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# Effect of Fiber Reinforced Polymer Tubes Filled with Recycled Materials and Concrete on Structural Capacity of Pile Foundations

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## Abstract

This paper deals with analyzing the structural responses of glass-fiber-reinforced polymer (GFRP) tubes filled with recycled and concrete material for developing composite piles, as an alternative to traditional steel reinforced piles in bridge foundations. The Full-scale GFRP composite piles included three inner and outer layers, using a fiber-oriented material that was inclined longitudinally, almost 40 degrees from the horizontal axis of the pile. The segment between these two layers was inclined 80 degrees from the longitudinal axis of the tube. The behavior of the filled GFRP tubes was semi-linear, and resulted in increasing the total ductility and strength of the piles. Adjusting the material's properties, such as the $E_{Axial}$, $E_{Hoop}$, and Poisson ratios optimized the results. The lateral strength of the GFRP composite pile and pre-stressed piles are comparable in both axial and lateral loading conditions.

**Keywords:** Pile design, Fiber Reinforced Polymer, GFRP, FRP, Composite Piles, Bridge design

## 1 Introduction

One of the major concerns of using conventional steel, concrete, or wooden piles in bridge structures is their short-term deterioration causing structural failure. In the marine environment, where salt water accelerates corrosion, traditional materials are prone to corrosion in splash and tidal areas. In the presence of moisture and oxygen, even concrete piles are susceptible to corrosion because of the

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existence of the steel bars inside the concrete. Several solutions have been presented in the past, such as using epoxy as a coating layer or galvanizing the steel member (1); however, these approaches had unsatisfying outcomes for increasing the lifespan of steel materials in a corrosive environment (2). In the long run, excessive use of steel and reinforced concrete materials for pile construction increases the demand for restoration and strengthening (3). The short lifespan of these conventional materials can increase the cost of maintenance significantly. For instance, either replacing or repairing these piling systems costs more than one billion dollars annually in the U.S. (4). Maintenance costs in Great Britain are also high, as the allocated budget for repairing bridges is roughly 500 million Euros per year ($592,070,000) (5).In contrast, Fiber Reinforced Polymer (FRP) is resistant to corrosion compared to steel and other traditional materials. Furthermore, FRP piles can dissipate and absorb the impact energy of ships and other vessels, as well as serve as mooring points. Based on the highly acceptable performance of FRP materials for applications in marine engineering, using FRP materials in construction has gained a reputation as a practical solution against corrosion, as well as to improve the durability of structural members in a marine environment. Moreover, FRP reinforcement is a more reliable replacement to steel reinforcement, as it enhances the strength of the structure member without adding considerable weight to the structure (6). Therefore, fiberglass piles are considered as an ideal material for construction in the marine environment.

For the design of composite deep foundations in bridge structures, hybrid fiber reinforced (FRP) materials have greater advantages, compared to non-hybrid materials. For instance, as a hybrid reinforcing method, glass-fiber-reinforced polymer (GFRP) sheets have superior features regarding strength, tensile ratio, and stiffness-to-weight ratio. GFRP is both nonmagnetic and nonconductive, which is an advantage compared to traditional materials (7). Furthermore, the constructability of GFRP is useful for structures having complex shapes. In addition, these hybrid FRP polymers are more resistant to hazardous environments when exposed to saltwater, or even during destructive hurricanes.

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Therefore, in specific environmental conditions, such as coastal areas, replacing conventional pile members with GFRP composite piles considerably improves the lifespan of the constructed members against corrosion. Because they enhance the lifespan of the pile, GFRP piles also are considerded as a cost-effective alternative for traditional piles, as they increase the repair cycle of pile bridge foundations.

Analyzing the behavior of a strengthened structural member, such as its flexural capacity, deflection response, failure modes, moment redistributions, and ductility, are significant factors for developing accurate design methods and practical structures. Ductility is a critical factor in the construction process; for example, in statically indeterminate structures, it governs moment redistribution within plastic hinges. Redistribution of the moment in structural members ensures the full-capacity usage of the members, which is an essential factor when designing structures that are economical (8).

GFRP is considered a preferred material for enhancing the strength of piles, following methods such as near-surface-mounted and externally-bonded reinforcement techniques (3). Developing the application of GFRP hybrid materials for use in construction enhances the ductility of the assembled structural members, as well as their flexural strength. Using epoxy resin for externally bonding GFRP sheets increases the strength of members during flexural loading.

An advantage of using hybrid FRP laminates, such as GFRP sheets, is their nonlinear stress-strain behavior (9). This behavior results in enhancing both the ductility and strength of the members (10), (11), (12). On the other hand, unlike steel, non-hybrid FRP sheets demonstrate linear stress behavior; in contrast, FRP adds to the flexural capacity of the member, but reduces the ductility of the member significantly (8).

Despite increasing demands for the use of FRP materials as an alternative method to replace traditional reinforcement techniques, the behavior of such hybrid materials as GFRP sheets have not been subject to extensive amounts of research. Moreover, the design and implementation methods of hybrid materials have not been sufficiently established in the guidelines such as EUROCOMP, CUR 96, and BD90/05 when compared to FRP materials. This study examined the behavior of hybrid fiberglass tubes filled with recycled material and concrete for use in deep foundations (piles). Many research studies have been conducted on the structural responses of recycled concrete material (13), (14), (15). In this study, fiberglass tubes were filled with concrete containing recycled materials, such as shredded and used tires, to determine if the use of recovered materials resulted in lowering construction costs in an environmentally friendly manner. In this way, seemingly worthless materials could be used as part of the construction process, without sacrificing natural resources or producing hazardous materials during the construction process.

Significant factors should be considered in the design of structural members, such as composite piles which are reinforced with FRP layers. Using the appropriate hybrid material – for example, GFRP, hybrid carbon, and glass reinforced polymers (HCG), or carbon fiber reinforced polymers (CFRP) – is one of these important factors. As another reinforced hybrid option, using basalt fiber-reinforced polymer (BFRP) sheets is almost 15% less expensive than using GFRP materials, and with the same compressive strength as GFRP (16). Moreover, the arrangement, thickness, and width, along with the number of the designated layers, and compressive strength of the hybrid material affect the experimental outcomes.

Another important parameter is the shape of the reinforced materials, in that various circular or squared arrangements of the specimens may result in different outcomes. Some experimental research works have been performed on the performance of circular tubes using FRP material (17), (18), (19), (20), (21), (22). Hybrid FRP materials such as GFRP are composed of either bonded or embedded fibers in a matrix arrangement. This specific matrix pattern transfers structural loads within mediums and reinforces the fibers against environmental hazards. With this arrangement, the fibers mainly are designed to sustain structural loads (23).

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Moreover, the direction of applied loads and the stiffness of a pile affect the results considerably. Based on the axial or lateral loading design criteria, the structure of the FRP tubes can be modified to enhance the strength capacities. For example, the tubes can be filled with concrete to increase their strength and stiffness. The filled tubes function as a permanent formwork that confines and protects the concrete. In addition, the tubes serve as flexural reinforcement for concrete by preventing local buckling of the tubes. Therefore, the considerable axial capacity and lateral strength of the FRP composite piles make them a reliable alternative to replace traditional piles.

## 2 Materials and Methods

This research studies the effect of using GFRP composite piles following the winding method on the capacity and durability of bridge structures. The test piles are precast members reinforced in in circular directions containing concrete or recycled materials as fillers. By applying a specific pattern using this technique, polyester material, such as resin, is utilized to create the appropriate fibers.

### 2.1 Structural Criteria

The accumulative wall thickness of the GFRP test pile was 7.5 mm and the outer diameter of the test pile was 600 mm. The GFRP composite pile included three inner and outer layers, using a fiber-oriented material that was inclined longitudinally almost 40 degrees from the horizontal axis of the pile. The segment between these two layers was inclined 80 degrees from the longitudinal axis of the tested tube. Expansive additive materials in the tube enhanced the strength of the existing concrete against shrinkage and maintained the compression strength of the member.

### 2.2 Experimental Tests on GFRP Piles

A full-scale pile sample using GFRP material was built and used in the laboratory to increase the accuracy of the test results. After determining the specific stiffness of the tested tube member, the sample's strength was calculated by applying axial-loading and moment-loading scenarios.

The performance of the GFRP tubes filled with recycled material was evaluated in both tensile and compressive loading scenarios. The structures of three different specimens were analyzed, and the ultimate capacities for loading and bending were measured. The loading conditions and the type of tube materials, as well as the span height, are presented in Table 1. Specifications for the GFRP piles – such as outer diameters, Poisson ratio, and other measured data – are illustrated in Table 2. The GFRP members were designed following the winding method. Considering the longitudinal tension forces in the axial direction of the tested piles, and based on lamination theory, the failure modes of the GFRP piles were analyzed. For measuring the bending forces, four stations were controlled; for the beam samples, three similar samples were utilized to evaluate the flexural resistance. Based on the experiments of the beams, the total member responses were linear; therefore, cracking could be omitted when considering higher amounts of loading strength under both flexural and axial loading conditions. In addition, the deflection responses of the test beams under incremental axial loading were measured.

Figure 1 illustrates that the samples' responses of three full-scale composite piles as BE1-1, BE1-2, and BE 1-3, were linear before reaching the failing points. Moreover, in all three beam tests, the ultimate load capacity was considerably greater than the calculated load for cracking the samples. Some minor data fluctuations occurred; however, they were insignificant due to the sample's calibration and initial measuring conditions (24).

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**Table 1 Experimental Data and Specifications of Samples**

| Test Pile ID | Tube Number | Eccentricity (mm) | Length of Span (m) | Axial Loading (KN) | Moment Loading (KN-M) |
|---|---|---|---|---|---|
| BE 1-1 | Tube 1 | ∞ | 4.5 | 0 | 112 |
| BE-AX 1-1 | Tube 1 | 647 | 1.60 | 198 | 176 |
| BE-AX 2-1 | Tube 1 | 322 | 1.60 | 326 | 144 |
| BE-AX 3-1 | Tube 1 | 239 | 1.60 | 312 | 126 |
| BE-AX 4-1 | Tube 1 | 144 | 1.60 | 427 | 237 |
| BE-AX 5-1 | Tube 1 | 54 | 1.60 | 344 | 117 |
| AX-1-1 | Tube 1 | 0 | 1.0 | 677 | 0 |
| BE 1-2 | Tube 2 | ∞ | 4.5 | 0 | 96 |
| BE-AX 1-2 | Tube 2 | 547 | 1.55 | 446 | 156 |
| BE-AX 2-2 | Tube 2 | 417 | 1.55 | 557 | 160 |
| BE-AX 3-2 | Tube 2 | 310 | 1.55 | 612 | 211 |
| BE-AX 4-2 | Tube 2 | 189 | 1.55 | 643 | 206 |
| BE-AX 5-2 | Tube 2 | 21 | 1.55 | 811 | 53 |
| AX-1-2 | Tube 2 | 0 | 0.97 | 901 | 0 |
| BE 1-3 | Tube 3 | ∞ | 4.50 | 0 | 116 |
| BE-AX 1-3 | Tube 3 | 733 | 1.75 | 288 | 136 |
| BE-AX 2-3 | Tube 3 | 522 | 1.75 | 401 | 255 |
| BE-AX 3-3 | Tube 3 | 319 | 1.75 | 522 | 274 |
| BE-AX 4-3 | Tube 3 | 199 | 1.75 | 622 | 144 |
| BE-AX 5-3 | Tube 3 | 71 | 1.75 | 848 | 202 |

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| | | | | | |
|---|---|---|---|---|---|
| AX-1-3 | Tube 3 | 0 | 0.94 | 1002 | 0 |

BE: Lateral Loading AX: Axial Loading

**Table 2 Tested Specifications for GFRP Piles**

| **GFRP Type** | **T-1** | **T-2** | **T-3** |
|---|---|---|---|
| Average $E_{Axial,}$ (GPa) | 14.3 | 16.6 | 19.5 |
| Average $E_{Hoop,}$ (GPa) | 15.2 | 17.3 | 21.4 |
| Outer Thickness (mm) | 4.31 | 4.87 | 5.24 |
| Poisson Ratio | 0.071 | 0.085 | 0.092 |
| Tensile strength* (MPa) | 178 | 201 | 263 |
| Compressive strength* (MPa) | 164 | 187 | 255 |
| Diameter (mm) | 227 | 236 | 241 |

***** Both tensile and compressive stresses were measured in axial directions

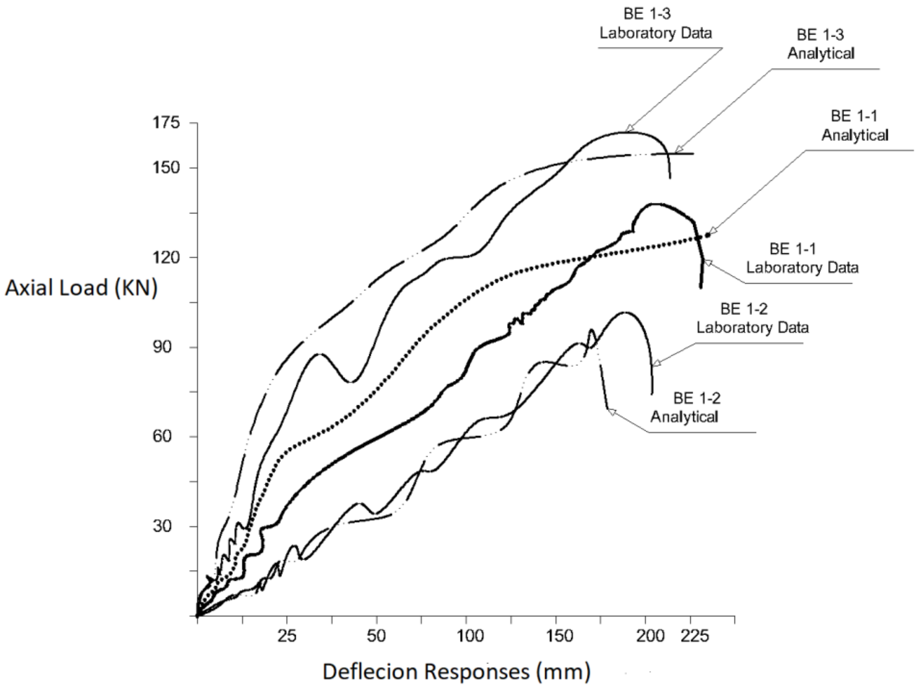

Figure 1. Deflection response of the test beams under axial loading

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## 3 Discussion and Results

Based on the resulting laboratory data, pile responses were analyzed, and their curvature graph was evaluated against the moment reaction of these composite members. The responses of the tube members after cracks were determined, as well as the overall slip of recycled materials adjacent to the tubes, were measured.

### 3.1 Material Verification

Material verification was controlled following the “coupon” testing methods and based on the lamination theory to calculate the maximum measured stiffness and strength capabilities of the GFRP members (25). The first step was to test a rectangular-shaped strip layer sample, with the dimensions of 25 mm by 600 mm, from the tube. The actual strength measurement of the tube had an error at the very end of both fixing locations because of the stress concentrations around those regions (26).

In the next procedure, steel tubes were used as a cover around the fiberglass tubes, along with resin to fill the empty voids. In this step, the GFRP coupons had a free (unfixed) length of 178 mm. After completion of the preparation stage, the GFRP samples at the fixed-end positions were tested under tension loading. Figure 2 illustrates the results of the accumulated strain and stress following the laboratory tests.

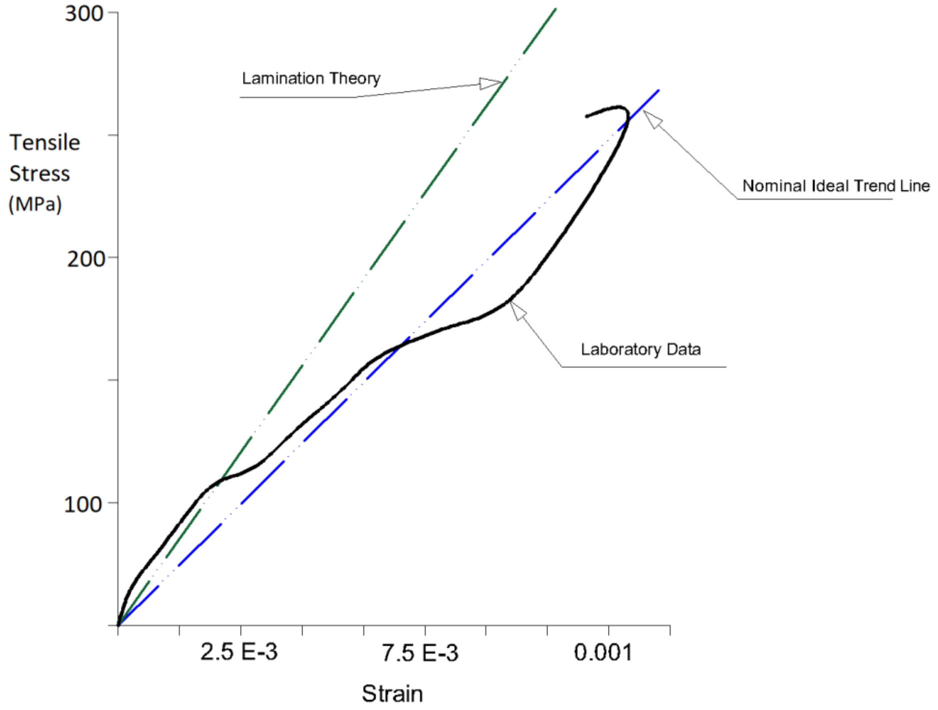

Figure 2. Comparison of axial stress-strain based on laboratory data, the lamination theory, and an ideal hypothetical line

### 3.2 Response Evaluation of GFRP and Pre-Stressed Piles

The responses of pile members in loading scenarios were based on their materials. As a result, various composite materials considered in this research – including GFRP, pre-stressed, and concrete materials – had different strengths during the loading experiments. Due to these types of discrepancies, designers of bridge structures use several types of design methods to deal with various types of pile members (27).

Based on the responses, analyses of the pile members were performed by comparing moment-curvature graphs (28). First, the geometric characteristics of the GFRP filled with recycled materials was analyzed. A filled GFRP tube was stripped longitudinally and sampled. From the stress-strain data gleaned from the experimental test, which was semi-linear, the internal forces acting on the

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filled materials and the GFRP were evaluated by conducting a numerical analysis, as well as using regression on the resultant laboratory data, as is shown in Figure 3. Second, in order to develop the moment-curvature diagram, the calculated internal forces were used to anticipate the internal moments in various locations following the estimated strain data. Three tests were conducted to compare the lateral responses of the GFRP piles.

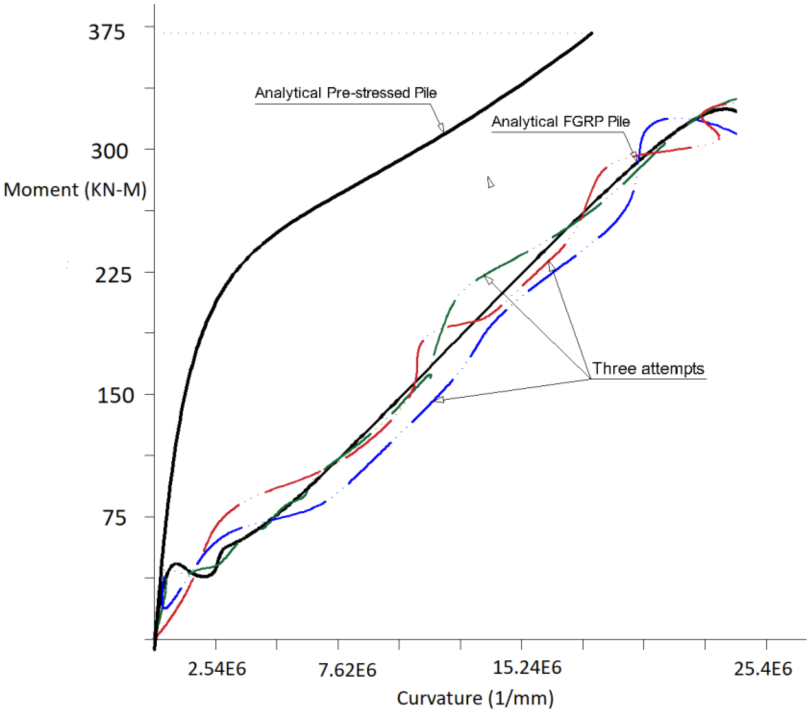

Figure 3. Moment-curvature analogy for pre-stressed and GFRP composite piles

Based on Figure 3, as the internal moments reached the failure point, cracking occurred and the flexural capacity of the GFRP, as a non-hybrid FRP material, decreased significantly following a non-linear response. Before the cracking, the stiffness capacity of the GFRP tubes and conventional pile were almost identical. Since the GFRP piles were filled with recycled materials, as a replacement of corrosive steel for reinforcement of the pile, the cracks that occurred will not affect the lifespan of the members in the long term because of eliminating the agent of the corrosion.

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### 3.3 Field Results on GFRP Piles

As mentioned before, the use of full-scale test piles results in more a reliable outcome for analyzing the responses of the GFRO composite piles (29), (30). The capacities of GFRP composite piles were measured under axial loading. Installed strain gauges and accelerometers measured the member's displacements for both longitudinal and lateral loadings. The lateral deflection and displacement of the pile, as well as the axial strain and displacement responses of the piles, were measured and analyzed. Based on the outcomes, the axial capacities of these composite members were considerably greater than their geotechnical capacities.

## 4 Conclusion

Following the experimental data analysis, the use of glass-fiber-reinforced polymer has many benefits for the design and implementation of pile structures in large-scale construction projects, such as bridge structures. The use of piles reinforced with GFRP material in bridge design results in increasing the durability of these deep foundations and decreasing their construction costs. The allocated expenditure for recovering and repairing pile structures in both North America and Europe exceeds $1.5 billion dollars. Therefore, maintenance cost is a significant factor for the design of cost-effective structures. Using recycled materials as fillers in reinforced GFRP tubes decreases the total cost of production. In the past decade, using steel-reinforcement methods increased the cost of construction; however, developing structural piles with hybrid GFRP materials resulted in reducing the use of steel materials as reinforcing members. In addition, hybrid FRP materials, such as GFRP, enhance the anticipated lifespan of pile structures, even in such hazardous environments as oceans, where corrosion is one of the main concerns for the durability of these structures. Finally, these hybrid materials increase the anticipated strength capacity of the structures significantly.

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The outcome of this research is based on a specific arrangement of GFRP layers, including their diameter, outer and inner thickness, and inclined degree from the horizontal axial axis. Adjusting these specifications, as well as changing the material's properties – such as $E_{Axial}$, $E_{Hoop}$, and Poisson ratios – optimized the results. Based on the results from three beam samples, the deflection responses were linear in an axial loading condition before reaching the failure criteria. Since recycled material was used as filler inside the tubes, the long-term effect of cracking was negligible for high values of calculated strength, as well as under axial or lateral loadings. Some minor inconsistencies in such parameters as initial measurements or the calibration of samples could affect the outcomes.

Analyzing the internal forces of the GFRP tubes filled with recycled material showed the semi-linear behavior of the pile members, which resulted in increasing the total strength and ductility of the reinforced piles. The lateral responses of both the GFRP piles and pre-stressed piles showed comparable results, in that the effect of cracking under axial and lateral loadings was negligible.

Future studies are recommended to investigate developing more reliable methods using more full-scale test piles. Furthermore, the effects of applying a basalt fiber-reinforced polymer as an alternative for GFRP material could be investigated for a more cost-effective design and implementation of piles.

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