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An overview on the application of FRP composites in piling system

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Abstract—**Traditional pile materials such as steel, concrete and timber have limited service life when used in harsh marine environment. Problems coupled with these piles include deterioration of wood, corrosion of steel and degradation of reinforced concrete. To offset this problem, a relatively new trend in deep foundation industry is to use a fibre reinforced polymer (FRP) composite materials as a substitute in piling system. The fundamental advantages of FRP composites compared to other pile materials include lightweight, high strength and possess resistance against corrosion. However, composite materials face hurdle because they do not have a long track record of use in civil engineering application particularly in piling system. To partly address this obstacle, this paper presents an overview in testing, design, and practice of composite piles. Importance is given to history, material types and properties, structural behaviour, geotechnical performance, and durability of composite piles.**

Keywords- Fibre reinforced polymers, composite piles, durability , driveability

Figure 1. Degradation of traditional piles [3 & 4].

I. INTRODUCTION

Problems coupled with the traditional pile materials such as concrete, steel and timber are inevitable and costly especially if installed in harsh marine environment. For instance, in the United States alone, the cost needed annually to repair defective piling systems is estimated to be nearly $2 billon [1]. Struggles to these traditional pile materials include deterioration of wood, corrosion of steel and degradation of reinforced concrete making its service life reduced. Examples of deteriorated traditional piles are shown in Fig. 1. To offset these obstacles, a relatively new trend in deep foundation industry is to use fibre reinforced polymer (FRP) composites as a substitute for traditional materials in piling system.

FRP composites present an alternative solution without most of the traditional piles' performance shortcomings. The basic advantages of FRP composites among other construction materials include lightweight, high strength-to-weight ratio, corrosion resistance, chemical and environmental resistance and low maintenance cost [2]. As a result, application of composite materials in piling industry started to surge in recent years, and indeed several studies around the world is currently underway examining its performance and extent of relevance in waterfront and highway structures.

Apart from the mentioned advantages, composite materials face hurdle because they do not have a long track record of use in civil engineering application particularly in piling system. To partly address this obstacle, this paper will present a review in testing, design, and practice of composite piles. Importance is given to history, material types and properties, structural behaviour, geotechnical performance, and durability of composite piles.

II. HISTORICAL BACKGROUND

Composite piles have been available in the North American market since the late 1980s, though their use has been limited mainly to marine fendering applications [5]. The first prototyped composite pile installed at the port of Los Angeles in 1987 was composed of steel pipe core encased by recycled plastic shell [6]. The 18 m long pile was consisted of a 6 m connected segments with 330 mm diameter recycled plastics and 125 mm diameter steel pipe core. However, the initial application of the first composite pile is unsuccessful since the product suffered from delamination due to the difference in thermal coefficient of expansions between the plastic shell and the steel core.

Presently, a number of rehabilitation, replacement and demonstration projects using composite piles were already documented. For instance, the Tiffany Street pier was constructed using composite pile made entirely from recycled plastics [7 & 8]. Three different pile types were also installed in Port Elizabeth in a research project sponsored jointly by the U.S. Army Corps of Engineers and a consortium of composite pile manufacturers represented by the Composite Institute [3]. These tests were conducted to determine the feasibility of using composite piles as fendering system to replace timber piles. Two of the composite piles set up in Port Elizabeth were made of recycled plastics and reinforced with fibreglass. The third pile was made of pultruded composite structural section. Timber piles were also installed as reference piles for comparison

Composite piles were also adopted in a number of military and civilian projects [9]. For example, composite piles were installed in a number of military facilities in California and Louisiana and a number of ports in Mexico, Florida, Delaware and California [3]. To date, a number of load bearing composite piles were already used in bridge rehabilitation including Route 40 Bridge over the Nottoway River in Sussex County, Virginia and Route 351 Bridge project in Hampton, Virginia [10].

III. Composite Pile Types and Materials

Review of the available literature shows that currently there are five common types of composite piles which are considered as potential substitutes [10]. These include plastic encased steel pipe core piles, structurally reinforced plastic piles, concrete-filled FRP piles, fibreglass pultruded pipe piles and fiberglass reinforced plastic piles. Among these five types of composite pile, the first three are considered to be better suited for load–bearing applications [11]. Fig. 2 shows the section of the different types of composite piles.

A. Steel Pipe Core Piles

Steel pipe core piles were the first composite piles introduced to the U.S. market [12]. This pile consists of two layers, an inner steel layer and thick outer plastic shell. The inner layer provides the structural strength while the outer shell is used to protect the steel from corrosion. The outer shell is often made from high-density polyethylene (HDPE) which consists of recycled plastic materials (i.e. plastic milk jugs and juice containers). Additives where also included to improve pile durability and ultraviolet (UV) resistance [10]. In the United States, Plastic Piling Inc. is currently the only manufacturer of this type of pile [13]. This type of pile is available in 20-30 cm outer diameter and up to 23 m long. The structural pipe cores range from 10-40 cm outer diameter, with wall thicknesses ranging between 6 and 40 mm. These piles were previously produced in 6 m segmental sections that were connected together with threaded coupling [6]. Early adaptations of this product suffered from delamination of the steel core from the plastic shell due to the difference in thermal coefficients of expansion. Presently, the manufacturer is currently producing products that are guaranteed against shrinkage and expansion cracking for a period of 5 years [3]. Steel pipe core piles are primarily used when piling obstacles such as boulders and stones are present, only a small amount of vibration is acceptable, a very long service life is required, or hard rock can be found at a modest depth [14]. If the plastic shell is used only in the upper portion of the pile that is exposed to water, the design procedure for this pile would be essentially the same as for a conventional steel pipe pile. The plastic shell does not come into play structurally, since its only function is to protect the steel pipe along the exposed portion of the pile. The most common uses for this pile type are as fender piles and pier piles in regions with marine influence. These piles were first installed in April 1987 at Berth 120 in the Port of Los Angeles. Steel core pipe piling has been also used in Pier 16 at the U.S. Naval Amphibious base in San Diego and in Terminal Porturia in El Sauzal, Mexico.

B. Structurally Reinforced Plastic (SRP) Piles

Structurally reinforced plastic (SRP) piles are composed of extruded recycled plastic matrix reinforced with fibreglass rods or steel rebar [5]. The outer surface of SRP piles is typically dense plastic and chemically treated with antioxidants and ultraviolet inhibitors to retard UV degradation [15 & 16]. Additionally, SRP piles are often composed of recycled materials such as plastic milk jugs, soap bottles and juice containers [17].

SRP piles are produced using continuous extrusion process which allows manufacturing of piles in a variety of lengths free of joints [15 & 17]. Piles are available in diameters between 254 mm to 406 mm and are reinforced with 6 to 16 FRP or steel reinforcing rods of diameters ranging from 2.5 cm to 3.5 cm. Pile lengths of up to 32 m can also be found. The reinforcing elements are arranged in a concentric pattern within the inner core of the plastic piling and extend the entire length of the pile. Depending on the structural requirements for the specific piling application, the type, size, and number of reinforcing elements are selected.

C. Concrete-filled Fibre Reinforced Polymer (FRP) Piles

Concrete-filled fibre reinforced polymer (FRP) piles are composed of an outer FRP shell with unreinforced concrete infill. The main role of FRP shell is to provide a stay-in-place structural formwork for the concrete infill, acts as noncorrosive reinforcement, gives confinement to concrete in compression and protects the concrete from severe environmental effects [18]. On the other hand, the concrete infill offers the internal resistance in the compression zone and increases the stiffness of the member and prevents local buckling of the FRP tube [19].

In the United States, there are two primary manufacturers of this type of pile, namely Hardcore Composites and Lancaster Composites. This type of FRP piles was labeled under the commercial names FTP and CP40 respectively [5]. Hardcore piles are typically filled with concrete after installation to improve their structural performance. Lancaster Composites CP40 piles are filled with concrete and cured, prior to driving. The FRP shells used by Hardcore Composites are fabricated using a vacuum-assisted resin transfer moulding process (VARTM), while Lancaster Composite’s FRP shells are made using a filament winding technique. Typically, both piles are available in diameters ranging from 203 mm to 610 mm, with wall thicknesses ranging between 4.6 mm to 9.1 mm. Currently, concrete-filled FRP piles are adopted in a bridge rehabilitation projects in Virginia, USA [10].

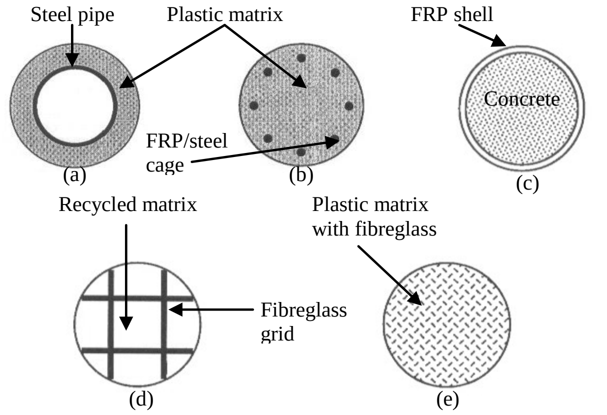

Figure 2. Composite pile types (a) steel pipe core pipe (b) SRP pile (c) concrete-filled FRP pile (d) fibreglass pultruded pipe pile (e) fibreglass reinforced plastic pile [5]

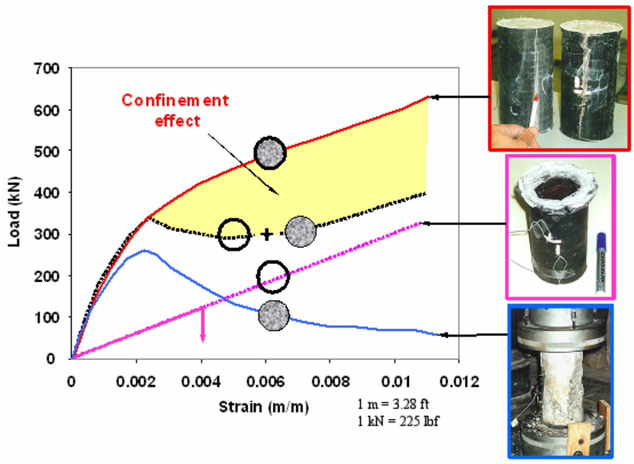

Figure 3. Confinement effect of FRP shell on concrete [19]

D. Fibreglass Pultruded Pipe Piles

Fibreglass pultruded pipe piles are composed of outer fibreglass sheet fitted with a fibreglass grid to provide structural strength. The grid consists of two sets of orthogonal plates joined at four intersecting points and forms a tic-tac-toe pattern. The grid inserts are sometimes filled with HDPE, plastic lumber, or polyethylene foam fills. In fender piling applications, the shell and inserts are used to help absorb the vessel impact and connect fendering fittings. This pile was used in 1996 in a demonstration project at Berth 7 in Port Newark, NJ and in Tifffany Pier Project.

E. Fibreglass Reinforced Plastic Piles

Fibreglass reinforced plastic piles consists of recycled plastic matrix with randomly distributed fibreglass reinforcement [3]. The dense solid outer shell is bonded to the peripheral surface of the inner plastic core which is foam-filled to reduce total weight. Various additives can be mixed with the plastic materials to enhance the performance of the structural member. These additives include antioxidants, colorants, UV protectors, fungicides and compatibilizers.

Trimax is currently the only manufacturer of this product consisting of high density extruded recycled polyethylene reinforced with approximately 20% fibreglass. Piles are available in 25 cm diameter with a standard length of 7.5 m. Presently, fibreglass reinforced plastic piles have limited use in structural applications with more common applications for retaining walls, sound barriers, car stops, walkways, railings and fender piles. Trimax lumber was used in the construction of the Tiffany Street Pier in New York City.

IV. STRUCTURAL BEHAVIOUR

A. Behaviour Under Axial Compression

Among the five types of composite piles, the behaviour of concrete-filled FRP pile has been the main concern of the past and present researchers since its application can be extended to structural members such as beams and columns. It should be noted that in the discussion of structural behaviour, this study adopted the term “concrete-filled FRP tube” instead of “concrete-filled FRP pile”. “Concrete-filled FRP tube” is a widely-used term by most of the researchers in characterizing the structural behaviour of composite materials with circular section.

Experimental results showed that response of concrete-filled FRP tubes under axial compression is bilinear in nature [19-21]. Mirmiran and Shahawy [20] stressed that this bilinear response consists of three distinct regions. In the first region, behaviour is similar to plain concrete, since lateral expansion of the concrete core is insignificant. This phenomenon can be explained in terms of the composite action between the FRP shell and the concrete core. At the earlier stage of the loading, the Poisson’s ratio of the concrete is lower than that of the FRP shell, thus, the FRP shell has no confining effect on the concrete core [21]. With the increase in micro-cracks, a transition zone is entered where the shell exerts a lateral pressure on the core to counteract the stiffness degradation of concrete. Finally, a third region is recognized in which the shell is fully activated, and the stiffness is generally stabilized around a constant rate. The response in this region is mainly dependent on the stiffness of the shell. The ultimate strength of the composite tube is governed by the failure of the FRP shell that fractures in a brittle manner [19].

Various analytical models have been developed to predict the response of concrete confined by FRP tube under axial compression. Models can be classified into two main categories: design-oriented model and analysis-oriented model [22]. Design-oriented model is generally defined using simple closed-form expressions and are suitable for direct use in the practical design. Example of design-oriented model was the work presented by several researchers [20, 21, 23-27]. On the other hand, analysis-oriented models predict the stress-strain curves of the FRP-confined concrete using incremental iterative numerical procedures [18, 19, 28-33]. The use of an incremental approach makes it inconvenient for these models to be adopted in hand or spreadsheet calculations in design, but they are suitable for use in computer analysis such as nonlinear finite element analysis. In general, the predicted response using these analytical models depends mainly on the compressive behaviour of the unconfined concrete and the confining effect of the FRP shell. Fam and Rizkalla [19] studied the effect of FRP confinement on the overall strength of the composite tube.

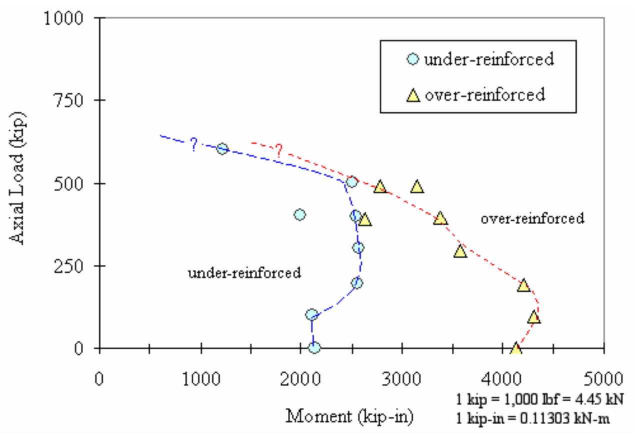

Figure 4. Strength interaction diagram of concrete-filled FRP tube [36].

As shown in Fig. 3, it clearly indicates that the capacity of the composite tube significantly exceeds the sharing capacity (superposed capacity of FRP shell and concrete core) of the two individual materials.

USDT-FHA [34] conducted a feasibility assessment on the compressive behaviour of structurally reinforced plastic pile used for major pile rehabilitation. The result illustrated that the recycled plastics appears to prevent buckling of the bars but does not effectively prevent the peripheral disintegration of the fibreglass; therefore it makes only a limited contribution to the axial compression strength of the composite pile. Only a limited work has been published related to the axial behaviour of the other types of composite piles and definitely more researches are needed in this area.

B. *Flexural Behaviour*

Generally, most of the investigated flexural behaviour of composite pile was focused on concrete-filled FRP tubes. The role of FRP shell during bending is to provide a noncorrosive reinforcement. Its confinement effect is less significant compared when it is under axial compression. The concrete core provides the internal resistance force in the compression zone and prevents the local buckling failure due to ovalization; therefore, the FRP tube is utilized to its ultimate strength [35].

Fam and Rizkalla [35] carried out an experimental investigation on the short-term flexural behaviour of concrete-filled FRP tubes. The outcome revealed that the concrete strength has very little effect on the flexural behaviour of the composite tube and its total behaviour is dependent on the stiffness of the FRP shell. It was also exposed that the stiffness of the beam was reduced due to slip occurrence (bond failure) between the concrete core and FRP shell unless shear transfer mechanism will be adopted.

A detailed study on concrete-filled FRP tubes under various combinations of axial and flexural loads was conducted by Mirmiran et al. [36]. This study adopted two types of FRP tubes to simulate the conditions of over-reinforcement (where compression failure governs) and under-reinforcement (where tension failure governs). The authors found out that over-reinforced specimens were found to behave better as beam columns as shown in the interaction diagram (Fig. 4). Over-reinforced specimens deflected to a lesser extent (ultimate deflections of the over-reinforced specimens were about 25 to 50% lower than the under-reinforced specimens), and failed at much higher bending moments. Failure of the over-reinforced specimens in compression was considered to be gradual or ductile while the under-reinforced failure mode was brittle and sudden. Test observations also indicated that bond failure or slippage in beam columns is not as significant as in beam specimens (pure flexure), as long as the end connections are designed properly. For beam specimens, shear transfer mechanisms such as internal ribs or treatments of the inner surface of the tubes were recommended to enhance the composite action between the FRP shell and the concrete core.

Information on the flexural behaviour of the other types of composite piles (i.e. structurally reinforced plastics and steel core pipe piles) are very limited. Most of the information is narrowed to the reports commissioned by pile manufacturer. This information consists of test results but it does not include design methods [10].

V. GEOTECHNICAL PERFORMANCE

A. *Pile Driveability*

Very few case histories are available with driving information of concrete-filled FRP piles. There are however parametric or analytical studies performed to investigate the feasibility of driving composite piles and to compare their performance to conventional steel and concrete piles.

Generally, pile driveability is dependent on the energy delivered to the pile by the pile driving hammer, the resistance to driving offered by the soil, the ability of the pile to transfer driving stresses to the pile tip, and the strength of the pile to resist driving stresses [10]. The ability of the pile to transfer the energy imparted by the driving hammer into a force in the pile is related to the pile impedance (or dynamic stiffness). Impedance is defined as $Z = EA/c$, where E is the elastic modulus of the pile, A is the pile cross-sectional area, and c is the wave propagation speed in the pile. The greater the impedance of the pile, the greater is the force that will be transmitted by the pile into the ground.

Mirmiran et al. [37] experimentally investigated and compared the behaviour of empty and filled composite tubes under the actual field driving impact. The authors found that driving stresses in filled tubes were comparable to that of the prestressed concrete pile. The empty tubes, however, were found to be susceptible to buckling and damage during driving unless driven to shallow depths in soft soils or with a steel mandrel.

Ashford and Jakrapiyanun [38] compared the drivability of FRP composite piles to conventional prestressed concrete and steel pile using wave equation analysis program (WEAP87). Result showed that the impedance of pile composed solely of GFRP tube is significantly lower than all other piles analyzed, and the results in the GFRP piles reaching a limiting capacity (at refusal) of only 65 to 75% of the other piles. The authors stressed that low area and modulus of elasticity of GFRP tube make its impedance lower, thus its refusal rate is lower compared to that of the other tested piles.

Wave equation analysis program (WEAP87) was also adopted by some researchers [5 & 13]. It was concluded from this study that the modulus of elasticity and specific weight has a significant influence on the drivability of composite piles.

However, damping has less effect on the drivability of composite piles.

Pando [10] compared the different impedance values of composite piles and prestressed concrete pile. Outcome explained that the prestressed concrete pile and the concrete filled FRP pile have comparable impedance values, and so far have the highest values. The plastic-encased steel pipe pile and the FRP-reinforced recycled plastic pile impedance values are about 55 percent and 29 percent of the impedance of the prestressed concrete pile, respectively. The lowest impedance value corresponds to the empty FRP shell with a value equal to about 12.5 percent of the prestressed concrete pile.

It is clear that a significant amount of research is needed in this area. Particularly, there is an urgent need for more field tests carried out on sites to carefully assess and verify the driveability of composite piles.

B. Axial Load Capacity

The axial load capacity of driven FRP composite piles depends mainly on three aspects namely; axial stiffness (AE) where A is the cross sectional area and E is the elastic modulus, residual stresses left in the pile and soil after installation, and the resistance of the soil to pile downward movement [10]. One significant disparity between the conventional and the composite piles is that the skin friction estimation used in determining the shear resistance against vertical load may not be applicable to both piles. This is because the shear strength at the interface of the pile and soil is mainly different for both pile materials due to unique interface properties such as the surface hardness and toughness of the adopted pile.

Pando et al. [39] evaluated the skin friction between sand and FRP materials experimentally using the interface shear test (IST). Outcome of the results indicated that the interface friction angles of the FRP composite piles depend on the values of the relative roughness parameters, such as the relative height and the relative spacing. Interface friction angles tend to increase as the relative height increases, and they tend to decrease as the relative spacing increases. Surface hardness and angularity of soil grains were also found to have important influences on the values of the interface friction angle for a relatively smooth FRP surfaces.

These findings were also identified in a comprehensive study describing the skin friction characteristics of FRP composite piles against sand [40 & 2]. Aside from the three factors mentioned by Pando et al. [39] that dominated the shear interface characteristics, Frost and Han [40] stressed out that the normal stress level and the initial density of the soil mass has also influence on the characteristics. On the other hand, specimen preparation method, the rate of shearing, and the thickness of the soil specimen had a little control on the measured interface friction coefficients.

Interface shear test data for other types of composite piles are currently not available, and clearly this area requires a considerable amount of study.

C. Lateral Load Capacity

The performance of composite piles against lateral load is mainly governed by its lateral deflections. According to Pando et al. [10], lateral deflections of single composite pile is highly dependent on the applied lateral load, the bending stiffness (EI) and the soil resistance to lateral movement (characterized by soil strength and stiffness). In the case of concrete-filled FRP composite piles, it is expected that generally this kind of piles will exhibit lower bending stiffness compared to traditional pile materials. Therefore, lateral deflections of the former pile material are expected to be greater than the latter pile materials.

Limited studies are available on the capacity of composite piles under lateral load. Pando et al. [10] presented the observed performance of the concrete-filled FRP composite pile in comparison with the standard prestressed concrete in response to lateral loading. Both piles were subjected to rapid lateral loading using Statnamic testing device. The result showed that initially, the concrete-filled FRP composite pile exhibited a lateral stiffness similar to that of the prestressed concrete pile up to 17% of the applied lateral load. Beyond this, the composite pile’s response was much less stiff than the prestressed concrete pile response. In general, the prestressed concrete pile and the concrete-filled FRP pile exhibited similar load-deflection while the plastic pile exhibited much larger deflections at the same lateral loads [10].

Certainly, more research is required in this area. Further research should not only aim to improve understanding of the load-deflection response of the composite piles, but also to develop a reliable and easy-to-use design procedures that can be readily implemented by practitioners.

VI. DURABILITY

For the past years, geosynthetic materials have already been used extensively in civil engineering construction with apparent success. Due to its application to environment that can contain significant amounts of chemicals, strength degradation may pose risk to its durability. The degradation of polymers upon exposure to adverse conditions depends on the macromolecular structure, the presence of additives, and the presence of contaminants commonly present in recycled plastics [3]. The principal result of this degradative mechanics is the loss of mechanical strength that may lead to unfavourable engineering performance and a shorter life cycle.

Pando et al. [42] conducted a study on the durability of concrete-filled tubular FRP piles. He stressed that the primary mechanisms of strength and stiffness loss considered are related to moisture absorption, fibre/matrix interface damage, and stress crack corrosion of the fibre and matrix degradation through chain scission. 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, fibre-matrix debonding, and corrosion of glass fibres. For instance in the report of Pando et al. [42], the recorded strength and stiffness reductions was on the order of 20% and 5%, respectively, for E-glass/vinyl ester composites submerged in 25 degrees Celsius water for a period of 200 days. The implications of such strength and stiffness reduction on the design of composite piles can be significant, especially in deflection-critical designs.

VII. CONCLUSION

This paper presents reviewed record and information related to composite piles. Significance is given to history, material types and properties, structural behaviour, geotechnical performance, and durability of composite piles. Result of the literature review shows that there is only a limited study on the geotechnical performance of the composite piles. There is a necessity for more field tests to carefully assess and verify the geotechnical performance of the composite piles to be used in developing reliable design procedures. To date, long-term durability research for composite piles is inadequate, and therefore needs significant studies to fully understand its behaviour under different degrading factors.

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