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Full Length Research Paper

Finding the safest planet for carbon structures in terms of thermal life

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With achieving higher technologies, and as the population of our planet grows and sources of Earth consume every day, scientists are trying to find an alternative planet to build a second home for mankind. During the last decades, Mars seemed to be the first planet as a candidate for second home of human. Nevertheless, a few years ago a new planet has been discovered to be suitable for human life. Titan, Saturn's moon, in spite of its great distance from the Earth has been identified as a good candidate for the second home for mankind due to its atmosphere which is a great shield against radiation. Recently, other planets have been discovered which appear to be habitable and suitable for human life. KOI 736.01, Kepler-22b, Gliese 581 c, and Gliese 581 g seem even more Earth-like when compared to Mars and Titan. Hence, the goal in this research is to estimate the thermal life of carbon structures on these planets to determine which planet offers the highest thermal life. Carbon structures have been recently used as aerospace structures due to their excellent lightweight and high strength.

Key words: Carbon structures, thermal life, KOI 736.01, Kepler-22b, Gliese 581 c, Gliese 581 g.

INTRODUCTION

Previously, thermal fatigue life of Unidirectional Carbon Fiber/Epoxy Composite (UD CF/EP) in Low Earth Orbit (LEO) was investigated by Anvari (2014). Additionally, because Mars is one of the closest and most similar planet to Earth, thermal fatigue life of UD CF/EP on Mars has been proposed in 2017 (Anvari, 2017). Furthermore, it is worth mentioning that the similarity of Mars to Earth, is one-way human mission to Mars has been proposed (Schulze-Makuch and Davies, 2010). Moreover, due to the atmosphere of Titan which is a great shield against radiation for human life, thermal fatigue life of UD CF/EP in Titan has been investigated in 2018 (Anvari, 2018). With the investigation of Mars' atmosphere, it appeared that it has a very small thickness in comparison with the Earth's atmosphere (Pasachoff, 1993). Hence, is not capable to create an enough shield against cosmic radiation. As a result, it is considered as a health-risk for human such as possibility of causing cancer and other diseases (Cucinotta et al., 2005; Horneck and Comet, 2006).

A few years ago, a scientist discovered that Titan which is a Saturn's moon has a thick atmosphere (Regius, 2016). This discovery turned out to be a very important observation because Titan's atmosphere is capable of creating a great shield against radiation. Thus, in Titan, there is no health-risk for human life regarding the

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Figure 1. The picture of Kepler-22b which is revealed by NASA.
Source: Kepler-22b: NASA/Ames/JPL-Caltech: August 7, 2017.

radiation effects.

Nevertheless, the minimum temperature on Titan is very low in comparison with that of Mars. Mars' minimum temperature is -123°C (Pasachoff, 1993), while the Titan's minimum temperature is -183°C (Lorenz and Mitton, 2002). As a result, thermal life of carbon structures on Titan appears to be lower than that on Mars.

Recently, four planets have been discovered that have the characteristics of a habitable planet (Zeipekkis, 2015; Lemonick, 2012). These four planets are KOI 736.01, Kepler-22b, Gliese 581 c, and Gliese 581 g. KOI 736.01 is just 1.6 times bigger than the Earth. On the other hand, it is believed that it is similar to Mars (Zeipekkis, 2015). Furthermore, KOI 736.01 is a meso-planet which means it is neither too big nor too small (Zeipekkis, 2015). The temperature variation on this planet is from 0 to 50°C which is very suitable for human life. Moreover, it has an atmosphere similar to Earth's atmosphere and is believed to have Oxygen. This planet is located in the goldilocks zone (Zeipekkis, 2015).

The other planet which has been discovered currently is Kepler-22b. This planet has a radius of about 2.4 times bigger than the Earth. This planet seems to be a water world and its temperature variation is from -11°C at coldest to 22°C at warmest environmental condition which can create a perfect environment for a habitable planet. This planet is also located in goldilocks zone (Zeipekkis, 2015; Neubauer et al., 2012; Borucki et al., 2012). In Figure 1, the picture of Kepler-22b that has been revealed by NASA is shown (NASA/Ames/JPL-Caltech: August 7, 2017).

Additionally, Gliese 581 c and Gliese 581 g appear to be habitable planets (Lemonick, 2012). There is no way to guarantee that Gliese 581 g has a rocky surface for life to walk or crawl around on (Lemonick, 2012). It could in principle be a water world (Lemonick, 2012). The temperature on Gliese 581 g is between -30 and -23°C (Lemonick, 2012). On the other hand, Gliese 581 c might be a rocky planet and it might even have oceans (Lemonick, 2012). A minimum of 5.6 times as massive as Earth and its temperature is between 0 and 40°C (Lemonick, 2012). In Figure 2, the picture of Gliese 581 g is shown (Space.com by Howell: May 4, 2016).

In a study by Anvari (2017), it has been approved that one of the key factors that decrease the thermal fatigue life of UD CF/EP is the high temperature variation for each thermal cycle in planets. By a simple comparison between the mentioned planets, it appears that temperature variation for each thermal cycle for Mars (Pasachoff, 1993), Titan (Lorenz and Mitton, 2002), and KOI 736.01 (Zeipekkis, 2015) is 100°C or 100K. It is important to notice that in this study, each thermal cycle means coldest to warmest temperature and back to coldest temperature.

On the other hand, in Kepler-22b (Zeipekkis, 2015) the temperature variation in each thermal cycle is -11 to 22°C and back to -11°C. It means that each thermal cycle is equal to 66°C which is less than the thermal cycles on Mars, Titan, KOI 736.01, and Gliese 581 c. By following this procedure, thermal cycles in Gliese 581 c and Gliese 581 g are 80 and 14°C, respectively (Lemonick, 2012).

According to this data and the results which have been obtained in 2017 (Anvari, 2017), it appears that Gliese 581 g has the potential to offer an environment which provides the highest thermal life for carbon structures. Nevertheless, there are some other factors that can affect the thermal fatigue life of carbon structures such as

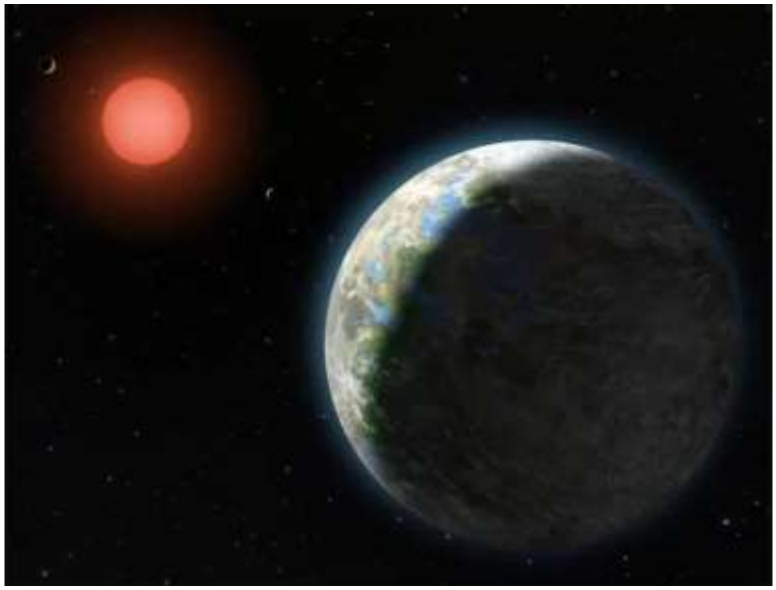

Figure 2. The picture of Gliese 581 g.
Source: Gliese 581 g: Space.com by Howell: May 4, 2016.

temperature difference between stress-free or crack-free temperature in carbon structures and environment temperature. Stress-free for carbon structures may be considered as 23°C (Park et al., 2012). It means that according to the results obtained in the study of Anvari (2017), that as the temperature difference between stress-free temperature and environment temperature increases, thermal fatigue life of carbon structures decreases due to high stress concentration and crack propagation. Thus, exact thermal analysis with considering all the effective factors is required to determine the thermal cycle numbers to failure for carbon structures on Mars, Titan, KOI 736.01, Kepler-22b, Gliese 581 c, and Gliese 581 g.

There are many studies related to the evaluation of the effect of thermal cycles on mechanical properties of materials (Park et al., 2012; Shin et al., 2000; Giannadakis and Verna, 2009). Nevertheless, it seems that there is no research to compare the thermal fatigue life of carbon structures in the mentioned planets.

In the present study, with extending and modifying the analytical methods which have been obtained by Anvari (2017), new relations have been developed to predict the thermal fatigue life of UD CF/EP which can be applied in carbon structures in Mars, Titan, KOI 736.01, Kepler-22b, Gliese 581 c, and Gliese 581 g planets.

MATERIALS AND METHODS

Carbon structures

Advanced carbon fiber-reinforced composite laminates have been widely used in satellite structures, where the advantages of these materials, their high specific stiffness, near-zero coefficients of thermal expansion (CTE) and dimensional stabilities make them uniquely suited for applications in a low-specific-weight environment. However, since the beginning of composite structure applications, there has been a strong need to quantify the environmental effects on the composite materials based on the coupon-level laminate test data. Recent studies have shown that the environmental conditions that are the most representative of space and that tend to degrade the properties of composite laminates involve vacuum, thermal cycling atomic oxygen (AO) and micrometeoroid particles. In this respect, there is significant interest in the construction of an experimental database to capture the collective understanding of the degradation mechanisms of composite laminate in in-service environments. It is necessary to be able to predict the long-term durability of composite laminates with engineering accuracy to use these materials with confidence in critical load-bearing structures" (Park et al., 2012). The cross-section (Anvari, 2014) and material properties (Park et al., 2012; Karadeniz and Kumlutas, 2007) of UD CF/EP is illustrated and indicated in Figure 3 and Table 1, respectively. Moreover, the cross-section's dimensions and arrangement of UD CF/EP is illustrated in Figure 3a and b, respectively. It is important to notice that in Figure 3 the diameter of carbon fibers' bundle embedded in epoxy is 0.5 mm. According to this cross-section (Anvari, 2014), the volume fraction of carbon fiber in UD CF/EP is 19.6%. Thus, the volume fraction of epoxy is equal to 80.4%.

Thermal fatigue life prediction

In order to estimate the thermal fatigue life of carbon structures in different planets, two methods are proposed in this study:

1. Extended Convex Curves Method (ECCM)
2. Modified Steady-Linear Method (MSLM)

ECCM is the extension of Convex Curves Method (CCM) which has been developed in 2014 (Anvari, 2014). Furthermore, MSLM is the modified version of Steady-Linear Method (SLM) (Anvari, 2017).

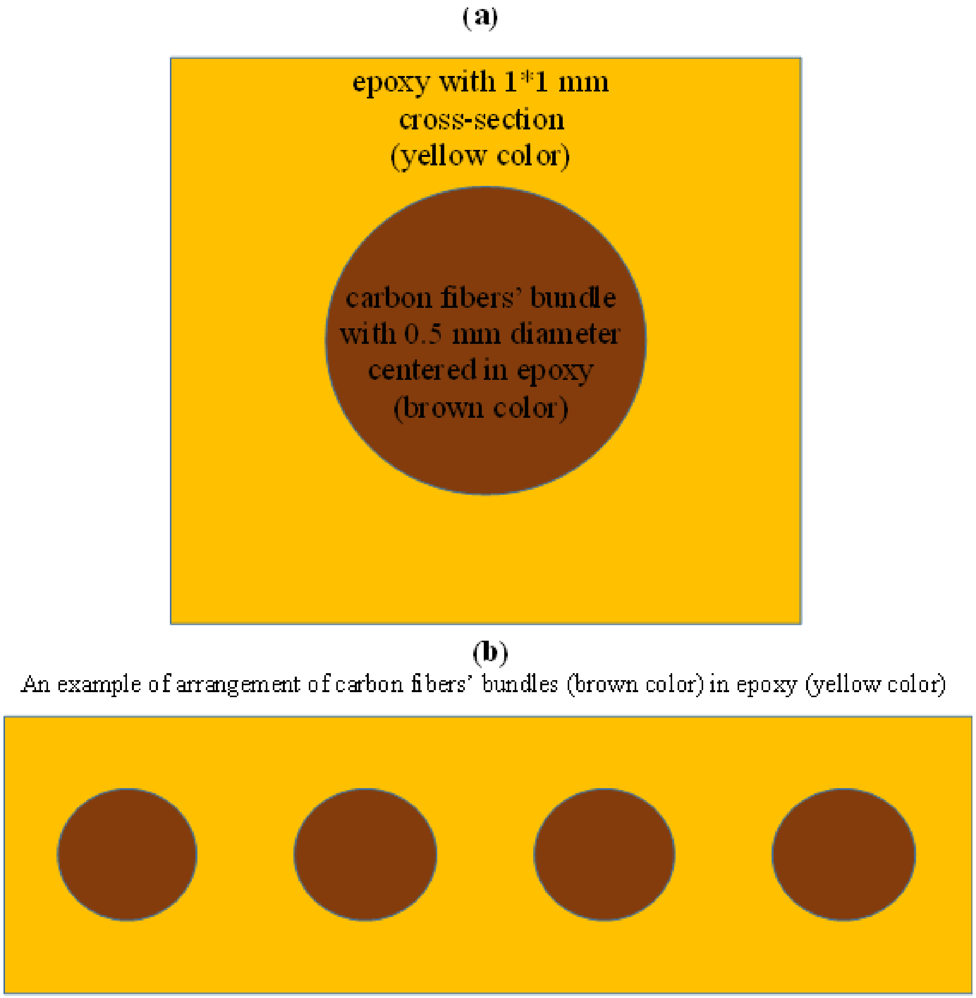

Figure 3. Cross section of the UD CF/EP **(Anvari 2014)**; dimensions (a) and arrangement (b), from up to down, respectively.

Subsequently, the procedure to obtain the thermal fatigue life of UD CF/EP with both ECCM and MSLM is explained.

Extended convex curves method

In this part of the manuscript, the procedure to apply ECCM for obtaining the thermal fatigue life of UD CF/EP in different planets (different thermal cycles) is explained.

The first step is to calculate the maximum Inter-Laminar Shear stress ($ILSs_{max}$) imposed on UD CF/EP in the planet. The equation for calculating the $ILSs_{max}$ is indicated as follows (Anvari, 2017):

$$ILSs_{max} = \Delta\alpha .\ \Delta T_{max} .\ G_{max} \quad (1)$$

Equation 1 represents the $ILSs_{max}$ in axial direction (along the fibers) of fiber/matrix interface areas. In Equation 1, $\Delta\alpha$ is defined as $\alpha_{epoxy} - \alpha_{carbon\ fiber}$. In this study, α is the Axial Coefficient of Thermal Expansion (ACTE). The numerical values of α_{epoxy}, $\alpha_{carbon\ fiber}$, and G_{max} which is the axial shear modulus of carbon fiber, are indicated in Table 1. ΔT_{max} is the maximum difference between the stress-free temperature (23°C) and planet's environment temperature. As an instance, in KOI 736.01 planet, temperature range is from 0 to 50°C. Hence, ΔT_{max} is equal to 50°C minus 23°C (stress-free temperature) which is 27°C and is the maximum temperature difference which is possible in this planet. If instead of 50°C, 0°C substitute in the relation, ΔT is equal to 23°C minus 0°C that is equal to 23°C which is less than the 27°C that has been derived, previously. Thus, 27°C can be substituted in Equation 1 as ΔT_{max} for KOI 736.01 planet. This procedure should be repeated to find ΔT_{max} for other planets as well. There is no concern related to the calculation of Δα and G_{max} because it is assumed that the numerical values of α_{epoxy}, $\alpha_{carbon\ fiber}$, and G_{max} are constant for all planets. It means that they are the mechanical properties of UD CF/EP and do not depend on the planet.

The second step is to solve the Convex Curves Equation (CCE) for Inter-Laminar Shear Strength (ILSS) while it is equal to $ILSs_{max}$ equation (Equation 1). Furthermore, because CCE for ILSS is related to LEO which represents 590°C temperature variation for each thermal cycle, a few changes have to be made. Equation 2 is the CCE for ILSS (Anvari, 2014).

$$ILSS = (-4.87e\text{-}6)\ (N_{LEO})^2 + (3.84e\text{-}3)\ (N_{LEO}) + 80.9 \quad (2)$$

Each thermal cycle in LEO is -175°C in solar eclipse, to 120°C in sun illumination, and back to -175°C (Park et al., 2012). Thus, each

Table 1. Material properties of UD CF/EP

Material	Epoxy	Carbon fiber
Axial coefficient of thermal expansion (1/°C)	43.92e-6	-0.83e-6
Transverse coefficient of thermal expansion (1/°C)	43.92e-6	6.84e-6
Axial Poisson's ratio	0.37	0.2
Transverse Poisson's ratio	0.37	0.4
Axial elastic modulus (GPa)	4.35	377
Transverse elastic modulus (GPa)	4.35	6.21
Axial shear modulus (GPa)	1.59	7.59
Transverse shear modulus (GPa)	1.59	2.21
Volume fraction (%)	80.4	19.6

Source: Park et al. (2012) and Karadeniz and Kumlutas (2007).

thermal cycle is 590°C in LEO. On the other hand, as an instance in KOI 736.01 planet, each thermal cycle is from 0 to 50°C and back to 0°C, which is 100°C. It means that each maximum thermal cycle in this planet is 100°C. As a result, the following changes have to be made in Equation 2 to obtain Equation 3.

$$ILSS = (-4.87e\text{-}6)\,(\Delta T_{PTC}.\,N_{Planet} / \Delta T_{LEO})^2 + (3.84e\text{-}3)\,(\Delta T_{PTC}.\,N_{Planet} / \Delta T_{LEO}) + 80.9 \quad (3)$$

In Equation 3, ΔT_{PTC}, ΔT_{LEO}, and $N_{planet,}$ are temperature variation for Planet Thermal Cycle, Temperature variation for LEO thermal cycle, and thermal cycle numbers to failure for the planet, respectively. With the substitution of the numerical values of ΔT_{PTC} (for KOI 736.01 planet) and ΔT_{LEO} in Equation 3, Equation 4 is obtained.

$$ILSS = (-4.87e\text{-}6)\,(100\,N_{Planet} / 590)^2 + (3.84e\text{-}3)\,(100\,N_{Planet} / 590) + 80.9 \quad (4)$$

Equation 4 is the Extended Convex Curve Equation (ECCE) of ILSS for UD CF/EP in KOI 736.01 planet. Hence, by solving this equation while it is equal to Equation 1, cycle numbers to failure for UD CF/EP in KOI 736.01 planet can be achieved. This relation is indicated AS follows:

$$ILSs_{max} = ILSS\ (ECCE), \quad (5)$$

which is equal to

$$\Delta\alpha.\ \Delta T_{max}.\ G_{max} = (-4.87e\text{-}6)\,(100\,N_{Planet} / 590)^2 + (3.84e\text{-}3)\,(100\,N_{Planet} / 590) + 80.9 \quad (6)$$

With substituting the numerical values of Table 1 and ΔT_{max} for KOI 736.01 in Equation 6, Equation 7 is obtained.

$$9.2\ (MPa) = (-4.87e\text{-}6)\,(100\,N_{Planet} / 590)^2 + (3.84e\text{-}3)\,(100\,N_{Planet} / 590) + 80.9 \quad (7)$$

By solving Equation 7, cycle numbers to failure for UD CF/EP in KOI 763.01 Planet is equal to 25,073 thermal cycles. This procedure is repeated to achieve the thermal cycles to failure for UD CF/EP in Mars, Titan, Kepler-22b, Gliese 581 c, and Gliese 581 g, and the results are shown in Table 2. It is important to notice that there are three kinds of ΔT in this procedure that each is different from another. ΔT_{max}, ΔT_{PTC} and ΔT_{LEO} which are explained in previous paragraphs.

Modified steady-linear method

In this part of the study, deriving the thermal cycle numbers to failure by the application of MSLM is explained. The first step like the ECCM is to derive the $ILSs_{max}$ with using Equation 1. Before, moving to the second step, it is necessary to mention that ILSS at zero thermal cycles for UD CF/EP ($ILSS_0$) is equal to 80.9 MPa which is the maximum ILSS and is used in following relations.

MSLM is divided into two parts; first, steady region, and second, linear region. In order to define the steady region, thermal cycle numbers for this region needs to be derived. The following relations can be used to derive the thermal cycle numbers for the steady region.

$$ILSS_0\text{-}((ILSS_0.\ \Delta T_{PTC}) / \Delta T_{LEO}) = ILSS\ (ECCM) \quad (8)$$

which is equal to

$$80.9\text{-}((80.9\Delta T_{PTC})/\Delta T_{LEO}) = (-4.87e\text{-}6)\,(\Delta T_{PTC}.\,N_{steady}/\Delta T_{LEO})^2 + (3.84e\text{-}3)\,(\Delta T_{PTC}.N_{steady}/\Delta T_{LEO}) + 80.9 \quad (9)$$

With substituting the numerical values of ΔT_{PTC} and ΔT_{LEO} in Equation 9, cycle numbers for steady region (N_{steady}) can be derived.

For deriving the total thermal cycle numbers to failure in UD CF/EP, the following relation is used. It is important to notice that the slope in Equation 10 is the average slope of Convex Curve (CC) for ILSS equation between 3000 and 4000 LEO thermal cycles (Anvari, 2014). The reason that this slope is chosen is because in this region of the convex curve the slope is approximately constant.

$$ILSS_0 = (LEO\ CC\ Slope)\,(\Delta T_{PTC} / \Delta T_{LEO})\,(N_{steady}) + a \quad (10)$$

In Equation 10, $ILSS_0$ as mentioned earlier is equal to 80.9 MPa. LEO CC Slope is equal to (Anvari, 2014)

$$(42\ (MPa) - 15\ (MPa) / (4000\ (cycles) - 3000\ (cycles))). \quad (11)$$

Therefore, with substituting the values for LEO CC Slope in Equation 10, Equation 12 is derived.

$$80.9 = -\,0.027\,(\Delta T_{PTC} / \Delta T_{LEO})\,(N_{steady}) + a \quad (12)$$

In this part, by substituting the values of N_{steady} which is derived from Equation 9, ΔT_{PTC} and ΔT_{LEO}, in Equation 12, the constant "a" can be derived. With deriving the value of "a", the final equation to obtain the cycle numbers to failure is achieved as follows:

Table 2. Thermal cycle numbers to failure (*N*) derived for UD CF/EP in different planets by ECCM and MSLM.

Method\Planet	Titan	Mars	KOI 736.01	Gliese 581 c	Kepler-22b	Gliese 581 g
MSLM (*N*)	14,872	19,318	28,139	34,375	39,172	146,573
ECCM (*N*)	11,449	17,409	25,074	31,735	37,442	170,410
Difference (%)	29.9	11	12.2	8.3	4.6	-16.3
Average difference (%)				8.3		

$$ILSs_{max} = - 0.027\ (\Delta T_{PTC} / \Delta T_{LEO})\ (N) + a \quad (13)$$

In Equation 13, the values for $ILSs_{max}$, ΔT_{PTC}, ΔT_{LEO}, and "a", are already derived or available. Hence, the value of *N* which is the thermal cycle numbers to failure for UD CF/EP can be derived. This process has been performed for Mars, Titan, KOI 736.01, Kepler-22b, Gliese 581 c, and Gliese 581 g, and thermal cycle numbers to failure for these planets have been derived with MSLM as shown in Table 2.

RESULTS AND DISCUSSION

As shown in Table 2, thermal cycle numbers to failure for UD CF/EP in Gliese 581 g is the highest. It means that the environment of Gliese 581 g is not only suitable for human life, but also is appropriate for carbon structures to extend their life. According to these results, the ranking of planets based on the longest to shortest thermal life for carbon structures is as follows:

(1) Gliese 581 g
(2) Kepler-22b
(3) Gliese 581 c
(4) KOI 736.01
(5) Mars
(6) Titan

Consequently, it appears that Gliese 581 g seem to be the best candidate for second home of mankind. The only issue is a huge distance between Earth and Gliese 581 g that it seems is not possible to reach with current space-travel technology (Lemonick, 2012). Furthermore, Kepler-22b planet is very far from the Earth and it seems almost impossible to travel there with current space-crafts.

With comparison between ECCM and MSLM, it appears that MSLM is in close agreement with ECCM in terms of prediction of thermal cycle numbers to failure for UD CF/EP. Thus, it seems that the theory of steady and linear region in "ILSS-Thermal cycle numbers" relation, is approximately correct. With the further investigation of the results in Table 2, it can be concluded that the method of ECC is more conservative than the method of MSL. The reason is due the average thermal cycle numbers obtained by MSL method which is 8.3% higher than that for ECC method. Therefore, it appears that ECC method offers higher safety factor when compared with MSL method.

Nevertheless, this conclusion is not always correct because as it is indicated in Table 2 for Gliese 581 g planet, the thermal fatigue life which is derived by ECC method has a higher value when compared with MSL value. As a result, the safest method to derive the thermal fatigue life is to make sure that the results of both methods have been derived, and between them, the minimum result for the thermal cycle numbers should be chosen for the design purposes in order to include the maximum safety factor.

As shown in Table 2, with comparison between Mars and Titan, it appears that Mars is a better planet in terms of higher thermal life for carbon structures. It seems that the only significant drawback is its atmosphere that cannot diminish the radiation and is a great danger for human health.

Conclusions

In the present research, by using new relations, thermal fatigue life of UD CF/EP which can be used in carbon structures in Mars, Titan, KOI 736.01, Kepler-22b, Gliese 581 c, and Gliese 581 g, has been derived. For this purpose, MSLM and ECCM have been employed. The comparison between these two methods has shown that the new MSLM has a close result to ECCM. Thus, based on the results obtained for thermal cycles to failure for UD CF/EP in the planets with both methods, it appears that the theory of steady-linear regions for ILSS as a function of thermal cycles is approximately correct. This prediction can contribute to estimate the thermal cycles to failure for UD CF/EP with higher reliability and safety factor. Additionally, according to the results obtained by MSLM and ECCM, Gliese 581 g appears to be the safest planet in terms of thermal fatigue life for UD CF/EP which can be used in carbon structures.

Abbreviations and symbols

ILSS, Inter-laminar shear strength; **$ILSS_0$,** inter-laminar shear strength at zero thermal cycles; **$ILSs_{max}$,** maximum inter-laminar shear stress; **$\Delta\alpha$,** Difference of axial coefficients of thermal expansion between carbon fiber and epoxy; **ΔT_{max},** maximum temperature variation between stress-free temperature in UD CF/EP and ambient temperature in planet; **G_{max},** maximum shear modulus in axial direction (Carbon fiber's axial shear modulus); $\alpha_{carbon\ fiber}$, Carbon fiber's axial coefficient of thermal expansion; α_{epoxy}, Epoxy's axial coefficient of thermal expansion; **N,** cycle numbers to failure; N_{steady}, cycle numbers for steady region; N_{planet}, cycle numbers to failure in planet; **ΔT,** temperature variation; ΔT_{LEO}, temperature variation in each thermal cycle in low earth orbit; ΔT_{PTC}, Temperature variation in each thermal cycle in planet.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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