Title:
# Expanding Automated Fiber Placement Beyond Aerospace: Overcoming Geometric Limitations

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## Introduction:

Automated Fiber Placement (AFP) represents a critical paradigm shift in the manufacturing of high-performance composite structures, particularly within the aerospace, space, and defense sectors. By integrating the multi-tow dispensing and cut-restart capabilities of filament winding with the compaction and out-of-plane path adaptability of automated tape laying (ATL), AFP enables the fabrication of complex, doubly-curved, and highly load-bearing composite components. Unlike labor-intensive hand-layup techniques that are prone to human error, or conventional ATL processes constrained to low-curvature surfaces, AFP dynamically manipulates narrow slit-tapes (called tows with dimensions from 0.25 inches to 3 inches) to conform to complex tooling geometries. Comprehensive foundational insights into the status, engineering challenges, and technological evolution of these systems can be found in Harik and Brasington (2025) and via afpbook.com.

Despite these technological advancements, transitioning from Computer-Aided Design (CAD) surface definitions to physical robot toolpaths introduces significant geometric and physical challenges. High-curvature steering forces the fiber tow to bend within the plane of the layer, generating compressive stresses along the inner edge of the path and tensile stresses along the outer edge. When the inner compressive stress exceeds a critical threshold, out-of-plane buckling occurs, resulting in wrinkle defects that severely degrade the mechanical properties of the finished laminate. Consequently, robust mathematical modeling of the tooling geometry and corresponding fiber trajectories is essential to guarantee both the manufacturability and structural performance of AFP-produced components. Data from the U.S. Department of Energy (DOE) Advanced Manufacturing Office indicates that AFP systems are capable of increasing deposition speeds by 35% to 45% in large aerostructure programs. Industrial platforms routinely operate at linear speeds up to 4,000 in/min (101.6 m/min) during deposition and traverse, with cut and re-feed cycles occurring at 3,000 in/min (76.2 m/min) (Assadi & Field, 2020). This high-rate deposition reduces large aerostructure assembly cycle times by 20% to 35%, directly addressing the high-volume production rates demanded by single-aisle aircraft replacement programs and space launch cadences.

To address these geometric constraints systematically, Rousseau et al. (2019) previously established a comprehensive state-of-the-art review on AFP path planning, introducing an initial geometry benchmark in Section 6.1 to evaluate trajectory generation algorithms. This paper provides a simplified viewpoint of that geometrical benchmark. The primary objective of refining this framework is to evaluate and expand the manufacturing envelope of AFP beyond traditional aerospace applications and to create a benchmark geometry for tooling. Driving down the high capital and operational costs of AFP requires scaling the technology into broader commercial domains. While immediate high-volume adoption in sectors like the automotive industry remains limited by current cycle times and cost thresholds, establishing this updated geometric benchmark is a vital step toward making AFP a viable, cost-effective manufacturing paradigm for non-aerospace industries.

### Classification of Structural Geometries in AFP Research

To systematically analyze the mathematical and physical environments encountered in AFP research, the geometries utilized to demonstrate path planning, defect mitigation, and optimization are classified into five distinct structural groups. This classification highlights how structural requirements dictate the choice of mathematical representation and toolpath generation algorithms.

#### *Axisymmetric and Revolutionary Geometries*

Axisymmetric shells constitute the foundational shapes for aerospace pressure vessels, rocket motor casings, fuselages, and payload adapters, as found in Wang et al. (2023) and Rousseau et al. (2019). These structures are generated by rotating a flat meridional curve around a central axis of symmetry, as found in Wang et al. (2023). Because they can be parameterized analytically, these geometries serve as standard benchmarks for evaluating fiber steering limits, shell coverage strategies, and wrinkle-free path algorithms, as found in Blom et al. (2009) and Rousseau et al. (2019). The primary geometries in this class include cylinders, conical shells, and ellipsoidal domes, as found in Tatting (1998), Blom et al. (2008), and Wang et al. (2023). Conical and cylindrical surfaces are particularly valuable for testing the transition between geodesic (non-steered, curvature-free) paths and constant-angle steered paths, as found in Blom et al. (2009) and Rousseau et al. (2019). In conical shells, the varying radius along the longitudinal axis forces steered fibers to undergo severe steering variations to maintain a constant orientation, providing a clear mathematical environment for validating path deviation and compaction modeling, as found in Wang et al. (2021) and Blom et al. (2009).

#### *Toroidal and Transition Geometries*

As launch vehicle and aerospace designs transition from multi-piece assemblies to highly integrated, unitized structures, the industry has adopted single-piece conical-cylindrical shells connected by toroidal transitions, as found in Tillotson Rudd et al. (2024) and Tillotson Rudd et al. (2023). Toriconical and toroidal geometries are mathematically demanding because they exhibit localized high curvature and require synchronous multi-axis motion control to maintain the normal alignment of the compaction roller, as found in Tillotson Rudd et al. (2024) and Qu et al. (2022). Toroidal configurations are also prominent in fusion energy components—such as the massive ITER cryogenic pre-compression rings fabricated using AFP, as found in Rajainmaki et al. (2014)—and in automotive high-capacity hydrogen storage tanks, where the toroidal configuration optimizes spatial efficiency and load distribution, as found in Pérez et al. (2020) and Daghighi et al. (2024).

#### *Doubly-Curved and Aerostructural Surfaces*

Aircraft wings, spars, winglets, helicopter side-shells, and engine fan blades feature complex, non-axisymmetric double curvature, as found in Zenker et al. (2020), Gao et al. (2021), and Zhou et al. (2025). In these geometries, the local surface normal and Gaussian curvature vary continuously across the coordinate space, as found in Gao et al. (2021) and Wang et al. (2025). Standard analytical parametric descriptions are rarely available for these complex shapes; instead, industrial applications rely on discrete triangular mesh models derived from CAD files, as found in Bruyneel and Zein (2013) and Xiao et al. (2020). Path planning on these surfaces demands advanced mathematical solvers, such as Eikonal equation approximations solved via the Fast Marching Method (FMM) or Fast Sweeping Method (FSM), to generate parallel, equidistant courses that minimize the accumulation of gap and overlap defects, as found in Bruyneel and Zein (2013), Ke Xu et al. (2022), and Wang et al. (2025).

#### *Variable-Stiffness Laminates and Structured Plates*

Flat or slightly curved plates featuring open holes or cutouts serve as the standard benchmark for Variable Angle Tow (VAT) or variable-stiffness laminates, as found in Hyer and Lee (1991) and found in Zucco et al. (2021). By continuously steering the fiber path within the plane of a flat panel, engineers can tailor the local in-plane stiffness to redistribute stress concentrations away from cutouts, significantly enhancing the buckling and post-buckling performance of the structure, as found in Hyer and Charette (1991), found in Tosh and Kelly (2000), and found in Nik et al. (2014). The mathematical modeling of these panels involves parameterizing the fiber orientation field using B-splines, level set functions, or Hermite/Ferguson splines while simultaneously imposing curvature and parallel alignment penalties to ensure manufacturability, as found in Brampton and Kim (2013), found in Lemaire et al. (2015), and found in Zhang et al. (2023).

*Micro-Geometric Defect and Waviness Profiles*

At the micro-scale, AFP path planning and consolidation physics are modeled using localized wave geometries to capture process-induced defects. Due to the localized gaps or overlaps generated during tow-steering, subsequent layers consolidated over these imperfections undergo out-of-plane undulations. These micro-geometries are mathematically modeled as sine-wave or corrugated profiles to evaluate the reduction in compressive, tensile, and interlaminar shear strengths of the cured composite. Although this is not a standard 'structural geometry', we wanted to provide that as a standalone section to enhance the perspective of the reader.

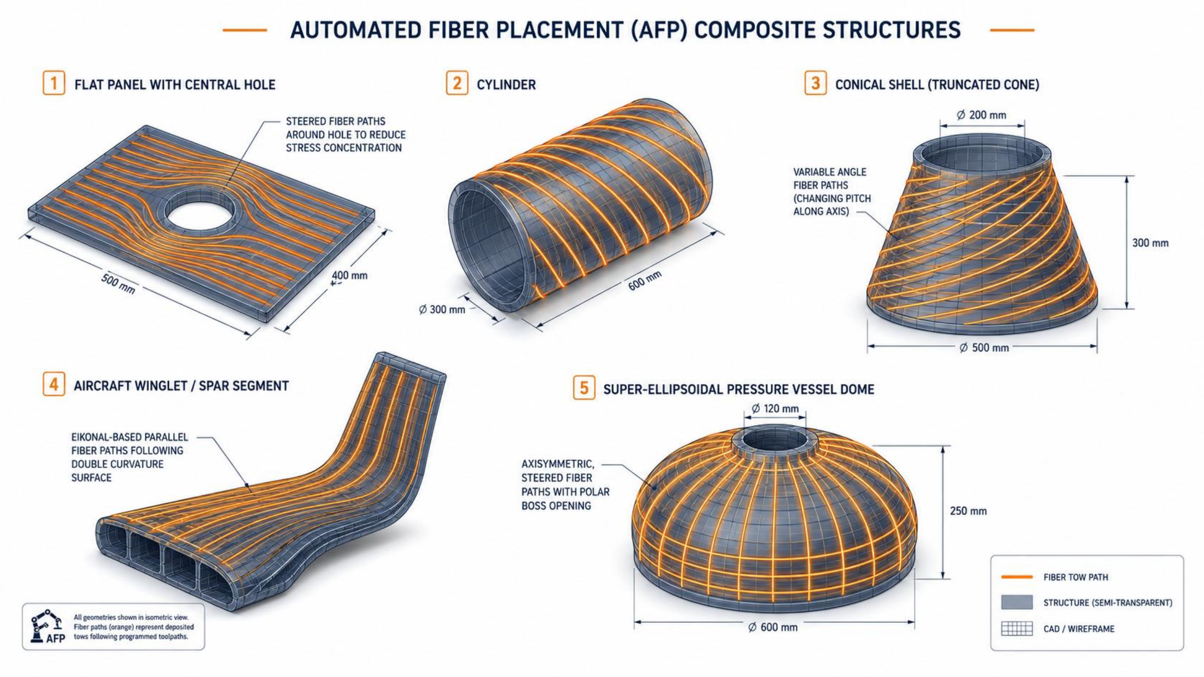

Fig. 1: Typical geometrical surfaces currently used in automated fiber placement.

<u>Conclusion:</u>

In conclusion, the primary objective of this abstract is to solicit critical feedback from the CAD community regarding a proposed reference geometry designed specifically for benchmarking AFP systems. The physical fabrication and commissioning of specialized AFP tooling represent a substantial capital expenditure, creating a significant barrier to iterative experimentation and cross-platform validation. Consequently, the establishment of an open-source, universally accepted standard benchmark geometry is imperative to streamline collaborative efforts, harmonize data collection, and normalize manufacturability metrics across disparate research institutions and industrial systems. To initiate this collaborative discourse and establish a quantitative baseline, the presentation at the conference will introduce a carefully engineered reference geometry. This artifact incorporates a spectrum of complex topological features—such as varying curvature radii, steering constraints, and ply drop-offs—serving as the foundational catalyst for defining standardized AFP process capabilities and material deposition limits.

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Gemini was used to organize the papers after selection, image generation, and to improve readability of the extended abstract.

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