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Research Article

Experimental and Theoretical Analysis of Hybrid Polymer Composite Behavior

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ABSTRACT

This research examines the cyclic tensile properties of a hybrid fiber reinforced polymer (FRP) composite made of polypropylene (PP) and glass fibers. The hybrid FRP is intended to take advantage of the high strength and stiffness of glass fibers and the improved ductility of PP fibers to enhance the seismic performance and repairability of structural materials under cyclic loading conditions. Cyclic tensile tests were performed to assess the stress-strain behavior, including envelope curves, unloading modulus, and plastic strain accumulation. The effect of the volume fraction of glass fiber on the behavior of the composite was also investigated. The results indicate that hybrid FRP has a lower plastic strain than pure PP FRP, providing better seismic repairability. In addition, the hybrid FRP's stress-strain performance exhibited a close-to-linear behavior prior to peak loading, which was followed by a sudden decrease in stress. The research sheds important light on the development of hybrid FRP materials for use in structural reinforcement, especially earthquake-resistant structures, for enhancing repairability and durability.

Keywords: Hybrid FRP, Cyclic Tensile Behavior, Polypropylene, Glass Fibers

INTRODUCTION

Existing structures' seismic performance is becoming increasingly important, and many will require strengthening in the future either because seismic design codes are being upgraded or because material performance is deteriorating. Fiber reinforced polymer (FRP) has seen a dramatic uptick in seismic retrofitting applications over the last several decades owing to its exceptional strength, low density, and resistance to corrosion (Zhou, et al. 2021). Carbon, glass, and basalt fibers are well-liked among many varieties of fibers because of their exceptional strength and rigidity. But these tiny rupture strain fibers

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(like basalt, glass, and carbon) are only about 3%, which means they might not be ductile enough to withstand powerful earthquakes in places like the plastic hinge region (Yeboah, & Gkantou, 2021). While large rupture strain fibers like polyethylene terephthalate (PET) and polypropylene (PP) fibers do provide new information, the fact that they are significantly less stiff than small rupture strain fibers and that they will undergo large plastic deformations under repeated loads owing to amorphous phase motion and molecular weight sliding has been the subject of much debate. This, in turn, reduces the repairability of structures following an earthquake.

A new hybrid FRP composite that combines small rupture strain fibers with large rupture strain fibers in the same resin matrix is an effective and economical way to achieve structural ductility while minimizing the plastic deformation of large rupture strain fibers under cyclic loading. The reason behind this is that the modest rupture strain fibers are able to prevent plastic behavior in the co-deformed material since they do not show plastic strains when subjected to cyclic loading. Based on experimental results, FRPs with minimal rupture strain are more resistant to plastic deformations than steel. Cyclic tensile tests on FRP-steel composite plates and bars also show less plastic strain than steel. According to Wang and Cai (2023), a similar process has been utilized to enhance the seismic repairability of steel structures through the employment of tiny rupture strain fibers. When large rupture strain fibers are subjected to repetitive loading scenarios, it is clear that small rupture strain fibers can significantly improve their effectiveness. This has led to a surge in interest in hybrid FRP-reinforced structures and their widespread use in practical engineering. A typical hybrid FRP-confined concrete in axial compression is shown in Fig. 1,1 wherein the hybrid FRP serves as confinement elements and primarily experience tensile loading.

The axial compression properties of concrete confinement covered with hybrid FRPs have recently been the subject of a number of investigations. For the first time, Wu et al. (2008) used axial compression experiments to examine the efficacy and feasibility of using different kinds of FRPs in hybrid applications within concrete confinement. To increase concrete's peak strength, they highlighted the need of a hybrid ratio, which is the volume fraction of two tiny rupture strain FRPs divided by one another. Axial compression was the subject of an experimental study by Ribeiro et al. (2018) on hybrid FRP-confined concrete. The results show that the compressive ductility is improved by avoiding explosive and abrupt failure modes of concrete and instead producing a flatted-topped curve with the help of hybrid FRP confinement. Then, by creating a functional relationship between the yield function, the flow rule, and the lateral confinement pressure, a simulation approach was created to mimic the axial compression behavior of hybrid FRP-confined concrete. Experimental investigations, on the other hand, have a particular emphasis on monotonic testing, whereas the aforementioned studies center on the hybridization of two small rupture strain fibers (e.g., carbon, glass, and basalt fibers). In 2011, a study was released that initially investigated the use of PET fibers in concrete confinement (Ispir, 2015). According to this research, ductile demand situations (like seismic retrofitting) are best handled by big rupture strain fibers. Following this, a cyclic compression test was performed on PET-confined concrete by Ispir (2015). Compared to tiny rupture strain FRPs, the plastic strain development of concrete limited by PET FRP shows similarities in the test results. When it comes to confinement applications, PET fibers outperform small rupture strain fibers because they can adapt to more lateral dilatation distortion of concrete and have a bigger rupture strain of 10%. In order to restrict concrete, Ispir (2015) and Tang et al. (2022) used a resin matrix that included PET fibers together with small rupture strain fibers made of carbon or glass. The improved ductility and strength of concrete were discovered during the monotonic axial compression test. Bai et al. (2024) and Ispir (2015) follow suit. investigated the feasibility of developing theoretical models for hybrid FRP-confined concrete by conducting cyclic axial compression experiments. This material is composed of a hybridization of PET-carbon (or PET-glass) fibers. The results of the aforementioned experiments reveal that concrete's strength and ductility can be significantly enhanced using the hybrid FRP confinement system. Adding big rupture strain fibers further improves the ductility even further. Hybrid FRPs are not taken into account as a cohesive composite material in this research.,

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The cyclic tensile behavior of a hybrid FRP composite with glass and PP fibers is examined in this work. The hybrid FRP underwent cyclic tensile testing, with the stress-strain curve's envelope curve, unloading modulus, and plastic strain development being the primary areas of analysis that followed. At the same time, it became clear that the cyclic tensile behavior of the hybrid FRP was affected by the volume percentage of the glass fiber layer

Problem Statement

The seismic performance of existing structures has become increasingly important, particularly with the rising demand for retrofitting because of material degradation or new seismic codes. Fiber reinforced polymers (FRPs) have become the most popular choice for seismic strengthening because of their strength, light weight, and corrosion resistance. Yet, the low rupture strain of small rupture strain fibers such as glass restricts them from achieving the ductility demand under seismic loading. This research aims to overcome the limitations of current FRP systems by investigating hybrid FRP composites that integrate large rupture strain fibers (e.g., polypropylene) with small rupture strain fibers (e.g., glass) to maximize both strength and ductility.

Objective of Study

The main goal of this research is to analyze the cyclic tensile behavior of a hybrid FRP composite comprising polypropylene and glass fibers, with an emphasis on the envelope curve, unloading modulus, and plastic strain evolution.

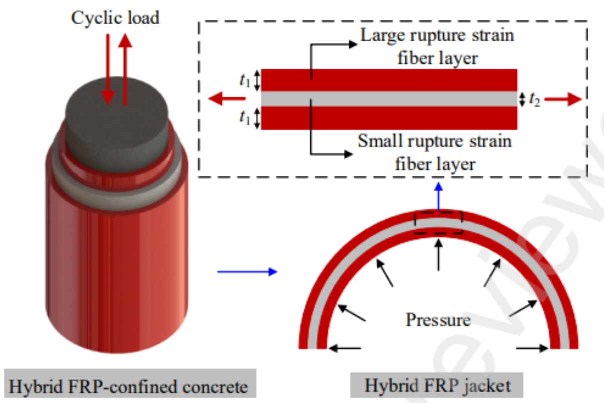

Fig. 1. Hybrid FRP compositions and its application in concrete confinement under cyclic loading

METHODOLOGY

Theoretical Background

The most intricate challenge in the application of hybrid FRP in engineering lies in the existence of four distinct failure modes, each resulting in a significantly disparate stress–strain response, as shown in Fig. 2. The potential occurrence of each failure mode is contingent upon the nominal thickness and proportion of individual fiber layers (Jalalvand, et al 2015). In addition, the mechanical properties (such as elastic modulus and peak strength) of hybrid FRP are influenced by both fiber layers and can be described using the rule of mixtures. The complex mechanical mechanism of hybrid FRP undoubtedly hinder the application of this material in engineering.

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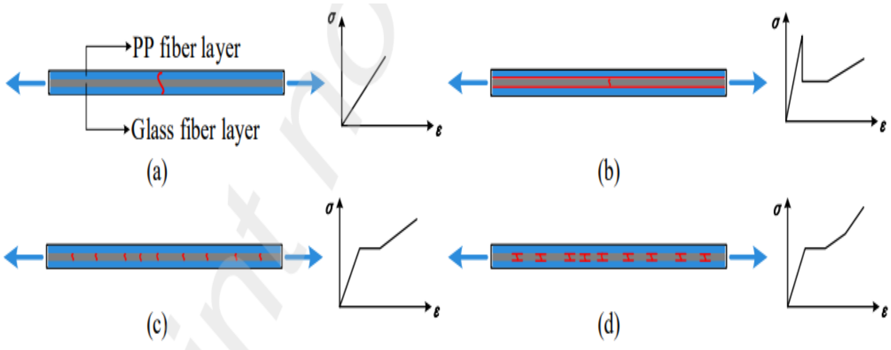

Fig. 2. Possible failure modes in hybrid FRP composites under cyclic tensile loads: (a) premature failure; (b) delamination; (c) small rupture strain fiber layer fragment; (d) small rupture strain fiber layer fragment & local delamination

As discussed before, an increasing number of research studies have commenced focusing on the practical implementation of hybrid FRP within the field of civil engineering. However, the current research on hybrid FRP applications remains conservative, with researchers may only considering failure modes as illustrated in Fig. 2 (c) and (d). Although these failure modes exhibit a monotonically increasing stress–strain relationship, achieving the desired outcomes typically necessitates precise control of the volume fraction within a small range for the small rupture strain fiber layer. Shen et al. (2023) conducted a study on the monotonic tensile behavior of hybrid FRP composed of PP and glass fibers. In contrast to previous studies, the findings from this study confirm that the delamination failure mode observed in the hybrid FRP is the only suitable failure mode for civil engineering applications. Moreover, it is concluded that the pre-peak mechanical behavior of hybrid FRP is solely governed by the glass fiber layer, while the post-peak mechanical behavior is exclusively controlled by the PP fiber layer. Importantly, this study demonstrates the decoupling of mechanical properties between the glass fiber layer and the PP fiber layer within a hybrid FRP, thereby enhancing the flexibility of hybrid FRP reinforced structures in a performance-based design. Building upon these understandings, the present study aims to broaden the application range of hybrid FRP comprising PP and glass fiber by investigating its mechanical response under cyclic tensile loads.

EXPERIMENTAL

Materials

Utilized were plain woven fabrics made of glass and PP, with thicknesses of 0.123 mm and 230 and 300 g/m^2, respectively. Bisphenol A-epichlorohydrin was the principal component of the two-component epoxy resin that made up the matrix, while phenolic aldehyde amine served as the principal curing agent. Tabulated in Table 1.1 are the tensile strengths of PP and glass fiber bundles, both with and without epoxy resin

Table 1. Tensile properties of raw materials of the hybrid FRP

Materials	E_1 [GPa] (SD [GPa])	E_2 [GPa] (SD [GPa])	σ_y [MPa] (SD [MPa])	ε_t[%] (SD [%])	σ_t [MPa] (SD [MPa])
PP fiber bundle	2.94 (0.32)	0.92 (0.39)	164.3 (42.8)	23.03 (0.04)	397 (11.0)
Glass fiber bundle	35.52 (2.35)	--	--	1.86 (0.21)	679 (11.3)
Epoxy resin	10.57 (0.83)	--	--	0.48 (0.10)	51.4(8.7)

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Manufacture of Hybrid FRP Specimens

Figure 3(a) shows the dimensions of the hybrid FRP specimen, which was developed with dimensions of 15×230 mm and manufactured using a wet lay-up procedure. Epoxy resin adhesive was used to firmly attach two 50 mm long sheets of aluminum alloy at both ends. There is prior documentation that describes the production procedure in detail for the hybrid FRP specimen. Prior to conducting formal testing, hybrid FRP specimens were subjected to a controlled laboratory conditioning period lasting more than seven days.

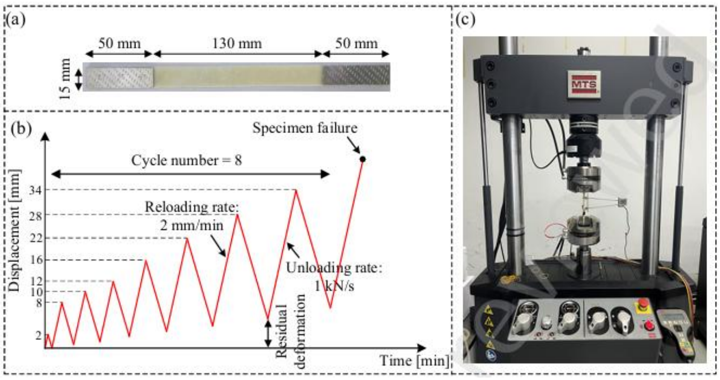

Fig. 3. Test set-up and unloading and reloading procedure: (a) geometry of tensile specimens; (b) cyclic unloading and reloading conditions; (c) test set-up.

Specimen Design

A total of nineteen specimens were prepared for the study on cyclic tensile behavior, comprising fifteen hybrid FRP specimens and four PP FRP specimens. The independent variable was the volume fraction of glass fiber layer, with PP FRP specimens serving as reference materials. All specimen details are listed in Table 2. Each specimen is assigned a name for ease of reference, following a naming convention that includes (i) a number and subsequent letter ("PP" or "G") indicating the number of woven fabric layers and corresponding raw material, respectively; (ii) the letters " M " or " C " denoting the loading mode; and (iii) the final letter ("I," "II," or "III") representing a parallel specimen. For instance, "1PP1G1PP-M-I" refers to a monotonic load-exposed specimen with stack sequence from top to bottom consisting of 1 layer of PP plain woven fabric, 1 layer of glass plain woven fabric, and 1 layer of PP plain woven fabric. All the designed hybrid FRP specimens were tested by a previously proposed failure mode map, which revealed that these specimens showed delamination failure as expected.

RESULTS AND ANALYSIS

Failure Modes: All hybrid FRP specimens showed delamination failure under cyclic tensile loads, with no appreciable slippage between the specimen and aluminum alloy sheets at the ends. The delamination developed as follows:

1. Glass fiber failure triggered the failure, resulting in relative displacement among PP and glass fiber layers.
2. Delamination began from the broken area of the glass fiber and propagated outward.
3. After complete delamination, the PP fiber layer took the rest of the tensile loads until ultimate failure.

Cyclic Tensile Stress-Strain Curves: The cyclic stress-strain response of the hybrid FRP was compared with PP FRP. The hybrid FRP had a very linear unloading and reloading stress-strain response prior to the peak, followed by high-stress drop after peak loading. The envelope curve of the hybrid FRP overlapped closely with its monotonic stress-strain curve, reflecting little energy dissipation

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on cyclic loading. Conversely, the PP FRP showed a reduced envelope curve in comparison to its monotonic curve when loaded cyclically.

Plastic Strain Development: The development of plastic strain in the hybrid FRP was contrasted with that of PP FRP. The major findings are:

1. In the hybrid FRP, the plastic strain was almost zero during unloading up to the point where the strain went beyond the peak, and the plastic strain increased directly with unloading strain.
2. For the PP FRP, the plastic strain was not zero prior to the peak point and had a greater rate of rise than the hybrid FRP.
3. The development of plastic strain was uniform in specimens with varying glass fiber layer volume fractions in hybrid FRP, which indicates that this volume fraction did not play an important role in the development of plastic strain.

Seismic Repairability

The plastic strain ratio (γr) of the seismic repairability of the material was determined for hybrid FRP and PP FRP. The findings revealed:

1. The hybrid FRP exhibited a greater plastic strain ratio (1.923) than the PP FRP (1.724).
2. This means that the hybrid FRP has better seismic repairability compared to the PP FRP, since a larger plastic strain ratio is associated with improved performance in repetitive loading situations.

Table 2. Hybrid FRP composites experimental findings

Specimen	Cycle Number (C1 to C8)	Unloading Stress (σ_un) [MPa]	Unloading Strain (ε _un) [%]	Plastic Strain (ε_) [%]
1PP1G1PP-C-I	C1 to C8	386.7, 184.7, 187.8, 187.7.'	1.45, 2.70, 7.05, ...	0, 1.05, 2.78, 4.84.'
1PP1G1PP-C-II	C1 to C8	384.7, 173.5, 174.4, ...	1.44, 5.43, 8.95, ...	0, 2.00, 4.07, 5.96, "
1PP2G1PP-C- III	C1 to C8	375.7, 174.9, 190.4, ...	1.45, 2.62, 5.79, ...	0, 0.15, 1.80, 4.05."

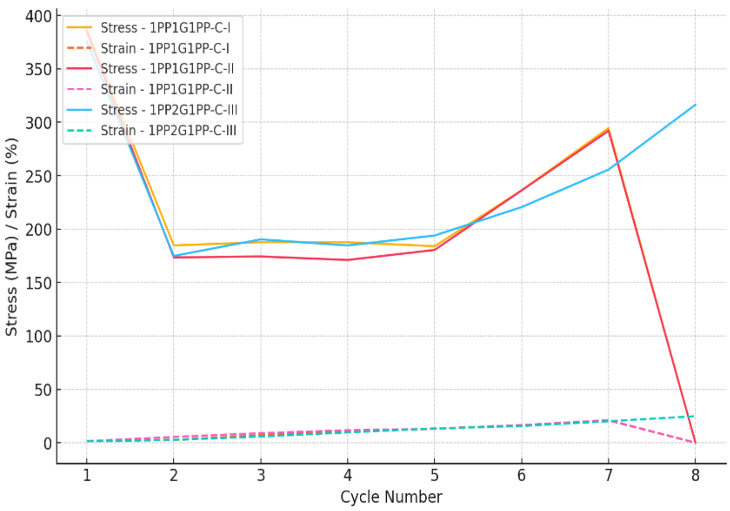

Fig. 4 Cyclic Tensile Behavior of Hybrid FRP

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CONCLUSION

The investigation emphasizes the ability of hybrid fiber reinforced polymer (FRP) composites, made with polypropylene (PP) and glass fibers, to improve the seismic behavior and repairability of structures subjected to cyclic tensile loading. The unloading and reloading stress-strain response of the hybrid FRP is found through experiments to be almost linear prior to peak loading followed by sudden stress reduction. When compared to PP FRP, the hybrid composite demonstrated much lower plastic strain and hence is a better option for enhancing seismic repairability. Further, the plastic strain ratio, a major factor of seismic repairability, was also observed to be greater for hybrid FRP (1.923) than PP FRP (1.724). The study also examined the effect of glass fiber volume fraction, which was found not to significantly impact the development of plastic strain in hybrid FRP. These results justify the application of hybrid FRP composites in practical applications, most notably in structures that are repeatedly subjected to seismic loading.

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