Construction and Building Materials 127 (2016) 237–247

Contents lists available at ScienceDirect

Construction and Building Materials

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

Hygrothermal aging effects on flexural behavior of pultruded glass fiber reinforced polymer laminates in bridge applications

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HIGHLIGHTS

- Flexural tests of pultruded GFRP laminates exposed to six different hygrothermal aging environments were conducted.
- The long-term hygrothermal aging effects on flexural properties accounting for temperature variation during exposure were predicted by combining Phillips equation and Arrhenius relationship.
- Predicted results were compared with design values prescribed by ACI-440, TR-55 and GB50608 design guidelines.

ARTICLE INFO

Article history:
Received 10 June 2016
Received in revised form 24 August 2016
Accepted 28 September 2016

Keywords:
Hygrothermal aging effects
Glass fiber reinforced polymer (GFRP)
Pultrusion
Long-term prediction
Highway bridges

ABSTRACT

It is significant for designers to consider not only short-term characteristics but also the long-term properties of composite materials that are commonly used in highway bridge applications. In this study, flexural tests were performed on composite specimens that were exposed to both fresh water and artificial seawater environments at 40 °C, 60 °C and 80 °C temperatures. The purpose of conducting these tests is to (1) investigate the hygrothermal aging effects on flexural properties of pultruded fiber reinforced polymer (PFRP) composites, and (2) to establish relationship between flexural strength and flexural modulus and hygrothermal aging time. Based on the results of this study, it was found that: (i) the degradation in both average flexural strength and modulus increases at higher temperatures; (ii) the degradation in transverse flexural strength and modulus is relatively higher as compared to those observed for longitudinal flexural strength and modulus; and (iii) the reduction in average flexural strength and modulus for specimens exposed to fresh water and artificial seawater environments is relatively small. The long-term hygrothermal aging effects on flexural properties of PFRP laminates, including temperature variation during exposure, were predicted using both Phillips equation and Arrhenius relationship. The predicted flexural strength, flexural modulus and coefficient "*A*" agreed well with experimental results. The hygrothermal aging effects on flexural properties, at room temperature (23 °C) after 100.0 years, were predicted and compared with design values prescribed by ACI-440, TR-55 and GB50608 design guidelines provisions. Results of this study confirmed the reliability of design values recommended by ACI-440 design guidelines that were found to be similar to experimental results, while design values produced by following procedures recommended by both TR-55 and GB 50608 documents are about 1.75–2.25 times larger than the predicted values.

1. Introduction

Due to its high strength, light-weight and superior corrosion resistance features, fiber reinforced polymer (FRP) composites have been widely used in different civil engineering applications. One of the successful and popular applications of composites is in the area of repair and rehabilitation of existing structures, as well as for new constructed facilities [1–3]. Pultrusion manufacturing process is considered as the most common methods for producing FRP composites for new civil engineering structures that includes bridge deck among other applications. In terms of cost factor, pultruded glass fiber reinforced polymer (GFRP) composites could meet the established design criteria with reasonable cost and were always recommended in newly constructed bridge and bridge decks [4–8].

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http://dx.doi.org/10.1016/j.conbuildmat.2016.09.151
0950-0618/© 2016 Published by Elsevier Ltd.

Nomenclature

σ_f	flexural strength
P	load applied at the middle of the beam for the three-point bending
h	thickness of laminate specimen
ΔP	load increment in the linear stage of load-displacement relationship
$f(x)$	probability density function
x	random variable
β	scale parameter
Γ	gamma function
t	time of hygrothermal aging
A, B	empirical constants in Phillips model, B is assumed to be 1.0 in this paper
T	absolute temperature (in K)
G	non-thermal constant in Arrhenius relationship
f_u	mean ultimate strength
f_{cu}	experimental ultimate strength with guarantee probability
C_E, γ_f, γ_m, γ_e	partial safety factors in corresponding specifications
E_f	flexural modulus
l	support span (distance between support)
b	width of laminate specimen
ΔS	displacement increment corresponding to the load increment ΔP
$F(x)$	cumulative distribution function
α	shape parameter
COV	coefficient of variation
μ	average value
P(t)	strength or modulus retention at time t
E_a	activation energy
$k(T)$	rate of the reaction at temperature T
R	universal gas constant (=8.3143 J K^{-1} mol^{-1})
f_d	design values
Σ	standard deviation of the test population

Naturally, bridge and other civil engineering structures are constantly exposed to harsh and changing environments such as moisture, salt-spray agents, freeze-thaw cycles, and large variation in both temperature and humidity. Due to such continuous exposure to harsh environments, degradation in both mechanical and physical properties of PFRP composite members is expected. Degradation caused by moisture diffusion may affect service-life of composite bridge components. For bridge applications, it is significant for designers to consider not only short-term characteristics, but also the long-term properties of composite materials that are commonly used in highway bridge applications. Hence, it is essential to understand the durability of composite materials to ensure reliability of such structures and to avoid premature failure that was witnessed for pultruded composites in harsh environments [9,10].

In the past few decades, several studies were conducted on the aging performance of composites. Liao et al. [11] tested the material behavior of PFRP before and after aging in water or salt solutions at 25 °C and 75 °C. The test results indicated that (1) both strength and modulus decreased with environmental aging, (2) environmental aging decreased the in situ fiber strength, and (3) the degradation of fiber/matrix interphase region occurred during aging. Fatigue behavior of PFRP materials was also evaluated by Liao et al. [12]. In this study, PFRP samples were subjected to four-point-bending fatigue in various environments such as water and salt solutions containing mass fractions of either 5% NaCl or 10% NaCl for up to 6570 h (nine months). Experimental results indicated that PFRP fatigue behavior was degraded significantly when aged in water at 75 °C for 2400 h prior to cyclic test at load levels above 30% of the dry flexural strength. Correia et al. [13] conducted an experimental investigation to assess the durability of glass/polyester PFRP profile for construction applications. In their study, accelerated aging of pultruded profiles was accomplished by exposing composites to different environments including moisture, temperature, and ultraviolet (UV) radiation. Results indicated that considerable chromatic changes were observed, especially when profiles were subjected UV radiation. Micelli and Nanni [14] investigated the physico-mechanical properties of five types FRP rods that were aged in alkaline simulated concrete pore solution and environmental agents. Experimental results showed that resin properties had a major effect on the durability of FRP reinforcement and that carbon reinforced fiber reinforced polymer (CFRP) rods that were not protected adequately by resins were sensitive to alkaline attack. Jiang et al. [15] investigated the moisture absorption process in the pultruded FRP composites under four aging environment. The experimental data indicated that high temperatures could speed up the moisture diffusion rate and moisture equilibrium contents. The experimental data were also fitted to one-dimensional moisture analytical model and related moisture diffusion coefficients could provide reference to numerical modeling. Abanilla et al. [16] investigated the aging properties of CFRP exposed to deionized water, salt and alkali water, freeze-thaw and accelerated aqueous environments for over 100 weeks. Their experimental results indicated significant strength degradation due to fiber/matrix interface deterioration, however, a relatively less stiffness degradation was observed. Karbhari and Abanilla [17] used two predictive models to estimate the long term deterioration of CFRP for a range of material characteristics, outlined a methodology that is capable of accounting for temperature variation during exposure and emphasized some weakness in current methodologies. Sun et al. [18] investigated the hygrothermal aging inter-laminar shear behaviors of carbon fiber/bismaleimide composite materials, indicating that inter-laminar shear strength reduction could come to a plateau during the first 14 days and the Arrhenius method confirmed that routes for water uptake were also instrumental in speeding up the drying. Al-Assafi and Mosallam [19] performed a study to assess the impact of aqueous environments on performance of pultruded composites. In their study, both polyester and vinylester pultruded composites were aged in distilled water and salt-water environments. The pultruded composites were tested to determine short beam shear strength (SBSS) prior and subsequent to aging. The results of the study indicated that a higher drop in glass transition temperature (T_g) occurred for polyester-based pultruded specimens subsequent to aging with lower levels of SBSS. However, re-dried E-glass/vinylester pultruded specimens exhibited full SBSS recovery. Dutta et al. [20] conducted a study on the response of PFRP composite joints subjected to hygrothermal environments. In the study several pultruded joints specimens, bolted, bonded and combined, were exposed to high temperatures up to 50 °C and low temperatures down to −30 °C under both moisture-saturated and dry conditions. Results of the study indicated that exposure to high temperature degraded the bond strength for both bonded and combined pultruded joints. Results also concluded that the adhesively bonding had the highest strength degradation when exposed to high temperature. Chapters 2, 5 and 7 of the