

MOISTURE EFFECT ON DURABILITY OF AXIALLY LOADED CONCRETE-FILLED TUBULAR FRP PILES

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ABSTRACT

Fiber reinforced polymer (FRP) composite piles are a possible foundation alternative for projects located in harsh marine environments. 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. 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 axial 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 (Lampo et al., 1998). Examples of deteriorated conventional piles are shown in Fig. 1. Overall it has been estimated that repair and replacement of piling systems costs the U.S. over \$1 billion annually (Lampo, 1996). 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 (Iskander and Hassan, 1998).



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

Fig. 1 - Degradation of conventional piles (adapted from Iskander and Stachula 1999)

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 in Fig. 2. In this paper, concrete-filled tubular FRP piles were studied (pile shown in Fig. 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 compressive load capacity (Fam and Rizkalla, 2000).

To date, composite pile use has been limited mainly to marine fender piles, as load bearing piles for light structures, or experimental use (Iskander and Hassan, 1998). 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. Mirmiran et al., 1999, Fam, 2000, Fam and Rizkalla, 2000; Fam and Rizkalla, 2001a). Although the geotechnical behavior has not been investigated to the same extent, there is a small body of work (e.g.

Ashford and Jakrapiyanun, 2001, Iskander and Hassan, 1998; Iskander and Stachula, 1999; Pando et al., 2000; and Pando et al., 2002). 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 (McBagonluri et al., 2000). This paper discusses the findings to date of a long-term durability study on concrete-filled tubular FRP piles.

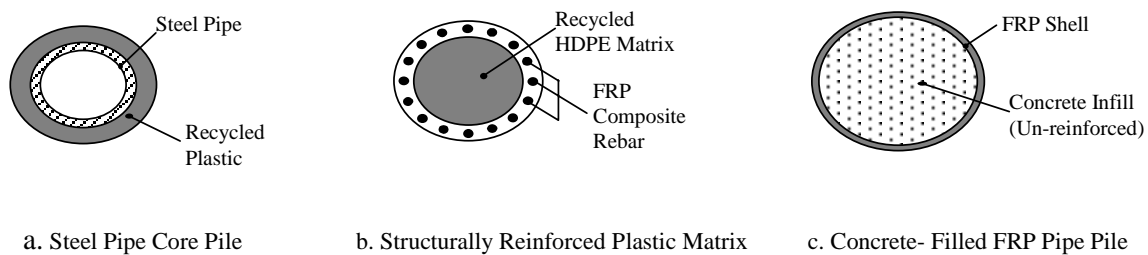


Fig. 2 - Some Common Types of Composite Piles

SHORT-TERM AXIAL STRUCTURAL CAPACITY

The short-term structural behaviour of concrete-filled FRP tubes has been studied by several researchers (e.g. Mirmiran et al., 1999; Fam, 2000; Fam and Rizkalla, 2001a; and Fam and Rizkalla, 2001b). A detailed description of the behavior of concrete-filled FRP tubes under axial compression loading can be found in Fam and Rizkalla (2001a, and 2001b). A brief description is provided herein.

The FRP tube of a composite pile contributes structurally to the pile by primarily providing confinement to the concrete core (Fam 2000). 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 (2001a), illustrated in Fig. 3. The figure shows how the capacity of the composite stub significantly exceeds the load sharing capacity of the two individual materials (Fam and Rizkalla, 2001a). 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 (Fam, 2000). 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.

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 (2001b). 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 by Mander et al. (1988). A detailed description of this model is provided in Fam and Rizkalla (2001b). Only a brief overview of the main features of this model are presented in this paper.

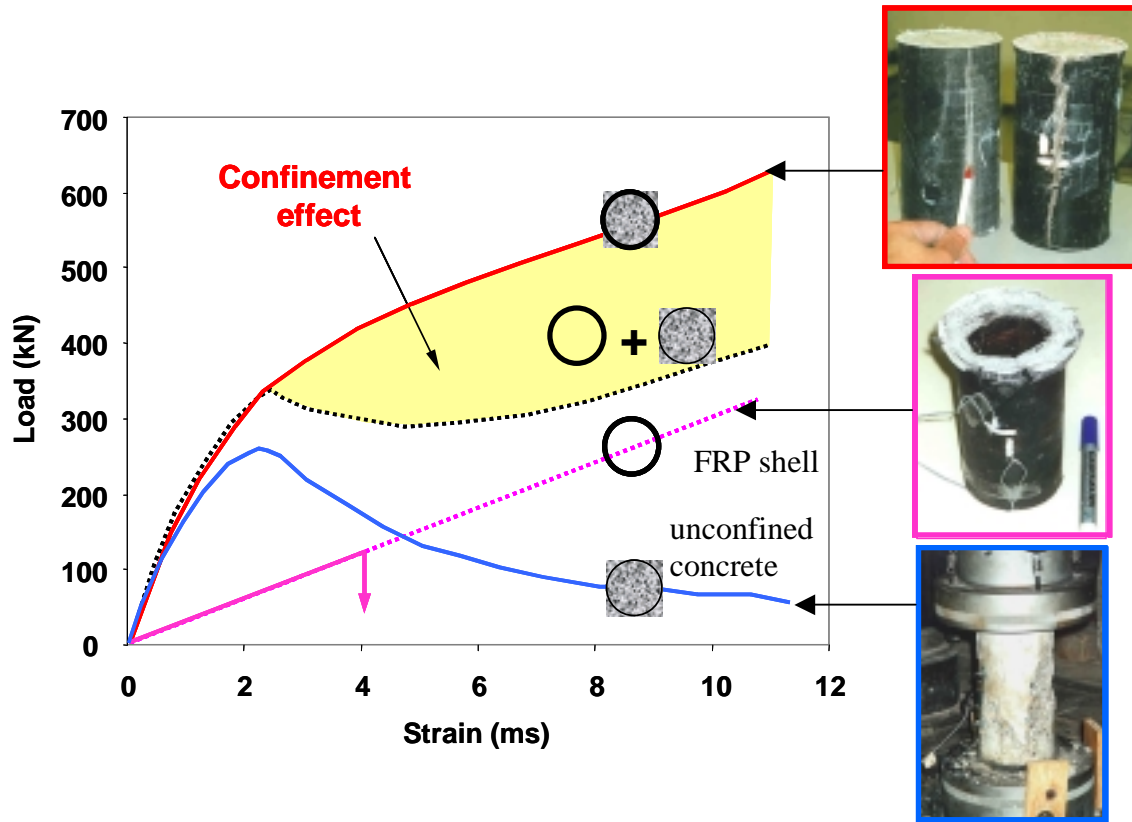


Fig. 3 - Confinement effect of FRP tube on concrete (Fam and Rizkalla, 2001)

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. For the case when both the concrete core and FRP shell are axially loaded with the same strain level (ϵ_{cc}), the radial confinement pressure (σ_r) can be estimated as follows (Fam, 2000):

$$\sigma_R = \frac{(\nu_c - \nu_{FRP})}{\frac{R_{FRP}}{E_{FRP-Hoop} \cdot t_{FRP}} + \frac{1 - \nu_c}{E_c}} \cdot \epsilon_{cc} \quad [1]$$

where

- ν_c is the Poisson ratio of concrete (can be varied by using the secant Poisson's ratio)
- ν_{FRP} is the Poisson ratio of the FRP shell (-hoop strain /axial strain under axial loading)
- R_{FRP} and t_{FRP} are the radius and wall thickness of the FRP tube respectively
- $E_{FRP-Hoop}$ is the elastic modulus of the FRP shell in the hoop direction (hoop tension)
- E_c elastic modulus of concrete core (can be varied by using the secant modulus)
- ϵ_{cc} is the axial strain of the concrete-filled FRP tube stub.

The variable radial confining pressure is obtained from Eq. 1 by using the secant elastic modulus and the secant Poisson's ratio of the concrete as a function of axial strain level.

The model relates the axial stress of the confined concrete core (f_{cc}), at any given axial strain level (ϵ_{cc}), to the peak confined strength of the concrete (f'_{cc}) as follows:

$$f_{cc} = \frac{f'_{cc} \times r}{r - 1 + x^r} \quad [2]$$

where:

$$x = \frac{\epsilon_{cc}}{\epsilon'_{cc}} \quad [3]$$

and where:

- ϵ'_{cc} is the strain at peak strength f'_{cc}
- $r = \frac{E_{co}}{E_{co} - E_{sec}}$
- E_{co} is the initial tangent elastic modulus of unconfined concrete ($\approx 5000 \sqrt{f'_c}$ in MPa)
- E_{sec} is the secant elastic modulus of confined concrete ($\approx f'_{cc} / \epsilon'_{cc}$)
- and the peak confined strength (f'_{cc}) can be estimated using the expression proposed by Mander (1988):

$$f'_{cc} = f'_c \cdot \left(2.254 \cdot \sqrt{1 + \frac{7.94 \cdot \sigma_R}{f'_c}} - 2 \cdot \frac{\sigma_R}{f'_c} - 1.254 \right) \quad [4]$$

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, 2001 study) are shown in Fig. 4. The figure shows good agreement between the model and the experimental results.

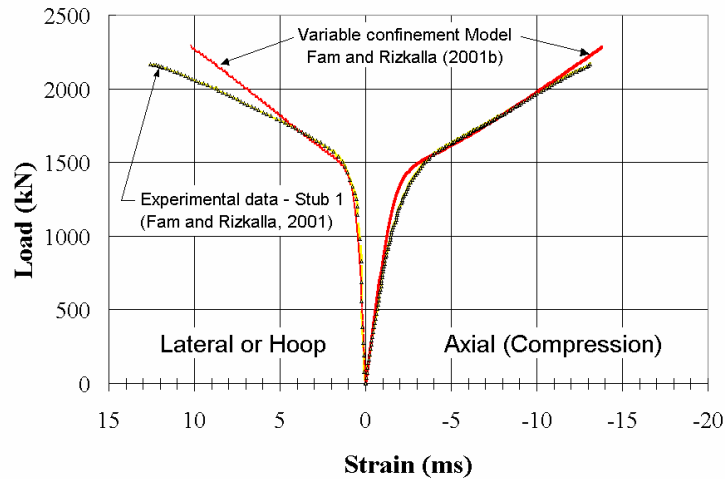


Fig. 4 - Experimental versus predicted load-strain behavior using Fam and Rizkalla model

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 have 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 (primarily in the hoop direction).

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 (McBagonluri et al., 2000). These changes are typically irreversible for pultruded glass/vinyl ester materials. Degradation due to moisture absorption may significantly reduce the life of FRP composites (Garcia et al., 1998). Absorbed moisture can cause pronounced changes in modulus, strength, and strain to failure (Springer et al., 1980). 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) (Garcia et al. 1998). For example, Schulheisz et al. (1997) 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 FRP will absorb while submerged. Fig. 5 shows schematically how time and temperature influence moisture absorption, how moisture absorption degrades property values, and how exposure time thus produces a reduction in property values.

A recent durability study of glass/vinyl ester composites carried out by Phifer and Lesko (2001) found that the residual 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 Fig. 6.

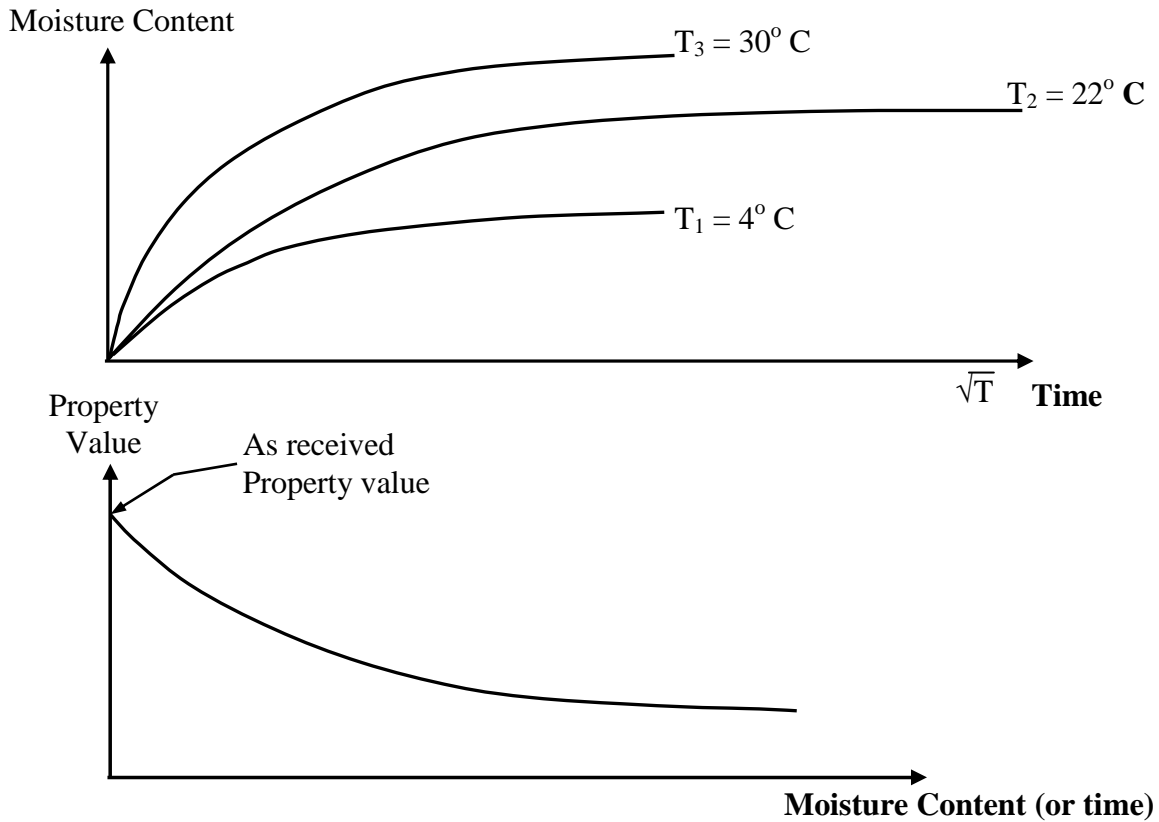


Fig. 5 - Moisture absorption related durability model

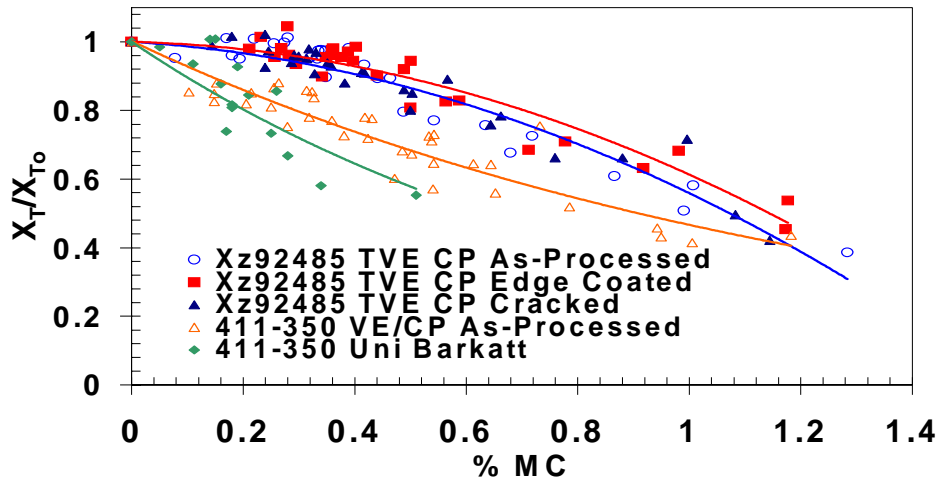


Fig. 6 – Normalized tensile strength versus moisture content (Phifer and Lesko, 2001)

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. (2000) 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 will be 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. We will not address how the moisture influences the internal frictional forces between the concrete and the FRP shell, which will certainly influence the performance. This methodology also does not include the effects of creep or chemical attack as a result of concrete. These factors should be included, but are not in the present model due to a lack of information.

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 axial compression capacity as a function of submergence time. The results presented in this paper only include the degradation measurements of mechanical properties of the FRP tubes of the Lancaster piles. 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 rovings. The 12-inch FRP shell was manufactured with epoxy resin and E-Glass rovings. The fiber layup obtained and pile dimensions for both FRP shells are summarized in Table 1.

Table 1 - Composite Piles FRP Shell Dimensions and Fiber Layup

Composite Pile Type	Dimensions (mm)	Fiber layer layup Fiber layup angles & Layer thicknesses
Lancaster CP40 24-inch	Diameter ⁽¹⁾ = 629 Wall thickness = 7.1 (liner = 1.27 mm)	[+35/-35/+85/+35/-35] _T [degrees ⁽²⁾] [1.17/1.17/1.17/1.17/1.17] [mm]
Lancaster CP40 12-inch	Diameter = 324 Wall thickness = 6.1 (liner = 1.1 mm)	[+84/+3/+84/+3/+84/+3/+84/+3/+84] _T [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. As discussed, the structural axial capacity of composite piles are mainly influenced by the FRP properties in the hoop direction, thus for the sake of brevity, only hoop properties will be presented and discussed.

Hoop properties: Split disk devices (12-inch and 24-inch) were designed and manufactured for this project. Split disk tests were performed in accordance with ASTM Test Method for Apparent Hoop Tensile Strength of Plastic or 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 – 4000 microstrains for axial tests, and 0 – 2000 microstrains for hoop tests.

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 °C, 35 °C, 45 °C, 55 °C, 65 °C and 80 °C). Typical moisture absorption plots, for the 12-inch and 24-inch diameter Lancaster shells are shown in Figs. 7 and 8, respectively. The submerged FRP coupons were about 100 mm long and 25 mm wide, with their coated edges to ensure I-D diffusion.

The equilibrium moisture for the 24-inch FRP shell immersed in 22 °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 cannot be inferred with confidence at this stage of monitoring since the curves have not yet levelled off.

Strength as function of time and moisture: The effect of time of immersion on the hoop mechanical properties was evaluated for aged specimens in 22 °C water. Hoop tensile tests were performed on aged specimens after different times of submergence. Normalized hoop strength versus moisture content for both Lancaster FRP shells are shown in Fig. 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 20 percent for the 24 and 12-inch diameter FRP shells respectively. The 24-inch shells have been submerged about 330 days, while the 12-inch specimens have only been submerged about 100 days. The difference in strength reduction could be due to the differences in resin and manufacturing, potentially resulting in void content and other defects. However, this difference in strength reduction is also

believed to be related to the larger percentage of fiber in the hoop direction of the 12-inch specimens. The hoop strength in the 24-inch specimen is more matrix dominated which could result in a different degree of degradation.

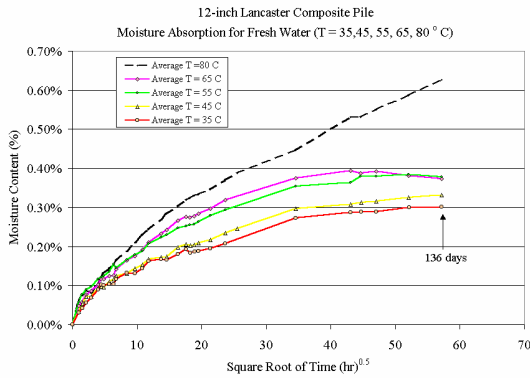


Fig. 7 – Moisture absorption curves for the 12-inch Lancaster FRP shell

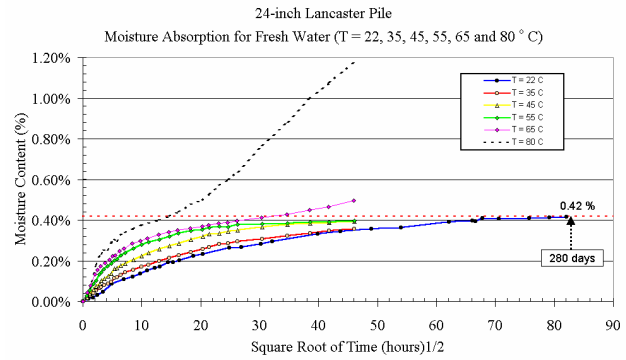


Fig. 8 – Moisture absorption curves for the 24-inch Lancaster FRP shell

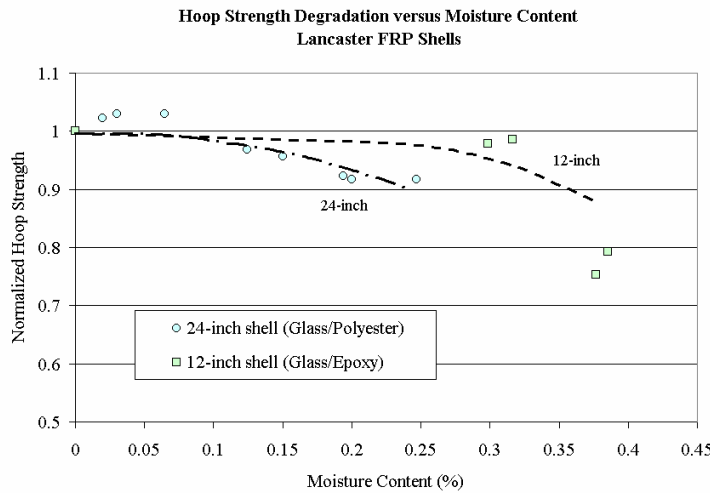


Fig. 9 – Normalized tensile hoop strength versus moisture content

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 modeled by calculating the average moisture content of the FRP shell as described in Pando et al. (2001) and reading the corresponding reduced normalized strength from Fig. 9.

LONG TERM AXIAL STRUCTURAL CAPACITY OF COMPOSITE PILE

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

For illustrative purposes, let us estimate the long-term capacity for the 12-inch Lancaster pile. Using the FRP dimensions and properties presented above we obtain the load-strain response curve shown in the solid line in Fig. 10. If we now include a 25% and 40% reduction for the FRP hoop stiffness and strength respectively, we obtain the dashed load-strain curve shown in Fig. 10. This represents approximately a 5 % axial capacity reduction.

This simplified example is intended for illustrative purposes only, but it helps illustrate the importance of incorporating in the pile capacity evaluation the moisture aging effects on the FRP strength. The experimental program on concrete-filled tubular stubs, which is currently underway, will help evaluate a durability model of the pile.

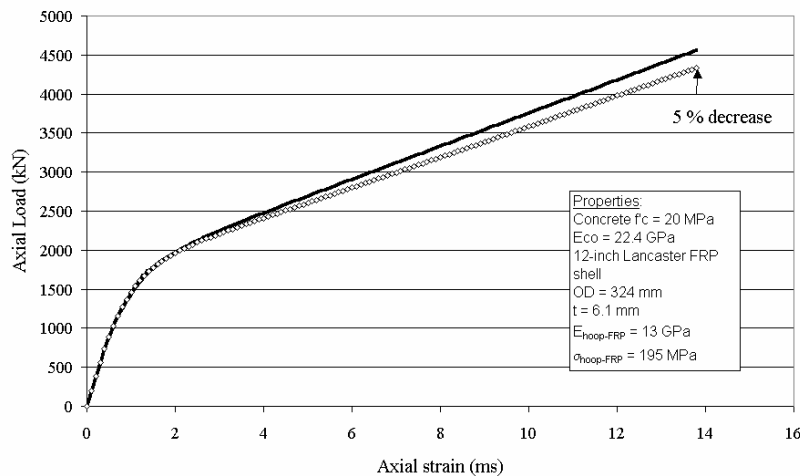


Fig. 10 – Estimated long-term axial capacity of the 12-inch Lancaster pile

CONCLUSIONS

We have described a simplified model for predicting the residual axial capacity of a concrete FRP pile subjected to tidal region moisture. The model does not account for the creep and chemical damage that can occur under more realistic conditions. The model does suggest that for the composite piles described in this paper and based on available data that the strength would reach a maximum reduction in capacity in about 330 days. Once durability data is available from the concrete-filled FRP stubs, the validity of this durability model to predict long term axial capacity will be assessed.

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