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Investigating Free Vibration and Buckling of Laminated Composites Under Thermal Conditions

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Abstract: This research presents a comprehensive methodology for investigating the free vibration and buckling behaviors of laminated composite and sandwich structures under thermal conditions using an ABAQUS-based finite element model (FEA). The study aims to advance the state-of-the-art in composite material analysis through five key objectives: proposing a finite element-based model, conducting free vibration and buckling analyses of laminated composites and sandwiches in plate and beam forms under thermal influence, and assessing the impact of various parameters on frequency and buckling load.The methodology involves four crucial steps: geometry modeling, mesh size determination through a convergence study, and subsequent analysis. A noteworthy achievement is the identification of a 16 × 16 mesh size as optimal for simulating a 10-layered square-shaped angle-ply SSSS laminated composite plate under thermal conditions, ensuring study accuracy.This research not only aligns with existing models but also advances them, enhancing its credibility. It notably emphasizes the role of ply-angle in non-dimensional natural frequency, finding that a 45° ply-angle yields the maximum non-dimensional frequency, regardless of the height-to-side-length ratio (h/a). This discovery holds practical implications for the design and manufacturing of laminated composite materials, especially in thermally challenging environments that may induce buckling or alter vibration behavior.While this research significantly contributes to understanding laminated composites under thermal conditions, it calls for future work. Opportunities include experimental validation, broader analyses encompassing different boundary conditions and thermal loading scenarios, and the exploration of multi-scale modeling approaches.In summary, this research sets a new benchmark in finite element analysis for laminated composites and sandwiches under thermal conditions. Its potential applications span across aerospace, automotive, and civil engineering fields, addressing critical concerns in the behavior of these materials under thermal loads.

***Keywords**: Laminated Composites, Sandwich Structures, Free Vibration, Buckling Behavior, Thermal Conditions, Finite Element Analysis, ABAQUS, Convergence Study, Ply-Angle, Non-Dimensional Natural Frequency, Material Properties, Multi-Scale Modeling, Aerospace, Automotive, Civil Engineering*.

1. INTRODUCTION

At the macroscopic level, a composite is a heterogeneous combination of two or more components. If the constituent elements are blended uniformly, the resulting material is an alloy rather than a composite since the constituent materials of composites cannot be distinguished with the human eye. An age-old method for getting the appropriate strength from the constituent elements is composite building. For instance, using straw when building with mud or plywood, etc. In the modern period, concrete, the most popular building material, is also a composite substance. Different forms of composites, including fiber-reinforced and resin-matrix composites, have recently been produced. The following categories fit these composites. Fibrous composites: These composites contain fibers that have been incorporated into the matrix. The arrangement of the fibers might be either uniform or non-uniform. For instance, a glass fiber plate. Laminate composites: Composites that have been laminated together from a number of layers of the same or different materials. Examples include laminated glass, clad metallic plate, and plywood. Particulate composites: Particulate composites are composites in which the matrix contains embedded particles. Concrete, for instance. In the case of composites, the flexibility to be customized is a great quality. Due to this quality, the desired attribute of the construction or structural element can be improved employing the lamina(s) in accordance with criteria (Jones, 2018). Composites are becoming more popular in the fields of aerospace, civil, automotive, marine, and naval engineering as well as pressure tanks and nuclear containers because to the aforementioned features. Laminated composite materials are created by bonding together two or more components in the form of layers. Lamina is the general term for the building block of laminated composite constructions. In a lamina, the fibers are arranged inside the matrix in any direction in a regular pattern. To obtain the necessary thickness and technical quality, these various laminas are combined and joined using the same material as the matrix. In relation to the reference axis, a layer's fiber orientation might vary (Figure 1.1). Sandwich structures are layered structures, much like laminated composite structures, except they contain a solid core as the center layer. As a result, sandwich constructions (Figure 1.2) always have an odd number of layers. Sandwich and laminated composite structures are gaining ground in the field of building a variety of structures due to their superior tailorability and high strength to stiffness ratio. The following are the sandwich constructions and laminated composites that are used most frequently: Composites have recently become one of the most essential materials due to its widespread use in engineering fields including aircraft, automobiles, and other fields. A substance called a composite is one that is constructed from two or more distinct constituents. Due to their usage and the environment in which they are employed, these materials are being created to achieve the desired qualities. The parent materials from which the developed composites are manufactured typically have better qualities than the composites themselves. Metals and non-metals can both be used to make composites. The matrix and reinforcement are its two main components. The matrix serves as the foundational material for the reinforcement. These materials have an edge over other materials due to their excellent stiffness to weight and strength ratios. They are costly and challenging to mold into the desired shape. Because they are anisotropic, composites take longer to manufacture. When exposed to typical loading, a column, plate, or bar might suddenly fail. This is known as buckling. Buckling happens when the load exceeds a critical load value because of rapid deflections.

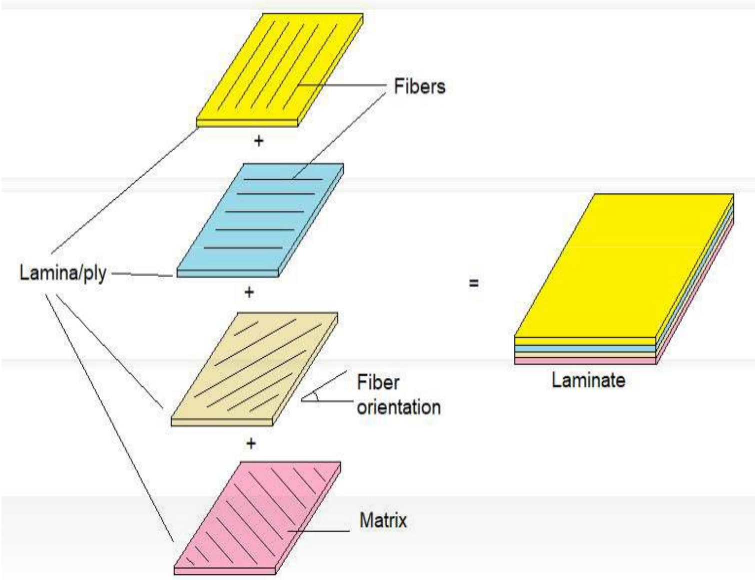

Figure 1.1 Laminated Composite Plate

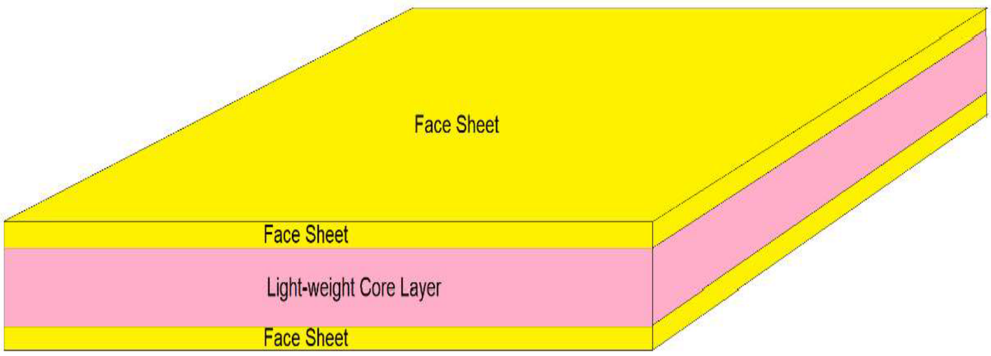

Figure 1.2 Laminated Sandwich Plate

According to the reinforcement, the composites are divided into three main groups as seen in Figure 1.3.

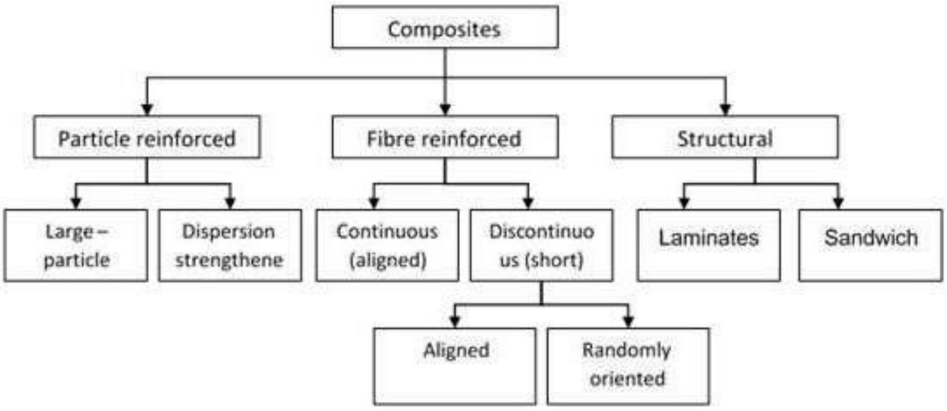

Figure 1.3 Types of composites

Particle reinforced composites are formed by dispersing bigger (or smaller) particles on a matrix, which typically takes a partial load when applied. When compared to other composite materials, these types of composites have a weaker strength. Due to the inclusion of reinforcing material in the form of continuous (or) fragmented fiber to the matrix, fiber reinforced composites have a higher strength than particle reinforced materials. These are made by the process of fullering. The materials in structural composites are stacked (or packed) in between the matrix, which sets them apart from the other two composites. The features of structural composites, which can be homogeneous or heterogeneous materials, are determined by the characteristics of the component materials as well as the size and shape of the structure. Laminated and sandwiched structural composites are two categories.

Sandwiched Composites

Composites are created and intended to have greater strength and greater stiffness. Sandwiched composites are created when two or more materials are pushed together in the shape of sheets to create a panel or beam. These sheets are adhered to the core using adhesives, and the outside sheets are more rigid and strong than the inner sheets. It is made in such a way to be able to endure direct tensile and compressive loading pressures. The outside sheets are comprised of a considerably heavier substance than the core. Figure 1.4 displays a layout with sandwiched panels**.**

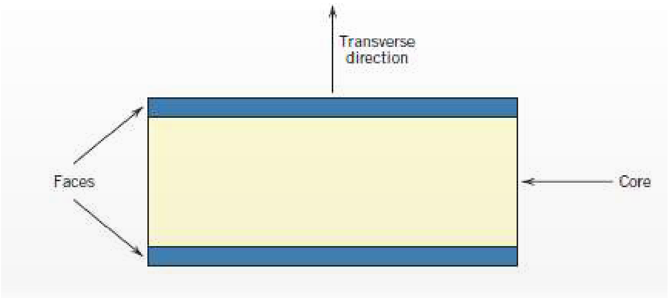

Figure 1.4 Configuration of Sandwiched Composite

Laminated Composite

These materials are constructed of two-dimensional sheets and panels with great strength. As seen in Figure 1.3, a number of layers are placed on top of one another and the pavement is laid as a single piece. The layers' strengths fluctuate, with the inner core having the lowest strength and the outermost layer having the greatest load bearing capability.

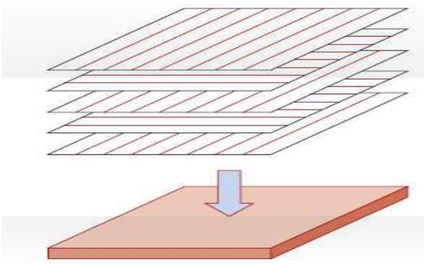

Figure 1.5 Laminate Composites

Fiber Reinforced Laminated Composites

Continuous and discontinuous fiber composites are two categories under which fiber reinforced laminated composites are categorized. Small illuminated fibers that are aligned either randomly or in the same way make up discontinuous fiber composites. Anisotropic materials are believed to have distinct characteristics in various directions. The material is viewed as being isotropic if the orientation is random. This kind of material is weaker and has a lower elastic modulus. If the reinforcement is considered continuous, the material's strength and elasticity modulus will be greater than before. The long continuous fibers that are frequently employed in aircraft structure are taken into consideration in this study effort. Because the fibers are essentially evenly distributed in all directions and have the same strength regardless of the direction, the randomly oriented fibers are generally thought of as isotropic materials. Figure 1.6 depicts the direction and the reinforcement.

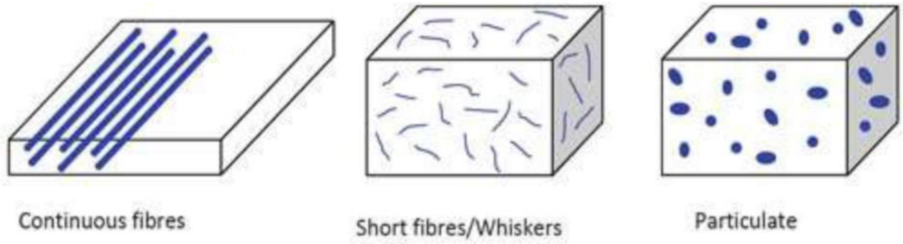

Figure 1.6 Types of fibre

Polymer Matrix Composites (PMCs) constitute a crucial class of materials, featuring a matrix of either thermoset or thermoplastic material reinforced with high-strength and high-stiffness fibers. PMCs are widely employed due to their exceptional strength-to-weight ratio and superior stiffness compared to traditional materials. Moreover, they offer the advantage of tailoring their properties to meet specific application requirements. Commonly used reinforcing fibers include glass, aramid, carbon, and other materials, while the properties of the resulting composite structure are primarily determined by the characteristics of the polymer matrix and the reinforcing fibers.

Matrix

The matrix serves as the substance that binds the reinforcement and provides the structural geometry to the composites. It plays several critical roles, including distributing weight among the fibers, defining the composite's shape, maintaining fiber orientation, separating fibers to prevent mechanical abrasion, and enhancing various characteristics such as lateral and impact strength. Matrix materials can include polymeric substances, refractory (ceramic) materials, metals, or carbon. Polymer matrices are commonly chosen due to their cost-effectiveness and proven performance in demanding applications. Carbon matrices are favored for components exposed to extremely high temperatures. Metal and ceramic matrix composites find use in environments with elevated temperature conditions.

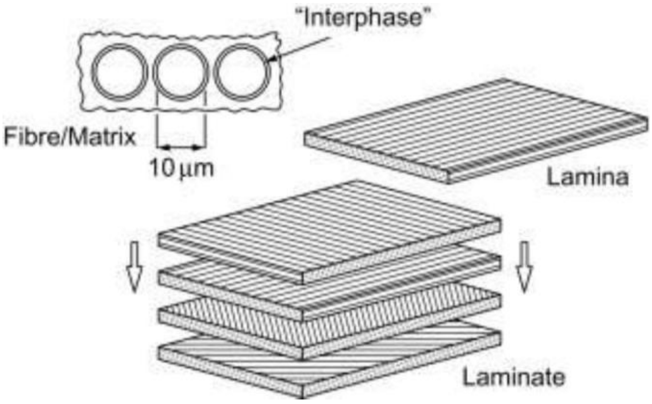

Figure 1.7 Laminates and Lamina

Fibers

Fibers constitute the primary component of Fiber Reinforced Polymer (FRP) composites, and their type, volume, and orientation significantly influence fundamental properties such as density, strength, and stiffness. Smaller-diameter fibers are preferred, as they offer increased load-transfer capacity per unit volume percentage. Commonly used fibers include glass, carbon, aramid, boron, and ceramic fibers, each with distinct properties. Glass fibers are resistant to fire and possess insulating qualities, with E Glass and S Glass being notable types. Carbon fibers offer exceptional tensile strength and stiffness but come at a higher cost. Aramid fibers, such as Kevlar, excel in bearing compressive loads, while ceramic fibers find applications in extreme high-temperature environments.

Terminologies in Laminate Composites

Laminated composites consist of layers, or laminas, of fibers embedded in a matrix, where coupling agents and filler materials enhance adhesion between the fiber and matrix. The stacking sequence, or laminated scheme, defines the fiber orientation sequence in a laminated composite and significantly impacts its performance under different loading conditions. Principal material directions run parallel and perpendicular to fiber directions, with ply angles determining the orientation of the laminate. Proper stacking sequence selection is crucial for optimal laminate properties and performance.

Application of Fiber Reinforced Composite

Laminated composites find applications across various industries, including aerospace, automotive, biomedical, and maritime. Their lightweight, high strength, and stiffness make them ideal for aircraft components, vehicle parts, and more. The biomedical industry benefits from their corrosion resistance and impact strength. Automotive applications rely on FRP composites for creating vehicle bodies and components. In the maritime sector, Glass Fiber Reinforced Polymer (GFRP) composites are prevalent. These materials have become integral to modern engineering, providing lightweight solutions with excellent structural integrity.

Finite Element Method

The Finite Element Method (FEM) is a powerful numerical technique for solving complex engineering problems, including the analysis of laminated composites. FEM involves breaking down a continuous problem into manageable elements and solving them iteratively. Governing equations are established based on material properties and geometry, and boundary conditions are applied. ABAQUS software is often used for analyzing laminate composites under various loading and environmental conditions.

Loads on Composites

Laminated composites can experience a wide range of loads, including mechanical, residual, environmental, and blast/impact loads. Environmental loads, such as temperature and moisture variations, are of particular concern. Hygrothermal loads, resulting from changes in temperature and moisture content, can lead to expansion, contraction, and dimensional changes in laminates. These changes can introduce stresses, affect material properties, and impact structural integrity.

Hygrothermal Loads

Hygrothermal loads encompass the combined effects of temperature and moisture changes on laminated composites. Matrix-dominated composites are more affected by expansion and contraction due to changes in temperature and moisture levels. Stiffness and strength of composites decrease with rising temperature and moisture content. The choice of fiber type, volume, and matrix-fiber interactions play a significant role in how laminates respond to hygrothermal loads.

The variation in material and mechanical characteristics in different regions of laminated composite structures under high-temperature conditions is a crucial consideration. The transition temperature, glass transition temperature (Tg), is particularly significant, and its dependence on moisture content must be considered. Understanding the effects of temperature and moisture on composites is essential for safe and reliable engineering design.

In summary, Polymer Matrix Composites (PMCs) are integral to modern engineering due to their exceptional strength-to-weight ratio and stiffness. Understanding the behavior of PMCs, especially under hygrothermal loads, is essential for their successful application in various industries. This understanding includes the roles of the matrix and fibers, the choice of fiber types, stacking sequences, and the impact of temperature and moisture variations. Analytical methods like the Finite Element Method (FEM) are invaluable for simulating and predicting the behavior of laminated composites under diverse loading and environmental conditions, ultimately contributing to the advancement and optimization of these materials in engineering applications..

II. LITERATURE REVIEW

Structural Health Monitoring (SHM) is crucial to prevent premature structural degradation caused by changing environmental factors. It enables engineers to identify issues quickly and implement necessary repairs and maintenance. Vibration-based SHM techniques, using high-precision sensors like accelerometers and strain gauges, are widely used. Artificial Neural Networks (ANNs) are commonly employed for accurate prediction models in SHM. Researchers have utilized ANNs extensively in various structural engineering applications, including failure prediction, crack detection, and predicting mechanical characteristics.In the field of LCS (Laminated Composite Structures) analysis, researchers have investigated the vibrational properties of LCS structures using experimental and numerical methods. They have explored the impact of temperature, moisture, and porosity on the free vibration response of these structures. Additionally, research has focused on active vibration control using piezoelectric materials, with studies examining the effectiveness of Active Constrained Layer Damping (ACLD) and the influence of temperature on ACLD therapy.Despite these advancements, there remain several research gaps. Firstly, there is limited research on the coupled effects of temperature, moisture, and porosity on the vibrational properties of LCS structures, especially in the context of 3D printed structures. Additionally, there is a lack of literature addressing the impact of temperature on all components of ACLD arrangements, including the host structure, viscoelastic layer, and piezoelectric layer. Further research is needed to fill these gaps and advance our understanding of LCS structures under challenging environmental conditions.

Environmental factors that are constantly changing may negatively impact the performance of materials, which might lead to premature structural degradation. To prevent the buildings from failing before they should, a systematic health monitoring system should be developed. Engineers can quickly identify problems and start the necessary repair and maintenance work thanks to the continuous health monitoring of structures. Furthermore, a methodical scientific investigation may help identify the cause of structural flaws, from which a suitable action plan may be developed to stop similar problems from occurring in the future. Structural health monitoring (SHM) is the practice of using a damage diagnosis technique for structures designed by civil, mechanical, and aeronautical engineers (Farrar et al., 2007). The most widely utilized non-destructive damage detection techniques are vibration-based SHM approaches (Sharnappa et al., 2007; Nguyen et al., 2018; Bouazza et al., 2020). To gather information on structural responses, mode forms, natural frequencies, damping parameters, etc., high-precision sensors like accelerometers, strain gauges, velocity transducers, laser displacement sensors, etc. are installed strategically on structures. A careful engineering analysis of the observed reactions can identify and/or foretell the extent of harm. For SHM applications, accurate prediction models built on current datasets are a better choice. On the basis of the preliminary dataset, artificial neural network (ANN) approaches are frequently employed to create prediction models (Salehi et al., 2018). The ANN method has been widely and successfully used in civil. (Paula et al., 2019; Paula and Marques 2019; Marques and Anderson 2001; Marques et al., 2005; Marques and Marques 2017; Paula et al., 2019; Paula and Marques 2019).

Researchers have recently used ANNs extensively for structural engineering applications like failure prediction, crack detection, delamination identification, quantification of damage magnitude, predicting the size and position of cutouts (Elshafey et al., 2013; Atilla et al., 2020), determining mechanical characteristics (Sharma et al., 2020; Mouloodi et al., 2020), etc. Recently, Zenzen et al. (2020) utilized an ANN and a transmissibility damage indicator to forecast the location and extent of harm. The damage location was estimated using the transmissibility function and mode shapes, and the magnitude of the damage was predicted using a trained ANN model. The suggested methodology was designed to predict outcomes quickly and accurately without requiring the collection of all modal analysis data. For the purpose of identifying delamination in plate-like structures, Gomes et al. (2019) combined a genetic algorithm (GA) with an artificial neural network (ANN). Fisher information matrix criteria were used to determine the best location for the sensor, and a feed-forward artificial neural network (ANN) was employed to find the damage using information from the finite element (FE) analysis. To examine the vibration response of the simply-supported porous functionally graded (FG) -order plate theory, Rjoub and Alshatnawi (2020) developed a mathematical model. The ANN model was then trained using the findings to forecast a system's natural frequency. The created ANN model was said to be simply adaptable to forecast the frequency response for different boundary conditions. Atilla et al. (2020) used numerical techniques to examine the effects of position, diameter, and the quantity of circular modal and buckling behavior. To further forecast the natural frequency and buckling loads of composite plates, the Levenberg Marquardt backpropagation technique was used to create the ANN model.

Elshafey et al. (2013) used the feed-forward backpropagation approach to create an efficient ANN model for crack width prediction of thick and thin concrete members. It was claimed that the findings produced utilizing the rules in the current building codes were less accurate than the expected average crack width values. Oliver and colleagues (2020) created an effective ANN-based damage detection module for employing frequency shifts to create composite plates. The modal data acquired from the FE analysis was used as training data by the damage detection module that was constructed. According to reports, the anticipated damage's position and severity were 95% accurate. Using experimentally discovered properties of composites, Jalal et al. (2020) created the best ANN model to predict the strength of a rubberized cement composite. The accuracy of the anticipated strength values was reported to be 98%. Jodaei et al. (2012) investigated the frequency response of FG annular plates using a state-space-based differential quadrature method. A superior ANN model was also put out to forecast the natural frequency of systems operating with various boundary conditions. According to reports, the ANN model accurately predicts frequencies and fits well with the general trend of semi-analytical results.Carbon nanotube (CNT) based composites are a popular option for high-end engineering applications because to their scale-dependent physical characteristics, outstanding thermo-mechanical capabilities, and improved elastic properties (Kundalwal and Meguide, 2015). The qualities of the CNT material are influenced by the atomic configuration, tube diameter and length, and tube shape. Both single-walled and multi-walled nanotube structures are marketed for use in various products. Laser ablation, arc discharge, chemical vapor deposition, and gas-phase catalytic growth techniques are generally used to create CNTs (Eric et al., 2001). The CNT particles are dispersed in a suitable matrix solution to create the CNT-based composite structures. The composites are further categorized as evenly distributed, X-type, V-type, O-type, etc. based on the distribution of the CNT pattern.

In 2017, Biswal and Ray conducted experimental and computational analyses of the modal behavior of hybrid laminate composite plates made of glass-epoxy and graphite-epoxy materials. The mechanical parameters gleaned from the non-destructive ultrasonic sound velocity measuring setup were input into well-known models like FSDT and third-order shear deformation theories (TSDT). Additionally, the outcomes of numerical models were contrasted with those of experiments. Similarly, Dewang et al. (2020) used computational and experimental methods to examine the impact of cutout settings on the vibration properties of a laminated composite plate. The modal behavior of composite plates was shown to be significantly influenced by the cutout's form, orientation, and location. Later on, the altered Emadadi et al. (2019) used coupled stress theory and FSDT to analyze the vibration behavior of an annular sandwich plate with CNTRC face sheets and FG porous core. A higher-order shear deformation theory (HSDT) based isoparametric FE model was created by Garg et al. (2006) to investigate the free vibration properties of skew laminated composite sandwich (SLCS) structures. Without utilizing a shear correction factor, the model was able to forecast the genuine non-linear variation of through-thickness displacements of sandwich constructions.

Heshmati and Daneshmand (2018) looked into the modal properties of weight-efficient FG non-uniform porous plates using a semi-analytical approach based on DQM. To comprehend the linear and non-linear vibrational behavior of sandwich structures, Katariya et al. (2021, 2020) carried out an experimental and computational analysis of epoxy-filled soft core sandwich plates with glass-epoxy face sheets. To comprehend the impact of porosity on a system's natural frequency, Kiran et al. (2018, 2018a) investigated the vibrational properties of FG porous skew magneto-electro-elastic (MEE) plate. Under static loads, Pan et al. (2002, 2005, 2013) were able to determine the precise solution for multi-layered and functionally graded MEE plates. For a novel hyperbolic shear deformation theory, Mahi et al. (2015) suggested a shear correction factor to examine the free vibration properties of sandwich plates. Similar to this, Mishra and Sahu (2015) reported on the experimental and numerical analysis of the vibration response of a glass-epoxy composite plate. Later, Prasad and Sahu (2018) reported on the vibration analysis of hybrid composite plates comprised of aluminum and glass-epoxy layers. Singh and Sahoo (2020) investigated the static and vibration properties of the FG-CNTRC sandwich plates using the inverse hyperbolic shear deformation theory. In order to articulate the huge amplitude vibrations of a smart viscoelastic doubly-curved sandwich shell construction with magnetorheological layers and a flexible core, Karimiasl and Ebrahimi (2019) employed Reddy's TSDT. The thick doubly curved carbon nanotube reinforced FG composite shells were subjected to modal analysis by Pouresmaeeli and Fazelzadeh (2016) utilizing the FSDT. Qin et al. (2020) found the unified Fourier series solution for the FG-CNTRC shells and plates under arbitrary boundary conditions.

Furthermore, Rouj and Alshatnawi (2020) created an analytical model to examine the free vibration properties of a FG plate with evenly distributed pores and surface cracks on the side. Additionally, the ANN model was created to forecast the system's inherent frequency. Behera et al. (2016) developed the multilayer ANN architecture to create a prediction model to calculate the surface roughness and delamination during drilling of a glass fiber reinforced composite construction. A new ANN-based bridge cable tension estimate model was put out by Haji Agha Mohammad Zarbaf et al. (2018) to help with the timely structural health monitoring of civil constructions. Similar to this, Karnik et al. (2008) developed an ANN-based prediction model to examine how high-speed drilling process factors affect the delamination behavior of carbon fiber reinforced structures. Based on experimental and extended isogeometric analysis, Khatir et al. (2020) later developed an improved ANN method to find a fracture in the plate. Additionally, Luo et al. (2020) accurately and speedily predicted the various types of curved geometries of composite laminates by combining FE and ANN approaches. The Lamb-wave-based damage detection model of a laminated composite plate coupled with a piezoelectric sensor patch was created by Qian et al. in 2020 in a similar manner.Using nth-order shear deformation theory, Abdelmalek et al. (2019) examined the impact of temperature and moisture on the vibration characteristics of isotropic and orthotropic composite plates. The investigation took into account the material's moisture and temperature dependencies. A new, better third-order zigzag theory was created by Kulkarni and Kapuria (2008) for the static and dynamic analysis of sandwich plates. A novel higher-order layer-wise FE model was created by Belarbi et al. (2017) for the static and dynamic analysis of laminated composite and sandwich plates. The first-order displacement field theory was taken into account for face sheets, whereas the core was studied using a higher-order displacement field theory. Using revised zigzag theory, Padhi and Pandit (2017) looked at how temperature and moisture concentrations affected sandwich plate static and vibration response. The vibrational and buckling behavior of composite sandwich plates reinforced with Ni-Ti-based shape memory alloy wires was statistically examined by Kheirikhah and Khosravi (2018). In order to better understand the thermo-mechanical bending behavior of sandwich plates with FG face sheets and a completely ceramic core, Daikh et al. (2020) employed HSDT. A piecewise shear deformation theory was proposed by Zhao et al. (2017) for the free and forced vibration analysis of composite and sandwich plates in temperature settings. According to a report, the fundamental frequency decreased as temperature rose for all values of the sandwich plate's length to thickness ratio. Similar to this, Joseph and Mohanty (2017) investigated sandwich plate buckling and free vibration properties using FSDT in a high-temperature setting. The investigation took into account the face sheets made of FG material and soft viscoelastic core. Smart FG sandwich plates exposed to thermal stress were able to accomplish active constrained layer damping (ACLD) thanks to work by Suresh Kumar et al. (2013). When operating under hygro-thermal and electro-mechanical sinusoidal loadings, a sandwich plate made up of a piezoelectric face sheet and a FG core was static and dynamically analyzed by Zenkour and Alghanmi (2019). Experimental research was conducted by Ding et al. (2018, 2019) to examine the effects of aging on sandwich composites made of vinyl-ester-based composite face sheets and polyvinyl chloride foam core under a variety of challenging conditions, including high temperature, moisture, and different hygrothermal profiles.

Sharma et al. (2019) have investigated the vibroacoustic properties of sandwich shells under harmonic stress in a hygrothermal environment using a higher-order finite boundary element approach. Swamy and Sinha (2006) looked at how the hygrothermal environment affected the non-linear transient response of the doubly-curved thick shells. They claimed that the existence of a hygrothermal environment has a significant impact on the radius of shell curvature. In both the pre-buckled and post-buckled stages, Kundu and Han (2009) examined the impact of temperature and moisture on the vibration response of doubly-curved shells. The occurrence of the snap-through phenomena in the presence of a hygrothermal environment received particular attention. To comprehend the impact of the hygrothermal environment on the free vibration response of a composite shallow shell, Biswal et al. (2015, 2016) carried out a computational and experimental analysis. It was noted that when moisture content and temperature increased, the natural frequency of shallow composite shells decreased. A nonlocal strain gradient model was used by Ebrahimi and Barati (2017) to examine the vibrational properties of the viscoelastic FG nanobeams that were altered by hydrothermal conditions. Using the higher-order zigzag theory and smoothed FE formulation, Nguyen et al. (2020, 2021) performed combined hydrothermal and mechanical study on viscoelastic laminated composite plates. Mahapatra et al. (2016) developed the Green-Lagrange type geometric nonlinearity model using a micromechanical technique to describe the nonlinear vibration behavior of doubly-curved shells working in a hygrothermal environment.

Pouresmaeeli and Fazelzadeh (2016) looked at the vibrational behavior of slightly thick doubly-curved FG-CNTRC shells when used in conjunction with FSDT. Similar to this, Lai et al. (2021) investigated the effect of thickness stretching on the static response of CNTRC doubly-curved nanoshells operating in an increased thermal environment and discovered that the nanoshell's deflection varies nonlinearly with an increase in temperature. (2015, 2017, 2018, 2020) Mehar et al.investigated the effect of temperature on the static and dynamic behavior of single-walled CNTRC doubly-curved shells using experimental and computational approaches. A non-linear thermo-mechanical buckling study of composite laminated shells reinforced with FG graphene and surrounded by an elastic foundation was carried out by Phuong et al. (2019, 2020, 2020a). Nam et al. (2020) looked at the FG-CNTRC cylindrical shells' non-linear torsional buckling properties. In a hygrothermal setting, a smart MEE sandwich plate with a CNTRC core was investigated by Dat et al. in 2020 for its nonlinear vibration behavior. Higher-order theory, or HSDT, underpinned the coupled magneto-electro-hydro-thermo-elastic model, and the closed-form solution was based on research done by Ga et al. (2012) utilizing FSDT to look into the static and dynamic properties of single-walled CNTRC plates. The outcomes of the built FE model and the outcomes acquired from the ANSYS commercial package agreed well.

1) 2.5.3 Active Vibration Control of Composite and Sandwich Composite Structures

The development of structural components that are both efficient and compact is of utmost importance in current engineering constructions. Many moving and static components are positioned near together in order to accomplish this. Moving structural components often shake, which increases system noise and instability. By providing adequate damping, the majority of harmful and undesirable vibrations in a building may be reduced. The two main types of vibration control mechanisms are passive and active vibration control systems. The damping mechanism in a passive control structure is unrelated to the vibration measurement. For instance, the rubber cushions for the lathe bed are set in their ability to dampen. Regardless of the amount of vibration, the rubber pads will dampen the vibrating lathe bed. In an active vibration control system, the damping force is created depending on the amplitude of the vibration, while feedback signals are generated based on signals collected from a sensor device. Piezoelectric materials are widely employed nowadays for the active control of many different constructions. Based on the phenomena of direct and reciprocal piezoelectric effects, piezoelectric materials are widely employed as distributed sensors and actuators for vibration control. Li 2012; Zhao et al., 2020a; Song et al., 2001. High-control voltage is necessary for the monolithic piezoelectric materials to effectively attenuate vibrations in base structures. The discovery of ACLD therapy was made possible by research into the creation of monolithic piezoelectric materials with limited control authority (Padeep and Ganesan, 2006; Ray and Pradhan, 2006, 2007, 2008). Viscoelastic materials are employed as a constrained layer in ACLD therapy, while piezoelectric materials are used as the constraining/actuating layer.

The examination of the vibration attenuation properties of intelligent composite beams, plates, and shells combined with the ACLD patches has been the subject of several scholarly studies. To examine the dynamic properties of isotropic beams combined with piezoelectric patches, Arafa and Baz (2000) created a FE model. The ideal size and location of the piezoelectric rod-based, viscoelastic matrix-embedded actuation patches were investigated. Using an isotropic plate implanted with ACLD patches, Baz and Ro (1996) experimentally controlled vibration by sandwiching a viscoelastic layer (DYAD 606) between two layers of polyvinylidene fluoride (PVDF) films. A similar examination of the vibration attenuation properties of a clamped aluminum plate for the frequency range of 0 to 600 Hz was carried out by Chantalakhana and Stanway (2001) using computational and experimental methods. A three-dimensional closed-loop model was created by Lim et al. (2002) to forecast the effects of active-passive damping on the vibrating cantilever beam. The ACLD treatment of orthotropic laminated composite plates was then quantitatively examined by Datta and Ray (2016) utilizing a three-dimensional fractional derivative model of the restricted viscoelastic layer in the time domain. A three-dimensional FE model was created by Kattimani and Ray (2014, 2015, 2017a, 2017b, 2018) to regulate the geometrically non-linear vibration of multiferroic fibrous composite plates using ACLD treatment. According to reports, the stiffening effect of the plates exhibits a significant rise in the electro-elastic and magneto-elastic coupling. On the other hand, little was said about how they affected the non-linear transient vibrations. A brand-new, condensed single-layer equivalent technique was put out by Zhao et al. (2019) to simulate the plate structure combined with ACLD patches. According to their findings, real-world engineering applications like wind turbines and aviation structures should benefit from the propped technique's assistance for vibration reduction.

To comprehend the impact of the shape of constraining layers on the performance of ACLD of laminated composite plates, Sahoo and Ray (2019) carried out numerical FE simulations. According to a research, elliptical ACLD patches are more effective than square and circular ones at reducing the vibration levels of composite plates. Using 1-3 piezoelectric composites, Kanasogi and Ray (2013) examined the effectiveness of ACLD therapy on smart skew laminated composite plate. A three-dimensional FE model was created by Suresh Kumar et al. (2012, 2013, 2016) to examine the ACLD performance of a smart sandwich plate made of vertically reinforced 1 3 PZC material. A thorough investigation was conducted into the impact of process variables on the vibration characteristics of a sandwich plate, including boundary conditions, face sheet fiber orientation, fiber orientation of 1-3 piezo-layers, different core materials, the ratio of core thickness to face sheet thickness, etc. Also mentioned were research on the vibration attenuation of sandwich plate vibrations that are geometrically non-linear. The effect of patch position on the active vibration control of a laminated composite plate integrated with discrete piezoelectric patches was investigated by Bendine et al. in 2019. A linear-quadratic index and genetic algorithm were used to assess the piezoelectric patches' ideal location.

Using an MFC sensor and actuators, Zippo et al. (2015) successfully accomplished active vibration control of a free edge rectangular sandwich plate. An LCS plate was made using the polymer paper core and carbon fiber reinforced polymer face sheets. The single-input, single-output and multiple-input, multiple-output systems were controlled up to a frequency range of 100 Hz using the positive position feedback approach. Sharma et al. (2015, 2016a, 2016b, 2018) used a fuzzy logic controller technique to study computationally and experimentally the active vibration control behavior of isotropic beams across a broad temperature range. The numerical investigation was then expanded to comprehend the damping properties of the FG-CNTRC plates positioned between the piezoelectric face sheets. Similar to this, Gupta et al. (2011) investigated the active vibration control of the isotropic plate combined with the piezoelectric sensor-actuator pair working at high temperatures using analytical and experimental approaches. Results indicated that a control rule that ignores the temperature-dependent material features of PZT crystal does not sustain the vibration attenuation performance at high temperatures. In 2017, Shankar et al. created a FE model to examine the piezoelectric actuators coupled with delaminated composite plates' capabilities for controlling vibration in a humid environment. It was claimed that when the control voltage was supplied, the frequency of the delaminated plate increased. Sfarra et al. (2016) created a brand-new non-destructive method to forecast the influence of hygrothermal aging on the composite material that was damaged. According to studies, laminates that have been subjected to hygrothermal aging will have significant internal flaws. To further accomplish active control of vibrating sandwich plates functioning in the thermal environment, Li et al. (2019) used a temperature feedback control technique. The numerical simulation took into account the laminated core and actuator face sheets made of piezoelectric fiber-reinforced composite material.

The thorough literature review shows that engineers and researchers are becoming more and more interested in LCS architectures. There is little research on how LCS structures behave when exposed to thermal, hygroscopic, hygrothermal, electrical, and magnetic fields. Creating mathematical representations of sandwich structure behavior in the face of hostile conditions is a difficult challenge. The coupling effect between the existing loadings is frequently ignored in the usual approach, which leads to inaccuracies or inaccurate conclusions. To estimate the multiphysics response of the structures, modern computational approaches like FE methods enable the insertion of complicated coupling components into the mathematical model (Nguyen-Thoi et al., 2009, 2010, 2012). Due of their higher computing speed, FE techniques are frequently used to resolve difficult structural problems even though they only yield approximations.

There is a wealth of material available that examines how temperature and moisture affect the vibrational properties of LCS structures. There aren't many studies, nevertheless, that discuss coupled thermo-elastic and hygro-elastic relations that take into account temperature- and moisture-dependent material characteristics. Similar to this, in the majority of research studies, the impact of temperature and moisture is included as force variables to the mathematical model. There is relatively little research in the literature on how temperature and moisture affect a structure's ability to respond to vibrations when its stiffness is reduced. In addition, the study There are relatively few outputs that describe the prediction models used to track the system's health in the presence of severe settings.

Numerous research teams have documented the impact of porosity on the natural frequency of the sandwich structure during the last few decades. The combined impact of temperature and porosity on the free vibration response of LCS structures, however, has not been discussed in many papers. It is impossible to avoid porosity in 3D printed constructions. To this aim, to the best of our knowledge, there is no open literature that addresses the impact of temperature and porosity on 3D printed structures. Additionally, the open-source contains the publications detailing the impact of temperature and moisture on the active vibration control of LCS structures. Researchers have also documented the impact of temperature on a structure's active constrained layer damping properties (Ray and Batra, 2008; Suresh Kumar et al., 2013). There aren't many articles, though, that discuss how temperature affects the physical behavior of all the elements that make up the ACLD arrangement (the host structure, the viscoelastic layer, and the piezoelectric layer). Additionally, there are no papers available that examine how exposure to an increased temperature environment affects the material qualities of the materials used in the ACLD therapy.

III. FINDING AND ANALYSIS

The analysis provides a comprehensive overview of the importance of SHM, the role of ANNs in SHM applications, and the analysis of LCS structures under different environmental conditions. Several key findings and areas for further research can be derived from this document:

1. **Significance of SHM**: The document underscores the crucial role of SHM in maintaining structural integrity and preventing premature structural degradation. It highlights the importance of identifying issues early to avoid costly repairs and maintenance.
2. **Use of Vibration-Based SHM**: Vibration-based SHM techniques are identified as a widely used method for monitoring structural health. These techniques rely on high-precision sensors to gather data on structural responses, such as natural frequencies and damping parameters.

3. **Role of ANNs in SHM**: Artificial Neural Networks (ANNs) are recognized as a powerful tool for creating accurate prediction models in SHM. They have been extensively employed in various structural engineering applications, from failure prediction to crack detection.

4. **Analysis of LCS Structures**: The document discusses the research on the vibrational properties of LCS structures. It highlights the impact of factors like temperature, moisture, and porosity on the free vibration response of these structures. Additionally, it mentions studies on active vibration control using piezoelectric materials like ACLD.

Table 1: Applications of ANNs in Structural Health Monitoring

Application	**Reference**
Failure prediction	Paula et al., 2019
Crack detection	Elshafey et al., 2013
Delamination identification	Gomes et al., 2019
Mechanical characteristics	Sharma et al., 2020
Natural frequency prediction	Rjoub and Alshatnawi, 2020

Table 2: Research on LCS Structures

Research Topic	**Key References**
Vibration properties of LCS structures	Biswal and Ray, 2017; Dewang et al., 2020
ACLD therapy for vibration control in LCS structures	Suresh Kumar et al., 2013; Shankar et al., 2017
Effect of temperature and moisture on LCS structures	Abdelmalek et al., 2019; Biswal et al., 2016
Impact of porosity on natural frequency of LCS structures	N/A (Limited studies mentioned)

Table 3: Research on Active Vibration Control

Research Topic	**Key References**
Piezoelectric materials in vibration control	Li 2012; Zhao et al., 2020a; Song et al., 2001
Active Constrained Layer Damping (ACLD) therapy	Ray and Batra, 2008; Suresh Kumar et al., 2013
Effect of ACLD on composite plates	Arafa and Baz, 2000; Kattimani and Ray, 2017a
ACLD in smart skew laminated composite plates	Kanasogi and Ray, 2013; Suresh Kumar et al., 2016
Optimal patch location for ACLD	Bendine et al., 2019

Table 4: Impact of Temperature and Moisture on LCS Structures

Research Focus	**Key References**
Temperature-dependent behavior	Kundu and Han, 2009; Li et al., 2019
Hygrothermal effects	Sfarra et al., 2016; Ebrahimi and Barati, 2017
Combined impact of temperature and moisture	Datta et al., 2018; Gostautas et al., 2020

Table 5: Research Gaps and Future Directions

Identified Research Gaps	**Suggested Future Directions**
Limited research on temperature effects on ACLD	Conduct comprehensive studies on ACLD behavior under varying temperature conditions, considering all components.
Lack of literature on porosity effects on LCS structures	Investigate the impact of porosity on the natural frequencies and mechanical properties of LCS structures.
Coupled effects of temperature, moisture, and porosity	Explore the combined influence of temperature, moisture, and porosity on the behavior of LCS structures.
3D printed LCS structures	Investigate the behavior of 3D printed LCS structures under different environmental conditions.
Comprehensive analysis of ACLD	Conduct in-depth studies on all aspects of Active Constrained Layer Damping (ACLD) therapy for vibration control.

These tables summarize key research findings and suggest future research directions based on the identified gaps in the existing literature. The document provides a valuable foundation for further research in the field of Structural Health Monitoring and the analysis of Laminated Composite Structures.

Structural Health Monitoring (SHM) is a critical field within structural engineering that plays a crucial role in ensuring the safety, longevity, and performance of various structures, including buildings, bridges, aircraft, and more. This theoretical analysis will delve into the fundamental concepts of SHM and its applications, particularly in the context of Laminated Composite Structures (LCS). We will explore the principles of SHM, the role of Artificial Neural Networks (ANNs), and the environmental factors affecting LCS, including temperature, moisture, and porosity.

1. Structural Health Monitoring (SHM):

Structural Health Monitoring is a systematic approach to assessing the condition of structures and identifying any anomalies or defects that may lead to structural failure. It involves the continuous or periodic monitoring of a structure's performance using various sensors and data analysis techniques. The primary objectives of SHM are:

- Early Detection of Damage: SHM aims to identify damage or deterioration in a structure at its earliest stages, well before it becomes critical or catastrophic.
- Preventive Maintenance: By detecting issues early, SHM enables engineers to plan and implement preventive maintenance measures, thus extending the lifespan of structures.
- Safety Assurance: SHM contributes to the safety of structures and the people who use them by reducing the risk of sudden failures.

2. Role of Artificial Neural Networks (ANNs) in SHM:

Artificial Neural Networks are computational models inspired by the human brain's neural networks. ANNs are employed in SHM for their ability to create accurate prediction models based on existing datasets. ANNs can process vast amounts of sensor data and learn complex patterns, making them valuable tools for various SHM applications, such as:

- Failure Prediction: ANNs can predict when and where structural failures might occur based on historical data and sensor inputs. This enables timely intervention.
- Crack Detection: ANNs can identify the presence and severity of cracks in structures by analyzing sensor data, such as strain measurements.
- Mechanical Characteristics Prediction: ANNs are used to predict mechanical properties such as stiffness, strength, and elasticity based on sensor readings and material properties.
- Delamination Identification: In composite structures like LCS, ANNs are employed to detect delamination, a common defect, by analyzing vibrational data.

3. Laminated Composite Structures (LCS):

Laminated Composite Structures are engineering components made by layering different materials, such as fibers and resins, to achieve specific performance characteristics. These structures are known for their lightweight, high strength-to-weight ratio, and resistance to corrosion. LCS are widely used in aerospace, automotive, marine, and civil engineering applications. However, several environmental factors can impact their performance:

- Temperature: Temperature variations can cause thermal expansion and contraction in LCS, affecting their dimensions and potentially leading to structural issues. SHM is used to monitor these temperature-induced changes.
- Moisture: Moisture absorption can weaken the structural integrity of LCS by causing delamination, which can be detected and quantified using SHM techniques.

- Porosity: Porosity, or the presence of voids within the composite material, can compromise structural properties. SHM can assess the level of porosity and its impact on the structure's performance.

Theoretical analysis of SHM and LCS reveals several key points:

- SHM is essential for ensuring the safety and longevity of structures, as it enables early detection of damage and informed decision-making regarding maintenance and repairs.
- ANNs have revolutionized SHM by providing accurate prediction models for various structural parameters and defects, improving the efficiency of monitoring systems.
- LCS offer significant advantages but are susceptible to environmental factors like temperature, moisture, and porosity. SHM helps assess the impact of these factors and allows for timely corrective actions.
- A comprehensive understanding of the theoretical principles underlying SHM and LCS is crucial for designing effective monitoring systems and maintaining the structural integrity of composite structures.

In conclusion, the theoretical analysis of SHM and LCS underscores their importance in modern engineering and construction. SHM, with the aid of ANNs and advanced sensor technologies, empowers engineers to monitor structures proactively and address potential issues, ensuring safety and reliability. The study of LCS highlights the need for careful consideration of environmental factors and the role of SHM in managing these challenges effectively

IV. CONCLUSIONS

The exploration of Structural Health Monitoring (SHM) and its application in Laminated Composite Structures (LCS) reveals significant advancements and noteworthy research gaps in the field of structural engineering. This comprehensive analysis demonstrates the critical role of SHM in ensuring the safety, reliability, and longevity of various structures, particularly LCS. It also highlights the integration of Artificial Neural Networks (ANNs) and the influence of environmental factors, including temperature, moisture, and porosity, on the performance of LCS. In conclusion, we can draw the following key findings:

Advancements in SHM:

1. **Early Detection and Prevention:** SHM has evolved into a proactive approach for early damage detection, allowing engineers to identify structural issues well before they become critical or catastrophic. This advancement has significantly improved the safety of structures and the people who use them.
2. **Artificial Neural Networks (ANNs):** ANNs have revolutionized SHM by enabling the development of accurate prediction models. They are extensively used in various applications, including failure prediction, crack detection, and mechanical characteristics prediction. ANNs have the capacity to process vast datasets and recognize intricate patterns, enhancing the effectiveness of SHM.
3. **Composite Structures Analysis:** Researchers have made considerable progress in understanding the vibrational properties of LCS using both experimental and numerical methods. They have investigated the impact of temperature, moisture, and porosity on LCS's free vibration response. Active vibration control using piezoelectric materials, particularly Active Constrained Layer Damping (ACLD), has been a subject of comprehensive study.

Research Gaps and Future Directions:

1. **Coupled Environmental Effects:** A notable research gap is the limited exploration of the combined effects of temperature, moisture, and porosity on LCS structures, particularly in the context of 3D printed structures. Future research should focus on addressing this gap to provide a comprehensive understanding of LCS behavior in challenging environmental conditions.

2. **Temperature Influence on ACLD Components:** While some research has examined the influence of temperature on ACLD therapy, there is a lack of literature addressing how temperature affects all components of ACLD arrangements, including the host structure, viscoelastic layer, and piezoelectric layer. Future studies should delve deeper into these components to enhance ACLD efficiency.
3. **3D Printed LCS:** The emerging field of 3D printing presents unique challenges and opportunities for LCS. Research into the impact of temperature, moisture, and porosity on 3D printed LCS is minimal. Investigating the structural performance of these innovative materials is crucial for future advancements.
4. **Multiphysics Modeling:** To better understand LCS behavior in adverse conditions, multiphysics modeling techniques, such as Finite Element Analysis (FEA), should be further explored. These models can account for the complex coupling effects between environmental factors, leading to more accurate predictions.
5. **Advanced Sensor Technologies:** As sensor technologies continue to evolve, the development of highly sensitive and robust sensors for SHM is essential. Integration with advanced data analytics and machine learning techniques can enhance the capabilities of monitoring systems.

In conclusion, the theoretical analysis of SHM and LCS underscores their paramount importance in the field of structural engineering. SHM, with the aid of ANNs and advanced sensor technologies, empowers engineers to monitor structures proactively and address potential issues, ensuring safety and reliability. However, there are notable research gaps that necessitate further investigation. Addressing these gaps will lead to a more comprehensive understanding of LCS behavior under challenging environmental conditions and drive innovations in structural engineering practices, particularly in the context of emerging technologies like 3D printing

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