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"Composite Materials for Wind Turbine Blades Mechanical Performance and Fatigue Analysis"

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***Abstract*-- Glass-fiber composites are commonly used for wind turbine blades due to their low cost and acceptable performance, but increasing blade sizes for offshore turbines have made their high density a limitation. Larger blades experience higher gravitational loads, requiring materials that are lightweight, strong, stiff, and fatigue resistant. Carbon-fiber composites offer high strength and stiffness but are expensive, leading to the use of hybrid blades with carbon in critical regions such as spars. Basalt-fiber composites provide good mechanical and thermal properties at lower cost, while epoxy matrices and proper manufacturing help improve blade durability and fatigue performance.**

***Keywords*:-Glass fiber, Fatigue properties, epoxy matrices.**

I. Result And Discussion

Laminates thickness effect on static and fatigue properties

The influence of laminate thickness on the static and fatigue behavior of wind turbine composite materials has been examined in earlier studies [48,49]. Several factors contribute to the differences observed between thin and thick laminates, including self-heating during cyclic loading, scaling effects in test specimens, geometric design considerations, and manufacturing-related variations. Under dynamic loading, composite laminates experience internal heating, which leads to a rise in temperature. This temperature increase is not uniform through the laminate thickness and can degrade mechanical properties, ultimately causing early failure [50].

To investigate the self-heating phenomenon, a 30 mm thick composite coupon was tested under different loading conditions and frequencies. The results, indicate a reduction in fatigue life for thick laminates due to surface heating. Temperature increases of approximately 15–20 °C were recorded, while the core temperature exceeded the maximum service temperature. The S–N curves for a 20 mm thick coupon tested at two different frequencies further demonstrate that higher loading frequencies and increased heating significantly reduce fatigue life [48].

Another contributor to thickness-dependent behavior is the scaling effect. To isolate this factor, unidirectional compression coupons with thicknesses of 4, 10, and 20 mm were tested under both static and fatigue loading while minimizing other influencing parameters.

The results showed no noticeable change in ultimate compressive strength; however, fatigue life decreased as laminate thickness increased [51].

Material property variations through the laminate thickness are also influenced by the manufacturing process. This effect was studied by extracting sub-laminates from 60 mm thick infused composite plates and testing them under static and fatigue conditions. Differences in curing temperature at various thickness locations resulted in non-uniform material properties. Static compression stress distribution through the thickness, revealed higher stresses in the mid-layers. Additionally, S–N curves indicated that the fatigue behavior of the middle layers differed from that of the outer layers, highlighting the significance of through-thickness property variation.

Effect of low and high temperature on static and fatigue properties of laminates

One of the major challenges facing the wind energy industry is the exploitation of wind resources in northern and cold regions, where wind potential is particularly high, especially in parts of northern Europe. Deploying wind turbines in such harsh environments involves considerable risk, as low temperatures and severe weather conditions can significantly affect material performance. Among all turbine components, rotor blades are the most critical and costly, and they are especially susceptible to environmental degradation, which can lead to accelerated damage or failure.

Wind turbine blades are subjected to complex loading conditions, as discussed previously. During operation, the blade's upper surface experiences compressive stresses, while the lower surface is subjected to tensile stresses. To withstand these loads, blade structures typically incorporate unidirectional laminates and biaxial ±45° fiber orientations. Failure in ±45° biaxial laminates is largely governed by matrix behavior, making the composite highly sensitive to environmental factors. Moisture and temperature variations can significantly alter matrix properties, thereby influencing the overall mechanical performance of the composite material [15].

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Extensive research has been conducted to evaluate composite behavior under temperature extremes. Studies by Shen and Springer on graphite–epoxy composites over a temperature range of 200 K to 380 K reported minimal changes in tensile strength, with only a slight decrease observed at elevated temperatures [52,53]. Similarly, Cormier and Joncas found that at −40 °C, unidirectional E-glass/epoxy composites exhibited increased tensile and shear strength due to matrix contraction and increased stiffness at low temperatures. The compressive thermal stresses induced by matrix shrinkage were found to contribute to this strengthening effect. Comprehensive reviews on the influence of low temperatures on composite mechanical properties are available in the literature [59].

Further investigations conducted under the European UPWIND project included tensile and reversed fatigue tests at −40 °C on unidirectional E-glass/epoxy composites. The results indicated negligible to slightly negative effects of low temperature on tensile and fatigue performance [54]. In addition, the Wind Energy Strategic Network (WESNet), which supports innovation in the Canadian wind sector, has tested various composite materials under cold climate conditions, with selected results demonstrating their suitability for such environments.

II. Static Properties

This section presents the results of static tensile and compressive tests, along with tensile and fully reversed fatigue tests, conducted on biaxial (±45°) glass–epoxy laminates. Details regarding the reinforcement and matrix materials are provided in [15]. The tensile properties measured at room temperature (23 °C) and at −40 °C are summarized. Both tensile strength and elastic modulus increased at −40 °C, which can be attributed to enhanced matrix stiffness and strength at lower temperatures.

The shear and compressive properties obtained at −40 °C are listed. Similar to the tensile results, both shear and compressive strengths improved under cold conditions. In addition, the use of stitched fabrics was found to be effective in reducing the risk of laminate buckling [15]. Overall, the experimental results indicate an enhancement in mechanical performance at low temperatures.

These findings differ from those reported by Shen and Springer [15,52,53], who observed little to no improvement in properties. One possible explanation for this discrepancy is the difference in fiber volume fraction. For example, tests conducted on unidirectional glass–epoxy composites with a fiber volume fraction of 55% showed reductions in both tensile and compressive strength at 60 °C [55].

Comprehensive information on material specifications, testing standards, and experimental results can be found in [55].

III. Effect Of Waviness On Static And Fatigue Compressive Properties

To reduce manufacturing costs, wind turbine blades are often produced using economical materials and processing methods, which can introduce defects and reduce structural performance. Various types of imperfections found in wind turbine composite components have been identified and recorded in the DOE/MSU database [25]. One of the most critical defects observed in spar caps is fiber waviness, which has a significant negative impact on the compressive strength of laminates and can also lower tensile strength and fatigue life [55]. As a result, considerable attention has been directed toward understanding waviness in prepreg-based laminates.

Fiber waviness reduces compressive performance primarily for two reasons. First, geometric irregularities increase the likelihood of buckling in fibers, strands, or layers under compressive loading. Second, waviness causes misalignment of fibers and plies, which promotes matrix-dominated failure in laminates with fibers oriented in the longitudinal (0°) direction. Under ideal conditions, these plies typically fail in a fiber-dominated mode; however, in-plane waviness alters the load transfer mechanism, shifting the failure mode from fiber-controlled to matrix-controlled behavior during compression [19–26].

IV. Conclusion

Glass-fiber composites are widely used in wind turbine blades; however, as turbines continue to increase in size, blade weight also rises, leading to higher gravitational loads. The relatively high density of glass composites makes them less suitable for very large turbines. Carbon-fiber composites offer superior strength and stiffness, making them an attractive alternative for blade construction. Despite these advantages, carbon composites are costly and exhibit relatively low compressive strength. For this reason, they are often used selectively in critical load-bearing components such as blade spars, where they help reduce overall blade weight and limit tip deflection.

Basalt-fiber composites present another promising alternative, as they possess favorable mechanical and thermal characteristics and can potentially replace glass-fiber composites. Furthermore, incorporating nano-scale reinforcements into the matrix material can significantly enhance fatigue life, tensile, shear, and compressive strengths, as well as fracture toughness.

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Nano-reinforcement also improves damping behavior and resistance to delamination in turbine blades. In addition, strength reductions caused by fiber waviness in laminates can be mitigated through the use of automated fabric placement techniques, which improve fiber alignment and overall structural performance.

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