan sistem pemantauan kesihatan yang baru untuk menara komunikasi berdasarkan algoritma AdaBoost, Bagging, dan RUSBoost sebagai algoritma hibrid, yang boleh meramalkan kerosakan melalui data frekuensi yang bising, rawak, tidak stabil, dan condong dengan ketepatan yang tinggi.

Bagi tujuan ini, sebuah menara UHPFRC berketinggian 30 meter dibina Model Unsur Terhingga (FEM) bagi menara tersebut telah dibangunkan. Frekuensi modal menara dinilai dalam pelbagai keadaan kerosakan konkrit dan sambungan di bahagian menara yang berlainan menggunakan simulasi unsur terhingga. Keputusan yang diperoleh digunakan untuk membangunkan algoritma pembelajaran hibrid berdasarkan kaedah

AdaBoost, Bagging, dan RUSBoost untuk meramalkan kerosakan di menara berdasarkan domain frekuensi dinamik. 78 senario kerosakan telah disimulasikan dengan menggunakan perisian unsur terhingga untuk menjana frekuensi menara komunikasi UHPFRC dengan pelbagai jenis kerosakan. Senario kerosakan terdiri daripada kehilangan bolt dan retakan menegak dan mendatar.

Frekuensi sebelum dan selepas kerosakan ditetapkan sebagai data latihan input, manakala jenis dan lokasi kerosakan ditetapkan sebagai data output (indeks kerosakan). Keputusan pengesahan menunjukkan bahawa semua kerosakan struktur telah diramalkan oleh pembangunan algoritma hibrid dalam kedua-dua kes iaitu kesihatan dan kerosakan dengan darjah ketepatan yang tinggi dalam mengesan kerosakan. Menara komunikasi UHPFRC berskala penuh telah diuji secara eksperimen bagi mendapatkan frekuensi dinamik untuk mengesahkan keputusan analisis berangka.

Tindak balas frekuensi struktur menara diperoleh dengan cara menarik menara dengan tukul kesan pada pelbagai titik, dan pecutan struktur menara dikumpulkan melalui tiga sensor meter pecutan yang diletakkan di bahagian atas, tengah, dan bahagian bawah struktur. Merosakkan keseluruhan menara adalah tidak praktikal; oleh itu, dua bahagian berbeza dari segmen menara dan sambungan mereka (1-2 dan 2-3) diambil kira dan diuji secara eksperimen dengan dan tanpa kerosakan untuk mengesahkan keupayaan algoritma hibrid yang telah dibangunkan untuk mengesan kerosakan. Penggerak dinamik digunakan untuk mengakibatkan kerosakan di segmen-segmen menara melalui daya getaran.

Sebagai tambahan, satu prosedur mudah dicadangkan untuk menentukan penyelesaian yang optimum dan meramalkan faktor korelasi dan frekuensi menara komunikasi yang rosak menggunakan kaedah Particle Swarm Optimization (PSO). Teknik ini mengelakkan prosedur percubaan-dan-kesilapan tradisional yang komprehensif untuk mendapatkan pekali faktor korelasi frekuensi untuk menara komunikasi yang rosak dengan menjalankan beberapa analisis. Penilaian baru keupayaan indikator untuk mengesan dan mengukur kecacatan dilakukan.Bagi tujuan ini, FEM dilaksanakan untuk mencontohi tiga menara komunikasi dengan ketinggian 15, 30, dan 45 meter untuk membangunkan faktor korelasi frekuensi. Hasil pengesahan menunjukkan bahawa teknik PSO boleh membangunkan faktor korelasi dengan ketepatan yang boleh diterima untuk meramalkan kerosakan.

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I certify that a Thesis Examination Committee has met on 1 June 2018 to conduct the final examination of Sarah Jabbar Gatea on her thesis entitled "Development of Optimized Damage Prediction Method for Health Monitoring of Ultra High Performance Fibre-Reinforced Concrete Communication Tower" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Major civil engineering structures, such as bridges, dams, offshore installations, and towers, are an important part of the wealth of a country. The maintenance costs of these structures are substantially high even with a small percentage of reduction in maintenance cost amounts to considerable savings. Structural health monitoring (SHM) is one of the most effective maintenance methods. Detection of early problems, such as cracks at critical locations, delimitations, corrosion, and spalling of concrete, can help prevent catastrophic failure and impairment of the structural system and reduce the maintenance cost. Furthermore, SHM can improve the serviceability and functionality and increase the lifespan of structures, thereby helping the national economy significantly. Thus, SHM of civil structures is becoming increasingly popular worldwide because of its potential application in maintenance and construction management.

1.2 Background

Structural health monitoring (SHM) is a process in which certain strategies are implemented for determining the presence, location and severity of damages and the remaining life of structure after the occurrence of damage. Health monitoring is typically used to track and evaluate the performance, symptoms of operational incidents and anomalies due to deterioration or damage as well as health during and after extreme events (Aktan et al., 1998). Damage identification is the basic objective of SHM.

Damage is determined at four main levels as presented by Rytter (1993).

Level 1: identification of the existence of damage;
Level 2: identification of the existence and location of damage;
Level 3: identification of the existence, location, and severity of damage; and
Level 4: identification of the existence, location, and severity of damage and prediction of the remaining life of the residual structure.

The ability of a system to determine the structural condition in long-term monitoring to prevent damage is a main feature of SHM. A good SHM system can locate and detect damage at an early stage (Li and Hao, 2016). The SHM system is installed permanently on a structure to monitor its conditions on a continuous basis and provide information on every structural component. In principle, sensors (accelerometers) are installed in the structure to gather the response measurements caused by internal or external forces. The measurements are then transmitted to a centralized computer that stores and processes the data collected by the sensors. Once stored in the centralized computer, the data can be analyzed automatically by software programs or manually by human experts. Many data analysis approaches have been developed to assess the integrity of structures.

The SHM system uses non-destructive sensing in-situ and analyzes the characteristics of a structural system to detect fault occurrence, find its location, and evaluate its seriousness to estimate its consequences on the structure's residual life. SHM has been used for structural safety or maintenance of existing structures; rapid estimation of structural damage after an earthquake; evaluation of the remaining life of structures; rehabilitation and modification of structures; and management, maintenance, or repair of historic buildings (Rainieri et al., 2008). The SHM principle, as reported by Balageas (2006), is shown in Figure 1.1.

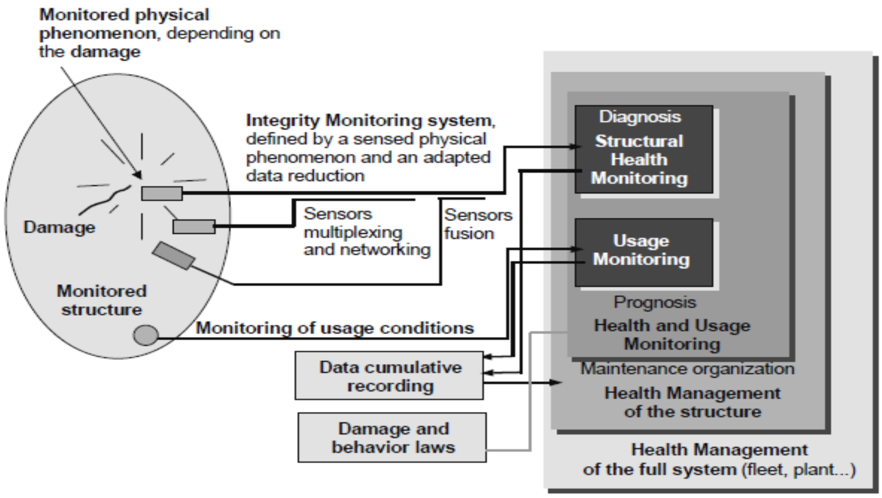

Figure 1.1 : Principle and organization of an SHM system

SHM aims to provide a non-destructive estimation of the structural state at any wanted moment of its remaining lifetime. Engineers should ensure the safe operations of the structure when its system integrity is estimated. Civil structures, such as buildings, dams, and bridges, and slender structures, such as towers and masts or wind turbines, are flexible and have low structural damping characteristics because they are sensitive to dynamic load. The durability and safety of civil structures are important in ensuring industrial prosperity and societal economy. Unfortunately, many aging civil structures are deteriorating because of cruel environmental conditions, uninterrupted loading, and inadequate maintenance. For example, the I-35W Bridge in Minneapolis, Minnesota, catastrophically failed on August 1, 2007 without warning, resulting in the death of 13 motorists (Figure 1.2) as reported by Swartz et al., (2007).

(a) (b)

Figure 1.2 : (a),(b)(Left) I-35W Bridge in Minneapolis, Minnesota USA; (right) catastrophic failure after collapse on August 1, 2007
(Source : Associated Press, 2007)

Furthermore, railways, especially their axles, undergo fatigue damage due to corrosion or load impact from vehicles, which lead to failure, passenger casualties, and even accidents. Therefore, an SHM system for railway axles can help eliminate service failure (Rolek et al., 2016). For example, a 150-year-old bridge near the Bhagalpur railway station in India's Bihar state collapsed as shown in Figure 1.3.

Figure 1.3 : Collapse of Railway Bridge near Bhagalpur
(Shanker, 2009)

Towers are among the most important structures because they enable the installation of equipment that allow various services, such as television, radio, and mobile communications. Damage is the main cause of structural failure and often occurs in structures. The absence of an alarm for structural damage and deterioration from loading, joint failure, and so on may cause tremendous disasters. As an example of tower failure, a 300-m communication tower mast in northern Netherlands collapsed as shown in Figure 1.4.

Figure 1.4 : Collapse of 300m communication tower mast in northern Netherlands
(Source : http://johnmarsyla.blogspot.my/2011/07/dutch-tv-tower-collapses-after-fire.html)

Many methods have been utilized to identify and locate damage in civil structures. The current non-destructive (NDT) damage identification techniques are based on visual inspection, acoustic emission, radiography, X-ray, eddy current, and ultrasonic and stress waves. The competence of these methods is limited to the accessibility of the structural location in limited areas and depends on the initial information concerning the probability of damage. Moreover, these methods are costly and time-consuming when applied to large structures and cannot identify damage without testing the entire structure. In addition, damages that are deep inside the structure may not be detected by these methods. Problems arise due to human errors because these methods require human experts to detect changes that indicate structural damage. Therefore, NDT damage identification methods are often insufficient for evaluating the condition of structural systems, especially when the damage is not observable. Vibration-based methods serve both as local and global damage identification approaches to identify the severity and location of damage. These methods are based on the principle that reducing the stiffness of structural systems leads to a change in their dynamic characteristics, such as the natural frequencies of the structure (Hakim et al., 2015).

The modern development of the SHM system for detecting damage depends on the mode of vibration. The physical characteristics of the structure directly affect the structure vibration characteristics. The stiffness of the structure changes when the structure is damaged and the vibration characteristics change as well.

When a structure is damaged, the stiffness decreases, which leads to the decrease of the natural frequencies of the system. Fatigue damage can arise when the structure is excited by the load impact and the load frequency is near the structural frequency. Therefore, natural frequencies are the most common dynamic parameters used in damage detection. According to the CEN. (2006), the first natural frequency is undoubtedly a key parameter in estimating the response of the structure (Antunes et al., 2012).

Natural frequencies can be easily obtained from a dynamic measurement anywhere on the system and are a common and popular damage indicator. Natural frequencies are used to detect damage in structural systems because changes in the structural properties result in shifts in these frequencies. Besides, natural frequencies can be used to detect damage because it can be quickly and easily conducted. Moreover, frequency measurements can be taken with relatively good accuracy, and doubts on the measured frequencies can be easily evaluated if the experimental measurements are conducted under perfectly controlled experimental conditions. The modal parameters, such as natural frequencies, can be determined from the acquired data through the experimental modal analysis test. However, in real-world scenarios, the recorded of low and high frequencies can be randomly unstable, noisy, and with skewed data, due to some uncontrolled noise, such as reciprocating motion in a machine, rotating imbalance in an automobile engine, or broadband noise from wind or road conditions in a vehicle, which should be resolved.

Machine learning methods for damage identification and detection have been presented by many researchers. Several methods have been investigated by researchers to estimate various types of damage, with the aim to develop approaches to determine the locations of damage or monitor the origin of damage. Machine learning has been widely used in SHM. There are two types of learning, supervised and unsupervised. In supervised learning should have info on the structure undamaged and damaged. On the other hand, are the unsupervised learning algorithms, in which case the information of the structure without damage is not available (Vitola Oyaga et al., 2016). Most of SHM systems for identifying damage in the structures based on an unsupervised learning method.

Recently, the need for communication towers has increased with the requirements for active communication, especially in the advent of radar, television, and radio. The configuration complexity of towers and the limited access to the structure, especially the inner part of the tower with a hollow section, make the monitoring of towers a challenging issue in maintenance. Therefore, a new health monitoring system for communication towers for damage detection with high accuracy is urgently needed.

The dynamic analysis of tall slender towers is commonly preferred in the frequency domain based on the frequency-dependent character of both of the wind loads and the mechanical properties of the structure. SHM is essential for determining the structural integrity and ensuring the lifetime of such structures. A key parameter to be monitored is the acceleration from which the natural frequencies of the structure can be determined. The changes verified in natural frequencies can be related to the degradation of the structure, and this parameter is an excellent indicator of structural health that allows preventive actions when necessary, thereby saving money and even lives (Antuneset al., 2012).

Therefore, this study aims to develop a new health monitoring system that can work with noisy, random, unstable, and skewed data for an ultra-high fiber performance-reinforced concrete (UHPFRC) communication tower, with 30-m height, located in Malaysia (Figure 1.5) by using frequency domain analysis. For this purpose, a hybrid learning algorithm based on the AdaBoost, Bagging, and RUSBoost algorithms is implemented to identify damage in the UHPFRC communication tower through the frequency domain data. Frequency response functions (FRFs) for damaged and healthy structures are determined using the excitation caused by an impact hammer and the signal collected by three accelerometer sensors that are attached to appropriate positions. The training samples for the algorithm are generated using the finite element (FE) method, and experiments are performed to obtain the testing samples. In addition, two cases that involve tower segments 1–2 and 2–3 are considered invalidating the hybrid learning algorithm for damage detection.

Figure 1.5 : Communication tower with 30 m height located in Malaysia

1.3 Problem statement

This research treats the problem of damage evaluation in communication tower in order to ensure their integrity and safety. In recent times, structural health monitoring (SHM) has attracted much attention in both research and development. SHM covered both local and global methods of damage identification (Zapico and González, 2006). In the local case, the assessment of the state of a structure is performed either by direct visual inspection or using experimental techniques such as ultrasonic, magnetic particle inspection, radiography and eddy current. A characteristic of all these techniques is that their applications require a prior localization of the damaged zones. The limitations of the local methodologies can be overcome by using vibration-based methods, which give a global damage assessment.

The most common vibration-based damage detection techniques include changes to mode shapes, modal curvatures, flexibility curvatures, strain energy curvatures, modal strain energy, flexibility and stiffness matrices. The other vibration-based techniques include numerical model updating and neural network based methods. The amount of literature in non-destructive vibration methods is quite large for treating single damage scenarios, however is limited for multiple damage scenarios. Most existing methods are based on a single criterion and most authors demonstrate these methods mainly in beam-like or plate-like elements.

Towers are one of the most important physical supports for the installation of radio equipment used for various services, such as radio, television and/or mobile communications. The dynamic analysis of tall slender towers is commonly performed in the frequency domain.

Therefore, developing a new system for damage detection in the communication tower structure and a health monitoring system with high accuracy are urgently required. However, the following challenges exist in tower maintenance:

The development of SHM for tall cylindrical structures, such as communication towers, is required due to the difficulty in measuring low-frequency responses.

- The configuration of the tower is complex and access to the body of the structure is limited, especially at the internal part of the tower that ensures structural integrity and stability.
- Many SHM systems for identifying damage in the structures using the frequency domain response are based on an unsupervised learning mode, which is challenging in precisely detecting and tracking damage in long-term monitoring.
- In an SHM system, the sensor network should be fail-safe during online monitoring. That is, the sensor should not be damaged after being installed in a structure. Otherwise, a redundancy algorithm is used to acclimatize to the new sensor network when one or more sensors are damaged.

1.4 Objectives

The main aim of this study is development of Structural Health Monitoring System (SHM) for Ultra High Performance Fibre Concrete (UHPFC) communication tower to detect damage in the structure as well in the joints. Therefore, the objectives of this study are listed as follows:

- To evaluate the response of communication tower in frequency domain under various damage condition by using numerical study through FE and experimental test.
- To develop the hybrid optimized prediction method as health monitoring system based on Adaptive Boosting, Bagging and RUSBoost algorithms for identification damage type and location of UHPFC communication tower.
- To verify the developed health monitoring system for damage identification in UHPFC communication tower through conducting experimental modal test on various segments of tower in healthy and damaged condition in frequency domain by using of impact hammer.
- To develop frequency correlation factor for UHPFRC communication tower with consider of structure damage.

1.5 Scope and Limitation of Structure

To achieve the objectives, the following steps are followed in the present study:

1. In order to develop an SHM system for communication tower, 30-m high UHPFRC communication tower in Malaysia is constructed. The tower consists of three segments with 10m long. The segments are linked to each other by using bolts and nuts. Besides, Eight presterss tendons used for reinforced UHPFRC tower.
2. FE simulation (ABAQUS software) is used to generate the frequency results of the UHPFRC communication tower to develop an SHM system based on the AdaBoost, Bagging, and RUSBoost algorithms for damage detection of UHPFRC communication tower.
3. Different damage scenarios are created using the FE method. These damages consist of removing bolts, vertical cracks and horizontal cracks.
4. Experimental modal analysis using the impact hammer test is conducted to test the UHPFRC tower with 30m height in a healthy condition to verify and validate the FE method and the proposed system
5. Two case studies that involve UHPFRC tower segments 1–2 and 2–3 are considered to validate the proposed model under healthy and damage conditions by using a dynamic actuator. The FE method and experimental modal analysis are applied.
6. The particle swarm optimization (PSO) method is implemented for the optimization correlation factor.

The present study has the following limitations:

1- The large size of the communication tower reduces the experimental testing for the full-scale UHPFRC communication tower.
2- The UHPFC material is considered.
3- The hollow circular tower is considered.

1.6 Organization

Chapter 1 highlights the importance and the definition of the problem chosen for the present investigation along with the objectives and scope of the study.

Chapter 2 introduces a review of health monitoring system, background of the theories of damage detection technique in frequency domain for communication tower and different other structures.

Chapter 3 presents the development procedure of 3D nonlinear communication tower, testing method with experimental set up in the performing procedure through experimental modal analysis (EMA), development of hybrid learning algorithm for damage detection of UHPFRC communication based on Adaptive boosting, Bagging and RUSBoost algorithm through frequency domain and development correlation factor of frequency for damage UHPFRC communication tower, different parametric study has been investigated.

Chapter 4 discuss FE results and experimental results for UHPFRC communication tower in frequency domain as been presented in this chapter, also, the application of the developed Hybrid learning algorithm to structural damage identification in the UHPFRC communication tower has been presented and verified through constructing two of tower segments (1-2 and 2-3). Then, the developed correlation factor of frequency for damage UHPFRC communication tower has been presented. Besides, the parametric study results has been carried out.

Chapter 5 presents the conclusion drawn from this study with the suggestion for the further research in this area.

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