MULTISCIA
JOURNALS PUBLISHERS

FRONTIERS IN CIVIL ENGINEERING AND CONSTRUCTION MATERIALS

ISSN: (3065- 4181)

editor.fcecm@gmail.com

https://multisciajournals.com/journals/index.php/fcecm

Frontiers in Civil Engineering and Construction Materials
Volume 2 Issue 2 2026

Durability Gap Analysis for Fiber-Reinforced Polymer Composites in Civil Infrastructure

B. Benmokrane; R. Morganrotey
Department of Civil

Article Info

***Received:* 27-01-2026 *Revised:*22-03-2026 *Accepted:*09-04-2026 *Published:*12-04-2026**

Abstract:

A major obstacle to the broad use of fiber-reinforced polymer (FRP) composites in civil infrastructure applications is the absence of a complete, verified, and easily accessible database regarding the materials' durability. This is of particular importance since the buildings under consideration are mostly load bearing and will likely be in use for long periods of time without major maintenance or inspection. This document summarizes the findings of a gap analysis research that was conducted by the Federal Highway Administration and the Civil Engineering Research Foundation to determine which gaps in durability data were the most important and to rank them in order of importance. The use of fiber-reinforced plastic (FRP) in seismic retrofitting, internal and exterior strengthening, structural profiles, panels, and bridge decks is the primary emphasis of the research. Environments of interest are moisture/solution, alkalinity, creep/relaxation, fatigue, fire, thermal effects (including freeze-thaw), and ultraviolet exposure.

Introduction

From reinforcing rods and tendons to wraps for seismic retrofitting columns and externally bonded reinforcement for walls, beams, and slabs, as well as all-composite bridge decks and hybrid structural systems (FRP composite with conventional materials) are just a few examples of the many civil infrastructure applications of fiber-reinforced polymer (FRP) composites. Anecdotal evidence provides substantial reason to believe that, if appropriately designed and fabricated, FRP composite materials can provide longer lifetimes and lower maintenance than equivalent structures fabricated from conventional materials. However, actual data on durability is sparse, not well documented, and/or not easily accessible to the civil engineer. In addition, there is a wealth of contradictory data published in a variety of venues that confuses the practicing engineer.

The lack of a comprehensive database on FRP materials makes it difficult for the practicing civil engineer and designer to use FRP composites on a routine basis. Despite the many recent reviews on the topic of durability and testing methods (Schutte 1994; Bank et al. 1995; Chin 1996; Liao et al. 1998), none of them have attempted to prioritize or highlight the most pressing areas where data collection, assimilation, and dissemination are most urgently needed. Instead, they have all focused on summarizing the current state of knowledge. This paper summarizes the results of such an effort in detailing critical gaps in knowledge vis-a`-vis the durability of FRP composites to be used in civil infrastructure applications.

Scope and Background of Study

The most immediately relevant applications and markets for FRP composites in the near future were determined through a series of workshops organized by the Civil Engineering Research Foundation (CERF) and the Market Development Alliance (MDA). The workshops brought together professionals from the user, owner, construction, design, materials, and manufacturing sectors. The topics covered included reinforcing bars (rebar), external reinforcement for concrete structures, seismic retrofitting of columns, piers, and masonry walls; bridge decks and systems; and wall panels and structural profiles. For the purposes of determining the long-term viability of FRP composites in the mentioned contexts, seven distinct environmental factors were determined to be crucial: moisture/solution, alkali, thermal (including temperature cycling and freeze-thaw), creep and relaxation, fatigue, ultraviolet light, and fire. "Synergistic effects" are those that arise when several environmental factors are combined.

MoistureÕSolution Effects

Every organic polymer undergoes thermophysical, mechanical, and chemical changes when exposed to moisture by diffusion. The resin itself undergoes hydrolysis, plasticization, saponification, and other processes that alter the polymer structure in both reversible and irreversible ways as a result of absorption. It has been shown that moisture may wick along the fiber-matrix interphase, damaging the fiber-matrix connection and leading to a breakdown at that level. It has also been shown that chemicals and moisture may lead to fiber-level deterioration in aramid and glass fibers. Degradation of glass fibers begins with the introduction of ions that remove water from the fiber, which changes its structural composition. Due to their ability to absorb moisture, aramid fibers may increase fibrilation under certain situations. Salt solutions, for example, for further information and findings, see the following publications: Marom and Broutman (1981), Apicella et al. (1983), Pritchard and Speake (1987), Weitsman (1998, 1991), Zheng and Morgan (1993), Schutte (1994), Sonawala and Spon- tak (1996), Karbhari and Zhang (2003), and Pritchard (1999).

While it's true that a material's durability is directly related to its composition, and that there are many different systems out there, not all of them have the same amount of historical data available (even though newer systems might actually be more resistant to degradation), Table 2 shows how data is perceived to be available depending on the material system being considered. Different effects are shown in this table for three types of specimens: those that are unloaded (U), those that are sustained (L), and those that are sustained (U) at levels below 25% of ultimate. Table 3 provides a summary of the findings according to the availability and significance of the data.

While our understanding is still limited, we may highlight the following broad points based on what is known thus far:
• For FRP composites to be used in this environment, the resin layer must be thick and remain uncracked for the duration of the product's intended use; otherwise, water and chemical solutions could quickly seep into the bulk material and attach themselves to the fibers. Understanding the cure kinetics of the resin and FRP composite is important, as is ensuring that materials are properly cured before being used in the field, since undercure may increase the resins' moisture sensitivity.

Alkali Effects

Although FRP composites can come in contact with alkaline media through interaction with a variety of sources, including alkaline chemicals, soil (or solutions diffusing through soil), and concrete, the main concern at the present time stems from the potential effects of degradation due to concrete pore water solu- tion, which is known to have a hydrogen ion concentration level as high as 13.5. A large body of research exists on the degradation of bare glass fibers in contact with (or in) alkaline solutions, es- pecially those derived from concrete, and there is no doubt that bare glass fibers in this environment are severely degraded due to a combination of mechanisms ranging from pitting, hydroxyla- tion, hydrolysis, and leaching. Although the presence of resins in FRP composites around individual filaments can be expected to protect the fibers from such attack, the alkaline solutions can ac- celerate the degradation of bond and of some resins themselves, especially if not fully cured. A good summary of mechanisms and effects can be found in Sen et al. (1993), Bank et al. (1995),

Katsuki and Uomoto (1995), GangaRao and Vijay (1997), Porter and Barnes (1998), Chin et al. (1999, 2001), and Zhang and Kar- bhari (1999).

The results of the gap analysis based on the synthesis of data pertaining to the importance of data, and its availability in easily accessible, validated form, are presented in Table 4. Based on the current state of knowledge, albeit incomplete, the following over- all aspects are highlighted:

- The use of mechanistic, and/or reliability based tools inte- grated with a risk-assessment methodology needs to be devel- oped for life-prediction,
- Since the polymeric resin plays a critical role in protecting the fiber and slowing the diffusion process, preference should be given to the use of appropriate epoxies and vinylesters. The use of polyester resins is not recommended,
- In order to decrease the possibility of rapid movement of moisture and alkaline salts into the bulk composite, and to- wards the fiber surface, it is critical that an appropriate thick- ness of resin rich surface exist in FRP composites used in this environment, with the resin layer remaining uncracked through the period of intended use,
- Acknowledging the role of undercure on increase in moisture susceptibility of resins, it is recommended that the resin and FRP composite be fully cured prior to use in the field, and
- Taking into account effects of degradation and damage toler- ance, the stress level in the FRP reinforcement should be lim- ited under sustained factored loads to less than 30% of guar- anteed design strength for GFRP and AFRP, and 40% of guaranteed design strength for CFRP.

Thermal Effects

In this part, we look at thermal effects, which include changes in reaction as a result of situations like freezing and thawing, as well as fluctuations and cycles in temperature. First things first: heat exposure isn't always bad; in fact, there are many of examples when it helps FRP components postcure, which is a huge boon. Resins and adhesives are known to soften at different temperatures, which makes them more viscoelastic, reduces their elastic mechanical performance, and makes them more likely to absorb moisture. In general, previous studies, tests on materials, and anecdotal evidence have shown that: • Matrix microcracking, fiber-matrix bond deterioration, and matrix hardening may occur when exposed to temperatures below freezing.
• Rapid deterioration may occur during freeze-thaw cycles when salt is present because to the creation and growth of salt deposits, as well as the effects of swelling and drying caused by moisture.
• Deterioration owing to thermal effects may follow an initial postcure when exposed to temperatures higher than processing temperatures,

and • Due to heat gradients and exposure, the FRP composite-adhesive-concrete interfaces might experience premature debonding, as adhesives' coefficients of thermal expansion can be orders of magnitude different than bulk resins' and composites'. Lord and Dutta (1988), Dutta (1988), Gomez and Casto (1996), Karbhari and Engineer (1996), Green et al. (2000), and Miyano et al. (1999) all provide results of testing and assessments of applications that are connected to infrastructure. In Table 5, you can see the outcomes of the gap analysis for both settings with high temperatures and conditions with freeze cycles. Important points to highlight are: • Freeze-thaw cycles pose the biggest threat to composite structures used in civil engineering because they may cause laminates to debond, • If the adhesive or laminating resin softens too much, it can also fail. For field application, it is essential to adhere strictly to the upper usage temperature, also known as the Material Operational Limit, of a certain laminating resin. This temperature is defined as the point at which the flexural strength drops to half of its room temperature value. • The glass transition temperatures (Tg) of materials should be at least 30 degrees higher than the highest projected usage temperature when designing with FRP composites, and these materials should not be subjected to temperatures higher than their Tg. • Additional research into the alterations in the reaction of materials and structural systems should take into account the synergistic impacts of moisture/solution and heat effects; and • It is important to think about the long-term consequences of variations in the elastic properties and coefficients of thermal expansion of the bonded materials. Both the in-process and post-process consequences of the presence of substantial heat sinks, such concrete, must be evaluated.

CreepÕRelaxation

It has been well established that aramid and glass fibers have a higher level of susceptibility to creep rupture at lower stress lev- els than carbon fibers, with carbon fibers exhibiting little to no chemical-induced strength degradation, but having a larger spread in median failure times under stress rupture conditions as shown in Table 6 (Chiao and Moore 1971; Chiao et al. 1972; Moore et al. 1974). Qualifications for this data are that aramid and glass fibers (Bentur et al. 1985) are very susceptible to alkali-induced, chemical-induced

In most cases, at the level of a structure or component, creep and stress relaxation can be guarded against or reduced signifi- cantly by taking advantage of the fact that creep and stress relax- ation response is likely to be resin dominated for most practical civil infrastructure applications. Thus appropriate selection and processing of resins, and the designed placement of fibers can solve a large part of the challenge. Readers are referred to the excellent reviews by Liao et al. (1998) and Scott et al. (1995) for further explanations. The results of the gap analysis are shown in Table 7. Based on the current state of knowledge at the materials and structural levels the following aspects are highlighted:

- Significant testing and characterization needs to be conducted for material systems cured under ambient conditions taking into account the synergistic effects of moisture, stress levels, and temperature,
- Effects of shearing deformations which are often erroneously neglected need to be accounted for in the prediction of time- dependent behavior, and
- The use of standardized materials forms as in metals is highly recommended.

Fatigue

Fatigue, which is generally defined as the physical phenomenon that causes a material or component to fail after the application of an applied condition or conditions (cycles) even though the level of that condition is not high enough to cause failure on the first cycle of application, is an important consideration for the dura- bility and safety of civil infrastructure. The loading may be me- chanical (due to vehicle traffic, for example), thermal (from varia- tions in temperature), or chemical (from seasonal road treatments, oxidation, NOX effects, water, etc.). Significant research is needed to develop a comprehensive understanding of the pro- cesses and mechanisms associated with fatigue failure in civil infrastructure components fabricated of FRP composites. Good reviews of the phenomena are given by Mandell (1982), Liao et al. (1998), and Konur and Matthews (1989), with the effect of environment; constituent materials and processes of fabrication being elucidated in Mandell et al. (1985), Branco et al. (1995), and McBagonluri et al. (2000). The results of the gap analysis are shown in Table 8 for various environmental conditions.

Data are currently available for a limited set of ‘‘fatigue’’ con- ditions, most notably constant amplitude fatigue at frequencies ranging from 1 to 10 Hz. Based on the work of Mandell (1982) and McBagonluri et al. (2000), the slope of the *S-N* curve for most planar glass/polymer composites can be expected to range from 10–12% ultimate tensile strength (UTS)/decade of life. There are existing life prediction methodologies such as devel- oped by Reifsnider (1991) that can be used to combine processes,

Ultraviolet „UV… Radiation

Radiation from the sun's UV rays reaches Earth's surface, exposing FRP to the elements. Be advised that although polymeric protective coatings may shield FRP surfaces from direct sunlight, they do not eliminate the possibility of UV-induced damage; rather, they act as a "self-sacrificing" layer. It is necessary to maintain the protective coating since it will eventually disintegrate due to UV exposure. Since UV damage is mostly surface-level, the most harmful consequences of UV exposure are likely not caused by it. cC: Effects at the substrate level.

Fire

A significant concern in any application of organic matrix-based composites is the possibility that an accidental (or deliberate) fire may ignite the composite material. This may result in the spread of flame on the composite surface, and may also release heat and generate potentially toxic smoke. The fibers displace polymer resin, making less fuel available to the fire. When the outermost layers of a composite lose their resin due to heat-induced gasifi- cation, they act as an insulating layer, slowing heat penetration and evolution of gases from the depth of the composite. It was recognized that fire-related issues associated with composite ma- terials are more severe in confined spaces (such as tunnels and buildings) as opposed to open spaces (such as roads and bridges). As such, the gap analysis was conducted on two bases: (1) fires in open spaces and (2) fires in confined spaces. The effect of fire is initially exhibited by the heating up of the composite surface. Over the depth of composite material heated up to temperatures past the glass transition temperature, the composite exhibits a corresponding loss of modulus. Below the temperature of chemi- cal degradation, this loss in modulus is reversible. Further in- crease in temperature, such as above 450°F for glass/vinylester, results in the degradation of the chemical structure of the resin. This thermal damage results in irreversible loss in load bearing characteristics. The overall ranking of gaps for fire effects is given in Table 10. A representative set of data, as an overview, can be gleaned from Sorathia et al. (1997), Sorathia et al. (1993), Milke and Vizzini (1993), Ohlemiller and Cleary (1999), Scud- amore (1994), Dao and Asaro (1999), and Ohlemiller and Shields (1999).

Summary and Recommendations

Based on the gap analysis conducted for each of the selected environmental conditions, it appears that there is a substantial commonality of needs, which provides for the selection of a set of data/research requirements that is critical to the generic imple- mentation of FRP composites in civil infrastructure. These needs, in no particular order of priority (since it is difficult to transition or compare the level of need within one category of environment to that in another), are as follows:

- Collection, assessment, and appropriate documentation of available data in a form useable by the civil engineer/designer,
- Testing over extended (18+ months) time periods. Tests con- ducted over short time periods (less than 18 months) can yield misleading results due to effects of postcure and slow inter- phase and fiber level degradation, and can provide an errone- ous level of comfort in some cases,
- Testing under combined conditions (stress, moisture, solution, temperature, and/or other regimes) at both the materials and structural levels is critical,
- Assessment and characterization of the effects of incomplete cure and undercure, especially for ambient temperature cure systems, are essential,
- Development of standardized solutions and conditions for laboratory studies that closely simulate actual field conditions, and
- Development of appropriate resin systems, gel coats, and coat- ings that would serve as protective layers for the bulk compos- ite against external influences including environmental condi- tions, intended, and accidental damage.

Based on the results of the gap analysis conducted through the present study, and on the overall results of the investigation (through review of literature, discussions with experts in the area of durability, results of discussions of the user and supplier pan- els, and subsequent discussions with members of the FRP com- posites and civil engineering industries) a three-pronged approach is recommended for future activities in continuation of this study as described in the following.

Integrated Knowledge System

Acknowledging the current difficulty in accessing data, and the possible loss of valuable data generated in the past through iso- lated studies, it is recommended that an integrated knowledge system be established at the earliest possible opportunity. This knowledge system would serve as a repository for data on dura- bility that would be pertinent to civil engineering applications and in a form that is of use and easy to access by civil engineers, contractors, and designers. The knowledge system would contain a number of sets of data sets, which could either be used as single sets of reference, or in an integrated manner to aid design.

Establishment of Methodology

The current gap-analysis exercise has provided a list of data needs related to specific application areas and environmental conditions. It is hoped that the results of this study will spur efforts to fill in areas identified as being high priority based on the importance and current availability of data. In order to ensure that efforts aimed at filling in gaps are not conducted in isolation and that appropriate protocols are used, it is recommended that appropriate protocols be established for testing, data collection, and valida- tion. These protocols would provide a basis for generation and collection of future data cognizant with the eventual requirements of a structural design methodology.

Implementation of Plans for Field Assessment

It is well established that durability data generated through labo- ratory experiments can differ substantially from field data. The determination of actual durability under field conditions over ex- tended periods of time is essential for the optimal design of FRP composites for use in civil infrastructure. It is thus critical that steps be taken to collect, on an ongoing basis, data from field implementations. This data is invaluable to the establishment of appropriate durability based design factors, and the opportunity of having

References

This was published in 1983 by Apicella, Migliaresi, Nicolais, and Roccotelli. The impact of resin chemical structure on the water aging of unsaturated polyester-based composites is discussed in Composites, volume 14, issue 4, pages 387-902.

This work was published in 1995 by Bank, Barkatt, and Gentry. "Determining the long-term behavior of FRP composite structures: Environmental effects: Accelerated test techniques." J. Reinf. Plast. Compos., 14(6), 559-587.

Schneider, D. J., Bentur, A., and Ben-Bassat, M. (1985). "The Alkali-Resistant Glass Fibers Used in Reinforced Cement: A Study on Their Durability," Journal of the American Chemical Society, 68(4), 203-208.

In 1998, Bradley, W. L., Puckett, S. W., and Sue, H. J. published a paper. "Thermoset viscoelasticity and E-glass reinforcement properties in pristine thermosets." The article is published in the Journal of Composing and Technological Research and has section numbers 51–60.

In 1995, Branco, Ferreira, Fael, and Richardson published a paper. "Examining the fatigue characteristics of pultruded phenolic composites and glass fiber reinforced plastic hand lay-ups," International Journal of Fatigue, 18(4), 255-263 (2008).

Moore, R. L., T. T. Chiao, J. K. Lepper, and N. W. Hetherington published their work in 1972. The stress-rupture behavior of basic S-glass/epoxy composites was published in the Journal of Composite Materials in the volume 6, pages 358–370.

In 1971, Chiao and Moore published a paper. "The stress-rupture of S-glass/epoxy multifilament strands," Journal of Composite Materials, 5(2), 7-11.

Author: Chin, J. W. "Infrastructure fiber-reinforced polymer composites: materials aspects." The National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, developed Rep. NIST-IR-5888.

In 2001, Chin, Aouadi, Haight, Hughes, and Nguyen published a paper. Composite matrix resins used in civil engineering: effects of water saturated solution and simulated concrete pore solution on their characteristics. Polym. Compos., 22(2), 282-297.

Aouadi, K., J. W. Chin, and T. Nguyen (1997). "Analyzing the impact of environmental factors on fiber reinforced plastic (FRP) building materials." Music Technology Research, 19(4), 205-213.

Published in 1999 by Chin, J. W., Nguyen, T., and Aouadi, K. "Diffusion and absorption of chlorophyll, saltwater, and concrete pore solution in composite materials." Journal of Applied Polymer Science, 71, 483–492.

Foundation for Research in Civil Engineering (CERF). (2001). New York: American Society of Civil Engineers, Gap analysis for the endurance of fiber reinforced polymer composites in civil infrastructure.

R. J. Asaro and M. Dao (1999). "Fiber composite failure prediction and design criteria subjected to fire degradation: a study" (Composites, Part A, 30(2), 123-131).

(Dutta, P. K.) in 1988. "Cold regulation engineering using structural fiber composite materials," Journal of Cold Regulation Engineering, 2(3), 124–134.

In 1997, GangaRao and Vijay published a book. "Deterioration of structural composites subjected to different environmental factors." Sapporo, Japan: Japan Concrete Institute, 2012, pp. 91–98.

Publication date: 1997 by George, G. A., Sacher, R. E., and Sprouse, J. F. Photographic oxidation and photoprotection of a glass fiber epoxy composite's surface resin was published in the Journal of Applied Polymer Science, volume 21, pages 2241-2245.

In 1996, Gomez and Casto published a paper. "Stability of composites during freezing and thawing," Proceedings of the 1st International Conference on Composites in Infrastructure (ICCI), Tuscon, Arizona, pp. 949–955.

Published in 2000 by Green, Bisby, Beaudoin, and Labossiere. "Research on the effects of freezing and thawing on the bond durability between concrete and FRP plate reinforcement." Civil Engineering in Canada, 27, 949-959.

The authors of the 1996 work are Karbhari and Engineer. J. Reinf. Plast. Compos., 15, 1194-1216, examines the impact of environmental exposure on the exterior reinforcement of concrete using composites, specifically focusing on the endurance of the bonds in the short term.

The authors of this work are Karbhari and Zhang (2003). Composites made of e-glass and vinylester in water. Technical Journal of Composites, Volume 10, Issue 1, Pages 19–48.

The authors of this work are Katsuki and Uomoto. "We can foretell the degradation of FRP rods caused by alkali attack." Supporting concrete without metal, E&FN Spon, London, 83–89.

In 1989, Konur and Matthews published a paper. "Review of the effect of component qualities on fatigue performance of composites:" Composites, 20(4), 317-328.

In 1998, Liao, Schultheisz, Hunston, and Brinson published a paper. An analysis of the long-term performance of fiber-reinforced polymer-matrix composites used in infrastructure. Published in the Journal of Advanced Materials, volume 30, issue 4, pages 3–40.

In 1998, Liau and Tseng published a paper. "The impact of continual exposure to ultraviolet light on composites composed of polymer matrix," Polym. Compos., 19(4), 440–452.

Dutta, P. K., and Lord, H. W. (1988). Concerning the implementation of polymeric composite constructions in cold climates. J. Reinforced Polymer Composites, 7, 435–458.

This was published in 1981 by Lucki, Rabek, Ranby, and Ekstom. "Photolysis of polyesters." European Polymer Journal 15, 919–926, 2015.