JOURNAL OF MATERIALS RESEARCH AND TECHNOLOGY 2022;21:4773–4789

Available online at www.sciencedirect.com

jmr&t Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Review Article

The fatigue performances of carbon fiber reinforced polymer composites – A review

Rui Guo [a,b,c], Chenggao Li [a,c,b], Yanzhao Niu [a,b,c], Guijun Xian [a,b,c,*]

[a] Key Lab of Structures Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Harbin, Heilongjiang 150090, China

[b] Key Lab of Smart Prevention and Mitigation of Civil Engineering Disasters of the Ministry of Industry and Information Technology, Harbin Institute of Technology, Harbin 150090, China

[c] School of Civil Engineering, Harbin Institute of Technology, Harbin, Heilongjiang, 150090, China

ARTICLE INFO

Article history:
Received 4 July 2022
Accepted 8 November 2022
Available online 12 November 2022

Keywords:
Carbon fiber reinforced polymer
Fatigue performances
Damage mechanism
Fatigue modelling

ABSTRACT

The fatigue loading is the proximate factor leading to the performances degradation of the Carbon fiber reinforced polymer (CFRP) composites and structures, which detrimentally affects the service-life and damage tolerance. The present review paper provides the most relevant and up-to-date information on the fatigue of CFRP composites. In order to summarize the main influence factors of fatigue performance evolution, the fatigue damage mechanism and characterization method. Furthermore, the fatigue models are discussed in detail. The number of research results show that the materials constituents, service environments and cyclic loads have significant effect on the fatigue performances of CFRP composites. The nature of composites fatigue is the damage initiation and propagation process, and the fatigue damage mechanism of CFRP composites is complicated due to the inhomogeneous of material and the differences of material constituents, service conditions and cyclic loads, as well as the complex interactions among of them. Furthermore, the related fatigue models are developed based the macro and micro fatigue damage evolution. However, all of those models are phenomenon-based, it is necessary and challenging to establish theoretical prediction models based on the fatigue damage initiation and propagation for CFRP composites, to obtain the fatigue performances evaluation of CFRP in the complicated service environment, and then establish the fatigue design methods for CFRP composite materials and structural.

© 2022 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Owing to the light weight, high tensile strength and superior corrosion and fatigue resistances [1–4], Carbon fiber reinforced polymer (CFRP) has been widely used in the fields of aircraft, ships and automobiles, etc. [5,6]. In the last few decades, CFRP has gained widely applications in structural strengthening [7–10]. Recently, CFRP is developing rapidly in

* Corresponding author.
E-mail address: gjxian@hit.edu.cn (G. Xian).

https://doi.org/10.1016/j.jmrt.2022.11.053

2238-7854/© 2022 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

new structures, such as CFRP replaces the steel cable for the bridge structures [11–14], the application of CFRP can significant reduces the dead load and improves the corrosion resistance [15,16], which achieves the breakthrough of long span and life for bridge structures.

It is well known that the CFRP composites is frequently subjected the tension–tension fatigue loading in engineering structure, which inevitable led to the irreversible damage and the remarkable decrease of service performances. In addition, the service life of civil engineering is much longer and the actual survive environment is more complicated than aircraft or aerospace structures [17–19]. The hash service environment (hygrothermal, temperature and corrosion solution) will accelerate the fatigue damage accumulation, which led to the premature fatigue failure of CFRP. Therefore, the fully understanding of fatigue damage behavior is the key to improve the service reliability, safety and life for CFRP material and structure [20].

A number of researches show that the fatigue resistance of CFRP is highly depended on the composite system itself, such as the types of fiber and matrix resin, lay-up sequence, residual stresses and defect at interface of fiber/matrix [21–23]. All of the factors mentioned above have an obvious effect on the fatigue damage process (crack initiation and propagation), which changes the final fatigue life and failure mode. The main fatigue damage includes the fiber breakage, resin matrix cracking, fiber/resin debonding and delamination [24]. If the reinforced fibers are of high stiffness, the matrix cracking can be retarded somewhat [25]. This is because the high stiffness and strength fibers can bear higher load, which limits the strain of CFRP, and thus reduce the cracking of matrix resin. The thermoplastic based composites shows small crack accumulation in matrix resin than that of thermoset based composites [21], which attributes to the thermoplastic matrix resin with high fracture toughness decreases the crack initiation and propagation at defects and stress concentration zone [26]. The interface debonding can occur when the interface between the fiber and matrix is weakly bonded, and the ply-delamination failure mode may occur if a composite is composed of multiple layers. In addition, cyclic loads and service environments have significant effect on fatigue resistance of CFRP though changing the performances of matrix resin and interface of fiber/matrix. Consequently, fatigue is a complex process as the lifetime of composites under cyclic loading can be affected by the above factors in tandem.

Fatigue is the progressive damage process of a material when subjected to repeat cyclic loading, and the fatigue failure mechanism of CFRP is complex since the inhomogeneous of material. Even if a material is loaded at stress levels well below the elastic limit, the damage occurs under the conditions of continuous cyclic loading. The detailed material failure can be subdivided into three distinct stages, including crack nucleation, micro-crack growth and macro-crack growth. The micro-damage accumulates throughout the material and can grow steadily into macro-cracks, and then causes the macro-scale damage leading to the ultimate failure of the material. In addition, the remarkable distinction of fatigue damage can be found in low-cycle fatigue and high-cycle fatigue. The low low-cycle fatigue with high stress induces the irrecoverable damage within CFRP. In the case of high-cycle fatigue, the stress is low that the material remains within its limit of elastic proportionality, which brings about the progressive fatigue damage of composites. If the stress is low enough, it can assume that there is no fatigue damage within CFRP and the fatigue life is infinite.

To sum up, a large number of studies have obtained the fatigue properties of CFRP based on experimental tests, and revealed the fatigue damage mechanism of composites materials. Based on the above fatigue results, the researchers develop the number of simple fatigue life prediction models. With the application of CFRP in civil engineering under complicated service environment, the existing research results cannot support the safe service of CFRP in engineering structures. Therefore, a new coupling fatigue test method for CFRP under complicated service environment needs to be developed, to investigate the fatigue behavior and damage mechanism of CFRP. Furthermore, developing the progressive fatigue damage model considering the damage initiation and propagation with finite element method to obtain the fatigue performances evaluation of CFRP in the complicated service environment, and then establish the fatigue design methods for CFRP composite materials and structural.

The present review aims to collection and analysis the fatigue researches of CFRP with the latest paper. To begin with, the review collected the three key influence factors on fatigue performances of CFRP composites, which includes the material constituents, service conditions and the cyclic loads, and then obtained the fatigue performances evolution rules of CFRP considering the effect of above three factors. Furthermore, the fatigue damage mechanism and characterization technique were summarized systematically. And then, three kinds of fatigue models were discussed in detail based on the above the fatigue performance evolution. Finally, the review summarizes the latest research advances and reveals the research gaps and urgent research problems for the future work.

2. Fatigue life of CFRP

2.1. *The effect of constituents on fatigue*

The fatigue resistance of CFRP depended on the properties of each constituent, such as fiber, volume fraction and orientation, matrix resin. The difference of above constituents had a remarkable effect on the crack initiation and propagation (fatigue damage accumulation) of CFRP under fatigue load, which changed the final fatigue life and failure mode. The detailed results will be discussed as following.

2.1.1. *Fiber type, volume fraction and orientation*

Carbon fiber as the main unit to bear the axial load for unidirectional CFRP, the effect of fiber performances on fatigue performances was significant. The modulus, failure strain, volume fraction and orientation of carbon fiber were the main concern factors according to the related researches. In the early 1970's, the effect of three types of carbon fiber with high modulus, high strength (medium modulus) and low modulus on fatigue behavior was investigated systematically [27]. It was reported that the fatigue behavior of composites related

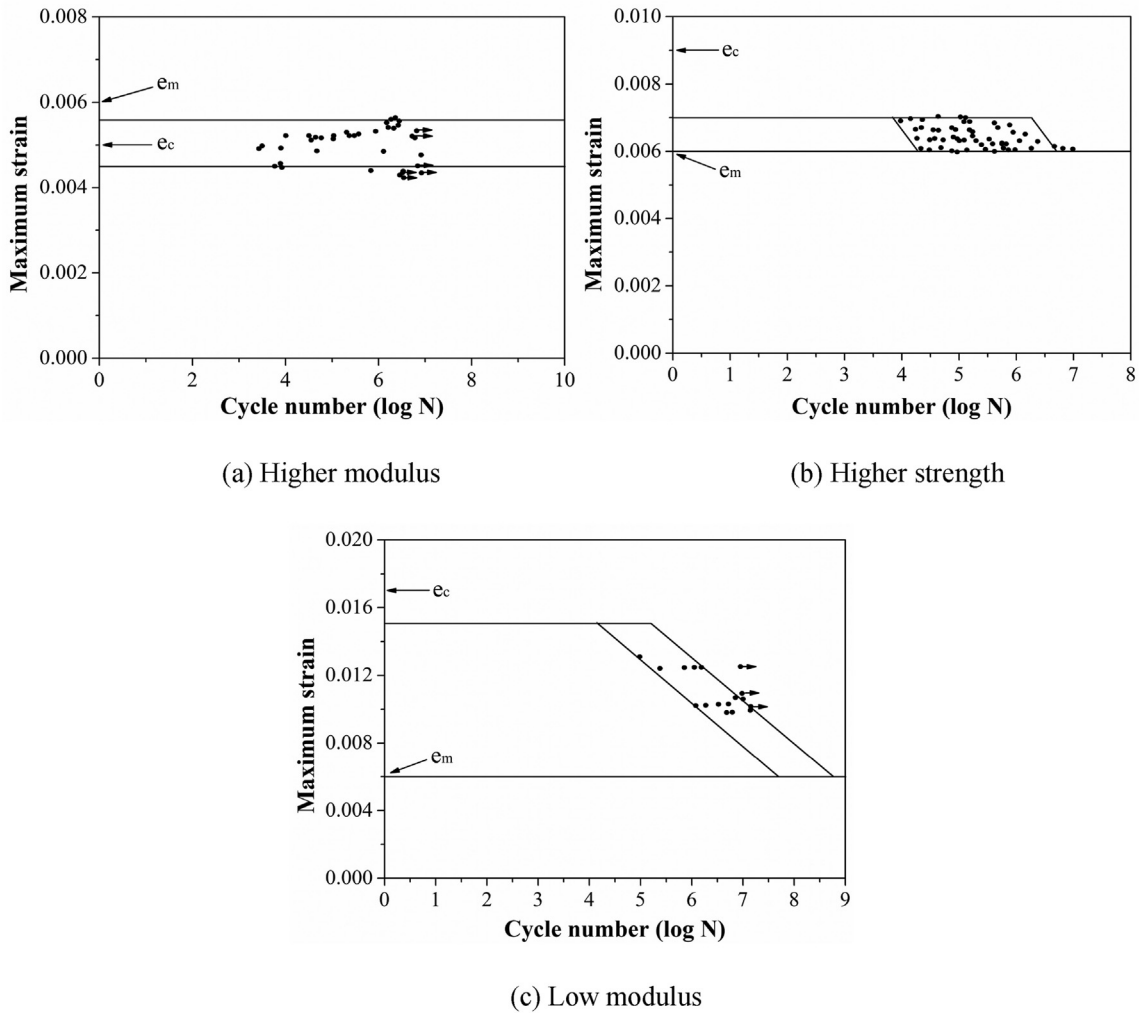


Fig. 1 – The strain-life diagrams of three kinds of carbon fiber reinforced unidirectional composites of (a) high modulus, (b) high strength and (c) low modulus. Figure inspired by the work of [27].

to the relations between the static failure strain (e_c) of composite and the fatigue strain limit (e_m) of matrix, the strain-life diagrams of three kinds of unidirectional CFRP were shown in Fig. 1. Sturgeon et al. [27] found that the high modulus carbon fiber reinforced composite only had the horizontal catastrophic damage band similar with the static failure (Fig. 1(a)). In this consequence, the static failure strain of cosmopolite was less than the fatigue strain limit of matrix. Meanwhile, the progressive damage band was observed in low modulus carbon fiber reinforced composite (Fig. 1 (c)), and the failure strain of composite was greater than the fatigue strain limit of matrix. Furthermore, Awerbuch et al. [2] reported that the failure strain of carbon fiber with high strength reinforced composite was slightly larger than the fatigue strain limit of matrix, the composite presented a small slopping progressive damage band (Fig. 1(b)).

The influences of the carbon fiber type on the fatigue properties of unidirectional CFRP were also investigated by Jones et al. [25]. The stress–life curves of three kinds of fiber reinforced composites were shown in Fig. 2. As shown in Fig. 2, high modulus carbon fiber reinforced CFRP had a superior fatigue property than that of low modulus carbon fiber, which was because the different fiber modulus brought about the difference of fatigue mechanism of CFRP [28]. The high modulus carbon fiber reinforced CFRP had a catastrophic

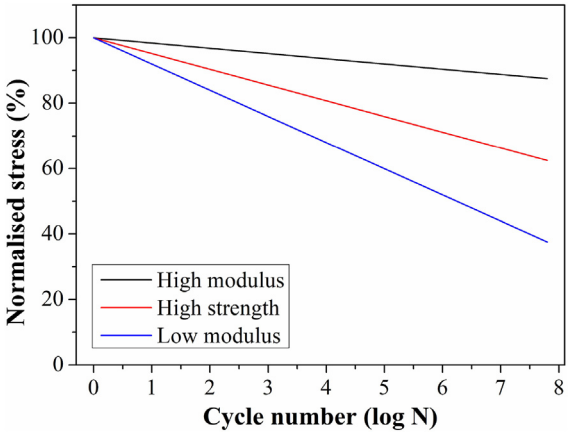


Fig. 2 – The stress–life curves of three kinds of carbon fiber reinforced unidirectional CFRP. Figure inspired by the work of [25].

failure mode with an explosive manner. By contrast, the progressive failure mode was observed in high strength carbon fiber reinforced CFRP. Meanwhile, the failure of low modulus CFRP was more stepwise and progressive than high strength. The difference of failure mode was attributed to the different energy stored in above three types of CFRP. Explosive failure occurred in high modulus CFRP owing to a large amount of stored energy released simultaneously once the matrix fractures. Contrarily, the gradual release of stored energy brought about the progressive failure of low modulus CFRP.

The failure strain of carbon fiber was another key parameter for the fatigue damage of CFRP. Four kinds of carbon fiber with high strength (1.2%), intermediate failure strain (1.5%), high failure strain (1.7%) and intermediate modulus (1.5%) were selected by cutis et al. [29,30] to investigate the fatigue behavior of unidirectional CFRP. The strain-life diagrams of four kinds of CFRP were shown in Fig. 3. As shown in Fig. 3, it was apparent from the curves that the fiber types have only a small effect on the fatigue performance of above four kinds of composites for the same epoxy matrix.

Owing to the carbon fiber was the prominent unit to bear the axial loading for the unidirectional CFRP, it was well known that the tensile strength and stiffness in fiber direction would increase with fiber volume fraction [31]. Therefore, the fiber volume fraction was a critical parameter for fatigue performances of unidirectional CFRP [32,33]. J. Brunbauer et al. reported that stress–life curves of unidirectional CFRP plates with high (55%) and low (30%) fiber volume fraction showed similar and very flat sloping band as shown in Fig. 4. The specimens with high fiber volume fraction always reached higher numbers of cycles to failure when testing at the same stress level as a result of the higher ultimate tensile strength. In addition, the fatigue damage of specimens with low fiber volume fraction was dominated by the matrix crack, while the fiber breakage was the main damage mode in specimens with high fiber volume fraction. Furthermore, the ensemble damage accumulation (EDA) model was developed by Hiremath et al. [34] to predict damage accumulation in CFRP subjected to cyclic loading. The results showed that the damage accumulation within the matrix decreased with the increase of fiber volume fraction and the increase of stress ratio for a given number of cycles.

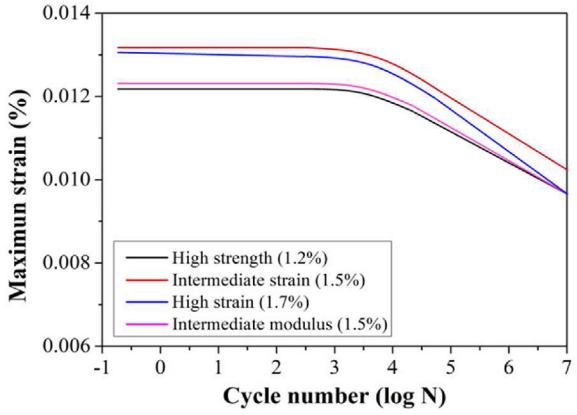


Fig. 3 – The strain-life diagrams of four kinds of CFRP. Figure inspired by the work of [29].

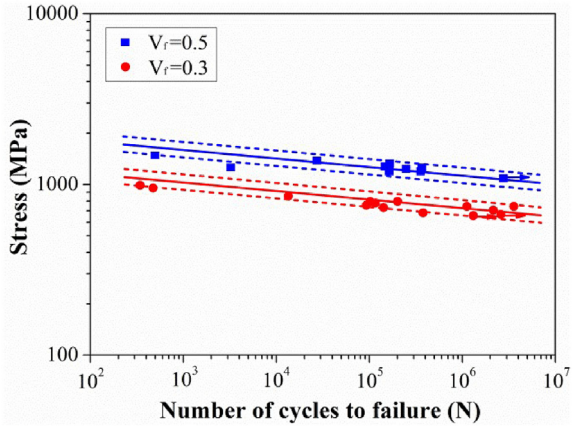


Fig. 4 – The stress–life curves of unidirectional CFRP plates with 30% and 50% carbon fiber volume fraction. Figure inspired by the work of [33].

Julia Brunbauer et al. [32]reported that the fiber orientation had significant effect on static and fatigue performances of unidirectional (UD) CFRP plates under different fiber volume. For UD 0° plates, the static compressive strength was about 30% of the tensile strength. By contrary, the static compressive strength of UD 45° and UD 90° plates was twice or three times higher than tensile strengths. In fatigue tests at R = 0.1, UD 0° and UD 45° plates with high fiber volume were tested at higher nominal stress amplitudes than their counterparts with low fiber content. In UD 90° plates, the fiber volume content mainly influenced fatigue performances in the high cycle fatigue, which was because the damage mechanisms changing from fiber pull-out at high stress levels to matrix cracking at lower levels in plates with 30% fiber volume content. In tension-compression fatigue tests, nominal stress amplitudes of UD 0° plate were lower and amplitudes for off-axis specimens were higher or similar compared to tension–tension fatigue tests. For UD 90° specimens, the fiber volume content did not influence the fatigue strength in tension-compression fatigue tests significantly.

Alok Behera et al. [35] investigated the tension–tension and tension-compression fatigue properties of $[\pm 45_4]_S$ and $[+45,-45,0,90]_{2S}$ laminates. The results showed that the fiber orientation had a minor impact on the static strength and fatigue life. The final failure under both static and fatigue loading was visible failed of individual layers parallel to fiber orientation. In addition, Huang et al. [36] investigated the fatigue behavior of filament wound Toray T700/Epotech X4201 composite pipes with different lay-ups. The work compared the fatigue behavior of coupon specimens manufactured with two different fiber orientations under tension–tension and tension-compression cyclic actions. The test results showed that the lay-up and stress ratio have significant effect on the failure mechanism and fatigue life of carbon fiber reinforced polymer (CFRP) composite coupons.

2.1.2. *Matrix resin*

It was reported that the matrix types had a pronounced effect on the fracture toughness of CFRP [26]. Consequently, the fatigue response was inevitable affected by the matrix type. It

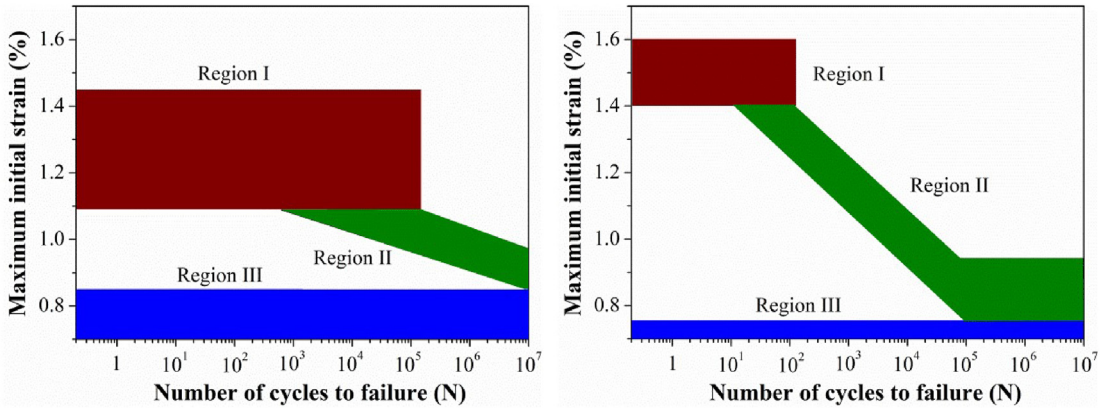


Fig. 5 – Fatigue life diagrams of (a) Epoxy based composite and (b) PEEK based composite. Figure inspired by the work of [21].

has been detailed that the composites with tougher matrix were found to degrade faster in fatigue life with a steeper slope of the strain-life diagram in region II [37]. However, the composites made from ductile matrix system together with high-strain fiber pronounced increased the fatigue resistance according to the research of [38]. Moreover, the fatigue behavior and the underlying micro-mechanisms of two different types of unidirectional CFRP loaded in tension–tension along the fiber direction have been studied by Gamstedt KE et al. [21]. As shown in Fig. 5, it was obvious that the epoxy based composite had more superior fatigue resistance than that of PEEK based composite. A few micro-cracks initiated at fiber break zone and propagated at a decelerating rate in epoxy based composite, which resulted in the more progressive in fatigue life diagram. By contrast, there was a more widely widespread debonding, crack propagation and matrix failure at a high rate, which led to the steeper slope in the fatigue life diagram in PEEK based composite. Which attribute the different fatigue damage mechanism occurred in the above two types of composites. For the better comprehensive the difference of fatigue damage mechanism, the fracture toughness of epoxy and PEEK based composite were investigated by Masaki H et al. [26], the results showed that the fracture toughness of PEEK based composite was higher than that of epoxy based composite. The high fracture toughness decreased the crack initiation and propagation of matrix resin at defects zone and aggravated the breakage of carbon fiber, which brought about the steeper degradation rate of fatigue life for PEEK based composite.

The fracture toughness of matrix resin was significant improved through the addition of nanoparticles [39,40], which can achieve more superior fatigue resistance for composites. The effect of multiwall carbon nanotubes (MWCNT) and few layered graphene (FLG) nanoparticles on the fatigue performance of CFRP was investigated by Knoll et al. [41]. The effect of nanoparticle modification on quasi-static mechanical properties was negligible. At all load levels, the addition of carbon nanoparticles with 0.3 wt% can significant improve the fatigue life, as shown in Fig. 6. In according to this, the stiffness of modified CFRP had a slow degradation process. This attributed to the increase of energy absorption and the change of dominant damage mechanism. The addition of nanoparticle formed the interface of nanoparticle/matrix, which brought about the additional nano-and micro-damages, such as nanoparticle/matrix debonding, plastic void growth and crack deflection. The additional energy was larger than that of the classic fatigue damage in CFRP, such as fiber/matrix debonding, matrix cracking, delamination and fiber fracture. The fracture transferred to the nanoparticle/matrix interface, where the matrix undergone enormous plastic deformation. In addition, there was an obvious difference in fatigue life improvement of CFRP for MWCNT and FLG. This was because FLG had higher specific surface area and additional layer separation failure modes, which contributed to absorb more energy than MWCNT and brought about the higher fatigue life.

2.2. *The effect of service environments on fatigue performance*

As mentioned above, the fatigue characters of CFRP depended on the properties of each constituent. The constituent properties will be changed in the long-term complicated service

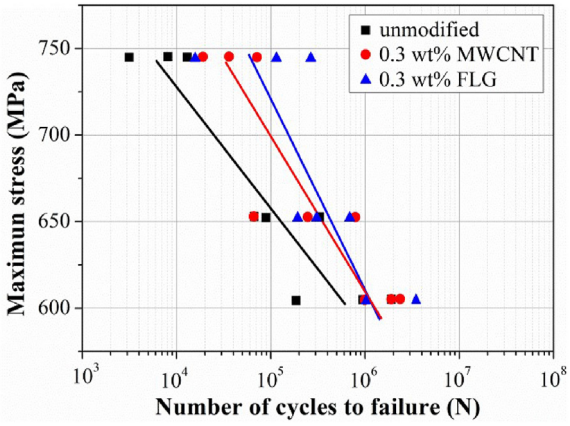


Fig. 6 – S–N curves of CFRP with carbon nanoparticles added. Figure inspired by the work of [41].

environment, such as the decline of matrix resin, interface debonding of fiber/matrix, erosion of fiber. The above factors weakened the mechanical performances and resulted in the rapid crack initiation and propagation, which brought about the premature fatigue failure of CFRP. The detailed effects of service environments on the fatigue performances of CFRP will be discussed as following.

2.2.1. *The effect of temperature*

Polymer based composites are viscoelastic materials and their mechanical properties are tended to affect by temperature. Mivehchi et al. [42] investigated the effect of temperature on fatigue strength and cumulative fatigue damage (D) of laminated fiber reinforced polymer composites. The effect of temperature on tensile properties of 0° plies was less than $[0/90]_{4S}$ $[0/+45/90/-45]_{2S}$ and 90°, while 90° lay-ups had the highest sensitivity to temperature changes. Furthermore, the author proposed temperature-dependent terms and equations and evaluated with the experimental data. The sensitivity of the mechanical properties to temperature was evaluated based on a constant, and the higher value corresponds to higher temperature sensitivity. In addition, the results were concluded from the D–N graphs that the cumulative fatigue damage was increased and the fatigue life was decreased with the increase of temperature.

The effect of temperature on the static and tension–tension fatigue behavior of CFRP composites was investigated by Wang et al. [43]. S–N curve, stiffness degradation, and displacement increment with lifetime under temperatures of −20 °C, 0 °C, 20 °C, 40 °C, and 60 °C were derived to evaluate the fatigue performance. As shown in Fig. 7, the fatigue life increased with the decrease of temperature at the same maximum cyclic stress, which was because the ability to transfer stress between fiber and matrix was increased. It should be noted that the effect of temperature on the fatigue life was negligible at the high cycle fatigue regime, which was because the impact of stress concentration of fiber/matrix and wear damage was less due to the slight softening of matrix resin at higher temperatures. In addition, the stiffness degradation and permanent displacement increment were sensitive to temperature. Greater stiffness degradation and permanent displacement increment was observed before failure at lower temperatures. This was because the specimen exhibited a longer fatigue life and greater wear damage, which allowed more damage to accumulate during loading.

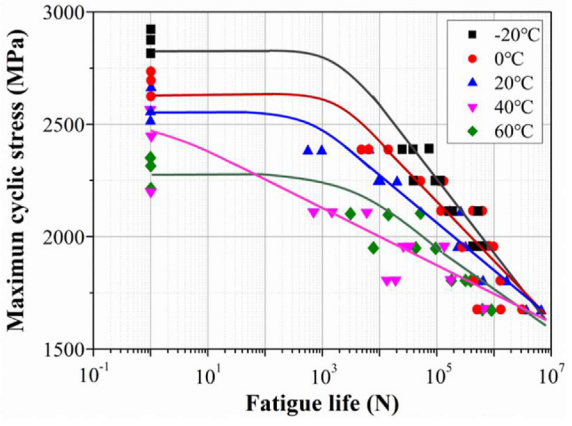


Fig. 7 – S–N curves under different environment temperatures. Figure inspired by the work of [43].

Temperature cycling was another significant factor to affect the physical continuum of CFRP composites and led to the local stress concentration at interface of fiber/matrix, which caused the growth of micro-cracking between the fiber and matrix along the fiber [44,45]. It was detailed that the producing of micro-cracking can remarkable reduced the mechanical performance of CFRP composites [46]. When the CFRP composites subjected the fatigue loading, the micro-cracking induced by the temperature cycling can significantly accelerate the damage accumulation and led to the premature fatigue failure of CFRP composites.

2.2.2. *The effect of hydrothermal ageing*

The absorption and diffusion of water molecular in composites was related to the polarity of matrix resin, the Fick's [47–49] and non-Fick's [50,51] water absorption behaviors were observed according to the related researches. Furthermore, the water molecular can be divided into two types of categories based on the bonding energy with resin matrix, which included the free water and bonding water [52,53]. When the water molecule ingresses into CFRP, the physical and chemical interactions between resin and water molecular were the prominent reason cause the decrease of mechanical properties [54,55]. The results showed that the degradation process of mechanical properties was mainly related to the water uptake content [56]. It was also found that the higher exposed temperature brought about the larger decrease of mechanical performances for the same water uptake content [57]. The free water will swell the CFRP and led to the interface damage through both shear [58] and compressive movement [59]. The bonding water weakened the initial inter-chain van der Waals force, hydrogen bonds and broken the resin backbone, which resulted in the resin plasticization and hydrolysis [52,60], which will significantly reduce the mechanical performances of CFRP composites.

The degradation of above matrix resin and interface induced by hydrothermal aging will remarkable affect the fatigue performances of CFRP composites. The delamination crack growth of unidirectional CFRP laminates under fatigue loading was investigated by Nakai Y et al. [61]. The results showed that the hydrothermal aging changed the cracking propagation process, and the distinct difference was found between Mode I and Mode II crack growth in water and dry condition. Mode II crack growth depended on the water absorption time, while Mode I crack growth depended on the number of loading cycles applied on the composites. It was found that maximum energy release rate of Mode II of water conditioned CFRP specimens tended to be lower than that of dry samples, this was because the ingress of water led to the plasticization of matrix resin [62]. It can be concluded that the fatigue micro-cracks in the initial stage was confined to the interface of fiber and matrix resin, and then the micro-cracks provided more diffusion path for the water molecular, which aggravated the plasticization of the matrix resin. At the later stages of fatigue life, the large scale fractures dominated the fatigue failure of CFRP composites and the more plastic

deformation of matrix resin decreased the crack growth owing to the plasticization effect. In addition, the hydrothermal aging has no remarkable effect on the tension–tension fatigue life of PEEK matrix CFRP, owing to the PEEK had the superior hydrothermal aging resistance [63]. For the not fully curing carbon/glass fiber hybrid rod, Xian et al. [64] investigated the effect of post curing immersed in water on fatigue performance. The results showed that the glass transition temperature increased significantly owing to the post curing. Consequently, the fatigue life after the immersion was three times than that of original specimens. The fatigue failure mode was local cracking of GFRP shell. The enhancement of fatigue life was attributed to the improvement in interface bonding strength and toughness of matrix resin owing to the post curing. The early cracking of the matrix resin and fiber/resin interface was delayed or prevented, which decreased the probability of fatigue damage.

2.2.3. *The effect of the corrosion solution*

The combination of seawater and sea sand concrete (SWSSC) and FRP bars was proposed to replace the traditional steel reinforced concrete structures in civil engineering, which were seen as a good strategy to relive the resource shortage and steel corrosion. In the long-term exposure of SWSSC environment, FRP bar had a remarkable decrease on the static performance [65,66], which attributed to the erosion of fiber, plasticization and hydrolysis of resin, interface debonding. In addition, the sustained stress will aggravated the degradation of mechanical performances. Therefore, it was undouble that the long-term seawater immersion had an remarkable effect on fatigue life of CFRP composites [67]. As shown in Fig. 8, the static strength and fatigue strength at low fatigue cycles of the specimens immersed in seawater greatly decreased owing to the rapid growth of interface debonding and delamination. By contrast, the effect of the interface and matrix resin deterioration on the fatigue strength was negligible at high fatigue cycles, which was because the fatigue strength was dominated by the carbon fiber at this consequence.

In addition, the influences of long-term immersion of water and alkaline solution on the fatigue performances of unidirectional pultruded CFRP plate were studied by the Wu et al. [68]. As shown in Fig. 9, the static tensile performances of the pultruded CFRP plates degraded slightly exposed in alkaline solution for two years, while the degradation of static tensile performances exposed in water can be ignored. In addition, the fatigue performance of the pultruded CFRP plate had slightly decreased exposed in water, while the corresponding fatigue life of the CFRP plate immersed in alkaline solution for two years decreased significantly, and the degradation was more obvious under higher stress level. Furthermore, the allowable stress levels were 68.72% for water and 60.75% for alkaline solution when the fatigue cyclic reached two millions according to the S–N equations.

2.3. *The effect of cyclic loads on fatigue performance*

2.3.1. *The effect of stress ratio*

The tension–tension fatigue behavior of carbon/glass fiber reinforced hybrid rod under three stress ratio (R) were investigated by Hu et al. [69]. As shown in Fig. 10 , it can be seen that the increase of stress ratio brought about the decrease of fatigue life. At 80% UTS, the stress ratio had slight effect on fatigue life, the fatigue life varied slightly between 1000 and 1500 cycles for stress ratio 0.50 and 0.68, and increased to 7000 cycles for R = 0.85. However, at a stress level of 60%, the fatigue life increased from 3000 (for R = 0.50) to 15,000 cycles (for R = 0.68) and was beyond one million cycles for R = 0.85. At R = 0.50, the catastrophic failure occurred for all stress level, while at R = 0.68, the failure occurred only for stress level more than 60%, and R = 0.85, the failure occurred for stress level more than 70%. Furthermore, the stiffness lose curves were obtained from the initial portion of the fatigue life until the final abrupt drop, which showed the same trend to fatigue life. The stiffness showed multiple small decrements for low stress level, while the stiffness remained constant over the most of fatigue cyclic and the rapid failure and modulus loss occurred near the end of fatigue life for high stress level.

Kawai [70] investigated the effect of alternating R on fatigue life of a woven fabric carbon/epoxy laminates. The fatigue life under alternating R was examined for different pairs of R (R_1, R_2) at different constant levels of fatigue stress. The experimental results showed that for all the pairs of stress

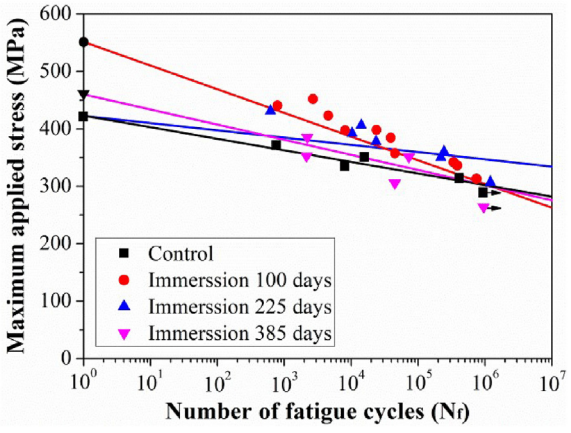


Fig. 8 – The S–N curves of tension–tension fatigue test of CFRP laminates. Figure inspired by the work of [67].

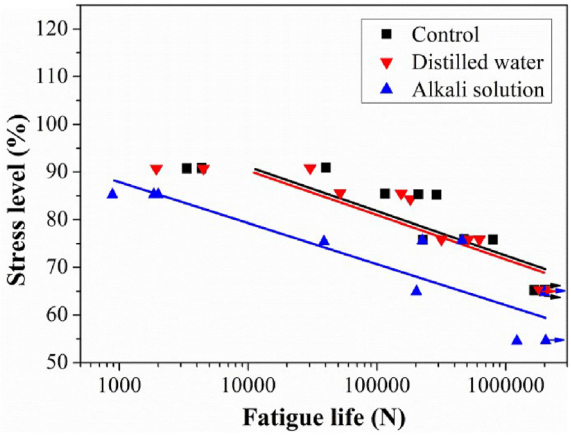


Fig. 9 – S–N curves of CFRP plates exposed at distilled water and alkali solution. Figure inspired by the work of [68].

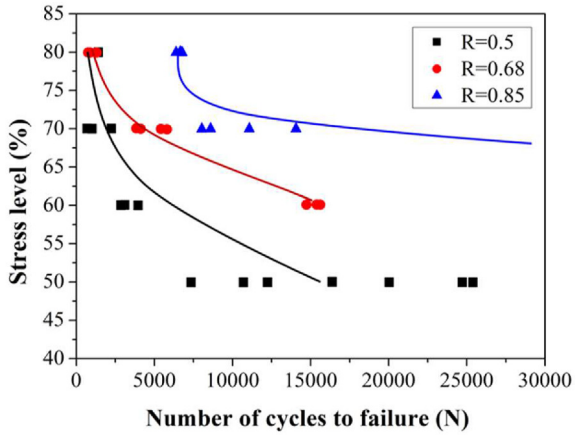


Fig. 10 – S–N curves of carbon/glass hybrid rods at three stress ratios. Figure inspired by the work of [69].

ratio R (R_1, R_2) tested, the fatigue lives N_f (R_1, R_2) were approximately distributed in the range from min {N_f (R_1), N_f (R_2)} to two times the value. It was also found that the Miner sum of cycle ratios for constant R loadings at R_1 and R_2 calculated by a given alternating R loading approximately took a value in the range from 0.5 to 2. The latter observation suggested that the Miner rule was applicable to prediction of fatigue life for alternating R-ratios loading.

2.3.2. *The effect of loading frequency*

A basic assumption was that the fatigue life and fatigue damage were independent from test frequency even with high value, which was important for the life prediction of structure subjected the much lower frequencies fatigue loading. This issue has been investigated by a large number of researches [71–75], although contradictory conclusions can be found in literature, the effect of loading frequency on fatigue life can be neglected as long as creeping did not play a role and temperature was kept far below glass transition temperature [76–78].

Tension–tension fatigue tests were carried out at three test frequencies (5, 10 and 20 Hz) for cross-ply $(0°/90°)_{4s}$ and angle-ply $(\pm45°)_{4s}$ composites by BARRON et al. [79]. The results showed that the loading frequency had significant influence on the fatigue behavior of the above composites as shown in Fig. 11. The dynamic mechanical response of cross-ply and angle-ply laminates showed a high dependence on loading frequency. For the cross-ply laminates, the results showed that the fatigue resistance decreased with an initial increase of loading frequency. Subsequently, the improved fatigue life was obtained with the test frequency increased from 10 to 20 Hz. By contrast, the fatigue resistance increased with an initial of loading frequency for angle-ply laminates. And then the fatigue resistance decreased with the further increase in loading frequency. This was because the fatigue failure was dominated by the propagation of fatigue crack at low loading frequency. At higher loading frequency, the friction heating brought about the considerable increase of temperature, which had a significant negative effect on the matrix dominated angle-ply specimens. In addition, the matrix resin began to soften with the increase of temperature, and the crack blunting reduced the fatigue damage propagation rate, which increased the fatigue life for cross-ply specimens.

The effect of frequency on fatigue life was also investigated by Hu et al. [69]. The results showed that reducing the cycle frequency from 5 to 2.5 Hz caused no significant deviation in fatigue life, which indicated that the effect of load frequency on fatigue life was negligible for this study. This was because the frequencies used were relatively low, and the heating temperature was far below glass transition temperature of matrix resin. Xian et al. [80] investigated the fatigue performance of large-diameter pultruded carbon core/glass shell hybrid rod at the frequency of 2 and 4 Hz. When the loading frequency increased from 2 Hz to 4 Hz, leading to an obvious reduced of fatigue life more than 61.5% at the same stress level. And the splitting failure of glass shell was observed for the sample subjected to 4 Hz. This was because the high loading frequency accelerated the fatigue damage at interface of carbon core and glass shell, which led to the fatigue load concentrated on the glass shell.

In conclusion, the fatigue resistance of CFRP depended on the properties of fiber, volume fraction, matrix resin and fiber orientation. In addition, the service environment and cyclic load also had the significant effect on the fatigue behavior of CFRP. In particular, the toughness of matrix resin, interface strength of fiber/matrix and fiber modulus are the primary influence factors on fatigue performances, the service environments had a significant effect on fatigue behavior through changing the performances of matrix resin and interface of fiber/matrix. The fatigue life increased with the decrease of stress ratio, while the effect of loading frequency on fatigue life can be neglected as long as the creep and frictional heating had no influence on matrix performance.

3. Fatigue damage mechanisms

3.1. *Fatigue damage mechanisms*

The fatigue damage mechanism of CFRP composites was complicated due to the material properties was inhomogeneous. The nature of fatigue was the initiation and propagation process of damage, which included different damage mode, as well as the complex interactions among of them [81–83]. The fatigue damage of composites mainly included the fiber breakage, matrix cracking, interface debonding and delamination [24]. The fatigue damage process can be affected by the material constituent, loading type and history, service environment. It was reported that the stress level had significant effect on the fatigue damage mechanism, and the fatigue life diagram including three regions of longitudinal composites in tension–tension fatigue had been proposed by Gamstedt et al. [21]. The region I represented the fatigue at high stress level, the fatigue damage was concentrated on the fiber breakage and the fatigue failure mode was similar to static tension. The region II had the progressive damage process with the crack initiation and propagation, including fiber breakage, resin matrix cracking and fiber/matrix debonding [80]. The region III was the fatigue limit region, there was no fatigue damage occurred. For region II, the fatigue damage resulted in the three-phase stiffness degradation under axial tension–tension fatigue loading [81]. As shown in Fig. 12, the first phase was caused by initiation and growth of matrix cracks in-between

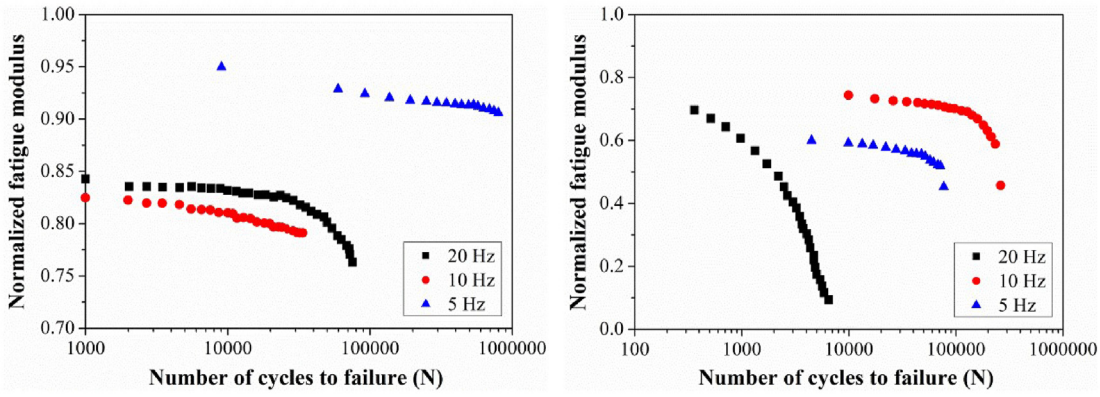


Fig. 11 – The variations of normalized fatigue modulus with the fatigue cycles for CFRP plates. Figure inspired by the work of [79].

the reinforcing fibers, which led to a rapid stiffness degradation of composites. In the second phase, transverse matrix cracks reached to saturation, the delamination and longitudinal inter fiber fracture occurred. In this phase, the stiffness degradation raised almost continuously but slowly. In the third phase, the damage increased rapidly and global failure of the composite occurred due to the quick delamination and fiber fractures. The different stages of damage can also be described by the Paris law [84]. In this law, the crack growth rate correlated to the applied energy release rate of the composite.

3.2. *Fatigue damage characterization methods*

The fatigue damage monitoring using acoustic emission (AE) energy was seen as a valuable method to provide the damage information of composites under fatigue loading. AE energy results were combined with ultrasonic C-scanning and microscopic inspection, which can identify the damage type, location and development process, providing the early warning before catastrophic failure of composites structure. Bourchak et al. [85] used AE to record the energy release, the

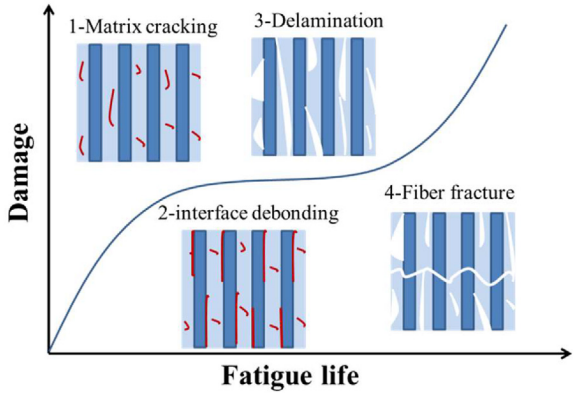


Fig. 12 – The fatigue damage and the characteristic damage state during the fatigue life of composites laminates. Figure inspired by the work of [81].

results showed that the intra and inter laminar damage occurred as early as 27% of ultimate tensile strength. The fatigue damage accumulation trends and effective fatigue failure states can be revealed by using these thresholds of typical AE energy. Consequently, AE energy provided an effective method to evaluation the residual life of composites based on the current damage state. Furthermore, Unnthorsson et al. [86] presented an AE based failure criterion through estimating whether the parameter being monitored exceeds a specified threshold. Therefore, AE techniques can be used to determine failure of complex shaped composites under complicated loading conditions.

A newly developed imaging technique of automatic crack counting (ACC) was adopted by Glud JA et al. [87] to characterize the crack state in tension–tension fatigue tests. And then combing the ACC method with a data mining approach to obtain the quantitative analyze of fatigue damage. For a constant stress level, the stochastic nature of off-axis crack initiation and crack growth was accurately modelled by the Weibull distribution, and the distribution parameters being efficiently derived using the developed approach. Consequently, ACC method with the data rich characterization can prove more detailed knowledge of the fatigue evolution process when considering the large number of influence factors on fatigue damage and the stochastic nature of the material.

In order to evaluate quantitatively the effect of stress level on fatigue damage of CFRP laminates, the energy release of transverse crack propagation and delamination growth per unit length were derived by Hosoi A et al. [88]. Furthermore, the growth process of transverse cracks and delamination was evaluated by the modified Paris law, which developed the relationship between damage growth rate and energy release. The results found that the Paris law constants can be used to evaluate the damage growth. This indicated that the damage mechanism was constant and the stress level just accelerated the damage growth rate.

Other studies used the three-dimensional finite element model to assess fatigue damage accumulation and residual strength of CFRP laminates under fatigue loading [89]. This model included the stress analysis using finite element

method, failure analysis using failure criterion based on polynomial stress, and material degradation using degradation rule. At certain number of fatigue cycles, the accumulated fatigue damage was estimated first, and then predicted residual tensile strength of the laminates. The results showed that the proposed approach can assess accurately the accumulation of damage and the residual strength of CFRP laminate under fatigue loading.

4. Fatigue modelling of CFRPs

The establishment of fatigue model in design criteria is the key problems for the application of CFRP composites in engineering fields. Although there are enormous literatures to investigate the fatigue failure of metals, the problem of metal fatigue failure model is still unsettled. In compared to metals, CFRP composites are heterogeneous and anisotropic, which includes the carbon fiber, matrix and interface. It is more difficult to develop fatigue models for CFRP composites than for metal materials due to the diversity of composition, manufacture and service conditions. Consequently, it is necessary and challenging to establish fatigue failure models for CFRP composites.

There were two kinds of methods of micro-approach and the macro-approach to establish the fatigue failure models. The micro-approach concentrated on the microscopic damage mechanism of CFRP, such as the fiber fracture, the matrix cracking and interface debonding, and then correspond this damage to the macroscopic properties of stiffness and strength. In comparison, the macro-approach was simple, which predicted the fatigue life based on the macroscopic phenomenon of residual stiffness and strength. Therefore, the existing fatigue failure models can be divided into different categories based on the above approaches: (a) fatigue life models based on experimental data such as S–N curves, (b) phenomenological models based on observed macroscopic properties during fatigue (residual strength and stiffness), and (c) progressive damage models which took into account damage mechanisms and correlated them to mechanical properties of stiffness and strength.

Hashin and Rotem had established the first fatigue failure models for unidirectional CFRP laminate under oscillatory plane stress [90]. The failure criterion had been developed by two distinct experimentally observed failure modes: the progressively failure mode of fiber and the matrix failure mode with the crack ran through the matrix and paralleled to the fiber. The criterion was expressed by three S–N curves and obtained from the off-axis uniaxial specimen tests under uniaxial loading, longitudinal tensile strength, transverse tensile strength and shear strength. The related fatigue failure model can be expressed in Eq. (1) and Eq. (2) as following:

$$\sigma_a = \sigma_a^S \tag{1}$$

$$\left(\frac{\sigma_T}{\sigma_T^S}\right)^2 + \left(\frac{\tau}{\tau^S}\right)^2 = \sigma_a^S \tag{2}$$

where σ_a is the longitudinal fiber stress, σ_T is the transverse stress, τ is the shear stress and σ_a^S, σ_T^S and τ^S the ultimate tensile, transverse and shear strengths, respectively.

Some of linear regression model was established based on the S–N curves [80,91]. Another common approach to fatigue life modeling was to use a constant fatigue life diagram, which plotted stress amplitude as a function of the mean stress at certain fatigue cyclic [92–94]. In addition, Miyano et al. developed the accelerated testing methodology to predict the long-term fatigue life of FRP laminates based on the time–temperature superposition principle [95–97]. The method was based on the four hypotheses: (a) same failure mechanisms for constant strain-rate, creep and fatigue failure, (b) same time–temperature superposition principle for all failure strengths, (c) linear cumulative damage law for monotonic loading, (d) linear dependence of fatigue strength upon stress ratio. Furthermore, it was possible to predict the long-term fatigue life for these FRP laminates under an arbitrary temperature and water conditions by using the master curves of fatigue. A number of researches on the fatigue properties of FRP composite under complex stress conditions were conducted by T.P. Philippidis et al. [98]. Based on this, a fatigue damage Simulator (FADAS) was developed and was implemented as a material model routine in a commercial FE code, which can used to predict the fatigue strength, stiffness degradation and residual static strength after cyclic loading. The residual strength models, residual stiffness models and progressive damage models were frequently adopted to predict the fatigue life of composites, the detailed discussion of the above three types of models will be presented as following.

4.1. *Residual stiffness models*

Residual stiffness was a well-defined engineering characteristic that was easy to obtain through the non-destructive testing, which was unlike strength and life. Stiffness change can be used to quantitative evaluate the damage development and predict the failure of composite structures. Salkind [99] reported that stiffness variation might be an appropriate measure of fatigue damage, and many researchers [100–102] had proved the effectiveness of the stiffness degradation of composite laminates as a measure of cumulative damage. Furthermore, Whitworth [103] proposed a stiffness degradation model for composite laminates under fatigue loading based on an assumed relationship between the failure stiffness and the applied stress:

$$E(n) = E(0)\left(\frac{S}{c_1 S_U}\right)^{1/c_2}\left[-h\ln(n+1) + \left(c_1\frac{S_U}{S}\right)^{m/c_2}\right]^{1/m} \tag{3}$$

where $E(n)$ is the residual stiffness when the fatigue cyclic reach to n; $E(0)$ is the initial stiffness; n.

Is the number of load cycles and m and h are parameters that depend on the applied stress, loading frequency and environmental conditions such as temperature, humidity, etc; S_u is the ultimate strength, S is the applied stress level, c_1 and c_2 are constants. Furthermore, in order to evaluate the model, a series of static and fatigue tests were performed using CFRP laminate specimens. The model parameters were evaluated by the experimental data and used to predict the statistical distribution of the residual stiffness. The results showed that the model prediction compare well with the experimental results as shown in Fig. 13.

Yang et al. [104] proposed a stiffness reduction model though assuming that the stress–strain to failure curve was linear. Their model had good applicability to the laminates with fiber-dominated properties. However, for laminates with matrix-dominated properties, the assumption of a linear stress–strain relationship was unsuitable for the case of laminates. The detailed expression of the stiffness degradation model was as following:

$$\frac{dE(n)}{dn} = -E(0)Q\upsilon n^{\upsilon-1} \tag{4}$$

where $E(0)$ is static stiffness, and Q and ν are parameter values dependent on the applied stress level, stress ratio and loading frequency. Yang et al. defined $E(0)$ in their model using lognormal statistical distribution. It should be noted that the model assumed that the strain of the specimen was equal to the static limit strain when the failure occurred. The model was also verified by using CFRP plates under tension-tensile fatigue loading, and the predicted fatigue life curve had a good correlation with the experimental results.

4.2. *Residual strength models*

Considering the fatigue damage of CFRP caused by variable amplitude loading was different under owing to the scatter of material properties. It was unrealistic to describe the damage development with one damage type and to establish the cumulative damage model under different loading conditions. This was because the degradation of CFRP under fatigue loading was the result of the interaction of various damage types. Therefore, Yao and Himmel [105] established a new cumulative damage model by taking residual strength as parameter and considering the macro performance and micro damage types under cyclic loading. It was assumed that the cumulative fatigue damage caused by the cyclic loading was proportional to the strength loss of FRP, and that the damage state in laminates can be described by residual strength.

Owing to the residual strength of CFRP under fatigue loading generally had the following characteristics: (a) the residual strength decreased quickly in the initial stage of fatigue cycles, which was mainly related to the small cracks formed in the matrix resin, (b) the residual strength decreased moderately and uniformly in the middle of fatigue cycles, which was mainly related to the fiber failure and delamination, (c) the residual strength decreased rapidly in the end of fatigue cycles, which presented the catastrophic failure. This behavior can be described by Eq. (5) for the FRP laminates as following:

$$R(n) = R(0) - [R(0) - S]\frac{\sin(\beta x)\cos(\beta - \alpha)}{\sin\beta\cos(\beta x - \alpha)} \tag{5}$$

where, S is the peak stress and R(0) is the static strength, R(n) is the residual strength at the nth fatigue cycles, $x = n/N_f$, α and β are parameters determined through experiments. By comparison the prediction model with experimental fatigue test data, it was proved that a reasonably good predictive capability of the new model has been demonstrated.

In addition, Whitworth [106] proposed the following strength degradation model:

$$S_R^r = S_U^r - \left[S_U^r - S^r\right]\frac{n}{N} \tag{6}$$

where r is a material constant determined experimentally and S_R is the residual strength. Based on the above residual stiffness model of Eq. (3), the fatigue life to be expressed as following:

$$N = \exp\left\{\frac{1}{h}\left[\left(\frac{c_1 S_U}{S}\right)^{\frac{m}{c_2}} - 1\right]\right\} - 1 \tag{7}$$

Substituting Eq. (7) into Eq. (6), obtaining the following relation for the residual strength:

$$S_R^r = S_U^r - J(S_U)n \tag{8}$$

where

$$J(S_U) = \frac{S_U^\gamma - S^\gamma}{\exp\left\{\frac{1}{h}\left[\left(\frac{c_1 S_U}{S}\right)^{\frac{m}{c_2}} - 1\right]\right\} - 1} \tag{9}$$

Eq. (8) represents the relationship between the residual strength and the number of fatigue cycles. Therefore, once the values of the parameters γ, h, m, c_1 and c_2 have been determined, this equation can be used to evaluate the residual

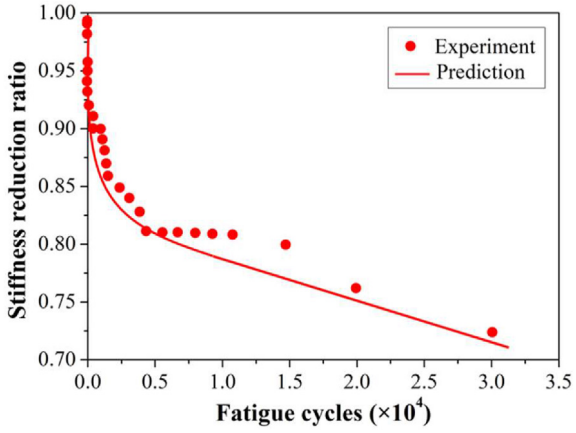


Fig. 13 – Predicted stiffness model and experimental data. Figure inspired by the work of [99].

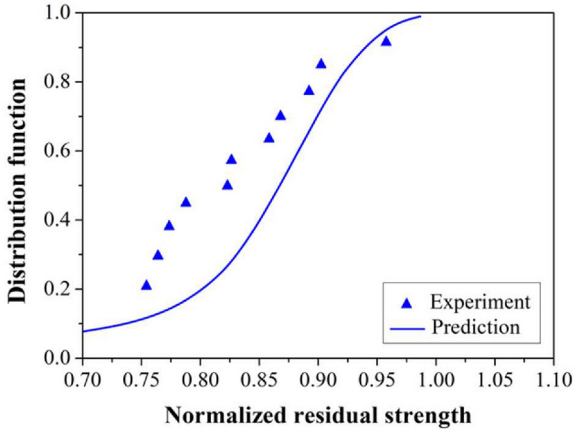


Fig. 14 – Residual strength data and the associated distribution function. Figure inspired by the work of [106].

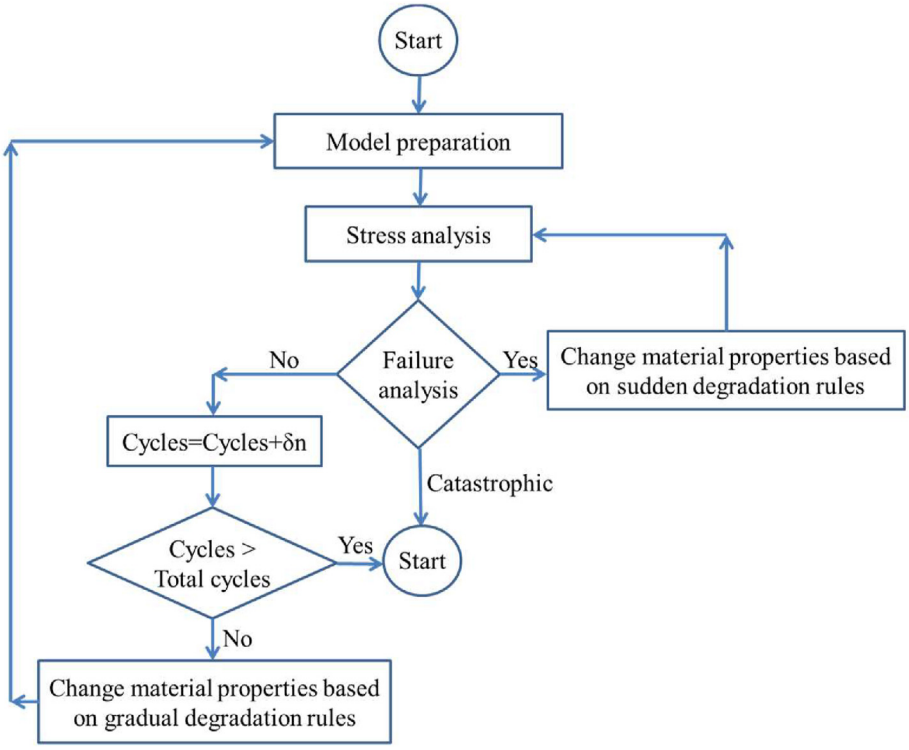


Fig. 15 – The framework of progressive fatigue damage model. Figure inspired by the work of [106].

strength. Furthermore, Whitworth also assumed that the ultimate strength was a statistical variable, which was expressed by a two-parameter Weibull distribution. The predicted residual strength showed good agreement with the experimental data at 50,000 constant amplitude fatigue cycles as shown in Fig. 14.

In addition, T.P. Philippidis et al. had detailed discussed the residual strength models in the research of [107]. The results showed that no model was consistent in accurately predicting the residual strength degradation behavior of laminates with different composites. Statistical predictions were also poor for various stress levels and life scores. The main conclusion was that the use of complex phenomenological models requiring a large number of experimental datasets for implementation may not necessarily pay off in terms of accurate prediction, so simple models requiring limited experimental effort should be preferred.

4.3. *Progressive damage models*

Progressive damage model was a widely used failure analysis method, which has been successfully applied to the failure analysis of composite laminates under static loading [108,109], which can be used to investigate the damage process of composite materials during the entire loading process. Furthermore, the concept of progressive damage modeling was extended from static loading to establish the framework of fatigue damage analysis of composite laminates. The related researches [110,111] detailed the progressive fatigue damage model included stress analyses, failure analyses and material degradation, which were the key points in the framework of progressive fatigue damage model of composite laminates as shown in Fig. 15.

For the above fatigue damage model, the solid elements were selected for the finite element stress analysis firstly. The free edge effect was addressed for by using the higher element density near edges and other areas with stress concentration, and an iterative scheme was adopted to consider the nonlinearity under failure stress state. Secondly, seven different failure modes for the unidirectional plates under multiaxial state of stress were considered, which were fiber tension, fiber compression, Fiber-matrix shearing, matrix tension, matrix compression, normal tension and normal compression failure modes. The failure Criteria was similar to Hashin static failure criteria [112], and the effect of material nonlinearity on the mathematical form of the failure criteria was also considered. The final part of the fatigue damage model considered the sudden and gradual degradation of material. If there was a sudden failure mode, the material properties of the failure plies were changed according to the sudden degradation laws of material performances. Meanwhile the stiffness matrix of the finite element model was also updated and carried out the new round of stress analysis and the estimate of fatigue damage. In addition, when there was no sudden failure mode, an increasing number of cycles were applied until the number of cycles was greater than the preset total number of cycles. Then the generalized material properties degradation method was adopted to change the material parameters of all elements according to the gradual material properties degradation laws. Subsequently, the stress analysis was then repeated

until a catastrophic failure occurs. The related researches showed that the model can determined the state of damage at any load level and number of cycles, and was able to predict the residual strength, residual life, failure mechanisms and final fatigue life of the composite laminates under fatigue loading.

A similar model was developed by Papanikos et al. [113] combining fatigue induced fiber strength and modulus degradation, irrecoverable cyclic strain effects and inter fiber fatigue. Seven failure modes were also considered in the model with a simple formula without nonlinear parameter. The fatigue modified version of the Puck multiaxial failure criterion for static failure was adopted for the inter fiber fatigue.

The model was implemented in a user material finite element subroutine and validated by the test of CFRP laminates under tension-compression fatigue loading. The results showed that the model not only give an accurate prediction of the fatigue life but also predicted the onset and growth of the correct damage modes. The delamination as the main failure mode for low stresses and fiber tensile failure for high stresses was observed in both the model and experimental results.

5. The latest research advances

In earlier studies of composite fatigue between 1950 and 1975, some basic experiments were conducted to investigate the fatigue behavior and failure mechanism. Meanwhile, several fatigue theories for life modeling and prediction were developed and validated against experimental data [90,114]. Fatigue of composite had attracted more and more attention of engineers, with the increasing application of composites in aerospace, automotive and civil engineering, etc. Then the study of composite fatigue entered the mature stage between 1975 and 2000, many fatigue experimental databases were established and a large number of theories were developed. Today, the fatigue failure mechanisms have been identified and their effects on fatigue life and damage evolution have been quantified according to the numerous papers and books. As composite were increasingly used in aerospace components, off-shore wind turbine blades and bridge cable with more complicated service conditions, the combined effects of several parameters gained more attention, such creep–fatigue interaction, fatigue loading and environmental combinations. In addition, the current research results were mainly focused on the fatigue properties of pure materials based on the accelerated aging test in laboratory. How to carry out the fatigue test research under real service environmental is an urgent problem to be solved in the follow-up research. In this way, obtaining the fatigue performance evaluation of CFRP in complicated service environment, and establishing the fatigue design method of CFRP in engineering structures with high reliability.

In addition, the effects of materials constituents, service environments and cyclic loads on fatigue damage were investigated systematically, and a large number of fatigue life prediction theories have been developed. However, most of these fatigue theories were empirical based on experimental data. With the development of computer technology, numerical simulation is considered to be one of the most potential technical methods to study the fatigue behavior of composites, the physical properties of materials during fatigue can be analyzed though inputting the material characteristics and boundary conditions, which can replace a part of costly physical experiment process under actual service environmental. Therefore, the establishment of numerical model is the key to obtain the quantitatively fatigue damage behavior and life of CFRP composites.

6. Conclusions

The present review focused on the effects of material constituents, service conditions and cyclic loads on the fatigue performances evolution rule of CFRP composites. Furthermore, the fatigue damage mechanism and characterization method were summarized systematically. Based on the above the fatigue performances evolution rule and mechanism, three kinds of fatigue models were discussed in detail. The following conclusions can be obtained based on the above summary and discussion.

(1) The number of research results showed that the toughness of matrix resin, interface strength of fiber/matrix and fiber modulus were the primary influence factors on fatigue performances of CFRP composites. The service environments had a significant effect on fatigue behavior through changing the performances of matrix resin and interface of fiber/matrix. The fatigue life increased with the decrease of stress ratio, while the effect of loading frequency on fatigue life can be neglected as long as the creep and frictional heating had no influence on matrix performance.

(2) The nature of composites fatigue was the damage initiation and propagation process, including fiber breakage, matrix cracking, interface debonding and delamination. The fatigue damage mechanism of CFRP composites was complicated due to the inhomogeneous of material and the differences of material constituents, service conditions and cyclic loads, as well as the complex interactions among of them. In addition, the techniques of acoustic emission, automatic crack counting, energy release and finite element model can be used to quantitative analyze the fatigue damage behavior of CFRP composites.

(3) In the actual engineering service, it was usually the coupling effect of environment and fatigue load lead to the performances degradation of CFRP. However, the current research results were mainly focused on the fatigue properties of pure materials based on the accelerated aging test in laboratory. How to carry out the fatigue test research under real service environmental is an urgent problem to be solved in the follow-up research.

(4) The macro-scale life and stiffness were used to characterize the fatigue damage accumulation of CFRP. The micro-scale testing techniques were applied to the revel of fatigue damage mechanism. Furthermore, the related fatigue models were developed based the macro and

micro fatigue damage evolution, including residual strength, stiffness and progressive damage models. However, all of those models were phenomenon-based, it is necessary and challenging to establish theoretical prediction models of fatigue damage initiation and propagation for CFRP composites.

Compliance with ethical standards

Funding

This research work was funded by National Key Research and Development Program of China (2021YFB3704402), National Natural Science Foundation of China (52008137), Heilongjiang Provincial Natural Science Foundation of China (LH2021E073) and Fundamental Research Funds for the Central universities (HIT. NSRIF202234).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] Guo R, Xian G, Li C, Hong B. Effect of fiber hybrid mode on the tension–tension fatigue performance for the pultruded carbon/glass fiber reinforced polymer composite rod. Eng Fract Mech 2022;260:108208.
[2] Guo R, Xian G, Li C, Hong B, Huang X, Xin M, et al. Water uptake and interfacial shear strength of carbon/glass fiber hybrid composite rods under hygrothermal environments: effects of hybrid modes. Polym Degrad Stabil 2021;193:109723.
[3] Guo R, Xian G, Li C, Huang X, Xin M. Effect of fiber hybridization types on the mechanical properties of carbon/glass fiber reinforced polymer composite rod. Mech Adv Mater Struct 2021:1–13.
[4] Guo R, Xian G, Li F, Li C, Hong B. Hygrothermal resistance of pultruded carbon, glass and carbon/glass hybrid fiber reinforced epoxy composites. Construct Build Mater 2022;315:125710.
[5] Lee YJ, Jhan YT, Chung CH. Fluid-structure interaction of FRP wind turbine blades under aerodynamic effect. Compos B Eng 2012;43:2180–91.
[6] Pradeep AV, Prasad SVS, Suryam LV, Kumari PP. A comprehensive review on contemporary materials used for blades of wind turbine. Mater Today Proc 2019;19:556–9.
[7] Xian G, Guo R, Li C. Combined effects of sustained bending loading, water immersion and fiber hybrid mode on the mechanical properties of carbon/glass fiber reinforced polymer composite. Compos Struct 2022;281:115060.
[8] Xian G, Guo R, Li C, Hong B. Effects of rod size and fiber hybrid mode on the interface shear strength of carbon/glass fiber composite rods exposed to freezing-thawing and outdoor environments. J Mater Res Technol 2021;14:2812–31.
[9] Xian G, Guo R, Li C, Hong B. Mechanical properties of carbon/glass fiber reinforced polymer plates with sandwich structure exposed to freezing-thawing environment: effects of water immersion, bending loading and fiber hybrid mode. Mech Adv Mater Struct 2022:1–21.
[10] Xian G, Guo R, Li C, Wang Y. Mechanical performance evolution and life prediction of prestressed cfrp plate exposed to hygrothermal and freeze-thaw environments. Compos Struct 2022;293:115719.
[11] Meier U. Carbon fiber reinforced polymer cables: why? Why not? What if. Arabian J Sci Eng 2012;37:399–411.
[12] Ai PC, Feng P, Lin HW, Zhu PC, Ding GZ. Novel self-anchored CFRP cable system: concept and anchorage behavior. Compos Struct 2021;263.
[13] Feng B, Wang X, Wu ZS, Yang YQ, Pan ZH. Performance of anchorage assemblies for CFRP cables under fatigue loads. Structures 2021;29:947–53.
[14] Lu Z, Li J, Xie J, Huang P, Xue L. Durability of flexurally strengthened RC beams with prestressed CFRP sheet under wet–dry cycling in a chloride-containing environment. Compos Struct 2020;255:112869.
[15] Lal HM, Uthaman A, Li C, Xian G, Thomas S. Combined effects of cyclic/sustained bending loading and water immersion on the interface shear strength of carbon/glass fiber reinforced polymer hybrid rods for bridge cable. Construct Build Mater 2022;314:125587.
[16] Uthaman A, Lal HM, Li C, Xian G, Thomas S. Mechanical and water uptake properties of epoxy nanocomposites with surfactant-modified functionalized multiwalled carbon nanotubes. Nanomaterials 2021;11:1234.
[17] Keller T, Tirelli T. Fatigue behavior of adhesively connected pultruded GFRP profiles. Compos Struct 2004;65:55–64.
[18] Li C, Yin X, Liu Y, Guo R, Xian G. Long-term service evaluation of a pultruded carbon/glass hybrid rod exposed to elevated temperature, hydraulic pressure and fatigue load coupling. Int J Fatig 2020;134:105480.
[19] Li C, Guo R, Xian G, Li H. Effects of elevated temperature, hydraulic pressure and fatigue loading on the property evolution of a carbon/glass fiber hybrid rod. Polym Test 2020;90:106761.
[20] Costa J, Ferreira J, Silva] H. Fatigue behaviour of glass fibre reinforced epoxy composites enhanced with nanoparticles. Compos B Eng 2014;62:65–72.
[21] Gamstedt EK, Talreja R. Fatigue damage mechanisms in unidirectional carbon-fibre-reinforced plastics. J Mater Sci 1999;34:2535–46.
[22] Dong H, Li Z, Wang J, Karihaloo BL. A new fatigue failure theory for multidirectional fiber-reinforced composite laminates with arbitrary stacking sequence. Int J Fatig 2016;87:294–300.
[23] Lasri L, Nouari M, EI Mansori M. Wear resistance and induced cutting damage of aeronautical FRP components obtained by machining. Wear 2011;271:2542–8.
[24] Shao Y, Okubo K, Fujii T, Ou S, Fujita Y. Effect of matrix properties on the fatigue damage initiation and its growth in plain woven carbon fabric vinylester composites. Compos Sci Technol 2014;104:125–35.
[25] Jones CJ, Dickson RF, Adam T, Reiter H, Harris B. The environmental fatigue behaviour of reinforced plastics. Proc Math Phys Eng Sci 1984;396:315–38.
[26] Masaki H, Shojiro O, Gustafson CG, Keisuke T. Effect of matrix resin on delamination fatigue crack growth in CFRP laminates. Eng Fract Mech 1994;49:35–47.
[27] Konur O, Matthews FL. Effect of the properties of the constituents on the fatigue performance of composites - a review. Composites 1989;20:317–28.
[28] Curtis PT, Moore B. A comparison of plain and double waisted coupons for static and fatigue tensile testing of unidirectional GRP and CFRP. Compos Struct 1983;2.

[29] Curtis PT. An investigation of tensile fatigue behavior of carbon fibre composite laminates. 1987.
[30] Curtis PT. An investigation of the mechanical properties of improved carbon fibre composite materials. J Compos Mater 1987;21:1118–44.
[31] Naik PS, Orangalu SA, Londhe NV. Effect of fiber weight fraction on mechanical properties of carbon-carbon composites. Polym Compos 2012;33:1329–34.
[32] Brunbauer J, Pinter G. Effects of mean stress and fibre volume content on the fatigue-induced damage mechanisms in CFRP. Int J Fatig 2015;75:28–38.
[33] Brunbauer J, Stadler H, Pinter G. Mechanical properties, fatigue damage and microstructure of carbon/epoxy laminates depending on fibre volume content. Int J Fatig 2015;70:85–92.
[34] Hiremath C, Senthilnathan K, Guha A, Tewari A. Effect of volume fraction on damage accumulation for a lattice arrangement of fibers in CFRP. Mater Today Proc 2015;2:2671–8.
[35] Behera A, Dupare P, Thawre M, Ballal A. Effects of hygrothermal aging and fiber orientations on constant amplitude fatigue properties of CFRP multidirectional composite laminates. Int J Fatig 2020;136:105590.
[36] Huang Z, Zhang W, Qian X, Su Z, Pham D-C, Sridhar N. Fatigue behaviour and life prediction of filament wound CFRP pipes based on coupon tests. Mar Struct 2020;72:102756.
[37] Harris B, Reiter H, Adam T, Dickson RF, Fernando GF. Fatigue behavior of carbon-fiber reinforced-plastics. Composites 1990;21:232–42.
[38] Baron C, Schulte K, Harig H. Influence of fiber and matrix failure strain on static and fatigue properties of carbon fiber-reinforced plastics. Compos Sci Technol 1987;29:257–72.
[39] Tian J, Li C, Xian G. Reciprocating friction and wear performances of nanometer sized-TiO2 filled epoxy composites. Polym Compos 2021;42:2061–72.
[40] Tian J, Tang Q, Li C, Xian G. Mechanical, bonding and tribological performances of epoxy-based nanocomposite coatings with multiple fillers. J Appl Polym Sci 2022;139:52303.
[41] Knoll JB, Riecken BT, Kosmann N, Chandrasekaran S, Schulte K, Fiedler B. The effect of carbon nanoparticles on the fatigue performance of carbon fibre reinforced epoxy. Composites Part A Applied Science and Manufacturing 2014;67:233–40.
[42] Mivehchi H, Varvani-Farahani A. The effect of temperature on fatigue strength and cumulative fatigue damage of FRP composites. Procedia Eng 2010;2:2011–20.
[43] Zhao X, Wang X, Wu Z, Keller T, Vassilopoulos AP. Temperature effect on fatigue behavior of basalt fiber-reinforced polymer composites. Polym Compos 2019;40:2273–83.
[44] Givler RC, Gillespie Jr JW, Pipes RB. Environmental exposure of carbon/epoxy composite material systems. ASTM Special Technical Publication; 1980. p. 11.
[45] Hyer MW, Cooper DE, Cohen D. Stresses and deformations in cross-ply composite tubes subjected to a uniform temperature change. J Therm Stresses 1986;9:97–117.
[46] Kaw AK. Mechanics of composite materials. 2nd ed. CRC Press; 2005.
[47] Xian GJ, Karbhari VM. DMTA based investigation of hygrothermal ageing of an epoxy system used in rehabilitation. J Appl Polym Sci 2007;104:1084–94.
[48] Jiang X, Kolstein H, Bijlaard FSK. Moisture diffusion and hygrothermal aging in pultruded fibre reinforced polymer composites of bridge decks. Mater Des 2012;37:304–12.
[49] Chin JW, Nguyen T, Aouadi K. Sorption and diffusion of water, salt water, and concrete pore solution in composite matrices. J Appl Polym Sci 1999;71:483–92.
[50] Jiang X, Kolstein H, Bijlaard FSK. Moisture diffusion in glass-fiber-reinforced polymer composite bridge under hot/wet environment. Compos B Eng 2013;45:407–16.
[51] Karbhari VM, Xian GJ. Hygrothermal effects on high V-F pultruded unidirectional carbon/epoxy composites: moisture uptake. Compos B Eng 2009;40:41–9.
[52] Zhou J, Lucas JP. Hygrothermal effects of epoxy resin. Part I: the nature of water in epoxy. Polymer 1999;40:5505–12.
[53] Lucas JP. Hygrothermal effects of epoxy resin. Part II: variations of glass transition temperature. Polymer 1999;40:5513–22.
[54] Grammatikos SA, Evernden M, Mitchels J, Zafari B, Mottram JT, Papanicolaou GC. On the response to hygrothermal aging of pultruded FRPs used in the civil engineering sector. Mater Des 2016;96:283–95.
[55] Aiello MA, Ombres L. Environmental effects on the mechanical properties of glass-FRP and aramid-FRP rebars. Mech Compos Mater 2000;36:395–8.
[56] Nandagopal RA, Boay CG, Narasimalu S. An empirical model to predict the strength degradation of the hygrothermal aged CFRP material, vol. 236. Composite Structures; 2020.
[57] Ray BC. Temperature effect during humid ageing on interfaces of glass and carbon fibers reinforced epoxy composites. J Colloid Interface Sci 2006;298:111–7.
[58] Wang Y, Hahn TH. AFM characterization of the interfacial properties of carbon fiber reinforced polymer composites subjected to hygrothermal treatments. Compos Sci Technol 2007;67:92–101.
[59] Collings TA, Stone D. Hygrothermal effects in CFRP laminates: strains induced by temperature and moisture. Composites 1985;16:307–16.
[60] Zhou J, Lucas JP. Hygrothermal effects of epoxy resin. Part II: variations of glass transition temperature. Polymer 1999;40:5513–22.
[61] Nakai Y, Hiwa C. Effects of loading frequency and environment on delamination fatigue crack growth of CFRP. Int J Fatig 2002;24:161–70.
[62] Matsuda Satoshi, Hojo Masaki, Ochiai Shojiro. Effect of water environment on mode II delamination fatigue in interlayer-toughened CFRP. Jsme Inter J 1999;42:421–8.
[63] Dickson RF, Jones CJ, Harris B, Leach D, Moore DR. The environmental fatigue behaviour of carbon fibre reinforced polyether ether ketone. J Mater Sci 1985;20:60–70.
[64] Li C, Xian G, Li H. Effect of postcuring immersed in water under hydraulic pressure on fatigue performance of large ⅋ iameter pultruded carbon/glass hybrid rod. Fatig Fract Eng Mater Struct 2019;42:1148–60.
[65] Wang Z, Zhao XL, Xian G, Wu G, Raman R, Al-Saadi S. Effect of sustained load and seawater and sea sand concrete environment on durability of basalt- and glass-fibre reinforced polymer (B/GFRP) bars. Corrosion ence 2018;138:200.
[66] Wang Z, Zhao XL, Xian G, Wu G, Raman R, Al-Saadi S, et al. Long-term durability of basalt- and glass-fibre reinforced polymer (BFRP/GFRP) bars in seawater and sea sand concrete environment. Construct Build Mater 2017;139:467–89.

[67] Koshima S, Yoneda S, Kajii N, Hosoi A, Kawada H. Evaluation of strength degradation behavior and fatigue life prediction of plain-woven carbon-fiber-reinforced plastic laminates immersed in seawater. Compos Appl Sci Manuf 2019;127:105645.
[68] Wu P, Xu L, Luo J, Zhang X, Bian W. Influences of long-term immersion of water and alkaline solution on the fatigue performances of unidirectional pultruded CFRP plate. Construct Build Mater 2019;205:344–56.
[69] Kar N, Hu Y, Barjasteh E, Nutt S. Tension-tension fatigue of hybrid composite rods. Compos B Eng 2012;43:2115–24.
[70] Kawai M, Yang K, Oh S. Effect of alternating R-ratios loading on fatigue life of woven fabric carbon/epoxy laminates. J Compos Mater 2015;49:3387–405.
[71] Stinchcomb WW. Fatigue damage mechanisms in composite materials: a review, fatigue mechanisms. ASTM STP.; 1979. p. 675.
[72] Kim HC, Ebert LJ. Fatigue life-limiting parameters in fibreglass composites. J Mater Sci 1979;14:2616–24.
[73] Frequency effects on the fatigue life and damage of graphite/epoxy composites. Composites 1987;21.
[74] Perreux D, Joseph E. The effect of frequency on the fatigue performance of filament-wound pipes under biaxial loading: experimental results and damage model. Compos Sci Technol 1997;57:353–64.
[75] Sun CT, Chan WS. Frequency effect on the fatigue life of a laminated composite. Astm International; 1979.
[76] Marin JC, Justo J, París F, Caas J. The effect of frequency on tension-tension fatigue behavior of unidirectional and woven fabric graphite-epoxy composites. Mech Adv Mater Struct 2018:1–7.
[77] Apinis R. Acceleration of fatigue tests of polymer composite materials by using high-frequency loadings. Mech Compos Mater 2004;40:107–18.
[78] Hosoi A, Arao Y, Karasawa H, Kawada H. High-cycle fatigue characteristics of quasi-isotropic CFRP laminates. Adv Compos Mater 2007;16:151–66.
[79] Barron V, Buggy M, Mckenna NH. Frequency effects on the fatigue behaviour on carbon fibre reinforced polymer laminates. J Mater Sci 2001;36:1755–61.
[80] Li C, Xian G, Li H. Tension-tension fatigue performance of a large-diameter pultruded carbon/glass hybrid rod. Int J Fatig 2019;120:141–9.
[81] Stinchcomb WW, Bakis CE. Chapter 4-fatigue behavior of composite laminates. Compos Mater 1991;4:105–80.
[82] May M, Hallett SR. Damage initiation in polymer matrix composites under high-cycle fatigue loading - a question of definition or a material property? Int J Fatig 2016;87:59–62.
[83] Quaresimin M, Ricotta M. Fatigue behaviour and damage evolution of single lap bonded joints in composite material. Compos Sci Technol 2006;66:176–87.
[84] Paris PC, Erdogan FA. Critical analysis of crack propagation laws. Trans ASME J Basic Eng J Basic Eng 1963;85:528–34. D.
[85] Bourchak M, Farrow IR, Bond IP, Rowland CW, Menan F. Acoustic emission energy as a fatigue damage parameter for CFRP composites. Int J Fatig 2007;29:457–70.
[86] Unnthorsson R, Runarsson TP, Jonsson MT. Acoustic emission based fatigue failure criterion for CFRP. Int J Fatig 2008;30:11–20.
[87] Glud JA, Dulieu-Barton JM, Thomsen OT, Overgaard L. Fatigue damage evolution in GFRP laminates with constrained off-axis plies. Compos Appl Sci Manuf 2017;95:359–69.
[88] Hosoi A, Takamura K, Sato N, Kawada H. Quantitative evaluation of fatigue damage growth in CFRP laminates that changes due to applied stress level. Int J Fatig 2011;33:781–7.
[89] Tserpes KI, Papanikos P, Labeas G, Pantelakis S. Fatigue damage accumulation and residual strength assessment of CFRP laminates. Compos Struct 2004;63:219–30.
[90] Hashin Z, Rotem A. A fatigue failure criterion for fiber reinforced materials. J Compos Mater 1973;7:448–64.
[91] Wu ZS, Wang X, Iwashita K, Sasaki T, Hamaguchi Y. Tensile fatigue behaviour of FRP and hybrid FRP sheets. Compos B Eng 2010;41:396–402.
[92] Harris B, Gathercole N, Lee JA, Reiter H, Adam T. Life-prediction for constant-stress fatigue in carbon-fibre composites. Philtransrsoclondon A 1997;355:1259–94.
[93] Kawai M, Matsuda Y, Yoshimura R. A general method for predicting temperature-dependent anisomorphic constant fatigue life diagram for a woven fabric carbon/epoxy laminate. Comp Part A Appl Sci & Manufac 2012;6:915–25.
[94] Kawai M, Yagihashi Y, Hoshi H, Iwahori Y. Anisomorphic constant fatigue life diagrams for quasi-isotropic woven fabric carbon/epoxy laminates under different hygro-thermal environments. Adv Compos Mater 2013;22:79–98.
[95] Nakada M, Miyano Y. Accelerated testing for long-term fatigue strength of various FRP laminates for marine use. Compos Sci Technol 2009;69:805–13.
[96] Miyano Y, Nakada M, Kudoh H, Muki R. Prediction of tensile fatigue life under temperature environment for unidirectional CFRP. Adv Compos Mater 1999;8:235–46.
[97] Miyano Y, Nakada M, Kudoh H, Muki R. Prediction of tensile fatigue life for unidirectional CFRP. In: Proceedings of the Eighth Japan-US Conference on Composite Materials; 1999. p. 335–44.
[98] Eliopoulos EN, Philippidis TP. A progressive damage simulation algorithm for GFRP composites under cyclic loading. Part II: FE implementation and model validation. Compos Sci Technol 2011;71:750–7.
[99] Salkind MJ. Fatigue of composites. Advanced approaches to fatigue evaluation. 1972.
[100] Reifsnider KL, Talug A. Analysis of fatigue damage in composite laminates. Int J Fatig 1980;2:3–11.
[101] Johnson WS. Modeling stiffness loss in boron/aluminum laminates below the fatigue limit. 1983.
[102] Hashin Z. Analysis of stiffness reduction of cracked cross-ply laminates. Eng Fract Mech 1986;25:771–8.
[103] Whitworth H. A stiffness degradation model for composite laminates under fatigue loading. Compos Struct 1997;40:95–101.
[104] Send Ec Kyj GP, Wang SS, Johnson WS, Stinchcomb WW, Jones DL. A stiffness-based statistical model for predicting the fatigue life of graphite/epoxy laminates. J Compos Technol Res 1989;11:129–34.
[105] Yao WX, Himmel N. A new cumulative fatigue damage model for fibre-reinforced plastics. Compos Sci Technol 2000;60:59–64.
[106] Whitworth HA. Evaluation of the residual strength degradation in composite laminates under fatigue loading. Compos Struct 2000;48:261–4.
[107] Philippidis T, Passipoularidis V. Residual strength after fatigue in composites: theory vs. experiment. Int J Fatig 2007;29:2104–16.
[108] Shokrieh MMMM. Failure of laminated composite pinned connections. 1992.

[109] Chang FK, Chang KY. Post-failure analysis of bolted composite joints in tension or shear-out mode failure. J Compos Mater 1987;21:809–33.
[110] Shokrieh MM, Lessard LB. Progressive fatigue damage modeling of composite materials, Part I: modeling. J Compos Mater 2000;34:1056–80.
[111] Shokrieh MM, Lessard LB. Progressive fatigue damage modeling of composite materials, Part II: material characterization and model verification. J Compos Mater 2000;34:1081–116.
[112] Hashin Z. Fatigue failure criteria for unidirectional fiber composites. J Appl Mech 1980;47.
[113] Kennedy CR, Brádaigh CM, Leen SB. A multiaxial fatigue damage model for fibre reinforced polymer composites. Compos Struct 2013;106:201–10.
[114] Vassilopoulos AP. The history of fiber-reinforced polymer composite laminate fatigue. Int J Fatig 2020;134:105512.

Rui Guo (First author): PHD, School of Civil Engineering, Harbin Institute of Technology, Heilongjiang, Harbin 150090, China. Research topic: Fiber hybrid, FRP fatigue and durability.

Chenggao Li (Second author): PHD, School of Civil Engineering, Harbin Institute of Technology, Heilongjiang, Harbin 150090, China. Research topic: Fiber hybrid, FRP fatigue and durability.

Yanzhao Niu (Third author): PHD, School of Civil Engineering, Harbin Institute of Technology, Heilongjiang, Harbin 150090, China. Research topic: Fiber hybrid, FRP fatigue and durability.

Guijun Xian (Corresponding author): PHD, School of Civil Engineering, Harbin Institute of Technology, Heilongjiang, Harbin 150090, China. Research topic: The civil engineering applications of fiber reinforced polymer composites and structure.