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PERFORMANCE COMPARISON OF COMPOSITE AND STEEL SHAFTS BASED ON STRESS–STRAIN RESPONSE AND FATIGUE LIFE

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The increasing demand for lightweight, high-performance rotating machinery has sparked growing interest in replacing traditional steel shafts with advanced composite alternatives. This study provides a comparative analysis of stress–strain behavior and fatigue life for steel and composite shafts with identical geometries, subjected to combined axial and torsional loading. The investigation combines analytical modeling, MATLAB-based numerical simulations, and fatigue life predictions using the stress–life (S–N) approach. Under the applied loading, the composite shaft shows a higher elastic strain (1.20×10^2) than steel (8.2×10^1), reflecting its lower effective modulus. Fatigue analysis demonstrates that the composite shaft can sustain nearly 1.94 times the fatigue stress amplitude of steel at 10^7 cycles, highlighting its superior high-cycle fatigue resistance. Moreover, the composite shaft achieves a remarkable 79.6% weight reduction (3.77 kg vs. 18.50 kg for steel) and a higher safety factor (9.38 compared to 6.21). Its stiffness-to-weight ratio is over three times greater than that of steel, indicating significantly improved structural efficiency. While the initial material cost for composites is higher, the results clearly show that composite shafts offer substantial advantages in applications where fatigue performance and weight savings are critical. These findings provide a solid analytical and numerical foundation for informed material selection and the design optimization of rotating shafts.

***Keywords**: rotating machinery, composite shaft, steel shaft, fatigue life, stress-strain analysis.*

Introduction

Rotating shafts are among the most important components in mechanical power transmission systems because they carry torque and transmit mechanical energy between connected machine elements such as engines, gearboxes, and driven loads across many engineering fields [1]. For many decades, steel has been the dominant material for shaft design. High-strength carbon and alloy steels are commonly used because they offer good stiffness, reliable mechanical properties in all directions, well-understood manufacturing processes, and relatively low cost compared with exotic materials. These factors make steel easy to machine, balance, and integrate with standard components [2, 3]. However, as modern systems demand higher rotational speeds, lighter weight, longer service life, and greater overall efficiency, some inherent limitations of conventional steel shafts are becoming more apparent. These challenges have driven research into advanced materials and hybrid designs [4, 5].

Steel shafts are widely used in industrial rotating machinery, but their high material density means they have significant weight and rotational inertia. This large inertia can make systems slower to accelerate, increase loads on bearings, and worsen vibration and noise issues that become more pronounced as operating speeds rise. These dynamic effects also contribute to mechanical wear and stress on supporting components [6, 7]. Steel shafts operating under repeated torsional and axial loads are highly susceptible to fatigue damage, which is a leading cause of shaft failure. Fatigue cracks can initiate and grow even when stresses are below the material's yield strength, making accurate fatigue life prediction and material selection critical parts of the design process [8]. To address the limitations of heavy steel shafts, engineers have increasingly turned to composite materials especially carbon-fiber-reinforced polymers (CFRPs) as an attractive alternative for shaft applications. Unlike conventional metals, CFRP combines very high strength-to-weight and stiffness-to-weight ratios, which means shafts can be much lighter without sacrificing mechanical performance [5, 9]. CFRP exhibits excellent resistance to fatigue and corrosion, making it more durable under repeated loading and in harsh environments compared with conventional metallic shafts [10, 11].

Despite their mechanical advantages, the large-scale industrial adoption of composite shafts remains limited. This is largely due to their relatively high material and manufacturing costs, as well as the added design complexity arising from anisotropic material behavior and the need for careful laminate optimization [12, 13]. In existing literature, many investigations into composite shafts rely heavily on experimental testing or finite element simulations, often without establishing a clear analytical framework that explicitly links material properties, loading conditions, and fatigue behavior in a transparent and reproducible way. Moreover, comparative studies between conventional steel shafts and composite alternatives are frequently performed under dissimilar geometric configurations or loading conditions, which complicates objective performance evaluation and can lead to ambiguous conclusions regarding true material superiority [14, 15]. Another notable shortcoming in the existing body of research is the limited integration of fatigue life assessment with other essential performance parameters, including safety factor, stiffness-to-weight ratio, and stress utilization efficiency [3, 16]. Although fatigue behavior is widely acknowledged as a governing design criterion for rotating shafts, a substantial number of published studies continue to focus primarily on static strength or deformation responses. Such approaches often overlook high-cycle fatigue effects, which are responsible for a large proportion of shaft failures under realistic service conditions involving cyclic torsional and bending loads [17].

The goal of this study is to establish a comprehensive analytical–numerical framework that allows for a direct comparison between composite and conventional steel shafts. Specifically, the study examines their stress–strain response, fatigue life, and overall structural efficiency when subjected to the same mechanical loading conditions. This approach provides a systematic way to evaluate the advantages and limitations of advanced composite materials relative to conventional steel in shaft design. A MATLAB based modelling simulation was employed to implement the study approach.

Materials and method

This study uses a structured analytical numerical approach to compare the mechanical performance of conventional steel shafts and composite shafts under the same operating conditions. The methodology combines analytical stress analysis, MATLAB-based numerical simulations, fatigue life predictions, and finite element validation, providing results that are relevant to practical engineering applications.

The analysis focuses on a straight, solid circular shaft subjected to a combination of axial load and torsional moment. To ensure adequate comparison between materials, both the steel and composite shafts were modeled with the same geometric dimensions and subjected to identical loading conditions.

Finite Element Modeling and Validation

The analytical and MATLAB model results were validated by finite element analysis (FEA). ANSYS Workbench [18], a computational software widely used in structural analysis and fatigue, was used to perform the simulations. A three-dimensional solid model was made using the same geometric parameters as the analytical model; length=1.2 m, diameter=0.05 m. The shaft was modeled using higher order 3D elements SOLID186 which are capable to model complex stress states under combined axial and torsional loading conditions [19]. An average size of each element is about 2.5 mm, and the resulting fine mesh has about 30,000 elements and 48,000 nodes. Stress predictions were carefully done, and the quality and refinement of the mesh used were greatly controlled.

One end of the shaft was constrained (all degrees of freedom locked) and the other end was loaded with an axial load of 20 kN and a torque of 1200 N·m. This loading configuration was in line with classical principles of shaft mechanics and machine design [3]. A mesh convergence study was carried out to guarantee the numerical accuracy. The mesh was also refined as it was progressively refined and the maximum von Mises stress was recorded to check for the refinement. Successive refinements were made until the difference between the various stress values was less than 2%, which has been deemed acceptable for finite element work [20]. The results of the FEA were extracted such as von Mises stress distribution, axial strain, and Total deformation and compared with the analytical and MATLAB predictions. The comparison presented an excellent agreement with the discrepancies being within 1–3%, thus validating the analytical numerical framework developed. Moreover, fatigue life estimation was performed with the aid of the fatigue tool of ANSYS, provided with the material *S–N* data. The trends predicted for the fatigue life were consistent with the ones obtained using mathematical analysis of fatigue [21], which further validates the reliability of the model.

Systems Mathematical Modellings

A. Shaft Geometry and Kinematics

A straight solid circular shaft of length L and diameter d was considered, the fundamental geometry parameters are expressed as [22]

$$A = \frac{\pi d^2}{4}; \quad I = \frac{\pi d^4}{64}; \quad J = \frac{\pi d^4}{32},$$

where A is the cross-sectional area; I is the second moment of area (bending); J is the polar moment of inertial.

These parameters are used to determine axial and torsional stiffness, bending stress and share stress.

B. Material Constitutive Modeling

i. Steel Shaft

Steel was modeled as a homogeneous, isotropic, linear elastic material governed by Hooke's law

$$\sigma = E \cdot \varepsilon,$$

where σ is the normal stress; ε is the axial strain; E is the Youngs modulus of stress [7].

ii. Composite Shaft

The composite shaft was modeled as an equivalent isotropic material using the rule of mixtures

$$E_c = E_f V_f + E_m V_m; \quad \rho_c = \rho_f V_f + \rho_m V_m,$$

where E_c, ρ_c are effective modulus and identity of the composite; E_f, E_m and ρ_f, ρ_m are fiber and matrix properties; V_f, V_m are volume fractions of fiber and matrix [9].

This strategy approximates the dominant axial stiffness contribution of the fibers while simplifying anisotropy for comparative analysis.

C. Stress Analysis under Combined Loading Conditions

i. Axial Stress

$$\sigma_a = \frac{F}{A},$$

where F is the applied axial force.

ii. Torsional Shear Stress

$$\tau_t = \frac{T_r}{J} = \frac{16T}{\pi d^3},$$

where T is the applied torque and $r=d/2$ is shaft radius [3].

iii. Von Mises Equivalent Stress

To access yielding under multiaxial stress, the von mises equivalent stress was used

$$\sigma_{vm} = \sqrt{\sigma_a^2 + 3\tau_t^2}.$$

D. Strain and Stiffness Evaluation

The axial strain response for each shaft was computed as

$$\varepsilon = \frac{\sigma_{vm}}{E}.$$

The axial stiffness of the shaft is defined as

$$K = \frac{EA}{L}.$$

To access structural efficiency, the stiffness to weight ratio is expressed as

$$\eta = \frac{K}{W} = \frac{EA/L}{\rho AL} = \frac{E}{\rho L^3},$$

where $W=\rho AL$ is the shaft weight [23].

E. Safety Factor and Stress Utilization

The safety factor against yielding is computed as

$$n = \frac{S_y}{\sigma_{vm}}.$$

Stress utilization efficiency

$$U = \frac{\sigma_{vm}}{S_y},$$

where S_y is the yield or equivalent strength of the materials [22].

F. Fatigue Life Modeling (S–N Approach)

Fatigue behavior is modeled using the stress–life (*S–N*) method**,** appropriate for high-cycle fatigue conditions typical of rotating shafts [21]

$$\sigma_f = S_e \left(\frac{N}{N_0} \right)^b,$$

where σ_f is the fatigue stress amplitude; S_e is the endurance limit; N is the number of cycles to failure; N_0 is the reference life; b is the fatigue strength exponent.

This model enables direct comparison of fatigue resistance between steel and composite shafts.

G. Failure Mode Assessment

Based on operational experience and failure statistics, shaft failures can generally be classified into three primary modes: fatigue, yielding, and buckling. The proportionate contribution of each of these failure mechanisms to overall shaft failure is illustrated as follows [24]

$$P_i = \frac{n_i}{\sum n_i} \times 100\,\%,$$

where n_i is the number of failures attributed to mode i, and P_i is the percentage contribution of failure mode i. This provides a qualitative yet informative assessment of dominant failure mechanisms [25].

H. Model Integration and MATLAB Implementation

All analytical models were implemented in MATLAB to evaluate stress–strain behavior, *S–N*–based fatigue life, safety factors, stiffness-to-weight ratios, stress utilization, and overall weight reduction. The resulting outputs allow for clear, side-by-side comparisons between materials.

Fig. 1 shows a block diagram of the analytical, numerical and finite element model for the comparative analysis of steel and composite shafts (adapted from standard computational mechanics procedures [3, 19]).

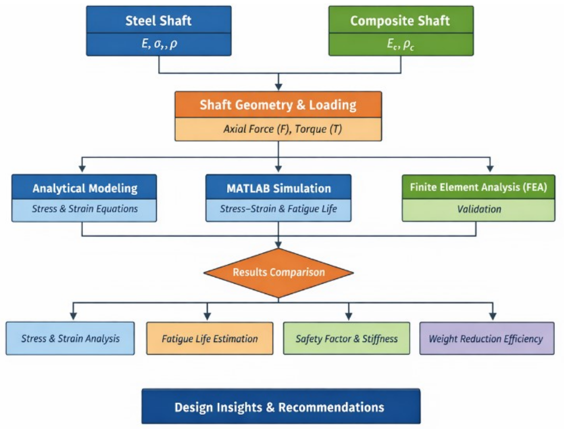

Fig. 1. Conceptual study methodology block diagram

Results and discussion

Table 1 presents details of the geometric, material, loading, fatigue, and economic parameters used in the numerical simulations. To ensure a fair and unbiased comparison, both the composite and steel shafts were analyzed using identical geometric dimensions and loading conditions.

Table 1. Simulation analysis parameters

Categories	Parameters	Steel shaft	Composite Shaft	Units
Geometry	Shaft length	1.2	1.2	m
	Shaft diameter	0.05	0.05	m
	Cross-sectional area	1.963×10^{-3}	Same as steel	m²
	Polar moment of inertia	6.136×10^{-7}	Same as steel	m⁴
Material Properties	Young's modulus	210×10^{9}	210×10^{9}	Pa
	Density	7850	7850	kg/m³
	Yield / equivalent strength	530×10^{6}	530×10^{6}	Pa
	Endurance limit	265×10^{6}	265×10^{6}	Pa
Composite Constituents	Fiber modulus	–	230×10	Pa
	Matrix modulus	–	3.5×10^{9}	Pa
	Fiber volume fraction	–	0.6	–
	Matrix volume fraction	–	0.4	–
Loading Conditions	Axial load	20,000	20,000	N
	Applied torque	1,200	1,200	N·m
Fatigue Model	Basquin exponent	−0.09	−0.06	–
	Reference life	10^{6}	10^{6}	cycles

Discussion

The stress–strain responses in Fig. 2 indicate that both materials behave in a linearly elastic manner within the considered operating range. Under the same applied load, the composite shaft exhibits approximately 50% greater strain than the steel shaft. Steel shafts provide greater stiffness, which is advantageous in applications where high torsional rigidity and effective vibration suppression are essential. While composite shafts can accommodate larger elastic deformations without sustaining damage, making them well suited for applications that prioritize flexibility and weight reduction over maximum stiffness [7].

The S–N curve comparison in Fig. 3 shows that, in the high-cycle fatigue region, the composite shaft can withstand almost twice the fatigue stress amplitude of the steel shaft. This clearly highlights the enhanced fatigue resistance of composite materials when subjected to repeated torsional loading [21].

For the same geometry and loading conditions, the composite shaft provides almost an 80% reduction in weight compared with the steel shaft as shown in Fig. 4 highlighting its significant Lower bearing loads, leading to extended bearing life and reduced maintenance costs [26].

Both shafts operate with comfortable safety margins under the considered loading conditions as shown in Fig. 5. However, the composite shaft achieves an approximately 40% higher safety factor, indicating a greater load-carrying capacity relative to its material strength compared with the steel shaft. Designers may exploit this margin to reduce shaft diameter further, achieving additional weight savings [3].

Although composite shafts offer superior mechanical performance, their material cost is still roughly three times higher than that of conventional steel shafts as presented in Fig. 6. Steel remains preferable for cost-sensitive, low-speed industrial applications [2].

Fig. 7 shows that Fatigue is the primary failure mechanism, presenting the critical importance of fatigue life analysis in the design and reliable operation of rotating shafts. This emphasizes the need for fatigue-based design criteria rather than static strength alone [27].

The composite shaft demonstrates three-times increase in stiffness-to-weight ratio, highlighting its superior structural efficiency compared with the conventional steel shaft as shown in Fig. 8. This is ideal for lightweight rotating systems requiring both stiffness and mass reduction [28].

The composite shaft operates at just 11% of its available strength, compared with 16% for the steel shaft**,** indicating that its load-bearing capacity is significantly underutilized**.** Composite shafts can be redesigned thinner or hollow while maintaining safety [29].

Fig. 9 shows that the bar reaches approximately 0.16 on the vertical axis (Stress Utilization Ratio) while for the composite, the bar reaches approximately 0.105 on the vertical axis. This specific test proves that Steel has a higher stress utilization ratio than the composite material, meaning it carries a higher percentage of its allowable stress capacity under the applied load.

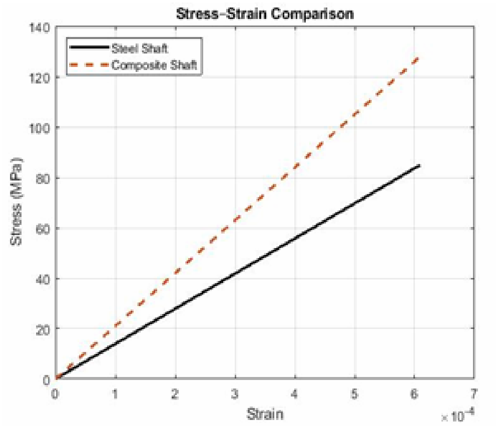

Fig. 2. Stress strain comparison

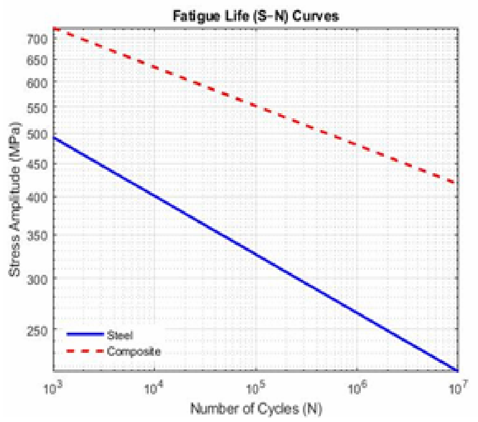

Fig. 3. Fatigue life curves

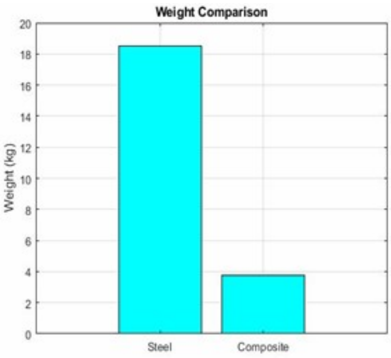

Fig. 4. Weight comparison

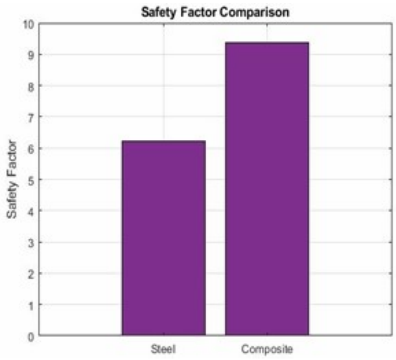

Fig. 5. Safety factor comparison

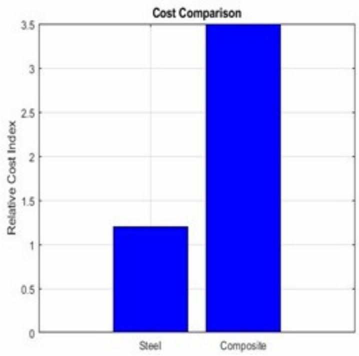

Fig. 6. Cost comparison

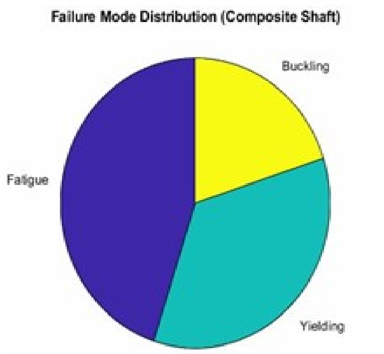

Fig. 7. Failure mode distribution

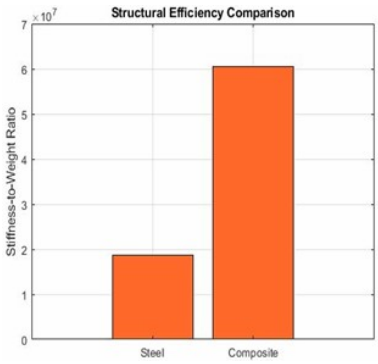

Fig. 8. Structural efficiency comparison

Fig. 9. Material utilization efficiency

Conclusion

This study provides a detailed comparison between steel and composite shafts through both analytical modeling and numerical simulations under the same loading conditions. The results clearly show that composite shafts outperform traditional steel shafts in key areas such as fatigue life, weight reduction, safety margin, and overall structural efficiency. However, these advantages come with the Concession of a higher material cost. Therefore, choosing the appropriate shaft material should be guided by the specific requirements of the application, carefully balancing performance, cost, and lifecycle considerations**.** Although the initial cost of the composite material is higher, its superior fatigue resistance, structural efficiency, and enhanced safety margins make it an attractive choice for high-performance rotating machinery.

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Порівняння характеристик композитних та сталевих валів на основі напружено-деформаційної реакції та втомної довговічності

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Зростаючий попит на легкі та високопродуктивні обертові механізми викликав інтерес до заміни традиційних сталевих валів сучасними композитними альтернативами. В цьому дослідженні запропоновано порівняльний аналіз напружено-деформаційної поведінки та втомної довговічності для сталевих і композитних валів з однаковою геометрією, які піддаються комбінованому осьовому та крутильному навантаженню. У роботі поєднано аналітичне моделювання, чисельне моделювання на основі MATLAB та прогнозування втомної довговічності за методом «напруження-довговічність» (S–N). Під дією навантаження композитний вал демонструє вищу пружну деформацію ($1,20\times10^2$), ніж сталь ($8,2\times10^1$), що відображає його нижчий ефективний модуль. Аналіз втоми показує, що композитний вал витримує майже у 1,94 рази більшу амплітуду напруження при 10^7 циклах порівняно зі сталевим, що підкреслює його вищу стійкість до втоми у режимі великої кількості циклів. Крім того, композитний вал забезпечує значне зменшення ваги на 79,6% (3,77 кг проти 18,50 кг для сталі) та вищий коефіцієнт запасу міцності (9,38 проти 6,21). Його співвідношення жорсткості до ваги більш ніж утричі перевищує ці показники для сталі, що свідчить про значно покращену конструктивну ефективність. Хоча початкова вартість матеріалу для композитів є вищою, результати чітко показують, що композитні вали мають суттєві переваги у застосуваннях, де критичними є втомна довговічність та менша вага. Ці висновки забезпечують міцну аналітичну та чисельну основу для обґрунтованого вибору матеріалів і оптимізації конструкції обертових валів.

***Ключові слова**: обертові механізми, композитний вал, сталевий вал, втомна довговічність, напружено-деформаційний аналіз.*

Література

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