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RESEARCH ARTICLE

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Investigation on the torsional property of hybrid composite/metal shafts at different service temperatures: Experimental and analytical study

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Abstract

Torsional tests were conducted to investigate the influence of service temperature on torsional property of composite/steel hybrid structures. In the experiment, two types of lightweight hybrid composite-metal shafts were tested at both room temperature and various elevated temperatures up to 150°C, including hybrid shafts with and without a metal core. Consequently, the torsional stiffness of the two hybrid shafts at different temperatures was calculated based on the recorded angular deformation-torque curves. The experimental results revealed a significant decrease in the torsional stiffness of the hybrid shaft without metal core as the increase of service temperature, while the torsional stiffness of the one with metal core remained almost unchanged, especially at high temperatures. In addition, a finite element model was proposed to predict the torsional behavior of the hybrid shafts at different service temperatures. In the model, an empirical equation was introduced, and micromechanical method was adopted to determine the temperature-dependant elastic properties of composite material and adhesive layer in the hybrid structure. Then, the predicted torsional property was compared to the experimental results for model verification.

Highlights

- Two types of hybrid composite-metal shafts are designed and manufactured.
- Torsional tests are conducted at both room and elevated temperatures up to 150°C.
- A finite element model applicable to shaft at various temperatures is proposed.
- The temperature-dependant property is characterized by an efficient equation.

KEYWORDS

elevated temperature, finite element model, hybrid shaft, torsional property

1 | INTRODUCTION

In recent years, hybrid shafts consisting of metallic part and a composite part have been increasingly introduced to replace traditional metal shafts in aerospace engineering structures and automobile structures due to the excellent mechanical properties of composite materials. Previous studies have shown that this hybrid structure could provide significant weight savings when compared to conventional metallic structures.[1]

As a torque transmission structure, the torsional performance of hybrid composite/metal shaft is a critical issue, and numerous studies have been conducted to research the torsional property of different types of hybrid shafts,[2–18] as summarized by Jarrett et al.[1] Mutasher et al.[2] carried out experimental research to study the influence of winding angles, the numbers of layers, and stacking sequence on the static torsion capability of a hybrid aluminum/composite drive shaft. In their torque test, the torque-twist angle curves of different hybrid driveshafts were recorded, and the failure mechanism under static torque loading was also studied. Their experimental results suggest that the static torque capacity of shaft with $\pm 45^{\circ}$ winding angle is larger than those with 90° angle, and an increasing number of layers could lead to higher torsional strength of the hybrid aluminum/composite shaft. In order to investigate the influence of reinforcement types on the torsional performance of hybrid composite shafts, Tariq et al.[3] designed and manufactured several hybrid shafts with different hybrid filament, including a combination of carbon, glass, and aramid fiber. According to their torsional test results, the shafts with hybrid reinforcement have lower torsional strength, stiffness, and resilience when compared to those with pure carbon. Additionally, it was found that replacing room temperature curing resin with hot-curing resin in the hybrid shafts could also lead to the decrease of torsional properties. Apart from static torsional properties, Lee et al.[6,7] investigated the torsional fatigue performance of a hybrid aluminum-composite shaft preloaded with axial compressive loading. They found that the preloaded axial compressive loading could result in longer torsional fatigue lives of the hybrid shafts up to the yielding of the metal tube. They also reported that the hybrid shafts with the same axial compressive residual stress have similar fatigue lives at room and subzero temperatures. In addition to torsional property, Sun et al.[19] studied the influence of winding angles and thicknesses on crashworthiness characteristics of aluminum/carbon fiber reinforced polymer (CFRP) hybrid tube based on quasi-static crushing tests.

Apart from the study on torsional property of hybrid composite/metal structure, some researchers have also paid attention to the mechanical properties of composite-steel joints in the hybrid structure.[20–26] Nguyen et al.[20] examined the mechanical performance of steel/CFRP adhesively-bonded double strap joints at elevated temperatures around the glass transition temperature (GTT) (T_g) of the adhesive. They found that as the service temperature approached T_g, the failure mode of adhesive layer changed to debonding from adherend failure, and the stiffness and strength decrease greatly as well. Experiments designed by Biscaia et al.[24] also aimed at the performance of CFRP-to-steel bonded joints under high temperatures. They also proposed a bi-linear temperature-dependent bond-slip model to simulate the mechanical behavior of CFRP-to-steel interfaces at different temperatures.

Although a lot of work has been done to study the influence of service temperature on the mechanical property of steel/composite joint, there still remains limited research on the torsional performance of hybrid composite shaft at different elevated service temperatures so far. Motivated by this reason, torsional tests were carried out on two types of newly designed hybrid composite/metal shafts at different elevated temperatures up to 150°C, one is a hybrid shaft with CFRP sleeve and metal core, and the other is a hybrid shaft without metal core. In the torsional tests, torque-angular deformation curves were obtained to analyze the influence of temperature on the torsional stiffness of different hybrid shafts. Additionally, the shear strains of the composite part and metal part were recorded by strain gages for the analysis of shear deformation of different parts during the tests.

Subsequently, a finite element analysis was performed in the software ABAQUS to model the torsional properties of the two hybrid shafts at different temperatures. In order to determine the elastic properties of composite sleeve in the finite element model, a micromechanical method was adopted using the software UnitCells© developed by Li et al.,[27] and an empirical model was introduced to predict the temperature-dependant elastic properties of CFRP and adhesive layer at different service temperatures. As a result, the predicted torque-angular deformation curves and torsional stiffness of the two hybrid shafts at different temperatures were compared to the experimental results.

2 | EXPERIMENTAL SETUP

2.1 | Specimen design and preparation

The schematic view of the two types of hybrid composite/steel shafts are shown in Figure 1.

In order to manufacture the hybrid shafts with a metal core, the metal part was created first with stainless steel, then the composite sleeve made from IM7/8552 epoxy carbon fiber reinforced twill weave composite was

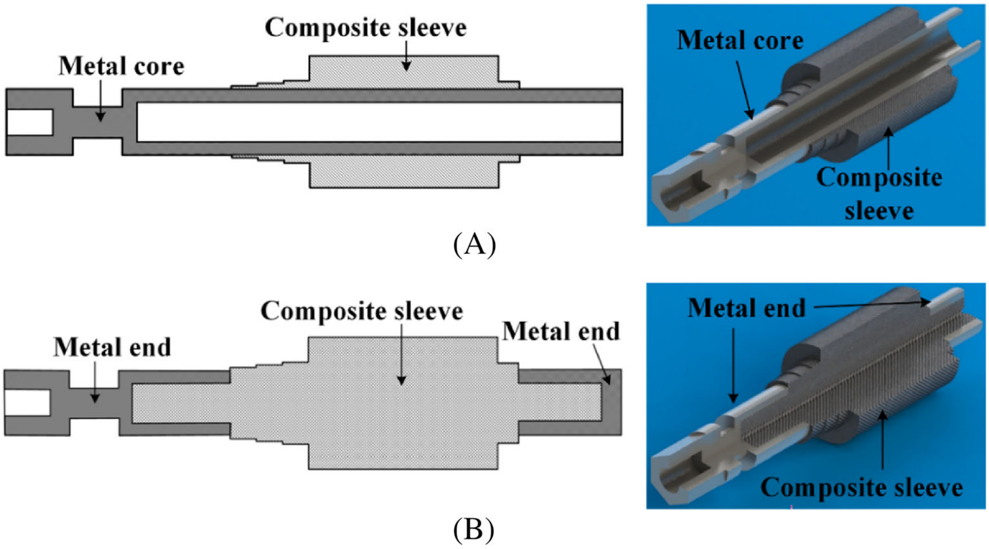

FIGURE 1 Schematic view of two composites-metal hybrid shaft specimens (dimensions in mm). (A) shaft with metal core, (B) shaft without metal core.

TABLE 1 Test matrix.

Test condition	Test sample	Sample number
Room temperature	Stainless steel core composite shaft	3
	Composite shaft with stainless steel ends	3
Elevated temperature (30°C, 60°C, 90°C, 120°C, 130°C, 140°C, and 150°C)	Stainless steel core composite shaft	3
	Composite shaft with stainless steel ends	3

wound onto the metal tube with a thin epoxy adhesive layer. For the hybrid shafts without metal core, two stainless-steel ends and a composite sleeve were manufactured separately, and then they were connected to each other with a thin epoxy adhesive layer.

In the test, several different service temperatures were considered to investigate the influence of service temperature on the torsion property of the two composite shafts, including the room temperature (15°C) and some elevated temperatures. The test matrix is shown in Table 1.

2.2 | Testing condition

The tests were performed according to the test standard ISO 7800-2012[28] and ISO 18338-2015[29] for room temperature tests and elevated temperature tests, respectively. As shown in Figure 2, the experiment was carried out on a torsion test machine KN-G500W, which could also record the applied torque and corresponding twist angle during the test. In order to record the shear deformation of composite and metal part under torque loading, two strain gages were placed on their surfaces, respectively.

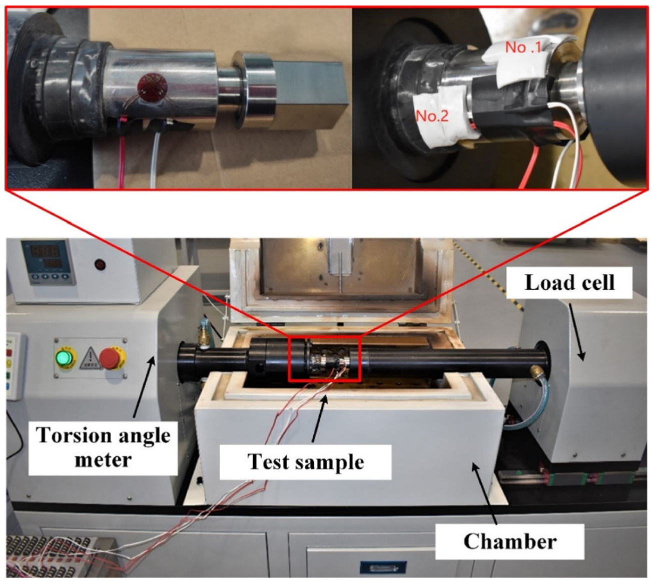

FIGURE 2 Illustration of test setup.

In the room temperature test condition, two-direction strain gauges numbered 1 and 2 were selected for the metal and composite parts, respectively, as shown in the picture on the right in Figure 2. After polishing and cleaning the surface of the test sample, the strain gauge is attached with a 45° angle using an instantaneous adhesive CC-35A KYOWA. Besides, SB tape was used to cover the strain gauge to protect it from environmental impact.

In the high-temperature test condition, a high temperature strain gauge KFH-2-120-C1-16 and a high temperature polyimide adhesive PI-32 were chosen since the highest environment temperature would be up to 150°C. It should be noted that the high temperature adhesive needs to be cure at high-temperature conditions along with the surface pressure. In addition, high-temperature Teflon tape LC-WY and silicone rubber layer

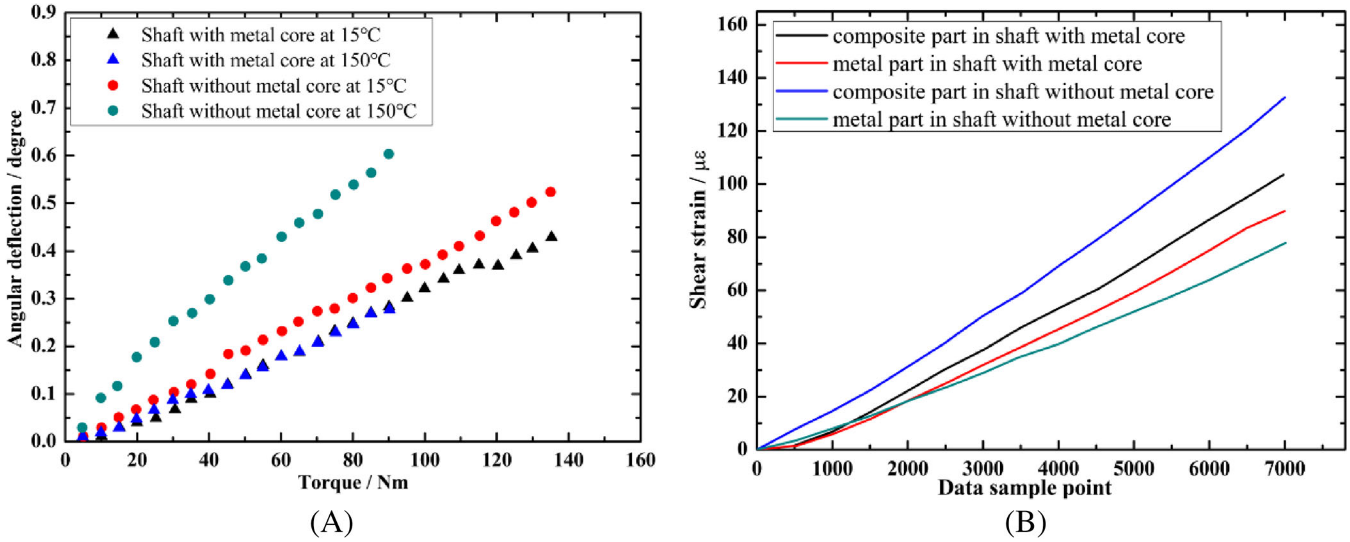

FIGURE 3 Experimental results of the two hybrid shafts at different temperatures. (A) Torque-angular deflection curves of the two hybrid shafts, (B) shear strain data of the composite part and metal part.

were placed to cover the strain gauge, and a metal clamping ring was used to apply the pressure between 200 kPa and 500 kPa on the strain gauge surface. In order to provide a stable environment during the curing process, a thermal chamber capable of heating up to 350°C was also used.

Before test, the samples need to be cured for 1 hour at 100°C and then 2 hours at 200°C, after which they were placed back in the thermal chamber to undergo the aging process. It should be noted that the KFH strain gauge needs to be heated from room temperature to 250°C at a constant rate of 5°C/min, then maintained for an additional 2 hours.

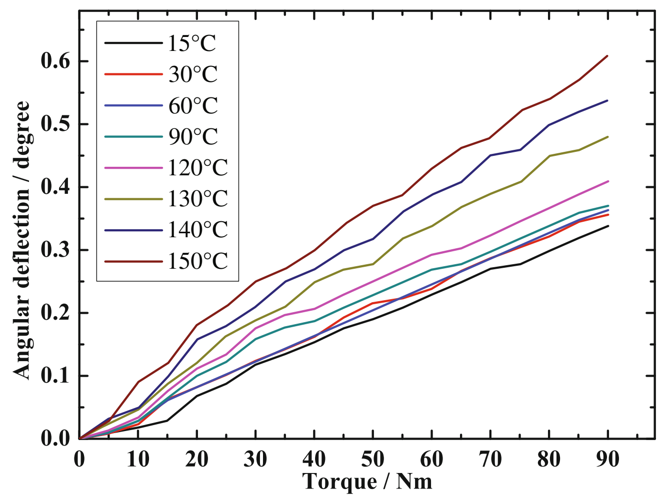

FIGURE 4 Torque-angular deflection curves of hybrid shaft without metal core at different environment temperatures.

2.3 | Experimental results

2.3.1 | Experimental results of the two hybrid shafts at different temperatures

Experimental results of torque-angular deflection curves of the two hybrid shafts and shear strain data of the composite part and metal part in the two hybrid shafts at room temperature and high temperature (150°C) are shown in Figure 3.

According to the experimental results in Figure 3, it is evident that elevated temperature has a much greater influence on the torsional property of the hybrid shaft without metal core, whereas for hybrid shafts with metal core the service temperature has no significant effect. As a key component of torque transmission structure, the torsional properties of the metal core in hybrid shafts remain almost unchanged at service temperatures up to 150°C, while for cores made from composite materials, the torsional properties would decrease noticeably with increasing temperature. As a result, the service temperature exerts a more pronounced influence on the torsional properties of hybrid shafts without a metal core.

2.3.2 | Experimental results of shafts without metal core at different temperatures

As shown in Figure 3, elevated service temperature could have a great influence on the torsional property of hybrid shaft without metal core. Hence, different elevated

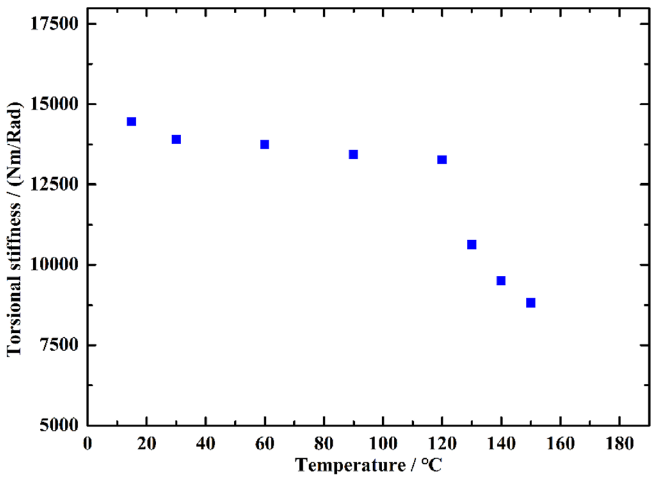

FIGURE 5 Torsional stiffness properties of hybrid shaft without metal core at different environment temperatures.

temperatures were considered in the torsional test of this type of hybrid shaft for further investigation, including 30°C, 60°C, 90°C, 120°C, 130°C, 140°C, and 150°C. Figure 4 shows the torque-angular deflection curves of the shaft without metal core at room temperature and several elevated temperatures.

Figure 4 shows the linear relationship between applied torque and angular deflection of hybrid shaft without metal core at different temperatures, indicating the linear torsional behavior of the shaft and an absence of damage initiation within the structure during the tests at different service temperatures.

Based on the results in the above figure, the torsional stiffness of the shaft without metal core at different temperatures could be also obtained according to equation (1),

$$S = \frac{T}{\theta}, \tag{1}$$

where S denotes the torsional stiffness of the structure, T and θ are applied torque and corresponding twist angle, respectively, and the results are shown in Figure 5.

The experimental results in Figure 5 show that there exists a critical service temperature (120°C), below which the torsional stiffness of the hybrid shafts decreases slightly, and then the torsional stiffness would decrease significantly as the temperature increases above 120°C. It should be noted that this critical service temperature is lower than the GTT of the epoxy resin which is around 150°C. This is mainly attributed to the fact that the stiffness of epoxy would begin to decrease greatly before its GTT, as revealed by some previous research,[30] which causes the degradation of matrix-dominated stiffness properties of composite structure, consequently resulting in the degradation of torsional stiffness of the hybrid structure.

3 | FINITE ELEMENT MODEL

In this section, an analytical model based on finite element method (FEM) was developed in the software ABAQUS to simulate the torsional performance of the two hybrid shafts at different temperatures, and the model results were compared to the experimental results for model verification. Besides, the model could also be used for further stress and failure analysis of hybrid composite shaft at different service temperatures.

3.1 | Determination of temperature-dependant material properties

It is known that elevated temperature has a great influence on the stiffness of epoxy. As a result, the elastic properties of adhesive layer and composite sleeve would change with the increase of service temperature. Many researchers also found that for different types of epoxy resins, the degradation laws of stiffness with the increase of temperature could vary.[23] So, for simplicity, it is assumed in this article that the relationship between the normalized stiffness of different types of epoxy resins and the service temperature normalized by their GTTs is similar, and could be described by the following empirical equation,[24]

$$\frac{E_T}{E_0} = 1 - \frac{1}{1 + e^{-k_1\left(\frac{T}{T_g} - k_2\right)}}, \tag{2}$$

where E_T and E_0 denote the stiffness of epoxy at elevated temperature and room temperature, respectively. T_g is the GTT of epoxy, T is the service temperature, k_1 and k_2 are model parameters whose values were chosen as 4.95 and 1.0 as suggested.[24]

In order to verify the above assumption and empirical equation, the normalized stiffness of different types of epoxy resins with respect to the normalized temperature predicted by the equation was compared to the experimental results reported,[23] as shown in Figure 6. It should be noted that in the figure, "S30," "A2014," "A420," and "J133" represent four different types of resin used in the reference. According to the comparison results, it could be concluded that the empirical equation could be adopted to describe the degradation of normalized stiffness of different types of epoxy resins.

It is also pointed out that an elevated temperature up to 200°C has no obvious effect on the stiffness of stainless steel and carbon fibers,[20,31] so their elastic properties are considered as temperature-independent, and they are listed in Table 2.

Given the fiber volume fraction, the elastic properties of carbon fibers and the elastic properties of epoxy resin

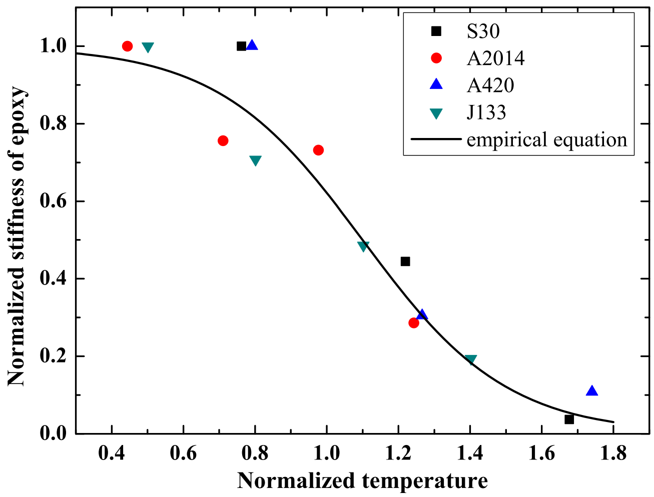

FIGURE 6 Comparison of normalized stiffness degradation of different epoxies between prediction result and experimental results.

TABLE 2 Elastic properties of steel.

	Elastic modulus (GPa)	Poisson's ratio
Stainless steel	200	0.28
IM7 carbon fiber	276	0.27

at different temperatures, the elastic properties of composite sleeve used in the experiment could be obtained by means of the micromechanical method with the software UnitCells© developed by Li et al.[27,32,33] Among different types of unit cells (UCs) available in the UnitCells©, a hexagonal UC was chosen to calculate the elastic properties of the weft and wrap yarn in the twill woven composite sleeve. Then a UC for twill woven composites was chosen to determine the elastic properties of composite sleeve at different service temperatures on the basis of calculated weft and wrap elastic properties, as shown in Figure 7.

The predicted degradation curves of elastic properties of twill woven composite sleeve with the increase of service temperature are shown in Figure 8. In the figure, E_1, E_2, and E_3 denote the longitudinal, transverse and out-of-plane elastic modulus of the twill woven, respectively, with the subscript "1," "2," and "3" representing the warp direction, the weft direction and thickness direction. G_{12} and G_{23} denote the in-plane and out of plane shear modulus, respectively. It should be noted that in the figure, the normalized stiffness properties were plotted for a more intuitive comparison, which was calculated by dividing the degraded stiffness properties by the initial value.

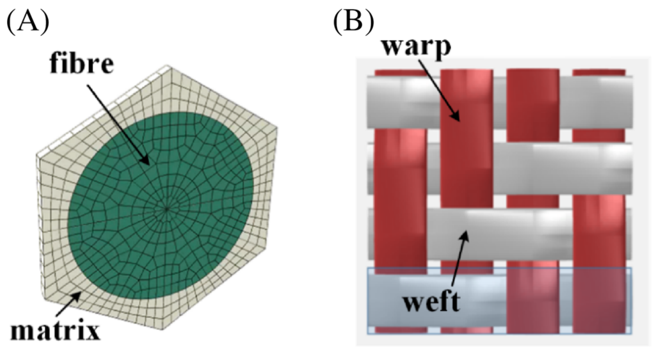

FIGURE 7 Unit cells to calculate the elastic properties of composite sleeve in the UnitCells©. (A) Hexagonal, (B) UC for twill woven composite.

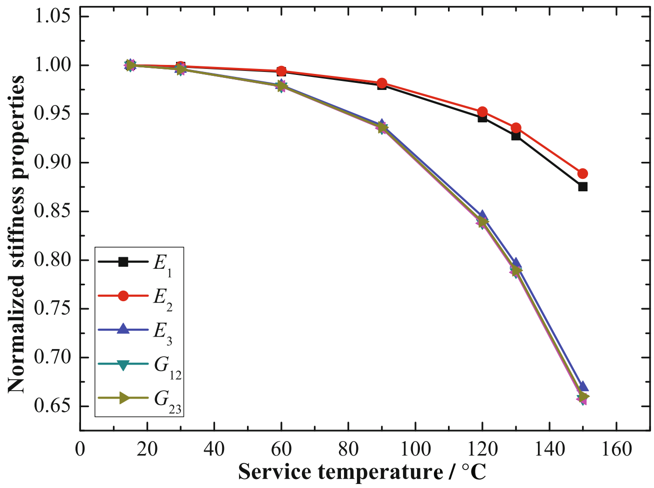

FIGURE 8 Predicted degradation curves of elastic properties of twill woven composite sleeve at different service temperatures.

3.2 | Loading, boundary, and mesh conditions

According to the practical condition in the experiment, a clamped boundary condition was applied to the surface of one metal end, and a torque loading was applied to the sleeve surface in the FEM model. The following figure illustrates the mesh condition of different parts of the hybrid shafts without metal core. In the model, all three parts are considered as linear elastic material, so an 8-node linear brick and full integration element C3D8 was used for the three parts, as shown in Figure 9.

3.3 | Results and discussions

Figure 10 shows the comparison between prediction results and experimental results of torque-angular

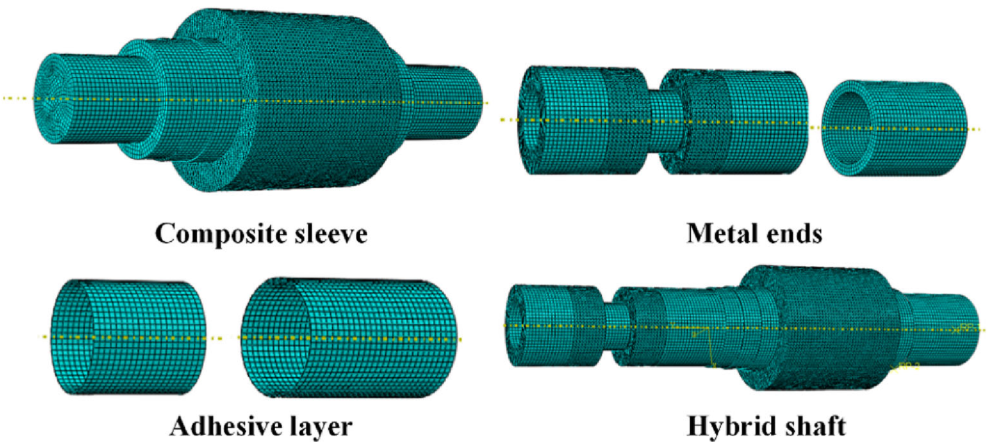

FIGURE 9 Mesh condition of different parts of hybrid shaft without metal core.

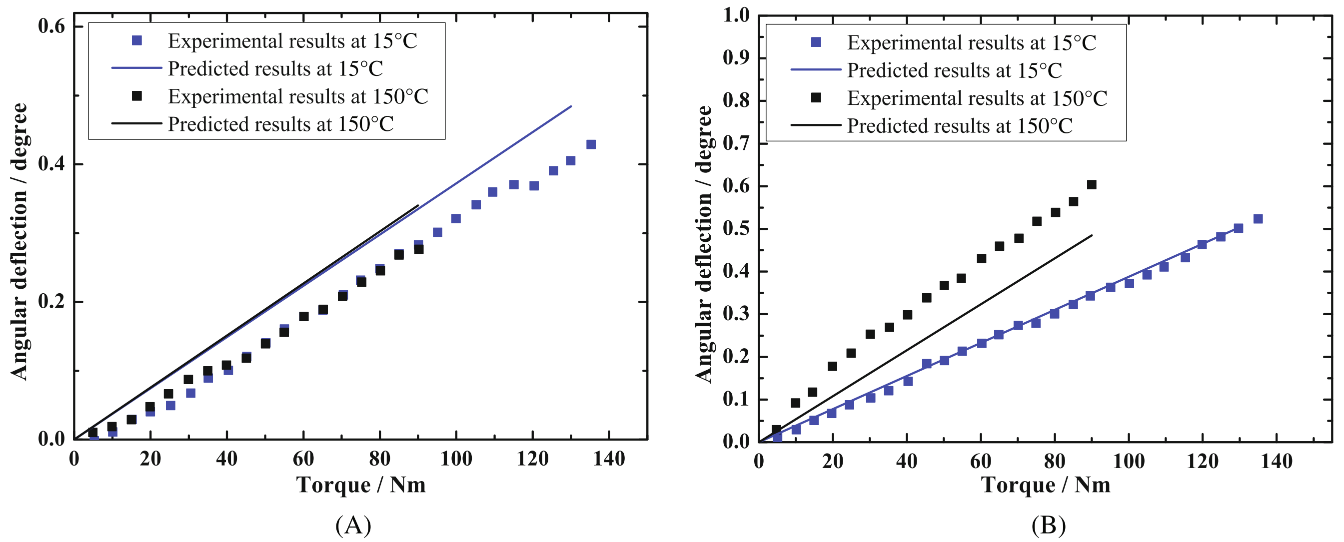

FIGURE 10 Comparison between experimental and predicted results of torque-angular deflection curves of the two shafts at 15°C and 150°C. (A) hybrid shaft with metal core, (B) hybrid shaft without metal core.

deflection curves of the two hybrid shafts under room temperature.

Figure 11 shows the comparison between prediction results and experimental results of torsional stiffness of the hybrid shaft without metal core at different elevated service temperatures.

According to the comparison results, the predicted torque-angular deflection curves of the two shafts and the trend of torsional stiffness degradation of the hybrid shaft without metal core as the increase of service temperatures are in agreement with experimental results, indicating that the developed FEM model could be used to model the torsional performance of composite/steel hybrid shafts.

As shown in Figure 11, the predicted torsional stiffness of hybrid shaft is generally larger than the experimental results, and the main reason is considered as the neglect of thermal residual stress in composite sleeve in the analytical model. As pointed out, the thermal residual stress arises due

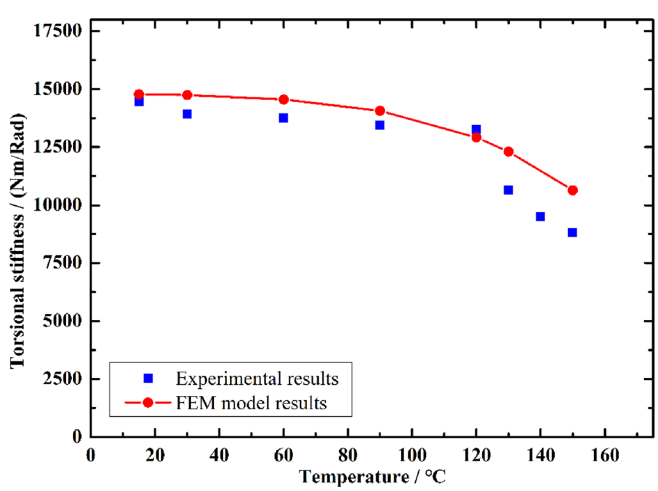

FIGURE 11 Comparison between experimental and predicted results of torsional stiffness of the shafts without metal core at different temperatures.

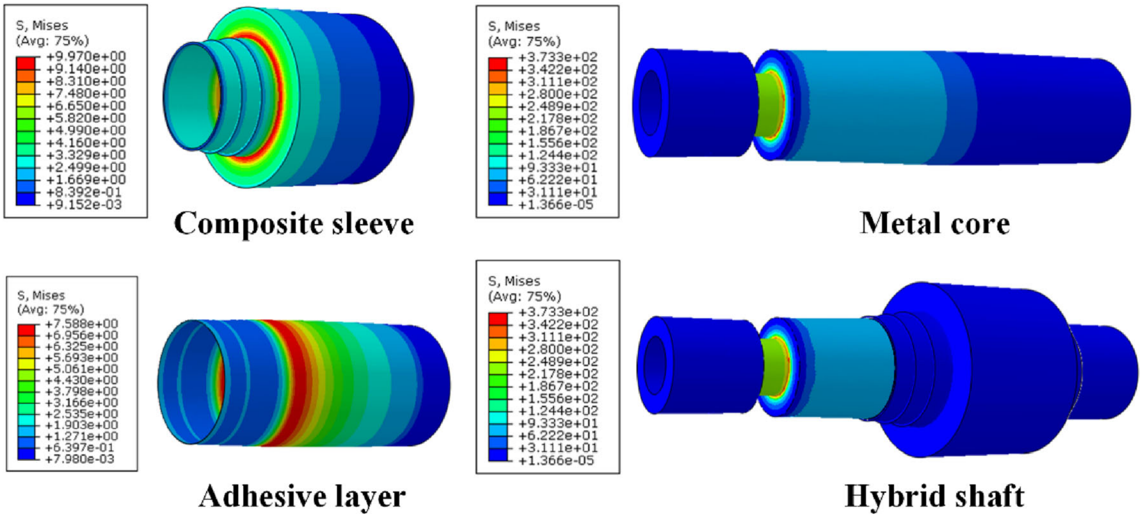

FIGURE 12 Stress fields in each part of hybrid shaft with metal core applied with 90 Nm torque at room temperature.

to the mismatch in coefficient of thermal expansion between the fibers and matrix as the service temperature changes.[34–36] This could result in the initiation of micro damages in matrix and micro delamination at the interface between the fibers and matrix, leading to further degradation of the matrix-dominated mechanical properties of composite structures, which dominate the torsional performance of the structure. Therefore, neglecting this effect would result in more conservative prediction results.

Apart from the torque-angular deflection curves and torsional stiffness, the stress filed in each part of hybrid shafts was also obtained by means of the FEM model, as shown in Figure 12. Further damage and failure analysis of hybrid shafts could then be conducted as a reference for hybrid shaft structure design and optimization.

4 | CONCLUSION

In this paper, torsional tests were conducted on two types of composite/steel hybrid shafts under different service temperatures (ranging from 15°C to 150°C) to investigate the influence of temperature on their torsional performance. In addition, a FEM model was developed in the software ABAQUS to simulate the torsional performance of hybrid shaft at different service temperatures. An empirical equation was introduced in the model to determine the temperature-dependant mechanical properties of the composite structure. The study in this paper could lead to the following conclusions:

According to the experimental results, it is found that service temperature has a much greater influence on the torsional stiffness of hybrid shaft without metal core, whereas for hybrid shafts with metal core the service temperature has no significant effect. Besides, the hybrid shafts without metal core exhibit a distinct critical service temperature at 120°C. Below this temperature, the torsional stiffness of hybrid shaft decreases slightly, while a significant decrease of the torsional stiffness was observed as the temperature increased above this threshold value. It is worth noting that this critical service temperature is lower than the T_g of epoxy used in the structure, which is around 150°C.

Comparison between the experimental results and predicted results of torsional performance of hybrid shaft without metal core at different temperatures has been made and indicates that the proposed FEM model is effective in simulating the torsional behavior of composite/steel hybrid structure at different service temperatures. Additionally, the FEM model could be used for further damage and failure analysis of hybrid structure based on the obtained stress field.

The neglect of thermal residual stress in the analytical model leads to more conservative results in predicting torsional stiffness, as thermal residual stress can induce the initiation of micro damages within matrix and interface, which further degrade the matrix-dominated mechanical properties and torsional stiffness of composite structures.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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