# Flight-Ready 3D-Printed Composite Fins:
## Structural and Vibration Analysis for Aerospace Innovation

D. Siebert, A. Tcharkhtchi, H. R. Vanaei

*Abstract*—**The demand for lightweight and high-performance components in the aerospace sector has driven the adoption of Additive Manufacturing technologies. Among several materials, polyamide 12 reinforced with carbon fibers (PA12-CF) offers a promising balance of mechanical strength, thermal stability, and printability, making it suitable for flight-ready components. This study investigates the structural performance of 3D-printed PA12-CF fins for rocket applications through a combination of experimental characterization and analytical modeling. Tensile, fatigue, and dynamic mechanical analysis tests were performed to establish the static and dynamic properties of the material. Modal and vibrational simulations, based on beam theory, were conducted to predict bending and torsional frequencies and to evaluate potential resonance with aerodynamic vortex shedding. Results show that PA12-CF provides superior stiffness and fatigue resistance compared to standard AM polymers, while dynamic analysis identifies critical frequency ranges requiring careful attention. Estimated vibration intensities indicate significant but manageable accelerations during flight. The study proposes that PA12-CF is a suitable material for aerospace-grade AM in laboratory scale, with future validation recommended through finite element analysis, computational fluid dynamics, and flight testing.**

*Keywords*—**Additive Manufacturing, Aerospace, 3D Printing, Composite, Modal simulation.**

## I. Introduction

In recent years, Additive Manufacturing (AM) has emerged as a disruptive technology across multiple industrial sectors, with the aerospace industry among the most promising fields of application [1-3]. The possibility of producing complex geometries directly from digital models without the constraints of traditional tooling has opened new horizons for the design of lightweight, optimized, and cost-effective components [4, 5]. In particular, the aerospace domain benefits greatly from weight reduction, as even marginal decreases in structural mass can result in substantial savings in fuel consumption and improvements in payload capacity. Moreover, AM significantly accelerates the prototyping cycle, allowing engineers to iterate designs rapidly and test new configurations in real operating conditions [6].

One application where AM shows great potential is the fabrication of rocket fins, which play a critical role in flight stability and aerodynamic performance. Rocket fins are responsible for maintaining trajectory alignment and mitigating perturbations during ascent, ensuring mission success and safety [7]. However, these components are subjected to severe thermo-mechanical and dynamic loads: aerodynamic heating due to high velocity flow, high mechanical stresses from inertial and aerodynamic forces, and vibrational excitations linked to vortex shedding and structural resonance. Designing fins capable of withstanding these conditions requires not only innovative geometrical solutions but also the careful selection of advanced materials tailored for both performance and manufacturability.

Traditionally, aerospace fins have been fabricated from metals such as aluminum alloys or high-performance composites processed via autoclave methods [8]. While these materials exhibit excellent mechanical strength and thermal resistance, their processing routes are costly, time-consuming, and less flexible when rapid prototyping is required. In contrast, 3D printing with thermoplastic polymers offers an attractive alternative, especially for experimental rocketry and small launch systems, where production agility and cost-effectiveness are decisive factors. However, a major limitation remains a challenge as conventional polymers such as ABS, PLA, PET-G, or ASA lack the thermal stability and structural rigidity necessary for high-speed aerospace applications [9]. For example, PLA exhibits relatively high stiffness but suffers from a low glass transition temperature, making it unsuitable under aerodynamic heating. ABS and ASA provide better toughness but are limited by thermal resistance (~100–105 °C). Even more advanced materials like polycarbonate (PC) or thermoplastic copolymers (TPC) offer only partial solutions, often requiring compromises between processability, flexibility, and long-term fatigue performance.

To overcome these limitations, research has increasingly focused on fiber-reinforced thermoplastics. These materials combine the ease of processing associated with polymers and the enhanced mechanical performance imparted by short or continuous fibers. Among them, Polyamide 12 reinforced with carbon fibers (PA12-CF) has emerged as a particularly promising candidate for aerospace-grade additive manufacturing [10]. PA12 offers intrinsic advantages such as low moisture absorption, good dimensional stability, and excellent compatibility with powder-bed fusion and extrusion-based processes. The addition of carbon fibers significantly increases Young's modulus, tensile strength, and thermal stability, making

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PA12-CF a strong candidate for structural parts subjected to severe loading.

Despite these promising attributes, the aerospace implementation of PA12-CF requires thorough validation [11]. In addition to static strength, dynamic behavior and fatigue resistance are crucial, as rocket fins are subjected to oscillatory loads that can trigger resonance phenomena, leading to structural failure. In particular, interactions between modal frequencies of the fin structure and aerodynamic excitations such as vortex shedding must be carefully analyzed. Understanding these complex phenomena necessitates both experimental material characterization and numerical vibrational analysis.

The objective of this study is to assess the suitability of PA12-CF for 3D-printed aerospace fins by bridging experimental characterization with predictive simulations. The results will not only clarify its potential for experimental rocketry but also pave the way for broader use of 3D-printed reinforced thermoplastics in next-generation aerospace systems, where performance, reliability, and manufacturability must be balanced.

## II. Materials and Methods

### A. Materials

The material investigated in this study is polyamide 12 reinforced with 15 wt.% carbon fibers (PA12-CF15), processed in filament form for extrusion-based AM.

Filaments were printed into standard specimens using a controlled extrusion-based 3D printing process. Printing parameters, such as nozzle temperature, layer height, and infill density, were optimized to minimize porosity and anisotropy. Specimens were conditioned prior to testing to limit humidity effects, which can otherwise impact the mechanical response of polyamide-based materials.

### B. Experimental Methodologies

Tensile tests were carried out according to the ASTM D638 Type IV standard on dog-bone specimens printed along the loading direction. The tests were performed under quasi-static conditions, and the tensile modulus, tensile strength, and elongation at break were measured. Fatigue behavior was evaluated using the same standard specimen subjected to tension–tension loading with a stress ratio of 0.1 at various frequencies, 10, 20, 30, 40, and 50 Hz. Different maximum stress levels, corresponding to 60%, 50%, and 40% of the ultimate tensile strength, were applied to establish S–N curves. Dynamic mechanical analysis was performed in a three-point bending configuration between 30 °C and 150 °C at multiple frequencies. The storage modulus, loss modulus, and damping factor were recorded as a function of temperature, allowing identification of the glass transition temperature and viscoelastic behavior.

### C. Numerical Approaches

To complement the experimental characterization, structural simulations were carried out using ANSYS® to evaluate the dynamic response of 3D-printed fins manufactured from PA12-CF (Fig. 1). The fins were modeled as cantilever beams attached to the rocket body, with a length of 300 mm, a chord length of 250 mm, a thickness of 8 mm, four fins in total, and a rocket body diameter of 154 mm.

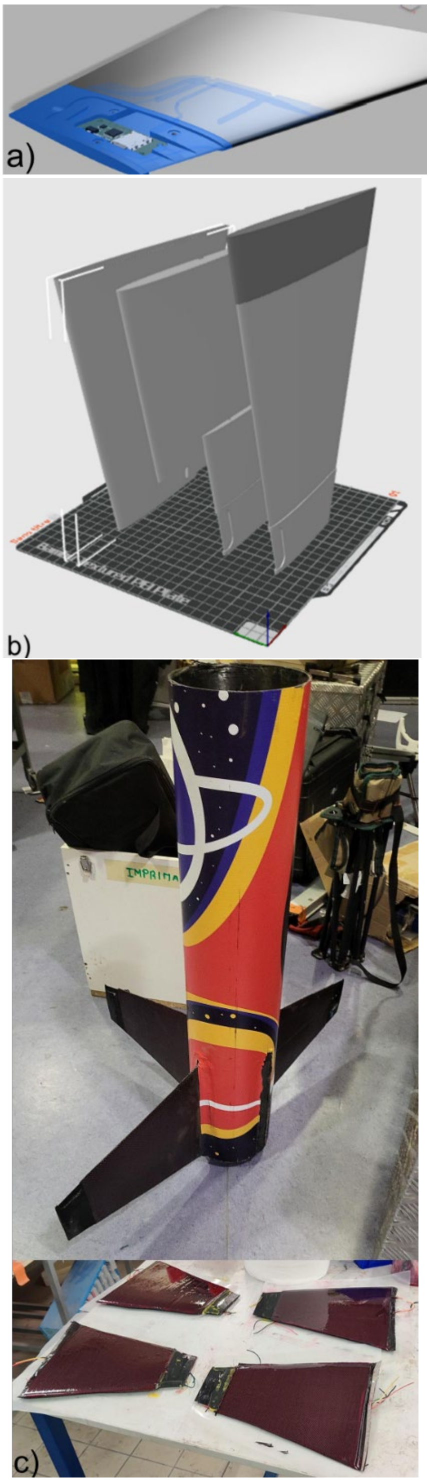



Fig. 1. Representation of 3D-printed Fins: a) 3D model with the sensor for vibrational measurement, b) 3D model in 3D-printer software, and b) 3D printed parts.

The bending modal frequencies were calculated using classical beam theory for a cantilever, expressed as:

$$f_n = \frac{\beta_n^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \qquad (1)$$

where $\beta_n$ are the modal constants (1.875, 4.694, 7.855 for the first three modes), $E$ is the Young's modulus, $I$ the area moment of inertia, $\rho$ the density, and $A$ the cross-sectional area.

For torsional resonance, the frequency was estimated as:

$$f_{torsion} = \frac{1}{2\pi}\sqrt{\frac{GJ}{\rho A L^2}} \quad (2)$$

with $G$ the shear modulus and $J$ the torsional constant of the section.

In addition, aerodynamic excitation frequencies due to vortex shedding were determined from the Strouhal relation:

$$f_v = St \cdot \frac{V}{D} \quad (3)$$

where $St=0.2$ is the Strouhal number, $V=172\ m/s$ the freestream velocity, and $D=0.25$ m the chord length.

Comparisons between the structural modal frequencies and vortex shedding frequency allow the identification of possible resonance risks. The corresponding vibrational accelerations were then estimated from aerodynamic forces to evaluate the dynamic loading intensity experienced by the fins during flight using implemented sensors.

This combined experimental–numerical methodology provides both fundamental material properties and applied structural predictions, enabling a comprehensive assessment of the suitability of PA12-CF for 3D-printed aerospace fins.

## III. Results and Discussions

### A. Tensile Properties

The tensile results are presented in Fig. 2. The stress-strain responses obtained from the three specimens exhibited a high degree of repeatability, confirming the reliability of the material and the printing process. The curves consistently showed a linear elastic region up to the yield point, followed by limited plastic deformation before failure. The measured Young's modulus was approximately 7.3 GPa, in close agreement with manufacturer data, while the ultimate tensile strength reached around 70 MPa. The elongation at break remained relatively low, reflecting the stiffening effect of carbon fiber reinforcement.

The similarity between the three curves highlights the reproducibility of PA12-CF tensile behavior and confirms that fiber reinforcement provides consistent stiffness and strength across specimens. Compared to standard 3D printing materials demonstrated superior stiffness and load-bearing capacity, establishing its potential for aerospace applications where dimensional stability and structural integrity are critical.

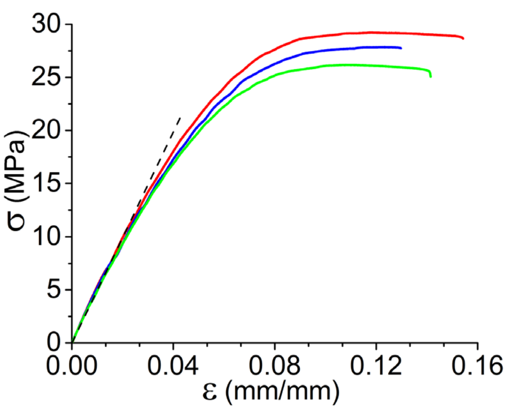



Fig. 2. Stress-Strain curves of the printed PA12-CF samples.

### B. Fatigue Behavior

The fatigue performance of PA12-CF was assessed under tension–tension cyclic loading with varying stress amplitudes and frequencies. The obtained Wöhler curves (Fig. 3) show the typical decrease of stress amplitude with increasing number of cycles, highlighting the progressive damage accumulation in the polymer–fiber microstructure.

A clear frequency dependence was observed. At low cycle regimes and high stress amplitudes, specimens tested at higher frequencies (30, 40, and 50 Hz) exhibited lower fatigue life compared to those tested at lower frequency (10 Hz). This effect can be attributed to reduced time for damage initiation and crack growth per cycle when loading is applied more rapidly. Conversely, in the high cycle regime (above $10^4$-$10^5$ cycles) and under low stress amplitudes, the effect of frequency on life-cycle is negligible. This inversion is likely linked to self-heating effects and viscoelastic dissipation at high stress amplitudes, which accumulate at higher frequencies and accelerate degradation over short durations.

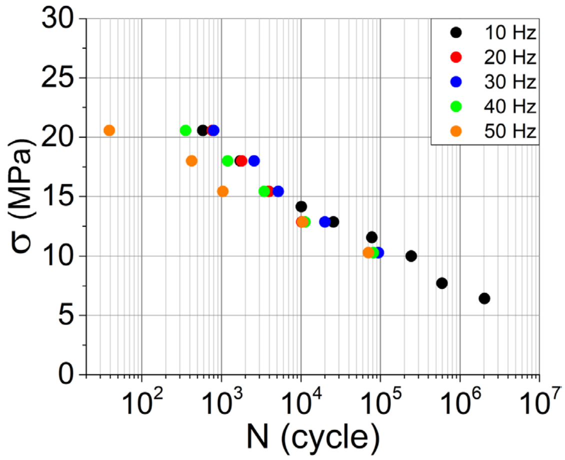


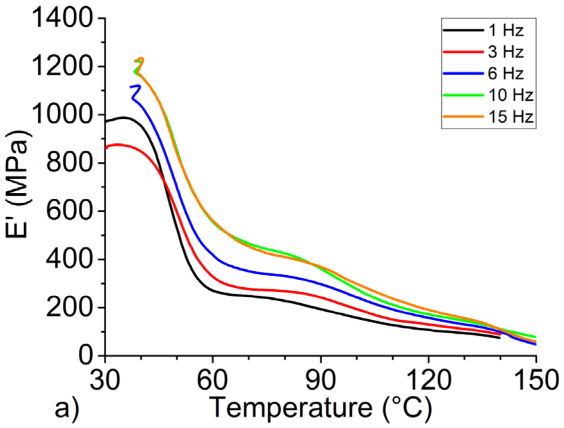

Fig. 3. Wöhler curve of the 3D-printed specimens subjected to fatigue test at different frequencies.

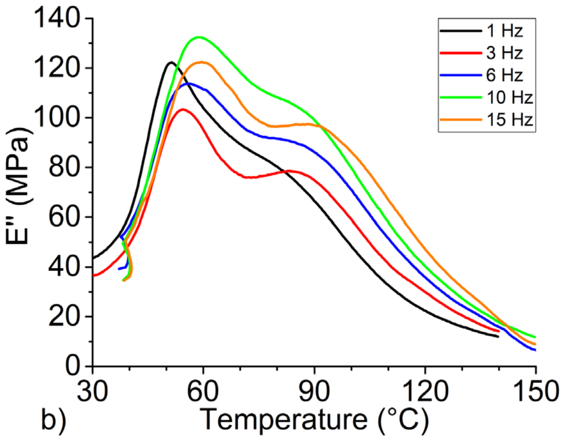
Give the above-mentioned results, a significant fatigue endurance observed with specimens surviving up to $10^6$ cycles at stress amplitudes around 8–10 MPa. The presence of carbon fibers plays a key role in delaying crack propagation and stabilizing the fatigue response compared to unreinforced PA12. However, the dual influence of frequency highlights that service conditions must be carefully considered. These findings demonstrate the potential of using composites such as PA12-CF for aerospace components subjected to vibrational loads, provided that operational stress levels remain below the endurance limit and that thermal and frequency effects are taken into account in the design.

### C. Dynamic Mechanical Analysis

DMA results provide key insights into the viscoelastic response of PA12-CF over a range of frequencies and temperatures are shown in Fig. 4. The storage modulus (E′) remained high at low temperatures, confirming the stiffness and structural stability of the composite. A sharp decline in modulus was observed in the vicinity of the glass transition temperature (Tg=45–55°C), consistent with the softening of the polyamide matrix. Importantly, the frequency dependence is evident: at higher frequencies (10 and 15 Hz), the storage modulus maintained higher values compared to lower frequencies (1 and 3 Hz), reflecting the time-dependent relaxation mechanisms of the polymer matrix constrained by carbon fibers. The loss modulus (E″) curves exhibited clear peaks in the $T_g$ region, associated with molecular mobility and energy dissipation. These peaks shifted slightly with frequency, indicating that higher frequencies delayed the onset of segmental relaxation, a common feature of viscoelastic polymers. The magnitude of the peaks also varied, with higher frequencies showing broader loss responses, which suggests stronger frictional effects between the polymer chains and the embedded carbon fibers.

The tan δ (E″/E′) curves further highlighted the damping behavior. The primary tan δ peak, shifted marginally to higher temperatures with increasing frequency, illustrating the frequency-temperature superposition principle. Peak intensity decreased with frequency, consistent with the stiffening effect of carbon fibers, which restrict chain mobility and reduce damping capacity. Nevertheless, even with reduced damping, PA12-CF retained measurable energy dissipation, a property beneficial for mitigating vibrational stresses during dynamic loading.



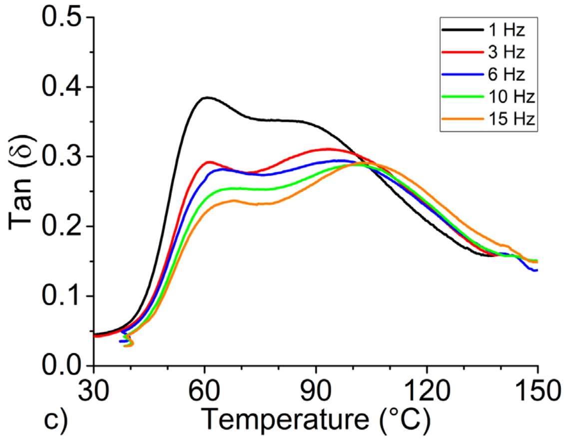




Fig. 4. DMA results at different frequencies: a) Storage modulus, b) Loss modulus, and c) Damping factor (Tan δ).

These observations confirm that PA12-CF maintains rigidity at $T_g$ while exhibiting frequency-dependent viscoelasticity in the transition region. These characteristics imply that the material is suitable for aerospace applications, provided that operating conditions remain above the $T_g$ and that frequency effects on stiffness and damping are accounted for in the design.

### *D. Modal Analysis of Fin Structures*

The numerical simulations performed on 3D-printed fins provided a detailed picture of their vibrational behavior as shown in Fig. 5. For a fin with dimensions 300 mm × 250 mm × 8 mm, the first three bending mode frequencies were calculated as $f_1 \sim 18.6$ Hz, $f_2 \sim 116.6$ Hz, $f_3 \sim 326.4$ Hz.

The torsional resonance frequency was found to be approximately 68.4 Hz. These values, derived from classical beam theory, fall within the range expected for lightweight aerospace appendages. When compared to the aerodynamic vortex shedding frequency ($f_v \sim 137.6$ Hz for a freestream velocity of 172 m/s), it appears that the second bending mode lies close to the excitation frequency. This proximity indicates a potential resonance risk, which could amplify vibrational amplitudes during flight. Such a finding emphasizes the need for careful design optimization and experimental flight validation.

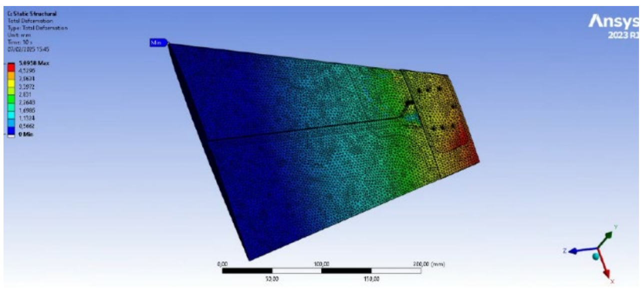



Fig. 5. Simulation results on the fin structure.

### *E. Dynamic Load Estimations*

Using aerodynamic force estimates, the maximum accelerations associated with vibrational modes were found to be:

- Bending acceleration ~ 5.7 g
- Torsional acceleration ~ 4.4 g

These values confirm that 3D-printed fins experience substantial dynamic loads, which could lead to fatigue damage or flutter phenomena if not properly managed. The relatively high fatigue resistance of PA12-CF demonstrated in previous section is therefore essential to ensure structural durability under these cyclic stresses.

### *F. Discussion*

The combination of experimental and numerical findings provides a coherent assessment of PA12-CF for aerospace applications. The material shows superior tensile and fatigue properties compared to standard 3D printing polymers, ensuring that fins can withstand both static and cyclic stresses. DMA results highlight the importance of thermal effects, suggesting that operational environments must remain above $T_g$ to avoid stiffness degradation.

A key outcome of the DMA study is the demonstration that the storage modulus and damping factor are both frequency- and temperature-dependent. This means that the effective stiffness used in simulations should not be treated as constant, but rather adjusted according to $E'(T,\omega)$. For instance, at approximately 40 °C, the storage modulus is about 1.2 GPa, but it decreases to 0.4 GPa at 85 °C, which would lower predicted modal frequencies by nearly 40%. Likewise, damping values derived from tan $\delta$ translate into modal damping ratios $\zeta$ in the range of 0.03–0.18, depending on temperature and excitation frequency, offering a more realistic input for vibration simulations.

From the structural perspective, modal analysis reveals possible resonance interactions with vortex shedding, a factor that should be addressed through either geometry optimization (e.g., fin tapering, modified thickness) or damping enhancement strategies. Incorporating the DMA-derived properties into the modal model highlights that resonance proximity is even more critical when the fins operate near $T_g$ or at high excitation frequencies, since both stiffness reduction and increased damping strongly affect the dynamic response.

The integration of mechanical testing, viscoelastic characterization, and vibrational simulations demonstrates that a composite such as PA12-CF is a viable candidate for 3D-printed rocket fins, provided that resonance risks are mitigated through design and validated through flight experiments. Future work should rely on time-temperature superposition (WLF shift factors) to extend DMA data toward the 100–150 Hz range of aerodynamic excitations, enabling even more accurate predictions.

## IV. Conclusion

This study investigated the suitability of PA12-CF composite for the Additive Manufacturing of aerospace structures, with a focus on rocket fins subjected to demanding thermo-mechanical and dynamic conditions. A combined experimental–numerical approach was adopted, including tensile, fatigue, and DMA testing, complemented by structural vibrational simulations.

The experimental results demonstrated that PA12-CF exhibits high stiffness and strength, with tensile performance significantly superior to conventional 3D printing polymers. Fatigue tests confirmed the material's ability to endure cyclic stresses, with an endurance limit that supports its use in vibrationally loaded components. DMA analysis revealed a stable storage modulus over a wide temperature range and identified a glass transition around 45–50 °C, while also showing frequency-dependent stiffness and damping. These findings provide essential input parameters for vibration modeling and emphasize the importance of considering operating temperature and excitation frequency in design.

Numerical modal analysis of representative fin geometries showed bending and torsional frequencies within ranges expected for lightweight appendages. Importantly, the second bending mode was found to be close to the vortex shedding frequency at flight velocities, indicating a potential resonance risk. When updated with DMA-derived modulus values, predicted modal frequencies decrease significantly near glass transition temperature, underscoring the need for careful evaluation of aeroelastic stability across temperature and frequency ranges. Aerodynamic load estimates confirmed that fins would experience accelerations on the order of 5–6 g, highlighting the need for robust design against flutter and fatigue-driven damage.

The results indicate that PA12-CF is a strong candidate for aerospace-grade additive manufacturing, particularly for experimental rocketry and lightweight structural applications. Its balance of strength, stiffness, and fatigue performance makes it superior to standard AM polymers, though resonance risks must be addressed through geometry optimization, damping strategies, and in-flight validation. Future work will focus on integrating Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) with DMA-based viscoelastic inputs for improved aeroelastic modeling, as well as on flight tests to validate predictions under real operating conditions. These steps are essential to advance the use of 3D-printed composites toward reliable, flight-ready aerospace components.

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