Construction and Building Materials 48 (2013) 360–370

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Review

Independent environmental effects on durability of fiber-reinforced polymer wraps in civil applications: A review

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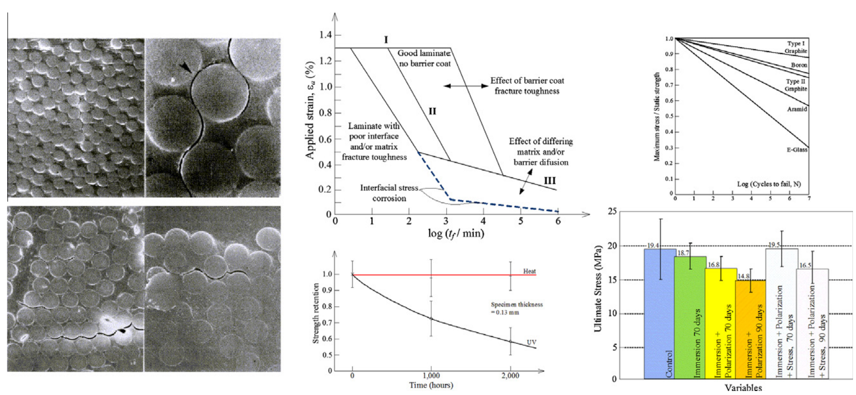
HIGHLIGHTS

- The long-term durability of FRP is comprehensively documented.
- The review article summarizes much of the currently published research on the durability of FRP composites.
- The review article discusses independent environmental factors.
- The review provides a body of knowledge that can be used to generate practical inspection and maintenance guidelines.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 March 2013
Received in revised form 28 May 2013
Accepted 17 June 2013

Keywords:
Durability
Fiber-reinforced polymer
Inspection
Maintenance
Environmental conditions

ABSTRACT

Fiber-reinforced polymers (FRP) are becoming a common method for repair and rehabilitation of civil engineering structures. FRP wraps are common because they are applied to the outer surface of the structure and therefore are easy to apply and cause little disturbance during the repair. FRP may prove to be inexpensive and durable. However the long-term durability of FRP is not comprehensively documented. This article reviews much of the currently published research on the durability of FRP composites, and discusses independent environmental factors.

Contents

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0950-0618/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.conbuildmat.2013.06.077

1. Introduction

Fiber-reinforced polymers (FRP) are being increasingly used in civil engineering applications such as concrete confinement, shear reinforcement, and flexural reinforcement in the form of wraps around beams and columns. FRPs have been successfully used in other areas such as the aerospace industry, but their use for civil engineering purposes is relatively new. Interest in FRP applications is increasing mainly because FRP wraps may prove to be a cheaper and more durable repair tool. However, little durability data is available, and there is no comprehensive durability document.

Civil rehabilitation is a relatively recent application of FRPs. Because of this, there is yet no comprehensive guide for the inspection and maintenance of FRP wraps. However, several authors from around the United States and throughout the international community have identified certain conditions that may prove damaging to installed wraps. These include moisture, alkalinity, thermal effects, creep, fatigue, ultraviolet radiation, and fire [7].

This study attempts to summarize much of the currently published research on the durability of fiber reinforced polymer composites (FRP). Laboratory data may not fully represent the complicated conditions of installed FRP in the field, but it is currently one of our best options for understanding the deterioration processes initiated by various environmental conditions. Each subsection of the following section discusses a different environmental factor.

2. Threats to fiber-reinforced polymers

2.1. Moisture

Moisture attacks composites at every level. The fibers, matrix, fiber–matrix interface (see Fig. 1), and adhesive are all susceptible to deterioration. Fluids can increase creep and relaxation, introduce residual stresses, cause osmotic pressure, and degrade polymers, fibers, and fiber/matrix interfaces via hydrolysis and chemical attack. Moisture accelerates fatigue degradation of composites, and shortens their fatigue life. Additionally, fatigue damage offers new paths for moisture ingress and significantly increasing the rate of moisture-related damage. However, the effect of fluids also contains some contradictory aspects. For example, fluids result in improved impact resistance. It may be a result of the impacting object being resisted by a larger volume of fibers, but over time, impact damage may allow more routes for moisture to penetrate the composite, and, thus, decrease the properties of the composite over time [43].

Moisture damage begins near the surface of the material and spreads inward over time, with cracks tending to grow parallel to the free surface. This damage is often localized, resulting in a small number of large cracks [42]. Crack growth is dominated by different effects at different levels of loading. At lower load levels, cracking is most influenced by chemical reactions. At moderate load levels, cracking is most influenced by diffusion. At higher load levels, stress-assisted corrosion controls crack growth [43]. The rate of degradation of FRPs has been observed to be directly correlated with the rate of moisture sorption [31]. Moisture is attracted to areas of air entrainment such as voids and delaminations. Thus, these areas can collect water over time [26]. Cracks and voids, even microscopic ones, allow easier penetration of water into the composite system via capillary action and diffusion [23]. Because of this, generous application of resin can potentially render moisture-related effects insignificant [2]. After an initial period of seeking out and filling cracks and voids, moisture begins to swell the composite. One study observed a linear relationship between strain and water uptake from the beginning of swelling on [45]. It is worth noting that water has been shown to diffuse more slowly through epoxy composites than polyester composites [38].

The moisture history of the material is important. Both maximum load at failure and fracture toughness have been observed to decrease linearly as time exposed to moisture increases [38]. A higher average moisture content over the life of the material will result in a higher level of damage, and desorption appears to be more destructive than absorption [42]. Additionally, wet-dry cycling has been observed to decrease the ultimate load of various FRP composites. Typically, glass fiber reinforced polymer (GFRP) composites suffer significantly more than carbon fiber reinforced polymer (CFRP) composites [5]. Repeated absorption and desorption seems to increase the ability of a composite to absorb moisture. However, the maximum water content does not appear to change. Rather, the composite simply absorbs moisture more quickly [34].

The thermal history is important, too. Rapidly increasing the temperature of the composite and then reintroducing the composite to moisture will increase the absorption of the composite [22,38]. However, the effect of hygrothermal aging on CFRP composites has been observed to be insignificant, and more related to thermal effects than moisture-related effects [4].

External stress has also been shown to affect the moisture effects on composites. The equilibrium weight gain of stressed composites is larger than that of unstressed composites, and increases as the angle between the loading and the fiber direction is increased. Diffusion coefficients are also significantly larger for stressed composites than for unstressed composites. However, diffusion coefficients are independent of loading angle. A composite under external stress will absorb more water more quickly than an unstressed composite. The rate of absorption, maximum moisture content, and coefficients of diffusion all increase with the application of external stress. Additionally, as the angle between the loading and the fiber direction increases, the rate of absorption and maximum moisture content increase [34].