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Development of Lightweight and High-Strength Composite Materials for Aerospace Application

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ABSTRACT

The finite element analysis (FEA) of laminated composite plates, particularly using First-Order Shear Deformation Theory (FSDT), plays a crucial role in developing lightweight and high-strength composite materials for aerospace applications. This technique allows engineers to simulate the behaviour of composite plates under various conditions, providing insights into stress, strain, deformation, and ultimate strength. In this study, the FEA approach has been implemented through a MATLAB code, demonstrating the capability to model complex composite plate behaviour and conduct detailed optimization. The code integrates orthotropic material properties, automatic mesh generation, boundary conditions, load distributions, stiffness matrix assembly, and stress/strain analysis. This comprehensive approach facilitates a thorough understanding of composite materials and their optimal configurations. The optimization aspect focuses on adjusting ply orientation angles to determine the best configuration for maximum strength and minimal weight. By addressing shear deformation, the code is suitable for thicker composite plates, making it highly applicable to aerospace components such as wings, fuselages, and structural frames. Additionally, the inclusion of failure analysis, specifically the Tsai-Wu failure criterion, enhances the reliability and safety of composite structures. The ability to predict potential failure points is critical in aerospace applications, where safety is paramount. Overall, this FEA approach provides a robust framework for evaluating and optimizing composite structures, enabling engineers to develop lightweight and high-strength materials that meet the demanding requirements of the aerospace industry.

Keywords: Finite Element Analysis, FSDT, High-Strength Composite Materials, Aerospace.

I. INTRODUCTION

These developments in aeroplane materials are a direct result of the rapid expansion that has taken place in the contemporary aviation sector. Utilising lightweight materials results in improvements to mechanical qualities as well as fuel economy, flying range, and payload, which ultimately leads to a reduction in the expenses associated with running the aircraft. As a result, researchers are focusing on the creation of materials that have qualities that have been optimised for reducing weight, resistance to fatigue and corrosion, and increased damage tolerance. These materials are primarily used in the production of Al alloys. Aluminium MMC is characterised by a number of important characteristics, including a greater specific modulus, a reduced thermal expansion, a substantial wear resistance, and a higher strength.

When magnesium sheets are utilised as a substitute for aluminium and steel, they have a better potential for weight reduction. This potential varies based on the stress profiles that are present in many applications. It is possible to obtain a tensile strength of 610 MPa using alloys that are based on

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magnesium, despite the fact that magnesium has a density that is only 1/4 of that of steel or 2/3 of that of aluminium. Furthermore, alloys based on magnesium offer outstanding damping and stiffness capabilities than other alloys. Significant advancements in the characteristics of alloys based on magnesium have allowed for the decrease of aircraft weight while simultaneously allowing for an increase in the payload capacity of aircraft. The strength of titanium alloys is much higher than that of aluminium alloys. Assuming, however, that the component does not have a gauge limitation, it is possible to achieve the weight decrease by substituting aluminium, despite the fact that aluminium has a density that is sixty percent higher than that of aluminium. For the purpose of determining how different titanium alloys may be used in the aerospace sector, the primary features of these alloys, as well as the manufacturing methods, were analysed together [1]. In addition, ceramic matrix composites are able to withstand high working temperatures of 1400 degrees Celsius, which enables them to fulfil the ever-increasing need for aircraft speed.

1.1 Historical Background of Composite Materials in Aerospace

Composite materials have been used in aircraft from ancient times, when early civilizations used composites in building and combat. This is where the history of composite materials in aerospace can be traced back. The contemporary period of composite materials, on the other hand, started to take form throughout the middle of the 20th century. This began to happen as a result of developments in materials science as well as the expanding aircraft sector.

Following the conclusion of World War II, aerospace engineers endeavoured to push the limits of flight, which resulted in a desire for materials that could provide extraordinary strength while yet maintaining their lightweight properties. This pursuit of innovation occurred at the same time as the creation of new synthetic polymers and reinforced fibres, which allowed for the establishment of the foundation for the development of contemporary composite materials.

The production of military aircraft is one of the early uses of composites in the aerospace industry. Composites were used in the construction of aircraft. In the 1950s and 1960s, manufacturers started experimenting with fiberglass-reinforced polymers (FRP) to develop components like radomes and fairings. These components were used in the production of aircraft. These early composites provided an appealing mix of strength, resistance to corrosion, and simplicity of manufacture, which paved the way for future investigation in aeronautical applications using composite materials. It was the introduction of carbon fiber-reinforced polymers (CFRP) in the 1970s that marked the beginning of a significant breakthrough for composite materials in the aerospace industry. Carbon fibres, which have an amazing strength-to-weight ratio, have revolutionised the building of aeroplanes by making it possible to manufacture components that are lightweight while yet producing an incredible amount of strength. With famous models like the Boeing 787 Dreamliner demonstrating the potential of carbon fibre reinforced plastic (CFRP) in commercial aviation, this marked the beginning of a new age of aircraft design that heavily relied on composite materials.

During the second part of the 20th century, developments in composite manufacturing processes further drove the incorporation of composite materials into aeronautical systems. Processes like as filament winding, resin transfer moulding (RTM), and automated fibre placement (AFP) made it possible to manufacture high-performance composite structures that were both complicated and efficient to an extent that had never been seen before. Not only did these manufacturing advances broaden the spectrum of uses for composite materials, but they also reduced the price of production, which means that composite materials are becoming more practical for mass-produced aircraft.

The 21st century has seen a continuous development in the usage of composite materials in the aerospace industry. This progress has been driven by an unrelenting quest of performance, efficiency, and sustainability. In order to achieve considerable savings in weight and fuel consumption, aircraft manufacturers are progressively introducing composites into important structural components such as wings, fuselages, and empennages. This has led to the incorporation of composites into these components. Furthermore, the advent of hybrid composites, which combine several kinds of fibres and matrices, has opened up new possibilities for the customisation of material characteristics and the improvement of structural performance.

Taking a look into the future, the future of composite materials in the aerospace industry looks to be becoming more promising, with continual developments set to redefine the frontiers of flight. Composite materials continue to play a pivotal role in determining the future of aerospace engineering, from the design of aircraft of the next generation to the development of innovative technologies for human space exploration. Composite materials are a tribute to mankind's capacity to harness the force of creativity to defy gravity and strive for the heavens. With humanity embarking on new frontiers in the skies and beyond, composite materials serve as a testament to our strength.

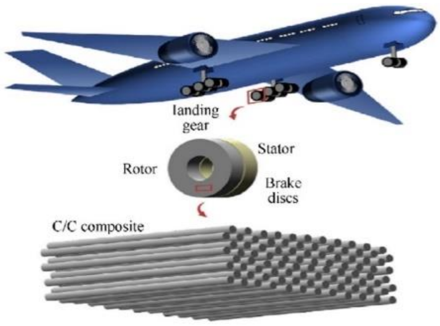

Figure 1: The Boeing 787's Composite Material Distribution as A Whole (Ref.) Parveez, (2022).

1.2 Composite Materials for Aerospace Application

The performance standards that are imposed upon materials in the aircraft industry might be far higher than those that are placed on materials in other fields. Critical elements include low weight, high strength, high stiffness, and exceptional fatigue resistance.

Figure 2: Aircraft Composites Made of Metal Matrix

The military was the first to make use of composites, and it wasn't until later that the technology was adapted to civilian aircraft. The modulus of glass, on the other hand, is very low in comparison to that of metals; hence, the development of primary composite structures did not occur until the incorporation of carbon reinforcements. Composite materials are becoming more popular in today's world.

The creation of main structures for space vehicles has been made possible as a result of the successful use of composites in missiles. In point of fact, different applications in space lend themselves to the utilisation of novel materials in a variety of different ways. In the case of satellites, for instance, the durations from idea to manufacturing might be as short as two years.

Some antenna reflectors also make use of the material in their construction.

However, carbon-fiber composite, often known as CFRP, is most frequently connected with applications in the space industry. On the other hand, because to the persistent push to reduce weight, several satellites have been constructed using a sub-system that is mostly composed of composite materials up to this point.

1.2.1 Types of Composites

They are distinguished by the fact that they are a unique mixture of two or more separate component elements. Each of these composites offers a unique set of qualities and benefits that are particularly well-suited to meet the needs of certain technical applications.

Due to the fact that they are versatile, inexpensive, and simple to fabricate, polymer matrix composites (PMCs) are perhaps the sort of composites that are utilised the most often all over the world. In PMCs, reinforcing fibres, which are generally composed of materials such as carbon, glass, or aramid, are bonded together by a polymer resin matrix. Examples of such a matrix include epoxy, polyester, and vinyl ester. The exceptional strength-to-weight ratios, corrosion resistance, and damping qualities that these composites possess make them a perfect choice for a wide variety of applications, including but not limited to aircraft components, automotive parts, damping characteristics, sports goods, and consumer electronics.

Composites made of metal matrix, often known as MMCs, are made out of a matrix made of metal alloys that is reinforced with ceramic or metallic fibres or pellets. In spite of the fact that they maintain the ductility and formability of metals, these composites have outstanding mechanical characteristics, such as high strength, stiffness, and thermal conductivity. Aluminium, titanium, and magnesium alloys are examples of matrix materials that are often used in MMCs. Reinforcements may be made up of silicon carbide, alumina, or carbon fibres according to requirements.

1.2.2 Properties of Composite Materials

Composite materials are extremely desired for a broad variety of engineering applications, including aerospace, automotive, marine, construction, and more. This is because composite materials display a wide range of qualities that make them very desirable. These traits are the outcome of the synergistic combination of two or more component elements, each of which contributes distinctive qualities to the composite:

There are a number of qualities that are particularly noticeable in composite materials, including strength and stiffness. Composites are able to attain remarkable levels of strength and stiffness while keeping a relatively low weight. This is accomplished by adding high-strength reinforcing fibres or particles into a matrix material. For instance, carbon fiber-reinforced composites have tensile strengths that are several times higher than those of steel, despite the fact that they are significantly lighter. This makes them an ideal material for applications in which weight savings and structural integrity are of the utmost importance, such as components for aerospace vehicles and high-performance sporting goods.

This is especially true in conditions where temperatures are high. Composites may be developed to display superior thermal conductivity, thermal expansion coefficients, and heat resistance, depending on the particular application requirements that are being met. Ceramic matrix composites (CMCs), for instance, are recognised for their outstanding thermal stability and resilience to thermal shock. As a result, they are very useful for aircraft propulsion systems, gas turbines, and other high-temperature applications where conventional materials would ultimately fail.

1.2.3 Manufacturing Processes

Manufacturing processes are very important in the aerospace sector since they are responsible for the production of high-quality components and structures that are able to fulfil the strict performance and safety criteria of aircraft and spacecraft. For the purpose of fabricating aerospace components with accuracy, efficiency, and dependability, a number of innovative manufacturing methods are used throughout the production process. The lay-up process, filament winding, pultrusion, and autoclave curing are some of the most important procedures that are used in the manufacture of aerospace products.

The lay-up manufacturing technique is one of the most common methods used in the aerospace industry for the production of composite components. In this technique, layers of reinforcing fibres, such as carbon or glass, are soaked with a resin matrix, often epoxy, and then put up manually or with the assistance of automated equipment onto a tool or mould in a certain orientation. The positioning of each layer is meticulously planned out in order to produce the necessary mechanical characteristics and fibre orientation. The composite structure is cured under regulated temperature and pressure conditions after the lay-up process has been completed. This process is done in order to glue the layers together and generate a solid component inside the composite. Lay-up is highly regarded due to its adaptability, which enables the manufacture of intricate geometries and individualised fibre structures that are adapted to the particular needs of aeronautical applications.

1.3 Advanced Composite Materials

1.3.1 Carbon Fiber Composites

Carbon fibre composites have brought about a revolution in the aerospace sector. These composites provide a one-of-a-kind mix of strength, stiffness, and lightweight qualities, which makes them necessary for a broad variety of applications. The design, performance, and efficiency of aeroplanes have been revolutionised in ways that were previously imagined because to the introduction of these cutting-edge materials, which are made up of carbon fibres embedded in a resin matrix.

When it comes to carbon fibre composites, the carbon fibres themselves are the most important component. Carbon fibres are extraordinarily lightweight and strong. These fibres are often produced from precursor materials, such as polyacrylonitrile (PAN) or pitch, which are then exposed to high temperatures and controlled conditions in order to build highly orientated carbon structures. Other examples of precursor materials include pitch. The fibres that are produced as a consequence have very high tensile strength and stiffness, which is superior to that of conventional materials like as steel and aluminium, while at the same time being substantially lighter.

Carbon fibre composites have been shown to provide a number of significant benefits in aerospace applications, which have resulted in a transformation of aircraft design and manufacture. Aircraft makers are able to decrease weight, boost cargo capacity, and extend flying range by replacing conventional metal components with carbon fibre composites. This results in considerable financial savings and environmental advantages for the aircraft manufacturers.

1.3.2 Glass Fiber Composites

Composites made of glass fibres are a category of innovative materials that are well-known for their remarkable mechanical qualities, adaptability, and extensive range of uses across a variety of sectors. These composites are made up of glass fibre materials. The composite materials that are produced as a consequence of the unique mix of glass fibres and resin matrix are better in terms of strength, stiffness, and durability when compared to conventional materials such as metals and plastics.

The extraordinary strength-to-weight ratio of glass fibre composites is identified as one of the most significant benefits of these materials. Glass fibres, which may be formed from molten silica or other elements that can be used to create glass, are recognised for their incredible tensile strength and modulus, which enables them to support considerable loads while yet maintaining their lightweight nature. These fibres, when implanted in a resin matrix, generate a composite material that is both strong and lightweight. Because of this, it is suitable for applications where weight reductions are of crucial importance, such as components for aerospace vehicles, parts for automobiles, and sports goods.

In addition, glass fibre composites have outstanding stiffness and rigidity, which enables them to provide structural integrity and stability in a broad variety of applications. Due to the high modulus of glass fibres, composite materials are able to resist deformation when subjected to load. This allows for the preservation of dimensional stability and the prevention of drooping or warping over time. Especially favourable are applications that need exact tolerances and dimensional precision, such as machine components, architectural structures, and maritime vessels. This rigidity is especially helpful in these kinds of applications.

In addition, glass fibre composites have an exceptional fatigue resistance, which enables them to sustain numerous loading cycles without deterioration or failure throughout the process. This resistance to fatigue may be due to the intrinsic flexibility and resilience of glass fibres, which have the ability to disperse energy and inhibit the development of cracks or fractures within the composite material. As a consequence of this, glass fibre composites are an excellent choice for applications that are exposed to cyclic loads. Some examples of such applications include aircraft structures, wind turbine blades, and automobile suspension components.

1.3.3 Aramid Fiber Composites

For their excellent strength, durability, and lightweight features, aramid fibre composites are a family of innovative materials that are well recognised for their exceptional qualities. Aramid fibres are a kind of fibre that is derived from synthetic aromatic polyamides. These fibres have extraordinary mechanical qualities, such as high tensile strength, modulus, and resistance to abrasion and impact. When aramid fibres are mixed into composite materials, they transmit these exceptional qualities to the structures that are produced. Kevlar®, which was invented by DuPont in the 1960s, is one of the aramid fibres that the public is most familiar with. The exceptional strength-to-weight ratio of Kevlar®, which makes it five times stronger than steel on an identical weight basis, is one of the company's most coveted characteristics. Kevlar® is an ideal option for applications where weight savings and high performance are vital, such as aerospace components, ballistic armour, and sports goods. Its amazing strength, coupled with its lightweight nature, makes it an outstanding choice for these applications.

When compared to conventional materials such as metals and other polymers, aramid fibre composites provide a number of significant benefits. In the first place, they have outstanding fatigue resistance and impact absorption qualities, which makes them very well-suited for applications that are exposed to dynamic loads or repeated loading. For this reason, aramid fibre composites are an excellent choice for use in aerospace constructions. These structures need components to be able to withstand cyclic loads during flight operations without compromising their performance or dependability.

1.3.4 Nano-Composites and Their Aerospace Applications

Aerospace engineering has been revolutionised by the introduction of advanced composite materials, which provide unparalleled strength, lightweight qualities, and increased performance characteristics. Nano-composites are a cutting-edge class of materials that use nanotechnology to further improve the qualities of conventional composites. They are one of the breakthroughs that have been introduced. Nano-composites are composite materials that are created by integrating nanoscale reinforcements, such as nanoparticles or nanofibers, into a matrix material. This results in composite materials that have better mechanical, thermal, electrical, and multifunctional capabilities. Nano-composites have a large amount of promise in the aerospace sector, since they have the ability to solve important problems and open up new opportunities across a significant number of different applications.

Nano-composites have an extraordinary strength-to-weight ratio, which is one of the most important benefits they provide in aeronautical applications. It is possible for nano-composites to attain much greater levels of strength and stiffness in comparison to traditional composites. This is accomplished by introducing nanoscale reinforcements into a polymer matrix. The creation of lightweight aerospace structures that provide greater structural integrity, durability, and resistance to fatigue and impact is made possible as a result of this. As a result, the overall performance and safety of aircraft and spacecraft are improved.

II. LITERATURE REVIEW

Gebrehiwet et al. (2023) highlights the extensive use of composite materials across various fields due to their adaptability and broad applications, focusing particularly on aerospace. They review different types, compositions, and properties of composites, examining recent research and potential future applications such as MESC electrochemical energy storage, isogrids, conductive fibers, and carbon fiber-reinforced silicon carbide composites. Their study includes detailed materials used in aerospace and automotive sectors, supplemented by charts and statistics to provide comprehensive insights.

Siengchin (2023) explores the significant investment in research and development by governments to advance the defense industry, emphasizing the use of lightweight materials in military applications. This study provides a thorough overview of recent advancements in lightweight materials, their historical and contemporary military applications, and potential future uses.

Ndukwe (2023) discusses the development of graphene nanoplatelet/epoxy nanocomposites for reinforcing epoxy matrices. The research includes the production of robust and lightweight mullite whisker networks using coal fly ash, bauxite, and kaolin. It also covers the creation of high-strength, low-density fly ash geopolymer composites, coextruded wood-plastic/lumber composites (WPLCs), and neutron shielding composites with ceramic/epoxy matrices.

Chen et al. (2023) focus on the advancements in manufacturing methods for fiber-reinforced composite structures, such as autoclaves, resin transfer moulding, and automated layup technology. They compare these technologies, discussing their benefits, drawbacks, and the challenges of intellectualization in industrial technologies, providing a valuable reference for scholars in the field.

Ozturk et al. (2023) examine the stringent requirements of the aerospace sector and the growing competitiveness of thermoplastic composites. They highlight the advantages of thermoplastic composites over thermoset composites, such as easier forming, shorter manufacturing cycles, and recyclability. The study underscores the increasing use of thermoplastics in aerospace and the significant investments in thermoplastic technology.

Ince et al. (2023) assess current advancements in materials for space applications, focusing on state-of-the-art materials that address the challenges of space travel. The study aims to provide information and recommendations for selecting innovative materials to expand space exploration.

Alam et al. (2022) review the continuous research and development of revolutionary materials in aerospace to reduce weight, improve fuel economy and performance, and cut costs. They discuss the growing use of composite materials in commercial aircraft production and the emergence of sophisticated hybrid composites as effective structural materials.

Parveez et al. (2022) provides an overview of recent advancements in aviation materials, focusing on composites with exceptional properties for the aircraft sector. They discuss the development of corrosion-resistant, high-performance materials and the manufacturing processes and applications of these composites in aviation.

Tiwary et al. (2022) investigates the compositions and applications of advanced composite materials used in space shuttle design. They explore the mechanical and thermodynamic properties of these materials, the advantages and disadvantages of their use, and potential developments in composite materials for space applications. The study aims to aid researchers in selecting appropriate materials for space shuttle construction.

III. METHODS AND MATERIALS

There is a lot of engineering, testing, and research that goes into making composite materials that are both strong and lightweight for use in aircraft. Weight reduction, structural integrity, thermal stability, and resistance to diverse climatic conditions are some of the particular needs for materials that scientists and engineers first evaluate when making their product specifications. The selection of appropriate raw materials and the construction of composite recipes are guided by these criteria.

Researchers in the lab build composite formulations by combining different reinforcing fibers—carbon, glass, or aramid—with a matrix material, often epoxy resin. How the finished material is to be used and what its desired qualities are will dictate the choice of fibres and matrix. Autoclaving, resin transfer moulding (RTM), and filament winding are some of the production procedures used to create composite components when the recipe is finalised. The material's strength and durability are improved by these operations, which guarantee that the fibres are aligned correctly and that the matrix is evenly distributed.

After that, the composites undergo rigorous testing to determine their chemical, mechanical, and thermal characteristics. They are validated in this testing step under simulated aircraft circumstances to verify they comply with high safety regulations and to certify their performance. Lightweight and high-strength composites have become vital in current aircraft engineering due to the continuous improvement and innovation in materials science and production processes.

3.1 Mathematical Model

Developing a mathematical model for the development of lightweight and high-strength composite materials for aerospace involves considering various factors such as material properties, manufacturing processes, environmental conditions, and performance requirements. Here's a simplified mathematical model outlining some key aspects:

3.1.1 Material Properties

Let's denote the material properties of the composite material by MM. These properties include:

- Density (ρ)
- Young's Modulus (E)
- Tensile Strength ($\sigma_{tensile}$)
- Compressive Strength σ compressive)
- Shear Modulus (G)
- Poisson's Ratio (ν)

3.1.2 Manufacturing Parameters

The manufacturing process parameters can significantly influence the properties of composite materials. Let's denote these parameters collectively by P. These parameters could include:

- Fiber orientation (θ)
- Resin content (RC)
- Curing temperature ($Tcure$)
- Curing time ($tcure$)

3.1.3 Environmental Factors

Environmental conditions, such as temperature (*Tenv*), humidity (*Henv*), and exposure to radiation, can affect the performance and durability of composite materials.

3.1.4 Performance Requirements

The performance requirements for aerospace applications may include specific criteria such as minimum weight, maximum strength-to-weight ratio, thermal stability, and resistance to fatigue.

The mathematical model can be represented by a set of equations that describe the relationships between the aforementioned factors. These equations could include:

3.1.5 Composite Density

$$\rho_{\text{composite}} = \rho_{\text{fiber}} \times RC + \rho_{\text{resin}} \times (1 - RC)$$

Young's Modulus of The Composite

$$E_{\text{composite}} = E_{\text{fiber}} \times RC + E_{\text{resin}} \times (1 - RC)$$

Tensile Strength of The Composite

$$\sigma_{\text{tensile,composite}} = \frac{\sigma_{\text{fiber}}}{RC}$$

Compressive Strength of The Composite

$$\sigma_{\text{compressive,composite}} = \frac{\sigma_{\text{fiber}}}{RC}$$

Shear Modulus of The Composite

$$G_{\text{composite}} = G_{\text{fiber}} \times RC + G_{\text{resin}} \times (1 - RC)$$

Poisson's Ratio of The Composite

$$\nu_{\text{composite}} = \nu_{\text{fiber}} \times RC + \nu_{\text{resin}} \times (1 - RC)$$

3.2 Manufacturing Techniques

3.2.1 Resin Transfer Molding (RTM)

Resin Transfer Molding (RTM) is a popular manufacturing technique in aerospace applications for producing composite parts with complex shapes and high strength-to-weight ratios. Here's a simplified overview of the RTM process and its mathematical modeling:

Process Description

The resin flows through the fiber reinforcement, impregnating it completely. The mold is then cured under controlled temperature and pressure conditions to solidify the composite part.

Key Parameters:

- Injection Pressure ($Pinj$): The pressure applied to inject the resin into the mold.
- Injection Rate ($Qinj$): The rate at which resin is injected into the mold.
- Resin Viscosity (μ): The viscosity of the resin, which affects its flow behavior.
- Fiber Volume Fraction (Vf): The volume fraction of fibers in the composite.
- Mold Temperature ($Tmold$): The temperature of the mold during resin injection and curing.

Mathematical Model

A mathematical model for the RTM process can be developed based on principles of fluid flow, heat transfer, and material behavior. Here are some equations that may be included in the model:

Darcy's Law for Flow through Porous Media

$$Q_{\text{inj}} = \frac{kA}{\mu}\frac{\Delta P}{L}$$

Where $Qinj$ is the injection rate, k is the permeability of the fiber preform, A is the cross-sectional area of the mold, ΔP is the pressure drop across the mold, and L is the length of the mold.

Mass Balance Equation

$$\frac{dV_r}{dt} = Q_{\text{inj}} - \frac{A}{V_m}\frac{dV_m}{dt}$$

Where Vr is the volume of resin in the mold, Vm is the total mold volume, and the terms represent the resin injection rate and mold volume change rate, respectively.

Heat Transfer Equation: $q = h(Tresin - Tmold)$ Where q is the heat transfer rate, h is the heat transfer coefficient, $Tresin$ is the resin temperature, and $Tmold$ is the mold temperature.

These equations, along with constitutive equations describing resin curing kinetics and fiber-resin interaction, can form the basis of a comprehensive mathematical model for the RTM process.

Simulation and Optimization

Once the mathematical model is developed, it can be implemented in numerical simulation software to predict the flow behavior, resin distribution, and final properties of the composite part. The model can also be used for process optimization to achieve desired part characteristics such as void content, fiber volume fraction, and mechanical properties.

By incorporating these mathematical equations and principles, engineers can better understand and optimize the RTM process for aerospace applications, leading to the production of lightweight, high-strength composite parts.

3.2.2 Autoclave Curing

In this process, composite layups, consisting of layers of reinforcing fibers such as carbon, glass, or aramid, impregnated with a resin matrix, are subjected to elevated temperature and pressure within an autoclave chamber. The controlled environment inside the autoclave ensures proper consolidation, curing, and bonding of the composite materials, resulting in components with desired mechanical properties and structural integrity.

The autoclave curing process typically involves several key steps:

- Preparation of Layup: Before the curing process begins, composite layups are meticulously prepared according to the design specifications. This involves laying down the reinforcing fibers in specific orientations and stacking them with alternating layers of resin to form the desired composite structure.

- Vacuum Bagging: Once the layup is complete, it is enclosed within a vacuum bag to remove any air trapped between the layers and ensure uniform resin distribution. The vacuum bagging process helps prevent voids and delamination, which can compromise the integrity of the composite material.
- Placement in Autoclave: The vacuum-bagged layup is then placed inside the autoclave chamber, which is sealed to create a controlled environment. The autoclave is capable of reaching and maintaining high temperatures, typically in the range of 100 to 200 degrees Celsius, and applying pressure ranging from a few psi to several atmospheres.
- Heating and Curing: Once the layup is inside the autoclave, the temperature and pressure are gradually ramped up to the prescribed curing cycle. The elevated temperature activates the curing agents present in the resin matrix, initiating cross-linking reactions that bond the fibers together and solidify the composite material. The applied pressure ensures intimate contact between the fibers and promotes the removal of entrapped air and volatiles from the resin system.
- Cooling and Depressurization: After the curing cycle is complete, the autoclave is gradually cooled down to ambient temperature, and the pressure is slowly released. This gradual cooling and depressurization help prevent thermal stresses and minimize the risk of warpage or distortion in the cured composite components.

Autoclave curing offers several advantages in aerospace applications, including precise control over temperature, pressure, and curing cycles, which allows for the production of composite components with tailored properties and high reproducibility. Additionally, the consolidation and compaction achieved during autoclave curing result in composite structures with exceptional strength-to-weight ratios and excellent fatigue resistance, making them well-suited for demanding aerospace environments. Despite its effectiveness, autoclave curing can be time-consuming and energy-intensive, and alternative manufacturing techniques such as out-of-autoclave processing are being explored to reduce production costs and cycle times while maintaining the desired performance characteristics of aerospace composites.

3.2.3 Vacuum Bagging

Vacuum bagging is an important manufacturing process for aerospace applications since it is used to make composite materials. This method creates lightweight, high-strength components with intricate geometries by using vacuum pressure to solidify layers of resin and composite materials. The composite materials, which usually consist of a matrix resin (like epoxy) and reinforcing fibres (like carbon, glass, or aramid), are prepared first in the hoover bagging process. It is common practice to use a mould or a tooling surface to arrange these materials in layers that correspond to the intended orientation and arrangement.

Carefully sealing a hoover bag around the perimeter creates an airtight enclosure after the lay-up is complete. The bag is then put over the composite components. After that, the bag is attached to a vacuum pump, which removes air from the sealed area, resulting in a low-pressure setting. The layers of composite materials are compressed together when the air is evacuated, resulting in close contact and consolidation due to atmospheric pressure.

IV. SIMULATION AND RESULT

Composite materials, with their high strength-to-weight ratio, have become essential in aerospace applications. This study focuses on the finite element analysis of laminated composite plates using the First-Order Shear Deformation Theory (FSDT), a significant advancement over the classical laminated plate theory (CLPT) in addressing shear deformation effects. The optimization process incorporates an analysis of the ultimate strength and stress effects under regular and uniform out-loads, employing a finite element model developed with Reissner's flat and thick shell element approach. The demand for lightweight and high-strength materials has driven the aerospace industry towards the use of advanced composite materials. Laminated composite plates offer a flexible approach to creating lightweight structures with customized mechanical properties. Traditional analysis methods like the Classical Laminated Plate Theory (CLPT) yield accurate results for thin plates but tend to be inaccurate for thicker plates (where (ath < 20)). The First-Order Shear Deformation Theory (FSDT) improves on this by accounting for shear deformation and rotary inertia effects.

4.1 Procedure

This study employs a finite element model based on Reissner's flat and thick shell finite element model, utilizing a 4-node, 20 degrees-of-freedom (DOF) structure. Shear deformation effects are addressed using FSDT, a critical factor in analyzing thicker composite plates.

Shear locking is a common issue in FSDT, especially with thick plates. To mitigate this, the stiffness reduction technique is employed. The stiffness matrix's non-shear components are integrated using a 3x3 Gauss-Legendre-Quadratic method, while shear components are integrated using a 2x2 Gauss-Legendre-Quadratic method.

Optimization analysis focuses on shear locking effects and employs simple stiffness reduction techniques. The analysis uses a customized MATLAB program that integrates non-shear and shear components. This program allows for a range of optimization settings, including varying the aspect ratio ((a/b)), height-to-thickness ratio ((b/h)), and ply orientation angles.

4.2 Results

Optimization outcomes show that specific ply orientation angles yield optimal results for various plate configurations. The results indicate that the optimal angle varies with the aspect ratio of the plate, suggesting that customization is necessary based on the geometry of the composite structure.

4.3 Key Findings Include

For a plate with aspect ratio (a/b = 1.0), the optimal angle is 45 degrees. As the aspect ratio increases, the optimal angle tends to decrease. For (a/b = 2.5), the optimal angle is 38.5 degrees. Ultimate strength and stress effects are effectively analyzed using this FSDT-based approach, providing a robust framework for further exploration. Our code is to be handling multiple aspects of the analysis, from material properties and mesh generation to stiffness matrix assembly and stress analysis. The important aspects and some suggestions for improvement.

Key Components in The Code

Material Properties

- ✓ Defines elastic properties for orthotropic material (e.g., (E_1), (E_2), (G_ {12}), (v_ {12})).
- ✓ Other relevant properties for stress analysis like tensile and compressive strengths ((X_t), (X_c), etc.).

Geometry and Mesh Generation

- ✓ Total dimensions for the plate are specified (e.g., `totalx`, `totaly`, `th`).
- ✓ An automatic mesh is generated based on the defined mesh values (`meshn`).

Boundary Conditions and Loads

- ✓ Matrix definitions to handle boundary conditions and global system loadings.
- ✓ Loads are distributed across the plate based on the mesh and force values.

Stiffness Matrix Calculation

- ✓ Uses a finite element approach to assemble the stiffness matrix.
- ✓ Employs the Gauss-Legendre Quadrature for numerical integration.

Stress and Strain Analysis

- ✓ Computes stress and strain across the laminated composite plates.
- ✓ Derives stress using an appropriate elasticity matrix based on given angles (`tetarandom`).
- ✓ Computes the Failure Index (FI) using the Tsai-Wu failure criterion.

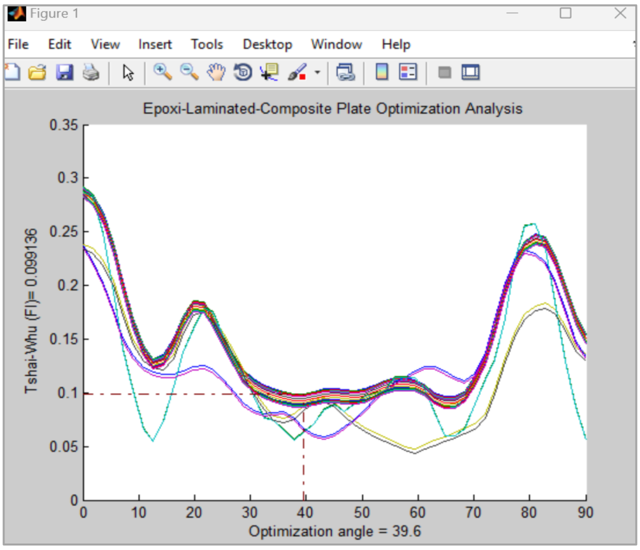

Figure 3: Simulative Outcome

The finite element analysis (FEA) of laminated composite plates using First-Order Shear Deformation Theory (FSDT) is pivotal in developing lightweight, high-strength materials for aerospace applications. This MATLAB code demonstrates an FEA approach to evaluate stress, strain, and ultimate strength in composite structures.

The key benefit lies in the optimization of composite layups by varying ply angles to achieve optimal strength-to-weight ratios. This is crucial for aerospace, where every gram counts for fuel efficiency and performance. The code addresses shear deformation, making it suitable for thicker composite plates often used in aerospace components like wings and fuselages.

Using orthotropic material properties, the code models real-world composite behaviors, allowing engineers to understand how these materials respond to different loads and stresses. The inclusion of failure analysis, such as the Tsai-Wu index, enhances safety by predicting potential failure points.

Overall, this FEA-based approach aids in rapid design iteration, enabling engineers to experiment with different configurations and materials. It supports the development of aerospace components that are lightweight, strong, and safe, ensuring they meet the industry's rigorous performance and safety standards.

V. CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

The finite element analysis (FEA) of laminated composite plates using First-Order Shear Deformation Theory (FSDT) is a powerful tool for the aerospace industry, offering insights that drive the development of lightweight and high-strength composite materials. Through the MATLAB code provided, this study showcases a comprehensive approach to analyzing composite structures, leading to significant benefits for aerospace applications.

Enhanced Structural Analysis

One of the key outcomes of this approach is the ability to perform detailed structural analysis on composite plates. By simulating the stress and strain under different conditions, engineers can predict how these structures will perform in real-world aerospace environments. This analysis is vital for ensuring the safety and reliability of aerospace components.

Optimization of Composite Layups

The optimization aspect of the FEA approach allows engineers to experiment with different ply orientations to achieve the best strength-to-weight ratio. This flexibility is crucial for aerospace applications, where every component must be optimized for weight and performance. The code demonstrates how varying angles can lead to different outcomes, enabling a more tailored design process.

Addressing Shear Deformation

FSDT accounts for shear deformation, providing more accurate results for thicker composite plates. This consideration is critical in aerospace applications, where structures must withstand significant forces and deformations during flight. The MATLAB code effectively addresses shear locking issues, leading to more reliable and realistic simulations.

Orthotropic Material Modeling

By defining orthotropic material properties, the FEA approach allows for a more accurate representation of composite materials. This capability is essential in aerospace, where composites are often orthotropic due to their layered structure. The code provides a framework for modeling these materials' behavior, enabling engineers to assess their performance in various conditions.

Failure Analysis and Safety

The inclusion of failure analysis, particularly using the Tsai-Wu failure index, enhances the safety and reliability of composite structures. The ability to predict potential failure points is crucial in aerospace applications, where safety is paramount. This aspect of the code provides a mechanism to identify and mitigate risks in the design phase.

Design Iteration and Customization

The FEA approach allows for rapid design iterations, facilitating experimentation with different configurations and materials. This agility is essential in aerospace, where the design process often involves multiple iterations to achieve optimal performance. The MATLAB code enables this flexibility, supporting a more dynamic design process.

Integration with Other Aerospace Design Tools

The FEA approach can be integrated with other aerospace design tools, allowing for a comprehensive analysis of composite structures. This integration supports a seamless workflow from design to manufacturing and testing, ensuring that composite materials meet industry standards.

The developed finite element model with FSDT and the associated optimization analysis techniques offer an efficient approach for evaluating the structural integrity of laminated composite plates in aerospace applications. By adjusting ply orientation angles and using the stiffness reduction method to mitigate shear locking, the program provides valuable insights into achieving lightweight and high-strength composite structures.

Future research could explore high-order shear locking effects and further optimization techniques for additional composite plate configurations, supporting the development of increasingly sophisticated aerospace structures.

5.2 Suggestions for Improvement

Code Structure and Organization

- ✓ Consider organizing your code into functions or scripts for each major component. This approach enhances readability and maintainability.
- ✓ Define reusable functions for common operations like stiffness matrix assembly, load distribution, stress calculation, etc.

Boundary Conditions and Loads

- ✓ Double-check the boundary conditions to ensure they're set correctly. Inadequate boundary conditions can lead to unrealistic results.
- ✓ Include comments explaining the meaning and context of different boundary conditions.

Error Handling and Validation

- ✓ Implement checks to validate inputs, like mesh density and aspect ratios. Consider adding error messages to guide users in case of incorrect inputs.

- ✓ Consider adding validation steps to check for convergence, ensuring that the finite element solution is robust.

Debugging and Performance Optimization

- ✓ If encountering errors or unexpected results, consider adding debugging lines to understand where the issue might be.
- ✓ For large meshes or complex simulations, consider performance optimization techniques like parallel computing.

Plotting and Visualization

- ✓ Ensure your plotting functions (like `FIinterface`) have descriptive axis labels, titles, and legends to clearly understand the results.
- ✓ Consider plotting intermediate results like mesh generation, load distribution, or stress distributions for better visualization.

Overall, our proposed code presents a comprehensive approach to finite element analysis of laminated composite plates using FSDT.

5.3 Future Considerations

While the provided MATLAB code offers a robust framework for FEA, future work could explore additional optimization techniques, higher-order shear deformation theories, and more complex composite structures. Additionally, integrating this approach with other simulation tools could lead to a more holistic understanding of composite behaviour in aerospace applications.

In conclusion, the FEA of laminated composite plates using FSDT is a valuable approach for the aerospace industry, offering insights that drive the development of lightweight and high-strength composite materials. Through detailed analysis, optimization, and failure prediction, this approach supports the design and development of safe, efficient, and high-performing aerospace components.

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