

A REVIEW ON TORSIONAL PROPERTIES OF COMPOSITES

Rajkumar Patil^{1,2,*} and Anand Reddy¹

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Abstract

Composite materials have gained significant attention in various engineering fields due to their unique mechanical properties and versatility. This review focuses on the torsional properties of composite materials, exploring the fundamental aspects that govern their behavior when subjected to torsional loads. Torsional properties, including shear modulus, fiber orientation, anisotropy, torsional strength, manufacturing considerations, and testing methodologies, are examined in detail. Understanding the torsional behavior of composites is crucial for optimizing their performance in applications ranging from aerospace to sports equipment. This review paper provides a concise overview of the key considerations and parameters involved in assessing the torsional properties of composite materials, offering a foundation for further research and application in this field.

Keywords: Composites; Torsional Properties; Torsion Testing; Shear Modulus; Fiber; Matrix

Scope and objectives of this review article

The torsional properties of composite materials are a crucial aspect of their mechanical behavior and performance. Composite materials, which are typically composed of two or more distinct materials with different mechanical properties, offer a wide range of advantages in various applications, such as aerospace, automotive, construction, and sports equipment. Understanding their torsional properties is essential for designing and utilizing composite materials effectively (Panchacharam and Belarbi, 2002; Lee and Lee, 2004; Ogasawara *et al.*, 2007; Tan *et al.*, 2013; Sevkati *et al.*, 2014; Alabdulhady *et al.*, 2017).

Therefore, the present paper provides a comprehensive review on the torsional behavior of composite materials, critical parameters and testing methods. Analyses of the torsional properties of composites, such as torsional stiffness, toughness, and fatigue resistance is presented. Further, the recent developments, current challenges in applications of composites are explored for the future research work.

Organization of the paper: Scope and objectives of the present review paper are given in the first section. Various parameters and the factors influencing the torsional properties of the

¹ KLE Institute of Technology, Hubli affiliated to Visvesvaraya Technological University, Belagavi, 590018, Karnataka, India.
E-mail: rdpatil@dkte.ac.in

² Karnataka and Faculty of DKTE Society's Textile and Engineering Institute, Ichalkaranji, Maharashtra, India.

* Corresponding author

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composites are discussed in the second section. Testing methods for torsional properties of the composites are provided in section three. Recent advancements in torsion testing and challenges in optimizing these parameters are presented in section four and five respectively. Finally the Potential areas for further research and conclusions of the paper are provided in section six and seven respectively.

Factors Influencing the Torsional Properties

The torsional behavior of materials, including composite materials, is influenced by a variety of factors that determine how they respond to applied torsional loads. Understanding these factors is essential for designing and analyzing structures and components. Here are some of the key factors that influence torsional behavior:

Material Composition:

The type of matrix material (e.g., polymer, metal, ceramic) in a composite significantly affects torsional behavior. Different matrix materials have different shear moduli and shear strengths. - Reinforcing Fibers or Particles: The type, orientation, and volume fraction of reinforcing fibers or particles play a crucial role in determining torsional properties. High-strength and high-modulus fibers contribute to enhanced torsional stiffness and strength (Shin and Pae, 1992a; Shadmehri *et al.*, 2007; Mutasher *et al.*, 2009; Hao *et al.*, 2019).

Fiber Orientation:

The orientation of reinforcing fibers in the composite material has a substantial impact on torsional behavior. Fibers aligned with the applied torsional load direction provide the most significant contribution to torsional stiffness (Vo and Lee, 2007; Alabdulhady and Sneed, 2019a; Chaht *et al.*, 2019). The different orientations are shown in Figure 1.

Anisotropy:

Most composite materials exhibit anisotropic behavior, meaning their mechanical properties vary with direction. Anisotropy in torsional behavior arises from the inherent anisotropy of the material constituents and the laminate layup. Engineers must account for anisotropy in design and analysis (Davalos *et al.*, 2002; Vo and Thai, 2012).

Temperature and Environmental Conditions:

Changes in temperature and exposure to environmental factors, such as moisture or UV radiation, can affect the torsional properties of materials. For example, temperature variations can lead to changes in material stiffness and thermal expansion, which can influence torsional behavior (Vo and Lee, 2008; Ju *et al.*, 2013; Liao *et al.*, 2022).

Laminate Configuration:

In the case of laminated composite materials, the stacking sequence and the number of plies have a significant impact on torsional stiffness and strength. Different laminate configurations may exhibit distinct torsional behaviors (Alabdulhady and Sneed, 2018; Zhao *et al.*, 2018). These configurations are shown in Figure 2.

Type	Fiber Architecture	Remarks
1	Unidirectional one layer	N/A
2	Unidirectional two layers	N/A
3	Bi-directional	Bi-directional one layer
		Bi-directional using 0°/90° unidirectional fibers (two layers)
4	Random	Chopped fibers (25-75 mm) placed randomly in matrix

Figure 1. Fiber Orientations in Composites (Alwan *et al.*, 2010)

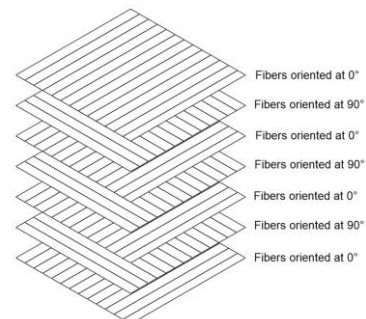


Figure 2. Laminated composite Configuration (Ipek *et al.*, 2018)

Manufacturing Quality:

Quality of manufacturing processes, such as layup, curing, and resin impregnation, can influence the homogeneity of the material and the presence of defects or voids. Variations in manufacturing quality can affect the torsional behavior of composites (Shokrieh *et al.*, 2004; Zhang *et al.*, 2018; Zhou *et al.*, 2022).

Testing Conditions:

The conditions under which torsional testing is conducted, such as temperature, strain rate, and test fixture design, can affect the observed torsional properties. Care must be taken to ensure that testing conditions are well-defined and consistent (Lakshman Kumar and Prakash, 2023).

Resin Type and Cure Process:

The choice of resin system and the curing process used in composite manufacturing can affect the material's torsional behavior. Curing conditions, such as temperature and pressure, can impact resin cure quality and subsequent torsional properties (Hoppel *et al.*, 1995; Stoddard, 1997; Branner *et al.*, 2007; Qureshi and Rao, 2014).

Moisture Absorption:

Some composite materials are susceptible to moisture absorption, which can weaken the material and affect its torsional performance. The rate and extent of moisture absorption depend on the material's matrix and reinforcement (Lee *et al.*, 1999; Ogasawara *et al.*, 2009).

Size and Geometry of the Specimen:

The size and geometry of the specimen used for torsional testing can influence the results. Smaller specimens may exhibit different torsional behavior compared to larger structural components [Günay and Sönmez, 2003; Zhou *et al.*, 2017; Alabdulhady *et al.*, 2019b].

Rate of Loading:

The rate at which the torsional load is applied can affect the material's response. Dynamic loading may reveal different properties compared to static loading (Zojaji and Kabir, 2012; Dobah, 2016; Taşdelen *et al.*, 2016; Won, 2021; Zhao, 2022).

Aging and Environmental Degradation:

Over time, composite materials may undergo aging or environmental degradation, which can lead to changes in torsional properties (Siriruk *et al.*, 2009). This is particularly relevant for materials used in long-term applications. Understanding and

controlling these factors is essential for predicting and optimizing the torsional behavior of composite materials in various engineering applications. Engineers and researchers must consider these factors in material selection, design, testing, and maintenance to ensure the desired performance and longevity of composite structures (Zhao and Pang, 1995; El-Assal and Khashaba, 2007; Khalid and Abdullah, 2018).

Case studies illustrating the factors influencing the torsional properties of composites are provided in Table 1. These case studies show the recent advancements, applications and potential future research directions.

Testing methods for Torsional Properties

The torsion testing of composite drive shaft is shown in Figure 3. Testing the torsional properties of composite materials is crucial for characterizing their mechanical behavior and ensuring they meet the desired specifications for specific applications. Several testing methods are commonly used to evaluate these properties (Sevkat and Tumer, 2013; Nhu and Tung, 2023). Here are some of the primary testing methods for torsional properties of composites:



Figure 3. Torsion Testing of Composite Drive Shaft (Lenwari *et al.*, 2022)

Torsion Testing:

Torsion testing involves subjecting a composite specimen to a twisting force, which induces shear deformation. The torque applied and the resulting angular deflection are measured to calculate the shear modulus and to observe the material's response to torsional loading. Torsion tests can be conducted in various configurations, including solid cylindrical specimens or tubular specimens, depending on the specific requirements (Hu *et al.*, 2017; Ramnath, 2017).

Table 1. Comparative analysis of the advantages and limitations of testing methods (Zhao and Pang, 1995; Tan *et al.*, 2013)

Factors/Applications	Details	Results
Hybrid Composites	A study comparing the torsional strength of hybrid composites with different fiber ratios, such as 50% carbon fiber and 50% glass fiber versus 75% carbon fiber and 25% glass fiber.	The 75% carbon fiber composite showed a 20% increase in torsional strength and a 15% reduction in weight compared to the 50% carbon fiber hybrid.
Nano composites	Incorporating 1% by weight of carbon nanotubes (CNTs) into an epoxy matrix.	The addition of CNTs resulted in a 30% increase in torsional modulus and a 25% increase in failure strain, demonstrating enhanced toughness and strength.
Damage Mechanisms	Analysing the failure modes of carbon fiber-reinforced polymer (CFRP) under torsional load using scanning electron microscopy (SEM).	SEM images revealed that matrix cracking initiates at 0.5% twist angle, followed by fiber-matrix debonding at 1% twist angle, leading to final failure at 1.5% twist angle.
Interface Studies	Comparing the torsional strength of composites with different surface treatments for improved fiber-matrix bonding.	Silane-treated glass fibers showed a 40% increase in torsional strength compared to untreated fibers due to improved interfacial adhesion.
Temperature Variations	Testing the torsional properties of a CFRP composite at -40°C, 25°C, and 80°C.	The composite exhibited a 15% increase in torsional stiffness at -40°C and a 10% decrease at 80°C, indicating significant temperature sensitivity.
Moisture and UV Exposure	Evaluating the torsional performance of composites after 1000 hours of UV exposure and water immersion.	UV exposure caused a 20% reduction in torsional strength, while water immersion resulted in a 10% decrease due to matrix degradation and fiber swelling.
Finite Element Analysis (FEA)	Using FEA to simulate the torsional behaviour of a composite drive shaft and comparing it with experimental results.	The FEA model predicted a torsional stiffness within 5% of the experimental value, validating the model's accuracy for design optimization.
Multi scale Modelling	Linking molecular dynamics simulations of polymer matrix behaviour to macro-scale torsional performance.	Predicted a 25% increase in macroscopic torsional strength when molecular-level crosslink density was increased by 10 %.
Non-Destructive Testing (NDT)	Applying digital image correlation (DIC) to monitor strain distribution during torsional testing of a composite beam.	DIC detected early-stage damage at 0.3% twist angle, allowing for timely intervention before catastrophic failure.
Standardization	Developing a new ASTM standard for torsional testing of composite tubes, including specific guidelines for specimen preparation and testing procedures.	Improved consistency and reproducibility of test results across different laboratories.
Fatigue and Durability	Performing cyclic torsional tests on a CFRP tube at varying load levels to determine fatigue life.	The composite tube endured 1 million cycles at 50 % of ultimate torsional strength but failed after 100,000 cycles at 75 % load level.
Creep and Relaxation	Measuring the creep behaviour of a glass fiber composite under a constant torsional load for 1000 hours.	The composite exhibited a 2 % twist increase due to creep, highlighting the importance of considering long-term deformation in design.
Aerospace and Automotive	Analysing the torsional performance of composite helicopter rotor blades under operational conditions.	Composite blades showed a 30% reduction in weight and a 25% increase in torsional stiffness compared to traditional aluminium blades, leading to improved fuel efficiency.
Biomedical Implants	Investigating the torsional properties of a composite bone plate used for fracture fixation.	The composite plate demonstrated a 20% higher torsional stiffness and better biocompatibility compared to metallic counterparts, reducing the risk of implant failure and promoting faster healing.
Machine Learning and Data Analysis	Using machine learning algorithms to predict torsional strength based on composite layup configurations and material properties.	The model achieved 95% accuracy in predicting torsional strength, enabling rapid optimization of composite designs.
Data-Driven Insights	Analysing a dataset of torsional test results to identify trends in material performance.	Data analysis revealed that increasing fiber volume fraction by 10% consistently improved torsional strength by 15%, providing guidelines for material selection.

Shear Test:

Shear tests are designed to measure the shear strength and shear modulus of composites. A specimen is loaded in pure shear, and the applied force and the resulting shear strain are recorded. Shear tests are often used to determine the in-plane shear properties of composite materials (Hii and Al-Mahaidi, 2006; Nirala *et al.*, 2020).

Torsional Resonance Testing:

Torsional resonance tests are used to evaluate the shear modulus and damping properties of

composites. These tests involve applying a sinusoidal torsional load at varying frequencies to a specimen. The specimen's response is analyzed to determine its dynamic shear modulus and the loss factor, which indicates the material's ability to dissipate energy (Joo *et al.*, 2010; Li *et al.*, 2004). The test set up is as shown in Figure 4.

Twist Angle Measurement:

In some cases, torsional properties can be assessed by measuring the twist angle of a specimen subjected to a known torque. The relationship

between the applied torque and the twist angle provides information about the shear modulus (Lee, 1993).

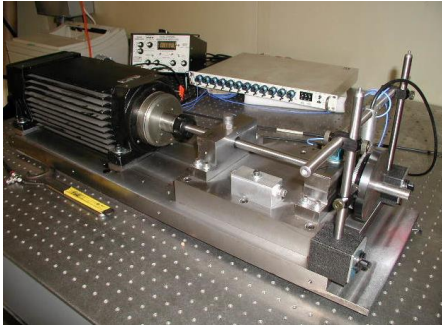


Figure 4. Torsional resonance Testing (Joo *et al.*, 2010)

Inter laminar Shear Test:

For laminated composite materials, inter laminar shear properties are essential to evaluate. These properties can be assessed using testing methods specifically designed to measure the shear behavior between adjacent layers or plies of composite laminates (Tibhe and Rathi, 2016).

Digital Image Correlation (DIC):

DIC is a non-contact, optical measurement technique that can be used to assess the deformation and strain distribution during torsional testing. It provides detailed information about the material's response to torsional loads (Minguet, 1989; Liu *et al.*, 2014).

Finite Element Analysis (FEA):

FEA is a computational method that can simulate the torsional behavior of composite materials based on their material properties, geometry, and boundary conditions. FEA can complement experimental testing and aid in the design and optimization of composite structures (Yoon *et al.*, 2017).

Acoustic Emission (AE):

Acoustic emission testing can be employed to monitor the onset of damage, such as micro cracking or fiber breakage, during torsional testing. It provides information about the integrity and damage progression in composite materials (Lee *et al.*, 2004; Chang *et al.*, 2022).

When choosing a testing method for assessing the torsional properties of composite materials, it is essential to consider the specific goals of the evaluation, the type of composite material (e.g., continuous fiber-reinforced, chopped fiber, laminates), and the available testing equipment. Additionally, standard testing procedures and guidelines, such as those provided by ASTM International or ISO, should be followed to ensure accurate and reproducible results.

The Comparative analysis of the advantages and limitations of the above explained Testing Methods is presented in Table 2. Further, the Standards and Guidelines for Torsion Testing Methods are listed in Table 3.

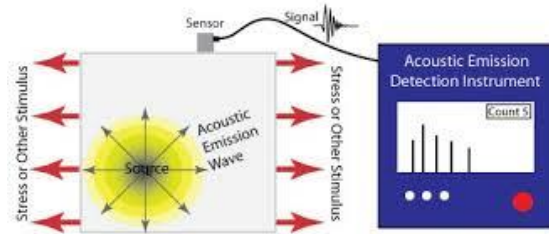
Table 2. Comparative analysis of the advantages and limitations of Testing Methods (Sevkat and Tumer, 2013 - Chang *et al.*, 2022)

Method	Advantages	Limitations
Torsion Test	Direct measurement, real-world simulation, simple setup	Stress concentrations, specific geometries, brittle materials
Shear Test	Direct shear properties, simple setup, versatile	Achieving pure shear, specimen preparation, limited strain range
Torsional Resonance Test	Dynamic properties, non-destructive, high sensitivity	Complex setup, limited frequency range, complex data analysis
Twist Angle Measurement	Simple and direct, real-time data, cost-effective	Accuracy, limited information, specific geometries
Inter-laminar Shear Test	Composite focus, critical property, direct shear measurement	Specimen preparation, limited to composites, complex failure modes
Finite Element Analysis	Non-destructive, complex geometries, parametric studies	Model accuracy, computational resources, validation
Digital Image Correlation	Full-field measurement, non-contact, high resolution	Complex setup, surface preparation, expensive equipment
Acoustic Emission	Early detection, non-destructive, real-time monitoring	Noise sensitivity, complex data analysis, localization challenge

Table 3. Summary of Standards and Guidelines (Sevkat and Tumer, 2013; Chang *et al.*, 2022)

Method	Standards and Guidelines
Torsion Test	ASTM E143, ASTM A938
Shear Test	ASTM D5379, ASTM D7078
Torsional Resonance Test	ISO 6721-6, ASTM E756
Twist Angle Measurement	ISO 7743, ASTM D4065
Inter laminar Shear Test	ASTM D2344/D2344M, ISO 14130
Finite Element Analysis	ISO 10303 (STEP), ASME V&V 10-2006, NAFEMS
Digital Image Correlation	ISO 16063-49, VIC-3D
Acoustic Emission	ASTM E1316, ASTM E2075, ISO 12713

Gu *et al.*, 2021; Jiang *et al.*, 2023; Mollaei *et al.*, 2023).

**Figure 5. Acoustic Emission Testing (AE) (Atea, 2017)**

Recent Advancements in Torsion Testing

Torsion testing of composites has seen several recent advancements driven by the need for more accurate, efficient, and comprehensive assessment of these materials. Some of the notable advancements in torsion testing of composites include:

Digital Image Correlation (DIC):

DIC technology has seen widespread adoption in torsion testing. It allows for non-contact, full-field strain measurement by tracking surface deformations using cameras. DIC provides valuable insights into strain distribution during torsional loading and helps identify localized stress concentrations (Mohamed and Benmokrane, 2015; Stedile Filho *et al.*, 2018; Wu and Pei, 2022).

Acoustic Emission (AE):

AE monitoring has become increasingly integrated into torsion testing setups. AE sensors detect and analyze the acoustic waves emitted by the material as it undergoes deformation. This technology can provide early detection of damage, such as micro cracking, and help assess the material's structural health (Park, 1985; Atea, 2017). The set up for acoustic emission is as shown in Figure 5.

High-Speed Torsion Testing:

Recent advancements in high-speed testing equipment have enabled the assessment of composite materials under dynamic or impact loading conditions. This is particularly important in applications where composites are subjected to rapid torsional forces, such as in impact-resistant structures or sports equipment (Berring *et al.*, 2007;

Micromechanics and Multiscale Modeling:

The development of advanced micromechanical models and multiscale modeling techniques has allowed for a deeper understanding of the behavior of composite materials during torsion. These models can predict the response of composites at various length scales and provide insights into the influence of microstructural features (Kumar and Mantena, 1996; Ogasawara *et al.*, 2007; Yang *et al.*, 2013; Bulut, 2019).

In Situ Monitoring and Imaging:

In situ testing and imaging techniques, such as X-ray computed tomography (CT) and scanning electron microscopy (SEM), have been employed to visualize and analyze the internal deformation and damage mechanisms of composites during torsional loading. This enables a better understanding of failure modes and mechanisms (Gaurav and Singh, 2018; Han *et al.*, 2020; Slovikov and Lobanov, 2020).

Digital Twin and Predictive Analytics:

The integration of digital twin technology and predictive analytics allows for real-time monitoring of torsional behavior and the prediction of material performance based on input conditions. This can lead to more informed decision-making in real-world applications (Baihaqi *et al.*, 2021).

Non-Destructive Testing (NDT):

Advances in non-destructive testing methods, such as ultrasonic testing and eddy current testing, have been applied to assess the internal quality of composite materials with minimal disruption. These NDT methods are especially valuable in the aerospace and automotive industries (Zhang *et al.*, 2023).

Automated Testing Systems:

Automation in torsion testing has gained popularity for its ability to increase testing efficiency and reduce human error. Automated systems can precisely control loading conditions and collect data more consistently (Kimoto, 2011).

Environmental Simulation:

Torsion testing setups now incorporate environmental chambers that can simulate various conditions, including temperature, humidity, and chemical exposure. This enables researchers to investigate how torsional properties change under different environmental factors (Shin and Pae, 1992b).

Data Analytics and Machine Learning:

Advanced data analysis techniques and machine learning algorithms are applied to the vast amount of data generated during torsion testing (Francis *et al.*, 1977; Chou *et al.*, 2019; Lu, 2022). These tools help extract valuable insights and patterns from complex data sets, leading to improved material characterization and prediction of material behavior. These recent advancements in

torsion testing listed in Table 4 have enhanced our ability to understand and evaluate the mechanical behavior of composite materials, ultimately contributing to the development of more reliable and efficient composite structures in a wide range of industries.

Challenges in optimizing torsional properties of composites

Optimizing the torsional properties of composite materials presents several challenges due to the complex interplay of various factors and requirements in material design and application. Some of the key challenges in optimizing torsional properties are as follows:

Anisotropy:

Composite materials are inherently anisotropic, meaning their properties vary with direction. Optimizing torsional properties in such materials requires carefully considering the orientation of reinforcing fibers and their effect on torsional stiffness and strength (Gong *et al.*, 2018).

Table 4. Advancements in torsion testing which addressed the limitations of traditional methods (Stedile, 2018; Chou *et al.*, 2019)

Advancement	Addressed Limitation
Enhanced Gripping and Fixtures	Minimizes stress concentrations, ensuring accurate results.
Automated Data Acquisition	Reduces human error, provides real-time data logging, and increases efficiency.
Integration with DIC	Offers full-field strain measurement and detailed deformation insights.
Improved Material Characterization	Expands the range of testable materials and geometries.
High-Temperature Testing	Allows testing under realistic operating conditions.
Micro/Nano-Scale Testing	Enables precise testing of small-scale specimens.
Torsional Fatigue Testing	Provides insights into cyclic loading and fatigue behavior.
Computational Integration	Enhances predictive capabilities and understanding of complex behaviors.
Hybrid Testing Systems	Offers comprehensive material characterization by combining multiple test methods.
Advanced Sensors	Increases sensitivity and measurement range, improving test accuracy.
Non-Destructive Techniques	Enables monitoring of damage initiation and progression without destroying the specimen.

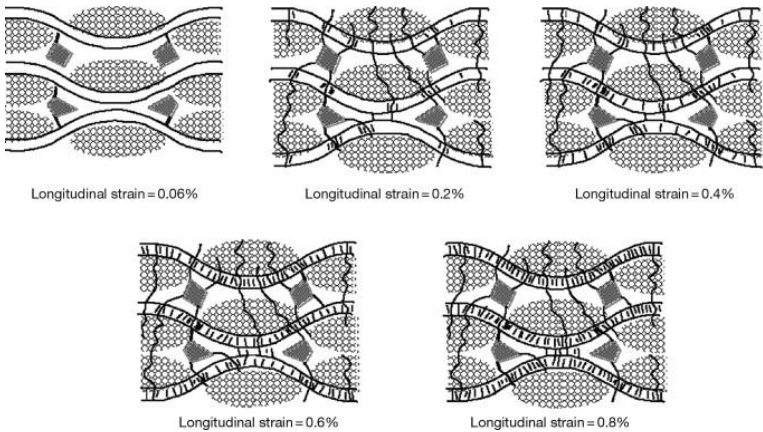


Figure 6. Fiber-Matrix Interface (Steinberg *et al.*, 2013)

Balancing Multiple Properties:

Engineering materials often require a balance between multiple properties, such as torsional stiffness, strength, weight, and cost. Achieving an ideal compromise between these factors can be challenging, as optimizing one property may negatively impact another (Yang *et al.*, 2018).

Fiber-Matrix Interface:

The quality of the bond between reinforcing fibers and the matrix material is crucial and it is demonstrated in Figure 6. Weak interfaces can lead to premature fiber pull-out or delamination during torsional loading. Achieving a strong fiber-matrix interface while maintaining other desirable properties is a challenge (Shokrieh and Hasani, 2002; Steinberg *et al.*, 2013).

Variability in Manufacturing:

The manufacturing process introduces variability in composite materials. Achieving consistent material properties and torsional behavior in large-scale production can be difficult due to variations in factors like fiber alignment, resin distribution, and curing conditions (Li *et al.*, 2011. Mahdi and Hamouda, 2013).

Environmental Effects:

Composite materials may be exposed to a range of environmental conditions during their service life, including temperature variations, moisture, and UV radiation. Optimizing torsional properties for long-term durability in such environments is challenging (Li *et al.*, 2001).

Scaling Effects:

Scaling up composite structures from small-scale specimens to full-scale components can be challenging. Material properties at the microscale

may not directly translate to macroscopic behavior. Ensuring the optimization of torsional properties at all scales is a complex task (El-Assal and Khashaba, 1999; Deifalla *et al.*, 2013; Porter *et al.*, 2015).

Damage Tolerance and Failure Modes:

Understanding and mitigating potential failure modes in composites under torsional loads is essential. Balancing torsional stiffness and strength with damage tolerance, such as the ability to resist delamination or fiber breakage, can be challenging (Gholami and Rezaeepazhand, 2011).

Material Selection:

Selecting the right combination of matrix material and reinforcing fibers is crucial. Different applications may require different material combinations to optimize torsional properties. The selection process is influenced by factors such as cost, availability, and processing requirements (Abdullah, 2017).

Non-Destructive Testing:

Ensuring the optimization of torsional properties requires reliable non-destructive testing methods for quality control and in-service monitoring. Developing and implementing effective NDT techniques for composites can be a challenge (Hsieh, 2007).

Interlaminar Shear:

Optimizing interlaminar shear properties, which are critical in laminated composites, can be challenging due to the need to maintain strong bonding between adjacent layers while achieving the desired torsional properties (Onta *et al.*, 2006; Gireesh *et al.*, 2013). The Inter Laminar shear is shown in Figure 7.

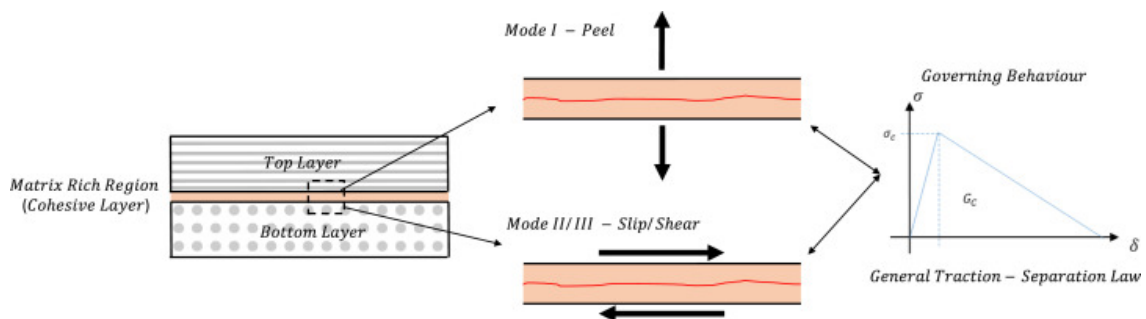


Figure 7. Inter laminar Shear(Onta *et al.*, 2006)

Cost and Production Constraints:

Composites can be expensive to manufacture, and achieving the desired torsional properties while staying within budgetary constraints can be a significant challenge for many industries (Wu *et al.*, 2018; Du *et al.*, 2019; Gay, 2022).

Regulatory and Certification Requirements:

In highly regulated industries like aerospace, meeting stringent certification standards while optimizing torsional properties can be a significant challenge (Maeda *et al.*, 1998). To address these challenges, a multidisciplinary approach is often required, involving materials science, engineering, manufacturing processes, and advanced testing and simulation techniques. Collaboration between researchers, engineers, and material scientists is essential for developing innovative solutions to optimize torsional properties in composite materials while meeting specific application requirements. Some of the successful optimization approaches for optimizing the torsional properties of composites are discussed below.

Successful optimization approaches:

Design of Experiments (DOE): DOE techniques, like Taguchi methods or response surface methodology, help identify the most influential factors affecting torsional behavior and optimize test parameters (Minguet, 1989; Mane and Patil, 2021).

Finite Element Analysis (FEA): FEA simulations allow for virtual testing and optimization of composite structures, reducing the need for physical prototypes and accelerating the testing process (Liu *et al.*, 2014; Yoon *et al.*, 2017).

Artificial Neural Networks (ANNs): ANNs can predict torsional behavior and optimize testing parameters by learning from experimental data and simulating various scenarios (Lee *et al.*, 2004).

Genetic Algorithm (GA): GA can optimize composite material properties, fiber orientation, and testing conditions to achieve desired torsional performance (Chang *et al.*, 2022).

Response Surface Optimization (RSO): RSO combines experimental design and statistical modeling to optimize torsion testing parameters and predict composite behavior (Stedile *et al.*, 2018).

Multi-Objective Optimization (MOO): MOO techniques, like Pareto optimization, balance competing objectives (e.g., maximizing strength while minimizing weight) in composite torsion testing (Mohamed and Benmokrane, 2015).

Machine Learning (ML): ML algorithms, such as support vector machines or random forests, can predict torsional behavior and optimize testing

conditions based on large datasets (Wu and Pei, 2022).

Optimization of Fiber Orientation: Optimizing fiber orientation can improve torsional strength and stiffness, achieved through techniques like fiber steering or tailored fiber placement (Park, 1985).

Hybrid Optimization: Combining multiple optimization techniques (e.g., FEA + ANN or DOE + GA) can lead to more efficient and effective torsion testing of composites (Atea, 2017).

Surrogate-Based Optimization: Using surrogate models (e.g., polynomial regression or radial basis functions) to approximate complex composite behavior can speed up optimization processes [Berring *et al.*, 2007].

These optimization approaches help improve the efficiency, accuracy, and cost-effectiveness of torsion testing in composites, leading to better material characterization and structural design.

Potential Areas for Further Research

The present study of recent advancements in estimating and enhancing the torsional properties of composites will provides us the several potential future research directions. Here are the some areas worth exploring:

Advanced Composites and Nona-composite Materials: Investigate the torsional behaviour of hybrid and bio composites to enhance mechanical properties. Study the effects of incorporating Nano-materials (e.g. carbon nanotube, graphene) on the torsional strength and stiffness of composite materials (Lee *et al.*, 1999).

Customizable Composites: Exploring 3D printing techniques to create composites with tailored torsional properties for specific applications. Investigating how different printing parameters affect the torsional properties and how to optimize these parameters for the desired performance (Alabdulhady *et al.*, 2019b).

Self-Healing Materials: Research on composites with self-healing capabilities under torsional stress could lead to materials that can repair micro-cracks autonomously, enhancing longevity and reliability (Günay and Sönmez, 2003).

Microstructural Analysis: Conduct detailed microstructural analyses to understand failure modes and damage mechanisms under torsional loads. Explore the role of the fiber-matrix interface in torsional performance and ways to improve interfacial bonding (Zhou *et al.*, 2017).

Comprehensive Characterization: Combining micro-scale and macro-scale analysis to gain a deeper understanding of the relationship between microstructural features and torsional performance (Taşdelen *et al.*, 2016).

Environmental Effects: Examine how different temperatures (e.g., cryogenic, elevated) affect the torsional properties of composites. Investigate the impact of environmental factors like moisture absorption and UV exposure on the long-term torsional performance of composites (Dobah, 2016; Zhao, 2022).

Modelling and Simulation studies: Develop FEA models to predict the torsional behaviour of complex composite structures. Implement multi scale modelling and simulation techniques to link microstructural properties with macroscopic torsional performance (Siriruk *et al.*, 2009).

Testing Methods and Standards: Explore advanced NDT methods (e.g., acoustic emission, digital image correlation) for real-time monitoring of torsional tests. Further developing standardized testing protocols for torsion tests specific to composite materials (Sevkat and Tumer, 2013).

Fatigue and Durability: Study the fatigue behaviour of composites under cyclic torsional loads and identify factors influencing fatigue life. Investigate the long-term creep and stress relaxation behaviour of composites under sustained torsional loading (Massa and Barbero, 1998).

Applications and Case Studies: Analyse the torsional performance of composites used in aerospace and automotive components to identify potential improvements. Research the torsional properties of composite materials used in biomedical implants and devices (Gaurav and Singh, 2018).

Machine Learning and Data Analysis: Utilize machine learning algorithms to predict torsional properties based on material composition and processing parameters. Leverage large datasets from torsional tests to uncover trends and optimize composite formulations (Han *et al.*, 2020).

Embedded Sensors: Developing composites with embedded sensors for structural health monitoring, allowing for real-time assessment of torsional loads and damage (Zhang *et al.*, 2023).

These research directions can help in furthering our understanding of composite materials' torsional behaviour and developing more robust and efficient composite structures for various applications.

Conclusions

The torsional properties in composite materials is of paramount importance as it has far-reaching implications across various applications. In the present paper the various parameters on which the torsional properties of composites depends are discussed. Experimental and numerical methods for evaluating the torsional properties of composites such as shear strength, shear modulus and damping characteristics are explained. Advanced torsional testings methods which addresses the limitations of traditional method are presented. Further, the potential research directions through which the torsional properties of composites can be enhanced for future applications and measured accurately are explored.

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References

- Abdullah, F.A. (2017). Effect of environment on torsional fatigue test of composite material. *International Journal of Energy and Environment*, 8(4):339-346.
- Alabdulhady, M.Y., Aljabery, K., and Sneed, L.H. (2019b). Analytical study on the torsional behavior of reinforced concrete beams strengthened with FRCC composite. *Journal of Composites for Construction*, 23(2):04019006. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000924](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000924)
- Alabdulhady, M.Y., and Sneed, L.H. (2018). A study of the effect of fiber orientation on the torsional behavior of RC beams strengthened with PBO-FRCM composite. *Construction and Building Materials*, 166:839-854. <https://doi.org/10.1016/j.conbuildmat.2018.02.005>
- Alabdulhady, M.Y., and Sneed, L.H. (2019a). Torsional strengthening of reinforced concrete beams with externally bonded composites: A state of the art review. *Construction and Building Materials*, 205:148-163. <https://doi.org/10.1016/j.conbuildmat.2019.02.011>
- Alabdulhady, M.Y., Sneed, L.H., and Carloni, C. (2017). Torsional behavior of RC beams strengthened with PBO-FRCM composite-An experimental study. *Engineering Structures*, 136:393-405. <https://doi.org/10.1016/j.engstruct.2017.01.012>
- Alwan, V., Gupta, A., Sekhar, A.S., and Velmurugan, R. (2010). Dynamic analysis of shafts of composite materials. *Journal of Reinforced Plastics and Composites*, 29(22):3,364-3,379. <https://doi.org/10.1177/0731684410371404>

- Atea, R.S. (2017). Torsional behavior of reinforced concrete T-beams strengthened with CFRP strips. *Case Studies in Construction Materials*, 7:110-117. <https://doi.org/10.1016/j.cscm.2017.03.002>
- Baihaqi, N.N., Khalina, A., Nurazzi, N.M., Aisyah, H.A., Sapuan, S.M., and Ilyas, R.A. (2021). Effect of fiber content and their hybridization on bending and torsional strength of hybrid epoxy composites reinforced with carbon and sugar palm fibers. *Polimery*, 66(1):36-43. <https://doi.org/10.14314/polimery.2021.1.5>
- Berring, P., Branner, K., Berggreen, C., and Knudsen, H. W. (2007). Torsional performance of wind turbine blades-part I: Experimental investigation. In 16th International Conference on Composite Materials, V43.
- Branner, K., Berring, P., Berggreen, C., and Knudsen, H.W. (2007). Torsional performance of wind turbine blades-Part II: Numerical validation. In International conference on composite materials (ICCM-16), 8-13.
- Bulut, M. (2019). Torsional behavior of thin section glass fiber/epoxy composite filament wound tubes: Numerical modelling. *European Mechanical Science*, 3(2):52-55. <https://doi.org/10.26701/ems.526761>
- Chaht, F.L., Mokhtari, M., and Benzaama, H. (2019). Using a Hashin Criteria to predict the damage of composite notched plate under traction and torsion behavior. *Frattura ed Integrità Strutturale*, 13(50):331-341. <https://doi.org/10.3221/IGF-ESIS.50.27>
- Chang, Y., Wen, W., Xu, Y., Cui, H., and Xu, Y. (2022). Quasi-static mechanical behavior of filament wound composite thin-walled tubes: Tension, torsion, and multi-axial loading. *Thin-Walled Structures*, 177:109361. <https://doi.org/10.1016/j.tws.2022.109361>
- Chou, T.Y., Tsai, H.Y., and Yip, M.C. (2019). Preparation of CFRP with modified MWCNT to improve the mechanical properties and torsional fatigue of epoxy/polybenzoxazine copolymer. *Composites Part A: Applied Science and Manufacturing*, 118:30-40. <https://doi.org/10.1016/j.compositesa.2018.11.014>
- Davalos, J.F., Qiao, P., Wang, J., Salim, H.A., and Schlussel, J. (2002). Shear moduli of structural composites from torsion tests. *Journal of Composite Materials*, 36(10):1,151-1,173. <https://doi.org/10.1177/0021998302036010486>
- Deifalla, A., Awad, A., and Elgarhy, M. (2013). Effectiveness of externally bonded CFRP strips for strengthening flanged beams under torsion: An experimental study. *Engineering Structures*, 56:2,065-2,075. <https://doi.org/10.1016/j.engstruct.2013.06.027>
- Dobah, Y., Bourchak, M., Bezazi, A., Belaadi, A., and Scarpa, F. (2016). Multi-axial mechanical characterization of jute fiber/polyester composite materials. *Composites Part B: Engineering*, 90:450-456. <https://doi.org/10.1016/j.compositesb.2015.12.013>
- Du, F., Alghamdi, S., Riabbans, B., and Tan, T. (2019). An experimental study on the fracture of a unidirectional carbon fiber-reinforced composite under quasistatic torsion. *Composites Part B: Engineering*, 172:547-554. <https://doi.org/10.1016/j.compositesb.2019.03.009>
- El-Assal, A.M. and Khashaba, U.A. (1999). Combined torsional and bending fatigue of unidirectional GFRP composites. In Proceedings of the second international conference on mechanical engineering. Adv Tech for Indus Prod. Egypt: Assiut University, 1:206-216.
- El-Assal, A.M. and Khashaba, U.A. (2007). Fatigue analysis of unidirectional GFRP composites under combined bending and torsional loads. *Composite Structures*, 79(4):599-605. <https://doi.org/10.1016/j.compstruct.2006.02.010>
- Francis, P.H., Walrath, D.E., Sims, D.F., and Weed, D.N. (1977). Biaxial fatigue loading of notched composites. *Journal of Composite Materials*, 11(4):488-501. <https://doi.org/10.1177/002199837701100405>
- Gaurav, A. and Singh, K.K. (2018). Fatigue behavior of FRP composites and CNT-embedded FRP composites: A review. *Polymer Composites*, 39(6):1,785-1,808. <https://doi.org/10.1002/pc.24113>
- Gay, D. (2022). Composite materials: design and applications. *Composite Materials*, 24. <https://doi.org/10.1201/9781003195788-9>
- Gholami Bazehhour, B. and Rezaeepazhand, J. (2011). Approximate torsional analysis of multi-layered tubes with non-circular cross-sections. *Applied Composite Materials*, 18:485-497. <https://doi.org/10.1007/s10443-011-9213-z>
- Gireesh, B., Sollapur Shrishail, B., and Satwik, V.N. (2013). Finite element and experimental investigation of composite torsion shaft. *International Journal of Engineering Research and Applications*, 3(2):1,510-1,517.
- Gong, L., Gao, X., Yang, H., Liu, Y., and Yao, X. (2018). Design on the driveshaft of 3D 4-directional carbon fiber braided composites. *Composite Structures*, 203:466-473. <https://doi.org/10.1016/j.compstruct.2018.02.075>
- Gu, Y., Zhang, D., Zhang, Z., Sun, J., Yue, S., Li, G., and Qian, K. (2021). Torsion damage mechanisms analysis of two-dimensional braided composite tubes with digital image correction and X-ray micro-computed tomography. *Composite Structures*, 256:113020. <https://doi.org/10.1016/j.compstruct.2020.113020>
- Günay, E. and Sönmez, M. (2003). Mechanical behavior of wood under torsional tensile loadings. *Gazi University Journal of Science*, 16(4):733-749.
- Han, H., Liu, L., and Cao, D. (2020). Dynamic modeling for rotating composite Timoshenko beam and analysis on its bending-torsion coupled vibration. *Applied Mathematical Modelling*, 78:773-791. <https://doi.org/10.1016/j.apm.2019.11.001>
- Hao, W., Huang, Z., Zhang, L., Zhao, G., and Luo, Y. (2019). Study on the torsion behavior of 3-D braided composite shafts. *Composite Structures*, 229:111384. <https://doi.org/10.1016/j.compstruct.2019.111384>
- Hii, A.K. and Al-Mahaidi, R. (2006). Experimental investigation on torsional behavior of solid and box-section RC beams strengthened with CFRP using photogrammetry. *Journal of Composites for Construction*, 10(4):321-329. [https://doi.org/10.1061/\(ASCE\)1090-0268\(2006\)10:4\(321\)](https://doi.org/10.1061/(ASCE)1090-0268(2006)10:4(321))
- Hoppel, C.P., Bogetti, T.A., and Gillespie Jr, J.W. (1995). Literature Review-Effects of hydrostatic pressure on the mechanical behavior of composite materials. *Journal of Thermoplastic Composite Materials*, 8(4):375-409. <https://doi.org/10.1177/089270579500800404>
- Hsieh, K. (2007). Numerical modeling and analysis of composite beam structures subjected to torsional loading. *Virginia Tech*, 1-105
- Hu, Y., Yang, M., Zhang, J., Song, C., and Hong, T. (2017). Effect of stacking sequence on the torsional stiffness of the composite drive shaft. *Advanced Composite Materials*, 26(6):537-552. <https://doi.org/10.1080/09243046.2016.1207126>
- Ipek, G., Arman, Y., and Celik, A. (2018). The effect of delamination size and location to buckling behavior of composite materials. *Composites Part B: Engineering*, 155:69-76. <https://doi.org/10.1016/j.compositesb.2018.08.002>
- Jiang, Q., Chen, H., Chen, L., Zhong, Z., Wu, X., Yi, H., and Wu, L. (2023). Experimental and Finite Element Simulation of Torsional Performance of Skin-core Carbon Fiber-reinforced Composite Rod. *Applied Composite Materials*, 1-18. <https://doi.org/10.1007/s10443-022-10090-9>

- Joo, S.H., Yoon, S.C., Lee, C.S., Nam, D.H., Hong, S.H., and Kim, H.S. (2010). Microstructure and tensile behavior of Al and Al-matrix carbon nanotube composites processed by high pressure torsion of the powders. *Journal of Materials Science*, 45:4,652-4,658. <https://doi.org/10.1007/s10853-010-4382-y>
- Ju, H., Lee, D.H., Hwang, J.H., Kang, J.W., Kim, K.S., and Oh, Y.H. (2013). Torsional behavior model of steel-fiber-reinforced concrete members modifying fixed-angle softened-truss model. *Composites Part B: Engineering*, 45(1):215-231. <https://doi.org/10.1016/j.compositesb.2012.10.030>
- Khalid Hamdan, Z., and Abdullah, F.A. (2018). Investigation of the adding nano particles to composite material under high strain rate torsion with hygrothermal effect. *International Journal of Mechanical Engineering and Technology (IJMET)*, 9(6):1,098-1,114. <https://doi.org/10.13189/ujms.2018.060102>
- Kimoto, N., Okochi, M., Matsumoto, N., and Nakamura, T. (2011). Studies of torsional strength of carbon fiber composites shaft by innovative sheet winding. In *Proceedings of the 18th International Conference on Composite Materials*.
- Kumar, S.S. and Mantena, P.R. (1996). Dynamic and static torsional characterization of pultruded hybrid cylindrical composite rods. *Journal of Composite Materials*, 30(8):918-932. <https://doi.org/10.1177/002199839603000804>
- Lakshmankumar, A. and Prakash, M. (2023). Investigation of the effect of spirally stacked fiber reinforcement on the torsional behavior of a polymer composite rod by AE analysis. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 45(9):490. <https://doi.org/10.1007/s40430-023-04416-2>
- Lee, C.S., Hwang, W., Park, H.C., and Han, K.S. (1999). Failure of carbon/epoxy composite tubes under combined axial and torsional loading 1. Experimental results and prediction of biaxial strength by the use of neural networks. *Composites Science and Technology*, 59(12):1,779-1,788. [https://doi.org/10.1016/S0266-3538\(99\)00038-X](https://doi.org/10.1016/S0266-3538(99)00038-X)
- Lee, D.G., Kim, J.W., and Hwang, H.Y. (2004). Torsional fatigue characteristics of aluminum-composite co-cured shafts with axial compressive preload. *Journal of Composite Materials*, 38(9):737-756. <https://doi.org/10.1177/0021998304042479>
- Lee, J. and Lee, S.H. (2004). Flexural-torsional behavior of thin-walled composite beams. *Thin-Walled Structures*, 42(9):1,293-1,305. <https://doi.org/10.1016/j.tws.2004.03.012>
- Lee, S.M. (1993). An edge crack torsion method for mode III delamination fracture testing. *Composites Technology and Research*, 15(3):193-201. <https://doi.org/10.1520/CTR10369J>
- Lenwari, A., Soysak, S., and Thongchom, C. (2022). Torsional behavior of reinforced concrete members wrapped with CFRP sheets. In *10th International Conference on FRP Composites in Civil Engineering: Proceedings of CICE 2020/2021*. 10:1,566-1,576. https://doi.org/10.1007/978-3-030-88166-5_136
- Li, C., Weng, G.J., and Duan, Z. (2001). Dynamic behavior of a cylindrical crack in a functionally graded interlayer under torsional loading. *International Journal of Solids and Structures*, 38(42-43):7,473-7,485. [https://doi.org/10.1016/S0020-7683\(01\)00046-4](https://doi.org/10.1016/S0020-7683(01)00046-4)
- Li, J., Shen, R., Hua, H., and Jin, X. (2004). Bending-torsional coupled dynamic response of axially loaded composite Timoshenko thin-walled beam with closed cross-section. *Composite Structures*, 64(1):23-35. [https://doi.org/10.1016/S0263-8223\(03\)00210-1](https://doi.org/10.1016/S0263-8223(03)00210-1)
- Li, M., Wu, L., Ma, L., Xiong, J., and Guan, Z. (2011). Torsion of carbon fiber composite pyramidal core sandwich plates. *Composite Structures*, 93(9):2,358-2,367. <https://doi.org/10.1016/j.compstruct.2011.02.019>
- Liao, Q., Su, Y., Yu, J., and Yu, K. (2022). Torsional behavior of BFRP bars reinforced engineered cementitious composites beams without stirrup. *Engineering Structures*, 268:114748. <https://doi.org/10.1016/j.engstruct.2022.114748>
- Liu, Y.N., Li, M., Gu, Y., and Zhang, Z. (2014). Characterization of torsion behavior and fracture morphology of single carbon fiber. *Journal of Composite Materials*, 48(16):1,993-1,999. <https://doi.org/10.1177/0021998313493810>
- Lu, G., Su, M., Zhou, X., Deng, X., Bai, Y., and Wang, Y. (2022). Numerical analysis on torsional behavior of rectangular and square CFDST members. *Journal of Constructional Steel Research*, 193:107294. <https://doi.org/10.1016/j.jcsr.2022.107294>
- Maeda, T., Baburaj, V., Ito, Y., and Koga, T. (1998). Flexural-torsional coupling effect on vibrational characteristics of angle-ply laminates. *Journal of Sound and Vibration*, 210(3):351-365. <https://doi.org/10.1006/jsvi.1997.1331>
- Mahdi, E. and Hamouda, A.M.S. (2013). An experimental investigation into mechanical behavior of hybrid and nonhybrid composite semi-elliptical springs. *Materials & Design*, 52:504-513. <https://doi.org/10.1016/j.matdes.2013.05.065>
- Mane, V.V., and Patil, N.K. (2021). A review on "Torsional behavior of rectangular reinforced concrete beams with encased welded wire mesh fiber." *Reliability: Theory and Applications*, 16(SI 1 (60)):304-317.
- Massa, J.C., and Barbero, E.J. (1998). A strength of materials formulation for thin walled composite beams with torsion. *Journal of Composite Materials*, 32(17):1,560-1,594. <https://doi.org/10.1177/002199839803201702>
- Minguet, P.J. (1989). Static and dynamic behavior of composite helicopter rotor blades under large deflections (Doctoral dissertation, Massachusetts Institute of Technology).
- Mohamed, H.M. and Benmokrane, B. (2015). Torsion behavior of concrete beams reinforced with glass fiber-reinforced polymer bars and stirrups. *ACI Structural Journal*, 112(5):679-686. <https://doi.org/10.14359/51687824>
- Mollaei, S., Babaei, M., and Asemi, K. (2023). Torsional buckling of functionally graded graphene reinforced composite laminated cylindrical panel. *Archive of Applied Mechanics*, 93(2):427-435. <https://doi.org/10.1007/s00419-022-02132-2>
- Mutasher, S.A. (2009). Prediction of the torsional strength of the hybrid aluminum/composite drive shaft. *Materials and Design*, 30(2):215-220. <https://doi.org/10.1016/j.matdes.2008.04.042>
- Nhu Trang, L.T., and Tung, H.V. (2023). Thermo-torsional postbuckling of CNT-reinforced composite toroidal shell segments with surrounding elastic media and tangentially restrained edges. *Journal of Thermoplastic Composite Materials*, 36(8):3,137-3,167. <https://doi.org/10.1177/08927057221122142>
- Nirala, A., Kumar, N., Singh, D.B., Sharma, S.K., Yadav, J.K., Prasad, H., and Chandan, S. (2020). Simulation analysis of composite helical spring for compression, torsional and transverse mode. *Materials Today: Proceedings*, 28:2,263-2,267. <https://doi.org/10.1016/j.matpr.2020.04.503>
- Ogasawara, T., Onta, K., Ogihara, S., Yokozeki, T., and Hara, E. (2009). Torsion fatigue behavior of unidirectional carbon/epoxy and glass/epoxy composites. *Composite Structures*, 90(4):482-489. <https://doi.org/10.1016/j.compstruct.2009.04.012>
- Ogasawara, T., Onta, K., Yokozeki, T., and Ogihara, S. (2007). Tension/torsion fatigue behavior of unidirectional GFRP

- and CFRP. In 16th International Conference on Composite Materials. <https://doi.org/10.2514/6.2007-2335>
- Ogasawara, T., Yokozeki, T., Onta, K., and Ogihara, S. (2007). Linear and nonlinear torsional behavior of unidirectional CFRP and GFRP. *Composites Science and Technology*, 67(15-16):3457-3464. <https://doi.org/10.1016/j.compscitech.2007.03.004>
- Onta, K., Ogasawara, T., Yokozeki, T., and Ogihara, S. (2006). Tension/torsion behavior of unidirectional CFRP and GFRP. In *Proceedings of the Twelfth US-Japan Conference on Composite Materials: September 21-22, 2006, The University of Michigan-Dearborn, Dearborn, Michigan*. DEStech Publications, Inc. p. 236
- Panchacharam, S. and Belarbi, A. (2002). Torsional behavior of reinforced concrete beams strengthened with FRP composites. In *First FIB Congress, Osaka, Japan*, 1:01-110.
- Park, H.C. (1985). Analytical and experimental study on micropolar elastic behavior in composite materials (torsion, bone, shear strain) (Doctoral dissertation, The University of Iowa).
- Porter, M.M., Meraz, L., Calderon, A., Choi, H., Chouhan, A., Wang, L., and McKittrick, J. (2015). Torsional properties of helix-reinforced composites fabricated by magnetic freeze casting. *Composite Structures*, 119:174-184. <https://doi.org/10.1016/j.compstruct.2014.08.033>
- Qureshi, M.A.M., and Rao, H.G. (2014). Torsional response of closed FRP composite sections. *Composites Part B: Engineering*, 61:254-266. <https://doi.org/10.1016/j.compositesb.2014.01.008>
- Ramnath, B.V., Elanchezian, C., Deepak, M., and Narayan, A. (2017). Investigation of torsional behavior of polymer composite golf shaft. *Materials Today: Proceedings*, 4(2):3,342-3,345. <https://doi.org/10.1016/j.matpr.2017.02.225>
- Sevkat, E. and Tumer, H. (2013). Residual torsional properties of composite shafts subjected to impact loadings. *Materials and Design*, 51:956-967. <https://doi.org/10.1016/j.matdes.2013.04.077>
- Sevkat, E., Tumer, H., Kelestemur, M.H., and Dogan, S. (2014). Effect of torsional strain-rate and lay-up sequences on the performance of hybrid composite shafts. *Materials and Design*, 60:310-319. <https://doi.org/10.1016/j.matdes.2014.03.054>
- Shadmehri, F., Haddadpour, H., and Kouchakzadeh, M.A. (2007). Flexural-torsional behavior of thin-walled composite beams with closed cross-section. *Thin-Walled Structures*, 45(7-8):699-705. <https://doi.org/10.1016/j.tws.2007.01.006>
- Shin, E.S. and Pae, K.D. (1992a). Effects of hydrostatic pressure on the torsional shear behavior of graphite/epoxy composites. *Journal of Composite Materials*, 26(4):462-485. <https://doi.org/10.1177/002199839202600402>
- Shin, E.S., and Pae, K.D. (1992). Effects of hydrostatic pressure on in-plane shear properties of graphite/epoxy composites. *Journal of Composite Materials*, 26(6):828-868. <https://doi.org/10.1177/002199839202600607>
- Shokrieh, M.M., and Hasani, A. (2002). Shear buckling of composite drive shafts under torsion. In *The 6th International Conference on Flow Processes in Composite Materials*, 15:16.
- Shokrieh, M.M., Hasani, A., and Lessard, L.B. (2004). Shear buckling of a composite drive shaft under torsion. *Composite Structures*, 64(1):63-69. [https://doi.org/10.1016/S0263-8223\(03\)00214-9](https://doi.org/10.1016/S0263-8223(03)00214-9)
- Siriruk, A., Weitsman, Y.J., and Penumadu, D. (2009). Polymeric foams and sandwich composites: Material properties, environmental effects, and shear-lag modeling. *Composites Science and Technology*, 69(6):814-820. <https://doi.org/10.1016/j.compscitech.2009.01.016>
- Slovikov, S.V. and Lobanov, D.S. (2020). Mechanical properties of a basalt-fiber-reinforced plastic rod used in composite high-voltage wires in torsion and three-point bending. *Mechanics of Composite Materials*, 56:353-360. <https://doi.org/10.1007/s11029-020-09886-2>
- Stedile Filho, P., Almeida Jr, J.H.S., and Amico, S.C. (2018). Carbon/epoxy filament wound composite drive shafts under torsion and compression. *Journal of Composite Materials*, 52(8):1103-1111. <https://doi.org/10.1177/0021998317722043>
- Steinberg, E.L., Rath, E., Schlaifer, A., Chechik, O., Maman, E., and Salai, M. (2013). Carbon fiber reinforced PEEK Optima-a composite material biomechanical properties and wear/debris characteristics of CF-PEEK composites for orthopedic trauma implants. *Journal of the Mechanical Behavior of Biomedical Materials*, 17:221-228. <https://doi.org/10.1016/j.jmbbm.2012.12.002>
- Stoddard, W.P. (1997). Lateral-torsional buckling behavior of polymer composite I-shaped members. *Georgia Institute of Technology*.
- Tan, T., Ren, F., Wang, J.J. A., Lara-Curzio, E., Agastra, P., Mandell, J., and LaFrance, C.M. (2013). Investigating fracture behavior of polymer and polymeric composite materials using spiral notch torsion test. *Engineering Fracture Mechanics*, 101:109-128. <https://doi.org/10.1016/j.engfractmech.2013.02.017>
- Taşdelen, M.E., Keleştemur, M.H., and Şevkat, E. (2016). Torsional behaviour and finite element analysis of the hybrid laminated composite shafts: Comparison of VARTM with vacuum bagging manufacturing method. *Advances in Materials Science and Engineering*, 2016. <https://doi.org/10.1155/2016/9490375>
- Tibhe, S.B., and Rathi, V.R. (2016). Comparative experimental study on torsional behavior of RC beam using CFRP and GFRP fabric wrapping. *Procedia Technology*, 24:140-147. <https://doi.org/10.1016/j.protcy.2016.05.022>
- Vo, T.P. and Lee, J. (2007). Flexural-torsional behavior of thin-walled closed-section composite box beams. *Engineering Structures*, 29(8):1,774-1,782. <https://doi.org/10.1016/j.engstruct.2006.09.008>
- Vo, T.P., and Lee, J. (2008). Flexural-torsional behavior of thin-walled composite box beams using shear-deformable beam theory. *Engineering Structures*, 30(7):1,958-1,968. <https://doi.org/10.1016/j.engstruct.2007.12.010>
- Vo, T.P., and Thai, H.T. (2012). Static behavior of composite beams using various refined shear deformation theories. *Composite Structures*, 94(8):2,513-2,522. <https://doi.org/10.1016/j.compstruct.2012.03.020>
- Won, D., Seo, J., Park, W.S., and Kim, S. (2021). Torsional behavior of precast segment module joints for a submerged floating tunnels. *Ocean Engineering*, 220:108490. <https://doi.org/10.1016/j.oceaneng.2020.108490>
- Wu, C., He, L., Ghafoori, E., and Zhao, X.L. (2018). Torsional strengthening of steel circular hollow sections (CHS) using CFRP composites. *Engineering Structures*, 171:806-816. <https://doi.org/10.1016/j.engstruct.2018.06.003>
- Wu, Q. and Pei, N. (2022). Structural health monitoring of carbon fiber-reinforced laminate composites with torsional loads by using acoustic emission. *Journal of Materials Science*, 57(28):13,433-13,445. <https://doi.org/10.1007/s10853-022-06995-2>
- Yang, I.H., Joh, C., Lee, J.W., and Kim, B.S. (2013). Torsional behavior of ultra-high performance concrete squared beams. *Engineering Structures*, 56:372-383. <https://doi.org/10.1016/j.engstruct.2013.06.029>
- Yang, M., Hu, Y., Zhang, J., Ding, G., and Song, C. (2018). Study on forced torsional vibration of CFRP drive-line system with internal damping. *Applied Composite Materials*, 25:1,307-1,322. <https://doi.org/10.1007/s10443-017-9668-7>

- Yoon, K., Lee, P.S., and Kim, D.N. (2017). An efficient warping model for elastoplastic torsional analysis of composite beams. *Composite Structures*, 178:37-49. <https://doi.org/10.1016/j.compstruct.2017.08.021>
- Zhang, D., Zhao, Q., Li, F., Tao, J., and Gao, Y. (2018). Torsional behavior of a hybrid FRP-aluminum space truss bridge: Experimental and numerical study. *Engineering Structures*, 157:132-143. <https://doi.org/10.1016/j.engstruct.2017.12.013>
- Zhang, X., Zhou, K., Wang, H., Jiang, Y., Sun, X., Liu, C., and Wang, H. (2023). On the cyclic torsion behavior of extruded AZ61A magnesium alloy tube. *International Journal of Fatigue*, 174:107704. <https://doi.org/10.1016/j.ijfatigue.2023.107704>
- Zhao, G., Zhang, L., Tang, C., Zhou, Y., Hao, W., and Luo, Y. (2018). Experimental study on the torsion behavior of a 3D 4-directionally braided composite shaft using DIC and AE. *Polymer Testing*, 72:122-131. <https://doi.org/10.1016/j.polymertesting.2018.10.008>
- Zhao, W., Pei, N., and Xu, C. (2022). Experimental study of carbon/glass fiber-reinforced hybrid laminate composites with torsional loads by using acoustic emission and Micro-CT. *Composite Structures*, 290:115541. <https://doi.org/10.1016/j.compstruct.2022.115541>
- Zhao, Y. and Pang, S.S. (1995). Stress-strain and failure analyses of composite pipe under torsion. *Composites Engineering*. <https://doi.org/10.1115/1.2842123>
- Zhou, C., Wang, J., Jia, W., and Fang, Z. (2022). Torsional behavior of ultra-high performance concrete (UHPC) rectangular beams without steel reinforcement: Experimental investigation and theoretical analysis. *Composite Structures*, 299:116022. <https://doi.org/10.1016/j.compstruct.2022.116022>
- Zhou, J., Shen, W., and Wang, S. (2017). Experimental study on torsional behavior of FRC and ECC beams reinforced with GFRP bars. *Construction and Building Materials*, 152:74-81. <https://doi.org/10.1016/j.conbuildmat.2017.06.121>
- Zojaji, A.R. and Kabir, M.Z. (2012). Analytical approach for predicting full torsional behavior of reinforced concrete beams strengthened with FRP materials. *Scientia Iranica*, 19(1):51-63. <https://doi.org/10.1016/j.scient.2011.12.009>