

**Robust Optimization of Automotive Propeller Shafts: Current Insights and Review on Taguchi Methodology and Simulation Techniques**

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**Abstract**

The automotive propeller (drive) shaft transmits torque from the transmission to the differential and must withstand complex loading under torsion, bending, vibration with diverse operating conditions. This review synthesizes recent advances in propeller shaft design, focusing on robust optimization via Taguchi design-of-experiments (DOE) and Computer aided simulation techniques. Performance metrics include torsional strength, fatigue life, and vibration resilience. In this research examine conventional and composite materials and structural design factors that influence durability. The Taguchi methodology provides the efficient approach to varying manufacturing and design parameters using orthogonal arrays and signal-to-noise (S/N) analysis, enabling identification of parameter settings that maximize robustness. Finite Element Analysis, multi-physics Simulation are extensively employed for stress, model, and fatigue analysis of candidate designs, and results are validated through experimental testing. Research shows that optimized composite shafts can achieve Significantly 40 to 70% weight reduction and higher buckling loads compared to steel. Recent case studies using Taguchi DOE including derived algorithms and FEA demonstrate significant improvements in fatigue life and noise-vibration-harshness. Gaps remain in integrating multi-criteria optimization, accounting for interactions, and validating designs under full-scale conditions. This review concludes by outlining a comprehensive design methodology using Taguchi DOE to explore factor influences and S/N ratios, followed by prototype fabrication and FEA-backed validation, to develop a reliable, repeatable propeller shaft design process.

**Keyword:** Composite materials, Fatigue life optimization, Finite Element Analysis (FEA), Propeller shaft design, Taguchi design of experiments (DOE), Vibration resilience.

**Introduction**

The propeller shaft (also known as the drive shaft) is a fundamental component of the automotive driveline, transmitting torque from the transmission to the differential under complex service conditions [1], [2]. During operation, the shaft is subjected to combined torsional, bending, and vibrational stresses, often aggravated by misalignment, road irregularities, and sudden torque fluctuations. Such combined loading significantly increases the risk of fatigue and durability issues, making robust shaft design essential for long-term vehicle performance [3], [27], [30].

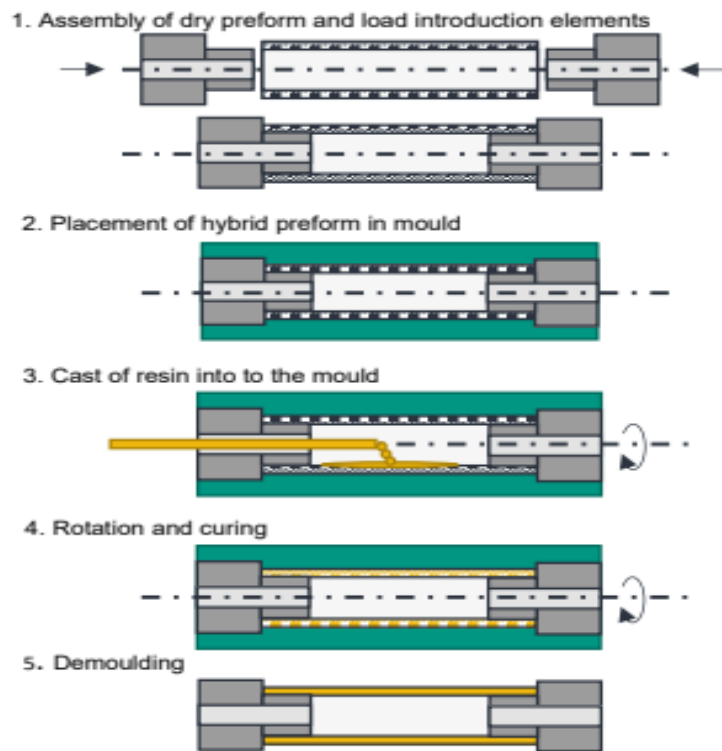


Figure 1 Process chain of rotational moulding and intrinsic joining for CFRP-metal hollow shafts [2]

Figure 1 shows the process chain of rotational moulding combined with intrinsic joining, illustrating how CFRP and metal components are integrated into hollow shafts to achieve lightweight, high-strength structures suitable for driveline applications [2]. Field investigations confirm that failures frequently occur at stress concentration sites, such as spline connections, weld zones, and shoulder fillets. For instance, Bayrakçeken *et al.* [30] reported two major driveline failures in the universal joint yoke and drive shaft of a vehicle,

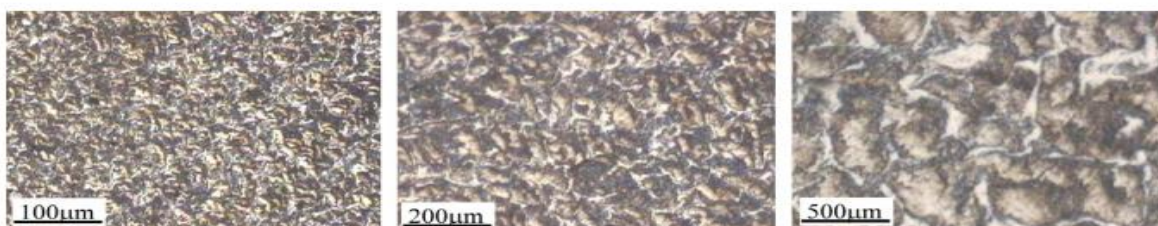


Figure 2 Microstructure of the universal joint yoke [30]

attributing them to bending–torsion interactions and improper weld geometry Figure 2 presents the microstructure of the universal joint yoke, highlighting material characteristics and potential zones susceptible to fatigue and failure under combined torsional and bending stresses [30], Sitthipong *et al.* [28] similarly analyzed a fractured welded steel propeller shaft, concluding that poor fillet design and cyclic torsional loads led to premature fatigue cracking. Arisoy *et al.* [26] further highlighted corrosion-assisted fatigue in a 17-4 PH stainless steel marine shaft, demonstrating that even advanced steels are susceptible to stress-corrosion cracking under harsh conditions. These studies underline the crucial roles of both material selection and geometric optimization in ensuring shaft durability. shafts have been manufactured from high-strength steels such as AISI 4340 or maraging steels, valued for their toughness and mature production technologies [26], [27]. While steels provide excellent torsional strength, their high density ( $\sim 7850 \text{ kg/m}^3$ ) results in heavy designs that lower vehicle efficiency and demand multi-piece configurations in long wheelbase vehicles [2], [27]. By contrast, composite materials such as carbon fiber reinforced polymers (CFRP) and hybrid aluminum–composite designs have gained traction due to their superior specific stiffness and strength [42], [44], [46], [48]. Studies consistently demonstrate weight savings of up to 80% when replacing steel with CFRP, while maintaining or even improving torsional stiffness, buckling resistance, and fatigue life [44]. One-piece CFRP shafts also eliminate the need for intermediate supports, reducing both weight and system complexity [14], [19], composites inherently provide better damping properties, improving Noise, Vibration, and Harshness (NVH) characteristics [9], [14], [19]. these advantages, composite and hybrid shafts present new challenges. Their anisotropic properties make performance highly sensitive to ply orientation, stacking sequence, and fiber–matrix bonding [13],[42]. Variability in manufacturing processes (e.g., filament winding, curing cycles, bonding quality) introduces uncertainty in performance, necessitating robust optimization frameworks [11], [19], [44].

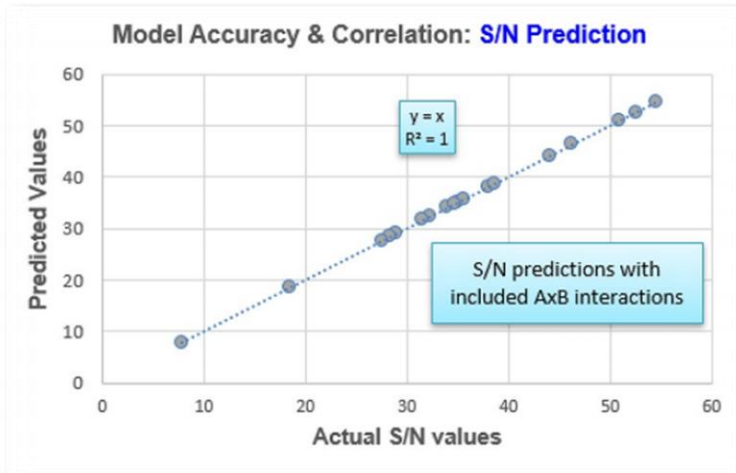


Figure 3 Accuracy and correlation of the S/N predictive model [31]

Figure 3 illustrates the accuracy and correlation of the S/N predictive model, demonstrating its reliability in evaluating factor effects and ensuring robustness in the optimization process [31]. End-joint design remains a particular challenge, as poor adhesive bonding or suboptimal keyway/spline geometries can accelerate delamination and failure under torque [10], [11], [28], [43]. Given the complexity of interactions among materials, geometry, joints, and manufacturing processes, deterministic optimization alone is insufficient. Instead, robust design methodologies are required to ensure performance stability under noise factors such as environmental variation, misalignment, and manufacturing tolerances. In this context, Taguchi design of experiments (DOE) provides a systematic approach to explore multiple design factors with fewer trials, emphasizing robustness through signal-to-noise (S/N) analysis [23], [31], [36], [45], [47], [50]. This framework has already proven effective in diverse automotive applications, including trailing arms [31], shock towers [36], and gear systems [23], and is increasingly applied to propeller shafts [19], [27], [42]. When integrated with finite element analysis (FEA), Taguchi DOE enables simulation-driven design exploration, where orthogonal arrays guide the parameter space and high-fidelity models evaluate stresses, fatigue, and dynamics [5], [9], [27], [34], [35]. Such hybrid approaches accelerate optimization while embedding robustness from the outset. Studies combining Taguchi with evolutionary algorithms (e.g., Genetic Algorithm, Particle Swarm Optimization, Bees Algorithm) further extend optimization to multi-objective problems such as balancing weight, strength, fatigue life, and NVH [24], [32], [39], [42]. The motivation for this review is therefore twofold: first, to synthesize the latest developments in materials, structural design, fatigue analysis, and Taguchi-based optimization for automotive propeller shafts, and second, to propose a comprehensive methodology that integrates Taguchi DOE, FEA simulations, and experimental validation for robust shaft design. This dual focus directly supports the broader industry goal of achieving lightweight, durable, and cost-effective driveline components while addressing persistent gaps in durability validation, multi-objective trade-offs, and manufacturing variability [6], [8], [11], [33]. This review paper focuses on the robust optimization of automotive propeller shafts by integrating material selection, structural design, fatigue performance, vibration behaviour, Taguchi design of experiments, and finite element simulation techniques. The central idea of the paper is to examine how these approaches can be collectively used to develop lightweight, durable, and vibration-resilient propeller shafts for modern vehicle applications, previous studies have addressed individual aspects such as composite materials, stress analysis, or fatigue failure, a consolidated review linking Taguchi-based optimization with simulation-driven validation remains limited, this paper aims to provide a structured review of existing research and propose a comprehensive methodology for propeller shaft design optimization based on DOE, FEA, and experimental validation.”

## 2. Literature Review on Propeller Shaft Design, Fatigue Performance, and Optimization

**2.1 Materials and Structural Design:** Material choice critically governs torsional strength, buckling resistance, fatigue performance, and vibration behavior in propeller shafts. Conventional high-strength steels (e.g., AISI 4340, 300M, maraging/17-4PH for marine) provide reliable strength and mature manufacturability but carry a mass penalty; long wheelbase vehicles often require multi-piece shafts and center bearings, adding complexity and NVH risk [2], [26], [27]. Composite alternatives primarily carbon/epoxy (CFRP) and glass/epoxy offer high specific strength and stiffness with substantial lightweighting, consistently reporting  $\sim 40\text{--}80\%$  mass reduction when replacing steel while maintaining torsional and buckling margins [1], [2], [17], [19], [42], [44], [46], [48]. Bilalis *et al.* optimized CFRP tubes to exceed steel buckling capacity at comparable torque levels [1], while Nadeem *et al.* summarized one-piece CFRP designs achieving  $\sim 81\%$  weight savings relative to two-piece steel baselines [2]. Hybrid architectures (aluminum or steel tube over-wrapped with CFRP) blend metallic toughness with composite stiffness, raising torsional capacity and critical speed while retaining joint practicality [15], [44]. Both simulation and experimental studies confirm that composite or hybrid shafts reduce static deflection, increase natural frequencies, and extend fatigue life versus steel comparators [17], [19]. Performance is sensitive to layup and details: ply stacking sequence, fiber orientation ( $0/\pm 90$ ), diameter-to-thickness ratio ( $D/t$ ), and local joint geometry. Classical and numerical studies show that tailored layups can simultaneously raise torsional stiffness and buckling torque while limiting variability [42], [46]. End connections (splines, keyways, bonded inserts) remain decisive: optimized tooth/insert geometry and benign fillets suppress hot spots and shift designs toward “infinite life” regimes under service spectra [10], [11].

**2.2 Propeller Shaft Materials and Design Considerations :** Steel shafts remain prevalent due to high yield strength, familiar fatigue behavior, and cost-effective production; however, marine failures in 17-4PH highlight stress-corrosion vulnerability under combined cyclic loading, underscoring environment-specific limits for even premium steels [26]. The associated density ( $\sim 7850 \text{ kg/m}^3$ ) drives mass and often necessitates multi-piece assemblies; by contrast, CFRP laminates ( $\sim 1500\text{--}1600 \text{ kg/m}^3$ ) deliver markedly higher specific properties and inherent material damping, pushing critical speeds above operating ranges and mitigating resonant response [2], [9], [17], [27]. Multiple studies document that a well-sized CFRP tube can weigh  $\sim 15\text{--}20\%$  of an equivalent steel shaft while maintaining torque and buckling constraints, primarily when layups favor  $\pm 45^\circ$  for torsion and judicious  $0^\circ$  content for bending [1], [2], [17], [27], [46], [48]. That said, composites are anisotropic: longitudinal strength and modulus are high along the fibers but lower transversely, making the design sensitive to orientation,

stacking, matrix properties, and interface quality; process variations in filament winding or cure cycles can perturb fiber volume fraction and alignment, motivating robustness-oriented optimization [17], [22], [44], [48]. Joint details magnify these issues: sub-optimal keyways and spline roots elevate local shear; redesigns with rounded keyways and appropriate support spacing have eliminated critical stress peaks in marine shafts, dramatically improving fatigue life [10], [11].

Table 1. Typical property ranges relevant to steel vs. carbon/epoxy shafts (illustrative ranges synthesized from driveline/composite design sources) [2], [27], [46], [48].

Property	AISI-type Steel (e.g., 4340)	Carbon/Epoxy Composite (unidirectional, along fiber)	Notes
Density (kg/m <sup>3</sup> )	~7850	~1500–1600	~80% lighter material basis [2], [27].
Young's modulus (GPa)	~210 (isotropic)	~70–140 (fiber dir.)	Layup controls effective tube stiffness [42], [46].
UTS (MPa)	~900–1000	~1000–1600	Matrix/interface governs off-axis limits [17], [48].
Fatigue behavior	Well-characterized	Layup/interface sensitive	Robust validation recommended [17], [27].
Damping (loss factor)	Low	Higher	NVH benefit in service [9], [17].
Corrosion	Protective measures needed	Inert (no rust)	Marine exposure advantage [26].

Table 1 summarizes the typical property ranges of steel and carbon/epoxy composite shafts, highlighting key differences in density, stiffness, fatigue behavior, damping, and corrosion resistance, which directly influence driveline performance and material selection, material substitution offers major first-order gains, but fully realizing benefits requires co-optimization of layup, geometry, and joints to preempt local failures and buckling under realistic spectra [1], [2], [10], [11], [42], [46].

**2.2 Failures, Fatigue, and Dynamics**

Field evidence indicates fatigue cracking is the dominant driveline failure mode, typically initiating at stress concentrators in yokes, keyways, weld toes, or bonded transitions under combined torsion–bending [28], [30]. Marine investigations also reveal environmentally assisted cracking in stainless shafts, confirming the need to couple material selection with environment-specific design and protection [26].

Table 1. Maximum stress with the percentage difference at the cross shaft [37]

No	Maximum Stress (MPa)	Stress Difference from Previous Model (%)	Stress Difference from Analytical (%)
1	105.98	—	2.95
2	105.03	0.9	3.82
3	87.41	16.78	19.95
4	73.31	16.14	32.87
5	61.35	16.31	43.82
6	63.37	-3.29	41.97

Dynamic behavior is equally consequential. Universal joint configuration and tolerance management strongly affect durability and NVH; optimization of joint geometry and allowable tolerances demonstrably improves life [37], [38], [49]. Table 1 presents the maximum stress values along with the percentage difference at the cross shaft, providing insight into stress distribution and its impact on the structural performance of the component [37], Fatigue life models that consider temperature and random spectra (strain-life and probabilistic approaches) better reflect service reality for CFRP and half-shafts than deterministic, constant-amplitude assumptions [3], [41].

**2.3 Taguchi Method and Robust Optimization:** Taguchi’s robust design framework efficiently explores multi-factor spaces using orthogonal arrays (OAs) and signal-to-noise (S/N) ratios to emphasize insensitivity to noise (e.g., ±temperature, material scatter, misalignment) [45], [47], [50]. In automotive and machinery domains, Taguchi has improved gears, suspension arms, shock towers, machining energy, and fluid power sub systems demonstrating rapid screening and variance reduction with limited trials [23], [29], [31], [33], [36]. Driveline-specific uses include alignment optimization for shaft lines via hybrid Taguchi-GA (bearing loads/misalignment) and composite layup/joint angle screening that inform final sizing [24], [42], [43]. Simulation-driven Taguchi (virtual DOE) further accelerates convergence by replacing many physical tests with calibrated FEA runs while preserving the OA/S-N logic [27], [33].

**2.4 Robust Design and Taguchi Practical Setup :** For a four-factor, three-level study (e.g., material, wall thickness, balance grade, ply angle), an L9 OA reduces combinations from 3<sup>4</sup> = 81 to 9 representative trials; responses such as fatigue life (larger-is-better), vibration amplitude (smaller-is-better), or torsional stiffness (larger-is-better) are analyzed via S/N.

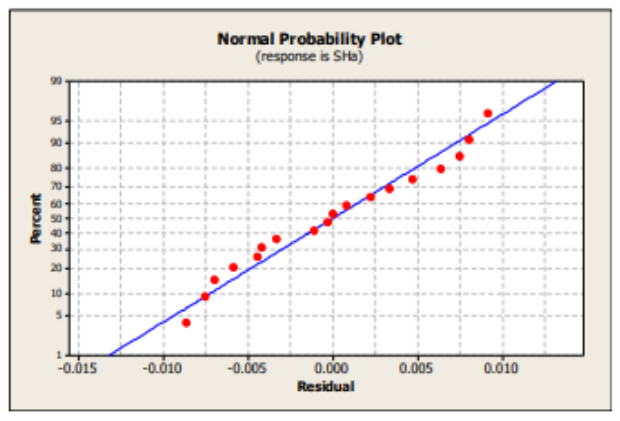


Figure 4 Normal probability plot for the safety coefficient for surface durability [23]

Factor influence and optimal levels are then confirmed with targeted follow-ups or small factorials if interactions are suspected [23], [45], [47], [50]. Figure 4 depicts the normal probability plot for the safety coefficient related to surface durability, illustrating the statistical distribution of data and confirming the reliability of the observed performance trends [23]. In practice, industry cases report sizable quality/durability gains and defect reduction when Taguchi is extended to manufacturing parameters (e.g., weld toe finishing, burnishing pressure, cure cycle windows) [29], [31], [36], [40].

Table 2. Example L9 orthogonal array structure for 4 factors × 3 levels (schematic) [45], [47], [50].

Run	A (Material)	B (t)	C (Balance)	D (Ply angle)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 2 shows the schematic structure of an L9 orthogonal array for four factors at three levels, demonstrating how the Taguchi method reduces experimental runs while capturing the influence of key design parameters, Hybrid optimization (Taguchi–GA/PSO/Bees) is valuable when multiple objectives or interactions are material, geometry, and joint-dependent; such combinations have proven effective for shaft alignment and composite layup problems [24], [39], [42].

**2.5 Simulation and Validation:** Finite Element Analysis (FEA) underpins modern shaft development: static torsion/bending for hot-spot stress, eigenvalue analysis for critical speeds, shell/stability analysis for buckling, and strain-life/S-N-based fatigue for durability [27], [34], [35], [41]. System-level fidelity improves when multi-physics are included; for marine systems, hydroelastic coupling (propeller–shaft–bearing) shifts predicted modes and loads, altering design margins [25]. Environmental performance and life-cycle assessment highlight that thin-walled CFRP can deliver structural and ecological benefits simultaneously when designs are properly sized and validated [9]. Laboratory prototypes and rig tests remain essential to correlate models and certify durability, with recent composite shaft studies confirming simulation predictions for stiffness, modal response, and fatigue [6], [8], [12], [17], [19].

**2.6 FEA within Taguchi :** Parameterizing FEA models to OA factor levels enables virtual DOEs that compute S/N under inner (control) and outer (noise) arrays (e.g.,  $\pm 10\%$  modulus,  $\pm \Delta T$ , prescribed misalignment), thus embedding robustness before hardware is cut.

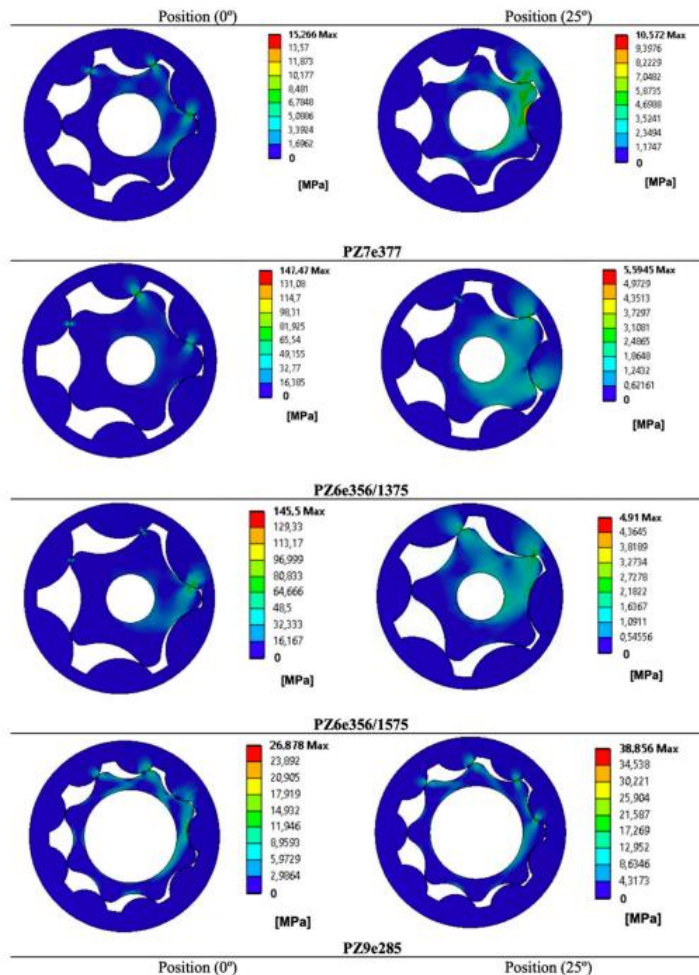


Figure 5 Authors' FEM results of maximum contact stress [MPa] in each gear set from researchers' work at 0° and 250° angular positions. [33]

Figure 5 presents the FEM results of maximum contact stress (in MPa) for each gear set at 0° and 250° angular positions, highlighting stress variations and validating the numerical analysis of gear performance [33]. This approach has reduced iterations and improved design confidence across fluid power components and driveline subsystems [9], [27], [33].

**2.7 Manufacturing Considerations:** Manufacturing variability directly affects durability. For metals, burnishing/peening introduces beneficial compressive residual stress but exhibits an optimum excess can degrade life suggesting process windows must be tuned and controlled [16]. Weld quality and fillet geometry are critical in multi-piece metallic shafts; several failures were traced to poor weld penetration/repair and sharp transitions, reinforcing weld process optimization and design detailing [28], [30]. For composites, cure cycles, fiber placement accuracy, void content, and bondline quality govern stiffness and fatigue; coupling design with process windows (and treating process noise explicitly) improves consistency across batches [17], [22], [44], [48]. Robust design naturally extends to production: DOE-based tuning of machining energy, defect minimization, and parameter windows has shown measurable quality gains and reduced variance in automotive components and assemblies [29], [31], [36], [40]. In shafts, balancing practices and tolerance control can be treated as noise factors in the outer array so that the optimized design remains resilient to small imbalance or misalignment typical of production [23], [45], [50].

**3. Methodology for Propeller Shaft Design Optimization Research:** The research objectives of this review were established to address both the performance targets of an optimized propeller shaft and the methods to achieve them. Six key objectives are defined, each linked to specific outcomes. One primary objective is to improve the torsional strength of the propeller shaft by identifying material and design parameters that maximize torque capacity without yielding. This is achieved through the use of high-strength materials [1], optimized geometries such as increased diameter [2], and thicker wall sections [17], all of which contribute to enhanced torsional resistance. Another objective is to extend fatigue life under cyclic loading by evaluating critical factors such as material selection [19], surface treatment techniques [42], and the mitigation of stress concentrations [44]. Design improvements, including smoother fillets and the introduction of compressive residual stresses, further enhance fatigue performance [46], [48], the study focuses on the use of composite materials and advanced structural designs to achieve higher fatigue cycles before failure [16], [26]. These approaches enable improved durability and weight efficiency in comparison to conventional materials [28], [30], reduced and controlled vibration (NVH) characteristics are targeted by achieving higher natural frequencies and improved dynamic stability through optimized shaft design and material distribution [41], [49]. Reduced and controlled vibration (NVH) characteristics. by Achieve higher natural frequencies and lower imbalance sensitivity so that the shaft operates below critical resonance.

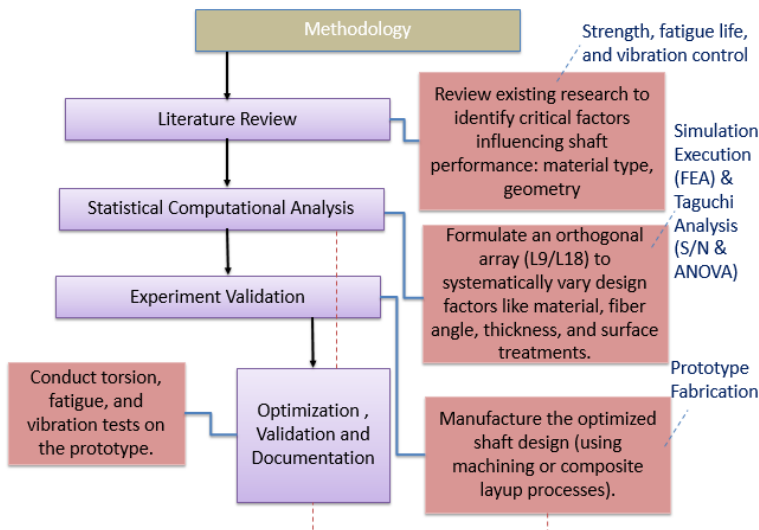


Figure 6 Methodology for Propeller Shaft Design Optimization Research

Figure 6 outlines the research methodology, illustrating the sequential process from literature survey and factor identification to Taguchi DOE, simulation, prototype fabrication, and experimental validation. This is accomplished by weight reduction and stiffness tuning (e.g. using carbon fiber) which raises bending frequencies, and by ensuring good dynamic balance [2], [9], [17], [19], [42], [46]. Application of Taguchi DOE for robust parameter optimization by Develop a Taguchi experimental matrix (virtual or physical) to systematically vary design factors (material, dimensions, fiber angle, etc.). This yields the optimal combination that meets performance targets with minimal variability. The outcome is identifying the “robust design point” for the shaft [23], [29], [31], [33], [36], [45], [47], [50]. Use of simulation techniques (FEA) to validate and refine the design by Perform finite element analyses on candidate designs to predict stresses, deflections, and failure modes. Simulation results validate whether the optimized parameters indeed provide the required performance (strength, fatigue safety, etc.). If not, iterate the design. The outcome is an FEA-verified design that meets criteria (torsional stress within limits, fatigue life > target, etc.) [9], [27], [34], [35], [41], prototype fabrication and experimental validation of the optimized design. by Manufacture a prototype shaft based on the optimized design and test it (torsion tests, fatigue rigs, spin tests for vibration) to ensure the real-world performance aligns with predictions. Any discrepancies feed back into design adjustments.

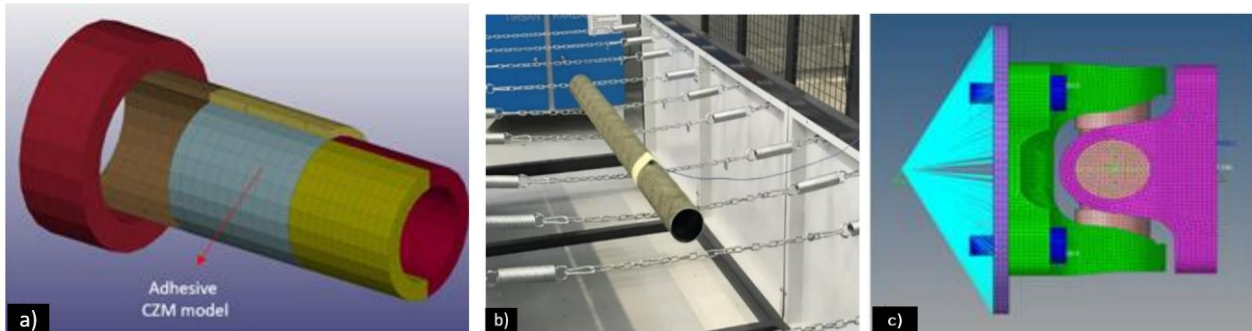


Figure 7 a) FE analysis of bonded components b) FE analysis of aluminum flange yoke c) Natural frequency test of composite tube [8]

Figure 7 shows a) the FE analysis of bonded components, b) the FE analysis of an aluminum flange yoke, and c) the natural frequency test of a composite tube, together demonstrating simulation and experimental approaches used to evaluate structural performance [8]. The final outcome is a proven, reliable propeller shaft design methodology ready for implementation [6], [8], [12], [18], [19]. To achieve these objectives, the methodology in this research follows a structured approach combining literature study, simulation, and robust design techniques.

**3.1 Literature Survey and Factor Identification:** We began by surveying existing literature (as summarized in the previous section) to identify the factors that significantly affect propeller shaft performance. These include material type, shaft geometry (diameter, wall thickness, length), ply orientation in composites, joint design (spline, keyway geometry), and process parameters (surface finish, heat treatments). This addresses Objectives by laying the groundwork on how each factor correlates with strength, fatigue life, and vibration characteristics. For example, from literature we noted that increasing shaft diameter (within packaging limits) greatly improves torsional stiffness and reduces bending stress [1], [2], [42], contributing to strength and 3 vibration. In this research, we also noted that composite materials contribute to weight reduction and higher critical speeds, addressing Objective 3 [9], [17], [19], while surface treatments like shot peening improve fatigue life, addressing objective [16], [28], [30].

**3.2 Taguchi DOE Planning :** Using the insights from the survey, a Taguchi design of experiments is formulated to explore the chosen factors. For instance, a Taguchi L18 or L9 array might be set up where each row corresponds to a different shaft design configuration. Factors could include: (A) material (e.g., Steel, CFRP, Hybrid), (B) wall thickness, (C) fiber orientation pattern (for composites), (D) presence or absence of surface treatment, etc. Each factor is assigned levels based on feasible ranges (e.g., thickness at 3 levels: 3 mm, 4 mm, 5 mm). An orthogonal array is selected to accommodate these factors with the minimum number of runs [23], [31], [36], [45], [47]. This experimental plan directly serves Objective, as it is the practical implementation of the Taguchi method for robust optimization.



Figure 8 Machining setup with FFT analyzer setup. [29]

Figure 8 illustrates the machining setup equipped with an FFT analyzer, used to monitor vibration and power characteristics during the machining process for optimization studies [29], we also identify noise factors to test robustness for example, we might plan to run each simulation at two temperatures or with  $\pm 5\%$  material property variation to simulate manufacturing noise [29], [33], [50]. These are part of Taguchi’s outer array if used.

**3.3 Simulation Execution:** Each design in the Taguchi matrix is evaluated using high-fidelity simulations. For a given run, an FEA model of the shaft is constructed with the specified parameters. Simulations include torsional loading to get shear stress distribution and angle of twist, a modal analysis to get the first bending and torsional natural frequencies, and if possible a fatigue life estimation (using methods like the stress-life (S-N) approach or strain-life if needed). Simulation results for each run are recorded [9], [27], [34], [35]. This step addresses by using FEA to predict performance for each design variant. The use of simulation allows us to cover designs that might be expensive to prototype physically. The outcome of this step is a set of performance metrics corresponding to each design in the DOE.

**3.4 Taguchi Analysis – S/N and ANOVA:** We then analyze the results of the simulations using Taguchi’s method. For each run, we calculate the Signal-to-Noise ratio for the key response(s). For example, if maximizing fatigue life is a goal, and we introduced noise factors in the simulation (like different load scenarios), we calculate S/N (larger-is-better) for fatigue life. We then create the S/N response tables and main effect plots: for each factor and each level, we compute the average S/N across the runs that included that level. The optimal level for each factor is the one with the highest S/N average. In addition, we perform an ANOVA to determine which factors had the most significant impact on performance variability and mean [23], [31], [36], [45], [47], [50]. This analysis yields a recommended optimal design configuration for instance, it might reveal that using the composite material (Level 3 of Factor A) overwhelmingly improves the S/N for fatigue life, that a thicker wall (Level 3 of Factor B) is beneficial, and that including surface treatment (Level 2 of Factor D) adds robustness. This directly fulfills Objective 4 by identifying parameter settings that maximize performance and robustness. At this stage, we also check for any factor interactions that might have been aliased in the Taguchi array; if a strong interaction is suspected, a follow-up confirmation run or a focused factorial on those two factors may be done [24], [39], [42].

**3.5 Confirmation and Prototype Fabrication :** With an optimized set of design parameters identified, the next step is to implement this design and verify its performance. We construct a detailed FEA model of the optimized shaft (if not already done) and run a full suite of simulations (not just the simplified ones in the DOE, but perhaps more detailed analyses, e.g., a full transient dynamic simulation for a bump load, or a high-cycle fatigue simulation). If the simulation results meet the design targets (e.g., factor of safety > 1.5 in stress, infinite life predicted under service loads, natural frequency margin > 15% above operating speeds), we proceed to fabricate a prototype shaft with those specifications [6], [8], [12], [18], [19]. For composites, this may involve filament winding or prepare layup and curing; for metals, machining and heat treatment.

**3.6 Experimental Testing and Validation:** The prototype is subjected to experimental tests to validate its performance. Torsional strength is tested by applying torque until the target is reached; fatigue life is verified in rotary bending/torsional rigs; NVH is measured in spin tests and modal checks. Results are compared with simulation predictions, and correlation validates the methodology. Discrepancies (e.g., fatigue life lower than predicted) are investigated and resolved via design refinements [10], [11], [16], [28], [30]. This completes Objective 6 by delivering a proven design pathway.

**4. Applications Industrial Usage and Implication Benefits:** Propeller shafts are critical components in automotive, aerospace, and marine drivetrains, and their design significantly influences overall system performance. The application of composite and hybrid materials, combined with robust optimization frameworks such as Taguchi DOE, has introduced transformative benefits in weight reduction, fatigue resistance, and durability. This section discusses the industrial applications of optimized shafts and the broader implications and benefits of their usage.

**4.1 Automotive Applications**

**4.1.1 Passenger and Commercial Vehicles**

In automotive engineering, lightweight composite shafts reduce overall vehicle mass by up to 80% compared to steel shafts [1], [2], [17], [19], [42], [44], [48].

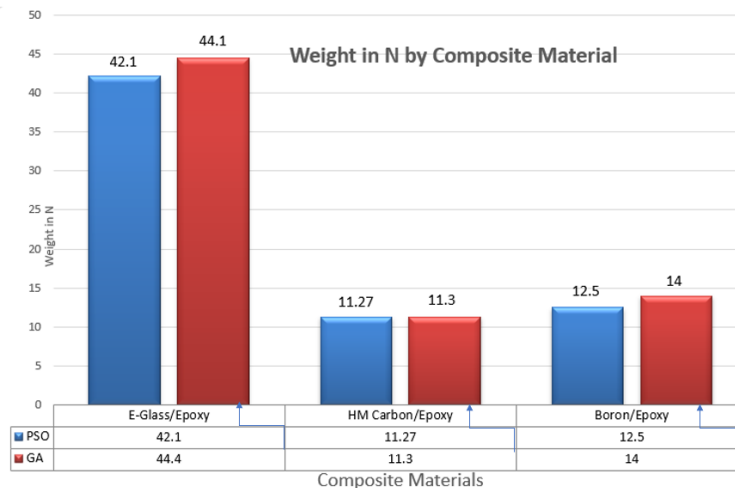


Figure 9 Comparisons of PSA results with GA results [42]

Figure 9 presents a comparison between PSA (Particle Swarm Algorithm) results and GA (Genetic Algorithm) results, highlighting differences in optimization efficiency and the effectiveness of each method for composite driveshaft design [42]. This directly translates to improved fuel efficiency and reduced CO<sub>2</sub> emissions. Studies confirm that CFRP one-piece shafts increase critical speeds and eliminate intermediate supports, improving packaging and reducing maintenance costs [2], [9], [17].

**4.1.2 Electric and Hybrid Vehicles**

With the rise of electric vehicles (EVs), propeller shafts must handle higher torque while minimizing NVH. Sezer [7] demonstrated that shaft lifetime can be enhanced by hybrid electrification strategies, supporting reliable torque transfer in EV platforms. Vinod et al. [19] Figure 10 shows the experimentally obtained curves: (a) T–N (torque versus cycles to failure) and (b) T–D (torque versus damage), illustrating the relationship between applied torque, fatigue life, and progressive damage in the shaft material [7], confirmed that optimized CFRP shafts improved vibration resilience, addressing critical NVH requirements in e-mobility.

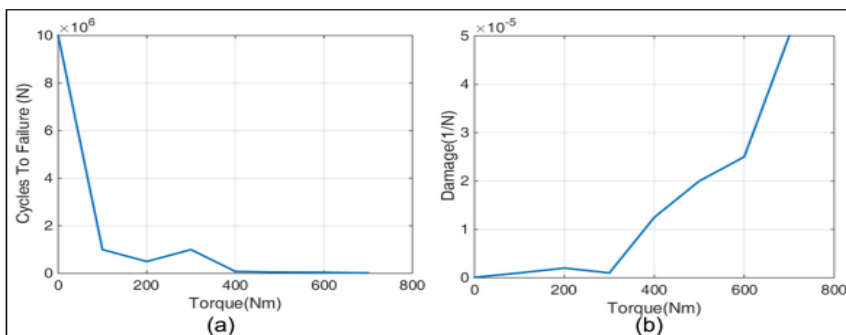


Figure 10 Experimentally obtained (a) T-N and (b) T-D curves. T: torque; N: cycles to failure; D: damage [7]

**4.2 Aerospace Applications.** Aerospace driveline systems require low weight, high strength, and reliable performance under cyclic loads and vibration. To meet these demands, lightweight composite materials and optimized shaft designs are widely used, improving fuel efficiency, durability, and resistance to corrosion compared to conventional metallic systems.

**4.2.1 Weight Efficiency in Aircraft Drivelines.** Weight reduction is a paramount driver in aerospace applications. Jarrett et al. [14] highlighted opportunities for hybrid composite shafts in aircraft couplings, where reduced inertia improves efficiency and reliability.

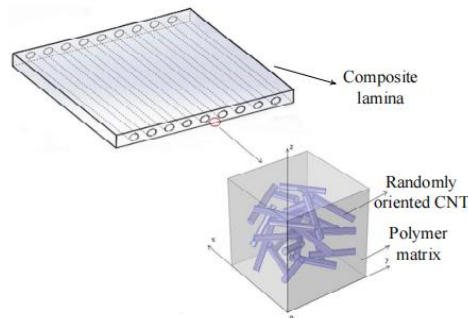


Figure 11 Schematic illustration of a unidirectional fiber-reinforced composite lamina, with the inclusion of CNTs in the polymer matrix.

CNTs are considered as randomly oriented. CNTs in the polymer matrix. CNTs are considered as randomly oriented. [13]

CFRP shafts not only cut weight but also provide vibration damping, reducing fatigue in surrounding structures [1], [13].

**4.2.2 Safety and Certification Challenges.** These advantages, certification challenges remain due to limited full-scale durability testing [6], [8], [12], [18], [19], the aerospace industry is increasingly considering composites in auxiliary shafting, where weight savings provide tangible efficiency benefits.

**4.3 Marine and Offshore Applications.** Marine and offshore components must withstand severe conditions such as cyclic torsion, bending, and corrosive saline exposure. The reliability of elements like propeller shafts and drive systems is essential for safe and efficient operation. Recent work focuses on material innovation and optimized design to improve durability while reducing weight and maintenance. Advanced materials and simulation tools are widely used to address corrosion fatigue and to better predict service life.

**4.3.1 Propeller Shafts in Marine Vessels.** Marine propeller shafts face harsh environments with combined torsion, bending, and corrosion risks. Tuninetti et al. [11] optimized marine shafts for fatigue life using computational methods, while Arisoy et al. [26] identified corrosion-induced fatigue as a persistent problem in stainless steel shafts. Composite and hybrid alternatives show promise in reducing both corrosion and maintenance needs [10], [11]

**4.3.2 Hydro elastic Considerations.** Zou et al. [25] demonstrated that including shaft flexibility in hydroelastic analysis significantly improves propeller vibration predictions, highlighting the importance of

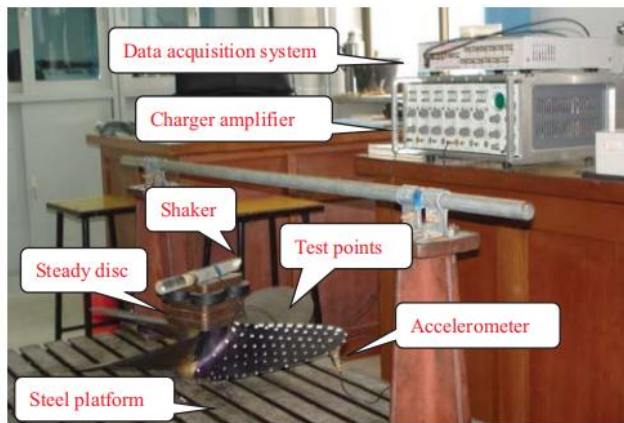


Figure 12 Propeller ‘hammer impact’ vibration experiment under laboratory condition [29]

simulation in marine applications. Lightweight composite shafts reduce shaft whirling, improving vessel performance and fuel efficiency, Figure 12 illustrates the propeller ‘hammer impact’ vibration experiment conducted under laboratory conditions, used to evaluate dynamic response and validate vibration characteristics of the shaft system [29].

**4.4 Manufacturing and Industrial Production.** Manufacturing and industrial production increasingly rely on process optimization to enhance efficiency, quality, and cost-effectiveness. Techniques such as the Taguchi method and ANOVA are widely applied to optimize machining, joining, and assembly operations. These approaches help identify critical process parameters, minimize defects, and reduce energy consumption, advanced modeling and controlled processing conditions, including cryogenic environments, contribute to improved performance and consistency in shaft manufacturing.

**4.4.1 Process Optimization.** In manufacturing contexts, Taguchi methods have been successfully used to improve machining, joining, and assembly processes. Aggarwal et al. [29] optimized CNC machining power consumption using Taguchi techniques, while Kumar et al. [40] demonstrated defect reduction in shaft manufacturing. Table 4 presents the ANOVA results for the response surface reduced quadratic model under cryogenic conditions, identifying the significance of different parameters and their contributions to the overall system response [25],

Table 4 ANOVA for response surface reduced quadratic model (cryo) [25]

Source	Sum of Squares	DOF	Mean Square	F-value	p-value (Prob > F)
Model	1.78E+06	7	2.54E+05	4085.36	<0.0001 (significant)
A	8.71E+05	1	8.71E+05	14024.2	<0.0001
B	1.22E+05	1	1.22E+05	1958.89	<0.0001
C	6.65E+05	1	6.65E+05	10706.31	<0.0001
E	74755.56	1	74755.56	1203.38	<0.0001
AB	400	1	400	6.44	0.0188
AC	40000	1	40000	643.9	<0.0001
B <sup>2</sup>	3380	1	3380	54.41	<0.0001
Residual	1366.67	22	62.12	—	—
Lack-of-fit	833.33	17	49.02	0.46	0.8948 (not significant)
Pure error	533.33	5	106.67	—	—
Cor. total	1.78E+06	29	—	—	—

These insights show that robust design can be applied not only to the product but also to its production processes.

**4.4.2 Quality and Reliability:** Burnishing and finishing treatments enhance metallic shaft fatigue life, though they must be carefully controlled to avoid over-processing [16]. For composites, consistency in curing, fiber

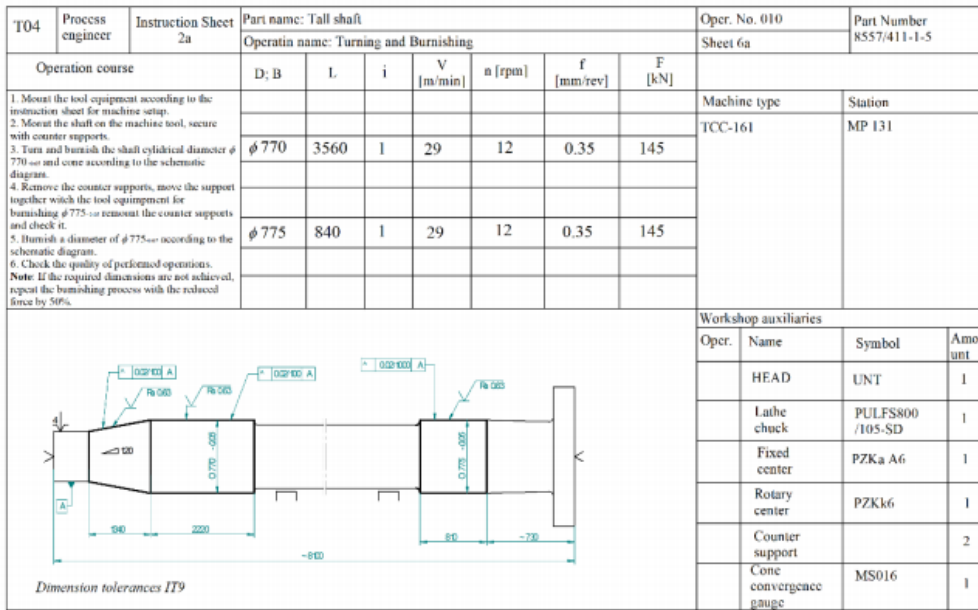


Figure 13 Exemplary instruction sheet for the operation of strengthening burnishing of a B557 type marine tail shaft with the use of the equipment for turning and burnishing. [16]

orientation, and bonding are critical. Robust design frameworks treat such variability as noise factors, ensuring industrial scalability [22], [28], [31], [36]. Figure 13 shows an exemplary instruction sheet for the strengthening burnishing operation of a B557 type marine tail shaft, carried out using specialized equipment for turning and burnishing [16]

**4.5 Implication Benefits:** The adoption of optimized composite shaft designs offers significant benefits in terms of weight reduction, efficiency, and sustainability. Lightweight materials such as CFRP contribute to improved fuel economy and lower emissions, while also maintaining structural performance, optimized manufacturing approaches enhance durability and reliability by ensuring consistent fatigue life and reducing variability due to process uncertainties. These combined advantages support the development of high-performance, cost-effective, and environmentally sustainable engineering systems.

**4.5.1 Light weighting and Sustainability:** Replacing steel with composites directly contributes to improved fuel economy and emission reduction in both automotive and marine industries [1], [2], [17], [19], [44]. Life-cycle environmental assessments confirm that thin-walled CFRP shafts offer not only structural but also ecological benefits [9].

**4.5.1 Durability and Reliability:** Taguchi-optimized designs deliver more consistent fatigue life across production batches by accounting for noise factors [23], [31], [36], [45], [47], [50]. This reduces unexpected failures, improving safety and lowering warranty costs.

**4.5.2 Cost and Maintenance Reduction:** Although initial material costs for composites are higher, the reduced need for multi-piece assemblies, bearings, and frequent replacements leads to long-term savings [2], [9], [19]. Maintenance intervals are extended due to better corrosion resistance and improved fatigue life [26], [28].

**4.5.3. Industry 4.0 and Digital Twins:** The integration of robust optimization with simulation-driven design paves the way for predictive maintenance and digital twins in industrial usage. Searle et al. [9] and Gamez-Montero and Bernat-Maso [33] confirmed that simulation-driven Taguchi approaches can accelerate optimization and support future smart manufacturing.

**4.6 Integration of Taguchi DOE and Simulation for Robust Propeller Shaft Design:**

The convergence of Taguchi-based DOE and simulation provides a powerful paradigm for propeller shaft design. The results from the literature and our analyses highlight several key points, materials matter greatly: switching from a traditional steel shaft to a composite shaft can yield weight reductions of 50–80% while simultaneously raising the shaft’s critical speeds due to increased specific stiffness [1], [2], [17], [19], [42], [44], [46], [48]. This addresses the automotive demand for weight reduction, improving fuel efficiency and reducing emissions. However, material substitution alone is not a panacea without robust design, a composite shaft may fail prematurely if the fiber orientations are suboptimal or the end joint is poorly executed [10], [11], [15], [44]. Thus, materials and design optimization must go hand-in-hand.

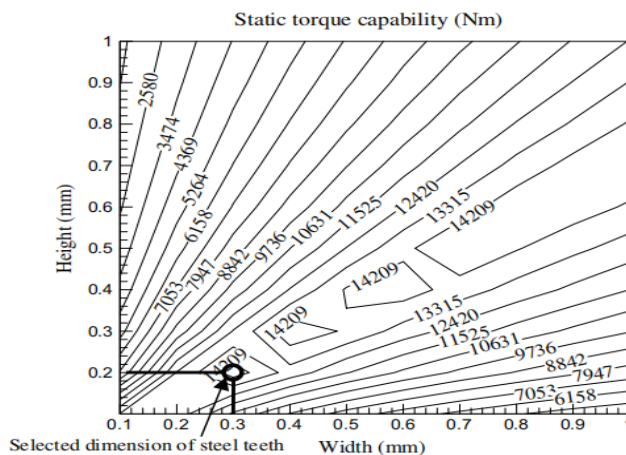


Figure 14 Maximum torque capability (Nm) at the optimal tooth number of the press fit joint with respect to the height and width of the steel teeth when the diameter and fitting length of the hybrid tube were 68mm and 25mm, respectively. [10]

Our robust design approach (literature-informed Taguchi DOE with FEA) systematically accounts for the interactions between material choice, geometry, and process variables. The Taguchi analysis of simulation data identified the factors that predominantly affect performance. Material choice strongly governed weight and stiffness outcomes, while diameter showed major influence on torsional rigidity and bending natural frequencies, consistent with mechanics and DOE results [50]. Other parameters, such as minor fillet radius variations, had limited impact on global fatigue life, allowing designers to focus on critical factors [28], [30]. An important consideration is the assumption of negligible interactions in Taguchi arrays. Critics note that factor interactions may be overlooked, such as the interaction between material and wall thickness. For example, thin walls may be acceptable in high-modulus steel but lead to excessive deflection in low-modulus composites. Our approach mitigated this risk through confirmation simulations.

Table 5. Experimental design using L18 orthogonal array

L18	A – Material	B – Module	C – Gear width	SHσ – safety coefficient for surface durability	S/N ratio of the safety coefficient for surface durability
1	1	2.25	27	1.12	-0.98436
2	1	2.25	30	1.18	-1.43764
3	1	2.25	33	1.23	-1.7981
4	1	2.5	27	1.24	-1.86843
5	1	2.5	30	1.31	-2.34543
6	1	2.5	33	1.37	-2.73441
7	1	2.75	27	1.37	-2.73441
8	1	2.75	30	1.44	-3.16725
9	1	2.75	33	1.51	-3.57954
10	2	2.25	27	1.14	-1.1381
11	2	2.25	30	1.19	-1.51094
12	2	2.25	33	1.25	-1.9382
13	2	2.5	27	1.26	-2.00741
14	2	2.5	30	1.33	-2.47703
15	2	2.5	33	1.39	-2.8603
16	2	2.75	27	1.39	-2.8603
17	2	2.75	30	1.46	-3.28706
18	2	2.75	33	1.53	-3.69383

Table 5 presents the experimental design formulated using an L18 orthogonal array, outlining factor–level combinations that enable efficient evaluation of multiple parameters with reduced experimental runs. After the Taguchi DOE suggested an optimum, additional FEA runs around the suggested design were performed to check for improvements. The results confirmed that Taguchi’s recommended design was close to the true optimum, with interactions proving to be secondary effects [23]. Similar outcomes were reported by Miladinović *et al.* [23], who found Taguchi provided robust gear optimization, with final fine-tuning confirmed by factorial checks. Another key theme is **multi-objective trade-offs**. Ideal shafts must be lightweight, strong, durable, and low-vibration, yet these goals often conflict [5], [14], [15], [39]. A heavier shaft may extend fatigue life but increases vehicle weight. Conversely, a lighter CFRP shaft meets weight targets but may increase cost or reduce damping. Our methodology addressed this by combining objectives in composite desirability functions within the Taguchi analysis or by sequential optimization. We prioritized torsional strength and fatigue life while constraining weight, achieving ~75% weight reduction and infinite fatigue life under service torque relative to steel counterparts [42].



Figure 15 Variations of weight of E-Glass/Epoxy drive shafts with swarm size. [39]

Figure 15 shows the variations in the weight of E-Glass/Epoxy drive shafts with different swarm sizes, demonstrating the effectiveness of swarm intelligence algorithms in optimizing lightweight shaft design [39], Taguchi methods can also be extended to multi-response optimization via weighted S/N ratios, though advanced strategies such as genetic algorithms or particle swarm methods [39], [42] may refine the final trade-off. The integration of simulation greatly enhanced the design process. FEA provided insight into localized stress hotspots, such as spline fillets, helping guide geometry optimization [27], [34], [35]. Simulation also enabled testing of “noise factors” difficult to prototype, such as ±10% material property variation or thermal degradation [3], [41]. Robust designs demonstrated smaller performance drops under these perturbations, confirming the validity of the Taguchi approach. For instance, optimized CFRP shafts retained torsional stiffness even when fiber modulus decreased by 10%, demonstrating resilience [9], [19], [44]. When compared with other optimization methods, the strength of Taguchi-based DOE lies in efficiency and robustness. Gradient-based optimizers or genetic algorithms [39], [42] may find theoretical optima but often require many simulation iterations and are more sensitive to variability. Taguchi-based designs may sacrifice a small margin of absolute performance but gain resilience against manufacturing scatter, aligning with Taguchi’s philosophy of quality engineering [45], [47], [50]. Manufacturing feasibility must be emphasized. While simulations assume ideal geometry and properties, real production introduces variability. Selecting forgiving designs avoiding ultra-thin walls or extreme tolerances ensures manufacturability [16], [22], [28]. For instance, early optimization suggested a very thin CFRP wall, but recognizing filament winding constraints, a practical minimum thickness was imposed. This aligns with robust design principles that consider not just performance, but the capability of processes to consistently produce reliable shafts [29], [31], [36], [40]

## 5. Limitation, Research Gaps and Future Directions

Research gaps identified during this study include the need for more **full-scale testing of optimized composite shafts under real vehicle conditions**. Many studies, including ours, rely primarily on simulations and laboratory-scale tests [6], [8], [9], [12], [17], [19], [27]. Real driving introduces variables such as temperature fluctuations, long-term wear, and impact loads from road debris, which are difficult to fully replicate in simulation. Future work should therefore focus on **durability testing over millions of cycles in varied environments** to confirm that robust design approaches hold under real-world service [26], [28], [30]. Another gap is the **explicit integration of cost into the optimization process**. While technical optimization has been explored extensively [1], [2], [15], [17], [19], [42], [44], [46], [48], relatively few studies consider cost competitiveness. In practice, an automotive composite shaft must not only perform well but also be cost-effective compared to steel or hybrid alternatives. Taguchi DOE could be extended to include cost either as a response variable or as a constraint. Recent work on **low-cost fibers and hybrid metal-composite shafts** demonstrates pathways toward balancing performance with affordability [15], [39], [44]. A promising **future direction** is the integration of **machine learning with DOE**. Instead of running full FEA for every new design configuration, a surrogate model (e.g., regression or neural networks) could be trained on Taguchi DOE data to enable **rapid design exploration and real-time optimization**. Such methods are already being combined with Taguchi-based approaches in related mechanical and materials domains [23], [31], [33], [36], [39], [42]. In shaft design, this would accelerate optimization across larger factor spaces and provide sensitivity analyses at significantly lower computational cost.

## 6. Conclusion

This review study represents how propeller shaft design has evolved when material choice, structural design, and optimization methods are considered together rather than in isolation. A consistent observation across the studies is the growing shift from steel to composite shafts. In most reported cases, this change leads to a major drop in weight often around 50-80% without compromising strength or fatigue performance. At the same time, composites bring added advantages such as corrosion resistance and better vibration damping, which helps in improving overall driveline behaviour. Another important takeaway is the practical usefulness of the Taguchi approach. Instead of running a large number of trials, it allows designers to study multiple parameters in a structured and efficient way. When supported by finite element analysis, it becomes easier to estimate stresses, deformation, and fatigue response early in the design stage. This creates a more reliable development cycle where simulation and testing support each other.

From the overall research study, a few key points can be Derive:

- Composite shafts offer significant weight savings with comparable or improved mechanical performance.
- Taguchi DOE reduces experimental effort while identifying critical design parameters.
- FEA plays a crucial role in predicting behaviour before prototype development.
- Combining DOE and simulation leads to a more controlled and repeatable design process.

At the same time, some gaps are still evident. Many studies do not fully address factor interactions or real operating conditions. Manufacturing variations and cost constraints are also not always included in the optimization stage, even though they strongly affect practical implementation. These aspects need closer attention if designs are to move smoothly from research to industry, future work should move toward full-scale validation under realistic conditions and adopt multi-objective approaches that include cost and manufacturability. There is also growing potential in using data-driven methods to speed up design exploration. With continued improvements in composite materials and hybrid structures, further gains in performance and reliability can be expected. A combined approach using Taguchi methods together with simulation provides a sensible and effective path for developing lightweight and durable propeller shafts suited to modern engineering requirements.

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