Preliminary Study on the Behaviour of Fibre-Reinforced Polymer Piles in Sandy Soils

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Abstract: Fibre-reinforced polymer (FRP) is a type of composite material used to provide resistance to corrosion when incorporated into piles. However, there is a gap in knowledge in terms of the behaviour of FRP piles under axial or lateral loading in soils. Thus, the aim of this experimental study is to assess the factors that influence the behaviour of FRPs under axial and lateral load in sandy soil. CFRP (carbon-fibre-reinforced polymer) and GFRP (glass-fibre-reinforced polymer) piles were tested in this experiment based on a special pressure chamber. The results show that the surface roughness (R_t), confined pressure (σ_c), and relative density (D_r) determined the shearing resistance of the soils and subsequently affected the bearing capacity of the FRP piles under an axial load. The flexural stiffness of the FRP piles was determined by the FRP type, pile diameter, and aging in the environment, which were affected under the lateral load. In addition, an alkaline environment was more aggressive to the FRP piles than those aged in an acidic environment. The numerical modelling results show that the sand types, in terms of the dilation angle and Young’s modulus, also had a great influence on the behaviour. This feature should be considered more carefully in future studies.

Keywords: fibre-reinforced polymer; composite pile; composite material; cohesionless soil

1. Introduction

Fibre-reinforced polymer (FRP) is a type of composite material that consists of two components—reinforcing and matrix components. Usually, the reinforcing component is formed of fibre, which controls the stiffness and strength of the FRP. The matrix component is made from polyester, vinyl ester, epoxy, phenolic, thermoplastic, etc., providing protection to the fibres. Fibres can also be reinforced by carbon, glass, and aramid, and these materials are often referred to as CFRP, GFRP, and AFRP, respectively. There are several factors that affect the properties of FRP, such as the fibre content, orientation, and its matrix, all of which thus affect the strength of the FRP [1–3].

Because of its advantages [4,5], the use of FRP in civil engineering has recently gained popularity around the world and engineers are confident applying this technology to civil engineering [2,6–10]. FRP materials are used as a reinforcing material for internal structure components such as beams and slabs. They are also used in external structures, such as road pavements, columns, foundation piles, and certain bridges. One innovative product in civil engineering is FRP tubes filled with concrete to form FRP piles [2]. An FRP pile is a composite material that has an outer FRP shell and an inner concrete core. The inner concrete core provides the compressive strength to the FRP pile and the outer FRP shell provides the tensile strength and resistance to corrosion.

In geotechnical engineering, piles are used to support heavy structures both inland and offshore; however, conventional piles made of steel, concrete, and timber may encounter problems in harsh environments from corrosion. Thus, the use of FRP piles for geotechnical engineering has recently become more popular because of its advantages of being easy to
maintain, having a long durability, and being environmentally friendly [11–13]. Investigations of FRP piles have been undertaken, including the structural behaviour of FRP piles, the characteristics of FRP types, and the resistance against corrosion [14–27].

As piles are used to support heavy structures, the soil condition is an important aspect that needs to be evaluated for FRP piles; however, most works mentioned above are based on the FRP piles alone and the effect of soil is not considered. In fact, investigations regarding FRP piles considering the effect of soil are lacking from the literature, and the amount of work on FRP piles is limited compared with that on conventional piles [28–33]. Giraldo and Rayhani [32] concluded that the current knowledge regarding FRP piles under different load modes is insufficient, resulting a gap in the current state of knowledge. Additionally, because of the relatively low stiffness of the FRP piles, one needs to be more careful in the installation of the FRP piles compared with conventional piles. Currently, there are no specific guidelines for the installation of FRP piles, resulting in limited applications of FRP piles [2]. On the other hand, there is an increasing demand to construct FRP piles safely and economically in practice. Therefore, the objective of this experimental study is to evaluate the possible factors that influence the behaviour of FRP piles under axial and lateral loads in sandy soil so that engineering decisions can be made to offer more efficient construction guidelines.

2. Materials and Methods

2.1. Experimental Apparatus

The pressure chamber was specifically manufactured in the workshop (Figure 1). The critical component of the pressure chamber was the soil cell, which was produced from 10 mm thick mild steel. The inside diameter and height of the soil cell was 300 mm and 550 mm, respectively. In order to simulate the various stress conditions that are similar to on-field situations, a plastic diaphragm was attached at the bottom of the soil cell, which could be operated separately. The diaphragm had pressure applied that was sourced from a digitally controlled external pump. For both the axial and lateral loading tests, the top plates were machined with holes of different shapes (Figure 2). These holes were made to allow the FRP piles (300 mm in length and 20 mm in diameter) to be tested under different axial and lateral loads. Finally, the pressure chamber was assembled in the laboratory prior to the actual test. Other apparatus included a GDS (Global Digital System) pump, LVDT (a linear variable differential transducer), a load cell, and a data recorder.

![Figure 1. Illustration and dimensions of the setup tested in the laboratory connected to the GDS controller and computer (not to scale).](image-url)
The axial loading tests consisted of a loading rod located at the top of the pile and in contact with the load cell, which was fixed to the MTS (material testing system) (Figure 3). Constant loading increments of 50 N were applied for the axial loading tests. After each incremental process, the load applied was held constantly for 2.5 min for the stress equilibrium. Then, the pile head settlement was recorded. Similarly, the lateral loading tests consisted of a hydraulic jack which was placed horizontally to the pile head and a steel frame that was fixed above the top plate (Figure 4a). Between the reaction frame and hydraulic jack, a 2.5 kN load cell was inserted in order to obtain the value of the applied lateral load at the pile head. In order to monitor the lateral displacement, an LVDT was placed on the reaction frame next to the soil (Figure 4b). The actual profile is shown in Figure 4c.
Surface roughness is an important factor that influences the behaviour of FRP piles under axial loading; thus, the surface roughness coefficient was measured using a Taylor Hobson Profilometer. The model used was a Surtronic 25. It used a transducer to measure the surface roughness through movement along the surface of the material. The transducer was in contact with the material surface and then the surface roughness was measured as the transducer moved. When the resolution was 10 μm, its accuracy was 0.01 μm. When the resolution was 100 μm, its accuracy was 0.1 μm. When the resolution was 300 μm, its accuracy was 1 μm. Each pile was measured three times using the profilometer and the average was taken.

Figure 4. Profile of the pressure chamber tested under lateral load (a), enlarged drawing of lateral loading setup (b), and actual profile of the test condition (c).
Surface roughness is an important factor that influences the behaviour of FRP piles under axial loading; thus, the surface roughness coefficient was measured using a Taylor Hobson Profilometer. The model used was a Surtronic 25. It used a transducer to measure the surface roughness through movement along the surface of the material alone. The transducer was in contact with the material surface and then the surface roughness was measured as the transducer moved. When the resolution was 10 μm, its accuracy was 0.01 μm. When the resolution was 100 μm, its accuracy was 0.1 μm. When the resolution was 300 μm, its accuracy was 1 μm. Each pile was measured three times using the profilometer and the average was taken.

2.2. CFRP, GFRP, and Mild Steel Tube

The FRP tubes used in this study were CFRP and GFRP. The orientation of the fibre was the same for both tubes; thus, the orientation effect was not investigated. The outer diameter of both the CFRP and GFRP was approximately 20 mm and the wall thickness of these tubes was 1.25 mm. The total length of the FRP tube was 300 mm, with 270 mm embedded in the soil. The surface roughness (μm) of the GFRP, CFRP, and mild steel was 27.3, 18.1, and 7.8, respectively.

2.3. Mortar

All of the tubes used in this study were filled with a mortar mix by funnelling. The composition of the mortar mix was based on the condition shown in Table 1. Mortar, as a filling material, is able to flow easily and eliminate the air pockets without any mechanical vibration, and thus a good filling quality is assured. After filling, the piles were cured at 20 °C for 1 day and then kept in water (20 °C) for two days to soak.

**Table 1.** Mixture conditions of mortar.

| Name       | Cement:Sanding:Aggregate | Water/Cement | Silica Fume % | Superplasticiser % |
|------------|--------------------------|--------------|---------------|--------------------|
| Mortar     | 1:2:0                    | 0.4          | 10 to cement  | 0.15               |

2.4. Sand

The sand used in this study was sourced in Congleton, England. The particle size distribution for this sand is presented in Figure 5. The maximum and minimum density of the sand were 1.74 and 1.52, respectively, with the specific gravity being 2.65.

![Figure 5. Particle size distribution of the Congleton sand.](image)

3. Methods

3.1. Preparation Procedures

A special “raining” technique was used during preparation to ensure the homogeneity of the sand, as well as for uniform distribution in the pressure chamber (Figure 6).
Sand was dropped in a hand controller which consisted of two sieves of different mesh sizes. These sieves were fixed to the device’s frame by bolting, the mesh sizes of the top and bottom sieves were 5 and 2.5 mm, respectively. The height of the diffuser sieves could be controlled by moving the device’s location in relation to the pressure chamber to form four layers of sand in the pressure chamber.

![Diagram of sand preparation process](image)

**Figure 6.** Raining method in order to prepare a uniform distribution of the sand in the cell (not to scale).

There were three preparation stages to install the pile in the sand in order to form these four layers (Figure 7): (1) sand preparation under the pile base, (2) fix the pile at the centre of the chamber, and (3) stop when the sand surface is levelled. The first layer in stage one formed a bottom layer to support the FRP piles, and the target level for the first layer was 85 mm above the diaphragm. As the relative density and volume of the sand were known (i.e., 80% or 60%), the required sand mass could be calculated and deposited into the pressure chamber using the raining method. Subsequently, the sand surface was levelled and statically compressed to the target height. In stage two, the FRP piles were hung vertically in the centre and then the sand was deposited using the raining method to form the second, third, and fourth layers, which had a target thickness of 90 mm. In stage three, the specific top plate (Figure 2) was placed in the pressure chamber before the final assembly.

![FRP preparation steps](image)

**Figure 7.** FRP preparation steps in the pressure chamber.
Although engineering practices make use of FRPs in marine and waterfront applications, their performance can be compromised in extreme environments. Thus, aging in the environment can be a critical factor affecting the FRP pile’s performance in the long term. The GFRP and CFRP piles were aged in two extreme environments in this study, namely acidic (pH = 2) and alkali (pH = 12) solutions, for a duration of 6 months. The rate of aging process was enhanced at 45 °C in the oven, which was also adopted by the authors of [34]. Finally, the CFRP and GFRP piles were moved out of the oven after 180 days and left to dry at 20 °C for three days.

3.2. Experimental Program

The experimental program is summarised in Tables 2 and 3. The factors affecting the FRP pile behaviour under an axial load include the surface roughness, loading rate, confined pressure, and relative density. Similarly, the factors affecting the FRP pile behaviour under a lateral load include the FRP type, pile diameter, and aging in the environment. There were 18 tests conducted in this experimental study.

Table 2. Program for the effect under axial load.

| Effect of Study     | Pile Type             | No. of Tests | Confined Pressure (kPa) | Relative Density % |
|---------------------|-----------------------|--------------|-------------------------|--------------------|
| Surface roughness   | GFRP/CFRP/Mild steel  | 3            | 250                     | 80                 |
| Loading rate        | CFRP                  | 3            | 250                     | 80                 |
| Vertical pressure   | GFRP                  | 2            | 250/100                 | 80                 |
| Relative density    | GFRP                  | 2            | 250                     | 80/60              |

Table 3. Program for the lateral flexural stiffness test.

| Study                      | Pile Type        | No. of Tests | Confined Pressure (kPa) | Relative Density % |
|----------------------------|------------------|--------------|-------------------------|--------------------|
| FRP type                   | GFRP/CFRP        | 2            | 120                     | 80                 |
| Pile diameter              | CFRP             | 2            | 120                     | 80                 |
| Aging in the environment   | GFRP/CFRP        | 2            | 120                     | 80                 |
| (pH = 2)                   |                  |              |                         |                    |
| Aging in the environment   | GFRP/CFRP        | 2            | 120                     | 80                 |
| (pH = 12)                  |                  |              |                         |                    |

4. Results

4.1. Factors Affecting FRP Pile Behaviour under an Axial Load

Figure 8 shows the settlement due to the axial load for all three types of piles tested at 250 kPa and with 80% relative density. It can be seen from Figure 8a that the bearing capacities of both GFRP and CFRP were higher compared with the mild steel variant, as a larger settlement was observed for the mild steel pile under the same load. The surface roughness coefficient of each material is shown in Table 4, indicating that the GFRP and mild steel pile had the highest and lowest surface roughness, respectively. Figure 8b illustrates the results of the loading rate (0.5, 1.5, and 5 mm/min) on the behaviour of CFRP piles, which was tested at 250 kPa and with 80% relative density. It can be concluded that the loading rate had an insignificant effect on the bearing capacity for all three kinds of piles. This behaviour was in agreement with another study [35]. Two tests considering different confined pressures (100 kPa or 250 kPa) were conducted on the GFRP piles embedded in sand with 80% relative density. Figure 9a illustrates that, when the confined pressure increased from 100 kPa to 250 kPa, the piles were able to sustain a larger axial load subjected to the same settlement. The effect of relative density (60% and 80%) was investigated on the GFRP piles tested with 250 kPa pressure. It is observed from Figure 9b that the bearing capacity of piles increased when the relative density increased.
Figure 8. Effect of surface roughness under an axial load (a) and effect of loading rate on CFRP piles under an axial load (b).

Table 4. Surface roughness (Rt) of different types of FRP.

| Pile Type   | Rt (µm) |
|-------------|---------|
| GFRP        | 27.3    |
| CFRP        | 18.1    |
| Mild steel  | 7.8     |

Figure 9. Effect of confined pressure on GFRP piles under an axial load (a) and effect of relative density on GFRP piles under an axial load (b).

4.2. Factors Affecting FRP Pile Behaviour under a Lateral Load

The effect of FRP was investigated based on the piles with a 20 mm diameter and embedded in sand with 80% relative density. First, 120 kPa pressure was applied by the GDS pressure pump. Figure 10a shows the CFRP and GFRP deflection due to the lateral load. The results suggest that the flexural stiffness of CFRP was higher than that of GFRP. Subsequently, the performance of the CFRPs with diameters of 12.5 and 20 mm
was evaluated. The tests were conducted under 120 kPa confining pressure and in sand with 80% relative density. From Figure 10b, the results show that the flexural stiffness is positively correlated with the diameter of the piles. In general, increasing the cross-sectional area will increase the piles’ stiffness, resulting in a larger flexural stiffness being obtained [36]. It should be mentioned that the flexural stiffness of CFRP piles is always larger than that of GFRP piles because of the higher stiffness of carbon fibre [1].

![Figure 10](image1.png)

**Figure 10.** Effect of FRP types under a lateral load (a) and effect of diameter under a lateral load (b).

The effect of aging in the environment on the FRP piles (CFRP and GFRP) was examined in terms of flexural stiffness under a lateral load. For both GFRP and CFRP after aging in acidic (pH = 2) and alkalic (pH = 12) environments, the lateral deflection was larger than the piles without aging (Figure 11a,b). Additionally, the deflections for the piles aged in the alkaline solution were always higher than those aged in the acidic solution. Therefore, the alkaline solution was considered to be a more aggressive medium than the acidic solution regarding the effect on the flexural stiffness of the FRP piles. In fact, the only failure captured in this experiment was for the GFRP pile, which was aged in the alkaline solution and the other tests did not reach the ultimate strength. Based on the failure profile of the GFRP pile in Figure 12, it is observed that the crack was on the tension side when the FRP piles were subjected to lateral loading and the depth that could be affected was about 35 mm.

![Figure 11](image2.png)

**Figure 11.** Aging effect on GFRP piles under a lateral load (a) and aging effect on CFRP piles under a lateral load (b).
Figure 12. Crack on the tension side of the GFRP pile after aging in pH = 12.

5. Discussion

Figure 13 summarises the factors that influence the behaviour of FRP piles under an axial load. The factors influencing the behaviour of the FRP piles can be categorised into two groups: the shearing resistance of the soils or the FRP type. The shearing resistance can be affected by the relative density or confined pressure of the soil condition. When the soil matrix becomes denser (i.e., higher relative density), the interlocking between the particles of soils becomes stronger, resulting in a larger shearing resistance in the soil. Similarly, when soils are confined in a larger pressure, the shear strength will increase based on the Mohr–Coulomb failure criterion (Equation (1)). A larger shear strength of soils will bring a larger shearing resistance against soil particles being pushed away, when a pile is pushed downwards.

\[
\tau = \sigma \tan \varphi + c
\]

where \(\tau\) is the shear strength of the soil, \(\sigma\) is the confined pressure, \(\varphi\) is the friction angle of the soil, and \(c\) is the cohesion of the soil (\(c = 0\) for sand).

Figure 13. Surface roughness (R_t), confined pressure (\(\sigma_c\)), and relative density (\(D_r\)) affecting the behaviour of FRP piles under an axial load.
The shaft resistance can be estimated using Equation (2) [33], which is also affected by the interfacial resistance between the soil particles and the surface roughness of the FRP pile (Figure 14). When the surface roughness coefficient is larger, \( q_s \) will be larger. A larger \( q_s \) will obtain a larger shearing resistance in the shaft \( (Q_s) \). Additionally, this shaft resistance is also in the vertical direction, so \( Q_s \) will resist the load in the axial direction. Therefore, an FRP pile with a larger surface roughness coefficient will resist a larger axial load.

\[
Q_s = CLq_s
\]

(2)

where \( Q_s \) is the shaft resistance, \( C \) is the pile circumference, \( L \) is the pile embedment, and \( q_s \) is the average shear strength.

![Illustration of the interfacial resistance between soil particles and the surface of the FRP piles.](image)

**Figure 14.** Illustration of the interfacial resistance between soil particles and the surface of the FRP piles.

The factors affecting the FRP pile behaviour under a lateral load are summarised in Figure 15. The increase in the diameter of the piles will increase the flexural stiffness, so that the tensile strength is enhanced. In addition, the tensile strength of an FRP pile also depends on the FRP type. In general, CFRP has been found to have a better tensile strength than GFRP [1,13]. In fact, because of the characteristics of carbon fibre, CFRP not only has a better tensile strength than the other types of FRP piles, but it also has a better resistance against dynamic loading, thermal expansion, creep, and fatigue [1].

![The aging environment and FRP type affect the behaviour of FRP piles under a lateral load.](image)

**Figure 15.** The aging environment and FRP type affect the behaviour of FRP piles under a lateral load.
Aging in the environment will affect the engineering property of the epoxy resin in the polymer [37], and micro cracking will be generated when epoxy resin is immersed in an aqueous solution [38]. It was observed that the piles aged in the alkaline environment were more vulnerable than those aged in the acidic environment. Because of the characteristics of the epoxy resin in the polymer, the alkaline solution was able to penetrate through the epoxy resin and affect the micro structure [1,39,40]. As a result, the matrix was separated in the micro structure between the fibre and epoxy resin. Consequently, the interfacial resistance and bonding strength between the fibre and epoxy resin in the matrix were compromised, leading to a reduction in the flexural stiffness of the FRP piles in the macro behaviour [34,41]. Meanwhile, the alkali environment also caused embrittlement to each individual fibre, resulting in a strength reduction in the fibre in the matrix. Thus, the overall flexural stiffness of the FRP piles was reduced after aging.

6. Numerical Modelling of Sand Type Influence

6.1. Model Construction and Validation

The finite element analysis software, Abaqus, was used for numerical modelling in the 3D analysis (Figure 16). The elasticity model for the piles and the Mohr–Coulomb model for the sand were used in this section. The interface friction contact technique was used to simulate the pile and sand interface [42]. The loading of the pile/soil numerical model was conducted following the loading procedure in the lab, where the lateral or axial load was applied incrementally (Abaqus steps option) on the loaded nodes on the top of the pile, and the generated displacement was observed. As a result of the axi-symmetrical numerical model loading, only a half-cylinder representing the sub-soil and the pile model was chosen and considered. A C3D8R-8-node linear brick, reduced integration, and hourglass control element type were used for the soil and the piles. The number of elements for the simulated piles and soil was 1908, the approximate global size was 14, and the maximum deviation factor for the mesh was $h/L = 0.1$. Local mesh refinement was applied near the pile tip to consider the high-stress variation in this zone. A fixed boundary was applied on the model base and lateral border in the radial directions, whereas on the symmetrical plan, a roller boundary was applied.

![Figure 16. 3D construction of the model.](image)

The materials of the FRP and sand are generally complex; therefore, in order to achieve simplicity, the tubes were modelled as being unidirectional orthotropic. The properties of the CFRP and GFRP are provided in Tables 5 and 6.

| Material Model          | Young's Modulus, $E$, (MPa) | Poisson's Ratio, $\nu$ |
|-------------------------|-----------------------------|------------------------|
| Pile Elastic            | 28,000                      | 0.22                   |
| Sand Mohr−Coulomb       | 41.5                        | 0.31                   |

| Property Symbol | Unit | CFRP | GFRP |
|-----------------|------|------|------|
| Density         | g/cm$^3$ | 1.6  | 2    |
| Longitudinal Modulus * $E$ | MPa | 135,000 | 50,000 |
| Transverse in-Plane Modulus * $E$ | MPa | 10,000 | 40,000 |
| Transverse in-Plane Modulus * $E$ | MPa | 10,000 | 8500  |
| In-plane Shear Modulus ** $G$ | MPa | 5000  | 4300  |
| Out-of-Plane Shear Modulus ** $G$ | MPa | 1900  | 3500  |
| Out-of-Plane Shear Modulus ** $G$ | MPa | 5000  | 4300  |
| Major in-Plane Poisson's ratio ** $\nu_{12}$ | ---- | 0.3  | 0.27  |
| Out-of-Plane Poisson's Ratio ** $\nu_{23}$ | ---- | 0.5  | 0.5   |
| Out-of-Plane Poisson's Ratio ** $\nu_{13}$ | ---- | 0.3  | 0.27  |

* Given by the manufacturer; ** Shaia 2013 [1].
In this study, CFRP was loaded under three dilation angles, namely, 0, 4, and 15 degrees. The results are shown in Figure 19. The results suggest that the CFRP piles responded to different dilation angles. The yielding capacity was reached for zero-dilatation sand ($\psi = 0$), while a nearly elastic response was observed at a high dilation angle ($\psi = 15$). In general, the responses of different piles showed negative correlation between the sand dilation angle and settlement. Generally, the angle of dilation had a greater influence on the settlement response under an axial load than a lateral load.
The effect of Young’s modulus from the sand to the CFRP piles was also investigated in this study. The investigation was carried out by subjecting the CFRP model to E values of 20, 41.6, and 65 MPa. Figure 20 shows the deflection behaviour due to the lateral load of the pile models under each E value. The curve responses show that the decreases in E can increase the deflection of the CFRP pile. As predicted, the pile deflection increased more significantly when it was in loose sand, as the lateral support was weaker. This result demonstrates that the Young’s modulus of the sand had a significant impact on the lateral deflection.
7. Conclusions

A pressure chamber was manufactured to assess the performance of the FRP piles in sandy soil. The factors affecting the behaviour of the GFRP and CFRP piles under an axial and lateral load were preliminarily studied. It was found that a larger confined pressure had a stronger resistance to sand as the settlement was yielded at about 1.5 kN and 2 mm at 100 kPa confined pressure, compared with the yielding point at 2 kN and 8 mm at 200 kPa confined pressure. Similar behaviour was observed for 80% relative density in sand compared with the 60% relative density condition. The 12.5 mm pile had almost double the deflection compared with the 20 mm diameter pile, because a stronger flexural stiffness was provided by the larger diameter. Aging in the environment was found to be a critical factor that changed the micro structure of the polymer matrix, resulting a reduction in the flexural stiffness of FRP piles in the macro behaviour. The alkaline environment had more of an impact than the acidic environment on the flexural stiffness of the FRP piles. The sand type also had a greater effect on the behaviour, as the larger dilation angle of the sand reinforced the sand at shearing, so as to provide a stronger resistance for settlement. Similarly, a lower Young’s modulus for the sand resulted in a larger deflection lateral loading because of less resistance being provided by the sand. This study also suggests conducting more tests considering different sands and materials in order to build a more general conclusion for engineering practice.

**Figure 20.** Effect of the Young’s modulus of sand under a lateral load on CFRP pile deflection.

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