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ISSN: 0193-4120 Page No. 3379 - 3388

An Examination on Durability and Degradation of Glass Fiber Reinforced Polymer Structures

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Article Info
Volume 81
Page Number: 3379 - 3388
Publication Issue:
November-December 2019

Article History
Article Received: *5 March 2019*
Revised: *18 May 2019*
Accepted: *24 September 2019*
Publication: *16 December 2019*

Abstract:
This paper reviews the literature available on glass fiber reinforced polymer (GFRP) and its applications as outdoor structure or component. The current trends on the usage of GFRP have been reviewed and various properties of GFRP are presented and discussed. Durability and degradation of GFRP performance in certain application have shown that mechanical strength behaviour decreases when GFRP structure or component was exposed to outdoor environment. Hence, GFRP structure are capable of withstanding extreme environmental condition with modification of GFRP composition. The review literature show GFRP composite material are more resilient in terms of strength, corrosion resistance, sustain capability in harsh nature and long life serviceability with performing as a good insulator in lightning impulse strength. It is concluded that application of GFRP in various application has contribute to the development of significant properties of high performance GFRP and also application of GFRP as high durability crossarm in transmission tower with prolong lifespan.

Keywords: *glass fiber; polymer; durability; degradation; crossarm;*

I. INTRODUCTION

Composites are widely used in many industrial applications, including in transmission tower as its cross arm. GFRP has great several advantages as compared to the other traditional materials which its durability has potential to improve under aggressive environments.

There are many reasons why damage occurs on composite structures. The damage of the composite can roughly attributed to one or more different stages in their live. Another major catastrophic effect arises from environmental degradation, where the properties of the GFRP are highly affected by ageing of GFRP composite components or structures due to harsh climates and temperature gradients. From the abovementioned, it can be seen that composite GFRP materials used in crossarms have several benefits as compared to the traditional wooden and steel cross arms which it compromises

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in major effect of strength and corrosion resistance, which will contribute to prolonging the lifespan of the cross arm structure. Besides the major requirement for GFRP cross arms in transmission line assemblies, it should compromise into other structural design variations due to other auxiliary devices, wire attachments, and other excessive attachment loads in the structure assemblies.

II. Durability

A review of a durability study of a pultruded GFRP structure application is presented. Previous study has investigate the effects of environmental agents such as temperature, ultraviolet radiation, and moisture on the performance of composite materials in order to understand the behaviour of various failure modes and loading conditions [1–11]. The environmental circumstances such as moisture and heat contribute to major structural defects in GFRP composite during their exposure [12–14]. The previous research has found that the possibility of undeniably destructive conditions which are influenced by extremely harsh environments [15–17]. Therefore, the GFRP composite structures of cross arms in transmission line towers are certain to be exposed to ecological factors, and many related studies have indicated that mechanical properties in the structure will decrease due to the simultaneous activity of mechanical loadings and natural effects such as elevated temperature, humidity, and others, which act as vicious agents that contribute to the degradation of composite material structures [18, 19]. Moreover, the major degradation effect in GFRP applications in this review are a concern prior to structures and durability elements, which leads to increases in cost and the design processes.

III. Physical Defects in GFRP

Damage on GFRP was due to time, high stress and environment. There are several type of damage that may occur such as matrix crack, debonding, delamination, present of void, wrinkles, or structural damage. Therefore, in this review a brief of general GFRP structure defects will be discussed to be a scale for composite cross arms in future studies.

A. *Torsion*

Mainly, the structure of a GFRP subjected to torsion will show cracking if it is not designed with appropriate detail, which will cause catastrophe deterioration of the structure due to the defect in torsional resistance and change in loading [20,21]. Study of GFRP structural tube by Lee et al. [22] regarding failure mode mechanisms specified that multiaxial loading is more complex than uniaxial loading in failure mode behaviour. Meanwhile, study by Cardoso [23] indicated that the flexural-torsional strength and global buckling strength are associated with global member bending, and additionally for thin-walled members it showed that stresses are approximately uniform through the wall thickness. Therefore, the general behaviour of buckling modes governed by torsion also involves bending of walls, producing stress gradients through the thickness in other structural applications. Another study by Cardoso et al. [24] determined the strength of GFRP pultruded square tube columns under concentric compression, resulting in a range of combinations of global and sectional slenderness, and the experimental result showed a similar defect of torsional which has interaction between crushing and local and global buckling. A study by Ogasawara et al. [25] on the torsional behaviours of unidirectional GFRP revealed that the degradation of torsional rigidity of a rotor blade helicopter causes splitting crack propagation along the fiber direction under a constant tensile axial load. Therefore, previous studies described [26-28] on the typical defect behaviour of buckling and slandering characterized by torsion, it can be adequate that there is a distinct phase of failure mode prior to the tension motion and shear which is identified as pre-buckling, post-buckling, deflection, and other severe damage growth. Moreover, there is a similarity with plate-like behaviour in the study of Shifferaw and Schafer [29] of post-buckling reserves in the global buckling of cold-formed steel angle columns and the post-buckling performance observed in FRP where both behaviours or mechanisms have addressed the same result at the end of the failure characteristics.

B. *Delamination*

The causes and factors of delamination in composite FRP have been identified by previous studies and researchers [30,31] which showed on various factors such as the fiber arrangement, plies arrangement, and the type of loading causes could also occur in the matrix of the composite. Delamination in composite materials has a presence as inter laminar damage and delamination of layers the complexity to the analysis in various forms such as matrix cracking, fiber kinking, and fiber breakage, which imposes an extra layer as shown in Table 2. A study by Turon et al. [32] used a simulation of a damage model of delamination propagation under high-cycle fatigue loading in order to analyse delamination under fatigue loading. The cohesive zone model concept formulated is used for static or quasi-static loads and it is shown that by using the constitutive fatigue damage model in a structural analysis, the experimental results can be reproduced without the need for an additional model which specify in diverse parameters. GFRP structure delamination has also been studied by Li et al. [33] and it was found that the results of delamination deficiencies have effects on the ultimate loading capacity of the specimens, of which the influence of delamination deficiencies in the skin is the most serious compared with specimens without deficiencies.

C. *Degradation of GFRP*

The cyclic loading of a composite structure which is subjected to multiple loading is one of the degradation processes of composite materials which consist of the formation and progression of micro-cracks until failure [34]. A study by Ray [35] of hydrothermal ageing has shown an important effect of interface weakening and damage when composites access or induced by the weathering effect, which the outcomes have concise the environmentally induced damage in humid and thermal environments factors. As discussed above, extreme conditions of moisture and temperature parameters will decrease the mechanical properties which will lead to premature failure of composite structures mostly in cross arm applications [36,37]. Therefore, an essential safe limits parameter should be developed as a service conditions parameter for the manufacture of GFRP cross arms. Thus, all studies of safe limit parameters should consider the necessary assessment in quality manufacturing which prevalent with the appropriate service lifespan and durability of cross arm applications in Malaysia [35].

D. *Moisture*

The performance of GFRP in marine vessels, piping, and storage tanks and in structural applications in corrosive industries theoretically improves the durability under aggressive conditions [36,40,41].

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GFRP structure are prone to subcritical crack growth, and this phenomenon is often signified to as static fatigue particularly when loaded and exposed in a humid environment [42]. Moreover, a composite structure will accelerate the uptake of water when matrix cracking grows and will influence the time-under-load dependent properties such as creep and cyclic fatigue [37-39]. There are prominent relationships between the durability of GFRP composites applications and moisture, thermal effects, and UV radiation. The particular interest of the study of Bond and Smith [40] show that moisture induce localized damage in the composite as shown in Table I. Meanwhile, a study by Wang et al. [41] discussed the application of traditional diffusion theory to identify the mechanism of moisture absorption and the relationships among the microscopic structures which are affected by moisture absorption. Moreover, the combination of cracking and flaking inside a polymer structure when exposed to moisture and elevated temperatures has been discussed in the study by Kasturiarachchi and Pritchard [11]. The result of a moisture study by Bach [42] on the fatigue properties of the glass/polyester and glass/epoxy laminates are sometimes reduces even inconsistent in the very high cycle and low stress range. A study by Xin et al. [43] on the effect of ageing due to the combination of moisture and elevated temperature on a perforated GFRP composite indicated that the temperature gradient of the structure is the most influential factor in ageing, reducing the flexural stiffness and bending capacity of composite structures. Moreover, the failure force and maximum displacement were considered in buckling experiments by Eslami et al. [44] on GFRP specimens, where the specimens were exposed to a humid environment. Several studies of the interlaminar shear stress of a composite structure [12,16,44,22] due to moisture uptake at elevated temperatures or immersion in water will attribute to the adverse effect and will stimulate the initiation and spread of damage [12,43] also expresses another environmental effect of moisture degradation.

TABLE I

INDENTATION DATA AFTER EXPOSURE TO UV AND HUMIDITY

Specimen/Exposure time /temp.	***E*estimated**	**Coefficients of thermal expansion/moisture diffussion**	**Reference**
0	1.23 ± 0.47 Mpa		
1000 h	3.75 ± 1.32 Mpa		[10]
4000 h	2.32 ± 0.64 Mpa		
Pure Hoop Dry	(-1.3)-839.9		
Water 20°c	(-1.2)-706.7		
Water 50°c	(-1.1)-558.2		
2 Hoop: 1 axial Dry	232.6-480.5		
Water 20°c	237.2-490.0		

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Water 50◦c	149.1-308.1		[51]
3 Hoop: 1 axial Dry	207.4-620.6		
Water 20◦c	267.4-799.9		
Water 50◦c	153.4-459.3		
Pure axial Dry	7.6-71.2		
Water 20◦c	3.5-49.5		
Water 50◦c	3.5-49.5		
Outer web 20◦c, 50% RH		3.804×10^{-5} mm^2/s	[2]
40◦c, 96% RH		7.365×10^{-5} mm^2/s	
20◦c, water		9.278×10^{-5} mm^2/s	
40◦c, water		24.92×10^{-5} mm^2/s	
Flange 20◦c, 50% RH		4.425×10^{-5} mm^2/s	
40◦c, 96% RH		5.750×10^{-5} mm^2/s	
20◦c, water		8.847×10^{-5} mm^2/s	
40◦c, water		29.38×10^{-5} mm^2/s	

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D11-40◦c-Water		1.75×10^{-6} mm^2/s	[52]
D11-40◦c-Seawater		2.04×10^{-6} mm^2/s	
D11-60◦c-Water		2.35×10^{-6} mm^2/s	
D11-60◦c-Seawater		2.50×10^{-6} mm^2/s	
D11-80◦c-Water		3.69×10^{-6}	
D11-80◦c-Seawater		3.38×10^{-6}	
Epoxy/GFRP		6.56×10^{-6}/◦c	[33]
40% fiber loading		1.67/s$^{0.5x10-4}$	[42]
50% fiber loading		2.45/ s$^{0.5x10-4}$	
55% fiber loading		2.11/ s$^{0.5x10-4}$	
60% fiber loading		2.18/ s$^{0.5x10-4}$	
65% fiber loading		3.84/ s$^{0.5x10-4}$	

E. *Ultraviolet radiation (UV)*

GFRP have great potential in the high-performance application industry but have also been highlighted in many major constructions for transmission and distribution line towers as crossarms, as they present several advantages compared with traditional materials, including potentially improved durability in aggressive environments [47]. A study by Rodrigues et al. [48] investigated the combined effects of humidity and ultraviolet radiation on the mechanical properties and found an instantaneous decrease in the mechanical properties, essentially due to increased diffusion kinetics caused by the temperature escalation. Meanwhile, Chin et al. [49], in a study of polymer composites, indicated that the polymer matrix is prone to degradation under UV radiation, moisture, temperature, and high pH environments. Furthermore, from the outcome of an experiment, Chin et al. found that polymer composites in outdoor applications are prone to photo-initiated oxidization leading to surface degradation.

TABLE III
DEGRADATION AND SHEAR OF GFRP

Specimen/Exposure time /temp.	Degradation depth	In-plane shear	Interlaminar shear	Reference
0	81.98 $\pm$ 8.60 nm			[9]
1000 h	51.97 $\pm$ 6.89 nm			

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4000 h	55.71 ± 5.16 nm			
-		53.7 ± 0.5 MPa	34.7 ± 4.5 MPa	[50]

F. *Thermal degradation*

In many applications of fibrous composite structures and components have owing to various desirable properties including high specific stiffness, high specific strength, and controlled anisotropy [55-56] and at the same time the fibrous composite structures are prone to heat and moisture when operating in changing environmental conditions. The temperature distinctions are among the most important ecological factors that may affect the durability of interfacial internal stresses of composite laminate in composite structures and eventually lead to micro cracks at the interfaces or even premature debonding failure. Moreover, the polymer matrix in a GFRP has the function of binding and orienting reinforcing fibers to carry intended loads, protects them from handling and the environment, and provides all of the inter laminar shear strength of the composite have also prone to elevated temperature and other environmental susceptibilities. Thus, investigation by Chin et al. [49], has shown that the mechanism GFRP under thermal exposure and loading condition will not permit improvement of the structural material's performance but will aid the design of acceptable accelerated ageing and allow forecasting of the predicted service life of the structure.

IV. CONCLUSION

This paper reviewed the existing literature on the application of GFRP in various industry. The conclusion is as below:

1. GFRP composite structures of cross arms in transmission line towers are certain to be exposed to ecological factors, and many related studies have indicated that mechanical properties in the structure will decrease due to the simultaneous activity of mechanical loadings and natural effects such as elevated temperature and humidity.
2. Dynamic analysis response of nature action in GFRP structure are always advantages in lightweight and slender structures however environment condition also may affect the life span of the GFRP structure other than creep due to the structure and load uptake.

Acknowledgment

The authors acknowledge Universiti Tenaga Nasional and Tenaga Nasional Berhad for the lab facilities and financial support (Tenaga Nasional Berhad Seeding Fund: U-TS-RD-19-03)-. Special thanks to those who contributed to this project directly or indirectly.

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