DURABILITY OF CONCRETE-FILLED TUBULAR FRP PILES

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Abstract

Traditional pile materials for bridge foundations include steel, concrete, and timber. These pile materials have limited service life and high maintenance costs when used in harsh marine environments due to corrosion, degradation, and marine borer attack. Problems associated with traditional pile materials used in harsh environments include concrete durability, steel corrosion, and marine borer attack or degradation of timber piles. High repair and replacement costs have led several North American highway agencies and researchers to investigate the feasibility of using FRP composite piles, such as concrete-filled tubular FRP piles. Fiber reinforced polymer (FRP) composite piles are a possible foundation alternative for projects located in harsh marine environments. These piles, if found viable, could offer such advantages as improved durability in harsh environments and cost savings in terms of life cycle analysis. However, one of the main drawbacks of composite piles is their relatively short track record of performance and absence of long-term durability data. Long-term service of typical bridge piles requires them to sustain combined axial and bending loading under severe environmental conditions such as exposure to moist chemistry environment. On-going research at Virginia Tech has found that moisture is the dominant damage mechanism, influencing the long-term durability of concrete-filled tubular FRP piles. This paper describes a durability methodology proposed to assess the long-term structural capacity of concrete-filled tubular FRP piles, and presents the durability experimental results to date.

Introduction

Traditional pile materials for bridge foundations include steel, concrete, and timber. These pile materials have limited service life and high maintenance costs when used in harsh marine environments due to corrosion, degradation, and marine borer attack [1]. Examples of deteriorated conventional piles are shown in Figure 1. Overall it has been estimated that repair and replacement of piling systems costs the U.S. over $1 billion annually [2]. High repair and replacement costs have led North American highway agencies and researchers to investigate the feasibility of using composite materials for transportation and civil engineering structures including bridge pile foundations [3].

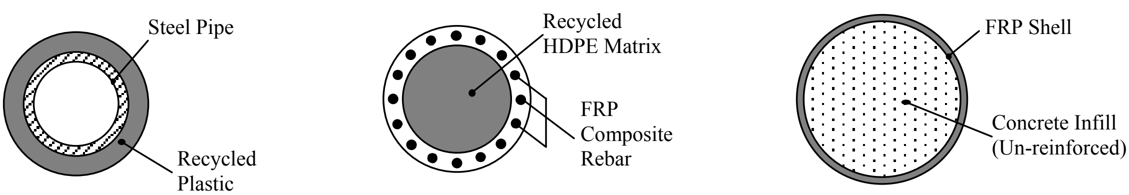
Since the 1980's, a number of American manufacturers have begun marketing alternative pile products known as "composite piles". The term "composite piles" usually refers to piles composed of fiber reinforced polymers (FRP), recycled plastics, or hybrid materials. Some of the commercially available composite piles are shown schematically in Figure 2. In this paper, concrete-filled tubular FRP piles were studied (pile shown in Figure 2 c). This type of composite pile has two main structural components: a fiber reinforced polymer (FRP) shell and a concrete infill (no steel reinforcement). The FRP shell provides, among other things, a stay-in-place concrete form, confinement to the concrete, tensile reinforcement and corrosion protection. The concrete infill provides primarily compressive load capacity [4].

a) Corroded steel piles b) Degraded concrete pile c) Deteriorated timber piles

Figure 1. Degradation of conventional piles (adapted from Ref. 3)

To date, composite pile use has been limited mainly to marine fender piles, as load bearing piles for light structures, or experimental use [3]. Composite piles have not yet gained wide acceptance in the civil engineering industry primarily due to the lack of a long track record of performance and higher initial cost. However, FRP composite piles, if designed correctly, can result in longer life cycle and improved durability in harsh marine environments, which presents the potential for substantially reduced costs.

The short-term structural behavior of concrete-filled tubular FRP piles, under axial and flexural loading, has been studied by several researchers [e.g. 4, 5, 6, 7]. Although the geotechnical behavior has not been investigated to the same extent, there is a small body of work [e.g. 3, 8, 9, 10, 11]. While these structural and geotechnical studies have advanced our knowledge about the behavior of composite piles, there are still significant gaps. One of the main gaps is the absence of comprehensive data characterizing the long-term durability of FRP composites coupled with the absence of adequate established design standards. This paper discusses the findings to date of a long-term durability study on concrete-filled tubular FRP piles.



a. Steel Pipe Core Pile b. Structurally Reinforced Plastic Matrix c. Concrete- Filled FRP Pipe Pile

Figure 2. Some Common Types of Composite Piles

General Design Considerations for Pile Foundations

Pile foundations are typically used to support structures underlain by weak or compressible soils or when the foundation is subject to scour [12]. Pile foundations must be capable of transmitting the loads from the substructure (such as a bridge) into the soil or rock. Typically, pile foundations must be able to handle axial, horizontal and uplift loads, although piles are predominantly loaded in axial compression.

The pile must be designed so they transmit the loads to the foundation soil without reaching either the ultimate limit state or serviceability limit state. The ultimate limit state of the pile corresponds to the maximum load carrying capacity, and can be reached through either structural or foundation failure [12]. The serviceability limit state is more related to unacceptable deformation levels in the foundation system. In this paper we will discuss mainly the long term assessment of the "structural" ultimate limit state of the pile.

Piles loaded in axial compression can derive most of their load carrying capacity from skin friction (i.e. shearing resistance developed between the pile perimeter and the surrounding soil) or from end or pile tip bearing (i.e. from the foundation reaction at the pile tip). Friction piles (first type of pile) will typically be more likely to reach the ultimate limit state through foundation failure. While end-bearing piles, with their tips founded on hard soil or rock, are more susceptible to "structural" ultimate limit state failure (either compression failure or buckling). In the case of laterally loaded piles, "structural" ultimate limit state is usually always a concern. The lateral load design of piles is typically governed by the serviceability limit state (maximum tolerable deflection) or the "structural" ultimate limit state [12]. A laterally loaded pile reaches its "structural" ultimate limit state through flexural failure when the induced bending moment exceeds the moment capacity of the pile. The moment capacity of the pile should be selected based on appropriate load-moment interaction diagrams.

In summary, the structural ultimate limit state will be an important design factor for axially loaded piles founded on hard soil or rock where their load carrying capacity is derived mainly from end-bearing, and for most laterally loaded piles. Since piles are typically required to have service lives of 50 to 75 years, the designer must check that both the short- and long-term structural ultimate limit states are adequate. The following section will present a brief description of the short-term axial and flexural structural behavior of concrete-filled FRP circular tubes. Later in the paper a durability model is outlined to help estimate the long-term structural ultimate limit state of these types of piles.

Short-Term Structural Behavior

The short-term axial and flexural structural behavior of concrete-filled FRP tubes has been studied by several researchers [e.g. 4, 5, 6, and 7]. A brief description is provided herein.

Axial Behavior

The FRP tube of a composite pile contributes structurally to the pile by primarily providing confinement to the concrete core [6]. The beneficial effect of confinement on the total load carrying capacity of a short concrete-filled FRP tubular element (length-diameter ratio of 2) was studied by Fam and Rizkalla [4], and is illustrated in Figure 3. The figure shows how the capacity of the composite stub significantly exceeds the load sharing capacity of the two individual materials [4]. The load-strain curve starts to depart from the unconfined concrete curve in the vicinity of the unconfined concrete strength. As this stress level is approached the concrete core starts to experience significant micro-cracking as well as increased lateral expansion. In response to the lateral expansion of the concrete, the FRP shell applies a radial confining pressure, which continuously increases due to its linear elastic properties [6]. The second slope of the load-strain curve is a function of the hoop tensile stiffness of the FRP shell, and the ultimate peak strength is governed by the hoop tensile strength of the FRP shell.

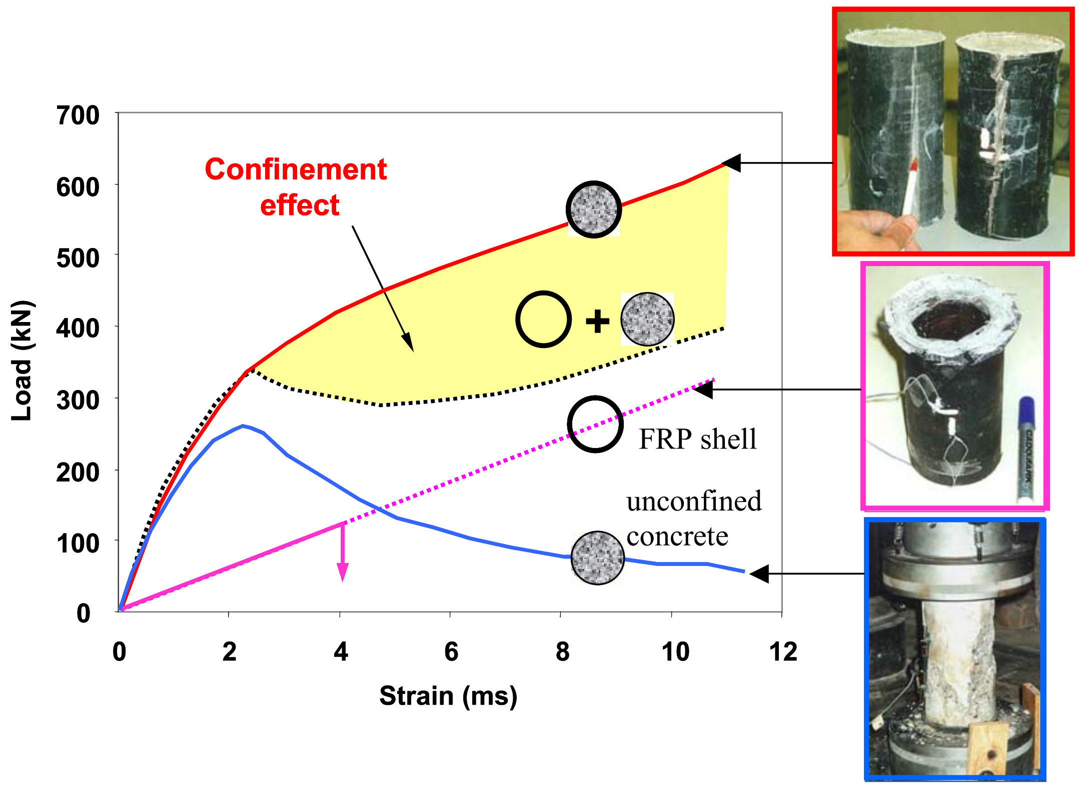


Figure 3. Confinement effect in axially loaded stub (adapted from Ref. 4)

The short-term axial capacity of a concrete-filled FRP tubes can be predicted using a confinement model such as the one proposed by Fam and Rizkalla [4]. This model is an incremental variable confinement model, which is based on equilibrium and radial displacement compatibility between the concrete core and the FRP tube and the constant confinement model. A detailed description of this model is provided in [4, 6].

The radial confinement pressure applied by the FRP shell can be obtained from equilibrium and by imposing radial displacement compatibility between the concrete core and the FRP shell.

The load-strain response, predicted using the above model, and the experimental load-strain behavior for Test Stub No. 1 (from the Fam and Rizkalla study [4]) are shown in Figure 4. The figure shows good agreement between the model and the experimental results.

This model will be used later in the paper to illustrate the influence that the degradation of the hoop properties (stiffness and strength) of FRP tube has on the long-term axial capacity of concrete-filled tubular FRP piles.

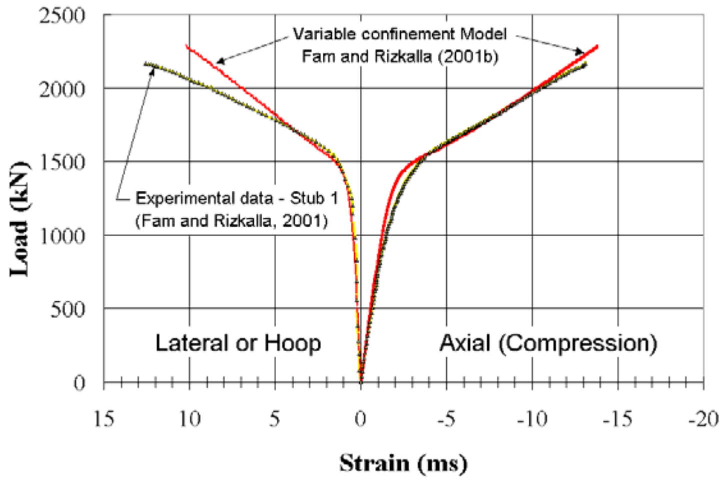


Figure 4. Experimental versus predicted axial load-strain curves using the Fam and Rizkalla model

Flexural Behavior

Concrete-filled FRP circular tubes can be used to resist bending moments. However, the benefits of concrete confinement are less in bending than the purely axial loading case [6]. In flexion, the FRP tube acts as a non-corrosive reinforcement, while the concrete provides the internal resistance force in the compression zone and increases the stiffness of the member [7]. The concrete core also prevents local buckling of the FRP tube.

A comprehensive full-scale experimental program to study the short-term flexural behavior and failure modes of concrete-filled FRP tubes was recently completed by Fam and Rizkalla [6, 7]. Their study showed that the flexural behavior is highly dependent on the stiffness and diameter-to-thickness ratio of the FRP tube, and to a lesser extent on the concrete strength [7]. The study also showed that in general the cracking moment resistance is relatively small compared to the ultimate moment capacity

The short-term flexural capacity of a concrete-filled FRP tubes can be predicted using a strain compatibility/equilibrium model such as the one proposed by Fam and Rizkalla [7]. The methodology assumes that sections normal to the neutral axis remain plane after bending, and that the FRP shell is perfectly bonded to the concrete interior (i.e. a linear strain distribution through the cross-section). The method consists in discretizing the pile cross section into a series of strip elements that help integrate the normal stresses over the cross-sectional area. The discretization will result in both FRP and concrete strip elements. The stress integration is done assigning the appropriate constitutive model for each material. Details of the development of the model and its validation through experimental results can be found in [6, 7].

The load-strain response, predicted using the above model, and the experimental load-strain behavior for Beams 4 and 13 from Fam and Rizkalla [7] are shown in Figure 5. The figure shows good agreement between the model and the experimental results, especially when accounting for tension stiffening.

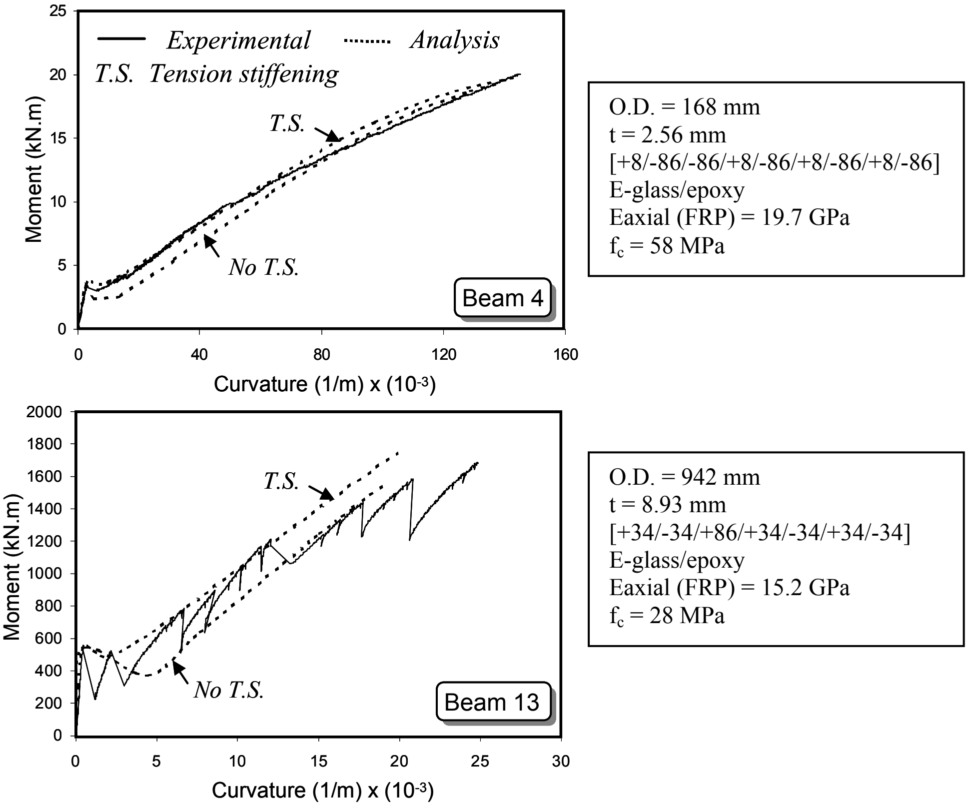


Figure 5. Experimental versus analytical moment-curvature response (adapted from Ref. 7)

This model will be used later in the paper to illustrate the influence that the degradation of the FRP tube properties (stiffness and strength) on the long-term axial capacity of concrete-filled tubular FRP piles.

Durability and Long-Term Strength Methodology

As mentioned earlier, conventional piles have degradation problems in marine environments. These piles typically degrade within a period of 20 years. Although the initial cost of concrete-filled FRP piles is currently about two to three times higher, manufacturers estimate their design lives to be 50-75 years, which could make them economically feasible in terms of life cycle cost. Given these facts, the engineering community must consider how the operating environment of the piles will influence the ability of the FRP system to carry out its intended function in such a long design life. As illustrated in the previous section, the long-term capacity of these piles will be governed by the long-term strength and stiffness of the FRP tube.

In this paper, the primary mechanisms of strength and stiffness loss considered are related to moisture absorption, and include fiber/matrix interface damage, and stress crack corrosion of the fiber and matrix degradation through chain scission [13]. These changes are typically irreversible for pultruded glass/vinyl ester materials. Degradation due to moisture absorption may significantly reduce the life of FRP composites [13]. Absorbed moisture can cause pronounced changes in modulus, strength, and strain to failure [14]. Moisture content of submerged FRP composites increases through diffusion. The absorbed moisture can act as a plasticizer of the composite resin, and can cause matrix cracking, fiber-matrix debonding, and corrosion of glass fibers (stress corrosion) [13]. For example, Schulheisz et al. [15] recorded strength and stiffness reductions on the order of 20% and 5%, respectively, for E-glass/vinyl ester composites submerged in 25 °C water for a period of 200 days. The implications of such strength and stiffness reductions on the design of composite piles can be significant, especially in deflection-critical designs.

In addition to submergence time, temperature and stress level also influence the amount of moisture that the FRP will absorb while submerged.

A recent durability study of glass/vinyl ester composites carried out by Phifer and Lesko [16] found that the residual strength (long-term strength) of such composites is purely a function of the moisture content - independent of how that moisture content was reached and how long it took (over a reasonable range of temperatures, 20° to 85°C, and times - up to 300 days). The tensile strength degradation versus moisture content found in this study is shown in Figure 7.

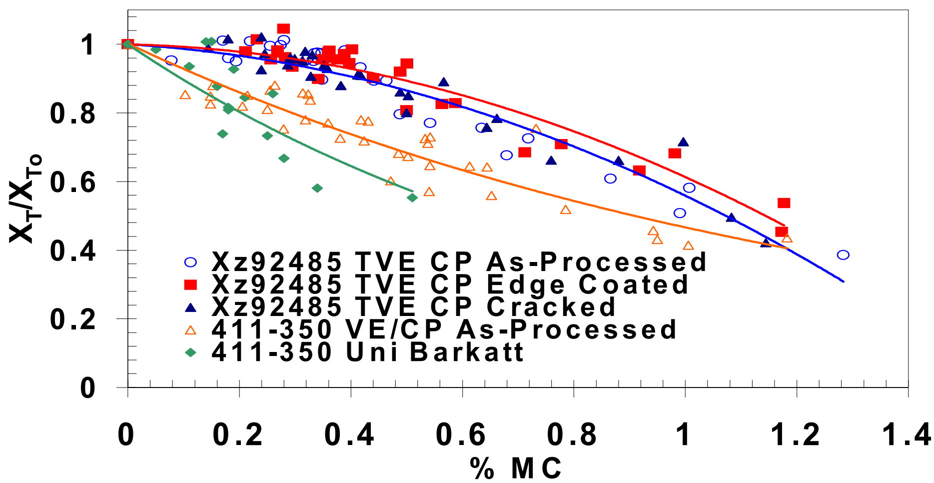


Figure 7. Normalized tensile strength versus moisture content (Adapted from Ref. 16)

A concrete-filled FRP pile installed in tidal regions would be exposed to salt water and potentially to chemical agents as a result of wet concrete inside the FRP shell. However, McBagonluri et al. [13] found that the rate of strength loss was not significantly affected by salt content but rather by absorption of moisture. Therefore, the durability experiments carried out for this study were performed using fresh water.

Our general approach is to track moisture diffusion into the material and to evaluate the residual strength of the shell as a function of submergence time. We will then relate this material strength (and stiffness) loss to the residual or long term axial capacity of the pile using the Fam and Rizkalla model described previously. This methodology does not address how the moisture influences the internal frictional forces or bond between the concrete and the FRP shell, which may also influence the long-term pile performance. The effects of creep or chemical attack (e.g. as a result of concrete) are not included either. These factors should be included, but are not in the present model. For a more accurate prediction these factors should be included.

Experimental Program

A comprehensive laboratory program is currently underway to study the long-term performance of commercially available concrete-filled tubular FRP composite piles. The piles studied in this paper were manufactured by Lancaster Composites Inc.

The proposed laboratory degradation study includes FRP shell characterization, determination of baseline mechanical properties, measurement of moisture absorption as a function of time, measurement of mechanical properties as a function of moisture absorption, and tests on concrete-filled tubular FRP stubs (12-in diameter x 24-in long) to evaluate the pile capacity as a function of submergence time. Tests to evaluate degradation of axial capacity of the concrete-filled tubular FRP stubs are currently underway.

FRP Shell Characterization

Lancaster FRP shells of 12-inch and 24-inch nominal diameter were used in this study. Both Lancaster FRP shells were manufactured using the filament winding technique. The 24-inch shell was made with isophthalic acid polyester resin (Ashland Chemical Apropol 7241) and Owens Corning Type 30 113 Yield E-Glass fiber rovings. The 12-inch FRP shell was manufactured with epoxy resin and E-Glass fiber rovings. The fiber lay-up obtained and pile dimensions for both FRP shells are summarized in Table 1.

Table 1. Composite Piles FRP Shell Dimensions and Fiber Lay-up

Composite Pile Type	Dimensions (mm)	Fiber lay-up angles & Layer thicknesses
Lancaster CP40 24-inch	Diameter [1] = 629 Wall thickness = 7.1 Liner = 1.27	Angles: $[+35/-35/+85/+35/-35]_T$ (degrees [2]) Thicknesses: [1.17/1.17/1.17/1.17/1.17] (mm)
Lancaster CP40 12-inch	Diameter = 324 Wall thickness = 6.1 Liner = 1.1	Angles: $[+84/+3/+84/+3/+84/+3/+84/+3/+84]_T$ Thicknesses: [0.39/0.67/0.44/0.58/0.55/0.82/0.39/0.77/0.39]

Notes: (1): Diameter refers to the nominal outside diameter.
(2): Angle measured with respect to pile longitudinal axis.

Baseline Mechanical Properties

To study the durability and long-term performance of FRP composite piles, it was necessary to first evaluate the baseline mechanical properties of the FRP shell in the longitudinal (axial) and hoop directions. Properties in the longitudinal direction were evaluated by means of tension tests carried out on longitudinal coupons. Hoop direction properties were obtained from split disk tension tests carried out on FRP rings cut from the pile FRP shell.

Hoop properties: 12-inch and 24-inch split disk devices were designed and manufactured for this project. Split disk tests were performed in accordance with ASTM Test Method for Apparent Hoop Tensile Strength of Reinforced Plastic Pipe by Split Disk Method (D2290).

Split disk specimens were cut from the Lancaster FRP shells at the Strongwell Corporation in Bristol, VA. The FRP ring specimens had an average width of 40 mm. The tests were carried out using a 534 kN Tinius-Olsen machine operated at a strain rate of 2.5 mm/min. Strain gages were mounted to measure both the hoop and axial strain. Split disk test results of the as-received specimens are summarized in Table 2.

Table 2. As-Received Mechanical Properties in the Hoop Direction

Property	24-inch Lancaster		12-inch Lancaster	
	Mean	St. Dev.	Mean	St. Dev.
Strength (MPa)	121.4	5.9	195.2	24.5
Initial Modulus (GPa)(1)	19.1	2.3	13.0	3.1

Note (1): Initial modulus value corresponds to strain range 0 – 2000 microstrains.

Longitudinal properties: Tensile tests were performed on longitudinal strip specimens in accordance with ASTM Test Method for Tensile Properties of Polymer Matrix Composite Materials (D3039). Test specimen strips were cut in the longitudinal direction using a water-cooled saw. The average test specimen dimension was 25 mm x 200 mm x 7.1 mm. The tests were carried out using an Instron test frame operated at a constant rate of displacement of 1.25 mm/min. Axial strain was measured with the use of extensometers and with strain gages. The obtained baseline (as-received) tensile properties are summarized in Table 3.

Table 3. As-Received Mechanical Properties in the Axial Direction

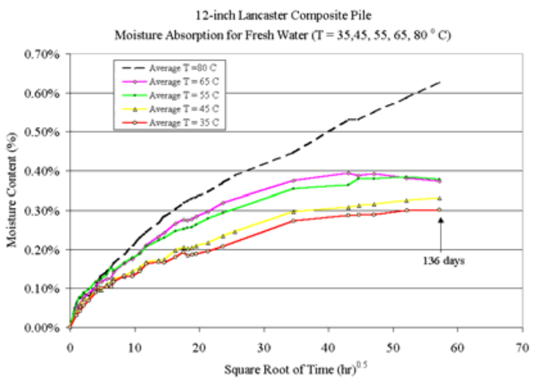
Property	24-inch Lancaster		12-inch Lancaster	
	Mean	St. Dev.	Mean	St. Dev.
Strength (MPa)	98.5	8.3	241	14
Initial Modulus (GPa)(1)	15.3	0.95	23	1.3

Note (1): Initial modulus value corresponds to strain range 0 – 4000.

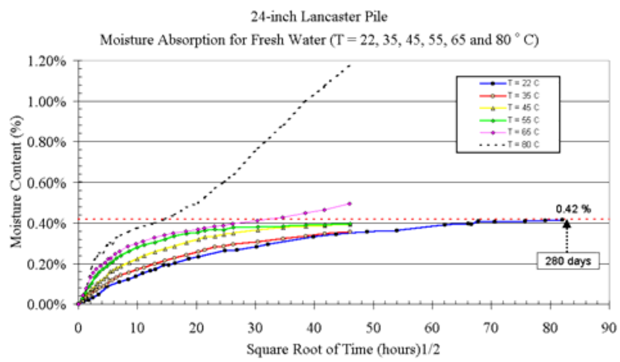
Properties as a Function of Time and Moisture

Moisture absorption: Moisture absorption iso-thermal curves were obtained by immersing samples in fresh water tanks at different temperatures (22 ^{o}C, 35 ^{o}C, 45 ^{o}C, 55 ^{o}C, 65 ^{o}C and 80 ^{o}C). Typical moisture absorption plots, for the 12-inch and 24-inch diameter Lancaster shells are shown in Figure 8a and 8b, respectively. The submerged FRP coupons were about 100 mm long and 25 mm wide, with their edges epoxy coated to approximate 1-D diffusion conditions.

The equilibrium moisture content for the 24-inch FRP shell immersed in 22 ^{o}C water is estimated to be about 0.42 % by weight. The equilibrium moisture content for the higher water temperatures was similar except at 65 °C and 85 °C. The equilibrium moisture content for the 12-inch FRP shell appears to be between 0.3 and 0.4 percent; however it cannot be inferred with confidence at this stage of the monitoring since the curves have not leveled off completely.



a) 12-inch Lancaster FRP shell

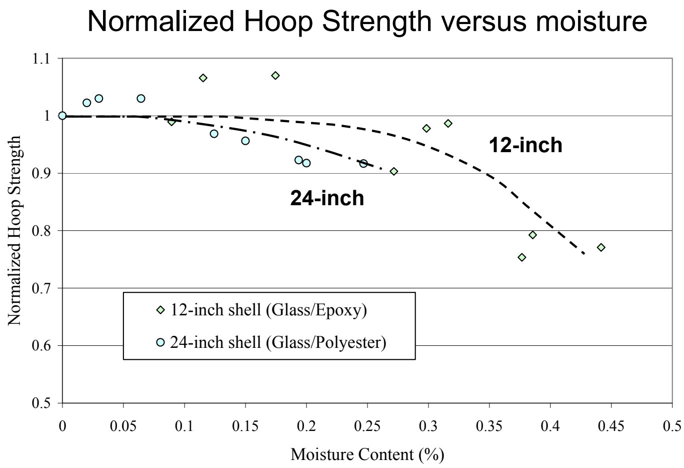


b) 24-inch Lancaster FRP shell

Figure 8. Moisture absorption curves obtained from submerged FRP shell coupons

Strength as function of time and moisture: The effect of time of immersion on the mechanical properties was evaluated for aged specimens in 22 ^{o}C water. Hoop tensile tests and axial tensile tests were performed on aged specimens after different times of submergence. Normalized strength versus moisture content for both Lancaster FRP shells are shown in Figure 9.

Tests are still underway, but based on the data available, it can be estimated that the hoop strength has decreased by about 10 and 25 percent for the 24 and 12-inch diameter FRP shells respectively. Axial tensile test results for the 24-inch FRP shell show no evidence of major longitudinal tensile strength loss. This is believed to be related in part to the fiber orientation of this composite $(\pm35^o/85^o/\pm35^o)_T$, which makes it matrix dominated in the longitudinal direction. To date, the axial strength reduction for the 12-inch FRP shell is about 10 percent. The 24-inch shells have been submerged about 330 days, while the 12-inch specimens have been submerged about 150 days. The differences in strength reduction behavior are believed to be related to differences in resin, fiber lay-up, manufacturing procedure, void content and other defects.



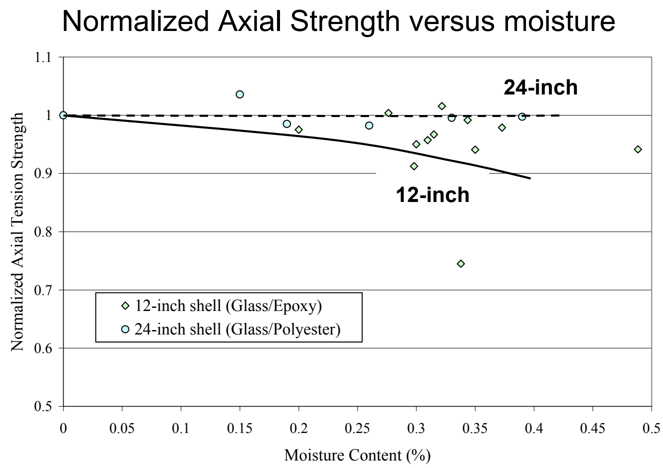


Figure 9. Normalized strength versus moisture content

FRP Strength as a Function of Time

The experimental data described above was obtained from water submerged FRP coupons whose edges were coated to approximate 1-D diffusion. For a concrete-filled FRP shell, the diffusion will be predominantly in the radial direction. However, the boundary condition on the inner and outer surfaces of the FRP will be different from the boundary conditions of the experimental program. A more realistic estimation of the FRP strength as a function of time can be made by calculating the moisture content profiles within the FRP shell using 2-D diffusion modeling of the pile incorporating more realistic moisture boundary conditions. Once the average moisture content has been computed for a given submergence time, under more realistic boundary conditions, we can estimate the corresponding reduced strength of the FRP shell using a figure similar to Figure 9. This modeling approach was described in Pando et al. [17].

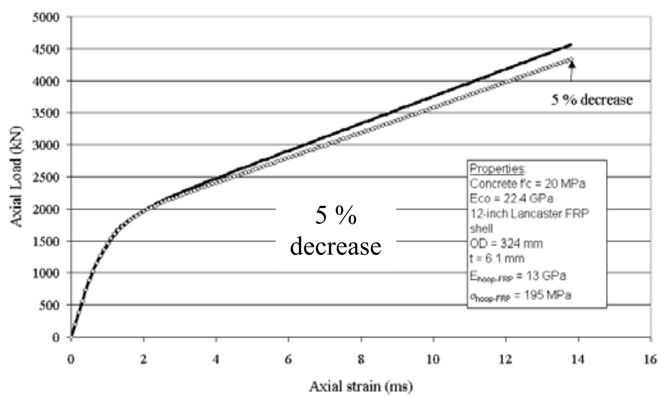
Long Term Structural Capacity of Composite Pile

As a first approximation, we can estimate the long-term structural capacity of the pile by using the two models outlined before, and by incorporating the reduced long-term FRP properties obtained experimentally.

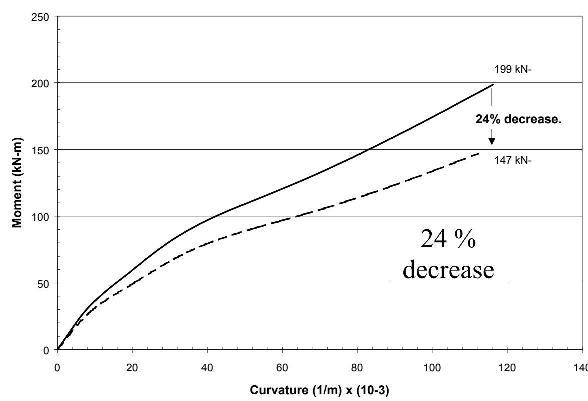
For illustrative purposes, let us first estimate the long-term axial capacity for the 12-inch Lancaster pile. Using the FRP dimensions and as-received properties presented above, we obtain the load-strain response curve shown in the solid line in Figure 10 a. If we now include a 25% and 40% reduction for the FRP hoop stiffness and strength respectively (these higher reduction values represent expected long-term values, which are similar to Figure 7 values), we obtain the long-term load-strain curve shown as the dashed line in Figure 10 a. This represents approximately a 5 % axial capacity reduction.

Similarly, the long-term flexural capacity for the same Lancaster pile can be predicted using the Fam and Rizkalla model [7]. The short-term moment-curvature response is shown as the solid line in Figure 10 b. Assuming similar stiffness and strength reduction levels as before, but in the longitudinal direction, we obtain the dashed moment-curvature curve shown in Figure 10 b. This represents a 24 % reduction in the flexural capacity (long-term).

This simplified example is intended for illustrative purposes only, but it helps illustrate the importance of incorporating in the pile capacity (structural ultimate limit state) evaluation the moisture aging effects on the FRP strength and stiffness (especially for the bending capacity). The values of strength and stiffness reduction used are based on experimental data from specimens submerged in fresh water at 22 °C for about 150 days. A durability study involving tests on concrete-filled FRP stubs is currently underway. The results from this study will help assess the validity of this durability model to predict long-term axial capacity of this type of piles.



a) Axial capacity



b) Flexural capacity

Figure 10. Estimated long-term capacity of the 12-inch Lancaster pile

Summary and Conclusions

A simplified model for predicting the long-term axial and flexural capacity of a concrete-filled FRP pile exposed to marine environment moisture has been presented. The use of the model was illustrated using available experimental data applied to a simple example. Based on the simplified example presented, it appears that the degradation of the FRP properties has a greater impact on the long-term flexural capacity of the pile. For the example presented, the long-term axial and flexural capacities were estimated to be 5 and 24 percent lower than the short-term capacities respectively. The simplified model presented is proposed as a first approximation since it does not account for creep, stress level dependency, or chemical damage that occur under more realistic conditions. For a more accurate prediction these factors should be included.

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