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Challenges for lightweight composites in the offshore and marine industry from the fatigue perspective

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Abstract. The offshore and marine industry has started to use lightweight composites since 1950s and this trend is rising as the exploration of oil and gas is towards deeper water. The fatigue performance has always been a critical issue to ensure the safety of the offshore and marine structures, since the harsh environment and working status make some of these structures subjected to long-term cyclic loading during the service life of 20 to 30 years. This paper performs a literature review on lightweight composites in the offshore and marine industry from the fatigue perspective. The paper first presents the previous investigations on the fatigue failure mechanism and fatigue life prediction models of FRP composites from the material level. Subsequently, the paper reviews the existing studies on the fatigue performance of lightweight composites applied in offshore and marine industry, such as composite risers, composite repair system and other related applications. Finally, the comprehensive review identifies the key challenges in investigating the fatigue performance of composite structures in offshore and marine industry.

Keywords: lightweight composites; FRP; fatigue; offshore and marine industry

1. Introduction

The offshore and marine industry has started to use lightweight composites since the early 1950s on various types of structures ranging from small components such as masts, pipes, valves, rudders, propellers, propulsion shafts, etc., to large-scale structures such as production risers, ship hulls, ship superstructures, and submersibles, etc. The most popular lightweight composite is the fiber reinforced polymer (FRP) composite, further classified according to the type of fiber material as the carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), basalt fiber reinforced polymer (BFRP), and polyparaphenylenl benzobisoxazole (PBO), etc. FRP composites exhibit excellent attributes such as high strength-to-weight ratio, good corrosion resistance, excellent thermal insulation, and attractive fatigue performance (Ochoa and Salama 2005). Extensive experimental, numerical and theoretical studies have been conducted on the fatigue behavior of FRP

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composites at the material level. Typical failure modes of FRP composites due to fatigue include the matrix cracking, debonding, delamination, and fiber fracture (Dyer and Isaac 1998). These failure modes occur either independently or interactively due to the influences of material variables and testing conditions (Degrieck and Van Paepegem 2001). Thus, compared to homogeneous and isotropic materials such as metals, composite materials are inhomogeneous and anisotropic, and exhibit a more complicated behavior.

As the exploration of oil and gas marches towards deeper water, composite risers are expected to gradually replace traditional metal risers to meet the encountered technical and economic challenges. A riser system is subjected to the sea environmental condition for the service life greater than 20 years with a minimum amount of maintenance (Summerscales 2014). Although composite risers have higher costs on material and manufacturing than traditional metal risers, the costs on maintenance and installation are largely reduced (Fowler *et al*. 1998, Ochoa and Salama 2005). Extensive experimental and numerical efforts have been conducted to investigate the mechanical behavior of composite risers in the past decades (Tafreshi 2006, Chen *et al.* 2013, Guades and Aravinthan 2013, Guades *et al.* 2013, Ahmad and Hoa 2016, Sarvestani *et al.* 2016). Alexander *et al*. (2011) assessed the performance of a composite reinforced steel riser through full-scale tests, which demonstrated good manufacturability and sufficient margins of safety against burst and impact damage. Other research efforts also examined the global and local analyses of risers (Zhao *et al.* 2000, Rasheed and Tassoulas 2001). Pham *et al*. (2016) presented a comprehensive review on the manufacture, experimental and numerical analysis of composite risers in deep-water applications. However, very few work has been done to investigate the fatigue performance of composite risers.

For traditional metal risers subjected to excessive corrosion or mechanical damage, composites also provide a good choice for repair to restore the strength in maintaining the safe and reliable operation. The composite repair system usually bonds the composite laminates to the defective pipe and held together between layers using an adhesive. Most of the studies on composite repair system focus on static loadings. Duell *et al*. (2008) investigated the effects of corrosion length on the structural performance of a corroded pipe subjected to internal pressure repaired with CFRP. Shouman and Taheri (2011) built a FE model to capture the buckling behavior of a composite repaired riser. Alexander and Ochoa (2010) extended the repair of onshore pipeline to the repair of offshore steel risers with CFRP composites by understanding the complex combined load profiles of the riser. Another important application of composite materials in offshore and marine industries is tidal turbine blades, very critical components of the device for obtaining tidal energy. Tidal turbine blades require high static and fatigue strength due to the harsh working environment, including extreme weather, turbulence flows, and erosion due to ice, sand and floating objects (Jaksic *et al.* 2016). Thus, it is necessary to use high strength FRP composites to design and manufacture the blades. However, similar to composite risers, the investigations on the fatigue behavior of composite repair system and composite turbine blades remain scant.

The common characteristic for the composite riser, composite repair system, and composite turbine blades is that they are subjected to long-term cyclic environmental or working loads around 20 to 30 years. Thus, their performance in resisting fatigue loading becomes highly important in the initial design and later maintenance. Due to the lack of experimental data at the structure level, most of the current studies use the coupon test results to estimate the fatigue life of large structures. However, this method is still questionable for composite material which is anisotropic. This paper first discusses the failure mechanism of FRP composites under fatigue loading and the existing models on fatigue life prediction. Both of the two topics are based on the material level. Then, the

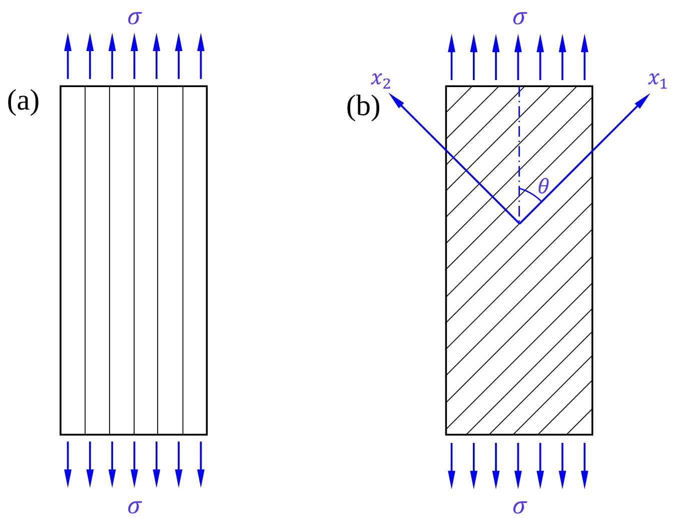

Fig. 1 Test of unidirectional fiber composites: (a) on-axis; (b) off-axis

paper reviews the existing studies on the fatigue behavior of composite risers, composite repair systems, and other related applications in offshore and marine industry. For composite risers, the paper introduces the design guidance on fatigue from three authoritative classification societies, namely American Bureau of Shipping (ABS), Lloyd's Register (LR), and Det Norske Veritas (DNV). Finally, the paper points out the key challenges in investigating the fatigue performance of composite structures in offshore and marine industry.

2. Failure mechanism of lightweight composites under fatigue loading

2.1 Fatigue failure mechanism

Compared to homogeneous materials like metals and metallic alloys, the composite materials exhibit a more complex fatigue mechanism, starting from the microscopic scale, involving failure in constituent fiber, matrix or fiber/matrix interface, to the final failure of the macroscopic structure. Due to the lack of knowledge on microfailure criteria, it is difficult to theoretically obtain the stresses and strains leading to microfailures, not to mention the interaction effects among the microfailures (Hashin 1983a). The present discussion first goes through the previous studies on the fatigue mechanism of unidirectional fiber composites, and then extends to fatigue failure of composite laminates, since the former lay a good foundation to the latter.

2.1.1 Unidirectional fiber composites

The fatigue failure of unidirectional composites subjected to on-axis tensile fatigue loading, as shown in Fig. 1(a), can be divided into three types: (1) fiber breakage and interfacial debonding; (2) matrix cracking; (3) interfacial shear failure. Based on Dharan (1975)'s work, Talreja (1981) proposed a conceptual framework to illustrate the fatigue damage mechanism of composites by establishing a fatigue life diagram, as shown in Fig. 2, which describes the relationship between the maximum strain and fatigue life cycles. The diagram chooses strain instead of stress as the fatigue

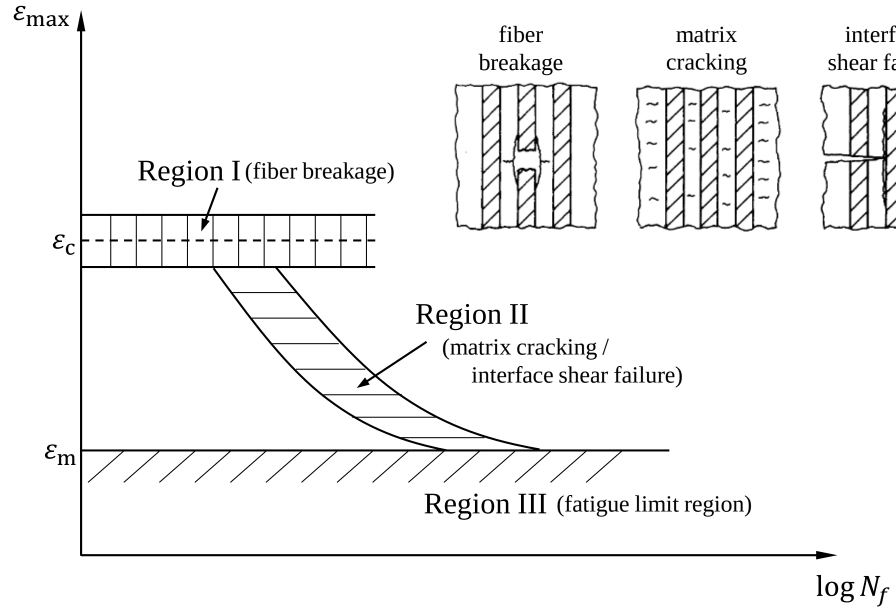

Fig. 2 Strain-life diagram for unidirectional composites under loading parallel to fibers (Talreja 1981)

driving force because both fibers and matrix suffer the same strain but different stresses during the loading. The diagram consists of three regions. The first region of the horizontal scatter band represents the non-progressive nature of the underlying mechanisms of the fiber breakage and interfacial debonding. The second region of the sloping scatter band corresponds to the two progressive failure mechanisms, matrix cracking and interfacial shear failure, which may occur simultaneously. The third region below the fatigue limit of matrix (ε_m) indicates no failure. ε_m is a material property and therefore fixed by a given matrix material. The composite fracture strain ε_c depends on the fiber stiffness. For composites with low fiber stiffness, e.g., glass-epoxy, ε_c is much larger than ε_m, while for composites with high fiber stiffness, e.g., graphite-epoxy, ε_c is very close to ε_m or even less than ε_m. Gamstedt and Talreja (1999) examined the effect of polymeric matrix in determining the fatigue behavior of unidirectional composites based on the fatigue life diagram. Microscopic and macroscopic fatigue investigations have been taken for two types of materials, CF/epoxy and CF/PEEK. The comparisons indicate that the use of the more ductile PEEK matrix invokes a more rapid rupture process of fibers due to some damage mechanism on the microscale.

For unidirectional fiber composites under off-axis fatigue loading (inclined to fibers, as shown in Fig. 1(b)), previous tests (Hashin and Rotem 1973, Awerbuch and Hahn 1981) exhibited two failure modes in tension-tension fatigue: fiber mode and matrix mode. The former is defined by fiber rupture due to the accumulation of microcracks and other flaws with an irregular rupture surface, while the latter fails by a sudden crack along fibers resulting in a plane fracture surface. Based on these two failure modes, Hashin and Rotem (1973) established a set of fatigue failure criteria in terms of S-N relationship for unidirectional fiber composites under off-axis fatigue loading. The failure mechanisms in tension-compression fatigue and in compression-compression fatigue are not as clear as that for tension-tension. Fiber buckling may occur due to the existence of compressive loading along fiber direction. The compressive strength increases with the shear modulus of matrix in static compression (Schuerch 1966). However, the deterioration in the shear

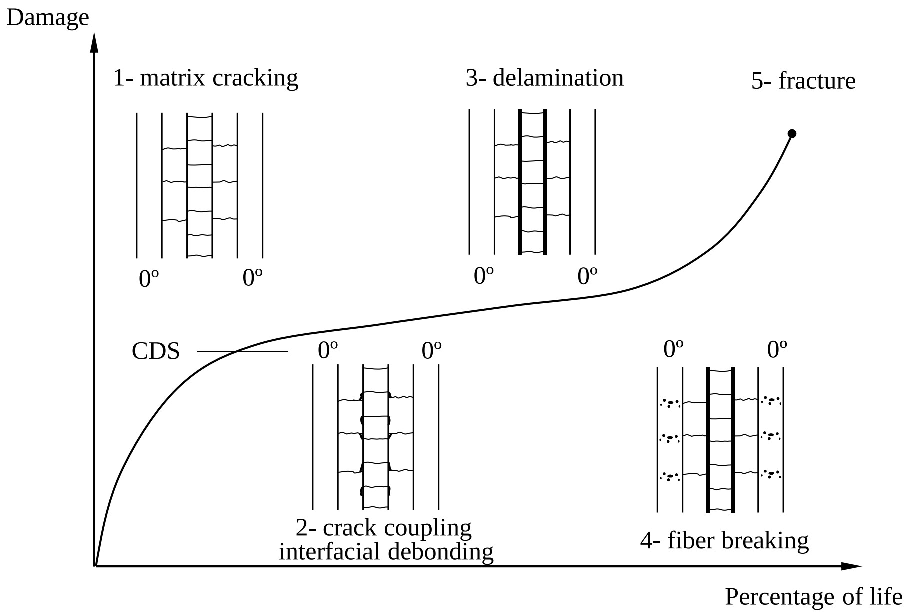

Fig. 3 Fatigue damage evolution in composite laminates (Reifsnider *et al.* 1983)

modulus of matrix and the initiation of longitudinal cracks at fiber/matrix interface caused by cycling may invoke the fiber buckling at a much smaller load than that under static actions. These uncertainties make it difficult to clarify the relationship between the transverse stress and the longitudinal failure stress (Hashin 1981).

For composites under complicated cyclic loadings, the prediction of lifetime needs to take account for the cumulative damage. A simplistic damage function widely used to estimate safe fatigue lives in metals is the Miner's rule, as the sum of various fractions of experienced fatigue cycles to those necessary to cause failure at a particular stress level. To apply this approach on composites, Halpin *et al*. (1973) put forward a concept of residual strength degradation, which is defined as the degradation of static strength after n elapsed cycles. Fatigue failure is invoked once the residual strength is degraded to the maximum stress amplitude. However, the Miner's rule has limited applications to the composites because the estimation obtained through this approach is unconservative (Heath-Smith 1979, Rosenfeld and Gause 1981). Some researchers (Hashin and Rotem 1978, Yang and Jones 1981, Hashin 1983b) also tried to analyze the cumulative damage based on the statistical theory, and the predicted results show a good agreement with some of the test data obtained in Broutman and Sahu (1972). However, the statistical approach is more complex requiring a function not only related to the elapsed loading cycles but also to the loading history.

2.1.2 Composite laminates

A composite laminate is an assembly of unidirectional reinforced layers, also called as laminae. Both the use of different composite materials for fibers or matrices, and the layup with different fiber orientations produce heterogeneity for composite laminates. The fatigue failure of fiber composite laminates includes two failure processes: the intralaminar process and the interlaminar process (Hashin 1983a). In the former process cracks occur in fiber or in matrix modes, while in the latter process cracks accumulate at the interlaminar edge which may split the laminates. Reifsnider *et al*. (1983) illustrated the interaction effects of these two failure processes.

Taken from this reference, Fig. 3 shows the development of damage in composite laminates. At the early stage, many non-interactive matrix cracks are expected to initiate along the fiber plies that have different orientations to the principal tensile stress direction, also called as the zero-degree direction. When the number of load cycles increases, the matrix crack density reaches a saturated state, called as Characteristic Damage State (CDS), indicating the termination of the first stage. At the following stage, short cracks start to form in the transverse direction to the primary cracks generated at the first stage and develop to the interlaminar cracks. Then, the interlaminar cracks result in interior delamination with the local separation of the fiber plies. This interior delamination subsequently extends to strip-like delamination zones with the growth and merge of the interlaminar cracks. As the severity of crack interactions increases, fiber breakage starts to dominate the composite failure and the ultimate fracture is invoked due to the rapid loss of material integrity (Talreja 1986, 1989).

2.2 Fatigue life prediction model

Based on the failure mechanisms discussed above, various fatigue models have been developed for FRP composites. These models are generally categorized into three groups: the fatigue life models; the phenomenological models; and the progressive damage models.

The fatigue life models, also widely used for metals, establish S-N curves or Goodman-type diagrams with the introduction of some sort of fatigue failure criteria. Ellyin and El-Kadi (1990) developed a failure criterion based on the strain energy density for fiber reinforced materials under cyclic loading. The life cycles to failure is related to the strain energy density through a power law function, the constants of which are sensitive to the fiber orientation. Reifsnider and Gao (1991) proposed a micromechanics fatigue criterion, involving the constituent properties and the interfacial bond, based on an average stress function derived from Mori-Tanaka method (Mori and Tanaka 1973). Fawaz and Ellyin (1994) presented a semi-log linear model to predict the fatigue failure of composites under multiaxial stresses and with different fiber orientations. The correlation between the model and the published data is quite accurate. Harris and his co-workers (Adam *et al.* 1994, Gathercole *et al.* 1994, Harris 1996, Beheshty and Harris 1998, Beheshty *et al.* 1999) built a normalized constant-life model, describing the relationship between the alternating and mean stresses, for fatigue life prediction, which is applicable to both undamaged composite laminates and impact-damaged laminates. Although fatigue life models are straightforward for life prediction, this approach requires a large number of experimental data. To minimize the dependency on the number of tests, Epaarachchi and Clausen (2003) developed a model incorporating the effects of stress ratio and load frequency. Predictions based on this model match the experimental data very well.

Unlike metals, composite materials under fatigue loading always display a change of the mechanical properties, such as the degradation of stiffness or strength. The phenomenological models usually develop an evolution law describing the degradation of the stiffness or strength from the macroscopic view. Ogin *et al*. (1985) developed a power function to calculate the rate of stiffness reduction caused by transverse-ply cracking. Integration of the power function enables the construction of a diagram which relates stiffness reduction to life cycles for different stress levels. Whitworth (1987) proposed that the residual stiffness degrades monotonically with the increase of life cycles. The model is capable of characterizing both linear and nonlinear material responses. Yang *et al*. (1990) developed a statistical model to estimate the distribution of the residual stiffness for the entire population of fiber-dominated laminates. Based on this model, the linear regression approach and the Bayesian approach can be used to predict the stiffness degradation for an individual specimen under a specified number of cycles. Halpin *et al*. (1973) assumed that the residual strength can be calculated through a monotonically decreasing power-law function of life cycles. This procedure has been widely referred to by other researchers (Hahn and Kim 1976, Chou and Croman 1978, Yang 1978, Chou and Croman 1979). Based on a series of experimental and theoretical investigations, Schaff and Davidson (1997a, b) developed a strength-based wearout model to predict the residual strength of the composite laminates under spectrum fatigue loading. This phenomenological and semi-empirical model provides excellent guidance for the design of composite materials.

The progressive damage models introduce damage variables to represent the deterioration of composite laminates based on the underlying damage mechanisms. Talreja (1985) proposed a continuum damage model to characterize the internal damage variables through a set of vector fields, each representing a damage mode. Ladeveze (1992) proposed a damage model at the mesoscale which simplifies the composite laminates as two elementary constituents: a single layer and an interface. The deterioration of the mechanical surface is indicated by three damage variables representing three different failure modes. Liu and Lessard (1994) adopted a global damage variable, D, to quantify the matrix crack density and delamination size. The critical global damage variable, D_f, is determined through the well-known strain failure criterion. Shokrieh and Lessard (2000a, b) established a progressive damage model to simulate the degradation of mechanical properties and predict the fatigue life of composite laminates. The model consists of stress analysis, failure analysis and degradation rules of mechanical properties, and is capable to detect different failure modes based on a set of failure criteria.

In summary, extensive models have been developed to indicate the damage accumulation and predict the lifetime of lightweight composites. The empirical fatigue life models establish the S-N curves to directly predict the fatigue life. However, these models require a large number of experimental work and may be not applicable to more general cases. The phenomenological models propose different evolution laws to describe the degradation of stiffness/strength of composite materials. Compared to the above two approaches, the progressive damage models investigate the fatigue behavior and predict the fatigue life of composite materials based on specific fatigue damage mechanisms. The obstacle in developing progressive damage models is the complex nature of composite materials, both in the geometry and the failure mechanisms.

3. Fatigue behavior of composites in offshore and marine industry

The lightweight composites have been widely applied in offshore and marine industry. Compared to onshore structures, the offshore and marine structures suffer harsher environment. The prolonged immerse in the sea water may lead to deterioration of mechanical properties and increase of structure weight. The penetration of sea water in a FRP laminate occurs both by diffusion through the resin and by capillary flow through cracks and voids and along imperfect fiber-resin interfaces (Shenoi and Wellicome 1993). Rege and Lakkad (1983) investigated the influence of saltwater on the mechanical properties of glass and carbon fiber materials. The strength reduction is more serious in saltwater and directly related to the percentage weight gain. Siriruk and Penumadu (2014) tested the fatigue performance of carbon fiber-vinyl ester-based composites in a sea-water environment. The experimental data show that the exposure to sea water shortens the fatigue life of the composite samples by up to 85% compared to that of dry laminates tested in the laboratory air. The fatigue life

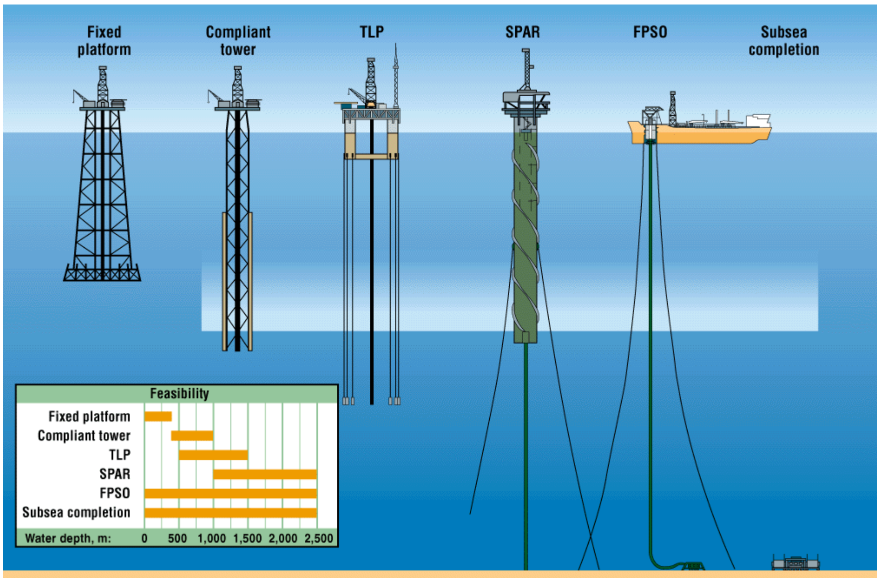

Fig. 4 Different types of platforms and risers (Courtesy: API)

of composites is also affected by temperature. In the coupon fatigue test conducted by Huang *et al*. (2019b), the cyclic loading introduces heat generation inside the matrix, leading to the elevated temperature of the specimen up to 90°C. The fatigue life thus obtained underestimates the real fatigue life of composite materials operating in a marine environment with an ambient temperature below 20°C. Thus, it is important to keep the test temperature as close to the sea temperature as possible during the fatigue test.

Although numerous models, including the fatigue life models, the phenomenological models and the progressive damage models discussed in Section 2.2, have been developed to represent the fatigue behavior of composite materials in the past few decades, the investigation on the fatigue performance of composites at the structural level remains scant. The fatigue models at the material level serve as the foundation for the development of fatigue models at the structural level. Because of the geometric and material complexity of composite, the existing fatigue life prediction models for offshore and marine composite structures are mainly empirical fatigue life models or semi-empirical residual strength or stiffness models. This section presents the applications of composite materials in offshore and marine industries, including composite riser, composite repair system, and other applications like composite turbine blades, composite propellers, etc. Since these structures or components are subjected to long-term cyclic loads or environmental loads, the fatigue performance is a critical issue for design purposes.

3.1 Composite riser

In offshore engineering, the introduction of new production system concepts, such as Compliant Tower, FPSO, TLP and SPAR, etc., enables the exploration and production activities to head towards deeper waters, as shown in Fig. 4. As the key component of the production system, production risers transport the hydrocarbon products from the wellheads at the seabed to the floating platforms at the sea surface. Traditional designs of risers using metallic materials including steel or titanium, namely the metal risers, cannot satisfy the practical, economical, and environmental requirements due to the increasing water depth. In contrast, CFRP composite risers represent an attractive alternative due to its overwhelming advantages including high strength-to-weight ratio, good corrosion resistance, excellent thermal insulation, and attractive fatigue performance (Salama *et al.* 2002, Bai and Bai 2018). There are two main types of production composite risers: bonded and un-bonded (Pham *et al.* 2014). The former often consists of a core of composite laminates bonded between a metallic/elastomeric inner liner and an outer liner made of thermoplastic or thermoset materials or metal alloys (Gibson 2003). For the latter, the different layers of the risers are allowed to move relatively to one another, exhibiting excellent flexibility in installation and maintenance (Hill *et al.* 2006). This section aims to provide a review of published literatures and existing design guidance on CFRP composite risers from the fatigue perspective.

3.1.1 Fatigue investigations on composite riser

Extensive experimental and numerical investigations have been reported on the mechanical properties of CFRP composite risers in the past decades (Tafreshi 2006, Theotokoglou 2006, Chen *et al.* 2013, Ahmad and Hoa 2016, Sarvestani *et al.* 2016). These efforts reveal that the current designs offer large safety margins for composite risers under short-term extreme loading conditions. In addition, the burst and collapse capacities of composite risers can also meet the design requirements (Kim *et al.* 2007). However, the lack of experimental data for the development of fatigue life estimation models remains a critical bottleneck, hindering the industrial adoptions of composite risers (Ochoa and Salama 2005).

Huybrechts (2002) has demonstrated that CFRP composite risers often entail a long fatigue life when the fatigue failure is governed by the fiber-failure. Unique specimens, with the shape of pressure vessel, were tested under tensile fatigue loadings to prove that the high consistency of the specimen properties with the real product properties leads to the enhanced reliability of the S-N curve. The cumulative damage using Miner's rule is not applicable to composite laminates. In order to solve this problem, Huybrechts (2002) adopted the remaining strength approach (Broutman and Sahu 1972) to log the decrease in strength continuously along the load cycles. This approach significantly reduces the fatigue safety factor than the Miner's rule approach. The limit of Huybrechts (2002)'s work is that the method is developed based on experimental database of the small-scale specimens under cyclic loading, thus raising the questions on the scaling effects.

Kim (2007) investigated the fatigue performance of a composite riser consisting of orthotropic carbon-epoxy layers. The long-term sea state is modeled using the Rayleigh probability density function. Due to the lack of experimental data, Kim *et al*. (2007) tried to use two different types of S-N relationships, namely semi-log function and power law function, to estimate the fatigue lives of the composite riser at the top and bottom sections of the riser. Different values are assigned to the material parameters within these two types of functions. However, it is found that the calculated fatigue lives are highly sensitive to these constants. In addition, these S-N curves show different predictions in the contribution of the predominant sea characteristics.

Singh and Ahmad (2015) assessed the reliability of composite risers for cumulative fatigue through probabilistic methods, including Monte Carlo simulation and Advanced First Order Reliability Method. The formulation of limit state function employed the S-N curve approach according to DNV-RP-C203 (2010). The sensitivities of various random variables on overall probability of failure have been studied. The reliability of composite risers is inversely related to the service life. However, the calculation of the cumulative damage is also based on Miner's rule, which is proved to be unconservative for composite materials as discussed above.

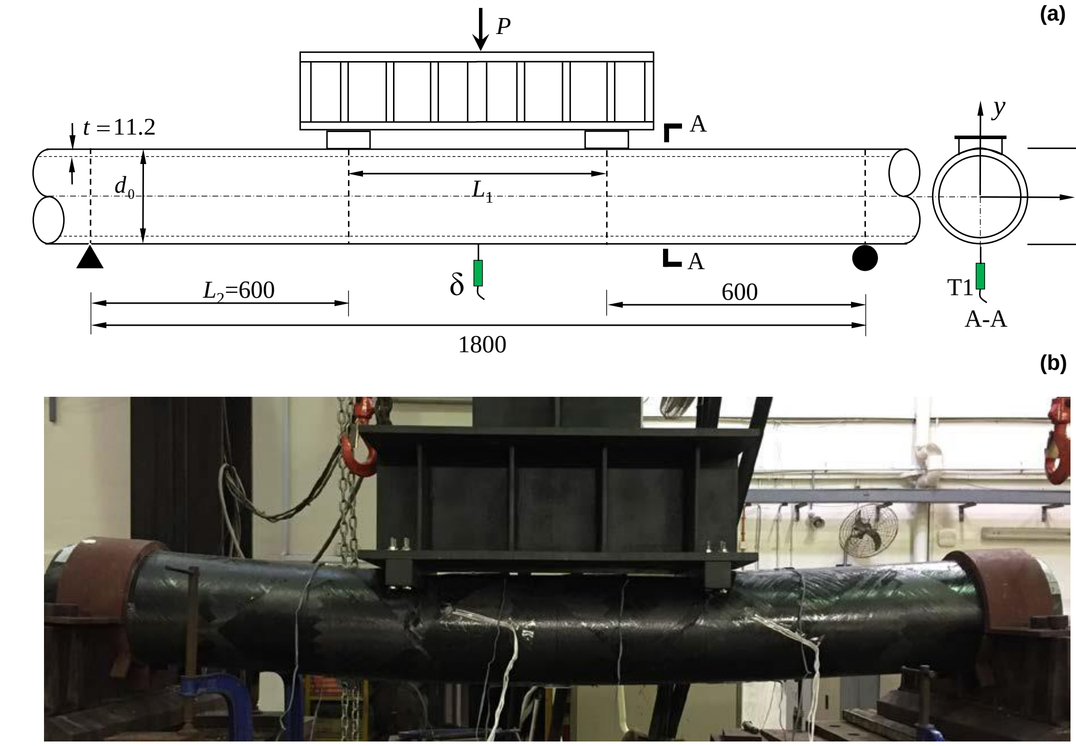

Fig. 5 Fatigue test of full-diameter CFRP composite riser pipe: (a) set-up; (b) specimen after test (Huang *et al.* 2019b)

Huang *et al*. (2019b) studied the fatigue behavior of filament wound CFRP composite risers and proposed an empirical approach to estimate the fatigue life based on the coupon test results. The monotonic tension tests conducted in the earlier paper, Huang *et al*. (2019a), examined the failure mode and ultimate strength of CFRP coupons with different layups; while the fatigue test conducted later examined the effects of stress ratios and fiber orientation on the life cycles of CFRP composites. By extending the empirical model proposed by Epaarachchi and Clausen (2003) for GFRP plates, Huang *et al*. (2019b) develop empirical equations to predict the fatigue life of CFRP composites with two different layups. The fatigue test program also examines 6 full-diameter CFRP pipe specimens with the complex layup under cyclic loading, as shown in Fig. 5. CFRP pipes with the complex layup exhibit an excellent performance in resisting fatigue load. The failure of the two damaged pipes originates from the stress concentration at the contact region between the loading beam and the pipe. Although the typical failure mode of interface delamination is not captured during the cyclic loading, the fatigue life predicted by the proposed model using stresses computed at the location of fracture initiation matches reasonably close to the test results.

Lindsey and Masudi (1999), Lindsey and Masudi (2002) and Cederberg (2011) have also conducted some fatigue tests and stress analysis on composite riser specimens. However, no detailed results are available in public literature.

3.1.2 Current design guidance

Compared to onshore pipelines, offshore risers are more complicated due to additional stresses, fatigue and harsh environment. As composite risers have been widely accepted for oil production in deepwater, the manufacture and maintenance have to comply with certain industry standards to ensure the safety and required lifetime. American Bureau of Shipping (ABS), Lloyd's Register (LR) and Det Norske Veritas (DNV) are the world leading classification societies in making standards, rules and regulations for maritime and offshore industries.

ABS (2008) specifies the requirements and acceptance criteria through long-term fatigue tests to qualify the composite riser joint, the connection between the composite pipe body and metallic flange. The qualification is accepted only if the riser joint has equal or longer service life than the pipe body. Either cyclic axial tension or cyclic bending is to be applied to the test specimen, depending on whichever is more critical. At the same time, the test is required to apply internal operating pressure to represent the realistic scenario. With the established S-N curve based on the fatigue test, the fatigue life can be calculated according to the realistic fatigue loading spectrum. The fatigue life is required to be larger than 10 times the design service life. The LR (2018) does not make any special regulations on the fatigue analysis of composite risers. Instead, the LR (2018) states "the fatigue S-N curves and polymer ageing data are typically proprietary information, so the stress, fatigue and aging evaluation reassessment are recommended to be performed by the original manufacturer".

Compared to ABS and LR, DNV has developed more detailed design philosophy, safety requirements and classification of loads for composite risers. The main contents are covered in the Recommended Practice document DNV-RP-F202 (DNV-RP-F202, 2010), which is linked to the Offshore Standard for Dynamic (metal) Risers DNV-OS-F201 (DNV-OS-F201, 2010) and the Offshore Standard for Composite Components DNV-OS-C501 (DNV-OS-C501, 2013). The relationship among these documents is presented in Fig. 6. The DNV-RP-F202 shows how to account for the fatigue amplitude and mean stresses, and how to calculate the fatigue life cycles based on a constant amplitude lifetime diagram. Both global analysis and local analysis are required to perform so as to detect possible failure mechanisms. The Miner's rule is followed to calculate the

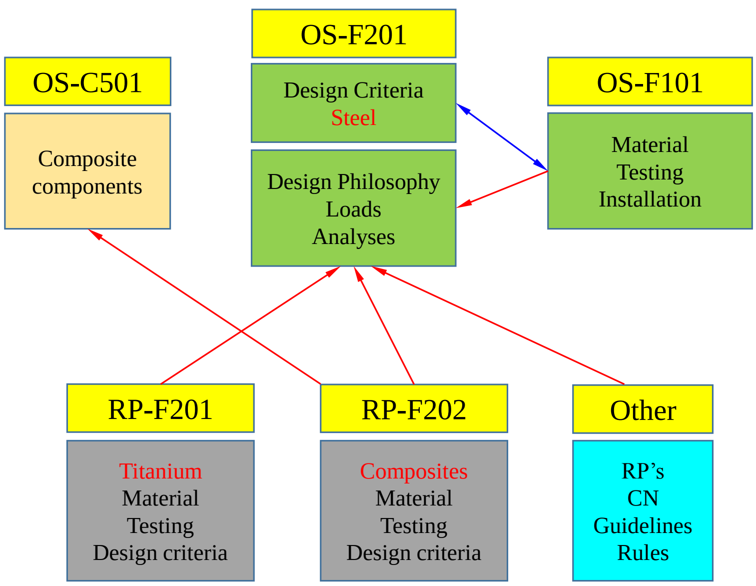

Fig. 6 Link between DNV standards and practices related to risers (Echtermeyer *et al.* 2002)

Table 1 Factor for fatigue calculations (DNV-RP-F202, 2010)

Safety class		
Low	Normal	High
15	30	50

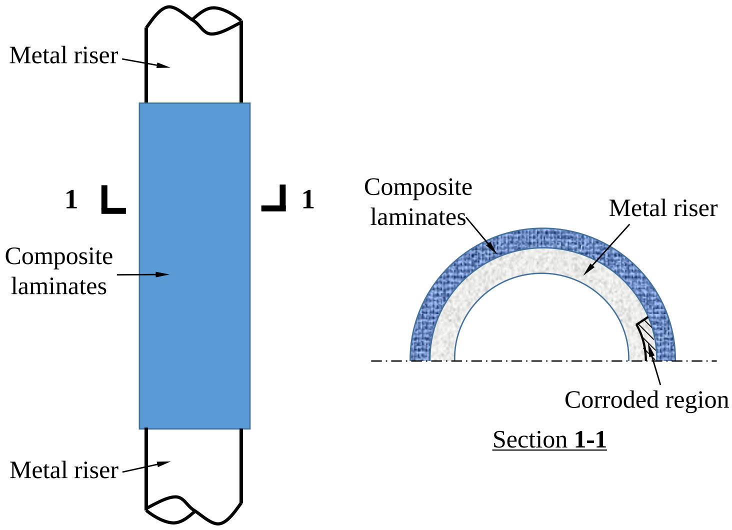

Fig. 7 Typical composite repair system (Chan 2017)

cumulative fatigue life. Table 1 lists the factors used for the fatigue life prediction, which account for the uncertainty in the Miner's rule. The DNV-RP-F202 has been applied to both the design of new riser systems and the operation and maintenance of existing risers.

3.2 Composite repair system

An offshore riser subjected to excessive corrosion or mechanical damage has to be carefully repaired to restore the strength in maintaining the safe and reliable operation. Traditional repair method through hyperbaric welding of steel clamps around the corroded section of the riser introduces high risks, such as underwater explosion since the main content in the riser is hydrocarbon substances and electric shock to the welder if the welding is operated manually, etc., (Chan 2017). In contrast, the use of lightweight high strength composites appears to be a promising alternative in repairing corroded offshore risers. The composite laminates are usually bonded to the defective pipe and held together between layers using an adhesive for the underwater repair, as indicated in Fig. 7.

Both Alexander and Worth (2006) and Lukács *et al*. (2010) conducted experimental investigations on the performance of damaged pipelines reinforced by CFRP composites subjected to cyclic internal pressure. In Alexander and Worth (2006)'s test, the use of the Aqua Wrap system in repairing the damaged pipes was capable of increasing the fatigue life of the specimens from 100 cycles to 100,000 cycles. For the specimens tested by Lukács *et al*. (2010), the fatigue test stopped after 100,000 cycles, and then the burst load was applied. Thus, the final failure of the specimen is due to the combination of the fatigue load and the burst load. Although the repaired specimens in both two tests presented excellent fatigue performance, no effort has been done to investigate the stress-strain behavior of the composite repaired pipes under cyclic loading.

In order to evaluate the performance of FRP composites in repairing fatigue crack in steel structures, Lam *et al*. (2011) built a FE model of a cracked steel tube member repaired by FRP patching to extract the Stress Intensity Factor (SIF), and then substituted the SIF into the Paris equation (Paris and Erdogan 1963) to calculate the fatigue life of the repaired tube member. The FE model employed the solid element (C3D20) to model the steel tube, and adopted the shell element (S8R) to model the FRP patching. The FE analysis indicates that the FRP patching is very effective in reducing the SIF of the cracked tube and the maximum reduction is higher than 50%. As a result, the predicted fatigue life for the tube members repaired by FRP patching is significantly increased due to the reduction of SIF.

Chan *et al*. (2014) conducted a FE simulation on the failure mechanisms of composite repair system in offshore pipe risers under low cycle fatigue loading using a direct cyclic simulation in ABAQUS. Two orientations of composite laminates are investigated: axially orientated and hoop orientated. The FE model adopts the shell element S4R as the element type for both the steel pipe and the composite sleeve. The Paris Law is followed to characterize the onset of fatigue delamination and debonding growth. Eq. (1) and Eq. (2) represent the fatigue crack initiation criterion and the crack evolution law respectively, in which N is the number of cycles, G_{max} and G_{min} indicate the strain energy release rates at the maximum load and minimum load respectively, c_1~c_4 are material constants obtained according to NASA's report (O'Brien *et al.* 2010, Krueger 2011). The results indicate that debonding at the interface between the steel and composite is more critical to the composite repair system than delamination within the composite laminates. Compared to the axially orientated laminate, the hoop orientated laminate provides better bond performance at the steel-composite interface.

$$f = \frac{N}{c_1\left(G_{\max} - G_{\min}\right)^{c_2}} \geq 1.0 \tag{1}$$

$$\frac{da}{dN} = c_3\left(G_{\max} - G_{\min}\right)^{c_4} \tag{2}$$

The composite repair system in offshore and marine industry is normally the FRP-steel composite structure, the fatigue life of which is strongly affected by the interfacial bond and debond behavior. Most of the existing studies have investigated the FRP-steel interface under monotonical loading, while only a few focus on the performance of the interface under fatigue loading. The experimental program usually adopts the single-shear bonded joints and/or double-shear bonded joints to examine the effect of FRP-steel interface. Iwashita *et al*. (2007) tested the single-shear bonded joints to investigate the interfacial behavior between CFRP sheet and steel plate subjected to fatigue loading. It is concluded that the fatigue life of the interface is negatively related to the load ratio. By testing the double-shear bonded joints, Colombi and Fava (2012) analyzed the stiffness degradation and proposed the corresponding S-N curves for the fatigue performance of CFRP-steel interface. Based on the tests of double-shear bonded joints, Liu *et al*. (2010) and Wu *et al*. (2013) investigated the influence of fatigue loading on the residual bond strength. Both of the test results show that the fatigue loading does not affect too much the bond strength of high/ultra-high modulus CFRP sheet-steel joints. Yu *et al*. (2018) examined the bond behavior of CFRP-steel double-lap joints exposed to marine atmosphere and fatigue loading. The resulting bond strength loss ranged from 1% to 11%. The environmental exposure and fatigue cyclic loading both leaded to the degradation of the bond joint stiffness.

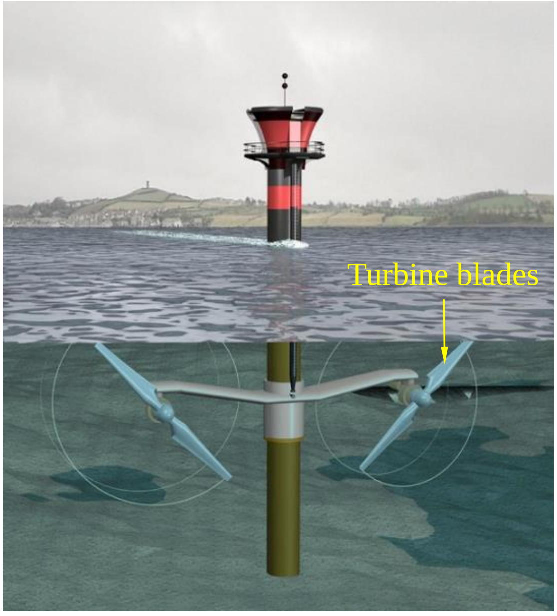

Fig. 8 Marine tidal turbine (Courtesy: International Rivers)

3.3 Other applications of composites in offshore and marine industry

Another important application of composite materials in offshore and marine industries is tidal turbine blades, as shown in Fig. 8. As a renewable energy source, tidal energy is highly efficient and predictable. However, it is difficult to foresee the intensity and variability of tidal current over small geographical areas (O'Rourke *et al.* 2010). The random current means the blades of tidal turbine have to suffer significant fatigue loadings over the designed lifespan of 25-30 years. In addition, tidal turbine blades are also subjected to harsh marine environment, extreme weather, as well as erosion due to ice, sand and floating objects. Thus, great potential exists to replace traditional metal turbine blades with composite turbine blades.

Tidal turbine blades have similar configuration with wind turbine blades. Thus, the hydrodynamic design of the former follows a similar pattern with that of the latter (Bahaj *et al.* 2007, Grogan *et al.* 2013). The composite blade is usually made as a solid laminate containing fibers or as a sandwich structure consisting of two thin, stiff, and strong composite faces, and a thick, lightweight and compliant core. Most of the blades use GFRP as the composite material, except for large blades, CFRP material with lighter weight offers even better performance (Grogan *et al.* 2013). Unlike wind turbine blades, tidal turbine blades normally work in a harsher environmental conditions, and are subjected to water ingress and saturation during the employment period (Davies and Rajapakse 2014, Jaksic *et al.* 2016). Akram (2010) designed a special sandwich composite construction with a single web for the turbine blade. The S-N diagram was developed through pure Finite Element method without experimental verification. Davies *et al*. (2013) first conducted static and cyclic tests at the material scale both in air and in sea water to quantify the influence of ageing in sea water on fatigue performance of tidal turbine blades. Then, they carried out flume tank tests on small scale three-blade tidal turbines to study the influence of both current and wave-current interactions. Compared to the current alone, the wave-current interaction can cause large additional

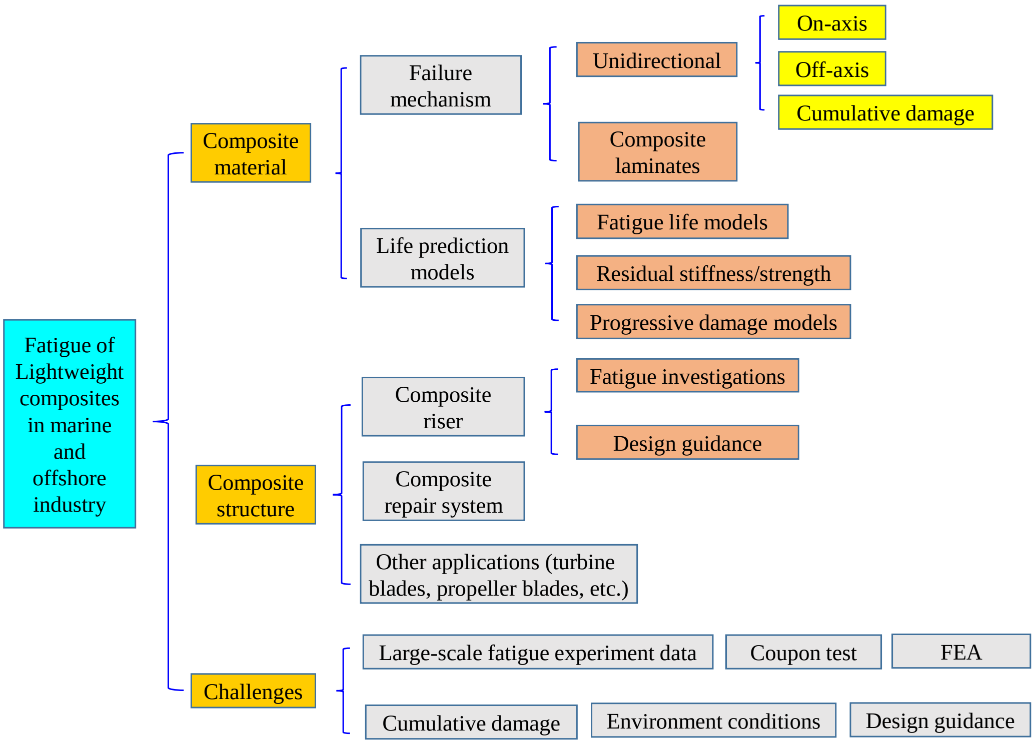

Fig. 9 Outline of this review

loading amplitudes. Jaksic *et al*. (2018) investigated the effects of water saturation on the fatigue behavior of GFRP tidal turbine blades through a series of coupon tests. The results show that the fatigue modulus is insensitive to the water absorption; instead, the fatigue strength is significantly degraded by water immersion aging.

Besides turbine blades, FRP composites are also applied on propeller blades, very similar structure like turbine blades. Previous studies on composite propeller blades mainly focus on the fluid-structure interaction (Lin *et al*. 2005, Young 2008), vibration and damping (Lin and Tsai 2008, Hong *et al*. 2012). It is found that the fiber orientation and stacking sequence affect the performance and efficiency of composite propellers in these behaviors (Lin *et al*. 2010). However, very few literatures can be found on the fatigue performance of composite propellers. One of the possible reasons is that for naval vessels, the design and performance of composite propeller systems are highly classified information and not allowed to be reported in the open literatures (Mouritz *et al*. 2001). The available information on the fatigue behavior of composite propellers is for the aerospace systems (McCarthy 1985, Zetterlind *et al*. 2003), which may serve as indirect guidance for composite propellers in marine industry.

4. Conclusions

Fig. 9 lists the outline of this review and the summarized challenges. The paper first examines previous investigations on the failure mechanism of FRP composite materials under fatigue loading.

Extensive models based on specific fatigue criteria have been proposed to predict the damage accumulation and lifetime of FRP composite materials with various constituents and layups. Due to the significantly enhanced performance compared to traditional metals, composite materials have been widely applied in the offshore and marine industry. The paper then presents the existing studies on the fatigue performance of composite riser, composite repair system and other related applications, respectively. According to the review, the following highlights the challenges in the application of FRP composites in offshore and marine industries:

(1) Fatigue studies on the structure level of marine structures or components are limited. Very few experimental data on full-scale or large-scale composite riser, composite repair system, and composite turbine blade exists in the public literatures. These data will be crucial to ensure the reliability and safety of these structures during their long-term service life.

(2) Most of the current studies use the coupon test data to predict the fatigue life of composite structures since the full scaled tests are not applicable in most of the time due to high cost and insufficient equipment. However, whether this approach is reliable or not for composites is still a doubt. The reason is that composite material is inhomogeneous and anisotropic, the coupon sample extracted from one local region in the specimen may have different properties with the coupon extracted from the other local region, due to different fiber orientations or composite layups, and cannot reflect the performance of the full-scale structure. Thus, how to develop an alternative and reliable approach to characterize the material properties to evaluate the structural performance would be a great challenge for future investigation.

(3) The sea environment, including water pressure, temperature, salinity, etc., is proved to have unignorable effects on the mechanical performance and fatigue behavior of lightweight composites. Duplicating the marine environment in the laboratory test setting is a challenging task for coupon specimens and large structural components. Thus, how to quantify the environmental effects becomes another challenge in order to extend the test data to the field application.

(4) Many researchers use Miner's rule to predict the cumulative damage. However, the applicability of Miner's rule on composites remains questionable because the estimation obtained through this approach may be unconservative. Therefore, the application of the Miner's rule while considering the uncertainty results in a large safety factor in the design guidance, e.g. DNV uses the safety factor of 15~50 for composite risers. Although some researchers propose to calculate the cumulative damage based on the statistical theory, this approach is too complicated for practical analysis and design. Thus, it is promising to develop a better approach to account for the cumulative damage in predicting the fatigue life of composite in the future work.

(5) Finite Element Analysis (FEA) has been considered as an effective tool to replace the costly experimental work. However, the development of FEA on composite structures remains insufficient. One of the reasons is due to the complex nature of composite materials. It is challenged to develop a benchmarked FE model considering both the micro-damage/macro-damage simultaneously to accurately predict the various failure modes of composite materials. In addition, the FE analysis of composite structures requires substantial computational resources and the simulation is time-consuming, especially for large structures in offshore and marine industries. To close this research gap, tremendous efforts are required to improve the current FE approach for composite structures, including developing more advanced damage models, increasing the computational efficiency, efficient approaches to incorporate the stochastic material effects at different scales, etc. In this case, multi-scale FEA technology will be a promising way forward to address these issues, coupled with experimental validations across

different scales.
(6) The current design guidance estimates the fatigue life of composite structures using large safety factors, which reflects the lack of understanding in the structural behavior and leads to the increase of the manufacturing cost. With the development of experimental, numerical and theoretical investigations on the fatigue behavior of composite structures, these factors are expected to be reduced. The improved design guidance will enable the application of lightweight composites in offshore and marine industry in a safe and economical way.

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