

The Effect of Epoxy Type on the Shear Bond Behavior of Abaca and Glass FRP Sheets Bonded to Concrete

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ABSTRACT

Fiber Reinforced Polymer (FRP) has been widely used in structural repair and strengthening because of its ease of application, corrosion resistance, and high strength-to-weight ratio. Despite these advantages, the reliance on synthetic fibers raises concerns related to the cost and environmental impact, leading to an increasing interest in natural fiber alternatives. This study focuses on the shear bond behavior of Abaca Fiber Reinforced Polymer (AbFRP) sheets bonded to concrete with two different epoxy adhesives and compares their performance with Glass Fiber Reinforced Polymer (GFRP). Experimental tests were carried out using AbFRP specimens (250×25×1.5 mm) and concrete blocks (250×100×100 mm). The parameters evaluated included the shear stress–slip relationship, maximum shear stress, and shear stress–strain response. The results revealed that the type of epoxy significantly influences the bonding performance and failure modes. Two distinct failure mechanisms were identified: debonding or composite failure, and adhesive failure, both typically accompanied by a partial detachment of the concrete substrate. Overall, the findings indicated that AbFRP has a considerable potential as a sustainable and cost-effective alternative to conventional FRP systems in structural strengthening applications.

Keywords-fiber reinforced polymer; abaca fiber; shear bond behavior; epoxy adhesive; concrete strengthening

I. INTRODUCTION

Structural strengthening represents a significant component of civil engineering, particularly for prolonging the service life of deteriorating infrastructure and enhancing the load carrying capacity. FRP materials have achieved extensive adoption owing to their superior tensile properties, resistance to corrosion, and simple application [1, 2]. However, the broad application of synthetic fibers, including carbon and glass, faces constraints emerging from the elevated costs and ecological impacts. Especially the carbon fiber, which although

provides outstanding mechanical characteristics, it remains economically unfeasible for numerous projects [3]. On the other hand, glass fiber, despite being more cost effective, exhibits durability problems in basic conditions and adds to the environmental harm [4-6]. Due to these limitations, Natural Fiber Reinforced Polymer (NFRP) technologies are gaining more attention as more cost effective and ecologically friendly solutions. Because of their decomposability and sufficient mechanical performance, natural fibers, such as sisal, kenaf, jute, bamboo, and flax, have been studied for use in building [5, 7-9]. Particularly, abaca fiber (*Musa textilis*) exhibits a

remarkable tensile strength, reaching 970 MPa, which is among the highest values, while the strength and structural reliability are improved by its higher cellulose content (60%) [10, 11]. Abaca fibers exhibit a significant potential for application in sustainable composite technologies, especially when their local availability is effectively utilized and appropriate treatments are applied to enhance the fiber-matrix bonding [12, 13]. Despite the increasing research on the NFRP mechanical performance, the interfacial bond behavior with concrete, which is essential for externally bonded strengthening systems, has been less explored [7, 14]. Most existing bond-slip models and anchorage theories were developed for the synthetic FRP systems [15-17], and may not directly apply to NFRPs due to their natural variability and differences in fiber-resin compatibility [18-20]. In addition, the choice of epoxy adhesive plays a vital role in defining the mechanical interaction between the FRP and concrete. It has been shown that the adhesive type influences the stress transfer and failure mechanisms, particularly under environmental exposure [4, 20-23]. However, limited studies have assessed these effects in natural fiber-based systems, including those using abaca [24].

The current study aims to evaluate the shear bond performance of AbFRP sheets on concrete using two epoxy variants, and compares the results with conventional GFRP systems. The findings contribute to assessing the AbFRP's feasibility as a sustainable material for structural strengthening.

II. MATERIALS AND METHODS

An experimental program was designed to evaluate the shear bond performance of AbFRP sheets with the concrete using two different commercial epoxy adhesives. For the comparison, control specimens strengthened with GFRP sheets were included. Concrete blocks with dimensions of 250 mm × 100 mm × 100 mm were cast using a normal strength mix proportioned for a target compressive strength of 25 MPa [7, 25, 26]. AbFRP sheets were fabricated by embedding abaca fibers into an epoxy matrix and cutting the cured composite into 250 mm × 25 mm × 1.5 mm strips [10, 11]. Three specimens were prepared for each configuration: CSA-A consisted of concrete blocks strengthened with AbFRP sheets bonded using Epoxy A, CSA-B, referred to specimens with AbFRP sheets bonded using Epoxy B, and CSG-A, represented concrete specimens strengthened with GFRP sheets bonded using Epoxy A, giving a total of nine tests. The use of two epoxy variants enabled the assessment of the influence of the adhesive type on the FRP-concrete bond performance [4, 20, 22]. All specimens were fabricated and tested under laboratory conditions at an average temperature of 27 °C and relative humidity of 70%. Mechanical roughening and surface cleaning were performed to provide consistent bonding interfaces.

A. AbFRP Composites

Initially, the abaca fibers were subjected to alkali treatment in a 0.5% sodium hydroxide (NaOH) solution to improve the surface roughness and interfacial adhesion [8, 12, 13]. Then, the treated fibers were aligned unidirectionally and impregnated with epoxy resin to form composite sheets, which were cured at ambient temperature for 24 h before use [10, 11] (Figure 1).

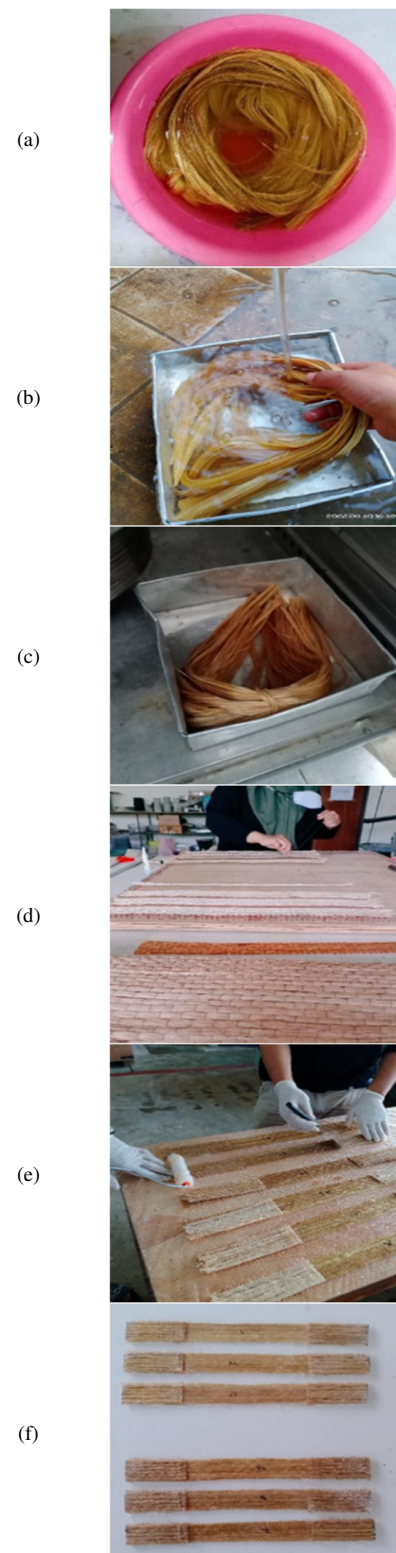


Fig. 1. Abaca Fiber Preparation: (a) soaking in NaOH, (b) washing, (c) drying, (d) weaving fibers into sheets, (e) applying epoxy resin, (f) measuring the specimens.

B. Specimen Preparation

Concrete block surfaces were mechanically roughened to enhance the bonding [26] and the AbFRP, GFRP sheets were applied using the wet lay-up technique with the designated

epoxy adhesives. After application, the specimens were cured for seven days at room temperature to ensure a sufficient adhesive setting [21, 27] (Figure 2).

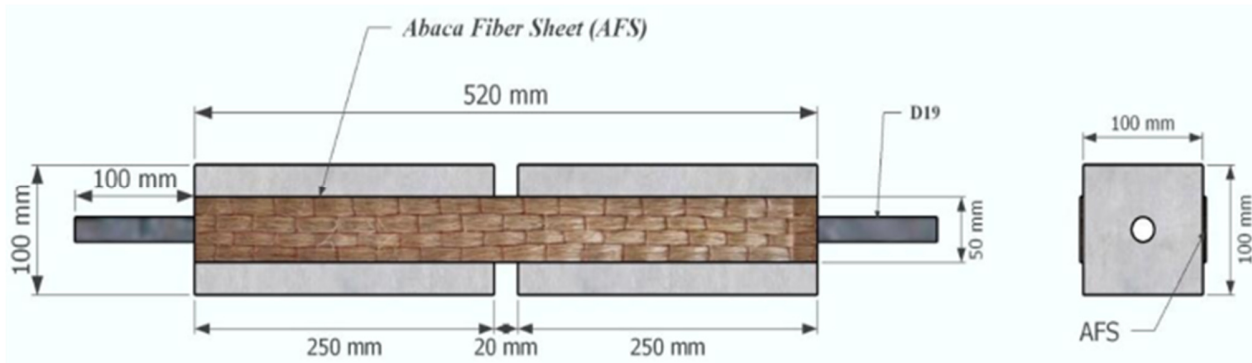


Fig. 2. AbFRP installation on beam test specimen.

C. Testing

Two types of tests were conducted. First, the tensile strength of AbFRP specimens was determined using a Universal Testing Machine (UTM) [15, 28] following the guidelines in [29]. Second, direct shear bond tests were performed to assess the FRP–concrete interface behavior [16, 17]. During the bond testing, the concrete block was restrained while tensile force was applied to the FRP sheet. The load and slip responses were recorded using a digital data logger connected to displacement sensors [5, 18].

inherent variability in natural fiber geometry and bonding characteristics, the abaca-based composites demonstrated sufficient mechanical integrity to support their use in structural strengthening systems, particularly in scenarios where a low to moderate strength enhancement is required, and the environmental impact is a key concern [7, 13].

D. Data Analysis

The bond performance was evaluated through the shear stress–slip relationships, ultimate shear capacity, and shear stress–strain responses [7, 14]. The failure modes were visually examined and categorized as debonding, cohesive failure within the adhesive or concrete substrate failure [2, 15, 24]. The experimental results were further compared with theoretical models from previous studies [16, 19, 20, 30] to verify consistency and reliability.

TABLE I. MECHANICAL PROPERTIES OF ABFRP BONDED BEAM SPECIMENS

Specimen	Specimen dimensions		Bonded area	Max tensile strength (fs)		Strain	Modulus of elasticity (N/mm ²)
	Thickness (mm)	Width (mm)		Max load (kg)	N/mm ²		
AbFRP-NT2	1.6	48.00	96.00	611.8	78.07	4.22	4624
AbFRP-NT3	1.8	49.00	112.70	703.5	78.18	4.19	4667
Average	1.7	48.50	104.35	657.7	78.12	4.20	4645
AbFRP-T2	1.6	48.00	100.80	606.7	77.42	3.75	5161
AbFRP-T3	1.6	54.00	129.60	504.7	57.25	2.97	4816
Average	1.6	51.00	115.20	555.7	67.34	3.36	5009

III. RESULTS AND DISCUSSION

A. Tensile Behavior of AbFRP Sheets

To determine the mechanical properties of the AbFRP composites, tensile tests were performed on specimens composed of abaca fibers embedded in epoxy resin (Table I). The testing showed an average tensile strength of 72.73 MPa, with a linear stress-strain response observed up to the point of failure. Although this tensile strength is notably lower than that of commercial GFRP sheets, which generally exceed 400 MPa [3], the performance of AbFRP remains acceptable in the context of applications where moderate structural demands are coupled with cost and sustainability considerations [10, 11].

B. Compressive Strength of Concrete

The average 28-day compressive strength of the concrete blocks was 26.33 MPa, consistent with the normal-strength concrete [6, 25]. This uniformity ensured that the differences in the bond performance could be attributed to the FRP and epoxy variations rather than to the substrate inconsistency.

C. Shear Stress-Slip Relationship

The shear bond behavior was analyzed through load–slip curves. Specimens bonded with Epoxy A consistently achieved higher stiffness and peak shear stresses compared with those bonded with Epoxy B. This indicates a stronger adhesive interaction and more effective stress transfer when Epoxy A was used [4, 21, 22].

The tests showed that the dominant failure mechanisms were the fiber pull-out and cracking within the epoxy matrix, which are consistent with the typical failure modes of the natural fiber composites, as documented in [10], and reflect the influence of the fiber-matrix interaction quality. Despite the

The GFRP specimens exhibited more uniform and pronounced slip behavior due to the systematic fiber alignment and controlled manufacturing processes, leading to consistent

stress distribution [1, 5]. In contrast, the AbFRP specimens displayed performance variability linked to the adhesive selection. Those with Epoxy A demonstrated enhanced stiffness and gradual slip development, whereas Epoxy B resulted in premature nonlinearity and reduced bond strength, often accompanied by adhesive failure [20, 23]. These findings reinforce those of earlier works [4, 21], which emphasized the role of the adhesive properties in the bond performance and also validated that the surface preparation techniques and adhesive infiltration properties serve as key determinants of the shear resistance in bonded systems [8, 12].

1) Effect of Epoxy Type

The choice of epoxy significantly influenced the bond performance between the FRP sheets and concrete substrates. Epoxy A provided better mechanical interlock and wetting, penetrating the surface irregularities of both the concrete and fibers, which improved the stress transfer and delayed debonding (Figure 3). Its higher tensile strength and modulus contributed to increased peak shear capacities [4, 23]. In contrast, Epoxy B resulted in early slippage and more frequent adhesive failures, which is consistent with the findings in [20]. Thus, the epoxy selection is critical for ensuring compatibility between the FRP reinforcement and the substrate [21, 27].

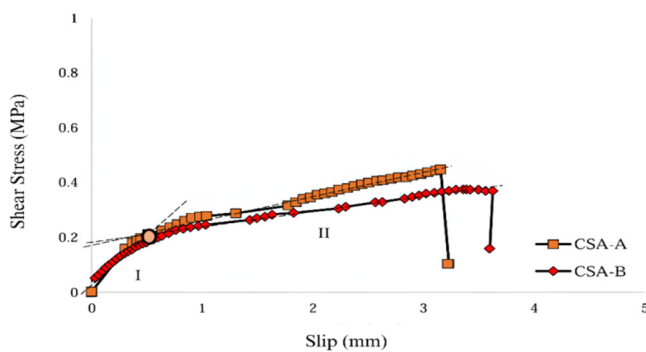


Fig. 3. Effect of epoxy type on shear stress-slip behavior.

2) Effect of Fiber Type

The fiber type also had a pronounced impact. The GFRP specimens exhibited a superior mechanical behavior, including higher tensile strength and sharper stress-strain responses (Figure 4), due to the uniform fiber geometry and optimized manufacturing [1, 3, 30]. Regarding the AbFRP specimens, although they were weaker in the ultimate bond strength, they displayed ductility and progressive failure, which can be advantageous in seismic retrofitting or energy-dissipative applications [14]. Notably, AbFRP bonded with Epoxy A approached the bond strength of GFRP, highlighting its potential as a sustainable alternative for moderate-strength applications. The performance variability, however, remains a challenge due to the fiber irregularities and manual fabrication, complying with previous reports on the natural fiber composites [7, 10, 31].

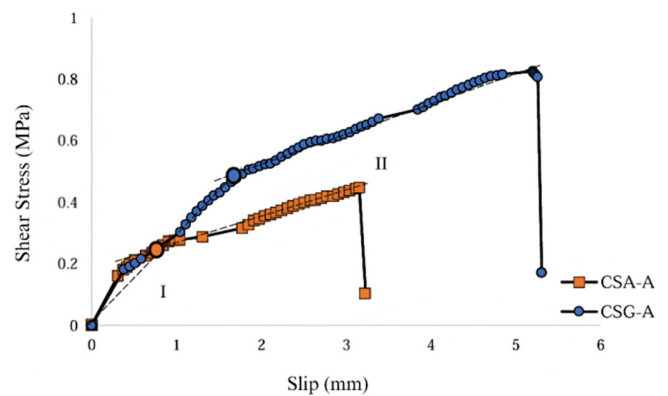


Fig. 4. Effect of fiber type on shear stress-slip behavior.

D. Maximum Shear Strength

The experimental findings (Figure 5) show that the maximum shear strength was significantly affected by both the fiber type and the epoxy adhesive applied. Among the specimens, CSG A achieved the highest ultimate shear stress of 0.826 MPa, followed by CSA A at 0.448 MPa, and CSA B at 0.376 MPa. These results suggest that Epoxy A enhances the interfacial bonding effectiveness for both the natural and synthetic fibers, likely due to its superior adhesive properties and better compatibility with both the concrete and fiber surfaces [4, 20]. Epoxy A improved the bond strength by 19.15% compared with Epoxy B.

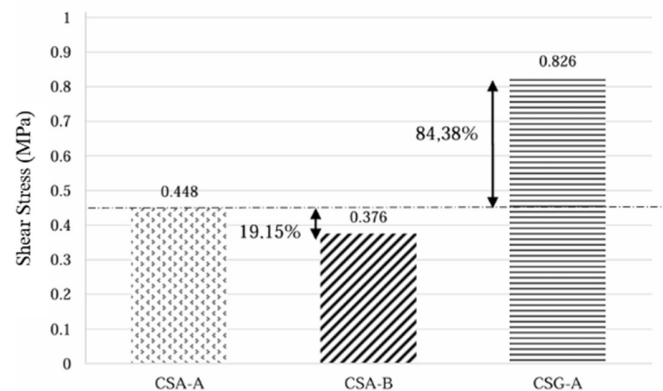


Fig. 5. Ultimate shear strength.

Although Epoxy B provided lower strength, it remains viable for light-duty applications, particularly when sustainability and cost efficiency are prioritized [10, 11, 27]. AbFRP-Epoxy A combinations are suitable for moderate-strength retrofitting, while GFRP-Epoxy A is better suited for high-demand applications, such as seismic upgrades [17]. These findings support previous design-based suggestions [2, 10], particularly in the context of lightweight retrofit systems or non-primary load paths.

E. Shear Stress-Strain Behavior

The stress strain responses confirmed the slip curve patterns. The GFRP sheets exhibited a sharper rise and brittle failure behavior, attributed to their higher modulus of elasticity and limited deformation capacity. As expected from the natural fiber composites, the AbFRP specimens, especially those bonded with Epoxy A, showed a more ductile behavior with a gradual stress reduction [31]. Applications, like seismic retrofitting, that need energy absorption and progressive failure mechanisms may be benefited from this ductility. These findings are consistent with the ones in [5], where it was discovered that the natural fiber composites are less likely to fail catastrophically because they experience more dispersed strain under shear pressures.

F. Crack Patterns and Failure Modes

Three primary failure modes were identified: FRP rupture, interfacial debonding, and partial substrate delamination. These reflect the interplay between the adhesive properties, fiber characteristics, and substrate strength [15, 18, 26].

1) Failure Mode of CSA A

The specimen type CSA A, which utilized AbFRP bonded with Epoxy A, demonstrated a mixed mode failure consisting of both cohesive failure within the adhesive layer and partial detachment of the concrete substrate. The visual evidence (Figure 6) showed clear signs of concrete fragments adhered to the back of the FRP sheet after testing, confirming that the failure propagated within the concrete substrate rather than entirely at the interface. This is generally considered favorable, as it reflects a robust adhesion and an efficient stress transfer [21, 32].

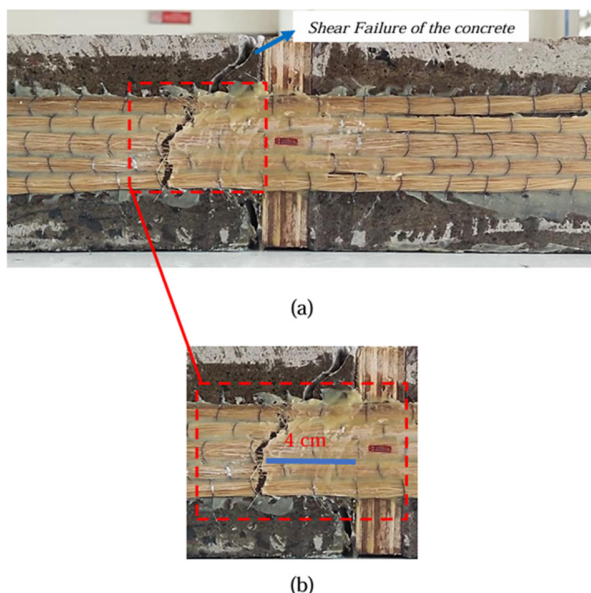


Fig. 6. CSA A failure mode: (a) shear failure of the concrete, (b) failure of the AbFRP composite material.

2) Failure Mode of CSA B

CSA B specimens consistently exhibited interface debonding or composite failure, which typically initiated at the

interface and propagated along the bonded length under load (Figure 7). The detached FRP showed minimal concrete residue, indicating insufficient bond strength, likely due to the lower viscosity of Epoxy B [20, 33].

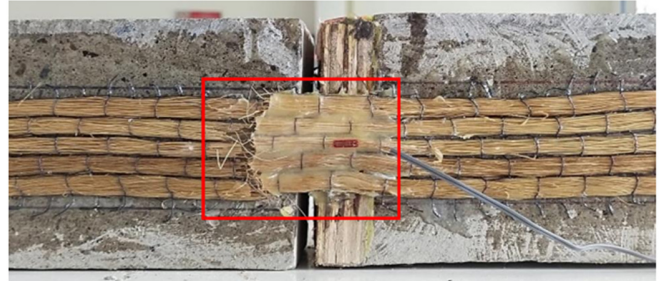


Fig. 7. CSA B failure mode.

3) Failure Mode of CSG A

The CSG A specimens experienced substrate failure, with the bonded GFRP sheet partially pulling away from the concrete surface (Figure 8). This failure represents a well-established interface and verifies the strength of industrial GFRP-Epoxy A systems [1, 33, 34].



Fig. 8. CSG A failure mode.

G. Comparison with Theoretical Predictions

To evaluate the credibility of the experimental outcomes, the obtained bond strength values were compared with established analytical models for the FRP-concrete bonding behavior, particularly those proposed in [16, 17, 20] (Figure 9). For the GFRP specimens, the results are closely aligned with these theoretical models, which support the reliability of the experimental methods and confirm that the conventional FRP systems generally behave under analytical predictions under controlled testing conditions [18].

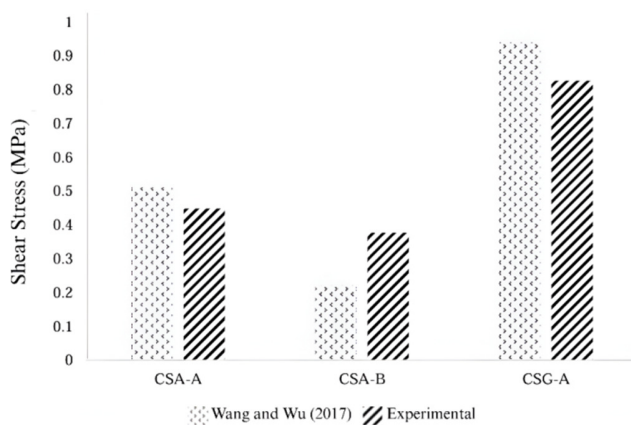


Fig. 9. Comparison of theoretical and experimental values.

On the other hand, the AbFRP specimens showed clear anomalies, with the measured shear strength values generally falling short of expectations, because of the inherent characteristics of the natural fibers. The uniform stress transfer at the bonded interface may be disrupted by the natural differences in the diameter, orientation, and distribution of abaca fibers. Furthermore, irregularities in fiber alignment and resin dispersion may be introduced during the hand production of AbFRP sheets, which would decrease the efficacy of the bond [7, 13].

The comparatively low level of resin impregnation in natural fiber bundles is another reason. Abaca fibers have a rougher and more porous structure than synthetic fibers, like glass, which have smoother and more consistent surfaces. This may make it more difficult for epoxy to penetrate and result in uneven micro level bonding, raising the possibility of localized debonding and reducing effective shear transfer [10, 11, 19].

These limitations are consistent with the observations in natural fiber composite studies [7, 13]. Improving the fabrication methods, fiber surface treatments, and standardization could reduce the variability and enhance the performance reliability [2, 19, 35]. Although design codes for natural fiber FRP systems are not yet established, the comparison with GFRP provides a useful benchmark for assessing the AbFRP feasibility under controlled conditions and contributes to the ongoing efforts toward standardization.

IV. CONCLUSION

This study compared the bond performance of Abaca Fiber Reinforced Polymer (AbFRP) sheets with conventional Glass Fiber Reinforced Polymer (GFRP) systems, focusing on their shear interaction with concrete when bonded using two types of epoxy adhesives. The results demonstrated that the adhesive selection played a critical role in determining the slip behavior and bond strength. Specimens bonded with Epoxy A consistently achieved higher shear strength and exhibited more gradual failure responses, whereas Epoxy B resulted in premature debonding and reduced capacity.

Three main failure modes were observed during testing: adhesive debonding at the FRP-concrete interface, rupture or delamination of the FRP sheet, and cracking with partial

detachment of the concrete substrate. Among these, AbFRP with Epoxy A exhibited a mixed failure mode involving cohesive fracture in the adhesive and concrete detachment, which reflects a strong interfacial bonding. In contrast, AbFRP with Epoxy B failed mainly by interface debonding, while GFRP with Epoxy A typically induced concrete substrate failure.

Overall, the experimental behavior of GFRP specimens followed well-established theoretical predictions, while AbFRP showed greater variability due to the natural fiber heterogeneity and manual fabrication. Despite this, the results confirm the suitability of AbFRP in applications requiring moderate strength enhancement, where the sustainability and cost reduction are key considerations. Future studies should address the long-term durability, repeated loading, and large-scale implementation to better establish AbFRP as a practical alternative in structural engineering.

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