

Research Article

Thermomechanical Fatigue of Unidirectional Carbon Fiber/Epoxy Composite in Space

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Thermomechanical fatigue is one of the challenges for spacecrafts during space missions. As a result of the extreme temperature variation in space, thermal cycles are created, and due to the imposed mechanical loads to spacecrafts such as engine loads while they turn on and off, mechanical cycles are created. The worst structural fatigue for spacecrafts occurs when both thermal and mechanical cycles happen, simultaneously. The reason is that both thermal and mechanical cycles could cause stress concentration in the spacecraft structure. Therefore, the probability of crack initiation or propagation in the spacecraft structure increases. In this study, for the first time, novel thermomechanical fatigue relations are introduced to evaluate the safety of unidirectional carbon fiber/epoxy composite in the space environment. This composite material has been used in the spacecraft structure due to its lightweight and high strength. Furthermore, with applying thermal fatigue relations, thermally-safe planets, moons, and asteroids in the solar system for unidirectional carbon fiber/epoxy composite are identified.

1. Introduction

Unidirectional Carbon Fiber-Reinforced Epoxy (UD CFRE) has been used in many applications such as aerospace, automotive, sporting goods, and ships. In the space industry, UD CFRE can be used to fabricate the spacecraft structures [1]. UD CFRE composites have been used in space application due to their best mechanical properties such as low weight and high strength. Nevertheless, one of the failure modes of UD CFRE is due to the thermomechanical fatigue in the space environment. Therefore, the effect of thermomechanical fatigue on the mechanical behavior of this material is under extensive study [2].

The application of UD CFRE is very broad in many industries. It could be applied in automobiles, tidal turbine blades, jet-engine fan blades, wind turbine blades, and structural members of an aircraft. Experiments have shown that the failure mechanism in UD CFRE could be in the form of interlaminar and intralaminar matrix cracks, fiber-matrix debonding, and fiber breakage [3]. Mechanical properties of CFRE include corrosion resistance, high strength to weight ratio, nonmagnetic properties, and fatigue resistance. Epoxy

is a thermosetting resin. Therefore, its mechanical properties degrade intensely when it is exposed to elevated temperatures in the space environment. The epoxy deterioration can be severe in cases where the extreme heat in space is higher than the glass transition temperature (T_g) and the decomposition temperature (T_d) [4, 5].

Design processes have shown that fatigue properties are important characteristics of engineering materials. The reason is the statistics which has indicated that fatigue failures are over 90% of all the failures. The experiments have shown that, at temperatures higher than 100°C, fatigue strength of CFRE decreases significantly. The reduction in the fatigue strength of CFRE is due to the induced defects which causes high stress concentration [6].

Since the birth of CFRE, many studies have been provided to evaluate the mechanical properties, failure, and fatigue of this composite [7–13]. Among these studies, “significance of defects in the fatigue failure of carbon fiber-reinforced plastics” is submitted by Prakash [7]. Furthermore, “micro-mechanisms of interlaminar fracture in carbon-epoxy composites at multidirectional ply interfaces” is published by Singh and Greenhalgh [8]. Additionally, “prediction of tensile

fatigue life for unidirectional CFRE, in: progress in durability analysis of composite system,” is studied by Miyano et al. [9].

A few studies have been provided to predict the thermal fatigue of UD CFRE [14, 15] in space. Nevertheless, there is no research to predict the thermomechanical fatigue of UD CFRE. Therefore, in this study, for the first time, relations are introduced to predict the thermomechanical fatigue of UD CFRE in space. Thermomechanical fatigue occurs when a spacecraft is exposed to thermal and mechanical cycles, simultaneously. Each time the spacecraft engine turns on and off, it is both a mechanical cycle and a thermal cycle because it imposes mechanical stress on the spacecraft, and the engine heats up and cools down, simultaneously. Furthermore, each time the spacecraft passes through a shadow of a planet, moon, or an asteroid, its temperature decreases, and while it passes through the sun illumination, its temperature increases. Therefore, a thermal cycle can be created as a result of cooling down and heating up.

Stress concentration and possible crack initiation and/or propagation can develop in a spacecraft structure as a result of thermal and mechanical cycles. Hence, while thermal and mechanical cycles happen at the same time, the stress concentration which is induced in the structure and the probability of crack initiation and/or propagation in the structure could be higher than when only thermal or mechanical cycle occurs. Therefore, an exact analysis to evaluate the thermomechanical fatigue in space missions is required. Thus, in this study, thermomechanical fatigue of UD CFRE is evaluated.

2. Problem Formulation

In 2018 [15], it has been proved that the degradation of Interlaminar Shear Strength (ILSS) of UD CFRE is the main cause of failure in a thermal fatigue condition. The reason is due to the Interlaminar Shear stress (ILSs) within the Carbon Fiber (CF) and epoxy interface while UD CFRE is exposed to thermal cycles. The main cause of developing ILSs within the CF and epoxy interface is the difference of the Coefficient of Thermal Expansions (CTE) between these two materials in axial direction. Therefore, ILSs equation [15] has been defined as follows:

$$\text{ILSs} = G_{CF} |(23 - T)| \cdot |\alpha_{\text{epoxy},A} - \alpha_{\text{CF},A}|. \quad (1)$$

In equation (1), G_{CF} is the shear modulus of CF in the axial direction, 23 is the crack-free or stress-free temperature in Celsius, T is the space temperature, $\alpha_{\text{epoxy},A}$ is the CTE of epoxy in the axial direction, and $\alpha_{\text{CF},A}$ is the CTE of CF in the axial direction.

In a thermal cycling environment, ILSs must be less than ILSS. As a result, relation (2) for thermal fatigue is developed. In relation (2), $F.S._T$ is the thermal fatigue factor of safety.

$$\frac{\text{ILSs}}{\text{ILSS}} = F.S._T < 1. \quad (2)$$

For deriving a relation for thermomechanical fatigue, mechanical fatigue expression must be added to relation (2). Therefore, the first thermomechanical fatigue relation is indicated as follows:

$$\frac{\text{ILSs}}{\text{ILSS}} F.S._T + \frac{\sigma_M}{\sigma_f} F.S._M < 1. \quad (3)$$

In relation (3), $F.S._M$ is the factor of safety for mechanical fatigue, σ_M is the amplitude of applied mechanical stress, and σ_f is the failure mechanical stress. σ_M and σ_f must be both either compression or tension. For the highest safety, both compression and tension stresses must be evaluated in relation (3). The next thermomechanical relation, which must be evaluated in order to have a safe design for UD CFRE, is as follows:

$$\frac{(\Delta T_{\text{space}}) N_T}{(\Delta T_{\text{exp.}}) N_{T,f}} F.S._T + \frac{\sigma_M}{\sigma_f} F.S._M < 1. \quad (4)$$

In the relation (4), $\Delta T_{\text{exp.}}$ is the temperature variation at each thermal cycle in the experiment which has been conducted on UD CFRE. $N_{T,f}$ is the number of thermal cycles to failure in the thermal cyclic experiment. ΔT_{space} is the temperature variation at each thermal cycle in space. N_T is the number of thermal cycles in space. If there are two or multiple space environments with different thermal cycles with different temperature variations at each thermal cycle, then the following relation must be used:

$$\frac{\sum_{i=0}^n \Delta T_i \cdot N_{T,i}}{(\Delta T_{\text{exp.}}) N_{T,f}} F.S._T + \frac{\sigma_M}{\sigma_f} F.S._M < 1. \quad (5)$$

ILSS, $F.S._T$, $F.S._M$, and $N_{T,f}$ must be obtained by conducting experiments on UD CFRE. According to this thermomechanical fatigue evaluation method, relations (2)–(4) must hold to make sure that UD CFRE is fail-safe or in other words, it does not fail under thermomechanical fatigue.

Based on the latest experiments, at temperatures less than 0°C, epoxy shows a brittle behavior. Therefore, at temperatures less than 0°C, mechanical fatigue tensile stress amplitude must be less than 600 MPa ($\sigma_M < 600$ MPa) [6]. Furthermore, the number of mechanical fatigue cycles must be less than 10^5 ($N_M < 10^5$) [2] to prevent brittle fracture. Additionally, experiments have shown that after epoxy had been exposed to thermal cycles, its glass transition temperature (T_g) has been reduced by 9% [5]. Therefore, in thermal cycling environments, the epoxy temperature must be always less than 0.91 T_g to make sure it can carry load and does not fail. It seems necessary to mention that for different applications such as aerospace and automotive, the values which can be chosen for mechanical and thermal fatigue factors of safety can be different. Nevertheless, based on the results of research studies and experiments which have been conducted [2, 5, 6, 14, 15], for the thermal and mechanical fatigue factors of safety in relations (2), (3), (4), and (5), the minimum value of 1.5 is recommended.

3. Safe Planets, Moons, and Asteroids in the Solar System for UD CFRE

In this section of the manuscript, thermal analysis is provided to identify which planets, moons, and asteroids are safe for UD CFRE in the spacecraft structure. For this purpose, the following relation is employed:

TABLE 1: Safe planets, moons, and asteroids for UD CFRE in the inner solar system [16].

Star, planets, moons, and asteroids in the inner solar system						
Star	Planet	Moon	Asteroid	Temperature range (°C)	Safety	
Sun	Mercury			5.507	Not safe	
				-173 to 427	Not safe	
				464	Not safe	
	Venus				-69 to 58	Safe
	Earth		Earth's moon		-233 to 123	Not safe
	Mars		Mars's moon, Phobos		-140 to 20	Safe
	Mars		Mars's moon, Deimos		-40	Safe
Ceres				-40	Safe	
				-106 to -34	Safe	
			Eros	-46	Safe	
			Gaspra	-92	Safe	
			Ida	-73	Safe	
			Itokawa	-67	Safe	

$$\text{ILSS} = \text{ILSs}. \quad (6)$$

Relation (6) indicates that when ILSs reaches the ILSS, it is the end of the thermal life for UD CFRE. For solving relation (6), it should be extended and written in the form of relation (7). All the parameters in the relation (7) are the same as in equation (1), and the only difference is that instead of ILSs at the left-hand side of the equation, ILSS is substituted.

$$\text{ILSs} = G_{CF} \cdot |(23 - T)| \cdot |\alpha_{\text{epoxy},A} - \alpha_{CF,A}|. \quad (7)$$

Since all the values of ILSS, G_{CF} , $\alpha_{\text{epoxy},A}$, and $\alpha_{CF,A}$ are available [15]. Therefore, with substituting these values in the relation (7), the following relation is obtained:

$$80.9e + 6 = (7.59e + 9) \cdot |(23 - T)| \cdot |(43.92e - 6) - (-0.83e - 6)|. \quad (8)$$

By solving equation (8), T is derived, and it has two values. $T_{\min} = -215^\circ\text{C}$ and $T_{\max} = 261^\circ\text{C}$. It means that the temperature of UD CFRE should be between -215 and 261°C . The reason is that if the temperature of UD CFRE reaches -215 or 261°C , the ILSs reach the ILSS and the composite material could fail at these temperatures due to the stress concentration in the CF and epoxy interface. Hence, UD CFRE is safe in temperatures between -215 and 261°C . However, if a mechanical load applies to UD CFRE at this temperature range, the safety must be evaluated based on the thermomechanical fatigue relations which have been introduced in the previous section. Please note that, in equation (8), ILSS and G_{CF} are in N/m^2 , T is in Celsius, and CTEs are in $1/^\circ\text{C}$ units.

Based on this safe temperature range ($-215^\circ\text{C} < T < 261^\circ\text{C}$), in this part, it can be evaluated which planets, moons, and asteroids are safe for UD CFRE. According to the data in Tables 1 and 2 which are provided by Chown in 2011 [16], temperature range of planets, moons, and asteroids in the inner (Table 1) and outer (Table 2) solar system are indicated. If the temperature range is between the -215 and 261°C , they are thermally-safe for UD CFRE.

4. Future Work

Due to the excellent properties of Carbon Nanotubes (CNT), nowadays, its application is broad in many industries such as aerospace and automotive industries. Carbon nanotubes have great mechanical properties such as high tensile strength, high Young's modulus, and high aspect ratio which makes CNT one of the best materials for different applications. Furthermore, the electrical conductivity of CNT is high [17, 18]. Hence, recently, for enhancing the knowledge regarding the CNTs, a few studies to further analyze the mechanics and forest synthesis of CNT have been published [19–22]. Since CNTs have superior mechanical properties when they are compared with carbon fibers such as higher tensile strength, they are expected to be applied widely in future space structures. Therefore, for the future work, research regarding to the “thermomechanical fatigue of CNT-reinforced epoxy” is recommended.

5. Discussion

As it has been discussed in Section 2, at temperatures less than 0°C , epoxy is brittle, and it can crack when applying a smaller load with a much higher crack growth rate. Therefore, at temperatures less than 0°C , the factor of safeties, which must be used in relations (2)–(5), needs to be adjusted according to epoxy brittleness. Hence, $F.S._T$ and $F.S._M$ must have higher values. However, the amount of the factor of safeties must be determined by conducting thermomechanical fatigue experiments.

Furthermore, after several hundred thermal cycles, the epoxy glass transition temperature will drop by 9%. Therefore, epoxy will soften at lower temperatures and is not capable to carry load and withstand mechanical cycles. Hence, this drop in T_g must be considered in design processes and determining the appropriate values of safety factors.

All the thermomechanical fatigue relations which have been introduced in this work can be applied for carbon nanotube-reinforced epoxy as well. Nevertheless, the amounts of safety factors, maximum allowed number of thermal and mechanical cycles, and maximum ILSs, and

TABLE 2: Safe planets, moons, and asteroids for UD CFRE in the outer solar system [16].

Planet	Moon	Asteroid	Temperature range (°C)	Safety
Jupiter			-163 to -121	Safe
	Jupiter's moon, Io		-183 to -143	Safe
	Jupiter's moon, Europa		-223 to -148	Not safe
	Jupiter's moon, Ganymede		-203 to -121	Safe
	Jupiter's moon, Callisto		-193 to -108	Safe
Saturn			-191 to -130	Safe
	Saturn's moon, Titan		-179	Safe
	Saturn's moon, Enceladus		-240 to -128	Not safe
	Saturn's moon, Lapetus		-173 to -143	Safe
	Saturn's moon, Mimas		-209	Safe
Uranus	Saturn's moon, Hyperion		-180	Safe
			-214 to -205	Safe
Neptune	Uranus's moon, Miranda		-223 to -187	Not safe
			-223 to -220	Not safe
Pluto	Neptune's moon, Triton		-235	Not safe
			-240 to -218	Not safe
Eris			-246 to -230	Not safe
Makemake			-243 to -238	Not safe

mechanical stress must be adjusted to the mechanical and thermal properties of CNT/epoxy.

For determining the thermally-safe planets, moons, and asteroids for UD CFRE, in Section 3, it has been assumed that the UD CFRE does not have a coating against the space temperature. Thus, if an appropriate coating can be applied to cover the UD CFRE, it can enhance the safety temperature range.

6. Conclusions

In this research, by applying physical equations [15] and experimental data [14], novel relations are developed to predict the fatigue life of UD CFRE. For the fatigue safety of UD CFRE, one thermal fatigue and three thermomechanical fatigue relations are provided. All these relations must be satisfied if a safe fatigue design is required. For deriving all the unknown parameters in these thermal and thermomechanical relations, fatigue experiments must be conducted. According to these relations, space temperature, ILSs, mechanical stress amplitude, and the number of thermal and mechanical cycles can affect the thermomechanical fatigue life of UD CFRE. However, these relations can be applied to predict the thermal and thermomechanical fatigue life of CNT/epoxy, if the parameters in these relations are adjusted to the CNT/epoxy properties.

As it is discussed in Section 3, thermally safe planets, moons, and asteroids can be identified with applying the thermal fatigue relation. Finally, according to the recent studies, CNT has a superior mechanical property when it is compared to CF. Therefore, it is expected to be applied in space composites such as CNT/epoxy in the future spacecrafts.

Data Availability

The data which have been used to write this manuscript are available in the following references: [2], [4], [5], [6], [14], [15], and [16].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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