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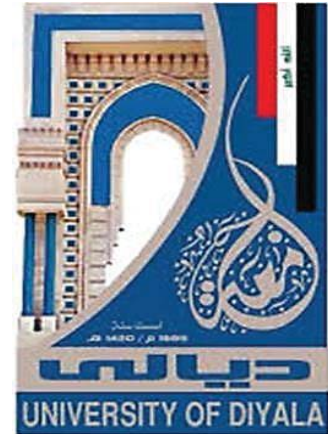**محمد جبار عباس**

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Numerical and Experimental Investigations of Health Monitoring of Composite Plates Using Dynamic Analysis

A Thesis Submitted to the Council of College of EngineeringUniversity of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

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CHAPTER ONE

INTRODUCTION

CHAPTRE ONE

INTRODUCTION

1.1 Introduction

Because of their high strength-to-weight ratio and good mechanical qualities, composite plates are widely employed in a variety of sectors. Composite plates are used in a variety of industries, including construction and aircraft (Shyamsunder et al., 2022), as well as sports equipment and medical devices. They are, however, vulnerable to damage from a variety of factors, including collisions, fatigue, and environmental deterioration. As a result, composite plate health monitoring is critical to ensure structural integrity and dependability.

Dynamic analysis is a common approach for evaluating the health of composite plates because it is non-destructive and may identify changes in the inherent frequencies and mode shapes caused by degradation (Kulkarni et al., 2018),(Yang et al., 2017), (Burlayenko et al., 2018). Theoretical and experimental research dynamic analysis are being applied to create effective health monitoring strategies for composite plates (Hassani et al., 2021).

Theoretical dynamic analysis entails the creation of mathematical models that characterize the behavior of composite plates under various loading circumstances (Mehar et al., 2017). These models are used to forecast the natural frequencies and mode shapes of the plates, which may then be utilized as a baseline for health monitoring. The models may also be used to mimic the response of the plates to various forms of damage, which can contribute in the development of damage detection algorithms (Khatir et al., 2019).

Physical tests are used in experimental dynamic analysis to determine the natural frequencies and mode shapes of composite plates (Khatir et al., 2018). These tests may be carried out using a variety of methodologies, including impact testing, vibration testing, and modal analysis. The results of these experiments may be utilized to evaluate theoretical models and identify changes in plate behavior caused by damage.

The development of effective health monitoring strategies for composite plates requires both theoretical and experimental research. Therefor theoretical models shed light on the behavior of composite plates, whereas experimental studies validate and verify the models. These findings may result in the development of precise and dependable health monitoring strategies for composite plates.

1.2 Composite Materials

Composite materials are created by mixing two or more distinct components to form a material with superior qualities (Clyne et al., 2019). Individual materials retain their distinct properties while combining to form a material that is stronger, lighter, or more durable than any of the individual materials alone (Rajak et al. 2019).

Composite materials are utilized extensively in a variety of industries, include aircraft, automobiles, building, marine, and sporting. Carbon fiber reinforced polymers (CFRP) (Karataş et al., 2018) fiber glass reinforced polymers (FRP) (Banazadeh-Neishabouri al et., 2021; Karataş et al.,2018)), and metal matrix composites (MMC) (Singh et al., 2020) are some examples of materials that are composite.

The properties of composite materials are dictated by the type and mix of materials used, as well as the manufacturing method. The manufacturing process normally begins with the components being combined in a mold or matrix, followed by curing or hardening the combination using heat, pressure, or chemical processes. The benefits of composite materials include excellent strength to weight ratios, corrosion resistance, toughness, and the ability to be molded into complex shapes. Composite materials, on the other hand, can be more expensive to make and repair than conventional materials (Vasiliev & Morozov ,2018).

1.3 Components of Synthetic Composites.

There are two major components:

1. Matrix: The matrix is the main component of the composite and typically provides the bulk of the material's structure. The matrix is often a polymer, such as epoxy.
2. Reinforcement: The reinforcement provides additional strength and stiffness to the composite material. It is usually made of fibers or particles of materials such as Glass, Carbon, or Aramid.

1.3.1 Epoxy

Epoxy resins are viscous liquids with low molecular weight, and their viscosity depends on the extent of polymerization. They are commonly produced through a reaction between epichlorohydrin and bisphenol-A, although alternative formulations may replace bisphenol-A with other chemicals. Curing agents trigger the polymerization process, resulting in a dense network of cross-linked polymer.

Diethylene triamine is a commonly used curing agent (Baroncini et al., 2016). The curing process time varies depending on the choice of resin and curing agent, and

can range from minutes to 24 hours. Heat can be applied to accelerate the curing process. Epoxies can be produced at room temperature or elevated temperature, and are available as two-part or one-part systems. One-part systems must be stored at low temperatures to prevent curing. The curing process does not produce any by-products and like polyesters, epoxies also undergo shrinkage during the curing process (Gibson, G. et al,.2017) .

Some of the main qualities of epoxy include (Xiang & Xiao, 2020) :

> ➢ High strength and stiffness.
> ➢ High dimensional stability.
> ➢ Low shrinkage during curing.
> ➢ Excellent adhesion to a broad range of substrates.
> ➢ Good chemical resistance.
> ➢ Good electrical insulation capabilities.

Epoxy is used in a wide variety of applications, including:

Epoxy is widely used as an adhesive in a range of industries, including construction, aerospace, and automotive (Capricho et al. 2020).

- Coatings: Epoxy coatings are frequently used to protect concrete floors, steel buildings, and other surfaces against corrosion, abrasion, and chemical attack (Hsissou, R. 2021).
- Electronics: As an encapsulant and adhesive, epoxy is utilized in electronic components such as circuit boards and semiconductors (Stennermann et al., 2022).

- Epoxy is commonly used as a covering and adhesive for boats and other watercraft in the marine industry (Sivasubramanian et al, 2021; Rubino et al., 2020) .

- Epoxy is used in several dental restorative materials, such as composite fillings and dental bonding agents (Gönder et al., 2023; Jabbour, O., 2023)).

- Epoxy is used as a matrix material in fiber-reinforced composites to produce high-strength, lightweight products (Almushaikeh et al., 2023; Patel et al., 2023). Overall, epoxy is a versatile and valuable chemical that may be used in a variety of applications due to its strength, durability, and other desirable properties.

1.3.2 Kevlar Fibers.

Kevlar is a well-known aramid fiber invented by DuPont that is widely used in ballistic applications. Kevlar is a particularly flexible and lightweight material, making it excellent for use in situations where weight is crucial and has a very high tensile strength-to-weight ratio, which implies it can sustain a significant amount of force without breaking (Priyanka et al., 2019). It is also chemically resistant. It is vital to note that Kevlar is not waterproof and should not be exposed to direct sunlight. If this occurs, the fibers will lose density, making it far less effective. That is why Kevlar is commonly employed as an inner lining or core of a product. Kevlar is a non-flammable material, which implies it will not catch fire (Ozen et al., 2022). Kevlar is available in several varieties, including Kevlar 29, 49, 129, and 149.

Kevlar is made up of repeating units of para-phenylenediamine and terephthalic acid that are reacted together to form a polyamide polymer. These polymers are spun into threads that can be woven or knitted together to form a textile it is known as Aramid fibers, these fibers consist of large phenyl rings attached to amide groups and have

qualities such as good abrasion resistance, resistance to organic solvents, strength, and non-conductivity (Zhao et al., 2020). They have no melting point, but disintegrate around 500°C and are acid and solvent sensitive.

The high strength-to-weight ratio of Kevlar fiber makes it ideal for use in applications requiring strength and durability, such as body armor and bulletproof vests (Naik et al., 2020) .

> ➤ The best thing of Kevlar is that it can be made stronger still by combining it with other types of composite material.

1.3.3 Carbon Fibers

Carbon is a chemical element represented by the symbol C. It is a non-metallic element that is one of the most plentiful elements in nature, and it exists in free form, as in diamond (D'Haenens-Johansson et al., 2022) and graphite (Speranza, G. 2019). Carbon has a high boiling point of 4,827 degrees Celsius and a high temperature of 3652 degrees Celsius. Carbon's physical properties change depending on the type of the link between its crystals. It is distinguished by its capacity to form strong chemical bonds with a wide range of elements, allowing it to produce a large range of compounds. Carbon atoms, on the other hand, are joined to each other in minuscule crystals that run parallel to the axis of our component fibers known as carbon fibers. Because of their parallelism or direction, the fibers are extremely strong for their size. Carbon fiber has an atomic structure similar to graphite. Carbon fiber filaments are in the extreme lightweight and have high tensile strength and durability (Newcomb, B. A. , 2016).

Carbon fibers are well-known for their excellent strength-to-weight ratio, stiffness, abrasion resistance, and resilience to temperature variations. It is also very flexible, allowing it to be molded into a wide variety of shapes making it an ideal material for applications such as aerospace, automobiles, boats and sporting equipment. preserving strength and durability by employing carbon fiber instead of heavier materials, making it an attractive alternative for applications where weight and performance are essential variables. Carbon fibers are also utilized in the production of composite materials, where they are combined with other materials such as polymers and other materials to provide high support (Lionetto, F. 2021).

1.4 The Main Methods of Manufacturing Composite Materials

Composite materials are generated by combining two or more separate materials, with the new composites exhibiting properties different from those of the component materials alone. There are various ways to make composite materials, including:

1. Layup: This process is done manually, where layers of reinforced fibers are placed on the surface of the mold, layer by layer, and resin is placed between them to bind the layers together. This is often done at room temperature (Elkington et al., 2015).

2. Filament winding: Is a popular method for producing axi-symmetric composite parts. The filament winding process is used to create composite pipes, tubes, tanks, cylinders, domes, and spheres. An axi-symmetric mandrel having an exterior surface corresponding to the inner surface of the component to be created is employed in this procedure to create the axi-symmetric composite part. As it passes through a resin bath, fiber from continuous-fiber rovings becomes wet. As it exits the resin bath, this resin-wet is wound on a mandrel, which rotates continuously on its axis of

symmetry. Fabrication of filament wound composite tubes, pipelines, vessels, and shafts is a popular use (Quanjin et al., 2018).

3. Compression Molding: Compression molding is a manufacturing technique that involves inserting a warmed molding material into a heated mold chamber and exerting pressure to drive the material into contact with all parts of the mold until it cures. Molding complicated, high-strength fiberglass reinforcements and innovative composite thermoplastic materials with unidirectional tapes, woven textiles, randomly oriented fiber mat, or broken strand is possible using this procedure. Compression molding has the advantage of being able to form large, intricate pieces at a lower cost than other technologies such as transfer molding and injection molding. Furthermore, it wastes little material, thus it's advantageous for costly compounds (Santos et al., 2021). The compression molding technique is also known as vulcanization in the case of rubber (Lundquist et al.,2020).

4. Resin Transfer Molding (RTM): Is a wet procedure that involves placing fibers and resin separately in a mold. After placing layers of fibers in the mold, pressure resin is supplied to saturate the fibers. The mold cavity has resin inlets and air vents. The apparatus is then heated to start the curing process. RTM employs low viscosity polymers, allowing for greater control over fiber orientation. Vacuum assisted resin transfer molding (VARTM) is a less expensive version of RTM in which vacuum pressure aids in resin flow and fiber wetting (Miranda et al., 2022; Bittrich et al., 2022).

5. Pultrusion: Is a composite manufacturing process that is similar to classical extrusion. Throughout this procedure. The reinforcing material is immersed in a resin bath in the form of a tape, mat, or roving. Following the resin bath, the reinforcing material is passed through a before-forming fixture, where it gains some cross-sectional area. At this point, it is also "squeezed" to

eliminate extra resin and cavities. Finally, the reinforcing material is forced through a heated die, where the resin is continuously cured and the composite is formed into its final shape and cross-section. Pultrusion, as opposed to extrusion, involves dragging reinforcing materials (fibers, tapes, rovings, mats, etc.) through a die (Correia, J. R., 2023; Barkanov et al., 2022).

1.5 Carbon fiber reinforced epoxy composite and Kevlar

Because of its higher strength and stiffness capabilities, epoxy composites reinforced with carbon fibers and Kevlar are extensively employed in high-performance engineering applications. The combination of these two reinforcing materials provides a good mix of strength, toughness, impact resistance, and fatigue resistance (Srivatsava & Sreekanth, 2020).

Carbon fibers have great tensile strength and stiffness, making them ideal for aerospace and automotive applications that demand high strength-to-weight ratios. Kevlar, on the other hand, is a synthetic fiber that is well-known for its durability and resistance to impact and abrasion. It is often utilized in ballistic armor and protective equipment (Mourad et al., 2020).

Carbon fibers and Kevlar have been intensively investigated as reinforcements in epoxy composites in recent years. According to the studies, combining these materials produces composites with superior mechanical characteristics, such as greater modulus, strength, and fracture toughness (Karthik et al., 2022), as compared to composites reinforced only with carbon fibers or Kevlar. The combination of these two reinforcing materials results in a balanced performance that is suitable for a wide variety of technical applications.

Furthermore, the use of epoxy as a matrix material results in composites with high strength and stiffness due to the excellent bonding properties between the fibers and the matrix (Gantayat et al., 2018).

1.6 Dynamic of Vibration

A physical phenomenon in which an item oscillates or travels back and forth around its equilibrium point is known as vibration (Shabana, A. A., 2018). Sound waves, seismic waves, and mechanical waves are all examples of vibration. Many fields of science and engineering rely on vibrations, including physics, mechanical engineering, engineering for civil construction and aerospace engineering. In fact , the study of vibrations entails examining the behavior of mechanical systems when subjected to forces or disturbances, as well as finding the natural frequencies and modes of vibration of these systems to understand fundamentals of mechanical vibrations(Momin, Z., 2019) . Understanding vibration characteristics is critical for developing buildings and mechanical systems that can withstand external forces.

Vibrations may be classified into three types:

1. Free vibrations. When a system is placed in motion and then left to vibrate on its own, it produces free vibrations.
2. Forced vibrations, when a system is exposed to an external force, it vibrates at a frequency that differs from its natural frequency.
3. Resonance. When a system is exposed to an external force that has the same frequency as its natural frequency, it begins to vibrate with increasing amplitude.

1.6.1 Vibrations and Natural Frequencies of Materials

Free vibrations and natural frequencies of materials are key topics of research in physics and engineering. These vibrations and frequencies are inherent features of materials and can have a substantial influence on their mechanical and physical properties (Ariesta et al., 2022). A material can vibrate at its natural frequencies when exposed to an external force. The physical properties of the material, such as stiffness, density, and shape, effected these frequencies (Jafari & Azhari, 2021). A material's natural frequencies can be used to forecast how it will react to external stimuli such as impact, vibration, or sound waves. Natural vibrations in materials can take several forms, including longitudinal vibrations, transverse vibrations, and torsional vibrations. Transverse vibrations occur when a material vibrates perpendicular to its longitudinal axis, whereas longitudinal vibrations occur when a material vibrates parallel to its longitudinal axis. When a material twists around its longitudinal axis, it produces torsional vibrations. Accordingly, the study of natural vibrations and frequencies of materials has numerous practical applications, including building, bridge, airplane, and other structural design and engineering (Bozyigit & Acikgoz, 2022). Engineers may build these structures to resist external vibrations by studying their natural frequencies.

1.7 Health Monitoring of Composite Plate

Monitoring the health of composite materials, often used in industries like aerospace and automotive, is crucial to ensure their structural integrity. Monitoring the health of a composite plate involves keeping an eye on various factors to ensure it's functioning as intended. Various techniques are used for composite material health monitoring, some common techniques include visual inspections, non-destructive testing (NDT) methods like ultrasonic testing or thermography, and structural health

monitoring (SHM) systems (Zhong, S., 2019; Lu & Wong, 2018; Wang et al., 2020). NDT methods use different technologies to inspect the internal structure without causing damage. Ultrasonic testing, for instance, uses sound waves to detect flaws or changes in material properties. Structural health monitoring involves embedding sensors in the composite structure to continuously monitor its condition. These sensors can detect changes in strain, temperature, or other parameters that might indicate damage or deterioration. Regular inspections, combined with advanced monitoring techniques, can help ensure the long-term health and performance of composite plates.

1.8 Defects Detection

Defect detection is the process of finding and characterizing any deformity or irregularity in goods, systems, or processes (Tabjula et al., 2021). Defects can vary from small cosmetic flaws to major concerns that jeopardize safety, reliability, or performance (Jeon et al., 2017). Depending on the type of product or system being tested, several procedures and techniques are utilized to find faults. Visual inspection, functional testing, non-destructive testing, statistical process control, and quality audits are all typical techniques(Gomes et al., 2018; Shoukroun et al., 2020). Effective defect identification is critical for assuring product quality, saving waste and rework, increasing customer happiness, and lowering liability risks. It is also an essential component of quality assurance and quality control procedures in a variety of sectors, including manufacturing, construction, healthcare, and software development (Wone et al., 2019). Destructive testing and non-destructive testing are two methods for detecting defects in a variety of sectors, including manufacturing, construction, and aerospace (Qu & Zhang, 2020).

Destructive testing includes physically harming or modifying the thing being evaluated in order to detect any flaws or vulnerabilities. This procedure is often employed on prototypes or samples rather than final items. Tension tests, compression tests, and impact tests are examples of destructive tests (Senthilkumar et al., 2021). Non-destructive testing, on the other hand, includes product testing without destroying or modifying it. This procedure is widely used on sections or buildings to confirm their integrity and discover any faults. Non-destructive testing procedures include visual examination, ultrasonic testing, X-ray inspection, and magnetic particle inspection. The major distinction between destructive and non-destructive testing is that the former requires the destruction of the tested thing, whilst the latter permits the object to stay intact.

1.8.1 The Main Ways for Detecting Defects in Materials

The most essential defect detection methods are determined by the type of fault and the object being inspected. Here are some of the most common methods for detecting defects in materials.

1. Visual inspection: This is the most basic approach of finding faults, and it is visually inspecting the thing to identify any obvious flaws or anomalies. This can be accomplished with the naked eye or with the use of magnifying lenses or microscopes. It is widely utilized in the industrial, construction, and maintenance industries. Visual inspection is a crucial aspect of assurance of quality since it helps discover surface problems, dimensional errors, fissures, and other apparent symptoms of damage (Zhong & Nsengiyumva, 2022; Harishyam et al., 2023).

2. Ultrasonic testing: Ultrasonic testing detects faults in metals, polymers, and other materials by using high-frequency sound waves. It can identify faults

like fractures, porosity, inclusions, and voids. A transducer emits sound waves that go through the substance being evaluated. When they come into contact with a defect, they are reflected back to the transducer, where they are converted into an electrical signal that can be analyzed. Ultrasonic testing is widely employed in the aerospace, automotive, and industrial industries (Tsenis et al., 2020; Shpil'noi et al., 2021).

3. Radiographic testing: Radiographic testing uses gamma or X-ray radiation to detect internal flaws in materials. It can identify fractures, porosity, inclusions, and other interior problems. The substance being examined is put between an X-ray or gamma-ray source and a film or detector, and the radiation travels through the material and generates an image on the film or detector. Radiographic testing is widely utilized in the aerospace, automobile, and petrochemical sectors (Wang et al., 2017).

4. Particle magnetic testing: Is a non-destructive way of finding surface and near-surface faults in ferromagnetic substances such as steel and iron. The field of magnets is directed to the material under scrutiny, and then iron oxide particles are placed to the surface. If a fault exists, the particles will be drawn to it, which may be seen with UV light. Magnetic particle testing is widely used in aerospace, automotive, and construction (Vignesh et al., 2019).

5. Dye penetrates tests: Is a non-destructive method for detecting surfaces faults in polymers, metals, and ceramics. It entails smearing a liquid dye on the surface of the object under examination. The surplus dye is removed after a set length of time, and a developer is added. The developer pulls the color out of any cracks or imperfections, highlighting them. In the aerospace, automotive, and industrial industries, dye penetrant testing is extensively utilized (He, Y. et al., 2023).

6. Eddy current testing: Is a non-destructive approach for detecting surface and subsurface defects in materials that are conductive. It makes use of a probe that produces an alternating electromagnetic field. Eddy currents are induced in the substance being evaluated when the probe is moved across it. Any flaws in the system will impact the flow of the eddy currents, which may be identified and evaluated. In the aerospace, automotive, and industrial industries, eddy current testing is extensively employed (Zhang, W. et al., 2022; Zhang, L. et al., 2022).

7. Natural frequency: Frequency-based detection of defects is a non-destructive test (NDT) method for identifying and locating flaws in materials by analyzing frequency signals. This approach is frequently used to verify the quality and safety of goods in sectors such as aerospace, automotive, and construction (Sreekanth et al., 2022; Maldar et al., 2023).

1.9 Thesis Objectives

In our quest to ensure the reliability and safety of composite structures, intricate techniques are delved into in the world of dynamic analysis, a powerful tool that enables us to not only understand the behavior of these materials but also to detect and assess potential defects and damage, even at their earliest stages. Through the fusion of theoretical models and experimental investigations, the aim is to pave the way for more robust, efficient, and cost-effective health monitoring techniques that can extend the lifespan of composite structures, minimize downtime, and enhance overall safety. The following is the aim of this study :

1. The aim to is to develop a dynamic analysis-based health monitoring system. Through determining the material type and determining the composite material characteristics.

2. Building a F E modeling which is used to anticipate the influence of defects on natural frequencies. the Ansys Package might be useful.

3. The goal is to pave the way for more strong, efficient, and cost-effective health monitoring technologies that can extend the life of composite structures, reduce downtime, and enhance public safety.

4. The goal is to find a high-quality customized model fitting for critical applications like aerospace vehicles, airplanes.

1.10 Thesis Outline

The present thesis is structured into six distinct chapters. Chapter one is to provide an introduction to the topic and provide comprehensive research framework.

The second chapter presents a comprehensive literature analysis on the various methodologies used for the purpose of diagnosing and finding structural degradation. Chapter three of this study discusses the theoretical framework for vibration analysis for detection and localization, the finite element approach, and computer programs for dynamic analysis, specifically designed to compute changes in natural frequencies, based on its foundation. Chapter four provides a comprehensive explanation of the equipment and the methodology used for the development of the experimental approach utilized in the acquisition of natural frequencies using empirical methods. The fifth chapter included the presentation and discussion of theoretical and experimental data. Finally, the last chapter provides a broad overview, findings, and recommendations for further research in this topic.

ABSTRACT

Health monitoring of structures is a crucial aspect of ensuring the safety and reliability of various industrial facilities and infrastructure. This process involves the continuous or periodic assessment of a structure's condition while with in service, without causing any damage or disruption to its operation. Non-destructive testing (NDT) techniques, such as routine vibration measurements, are commonly employed to detect defects and assess the structural integrity of various components like fans in cement factories and frames in oil rig structures. The present work presents a vibrational technique for testing the integrity of a composite panel by measuring changes in natural frequencies.

The first part in this work discusses the design and analysis of hybrid composite plate's part using vacuum molding techniques. Two models (A and B) composed of six layers of carbon fibers and Kevlar fibers with varying proportions for each model with epoxy resin were studied. Experimental testing was conducted to determine the physical and mechanical properties of composite materials used in the production of composite panels.

The second part of this work takes place in the discussion of defect detection through non-destructive testing using numerical and experimental mathematical analysis of manufactured plates by changing the values of natural frequencies. The finite element approach was utilized for dynamic analysis of plate structures under various loading and support conditions, with the ANSYS 16.0 program used to calculate natural frequency changes and identify damage sites based on these measurements. The test was carried out on the plate with and without a defect, as different scenarios of the defect were used to study its effect on the composite plates. The results showed that the composite materials achieve a significant increase in the mechanical

properties such as (Young's modulus, flexural modulus), which increase to (25%), (33.33%), in the composite materials (four layers of carbon fiber mat fabric and two layers of Kevlar fiber mat) compared with composite materials (two layers of carbon fiber mat and four layers of Kevlar fiber mat).

The study found that cracks in composite plates decrease natural frequency values, as damage weakens the material's stiffness values, resulting in a decrease in frequency value. The maximum discrepancy between the frequency values was 7.09% between the experimental and numerical results. The results demonstrated that the size of cracks that begin early can be calculated based on measuring the values of natural frequencies. The study demonstrated the potential of this test to identify variations in frequency values across various scenarios, including crack length, location, direction in relation to the fixation axis, and the number of cracks, and to detect the distinction between these values.