Behaviour of fibre composite pile under axial compression load

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ABSTRACT: Fibre reinforced polymer (FRP) composite piles offer advantages compared to traditional pile materials since the latter materials have limited service life when used in marine environment. As a result, application of composite piles started to gain acceptance in pile rehabilitation and replacement. Apart from composite piles' advantages, there is a need to assess its structural behaviour under different loading conditions. To perform this, the present paper experimentally and numerically investigates the behaviour of hollow FRP composite pile under axial compression. It was found that fibreglass-reinforced lamina bears 96% of the applied load while 4% was carried by Soric XF-reinforced lamina. Lateral strain of the plies remains the same across the thickness of the tube irrespective of the loading magnitude while axial strain variations on plies were developed at increasing applied load. Furthermore, the load-strain curves of the finite element model are in close agreement with the experimental results.

1 INTRODUCTION

For the past decade, fibre reinforced polymer (FRP) composites have found increasingly wide applications in civil engineering, both in retrofit of existing structures and in new construction. FRPs offer advantages compared to traditional construction materials for being lightweight, high strength and corrosion resistant. As a result, application of composite piles started to gain acceptance in pile rehabilitation and replacement. Indeed, several studies around the world are currently underway examining its behaviour and its extent of relevance in waterfront and highway structures.

Pile materials such as steel, concrete and timber have limited service life when used in harsh marine environment due to corrosion, degradation and marine borer attack. These problems coupled to traditional materials led researchers to investigate the feasibility of adopting FRP composite piles as an alternative in piling system. Review of the available literature shows that currently there are five common types of composite piles which are considered as potential substitutes. These include plastic encased steel pipe core piles, structurally reinforced plastic matrix piles, concrete-filled FRP tubular piles, fiberglass pultruded piles and plastic lumber piles (Niroumand, 2009). Among these five pile types, the first three are considered to be better suited for load–bearing applications (Lampo et al., 1998). Concrete-filled FRP piles, which somehow have a relation to the present study, may be made from filament winding, pultrusion, and resin transfer molding processes (Iskander & Hassan, 1998). The FRP shell provides, among other things, a stay-in-place concrete form, confinement to the concrete, tensile reinforcement, and corrosion protection (Fam & Rizkalla, 2001) while the concrete infill provides compressive load capacity.

Basic among the in-need for assessment in FRP composite piles is its behaviour when subjected to axial compression. The response of the pile under axial loading is considered to be among the factors that most affect the superstructure's behaviour especially for gravity loading (Comodromos et al., 2009), thus this necessitates attention.

Studies on hollow FRP composite piles are very rare due mainly to some issues particularly on its performance when driven on the ground. Mirmiran (2002) found out that empty tubes are susceptible to buckling and damage during driving due to lower impedance and can only sustain driving stresses up to 40-50% of the refusal rate of the concrete piles, unless driven to shallow depths or in soft soils. However, this driving issue is not considered as significant if hollow FRP composite piles are used in partial replacement of a damaged traditional pile where driving force is not required.

Outcome of the previous study conducted by Pando et. al. (2002) on concrete-filled tubular pile revealed that both of the components responded significantly until failure with unique responses at different stress levels. At the maximum stress level, concrete core started to experience apparent micro-cracking while FRP shell applies a radial confining pressure increasingly due to its elastic properties. It was concluded from this study that ultimate peak strength of the composite pile was mainly governed by the hoop tension of the FRP shell.

FRP tube behaviour was investigated by Hashem and Yuan (2000) using experiment and numerical analysis. Result showed that the compressive stress-strain relations for all specimens were largely linear. Initiation of failure in these segments occurred at the bottom surface of the specimen. The complete collapse happened after micro-buckling leading to the delamination of all four laminates making up the cross section and the virtual crushing of the bottom surface of the specimen.

This paper experimentally and numerically investigates the behaviour of hollow FRP composite pile under axial compression. Both results are presented to compare its behaviour derived from experiment and FE analysis.

2 EXPERIMENTAL PROGRAM

Test on short FRP pile was conducted to determine its behaviour under axial compression load prior to laminate test. FRP pile was loaded up to a maximum load of 414 kN. Detail of this experiment is later considered and discussed in this section. Discussions include pile material properties, laminate lay-up and test methodology.

2.1 *Materials and pile laminate layup*

Two basic lamina materials were used in the experiment and in finite element analysis namely; 0.5 mm thick lamina reinforced by 601 (600 gsm) biaxial [0/+90] fiberglass with vinyl ester and 2.0 mm thick lamina reinforced by Soric XF with vinyl ester. The geometric properties and laminate lay-up of the FRP composite tube are presented in Tables 1 and 2, respectively.

2.2 *Test methodology*

To characterise the behaviour of both laminate and FRP tube, two basic types of tests were undertaken in this study. Laminate testing was done to determine the material properties of the laminate material and compression test was performed on short FRP composite pile to evaluate its behaviour under axial compression load excluding the effect of buckling.

Laminate test was undertaken in this study to determine the material properties of a 22mm thick laminate (i.e. combined effect of fiberglass and Soric XF reinforced laminae). Four test coupons taken directly from the composite tube were tested according to ISO14126:1999- Plastic Compression Test. To monitor the deformation, two strain gauges were positioned on the mid-height of the specimen. Collections and recordings of data were generated using Systems 5000 data logger connected to the upper load cell and strain gauges. Figure 1 shows the set-up and instrumentation of the laminate test.

Compression test on short pile was conducted using a 500 kN loading capacity AVERY testing machine. Test set up was arranged as shown in Figure 2 including indicated pile dimensions. To protect pile circumference edges from compressive crushing, a piece of plywood was placed on both ends of the specimen. The specimen was loaded up to a maximum load of 414 kN at a rate of 2 mm per second. Four unidirectional strain gauges were positioned at the mid-height of the specimen. Collections and recordings of data were generated using Systems 5000 data logger connected to the upper load cell and strain gauges.

Table 1. Geometric properties of FRP tube.

Properties	Property value	Unit
Thickness	22	mm
Outside diameter	294	mm
Inside diameter	250	mm
Height	230	mm

Table 2. Laminate lay-up and stacking of FRP tube.

Stacking sequence	No. of layers
[G*/G/G/G/S/S/G/S/S/ G/S/G/S**/G/G/G/G /G/G/G/G/G/G/G/G***]	26

Note: * = Ply 1, ** = Ply 13, *** = Ply 26
G = glass-reinforced lamina S = Soric XF-reinforced lamina

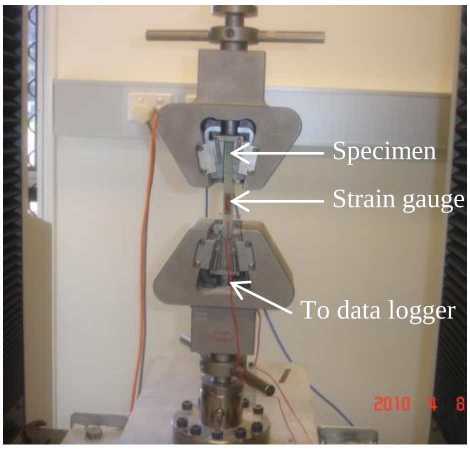


Figure 1. Laminate test set-up and instrumentation.

3 EXPERIMENTAL RESULTS AND DISCUSSION

Table 3 shows the summarized result derived from the laminate test. It should be noted that values given are average values at failure. As illustrated in the table, the compressive strength of the laminate is 87.50 MPa while the strain at failure is 0.00612. Concurrently, the compressive strength of the laminate can be considered as predicted strength of the composite pile assuming no buckling will take place. Apparently, load beyond this value will initiate compression failure on the pile.

Figure 3 shows the applied axial load - axial and lateral strain behavior at the mid-height of the 230 mm FRP tube. The axial and lateral strain of the composite pile under 414 kN (22.02 MPa equivalent stress) applied load are 1,523 microns and 452 microns, respectively. The compressive modulus of FRP composite pile using linear regression is estimated to be 14,270 MPa. This value is comparable to the compressive modulus (14,300 MPa) derived from laminate test. Based from this result, the applied load (i.e. 22.02 MPa) is only 25% of the composite pile's predicted compressive capacity (i.e. 87.50 MPa). Therefore, compressive failure is not expected to occur at this loading stage.

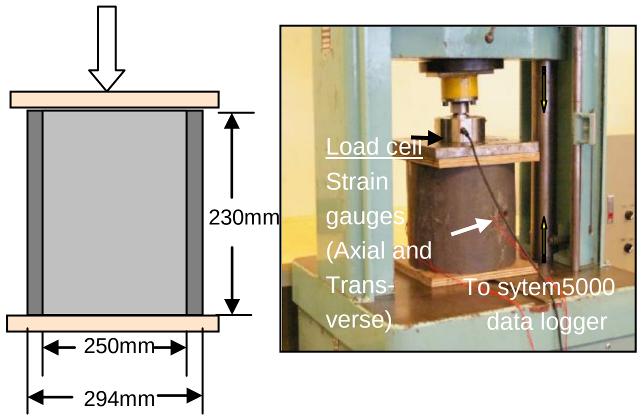


Figure 2. Compression test set-up on short pile.

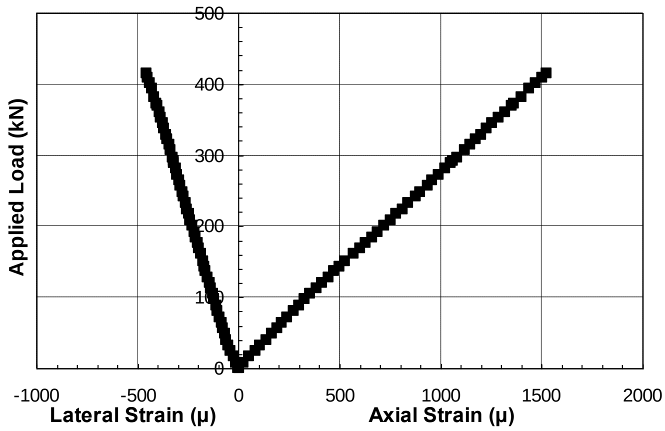


Figure 3. Applied load-strain curve.

Table 3. Material properties of laminate at failure.

Properties	Property value	Unit
Compressive stress	87.50	MPa
Axial deformation	3.46	mm
Axial strain	0.00612	-
Compressive modulus	14,300	MPa

4 FINITE ELEMENT ANALYSIS

To simulate the behavior of the short and hollow FRP pile, linear finite element analysis was employed using the general-purpose FE software package Strand 7. The objective of using FE analysis in this study is to determine its viability in predicting the behaviour of the FRP composite pile based on the material properties derived from tests and provided data.

4.1 *Mesh model*

All FE models were generated using a 4-node shell element. The mesh model comprised of 1280 nodes and 1200 shell elements with a uniform mesh of 11mm x 15mm. In this modeling, laminate properties were adopted as property attributes of shell elements. To do this, lamina stacks made of the composite pile's two component materials (i.e. fibreglass and Soric XF-reinforced laminae) were modeled. Assigned property values of each lamina where taken from the previous coupon tests and provided data. It should be noted that the mass of each lamina has a small effect on stress formation compared to the applied load and therefore is neglected in this study. Table 4 shows the property values adopted in the FE analysis.

4.2 *Boundary and load conditions*

In the conducted experiment, the composite pile was in contact with stiff loading plates at the two ends. Even if the support condition may emerge to be close to a simply-supported condition, previous research conducted showed a much closer value to the experiment results if a "clamped support condition" is adopted (Teng and Hu, 2006). Therefore, the clamped-end condition is more appropriate for this model. To adopt such support condition, the two ends were fully fixed in all direction except that the axial displacement of the top end was left unrestrained to allow the application of axial loading.

In order to properly simulate the loading condition on the specimen as described in Figure 2, vertical uniformly distributed pressure on the top of the model was applied. A 22.02 MPa uniform distributed pressure load was applied on the top face of the model. This applied load was identical to that of the load used in experiment (414 kN) to predict the composite pile's behaviour under axial compression.

5 FEM RESULTS AND DISCUSSION

Figure 4 demonstrates the finite element model and deformed mode of the hollow FRP pile generated from the analysis. It is evident from the figure that both support ends of the pile undergone response from the applied load. To visibly compare the stress distribution between the top support face going to the bottom support, displacement scale was modified such that a clear deformation at the mid-height is noticed. The difference of the stress distribution in all regions using finite element method is diminutive so that the strain is almost constant at the ends and at the mid-height of the composite piles in axial direction.

Table 5 summarizes the stress, load and strain results at the mid-height section of the FRP composite pile under a maximum applied load of 22.02 MPa (414 kN). It is noticeable that values in axial direction vary along its thickness with this type of laminate lay-up. To better understand the behaviour of the composite pile, values of plies were analysed and are shown in Figures 5 and 6.

Table 5. Summarized stress, load & strain results of the plies at the mid-height of the pile.

	Unit	Ply number 1	2	3	4	5	6	7	8	9	10	11	12	13
σ_A	MPa	39.21	39.36	39.51	39.66	1.16	1.18	41.03	1.20	1.22	42.40	1.24	43.17	1.26
P_A	kN	18.11	18.18	18.25	18.32	2.14	2.17	18.95	2.21	2.25	19.58	2.29	19.93	2.33
ε_A	-	1384	1389	1394	1399	1412	1432	1445	1458	1479	1492	1504	1517	1530
ε_L	-	316	316	316	316	316	316	316	316	316	316	316	316	316

	Unit	Ply number 14	15	16	17	18	19	20	21	22	23	24	25	26
σ_A	MPa	43.93	44.08	44.23	44.38	44.54	44.68	44.84	44.99	45.15	45.30	45.45	45.60	45.76
P_A	kN	20.29	20.36	20.43	20.50	20.57	20.64	20.71	20.78	20.85	20.92	20.99	21.06	21.13
ε_A	-	1543	1548	1553	1558	1563	1568	1574	1579	1584	1589	1594	1599	1604
ε_L	-	316	316	316	316	316	316	316	316	316	316	316	316	316

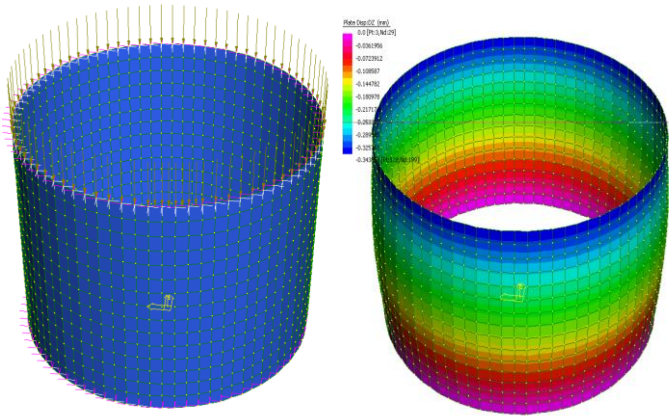
σ_A = axial stress, P_A = axial load, ε_A & ε_L = micro-strain in axial and lateral directions, respectively.

Figure 5 gives detail on the axial stress and the applied load distribution between the FRP composite pile and the main component materials at the mid-height. The adopted values of the component materials were referred from its individual average stress,

Table 4. Material properties of lamina used in FE analysis.

Properties	Notation	Property value G	S	Unit
Elastic Modulus	E_{11}	28,500	800	MPa
	E_{22}	28,500	800	MPa
Poisson's ratio	ν_{12}	0.20	0.30	-
	ν_{21}	0.20	0.30	-
Shear Modulus	G_{11}	11,875	307.69	MPa
	G_{22}	11,875	307.69	MPa

Note:
G = glass-reinforced lamina S = Soric XF-reinforced lamina



a b

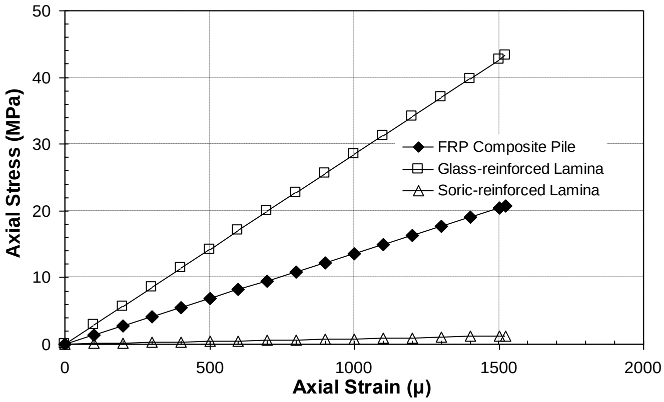
Figure 4. (a) Finite element model (b) deformed mode.

load and strain values. Axial stress of the FRP composite pile remains intermediate as individual strain increases under this loading condition as shown in

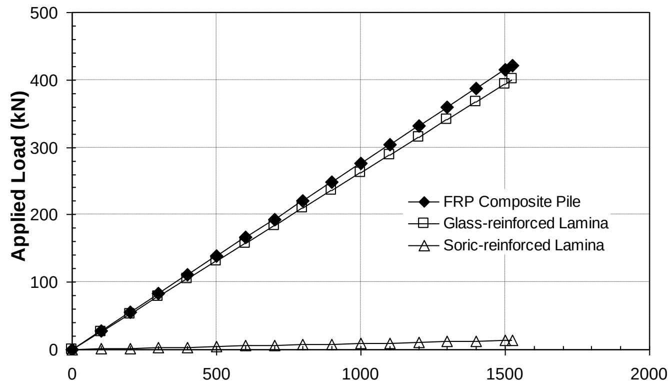
Figure 5a. Based from Figure 5b, it was found that glass-reinforced lamina carries 96% of the applied load compared to that of the Soric XF-reinforced lamina. It can be ascertain from the result that former component material bears most of the load. Moreover, it can be inferred that the total behaviour of the FRP composite pile under axial compression with this kind of laminate lay-up depends solely on the response of glass-reinforced lamina and the effect of Soric XF-reinforced lamina is very minimal.

The relationship of the applied load to the strain of selected representative plies on the mid-height of the model for both axial and lateral direction is given in Figure 6. For clarity, section of the tube at the mid-height is reflected indicating the labeling number of the plies (i.e. ply 1 and ply 26 at the most inner and relation of the composite tube's behaviour under axial compression.

The applied load-strain relation of the experiment outer face of the tube, respectively). It can be observed from the graphs that plies at this section behave differently in axial direction but not laterally if strained under axial compression. From Figure 6a, strain variations of the plies on the axial direction were developed. The strain variations indicate that at increasing load magnitude, section at the mid-height starts to undergo wall buckling, although this premature deformation will not cause local failure or sudden collapse to the FRP composite pile as discussed earlier. On the other hand, lateral strain of the plies remains the same across the thickness (i.e. ply 1, ply 2 … ply 26) of the tube irrespective of the loading magnitude as shown in Figure 6b.

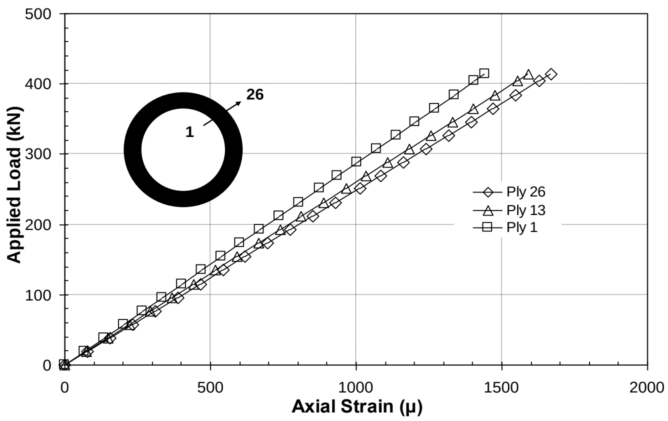


(a)

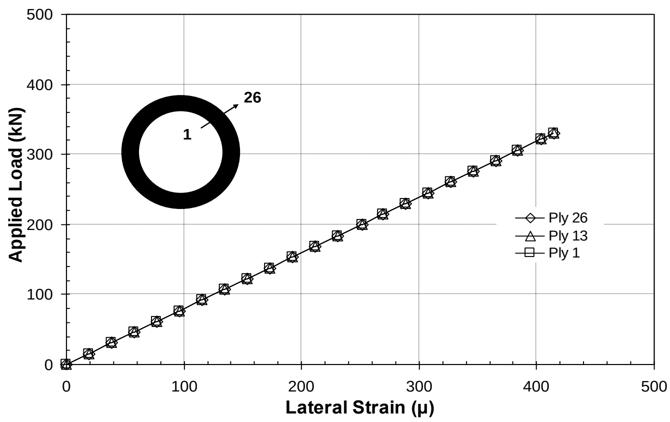


(b)

Figure 5. Mid-height axial strain of FRP pile and its component materials versus (a) applied load (b) axial stress.



(a)



(b)

Figure 6. Mid-height applied load-strain relationship of selected plies in (a) axial direction (b) lateral direction.

6 COMPARISON OF RESULTS

This chapter compares the results obtained from the experiment and FE analysis. Specifically, focus is on the graphical comparison of the applied load-strain and FE analysis results is exposed in Figure 7. Apparently, the calculated value from the finite element analysis is at par to the experimental value. The use of FE method, thus, proved to be effective in determining the overall compressive modulus of the FRP composite pile in particular and its compressive behaviour in general.

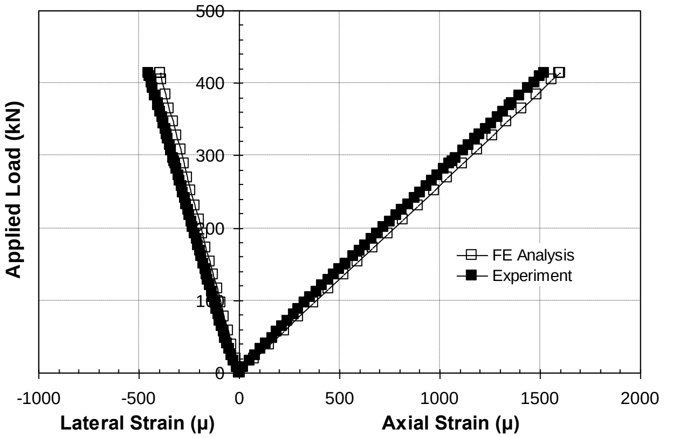


Figure 7. Comparison of applied load-strain curves of experiment and FE analysis.

7 CONCLUSIONS

A study on the behaviour of FRP composite pile was presented using experiment and FE analysis and later compared. Based from the result, the following conclusions were drawn:

- The applied load is only 25% of the composite pile's axial compressive capacity (predicted) and no compressive failure will occur at this loading regime;
- Fibreglass-reinforced lamina bears 96% of the applied load while 4% was carried by Soric XF-reinforced lamina;
- Lateral strain of the plies remains the same across the thickness irrespective of the loading magnitude while strain variations of the plies on the axial direction were developed and more pronouncedly at the maximum applied load;
- The use of FE method proved to be effective in simulating the behaviour of the FRP composite pile under axial compression.

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