

Flexural Response and Numerical Simulation of Unidirectional Areca–Pineapple Leaf Fiber Hybrid Epoxy Composites

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Abstract

The increasing demand for lightweight and environmentally sustainable materials has accelerated the development of natural fiber-reinforced polymer composites for engineering applications. In the present study, unidirectional areca and pineapple leaf fiber (PALF) reinforced hybrid epoxy composites were fabricated using a simple hand lay-up process. Before fabrication, the fibers were chemically treated to improve fiber–matrix adhesion and enhance the mechanical performance of the laminates. Four different stacking sequences (A8, A7P1, A6P2, and A5P3) were prepared to investigate the influence of PALF incorporation on the flexural behavior of the composites. Flexural performance was evaluated experimentally using a three-point bending test in accordance with ASTM D7264, and the experimental results were validated through finite element analysis using ABAQUS. The experimental and numerical results showed good agreement, confirming the reliability of the developed finite element model. The results demonstrated that increasing the PALF content improved the flexural strength, stiffness, and load-carrying capability of the hybrid laminates due to enhanced stress transfer and improved interfacial bonding between the fibers and the epoxy matrix. Among the fabricated composites, the A5P3 laminate exhibited the highest flexural performance, followed by A6P2, A7P1, and A8. Minor differences between the experimental and simulation results were attributed to fabrication-induced defects such as voids and local fiber misalignment. The developed areca/PALF hybrid epoxy composites demonstrate good potential for lightweight automotive interior components, partition panels, furniture, and other semi-structural engineering applications.

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INTRODUCTION

The growing need for lightweight and environmentally sustainable materials has increased the utilization of natural fiber reinforced polymer composites in modern engineering applications. Conventional synthetic fiber composites – such as glass and carbon fiber reinforced materials – possess excellent mechanical performance; however, issues related to high production cost, non-biodegradability, and disposal difficulties have

encouraged researchers to explore sustainable alternatives [1, 2]. Natural fibers offer several advantages including low density, biodegradability, renewability, easy availability, and reduced processing cost, making them suitable for lightweight engineering structures and interior applications. The natural fibers considered in the present investigation, namely areca fiber and pineapple leaf fiber (PALF), are shown in Figure 1.



Figure 1. Natural fibers: (a) Areca fiber and (b) Pineapple leaf fiber (PALF).

Among various natural fibers, PALF has attracted considerable attention because of its higher cellulose content and superior stiffness characteristics, whereas areca fiber is widely available at low cost and exhibits good toughness and lightweight behavior [3–5]. The combination of these two fibers in hybrid form provides an effective approach for developing sustainable composite materials with balanced mechanical performance and economic feasibility.

Although several studies have been reported on natural fiber hybrid composites, most investigations are focused on randomly oriented fiber systems and complex manufacturing methods such as compression molding, extrusion, and injection molding [6, 7]. Random fiber orientation often leads to non-uniform stress distribution and reduced load transfer efficiency within the composite structure. In contrast, unidirectional fiber alignment improves stress transfer along the loading direction and enhances the flexural response of composite laminates, as illustrated in Figure 2.

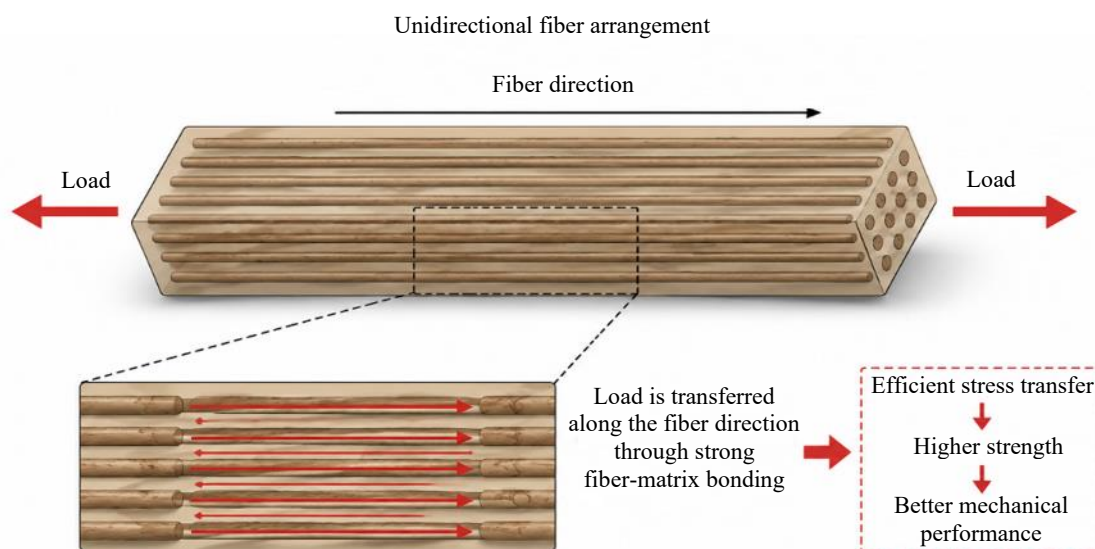


Figure 2. Unidirectional fiber load transfer mechanism.

Limited studies are available on unidirectional areca/PALF reinforced epoxy composites fabricated through a simple hand lay-up process, particularly for flexural loading applications. Moreover, the effect of PALF incorporation on the flexural behavior and deformation characteristics of areca fiber hybrid laminates remains insufficiently understood [8]. Therefore, the present work focuses on the fabrication of unidirectional areca/PALF hybrid epoxy composites using a cost-effective hand lay-up technique and the evaluation of their flexural performance through three-point bending tests. Experimental investigation and ABAQUS based numerical simulation were carried out to analyze the deformation behavior and load carrying capability of the developed laminates. The developed hybrid composites are intended for lightweight applications, such as automobile interior door panels, roof liners, partition boards, and furniture components, where moderate strength, reduced weight, and environmental sustainability are important design requirements [9, 10].

MATERIALS AND METHODS

Unidirectional areca fibers and banana fibers were used as the reinforcing materials for the fabrication of hybrid epoxy composites. The areca fibers were extracted from mature areca husks, whereas banana fibers were obtained from the pseudostem of mature banana plants collected from locally available agricultural sources [11]. Prior to fabrication, both fibers were thoroughly washed with distilled water to remove dust, dirt, and other surface contaminants. The cleaned fibers were chemically treated by immersing them in a 5 wt.% sodium hydroxide (NaOH) solution for 24 h to improve surface roughness and enhance fiber–matrix interfacial adhesion [12–14]. After alkali treatment, the fibers were repeatedly washed with distilled water until a neutral pH was obtained and then dried under ambient laboratory conditions for 24 h to remove residual moisture before composite fabrication.

A commercially available epoxy resin and compatible hardener were used as the matrix material because of their excellent adhesion characteristics, dimensional stability, and mechanical performance. The resin and hardener were mixed according to the manufacturer’s recommended mixing ratio to obtain a homogeneous matrix system before fabrication [15]. The mechanical properties of the constituent materials used in the present investigation are summarized in Table 1.

Table 1. Mechanical properties of epoxy resin, areca fibers, and pineapple leaf fibers (PALF).

Mechanical properties	Epoxy resin	Areca fibers	PALF fibers
Density (kg/m ³)	1100–1200	900–950	1350–1500
Tensile Strength (MPa)	70–85	120–250	400–1627
Young’s Modulus (GPa)	3–3.5	4–6	34–82
Shear Modulus (GPa)	1.2–1.5	1.5–2.5	12–20
Failure Strain (%)	4–6	10–13	1–3
Poisson’s Ratio	0.35	0.3	0.28

The composite laminates were fabricated using the hand lay-up technique. Initially, the mold surface was thoroughly cleaned with acetone and coated with a suitable releasing agent to facilitate easy removal of the cured laminate. A thin layer of epoxy resin was first applied over the mold surface using a brush [16]. The treated areca and banana fibers were then arranged carefully in a unidirectional orientation according to the designed stacking sequences. After placing each fiber layer, additional epoxy resin was uniformly applied to ensure complete impregnation of the reinforcement. The overall fabrication and testing procedure adopted in the present study is illustrated in Figure 3.

A hand roller was used after the placement of each layer to remove entrapped air bubbles, improve resin penetration, and minimize void formation within the laminate. The stacking process was repeated until the required laminate thickness was achieved for each composite configuration [17]. The fabricated laminates were then covered with a flat plate and subjected to uniform pressure during curing to obtain consistent laminate thickness and improved surface finish. All laminates were cured at room temperature for 24 h before being demolded. The major stages involved in laminate fabrication are presented in Figure 4.

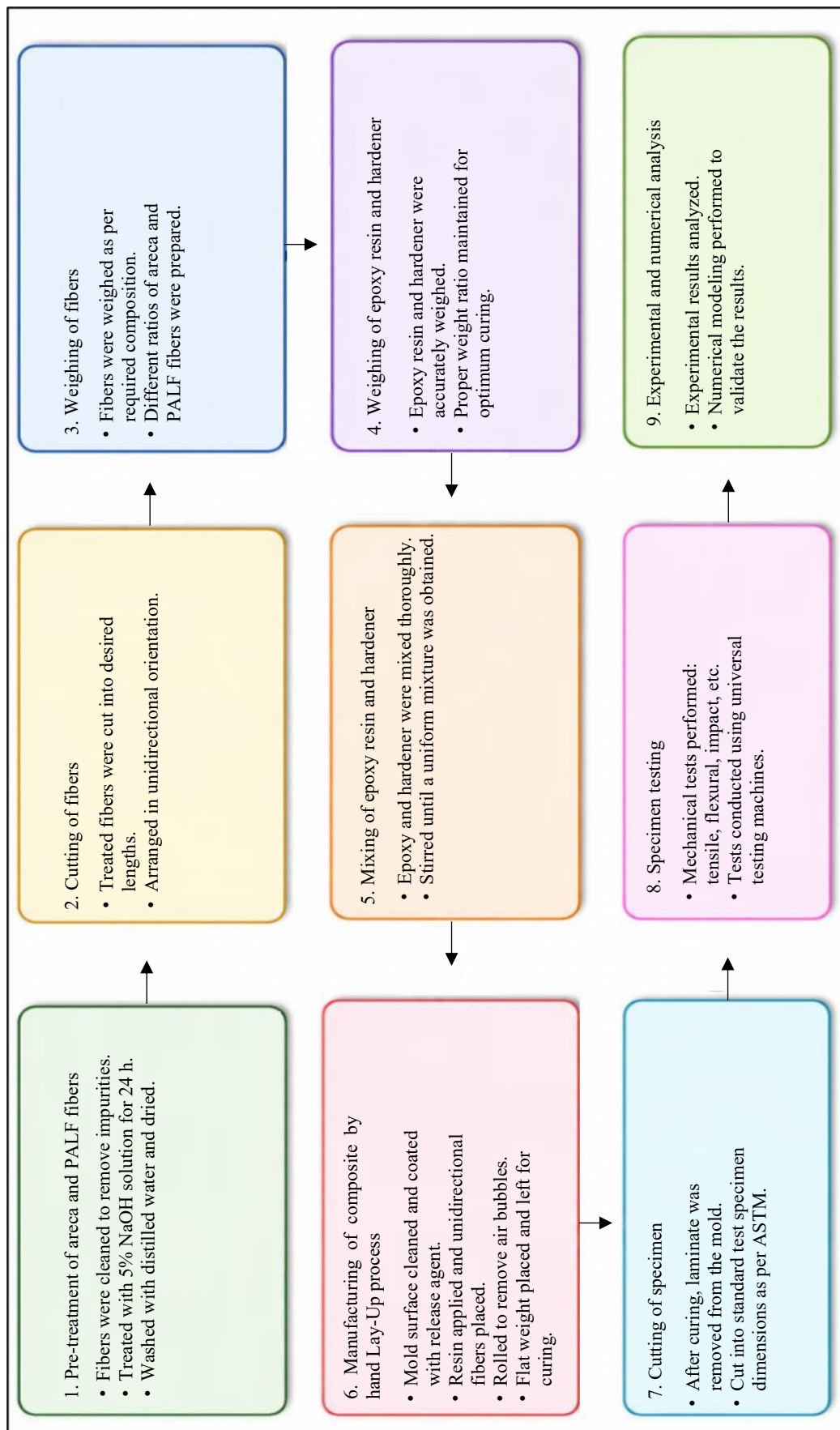


Figure 3. Layout of the fabrication and testing process of unidirectional areca/PALF hybrid epoxy composites.



Figure 4. Manufacturing stages of unidirectional areca/PALF hybrid composite.

After complete curing, the composite laminates were removed from the mould and trimmed to the required dimensions using a precision cutting machine. Flexural test specimens were prepared according to ASTM D7264. The specimen dimensions were approximately 80 mm in length, 14.6–14.8 mm in width, and 2.73–3.05 mm in thickness, depending on the stacking sequence [18]. Three identical specimens were prepared for each laminate configuration, and the average values obtained from the experimental tests were considered for further analysis.

The fabricated laminates consisted of four different stacking configurations to investigate the influence of banana fiber incorporation on the flexural behavior of areca fiber reinforced epoxy composites [19, 20]. The laminate configurations were designated as A8, A7B1, A6B2, and A5B3, corresponding to 8 layers of areca fiber, 7 layers of areca and 1 layer of banana fiber, 6 layers of areca and 2 layers of banana fiber, and 5 layers of areca and 3 layers of banana fiber, respectively. The details of the fabricated laminates, including stacking sequences and specimen weights, are presented in Table 2.

Table 2. Details of the fabricated unidirectional areca/PALF hybrid epoxy composite specimens.

Stacking sequence	Samples	Weight (g)	Description
A8	A8-1	18.92	8 layers of unidirectional areca fibers.
	A8-2	18.87	
	A8-3	18.9	
A4P1A3 (A7P1)	A4P1A3-1	18.45	4 layers of areca fibers, 1 layer of PALF, and 3 layers of areca fibers.
	A4P1A3-2	18.39	
	A4P1A3-3	18.42	
A3P2A3 (A6P2)	A3P2A3-1	17.26	3 layers of areca fibers, 2 layers of PALF, and 3 layers of areca fibers.
	A3P2A3-2	17.18	
	A3P2A3-3	17.22	
A3P3A2 (A5P3)	A3P3A2-1	16.11	3 layers of areca fibers, 3 layers of PALF, and 2 layers of areca fibers
	A3P3A2-2	16.06	
	A3P3A2-3	16.09	

The dimensions of the prepared flexural test specimens are summarized in Table 3. It can be observed that the laminate thickness increased slightly with increasing banana fiber content because of variations in fiber packing and resin distribution during the hand lay-up process [21].

Table 3. Dimensions of fabricated composite specimens after cutting.

Stacking sequence	Thickness (mm)	Total length (mm)	Average width (mm)
A8	2.73	80	14.81
A7P1	2.80	80	14.70
A6P2	2.93	80	14.60
A5P3	3.05	80	14.55

MECHANICAL TESTING

According to ASTM Standard D7264, a three-point bending test was performed to investigate the flexural behavior of the fabricated unidirectional areca/PALF hybrid epoxy composites [22, 23]. The test was conducted using a universal testing machine (UTM) under controlled loading conditions, and the experimental setup used for flexural characterization is illustrated in Figure 5.

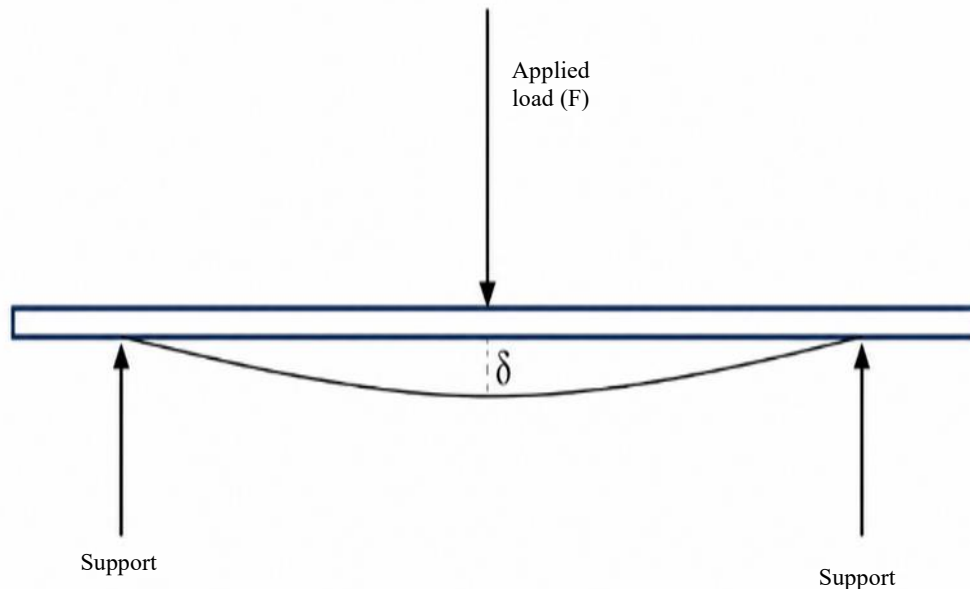


Figure 5. Schematic diagram of 3 point bending test.

The flexural stress and strain values were calculated using the following relations [24, 25]:
Flexural stress was calculated using:

$$\sigma = \frac{3PL}{2bh^2} \quad (1)$$

where

σ = flexural stress (MPa).

P = applied load (N).

L = support span length (mm).

b = specimen width (mm).

h = specimen thickness (mm).

Flexural strain was determined using:

$$\varepsilon = (6\delta h) / L^2 \quad (2)$$

where

ε = flexural strain.

δ = midpoint deflection (mm).

L = support span length (mm).

h = specimen thickness (mm).

NUMERICAL SIMULATION

To validate the experimental flexural behavior of the fabricated laminates, a three-dimensional finite element model was developed using ABAQUS/CAE 6.14 [26]. The numerical model was designed to simulate the three-point bending test under conditions identical to the experimental setup. The geometry of the composite specimen was created according to the dimensions listed in Table 3, while the material properties used in the simulation were adopted from the experimentally measured values and the engineering constants presented in Table 4 [27].

Table 4. Engineering constants used for numerical simulation of unidirectional areca/PALF hybrid epoxy composites.

Physical property	Areca/epoxy lamina	PALF/epoxy lamina
Density (kg/m)	920	1450
E1 (MPa)	6200	14800
E2 (MPa)	3200	5200
E3 (MPa)	3200	5200
G12 (MPa)	1180	2100
G23 (MPa)	980	1850
G13 (MPa)	980	1850
ν_{12}	0.31	0.28
ν_{23}	0.34	0.3
ν_{13}	0.34	0.3

Each laminate was modelled as a multilayer composite with eight unidirectional fiber plies arranged according to the respective stacking sequences (A8, A7P1, A6P2 and A5P3). The composite lay-up module available in ABAQUS was used to define the thickness, material orientation and stacking sequence of each ply. The fibers were assumed to be perfectly bonded with the epoxy matrix, and the laminate was considered to exhibit linear elastic orthotropic behavior until the initiation of failure [28].

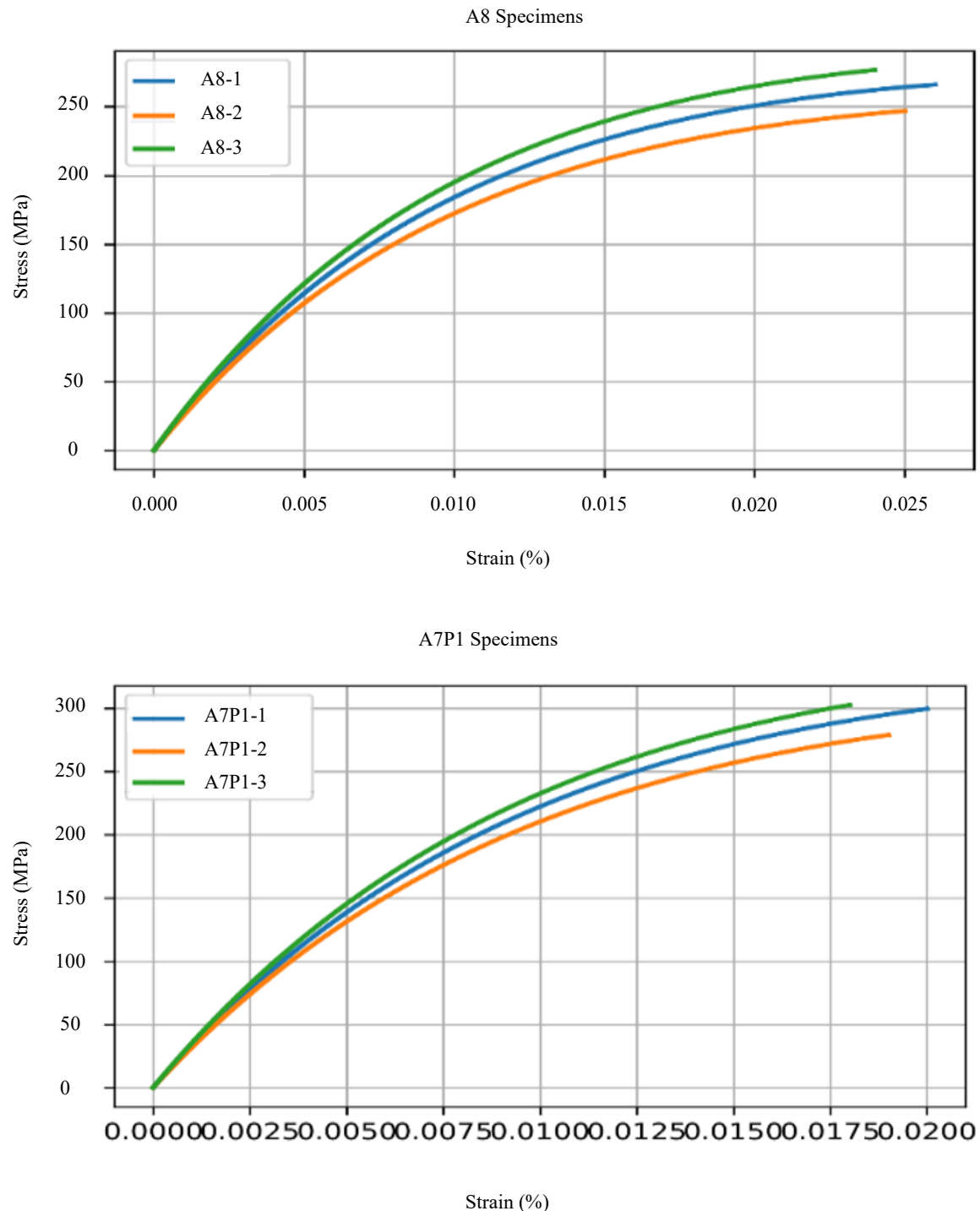
The three-point bending fixture consisted of two rigid cylindrical supports and a centrally positioned rigid loading nose. The lower supports were constrained in all translational degrees of freedom, while a vertical displacement was applied to the loading nose to simulate the experimental loading conditions. Surface-to-surface contact interactions were defined between the specimen, supports and loading nose using a frictionless contact formulation to ensure stable load transfer during deformation [29]. The composite specimen was discretized using three-dimensional continuum elements with an adequately refined mesh to capture the stress distribution during bending. Mesh refinement was performed in the loading and support regions to improve the accuracy of stress prediction while maintaining computational efficiency. A mesh convergence study was carried out to ensure that further mesh refinement produced negligible variation in the predicted flexural stress [30].

The numerical analysis was performed using the ABAQUS Standard implicit solver. The maximum von Mises stress, stress distribution, displacement and deformation patterns were extracted from the simulation and compared with the corresponding experimental results obtained from the three-point bending tests. The numerical model was subsequently validated by comparing the predicted flexural behavior with the experimentally measured stress–strain response of each laminate configuration [31, 32].

RESULTS AND DISCUSSION

Flexural Test Results

The load–displacement data obtained from the universal testing machine during the three-point bending test were converted into flexural stress–strain values using Equations (1) and (2) [33, 34]. The stress–strain behavior of all fabricated unidirectional areca/PALF hybrid epoxy composites is presented in Figure 6. Minor variations were observed among the pure areca fiber laminates, whereas the hybrid laminates exhibited comparatively stable and consistent flexural behavior due to improved stress transfer between the reinforcing fibers and the epoxy matrix.



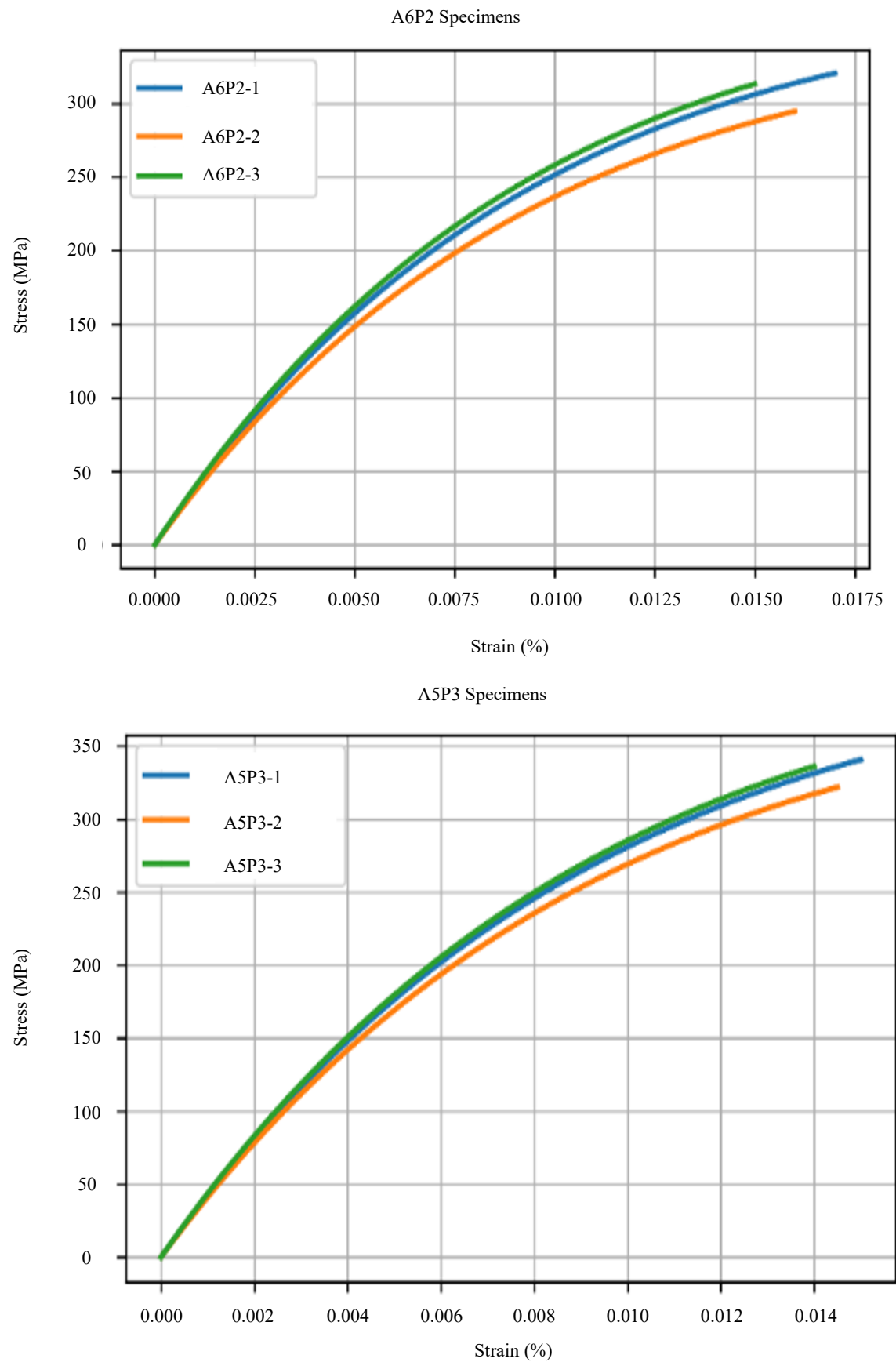


Figure 6. Stress–strain behavior of unidirectional areca/PALF hybrid epoxy composites.

The experimental flexural strength values obtained from three specimens for each laminate configuration are presented in Table 5. The average values and standard deviations were calculated to evaluate the repeatability and consistency of the experimental measurements. The relatively low standard deviation values indicate good reproducibility of the hand lay-up fabrication process and reliable experimental results. A progressive increase in average flexural strength was observed with increasing PALF content. Among the fabricated laminates, A5P3 exhibited the highest average flexural strength (172.07 ± 0.73 MPa), followed by A6P2 (159.43 ± 0.65 MPa), A7P1 (146.47 ± 0.67 MPa), and A8 (131.73 ± 0.86 MPa). Compared with the A8 laminate, the flexural strength increased by 11.2%, 21.0%, and 30.6% for A7P1, A6P2, and A5P3, respectively, confirming that PALF reinforcement significantly enhanced the flexural performance of the hybrid composites [35–37]. The stress–strain curves shown in Figure 6 support these findings by exhibiting an approximately linear elastic response during the initial stage of loading, followed by nonlinear deformation prior to failure. The superior flexural performance of the A5P3 laminate can be attributed to the higher stiffness of PALF and improved fiber–matrix load transfer resulting from the unidirectional reinforcement architecture [38].

Table 5. Experimental flexural strength of unidirectional areca/PALF hybrid epoxy composites.

Laminate	Specimen 1 (MPa)	Specimen 2 (MPa)	Specimen 3 (MPa)	Mean $\pm$ SD (MPa)
A8	132.5	130.8	131.9	131.73 ± 0.86
A7P1	146.3	147.2	145.9	146.47 ± 0.67
A6P2	158.8	160.1	159.4	159.43 ± 0.65
A5P3	171.5	172.9	171.8	172.07 ± 0.73

Figure 7 presents the comparison of the average flexural strength of all fabricated laminate configurations. The results indicate a progressive increase in flexural strength with increasing PALF content in the hybrid composite. The A5P3 laminate exhibited the highest average flexural strength, whereas the pure areca fiber laminate (A8) showed the lowest bending resistance. The improved flexural performance of the hybrid laminates can be attributed to the superior mechanical properties of PALF, which enhanced stress transfer efficiency and improved fiber–matrix interfacial bonding during bending [39, 40]. Furthermore, the statistical analysis presented in Table 5 demonstrates that the variation among the tested specimens was relatively small, confirming the repeatability of the fabrication process and the reliability of the experimental results. Compared with the A8 laminate, the average flexural strength increased progressively for A7P1, A6P2, and A5P3, indicating that the incorporation of PALF significantly improved the bending performance of the hybrid composites.

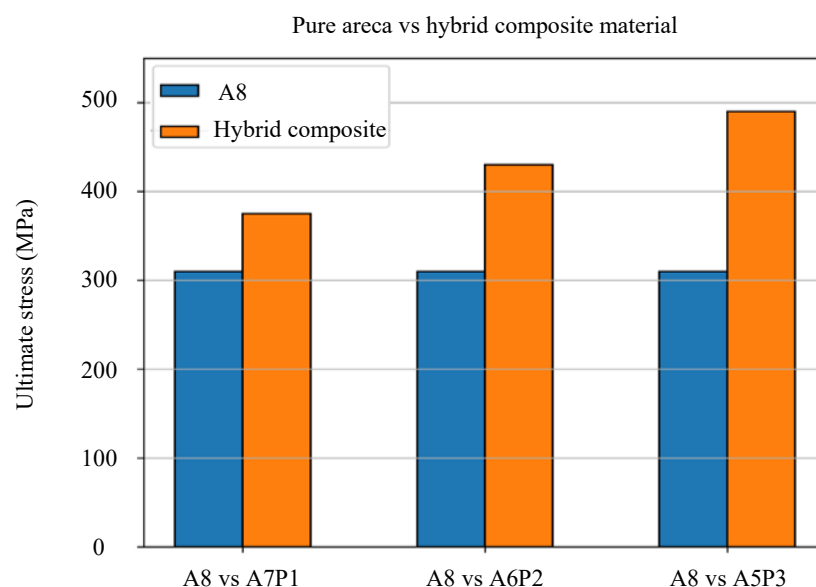


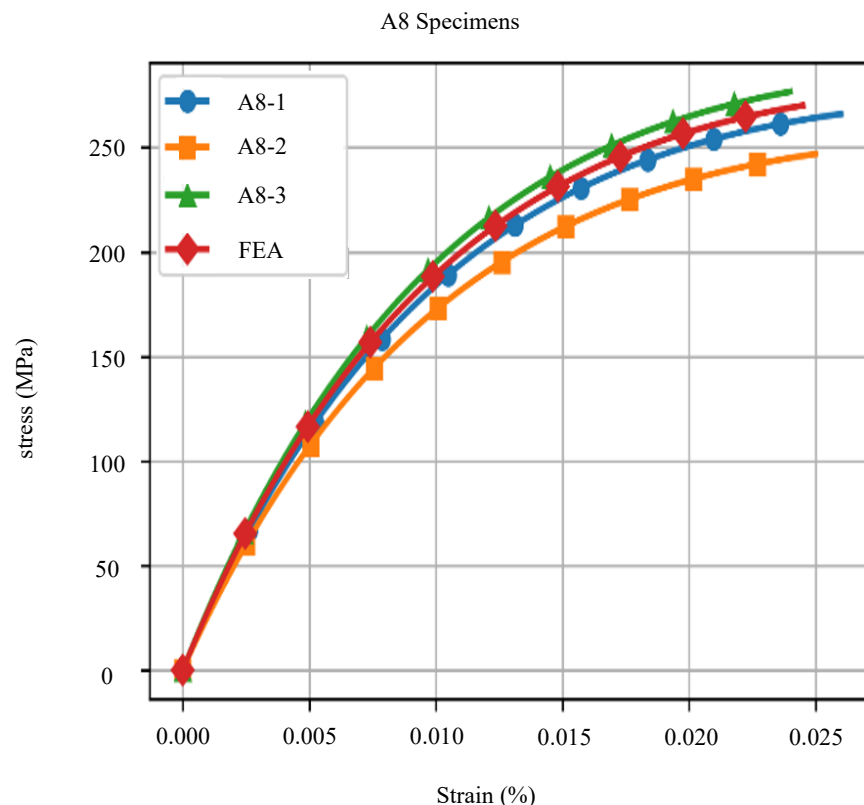
Figure 7. Comparison of flexural strength of unidirectional areca/PALF hybrid composites.

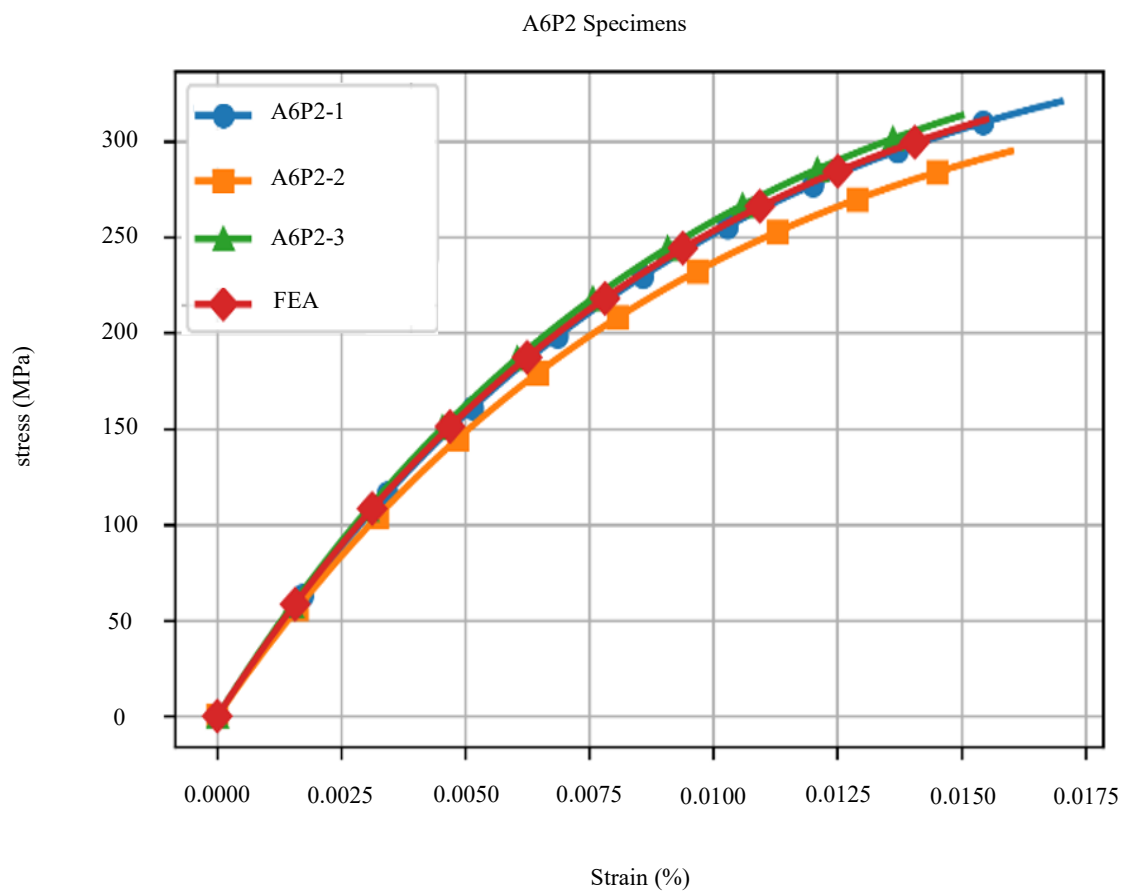
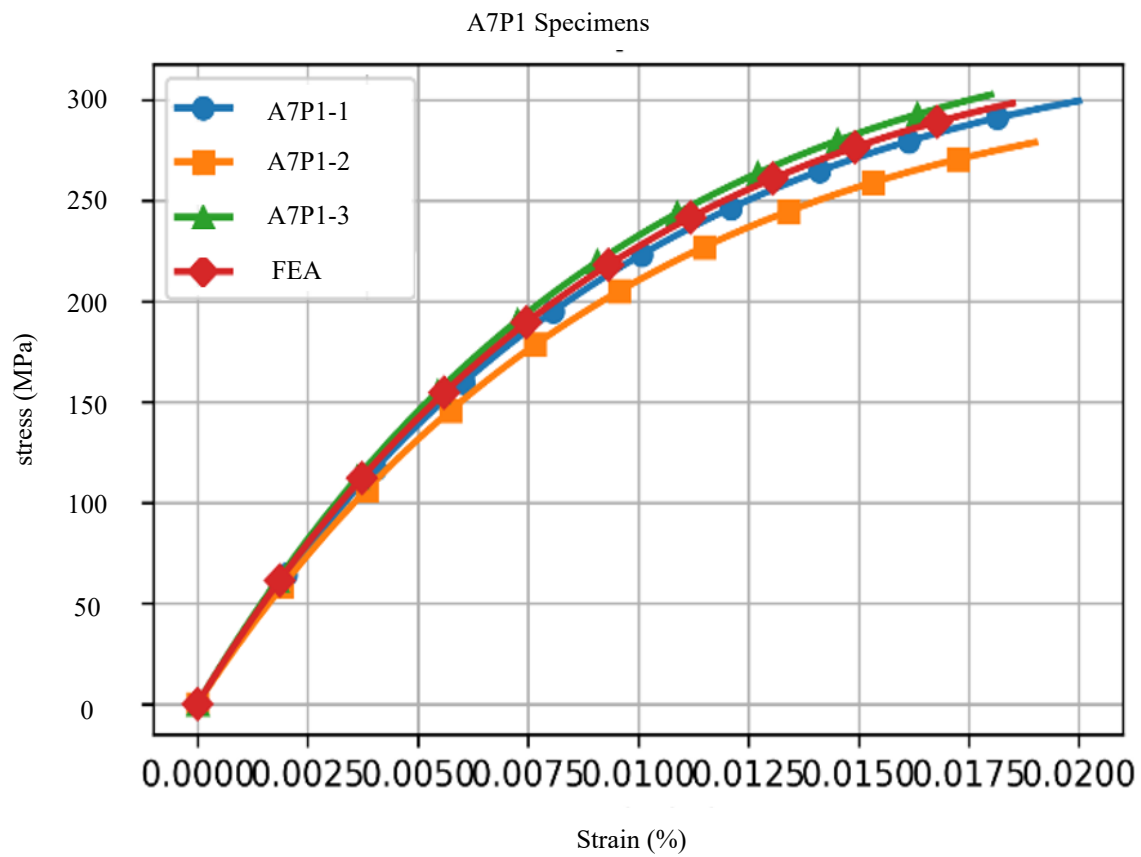
The comparison between the experimental and ABAQUS predicted flexural strength values is summarized in Table 6. The numerical model successfully reproduced the experimentally observed flexural behavior for all laminate configurations. The percentage differences between the experimental and numerical results ranged from 1.62% to 2.15%, indicating a close correlation between the finite element predictions and the experimental observations [35]. The minimum deviation was observed for the A6P2 laminate, whereas the maximum deviation occurred for the A8 laminate. These relatively small differences demonstrate that the adopted material properties, laminate configuration, loading conditions and boundary conditions were appropriately represented in the finite element model. The minor discrepancies may be attributed to unavoidable experimental factors, such as slight fiber misalignment, resin-rich regions, entrapped air voids, and local variations in fiber volume fraction, which cannot be completely incorporated into the numerical model.

Table 6. Comparison between experimental and ABAQUS flexural strength.

Laminate	Experimental (MPa)	ABAQUS (MPa)	Difference (%)
A8	131.73	128.90	2.15
A7P1	146.47	143.95	1.72
A6P2	159.43	156.84	1.62
A5P3	172.07	169.12	1.71

Figure 8 compares the experimental stress–strain response with the corresponding ABAQUS numerical predictions for all laminate configurations. Both approaches exhibited similar stress–strain characteristics and followed the same performance trend ($A5P3 > A6P2 > A7P1 > A8$). The numerical model successfully reproduced the elastic response and overall flexural behavior observed during the experimental investigation. The minor deviations between the experimental and simulated curves may be attributed to practical manufacturing factors, including slight fiber misalignment, entrapped air voids, non-uniform resin distribution, and local variations in fiber volume fraction, which are difficult to represent completely in the finite element model.





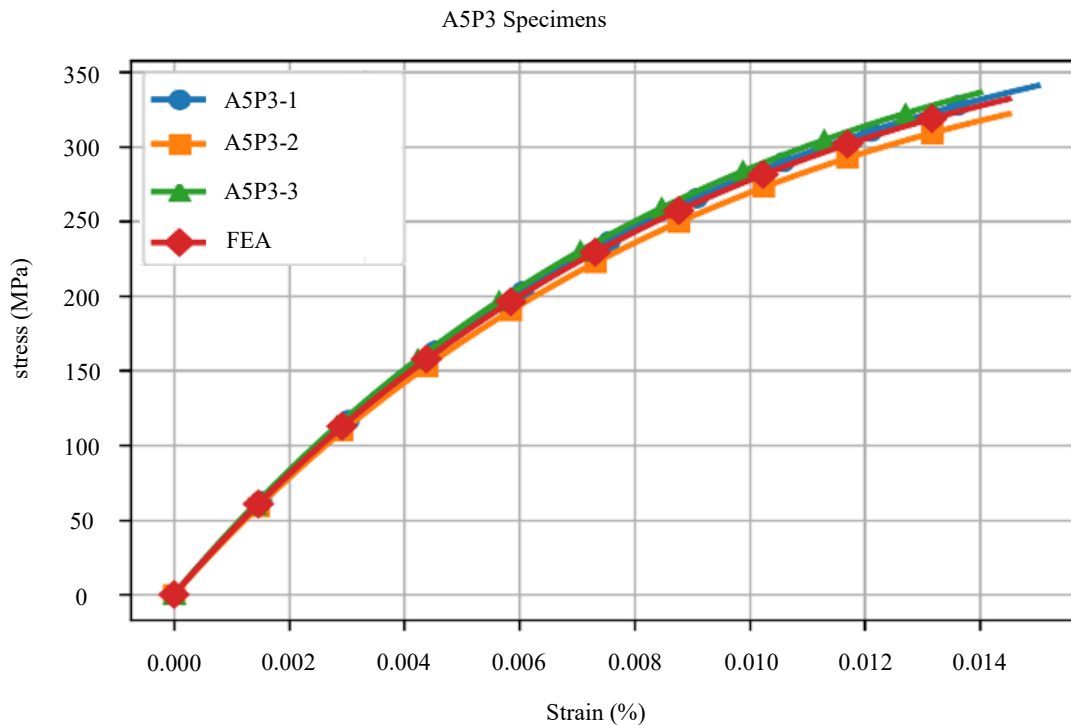


Figure 8. Comparison between experimental and ABAQUS numerical simulation results.

CONCLUSIONS AND FUTURE RECOMMENDATIONS

Unidirectional areca/PALF hybrid epoxy composites were successfully fabricated using the hand lay-up technique and evaluated through three-point bending experiments and ABAQUS finite element simulations. The experimental results demonstrated that the incorporation of PALF significantly improved the flexural performance of the composites. Among the fabricated laminates, the A5P3 configuration exhibited the highest average flexural strength of 172.07 ± 0.73 MPa, representing an improvement of approximately 30.6% compared with the pure areca fiber laminate (A8). The ABAQUS predictions showed good agreement with the experimental results, with percentage differences ranging from 1.62% to 2.15%, confirming the capability of the developed numerical model to predict the flexural behavior of the hybrid laminates. The enhanced performance was attributed to improved fiber–matrix load transfer and the higher stiffness contributed by PALF reinforcement. Based on the experimental and numerical findings, the developed areca/PALF hybrid composites demonstrate good potential for lightweight automotive interior components and other semi-structural engineering applications. Future work may focus on optimizing fiber orientation and stacking sequence, improving fiber–matrix interfacial bonding, and investigating the long-term durability, moisture absorption, fatigue, vibration, and thermal behavior of these hybrid composites under service conditions.

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