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Aerodynamic And Structural Simulation Framework for Recycled Plastic-Based Shear Webs in Wind Turbine Blades using COMSOL and Python Automation

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***Abstract*— The increasing accumulation of plastic waste presents a significant environmental challenge, particularly in rapidly urbanizing regions such as Chennai, India. Simultaneously, the wind energy sector faces sustainability concerns due to the limited recyclability of conventional blade materials such as glass fiber reinforced polymer (GFRP) composites. This study presents a preliminary aero-structural simulation framework for evaluating sustainable shear web concepts for wind turbine blade applications.**

A representative cantilever blade section based on a NACA 4414 airfoil profile was developed with an internal I-section shear web geometry. Aerodynamic, structural, and modal analyses were performed using COMSOL Multiphysics under a freestream airflow velocity of 25 m/s. Aluminum was used as a baseline material to validate the computational workflow and establish reference structural behavior. Computational fluid dynamics (CFD) simulations were coupled with structural finite element analysis (FEA) to evaluate pressure distribution, deformation, stress response, and the first six eigen modes of the blade section.

A Python-based automation framework was developed to streamline post-processing of simulation outputs, enabling automated extraction of stress and deformation. In addition, additive manufacturing design feasibility and nanotechnology-based reinforcement concepts for recycled plastics such as HDPE, PP, and PET were evaluated conceptually as future extensions of the framework.

The results demonstrate the successful implementation of an integrated aerodynamic, structural, and modal analysis workflow for wind turbine blade substructures. The developed methodology provides a scalable foundation for future comparative studies involving recycled thermoplastics and sustainable blade component design.

***Index Terms*— Additive Manufacturing, Finite Element Analysis, Python Automation, Recycled plastics, Wind Energy**

I. INTRODUCTION

The increasing accumulation of plastic waste has emerged as a major environmental challenge, particularly in rapidly urbanizing regions such as Chennai, India. Large quantities of post-consumer plastics, including high-density polyethylene (HDPE), polypropylene (PP), and polyethylene terephthalate (PET), are generated annually, with a significant proportion remaining unrecycled. The need to identify high-value engineering applications for recycled plastics has therefore become increasingly important within the context of sustainable manufacturing and circular economy initiatives.

Simultaneously, the wind energy sector continues to expand globally as a key contributor to renewable energy generation. Modern wind turbine blades are primarily manufactured using glass fiber reinforced polymer (GFRP) composites due to their favorable stiffness-to-weight ratio and fatigue resistance. However, these materials present substantial sustainability concerns because of their limited recyclability and difficult end-of-life disposal processes.

Recent research has therefore focused on exploring alternative materials, additive manufacturing methods, and computational approaches that could improve sustainability within wind turbine blade design. In particular, internal blade substructures such as shear webs present an opportunity for investigating alternative lightweight materials due to their comparatively lower structural demands relative to primary load-bearing regions.

Advances in computational multiphysics simulation tools have enabled detailed aerodynamic, structural, and dynamic analysis of blade structures prior to physical prototyping. Coupled with automation tools such as Python, these simulation workflows can be significantly accelerated through automated extraction and processing of engineering data.

In addition, additive manufacturing techniques such as fused deposition modeling (FDM) provide new opportunities for fabricating lightweight internal structures using thermoplastic materials. Nanotechnology-based reinforcement strategies further offer the potential to improve stiffness, fatigue resistance, and interlayer adhesion characteristics of recycled polymers.

The present study establishes a preliminary aero-structural simulation framework for evaluating wind turbine blade substructures using COMSOL Multiphysics. A cantilever

blade section incorporating an internal I-section shear web was analyzed under a freestream airflow velocity of 25 m/s using aluminum as a baseline validation material. The study integrates computational fluid dynamics (CFD), structural finite element analysis (FEA), modal analysis, and Python-based automation of post-processing results.

Furthermore, the study investigates the future potential of applying recycled plastics, additive manufacturing methodologies, and nanotechnology reinforcement concepts to sustainable wind turbine blade substructures. The developed workflow serves as a scalable foundation for future comparative studies involving HDPE, PP, PET, and GFRP materials.

II. LITERATURE REVIEW

The structural design of wind turbine blades has been extensively studied, with fiberglass-reinforced polymer (GFRP) composites emerging as the dominant material due to their high stiffness-to-weight ratio, fatigue resistance, and durability under cyclic aerodynamic loading. Mishnaevsky Jr. et al. provide a comprehensive overview of wind turbine blade materials, emphasizing that while composite systems are structurally efficient, they pose critical challenges related to recyclability and end-of-life disposal [1]. As the global installed wind capacity increases, blade waste management has become a growing concern.

Recent research has explored thermoplastic composites as potential alternatives to conventional thermoset-based systems. Cheng et al. reviewed thermoplastic composite materials for wind turbine blade applications and highlighted their advantages in terms of recyclability and processing flexibility [2]. However, their widespread adoption remains limited due to high material costs, manufacturing complexity, and the need for specialized processing infrastructure.

In parallel, significant research efforts have focused on recycling strategies for wind turbine blades and plastic waste. Tayebi et al. examined recycling pathways for wind turbine blades and concluded that current technologies are largely energy-intensive and economically constrained [3]. Rathore et al. similarly reviewed environmental impacts and recycling technologies, emphasizing the importance of developing alternative material pathways that allow waste integration into new engineering applications rather than downcycling [4]. These studies reinforce the need for innovative approaches that combine waste management with functional structural use.

Finite element analysis (FEA) has become a key tool for evaluating wind turbine blade performance under complex loading conditions. Zhang and Chen demonstrated the importance of advanced structural modeling for predicting fatigue damage and structural response under uncertain wind loads [5]. Zhupanska and Hu further highlighted that integrated aerodynamic–structural analysis is essential for accurate stress prediction and life assessment of blade components [6]. These works establish FEA as a reliable framework for assessing novel materials prior to experimental validation.

Additive manufacturing has recently emerged as a promising enabler for sustainable material utilization in structural applications. Jensen et al. demonstrated the feasibility of recycling wind turbine blade materials into reinforced filaments suitable for fused deposition modeling, illustrating the potential for circular material systems [7]. Lagos et al. reviewed advances in polymer-based additive manufacturing and identified its suitability for lightweight structural components, while also emphasizing challenges related to anisotropy and reduced mechanical performance compared to conventional manufacturing methods [8].

Despite these advances, limited literature exists on the combined evaluation of recycled plastics, additive manufacturing design constraints, aerodynamic loading, and automated finite element post-processing for wind turbine blade components. In particular, the application of recycled plastics to secondary blade substructures such as shear webs remains underexplored. This study addresses this gap by integrating recycled material assessment, COMSOL-based structural analysis, and Python-automated workflows to evaluate the feasibility of sustainable shear web designs.

III. MATERIALS AND GEOMETRY

This study adopts a simulation-driven methodology to evaluate the feasibility of recycled plastic materials for shear web applications in wind turbine blades. The workflow integrates material selection, aerodynamic load estimation, structural finite element analysis, Python-based automation, and additive manufacturing design considerations.

A. Material Selection

Plastic waste streams commonly observed in urban regions such as Chennai were reviewed to identify candidate materials suitable for structural evaluation. Based on availability, recyclability, and mechanical properties reported in literature, the following thermoplastics were considered:

- High-Density Polyethylene (HDPE)
- Polypropylene (PP)
- Polyethylene Terephthalate (PET)

Among these, HDPE and PP were selected for detailed analysis due to their widespread availability and compatibility with fused deposition modeling. Conventional glass fiber reinforced polymer (GFRP) was used as a benchmark material for comparative evaluation. Representative mechanical properties used in the simulations are summarized in Table I.

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Table 1: Mechanical Properties of Materials Used in Structural Analysis

Material	Young's Modulus (GPa)	Tensile Strength (MPa)	Density (kg/m³)	Poisson's Ratio
Aluminium	70	250	2700	0.33
HDPE	0.8	25	950	0.4
PP	1.5	35	900	0.4
PET	2.5	60	1380	0.38
GFRP	35	600	1900	0.25

B. Blade Section Geometry

A representative wind turbine blade section was modeled using a standard NACA-series airfoil profile. The selected section included an internal single shear web connecting the pressure and suction sides of the blade shell. The geometry was simplified to focus on load transfer behavior while maintaining realistic blade proportions. The spanwise length of the modeled section was limited to one meter to reduce computational cost while preserving structural relevance.

The shear web was modeled as a simplified I-beam structure positioned at 35% of the chord length. The geometry consists of a vertical web and top and bottom flanges to improve bending stiffness and load transfer. This configuration provides a more realistic representation of internal blade structures while maintaining computational simplicity.

Blade Section Details:

Airfoil Profile selected : NACA 4414
Chord Length: 1 m
Spanwise section length: 0.5 m
Shell Thickness: 4mm

Shear Web Dimensions: I-section at 0.35 m of chord from Leading Edge

Top and Bottom flanges: 6 mm thickness 50 mm width
Vertical Web: 10 mm thickness and 130.8 mm height

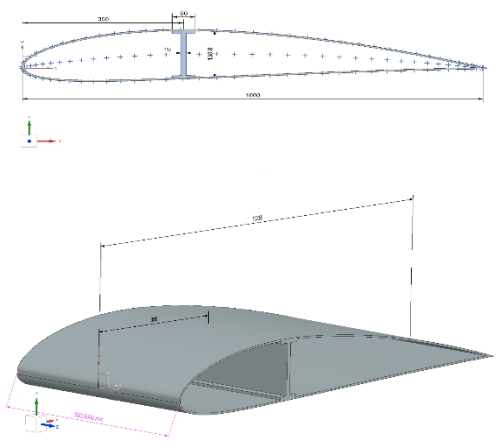


Figure 1 Geometry of Blade Profile

IV. AERODYNAMIC AND STRUCTURAL ANALYSIS USING COMSOL

In this study, a preliminary aerodynamic and structural analysis was performed using aluminum as a baseline material to validate the workflow and establish reference behavior. A representative wind turbine blade section with a cantilever support at the root was analyzed under a freestream airflow of 25 m/s using the CFD and Structural Mechanics modules in COMSOL Multiphysics.

A. Aerodynamic Analysis

Aerodynamic analysis of the blade section was performed using the CFD module in COMSOL Multiphysics to estimate pressure distribution under representative operating conditions. A one-way fluid–structure interaction approach was adopted, where aerodynamic pressure loads obtained from CFD simulations were transferred to the structural model for stress analysis.

A three-dimensional computational fluid domain was created around the blade section based on the NACA 4414 airfoil geometry. The fluid domain dimensions were selected to minimize boundary effects, extending five chord lengths upstream and vertically from the airfoil and ten chord lengths downstream.

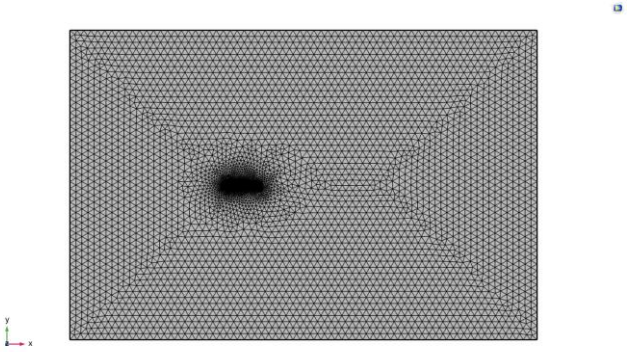


Figure 2 CFD computational domain

Air was modeled as an incompressible fluid with density $\rho = 1.225\, kg/m^3$ and dynamic viscosity μ=1.81×10−5Pa·s. A uniform inlet velocity of 25 m/s was applied at the upstream boundary to represent moderate wind operating conditions. The downstream boundary was defined as a pressure outlet with zero gauge pressure.

The turbulence effects were modeled using the k–ω SST turbulence model, which provides improved accuracy for boundary layer prediction and external aerodynamic flows over airfoil geometries.

The blade surface was treated as a no-slip wall condition. A refined mesh with boundary layer inflation elements was generated near the airfoil surface to accurately capture pressure gradients and flow behavior.

Steady-state simulations were performed until convergence criteria for residuals and aerodynamic coefficients were satisfied. The resulting pressure contours and streamline distributions were extracted and used to

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evaluate aerodynamic loading characteristics.

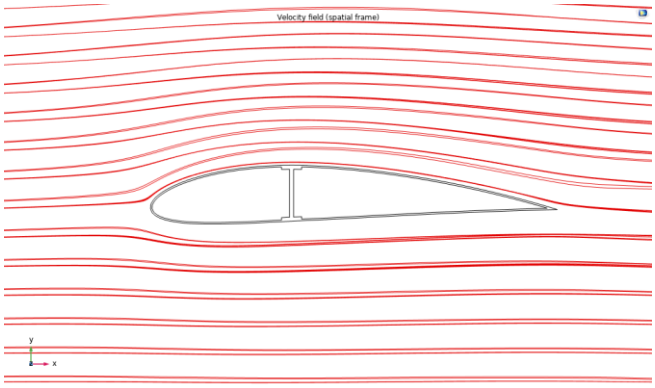


Figure 3 Velocity Field (spatial frame)

The CFD results indicated pressure concentration near the leading edge and accelerated flow over the suction surface, producing realistic lift-generating behavior consistent with airfoil aerodynamic theory.

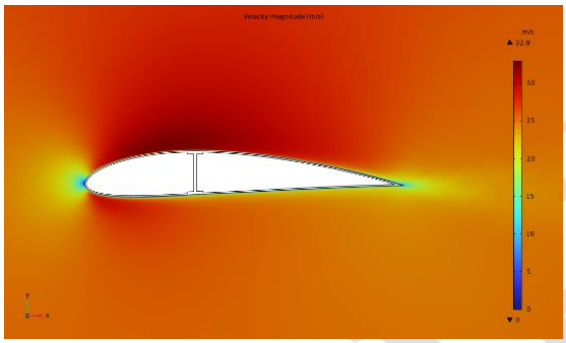


Figure 4 Velocity Magnitude, Max value = 32.9 m/s

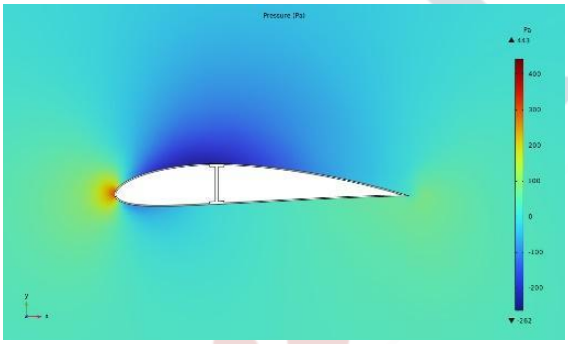


Figure 5 Pressure Plot, Maximum value 443 Pa

Future work will extend these analyses to HDPE, PP, PET, and GFRP, enabling comparative evaluation of aerodynamic–structural response among recycled plastics

B. Structural Analysis

The blade section was modeled as a cantilever with a fixed root. Aluminum properties were assigned (E = 70 GPa, ρ = 2700 kg/m³). Aerodynamic pressure loads were applied to evaluate deformation, stress, and safety factors. A tetrahedral mesh with refinement at critical regions (root and shear web junctions) was used, and mesh convergence was verified.

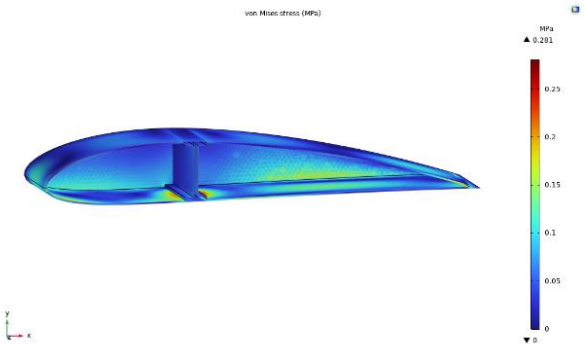


Figure 6 Von Mises stress distribution – Max = 0.281 MPa

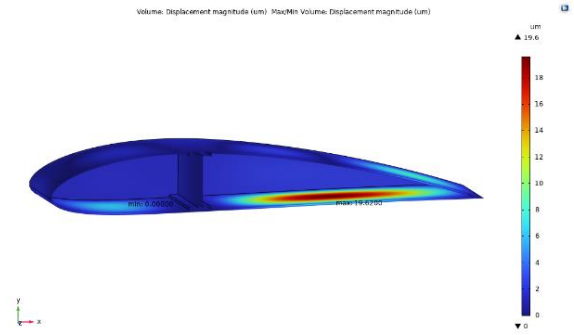


Figure 7 Displacement, Max 19.6 um

Results for aluminum served as a reference baseline, allowing future comparisons with recycled plastics once simulations for HDPE, PP, PET, and GFRP are completed.

C. Modal Analysis

Modal analysis was performed using the Eigenfrequency study in COMSOL Multiphysics to evaluate the dynamic characteristics of the cantilever blade section.

The same geometric configuration, mesh, and boundary conditions used in the structural analysis were retained for modal evaluation. The root section was constrained with a fixed support condition while the remaining structure remained free.

The current span considered is only 0.5 m and hence the results are limited. Further study will include a more realistic modelling of the blades and the first six eigen modes will evaluate:

- Natural frequencies
- Bending behavior
- Torsional response
- Dynamic stability characteristics

The governing eigenvalue equation for free vibration analysis is expressed as:

$$[K-\omega 2M]\phi=0$$

where: K = global stiffness matrix
M = global mass matrix
ω = natural circular frequency
ϕ = mode shape vector

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The modal analysis provides insight into vibration susceptibility and structural stability under operational conditions. Future work will investigate how recycled plastics influence natural frequencies and modal response behavior compared to the aluminum baseline.

Table 2: First Six Natural Frequencies for Aluminum Baseline

Mode	Natural Frequency (Hz)
1	111.79 Hz
2	174.04 Hz
3	206.51 Hz
4	232.78 Hz
5	252.81 Hz
6	299.14 Hz

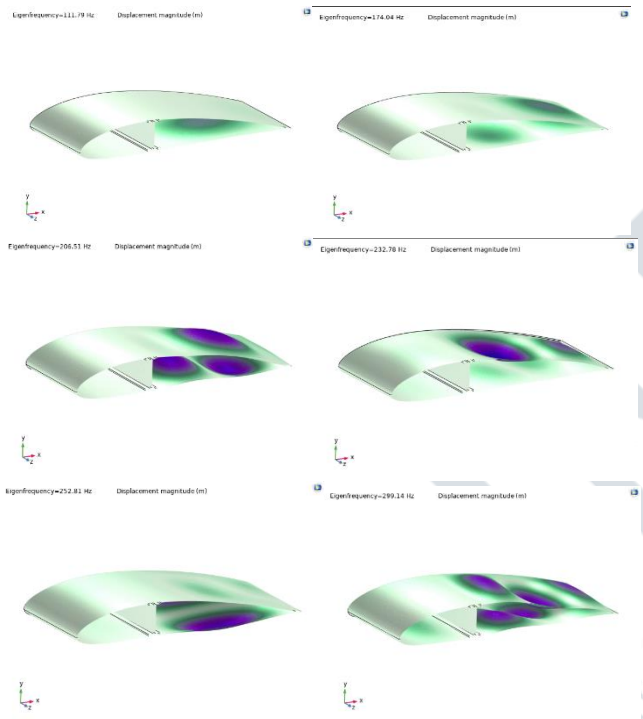


Figure 8 Comparison of the first six natural frequencies for the aluminum baseline configuration

V. PYTHON-BASED AUTOMATION OF POST-PROCESSING RESULTS

A Python-based automation framework was developed to automate post-processing of simulation results exported from COMSOL Multiphysics.

The framework currently processes aluminum baseline results and will later be expanded for comparative analysis of HDPE, PP, PET, and GFRP materials.

Python Automation Workflow

1. Export simulation results from COMSOL
2. Read exported CSV files
3. Extract structural and modal parameters
4. Generate automated plots
5. Create summary tables

Python Code for Automated Post-Processing

```
#python
import pandas as pd
import matplotlib.pyplot as plt

# Aluminum yield strength
yield_strength = 250 #MPa

# Read simulation results
data = pd.read_csv('Stressplot.csv')
data1 = pd.read_csv('dispplot.csv')

print("data read successfully:")
stress =  data.iloc[:, 3].max()
print('max stress',stress)
deformation = data1.iloc[:, 3].max()
#frequency = data['Natural_Frequency_Hz']

# Safety factor
sf = yield_strength / stress

# Add to dataframe
data['Safety_Factor'] = sf

print('factor of safety:', sf)

# Stress plot
plt.figure(figsize=(6,4))
plt.bar(['Aluminum'], stress)
plt.ylabel('Stress (MPa)')
plt.title('Maximum Stress')
plt.grid(True)
plt.show()

# Deformation plot
plt.figure(figsize=(6,4))
plt.bar(['Aluminum'], deformation)
plt.ylabel('Deformation (um)')
plt.title('Maximum Deformation')
plt.grid(True)
plt.show()
```

The above python code generated maximum stress and displacement plots in line with the COMSOL results, validating the code. Hence, the code can further be used to calculate the factor of safety. In this case, it is 748, which is very high due to the simplistic modelling.

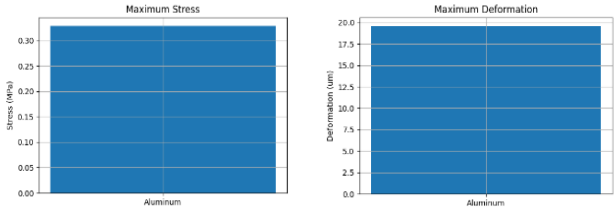


Figure 9 Python results matching COMSOL

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The automation framework reduced post-processing time and improved repeatability of result extraction and visualization.

VI. ADDITIVE MANUFACTURING DESIGN FEASIBILITY

The feasibility of producing internal shear web structures using fused deposition modeling (FDM) was evaluated conceptually for HDPE, PP, and PET materials.

Although structural simulations were currently limited to aluminum baseline analysis, additive manufacturing considerations were incorporated to guide future plastic-based implementations.

Table 3: FDM Design Parameters for Recycled Plastics

Parameter	HDPE	PP	PET
Nozzle Temperature (°C)	220–250	210–240	240–260
Bed Temperature (°C)	90–120	80–100	70–90
Infill Density (%)	40–60	40–70	50–80
Layer Height (mm)	0.2–0.3	0.2–0.25	0.1–0.2
Warping Tendency	High	Moderate	Low
Interlayer Adhesion	Moderate	Good	Very Good

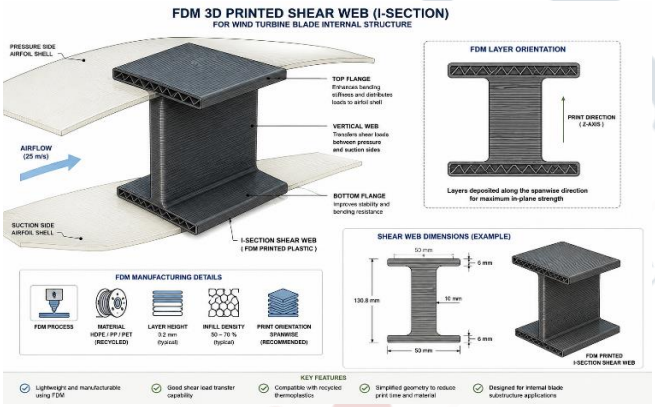


Figure 10 Conceptual FDM shear web diagram with plastics

VII. NANOTECHNOLOGY INTEGRATION POTENTIAL

Nanotechnology-based reinforcement approaches were evaluated conceptually as a future enhancement strategy for recycled plastics used in wind turbine blade substructures.

Potential nanomaterials include:

- Carbon nanotubes (CNTs)
- Graphene nanoplatelets
- Nano-silica
- Nanoclay additives

Table 4: Estimated Nanomaterial Performance Improvements

Nanomaterial	Modulus Improvement	Strength Improvement
CNT	30–70%	25–60%
Graphene	25–60%	20–50%
Nano-silica	15–35%	10–25%
Nanoclay	10–30%	10–20%

Future work will integrate these nanomaterials into HDPE, PP, and PET simulations to evaluate their influence on stiffness, deformation resistance, and modal behavior.

VIII. RESULTS

Currently, results are only for aluminum baseline:

Table 5: Structural Response Table

Parameter	Aluminum
Max Deformation (um)	19.6
Max Stress (MPa)	0.281
Safety Factor	748
First 6 Eigen Frequencies (Hz)	111.79, 174.04, 206.51, 232.78, 252.81, 299.14

Future Work will add similar overview for HDPE, PP, PET, and GFRP for direct comparison.

IX. DISCUSSION

The aluminum baseline demonstrates the workflow's feasibility for:

- CFD and it's corresponding Structural load transfer
- Modal analysis of first six eigen modes
- Python automation of post-processing
- Additive manufacturing design considerations

Insights from aluminum provide a reference for evaluating plastics in future work. Expected observations:

Plastics will exhibit higher deformation and lower natural frequencies compared to aluminum

PET likely to perform best among plastics in stiffness and vibration response

AM feasibility will vary due to warping and layer adhesion properties

The workflow confirms that this methodology is suitable for future comparative studies of recycled plastics

X. CONCLUSIONS

This preliminary study used aluminum as a baseline material for a cantilever wind turbine blade section subjected to a 25 m/s airflow. Key outcomes:

- CFD-generated pressure distributions were successfully mapped to structural analysis
- Structural and modal analysis of aluminum validated the simulation workflow
- Python automation efficiently processed results and generated plots and tables

- Conceptual additive manufacturing and nanotechnology assessments were established for future application to plastics

Future work will extend the analysis to HDPE, PP, PET, and GFRP to compare aerodynamic, structural, and dynamic performance. Include numerical evaluation for AM and nanomaterial reinforcement, enabling a comprehensive assessment of recycled plastics in wind turbine shear webs.

REFERENCES

[1] L. Mishnaevsky Jr., K. Branner, H. N. Petersen, J. Beauson, M. McGugan, and B. F. Sørensen, "Materials for wind turbine blades: An overview," *Materials*, vol. 10, no. 11, p. 1285, 2017.

[2] X. Cheng, Y. Liu, and Z. Wang, "A review of thermoplastic composites for wind turbine blade applications," *Compos. Sci. Technol.*, vol. 247, pp. 110345, 2025.

[3] S. T. Tayebi, A. R. Karimi, and M. Rezaei, "Waste management of wind turbine blades: Recycling pathways and challenges," *Sustainability*, vol. 16, no. 11, p. 4517, 2024.

[4] N. Rathore, S. Sharma, and A. Gupta, "Environmental impact and recycling technologies for wind turbine blades," *Waste Manag. Res.*, vol. 41, no. 2, pp. 123–140, 2023.

[5] C. Zhang and H.-P. Chen, "Monitoring-based fatigue damage prognosis of wind turbine composite blades under uncertain wind loads," *arXiv preprint* arXiv:2404.10021, 2024.

[6] O. I. Zhupanska and W. Hu, "Integrating variable wind load, aerodynamic, and structural analyses towards fatigue life prediction in composite wind turbine blades," *Struct. Multidiscip. Optim.*, vol. 53, no. 4, pp. 875–892, 2016.

[7] J. P. Jensen, M. Skjold, and A. Villumer, "Recycling of fiberglass wind turbine blades into reinforced filaments for additive manufacturing," *Compos. Part B*, vol. 145, pp. 157–165, 2019.

[8] F. Lagos, R. Navarro, and P. Torres, "Recent advances in polymer-based additive manufacturing for structural applications," *Polymers*, vol. 17, no. 17, p. 2339, 2025.