This paper presents a finite element analysis of a composite shaft under dynamic variable fatigue loading. The object of this study is the behavior of the fatigue life of a composite shaft under dynamic variable fatigue loading. The fatigue life of the shaft is then determined by analyzing the stress distribution and its effect on the material's fatigue strength. The investigation of fatigue behavior involves evaluating factors such as stress concentrations, fatigue crack initiation and propagation, and the cumulative damage caused by cyclic loading. The study explores the impact of biaxial loading on the shaft's fatigue performance and provides insights into its significance in predicting fatigue life and it is 10e7 cycles. Furthermore, a damage indicator is predicted to assess the accumulated damage and monitor the progression of fatigue-related degradation. This indicator serves as a valuable tool for predicting the remaining useful life of the composite shaft. The equivalent alternative stress is calculated to characterize the combined effect of different loading conditions on the fatigue life of the composite shaft. By quantifying the stress level and variations experienced by the structure, this parameter allows for a comprehensive assessment of the fatigue performance under variable loading scenarios 250 N. The findings of this research contribute to the understanding of fatigue behavior in composite shafts under dynamic variable fatigue loading. The insights gained from the fatigue life investigation, biaxiality indication, damage prediction, and equivalent alternative stress calculation can aid in optimizing design considerations, maintenance planning, and enhancing the reliability and durability of composite shafts in various engineering applications

***Keywords:** composite shaft, variable loading, fatigue life, biaxiality indication, damage indicator*

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IDENTIFYING THE MECHANISM OF THE FATIGUE BEHAVIOR OF THE COMPOSITE SHAFT SUBJECTED TO VARIABLE LOAD

Imad O. Bachi Al-Fahad
Assistant Professor
Department of Materials Engineering
College of Engineering
University of Basrah
Al Basrah, Iraq, 61004

Hussein Kadhim Sharaf
Corresponding author
Senior Lecturer
Department of Aeronautical Techniques Engineering*
E-mail: hk.sharaf92@gmail.com

Lina Nasseer Bachache
Senior Lecturer
Department of Medical Instrumentation Techniques Engineering
Dijlah University College
Al-Dora, Baghdad, Iraq, 00964

Nasseer Kassim Bachache
Assistant Professor
Department of Electric Power Techniques Engineering*
*Bilad Alrafidain University College, Al-Quds Intersection
Baqubah, Diyala, Iraq, 32001

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1. Introduction

Amputations of lower limbs have a devastating impact on quality of life because they limit basic bodily functions including movement. Amputees can regain not only their mobility but also their sense of well-being with the help of a shaft. The use of prosthetics is one of the most important aspects of rehabilitation for amputees missing lower limbs model. Since the SACH (Solid-Model Cushion) model was invented in 1957 [1], there have been various different forms of shaft introduced that are intended for this function. Patients with disabilities have been given SACH as a prescription because it has the potential to reduce the impact loading experienced during striking [2]. Nevertheless, this shaft model is capable of storing and then releasing a negligible quantity of elastic energy [3]. Other previous versions of shaft, made of materials such as wood, metal, and vulcanized rubber, confronted amputees with a number of challenges, including a lack of longevity and a sense of unease. Previously, difficulties with shaft model designs such as the Shape and Roll model, the Niagara Model, and the Jaipur model were explored by a number of studies [4]. These studies all stated that the same problems of decreased durability and increased weight existed with these designs. According to the findings of prior research [5], Al alloys were deemed to be an appropriate alternative to the materials that were originally utilized for shafts, which caused a number of issues. [6] advocated for the utilization of composite structures in the development of shafts due to their potential for energy storage. This capacity offers a rehabilitative advantage to amputees who need to maintain a high level of activity.

A study that was quite similar to this one [3] argued for the use of Al composite and glass fiber in shaft applications because of the low density, lightweight quality, and remarkable strength that both of these materials exhibit. A recent study carried out in Vietnam has contributed new evidence to the expanding body of evidence indicating that the Al composite laminated shaft model can store elastic energy [5]. Because of this, the body is able to move forward, while at the same time, the impact force placed on the other limbs is reduced [4]. This feature increases the shaft model's flexibility, which enables it to work in a manner that is comparable to that of a natural model.

Carbon fiber reinforced plastic (CFRP) is advantageous because of its long service life, resistance to fatigue and corrosion, and capacity to withstand high temperatures. According to [7], carbon fiber composites have found widespread application in the aerospace, renewable energy, and public transportation sectors. However, the CFRP shaft tube structure is frequently subjected to alternate loads while in operation. Because the interior micro-cracks will steadily expand, fatigue damages such as matrix cracking, delamination, fiber fracture, and so on can occur even when the stress is below the structure's maximum strength [8]. Therefore, the concealed danger of the attenuation's structural strength, stiffness, and other mechanical attributes increases the chance of significant accidents when composite components are used. Therefore, it is crucial to study its fatigue characteristics under a three-point bending fatigue load and master its fatigue damage evolution mechanism in order to develop timely inspection and maintenance strategies for CFRP shaft tubes and increase the reliability and safety of the tubes while in service [9].

Experts from throughout the world and the United States have contributed to our understanding of the fatigue damage mode of composite materials, the evolution mechanism of fatigue damage, fatigue life, and damage detection [10]. According to [11], researchers examined the fatigue behavior of CFRP laminates subjected to three-point bending at different fatigue load levels and fatigue loading frequency. Stiffness failure criteria and the residual stiffness degradation model were developed in [12]. CFRP laminates' fatigue lives were also theoretically studied. It is only via experimental testing that the evolution process of these traits can be explored [13].

In addition, [14] noted that because fiber composite structures have better qualities, they are suitable for employment not only in the industry of prosthetics but also in other fields like sports, aeronautics, and aerospace. In recent studies, a number of different kinds of composites, such as polypropylene (PP)-based nanocomposites, have been changed with nanoclay, basalt fibers, and graphene in order to make them suitable for use in the aerospace sector [15]. These modifications have made it possible for these composites to be put to use in the industry. An additional category of composites called fiber laminated metals (FML) has also been looked into for the aim of determining the impact that they have on the mechanical strength of aircraft components. The goal of this research was to find out how these composites affect the strength of aviation components. When fiber-laminated metals were employed, the findings indicated that there was an increase in the overall tensile strength of the material [16].

Therefore, studies devoted to explaining the impact of dynamic load on the fatigue behavior of a simply-supported composite shaft are of scientific relevance.

2. Literature review and problem statement

Composite materials are becoming more common in structural applications, mostly as a result of the intrinsically high specific mechanical qualities these materials possess as well as their resistance to corrosion. Composite structures are used in a wide variety of industries, including automotive, aerospace, aeronautics, marine, and civil engineering, to name just a few of them. When components for high-performance automobiles are required to be both lighter and stronger, composite structures are sometimes chosen as the best option. Composite cylinders are gradually replacing metallic drive shafts because they offer greater vibration dampening, lower wear on engine components, and increased tire traction [17]. Composite cylinders also give increased tire grip. Each set of driving wheels has its own drive shaft that connects to the differential. Universal joints connect the cylindrical steel bars that make up the shafts and allow the suspension to move in a variety of ways [18]. It is necessary for a drive shaft to fulfill specific requirements in order to avoid whirling vibration. These requirements include a basic bending natural frequency of 9,200 revolutions per minute and a maximum allowable torque of 3,500 Nm. Steel shafts are often constructed in two halves with universal joints, a center supporting bearing, and a bracket. This is done because a steel shaft's natural frequency is typically lower than 5,700 revolutions per minute (for a length of around 1.5 meters), which results in an increase in both the overall weight and the amount of fuel consumed. In comparison, a carbon-epoxy composite shaft can be fabricated in a single piece, operated at speeds greater than 9,200 revolutions per minute, and generate a substantially lower amount of noise and vibration than a standard shaft material. From a design point of view, some of the parameters that are employed the most frequently are things like natural frequency, critical buckling torque, torsional frequency, and torque gearbox strength [19]. For example, if the natural frequency of the shaft is too close to the rotating frequency, this could result in significant vibration and, in the worst-case scenario, early failure. The natural frequency of composite drive shafts for different fiber orientations was evaluated by [20], who arrived to the conclusion that in order to attain the maximum natural frequency, the fiber should be placed as close to the longitudinal axis as is practically possible. Khoshravan and Paykani conducted a study in which they compared metal and carbon/epoxy composite drive shafts. They discovered that the latter type of drive shaft may benefit from a longer cylinder in order to improve its natural frequency. There is a one-to-one correspondence between torsional frequency and torsional stiffness, denoted by the formula T=', where ' is the torsional angle. When a torsional load is applied to the drive shaft, this leads to the development of a buckling load or torque. The buckling behavior of graphite/epoxy shafts under torsional loading was investigated by [21], who discovered that theoretical and experimental results agreed with one another in a satisfactory manner. It was discovered that increasing the layer count of filament wound hybrid carbon/glass composite shafts improved the torsional performance of the shafts [22]. According to [13], the maximization of the critical buckling torque requires the use of hoop layers. This is because the critical buckling torque is more closely related to the transverse direction than it is to the longitudinal one.

Drive shafts are subjected to a number of forces at once, so this study employs analytical and numerical analyses to examine carbon/epoxy composite cylinders with varying stacking sequences for drive shafts with regards to torque behavior, natural frequency, critical buckling torque, and torque carrying capacity. To check the accuracy of the simulations, a prototype 3.15-mm-thick laminate was produced. A GIM equipment was used to perform torsion trials on the cylinder, with one end fully clamped and the other subjected to torque loading till breakage [24].

In order to make composites more useful in a wide variety of manufacturing sectors, their mechanical qualities can be enhanced in a number of ways. The capacity of composite materials to retain energy and their malleability have made them indispensable in the field of composites, as stated in [25]. In order to alter the physical properties of reinforced composites, epoxy resins and woven materials can be used. By carefully controlling the angles and tailoring the matrix, lamination offers the ability to combine precise tensile characteristics and stiffness [26]. The experimental protocol developed by [27] shows that blended polymer frameworks can be built using different lamination techniques. This can be done with the help of these frameworks. Laminations of metal, plastic, or other materials are used in today's fast prototyping systems to produce orthotic and shaft devices [28].

Several studies have examined the influence of polymer laminate orientation and reinforcement material on the tensile strength of materials. It has been observed that the orientation of polymer laminates may not have as significant an impact as the choice of reinforcement material. Researchers have found a correlation between the weight percentage of the reinforcing material and the material's tensile strength. Altering the weight percentage of the reinforcement has shown to enhance the elasticity, yield strength, and ultimate strength of the material. The mechanical properties, such as tensile strength, ultimate strength, and yield strength, play a crucial role in determining the material's performance [29].

In recent decades, various techniques have been developed to improve the mechanical properties of composites during production. These techniques aim to achieve efficiency and cost-effectiveness. Methods such as hand layup, compression molding, vacuum bagging, and vacuum-assisted resin transfer molding have been employed to produce epoxy-based composites. The effectiveness of these techniques heavily influences the improvement of composite attributes.

For instance, previous studies have utilized the hand layup method followed by vacuum bagging to fabricate composite laminates, resulting in a significant enhancement of the mechanical performance of the composite. Comparatively, the vacuum bagging method has demonstrated a substantial increase in the material's tensile and flexural strength compared to the hand layup procedure [30]. This body of research highlights the importance of reinforcement material selection, weight percentage adjustment, and manufacturing techniques in optimizing the mechanical properties of composite materials. Understanding and implementing appropriate and efficient processes are essential for achieving improved material performance.

Therefore, this study estimated the fatigue behavior of a composite structure using the finite element method and the structural tool in the ANSYS program. It allowed for a thorough analysis of the structure's behavior under different loads by providing precise models and forecasts. The research allowed for a comprehensive evaluation of the composite material's internal stress distribution, deformation, and damage buildup.

3. The aim and objectives of the study

The aim of the study is to establish norms for the fatigue behavior of enhanced carbon-fiber composite structures suited for use as shaft structures.

To achieve this aim, the following objectives are accomplished:

– to investigate fatigue life based on fatigue behavior;

– to explain the biaxiality indication;

– to predict the damage indicator;

– to calculate the equivalent alternative stress.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this study is the behavior of the fatigue life of a composite shaft under dynamic variable fatigue loading. The study hypothesizes that the fatigue life of the composite shaft will be influenced by the loading conditions, including amplitude and frequency. Additionally, the presence of biaxial loading will affect the fatigue behavior. The study also aims to predict the damage indicator and calculate the equivalent alternative stress. The study assumes a homogeneous and isotropic material for the composite shaft. It simplifies the analysis by neglecting environmental factors and focusing solely on fatigue behavior. The study employs a finite element model with appropriate simplifications to capture essential aspects of the shaft's behavior.

4. 2. Mechanical properties

The mechanical parameters of the composite structure have to be specified in advance in order for the simulation technique to be utilized. The composite features in mind: Differences in the Ultimate Tensile Strength, Measured in Percentage of Pascals Maximum Stress, Measured in Megapascals Variations in the Ultimate Tensile Strength (MPa). 1.5 % of the nanoparticles in this investigation were found to be composed of alloy. In Table 1, the mechanical characteristics of the materials that are currently available are presented.

Table 1

Mechanical properties of alloys structure of the composite

Modulus of elasticity, GPa	Ultimate tensile stress, MPa	Poisson's ratio, unit less	Density, kg/m^3
228	500	0.31	1,750

In order to carry out the simulation process by making use of the static structural tool, four primary parameters were taken into consideration.

4. 3. Meshing and geometry of the composite shaft

The meshing procedure was executed with the assistance of meshing, which was employed in order to execute the meshing procedure for the issue at hand. The composite shaft that initially comprised a limitless number of particles must go through the process of meshing in order to have that number of particles cut down to a more manageable level. A fine mesh was crafted with the use of a structured mesh grid so that accurate responses could be obtained. Because of this, it was possible to manufacture the mesh. The desired result of the fine mesh was accomplished with the assistance of managing the sizing by employing the curvature size with a coarse mesh and the element size with face meshing. This allowed for the achievement of the desired outcome of the fine mesh. It has been determined that a total of 42334 binary nodes have been formed as a consequence of the development of binary nodes for the wedge across all of its zones. Fig. 1 provides a picture of the type of mesh in a space that is just two dimensions deep. Because the 3D wedge is symmetric, the only feature of the composite shaft that has been developed so far is the aspect that is symmetric. This is because the symmetry of the 3D wedge was discovered by accident. In this particular piece of study, the authors made use of three different forms of boundary conditions: wedge, symmetry, and far field.

The composite shaft was processed for edges to use in the selection process, which finally led to the production of this list of requirements as shown in Fig. 1.

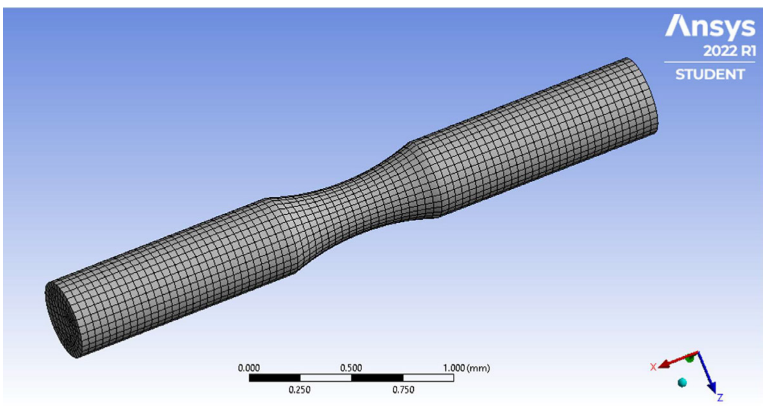

Fig. 1. Meshed composite structure of the $COMPOSITE_4$

4. 4. Boundary conditions

Within the context of this experiment, a uniaxial fatigue test was carried out. The force that was used to exert pressure was 250 N. This inquiry used a technique for the fatigue tests that was based on a real shaft model, and the specimens were loaded while being subjected to tension-compression stress while the test was being conducted. When a material has been put through a number of load cycles with amplitudes that are smaller than the material's ultimate static strength, a failure due to fatigue can occur [31]. In the course of this inquiry, fatigue tests were performed in a laboratory on a sample constructed of the composite structure of the composite shaft.

4. 5. Convergence analysis

A convergence test is a method that has been chosen for use in the empirical studies that have been conducted on the connection. This method is used to carry out the results of the numerical analysis. The purpose of this test is to evaluate and contrast two different sets of findings that have been computed numerically. It has been decided that the life forecast that is offered in the fatigue tool would be the primary indicator for convergence as shown in Fig. 2. This was reached through consensus. By taking into consideration two different answers, the procedure for obtaining convergence has been finished and is now complete. The number of cycles counted at the beginning for the first solution was 3.5 mm, whereas the number of cycles counted at the beginning for the second solution was 3.62.

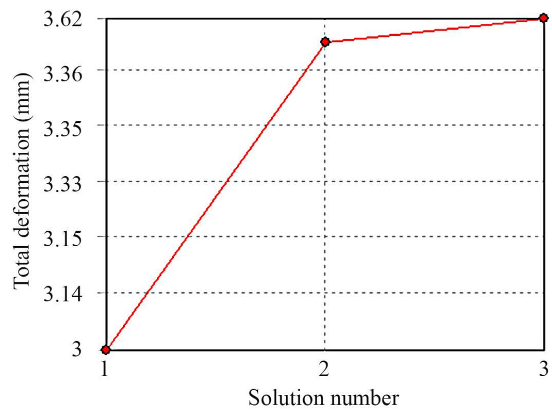

Fig. 2. Convergence analysis of the composite shaft

The mesh that is used in the present composite shaft has been improved so that it shows the second solution more correctly in order to reflect the changes that have been made. The addition of new data helped make this advancement work out in a way that was before impossible.

5. Results of finite element analysis of the composite shaft subjected to static and dynamic variable fatigue loading

5. 1. Fatigue life investigations

To investigate the durability of nano particle-reinforced fiber composite specimens under alternative loads, this study aimed to predict the functional lifespan of the fatigue specimen. Applying a 250 N fatigue load, the research conducted a life expectancy prediction analysis, with the results presented in Fig. 3.

Throughout the simulation process, the ANSYS software's Static structural tool was utilized to facilitate the analysis. The computational analysis revealed that the composite structure specimen reinforced with kenaf particles had a maximum tolerance for cycles nearing one million. Consequently, it is suggested that the current analysis be considered invalid after approximately one million cycles.

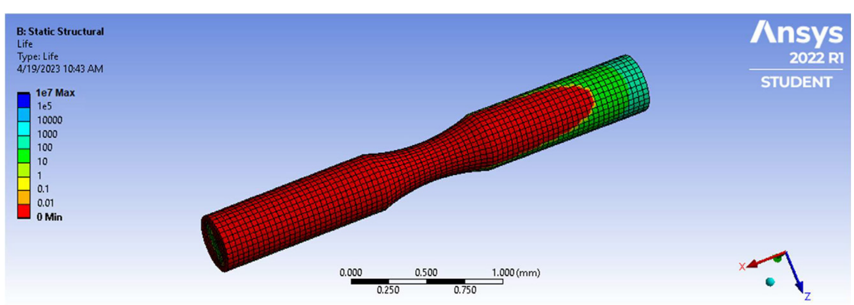

Fig. 3. Life prediction of the current geometry

The composite specimen was employed with a maximum number of cycles that can be applied to it that is fairly close to 1e7. This allowed for the maximum amount of wear and tear that might occur. As a consequence, it is suggested that the existing analysis be disregarded altogether somewhere around the 1e7 cycle.

5. 2. Biaxiality indication

In the present investigation, the biaxiality indication played a crucial role in providing insights into the stress condition experienced by Composite structure 4 and how the results should be interpreted. Both the results and the biaxiality indication contain relevant information pertaining to this aspect.

Specifically, in this scenario, the biaxiality indication was calculated by dividing the principal stress with the smaller magnitude by the principal stress with the larger magnitude, while excluding the principal stress closest to zero. This calculation aimed to assess the presence of biaxiality in the material. When stress only acts in one direction (uniaxial stress), it indicates the absence of biaxiality.

Upon application of the alternative load of 250 N, the biaxiality indicator reached a minimum of –0.8798 before settling at a value of 0.709. This change signifies the existence of biaxiality in the material. The simulation results, depicted in Fig. 4, highlighted the tip locations as the areas where the maximum biaxiality indication occurred.

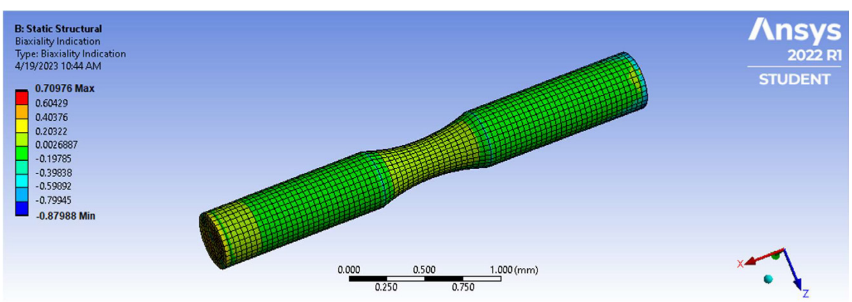

Fig. 4. Biaxiality indication due to the applied load

Hence, the biaxiality indication served as a valuable metric for assessing the stress conditions and understanding the biaxial behavior of the material, with the simulation results illustrating this information effectively.

According to the findings of the simulation, the tips were the places where the largest case biaxiality indication took place. This was discovered by looking at the results. Within the framework of the simulation, this information was discussed.

5. 3. Damage calculation

The likelihood that loading will cause the structure to sustain damage is depicted in Fig. 5, which shows how likely it is. It was shown that this prospect has become a reality. In order to complete the computational Composite structure of the 3D fatigue specimen, specimens have been loaded with an alternative force that is equivalent to 250 N. They have been entrusted with the duty of bearing this burden on their shoulders.

The minimum number of cycles that need to be finished before the potential for maximum damage can be reached is 1e 29 cycles, while the number of cycles that need to be finished before reaching the potential for maximum damage is also 500. According to the findings of the simulation, the damage will most likely start to become noticeable somewhere in the middle of the fatigue specimen.

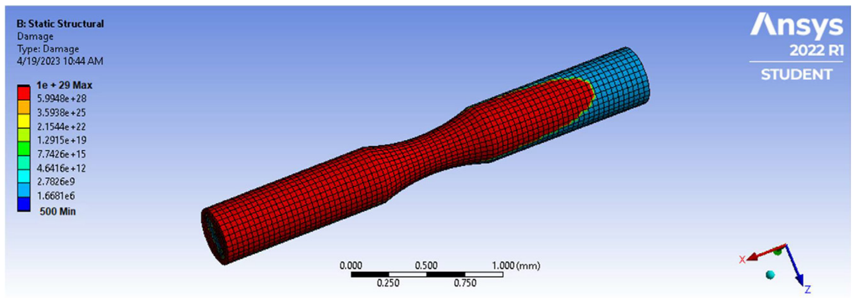

Fig. 5. Damage explanation due to the applied load

The fatigue indicator was used in the ANSYS software to make a prediction of the damage indication. The simulation of the dynamic applied load was carried out using the structural Composite structure that was static.

5. 4. Equivalent alternative stress

The results of the simulation have made it possible to identify the regions of the specimen that were affected by the alternative load of 250 N that was applied. This has been made possible as a result of the findings of the simulation, which have made it possible to pinpoint these regions. The strain is delivered along a uniaxial axis all the way through the body of the specimen that is being tested. This ensures that the strain is distributed evenly. The body of the fillet that was used for the fatigue sample was subjected to alternating stresses that were concentrated there. There was a concentration of these pressures there. According to the findings of the investigation, the fillet parts of the specimen are subjected to a maximum alternative stress of 49,885 MPa. This value was determined based on the results of the investigation. As shown in Fig. 6, the alternative stress must be at least 18.3 MPa in order to be considered acceptable.

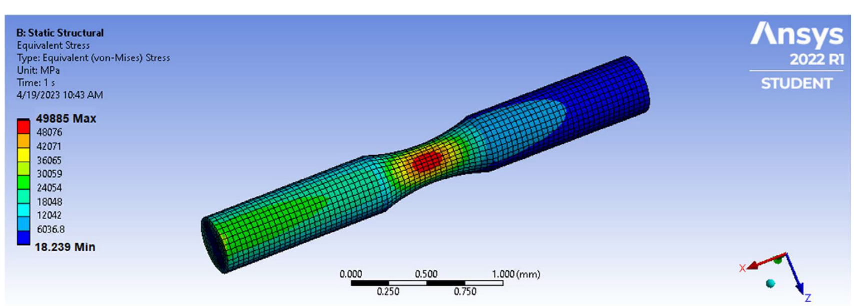

Fig. 6. Numerical results of equivalent alternative stress

The stress is applied along a uniaxial axis all the way through the body of the specimen that is being examined. This ensures that the stress is distributed evenly. This ensures that there is no uneven distribution of the strain. Alternating loads that were focused there were applied to the body of the fillet that was utilized for the composite fatigue sample. These stresses were applied repeatedly.

6. Discussion of finite element analysis of the composite shaft subjected to static and dynamic variable fatigue loading

The results of the study can be explained by several factors such as the fatigue behavior and fatigue life of the composite shaft can be influenced by the specific loading conditions applied. Higher loading amplitudes or frequencies may lead to increased stress levels and accelerated fatigue damage, resulting in shorter fatigue life. The presence of biaxial loading, combining axial and torsional stresses can have a significant impact on the fatigue behavior of the shaft. Biaxial loading scenarios often induce more complex stress distributions, leading to higher stress concentrations and reduced fatigue life compared to uniaxial loading conditions. As well as fatigue damage in the composite shaft accumulates over time due to cyclic loading. Factors such as the initiation and propagation of microcracks, the interaction between cracks, and the material's ability to resist crack growth all contribute to the overall fatigue behavior and determine the fatigue life.

The results of the present numerical investigation on the fatigue behavior of the composite shaft structure have been experimentally verified using standard laboratory equipment [19]. The experimental tests closely aligned with the numerical analysis, validating the accuracy and reliability of the computational model. This verification enhances confidence in the findings and provides a solid benchmark for future research and design optimization in composite shaft structures. The numerical findings of this study have been validated by examining how they stack up against the results of an earlier investigation.

This study found that when the composite shaft was subjected to varying loads, fatigue cracks developed. The simulation results suggest that the minimum achievable value is 10e7 cycles mm for the number of life cycles. The von Mises stress, or equivalent stress, that the variable load causes to the composite shaft is calculated. Fig. 3 is a visual representation of the research on elastic strain analogs. Fig. 4 depicts the simulation results, which reveal that the maximum equivalent stress is 18.3 MPa.

The results of this study offer valuable insights into the fatigue behavior and fatigue life prediction of composite shafts under dynamic variable fatigue loading. By analyzing the influence of loading conditions and considering factors such as biaxiality, the study enhances our understanding of the performance and durability of composite shafts in real-world applications. The findings provide a foundation for optimizing design considerations, improving maintenance planning, and enhancing the reliability of composite shafts in engineering practices.

The results of this study help address the identified problem of understanding fatigue behavior and predicting fatigue life in composite shafts. By investigating the relationship between loading conditions and fatigue performance, the study contributes to filling the knowledge gap in this specific area. The findings provide a stepping stone towards developing more accurate fatigue life prediction models and strategies for composite shafts, aiding in the development of more reliable and durable engineering solutions.

It is essential to acknowledge the limitations and simplifications of this study. The study assumes a homogeneous and isotropic material for the composite shaft, which may not fully capture the complexities of real-world material properties. Furthermore, the analysis neglects environmental factors, such as temperature and humidity, which can influence fatigue behavior. Additionally, the study incorporates certain simplifications in the modeling process to balance computational complexity and model accuracy.

One of the main shortcomings of this study is the limited information provided on the verification of the research findings. While the analysis focuses on fatigue behavior and fatigue life prediction, a more thorough verification process could enhance the robustness and reliability of the results. Additionally, the study may benefit from further sensitivity analyses or validation using experimental data to strengthen the conclusions drawn.

This study provides a solid foundation for future research and development. Further studies can expand on the findings by incorporating more advanced modeling techniques, considering more realistic material properties, and including a broader range of loading scenarios. Additionally, experimental validation of the predictions can help refine the fatigue models and provide more accurate fatigue life estimations. Exploring the impact of other factors, such as manufacturing processes or composite material variations, can also contribute to the further development of this study and provide a more comprehensive understanding of composite shaft fatigue behavior.

7. Conclusions

1. The computational method employed in this study has proved effective in forecasting the fatigue life of the composite shaft. The numerical findings indicate that the maximum expected life of the composite foot reaches 10e7 cycles. This information is crucial for assessing the durability and longevity of the shaft in real-world usage scenarios.

2. The study also highlights the significance of biaxiality indicators in understanding the fatigue behavior of the composite. The biaxiality indicator dropped to a value of –0.87 when the alternate load was applied. This observation suggests that the presence of biaxial loading conditions can significantly influence the fatigue performance of the composite shaft, potentially leading to reduced fatigue life compared to uniaxial loading scenarios.

3. In estimating the damage indicator, the study revealed that the maximum damage potential is reached after a certain number of cycles. Specifically, the simulation results indicate that damage is likely to become visible at approximately 10e29 cycles in the center of the fatigue specimen. This insight allows for better monitoring of the composite foot's structural integrity and aids in determining maintenance and replacement intervals.

4. The investigation into the equivalent alternate stress focused on analyzing the fillet regions of the specimen. The analysis identified that these regions experience a maximum alternate stress of 49,885 MPa. This finding provides a crucial understanding of the stress distribution within the composite foot and assists in optimizing design considerations and material selection for enhanced fatigue resistance.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data cannot be made available for reasons disclosed in the data availability statement.

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