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Development and Characterization of Pineapple Leaf Fibre Reinforced with Graphene and Fibre Glass Composites for Aerospace Application

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Abstract

Natural fibre-based composites such as Pineapple leaf fibre (PALF) are valued for their environmental friendliness and unique properties, can be combined with graphene and glass fibres to create advanced aerospace composites. This study investigates the effects of graphene content and PALF composition on the mechanical properties of the composite. PALF is made using environmentally friendly methods, with graphene treated for better integration and fibre glass added through layering. This study compares the strength and flexibility of two samples with different PALF-to-fibreglass ratios: 50:50 and 70:30, and one sample with a 70:30 PALF-to-fibreglass ratio reinforced with 1% graphene, using tensile and flexural tests. The 70:30 composition ratio results in a lower maximum tensile strength and Young's modulus, but a higher bending stress than the 50:50 ratio due to the higher volume of PALF in the sample. 70:30 PALF/fibreglass reinforced with 1% graphene is stiffer, resulting in a higher Young's modulus compared to the sample without graphene. There is a slight decrease in flexural strength for the 70:30 PALF/fibreglass ratio reinforced with 1% graphene, while still maintaining superior bending stress strength compared to 50:50 ratio compositions. From the SEM test, PALF/fibreglass samples exhibited fibre pull-out, while 70:30 samples reinforced with graphene showed fibre breakage. Graphene enhanced the bonding between fibres and resins, leading to the breakage. Without graphene, weaker bonding led to fibre pull-out. Therefore, the PALF/fibreglass reinforced with graphene has the potential for aerospace applications, particularly in components subjected to high bending stress, such as aircraft wings or the horizontal tail.

1. Introduction

This study aims to develop sustainable composites for aerospace applications by combining pineapple leaf fibre (PALF), graphene, and glass fibre. Natural fibre-based composites are being extensively researched due to their environmentally friendly nature and unique properties. Natural fibres have the advantage of being readily available, easy to handle, and biodegradable. Although natural fibres have admirable physical and mechanical properties, they vary depending on the plant source, species, geography, and so on [1]. The study addresses the underutilization of PALF waste in Malaysia and seeks to improve the mechanical and physical properties of these composites through controlled fabrication and testing. Pineapple leaf waste is now recognised as a major environmental concern in Malaysia, owing to the common practice of harvesting only the fruit and ignoring the potential value of the leaves. The growth of these discarded leaves poses several challenges, both ecologically and economically [2]. This study investigates the reinforcement of PALF/fibreglass with graphene and the effects of combining these materials.

Table 1 *Different kinds of natural fibre mechanical properties for composites application [6]*

An example of a column heading	Tensile strength (MPa)	Young Modulus (GPa)
Pineapple	1020-1600	71
Kenaf	745-930	41
Jute	325-770	37.5-55

PALF has a high cellulose content, is inexpensive, eco-friendly, and has good fibre strength. PALF has excellent mechanical properties and is made up of cellulose (70-82%), lignin (5-12%), and ash (less than 2%, 1.1%). PALF has a tensile modulus of 41 GPa and a tensile strength of 1020-1600 MPa just like shown in **Table 1**. PALF outperforms other cellulose-based composite materials in stiffness and strength due to its high alpha-cellulose content, low microfibrillar angle, and superior mechanical properties [7].

Glass fibre composites are materials that combine glass fibres with a matrix, typically made of polymer resin, to create a more rigid and strong composite. Glass fibres, which are typically formed by drawing molten glass into thin strands, serve as the reinforcing element. These fibres are known for their lightweight, corrosion-resistant, and high tensile strength [3]. When incorporated into a matrix such as polyester or epoxy resin, the composite material benefits from the advantages of both components. Glass fibre composites are commonly used in a variety of industries, including sports equipment, automobiles, aircraft, and construction. In aerospace, these composites produce strong, lightweight structures that boost performance and fuel efficiency.

Graphene is a two-dimensional honeycomb structure as shown in **Fig. 1** made up of a single layer of carbon atoms organized in a hexagonal pattern. It has exceptional mechanical, electrical, and thermal properties. Graphene is also an essential component of other carbon allotropes such as fullerenes and carbon nanotubes [4]. Graphene is remarkably strong and lightweight at the same time, with a tensile strength greater than 100 times that of steel [5]. Its transparency and flexibility make it suitable for a wide range of applications, from electronics and energy storage to medical devices and composite materials.

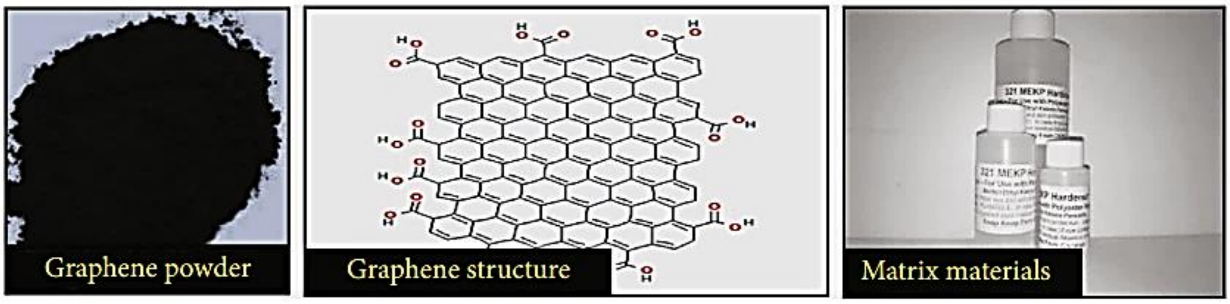

Fig. 1 *Photographic images of nanofiller and matrix materials [9]*

In Malaysia, the Malaysian Pineapple Industrial Board manages pineapple plantations that cover over 147,000 hectares and generate significant waste from pineapple leaves. This waste, if not properly managed, causes environmental and economic problems such as land pollution, greenhouse gas emissions, and strain on waste management systems [8]. However, pineapple leaves contain valuable fibres that can be used to create sustainable and environmentally friendly products.

The purpose of this research is to create and analyse a composite material made of pineapple leaf fibre (PALF) reinforced with graphene and glass fibre for aerospace applications. The objectives include determining the effects of graphene and PALF content on the composite's mechanical properties, assessing its physical properties, and characterizing its composition and microstructure. The research involves making the composite, performing tensile, SEM, and flexural tests, and analysing flaws. The expected outcome is a high-quality, thermally stable, and efficient composite material that improves performance and provides long-term solutions for the aerospace industry.

2. Methodology

PALF is prepared using both traditional hand-scraping methods and modern machinery such as the Pineapple Leaf Fibre Machine. As shown in **Fig. 2**, the fibres are extracted, cleaned, and dried to prepare them for use in composites. The graphene preparation process is detailed, with steps such as dispersing graphene nanofillers in ethanol, sonication, and mixing with DGEBA epoxy resin. The composite is then stirred, degassed, and cured to produce a strong and uniform material. Fibreglass preparation is described, with a focus on the extrusion and attenuation of molten glass to form fibres that are then used to reinforce composite materials. Samples of PALF/fibreglass and PALF/fibreglass reinforced with graphene were fabricated using the standard sandwich layup method.

Fig. 2 *Extracted PALF*

The sandwich layup technique for PALF and fibreglass as shown in **Fig. 3** starts with meticulously preparing Pineapple Leaf Fibre (PALF) by combing it thinly to improve resin absorption. This ensures each fibre is fully coated with resin, crucial for composite strength. The resin and hardener are mixed in a 2:1 ratio. The process begins with a layer of resin on a steel plate, followed by prepared PALF fibres, another resin layer, and then fibreglass. This layering alternates between PALF and fibreglass, ending with a five-layer structure. A top steel plate is added, and pressure is applied to eliminate air pockets and ensure bonding until the resin cures, resulting in a strong composite material.

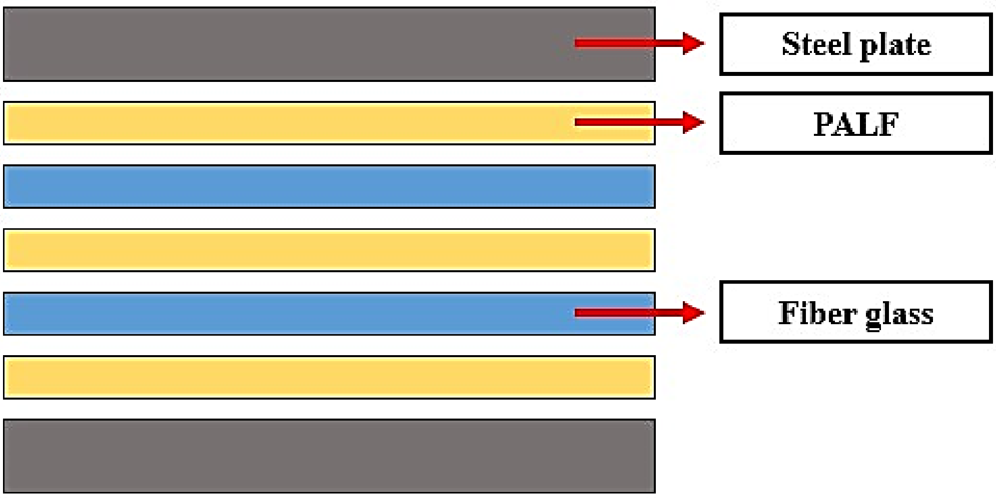

Fig. 3 *Sandwich layup method for PALF/Fibreglass*

Three tests were conducted to analyse the samples: tensile, flexural, and SEM. These tests were performed to identify the characteristics of the PALF/fibreglass and PALF/fibreglass reinforced with graphene. Each test has different dimensions according to the machine's specifications.

3. Results and Discussions

3.1 Tensile Test

The tensile test had two parts, each aimed at comprehensively characterizing composite materials. The first phase focused on testing samples of PALF/fibreglass ratio by testing samples with different compositions, i.e. 50:50 and 70:30. The 50:50 ratio acted as the control of the test. 70:30 sample, with more PALF, exhibited a lower Young's modulus, making it more elastic than the 50:50 sample. Additionally, the 70:30 sample had higher strain, resulting in greater ductility, toughness, and material deformation.

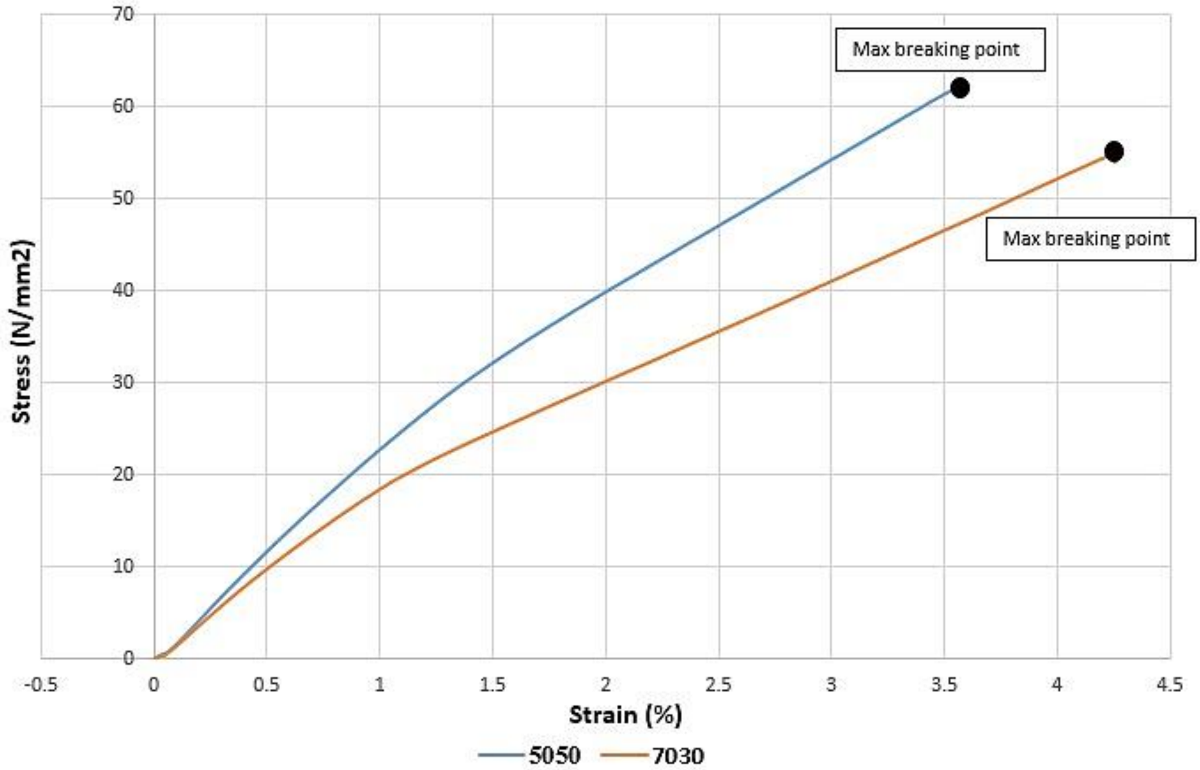

Fig. 4 *Graph for tensile test of PALF/fibreglass compositions: 50:50 and 70:30*

Table 2 *Tensile test results for PALF/fibreglass*

PALF/fibreglass compositions	Maximum Stress (N/mm2)	Maximum Strain (%)	Breaking Stress (N/mm2)	Break Strain (%)	Young's Modulus (GPa)
50:50	62	3.554	61.96	3.555	17.445
70:30	54.6604	4.236	53.853	4.253	12.904

Table 2 and **Fig. 4** show that the 70:30 PALF to fibreglass ratio has a lower Young's modulus (12.904 GPa) compared to the 50:50 sample (17.445 GPa). A lower Young's modulus indicates higher elasticity, allowing the material to deform under stress without breaking. This increased elasticity is due to the higher concentration of flexible PALF fibres. Consequently, the 70:30 compositions are less strong than the 50:50 compositions but are more environmentally friendly due to the higher PALF content. The values of stress and strain between these two ratios were slightly different. This foundation of increased elasticity and environmental friendliness in the 70:30 composition guided further research, leading to the testing of PALF/fibreglass samples reinforced with graphene to evaluate their improved mechanical integrity.

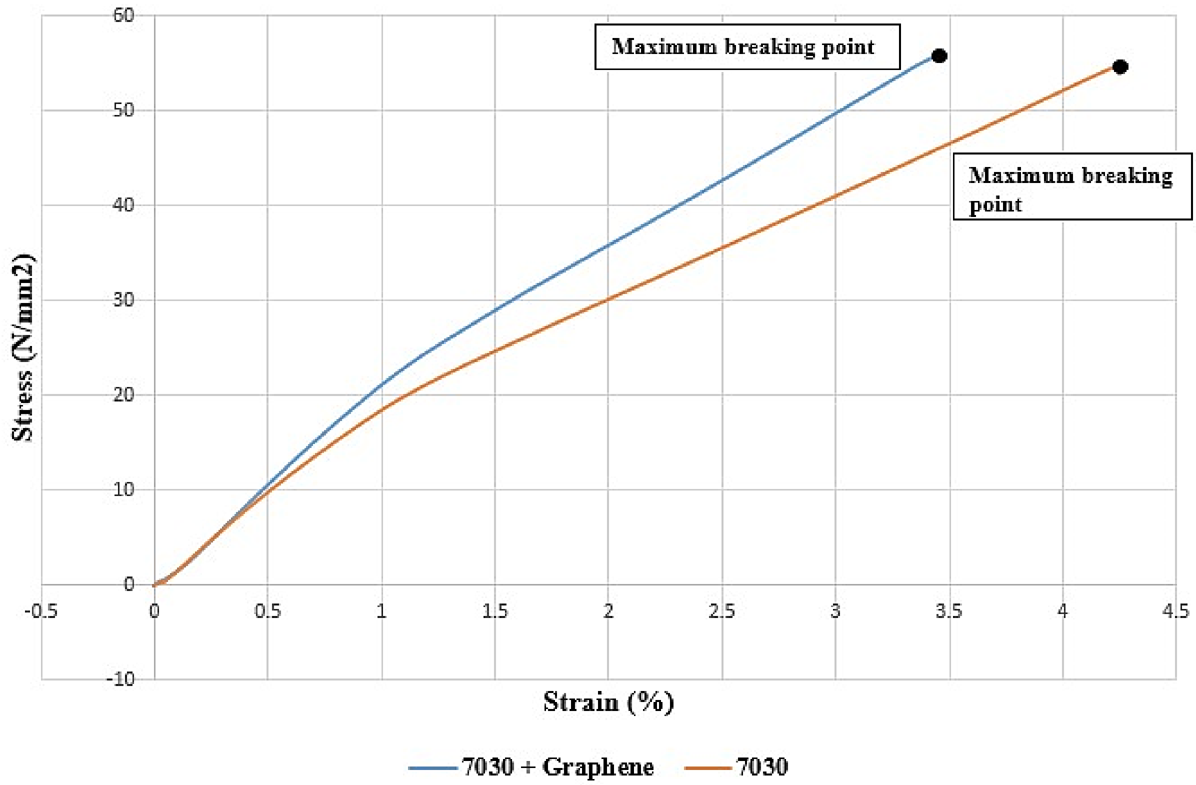

Fig. 5 *Tensile test results for PALF/fibreglass (70:30) and PALF/fibreglass with graphene reinforcement*

Table 3 *Tensile test results for PALF/fibreglass and PALF/fibreglass with graphene reinforcement*

PALF/fibreglass compositions	Maximum Stress (N/mm2)	Maximum Strain (mm)	Breaking Stress (N)	Breaking Strain (%)	Young's Modulus (GPa)
70:30 + Graphene	55.854	3.445	55.82	3.449	16.211
70:30	54.6604	4.236	53.853	4.253	12.904

The tensile test results showed minimal differences in stress and strain value between PALF/fibreglass composites and those with 1% graphene by weight, indicating that the low concentration of graphene did not significantly affect overall strength. However, the Young's modulus results revealed that the PALF/fibreglass (70:30) composite with graphene was stiffer than the one without, making it less flexible and more prone to breaking under stress. This suggests that while graphene can increase stiffness, further enhancements might need higher graphene content or different reinforcement techniques. The tensile tests in **Table 3** and **Fig. 5** show minimal differences between PALF/fibreglass composites and those reinforced with 1% graphene by weight, due to the low concentration of graphene. This small addition did not significantly impact the strength characteristics. Although graphene is known to enhance mechanical properties, its effect at such low levels is negligible. To achieve significant improvements, higher graphene content or alternative reinforcement methods may be needed. Further research into graphene dispersion and interaction within the composite could help optimize the properties and fully utilize graphene reinforcement in PALF/fibreglass composites.

3.2 Flexural Test

The flexural test consists of two phases to fully characterise the composite materials. In the first phase, the flexural test was conducted to compare the bending strength between 50:50 and 70:30 of the PALF/fibreglass ratio. The test then focused on comparing 70:30 of PALF/fibreglass without graphene with PALF/fibreglass reinforced with graphene at a ratio of 70:30. This method provided a comprehensive analysis of the composite's mechanical properties at various ratios, as well as its response to graphene reinforcement, providing valuable insights for optimising material performance.

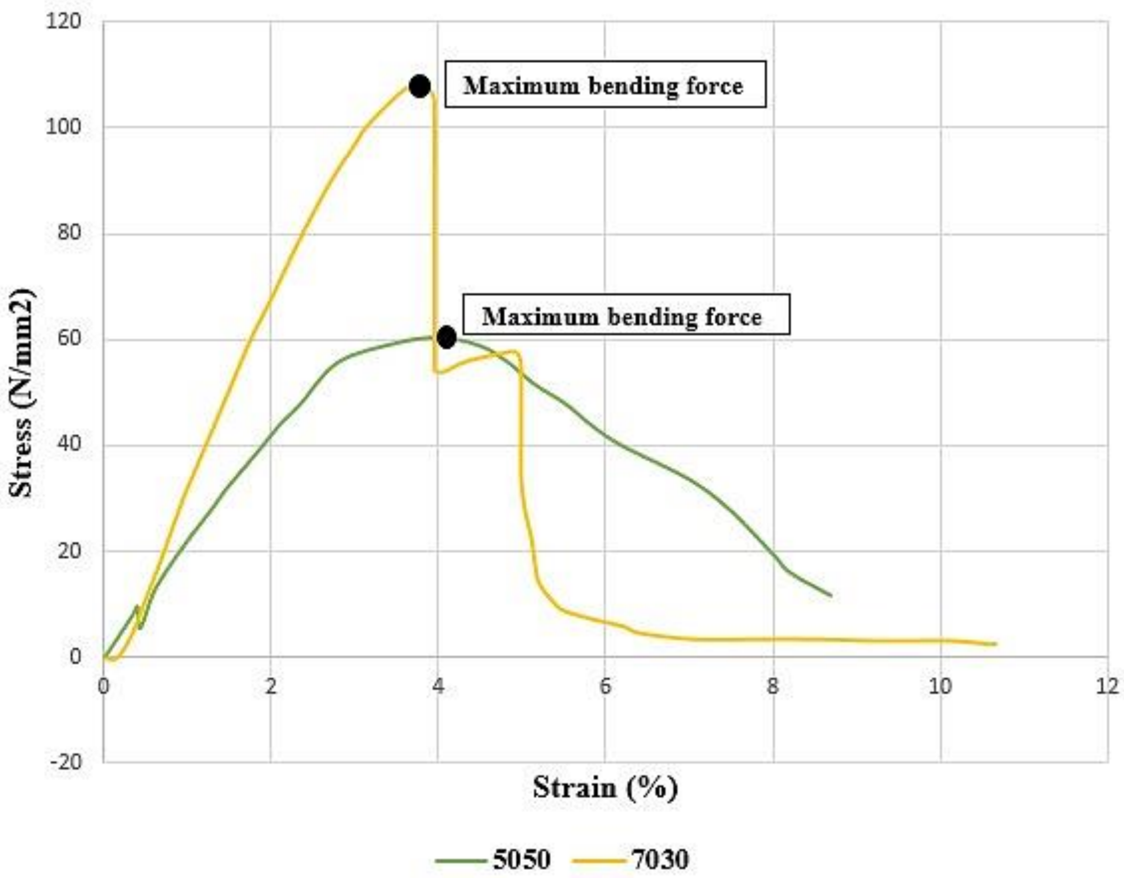

Fig. 6 *Flexural test results for PALF/fibreglass with ratios of 50:50 and 70:30*

Table 4 *Flexural test results for PALF/fibreglass*

PALF/fibreglass compositions	Maximum Stress (N/mm2)	Maximum Strain (%)
50:50	61.045	4.096
70:30	108.466	3.733

As shown in **Table 4** and **Fig. 6**, the maximum stress for the 70:30 ratio of PALF/fibreglass is higher compared to the 50:50 ratio. Specifically, the stress for the 70:30 sample is 108.466 N/mm^2, whereas for the 50:50 sample, it is 61.045 N/mm^2. This indicates that the 70:30 composite can withstand higher levels of applied stress before deforming or failing, highlighting its superior mechanical strength compared to the 50:50 composite. The composition of PALF makes the specimen even more elastic. The 70:30 ratio was chosen not only for its superior mechanical properties but also because it is more environmentally friendly. Using a higher proportion of PALF, a natural and renewable fibre, reduces the need for synthetic fibreglass, lowering the environmental impact. This makes the 70:30 composite a more environmentally friendly option while maintaining excellent mechanical performance.

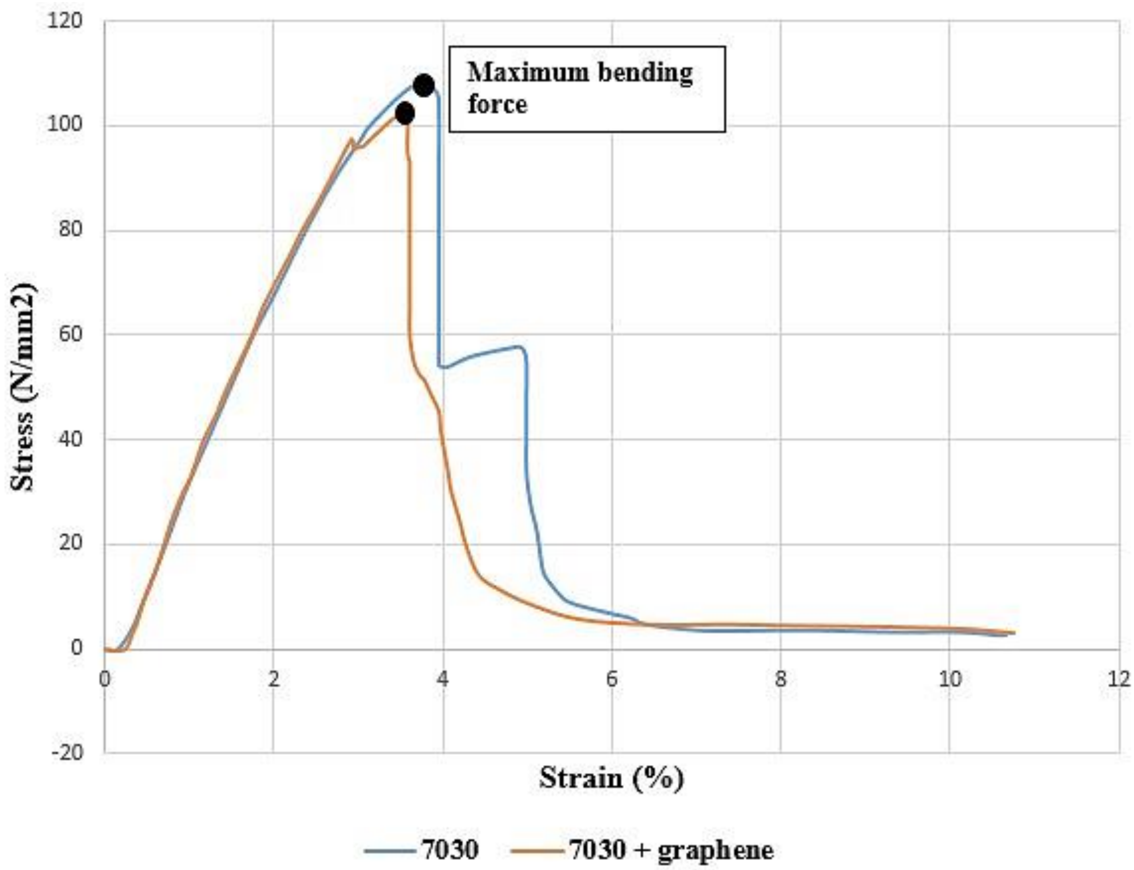

Fig. 7 *Flexural test results for PALF/fibreglass (70:30) and PALF/fibreglass with graphene reinforcement*

Table 5 *Flexural test results for PALF/fibreglass and PALF/fibreglass reinforced with graphene*

PALF/fibreglass compositions	Maximum Stress (N)	Maximum Displacement (mm)
70:30 + Graphene	102.62	3.52
70:30	108.466	3.733

As shown in **Table 5** and **Fig. 7**, the stress and strain of the 70:30 PALF/fibreglass sample were slightly reduced when graphene was added. Hence, the 70:30 PALF/fibreglass has a higher maximum stress and strain compared to the graphene-reinforced 70:30 PALF. However, the decrease in stress and strain value is not significant, most likely due to the small amount of graphene added (1% relative to the weight of PALF/fibreglass). The incremental effect is low at this percentage, suggesting that a higher graphene content may be required to significantly increase the flexural strength of the composite.

3.3 SEM Test

Two SEM tests were carried out on PALF/fibreglass samples, one without graphene and one with graphene. These tests were designed to examine the microstructure of the samples that underwent tensile testing to detect any differences.

Fig. 7 and **Fig. 8** show a composite material made of PALF and fibreglass that has undergone fibre pull-out. The reason for this phenomenon is attributed to insufficient bonding between the fibres and matrix. Poor fibre-matrix adhesion weakens the interfacial region, resulting in inefficient load transfer from the matrix to the fibres. As a result, during tensile testing, the fibres may slip out of the matrix rather than distribute the stress, compromising the composite material's structural integrity and mechanical performance.

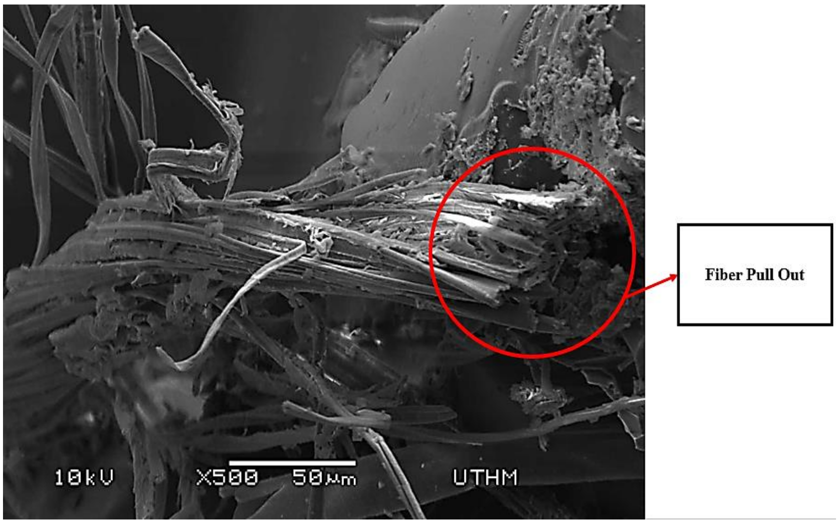

Fig. 8 *Fibre pull out at the end of PALF/fibreglass composition at x500 magnification*

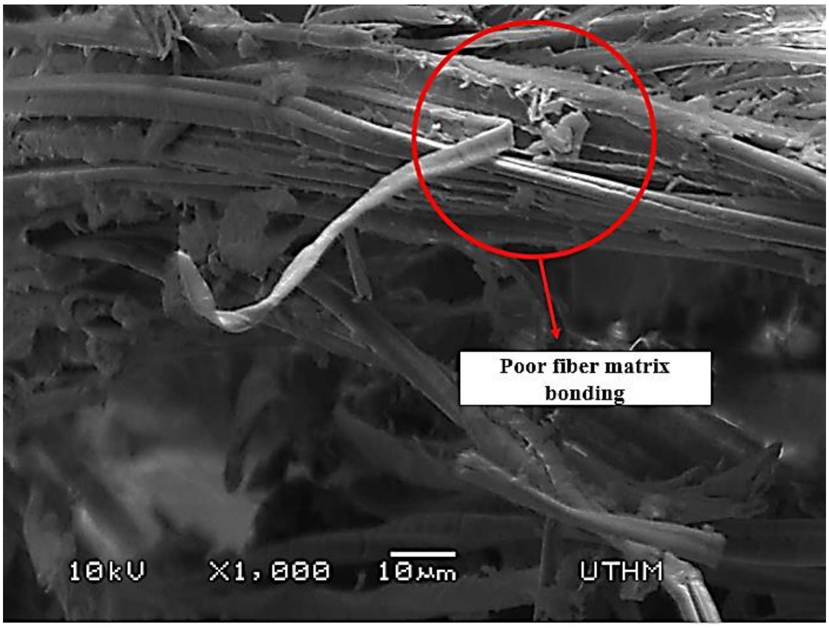

Fig. 9 *Example of poor fibre matrix bonding of PALF/fibreglass composition at x1000 magnification*

Fig. 10 *Fibre break on PALF/fibreglass reinforced with graphene at x500 magnification*

Fig. 9 shows the results of a 500x magnification SEM test of a PALF/fibreglass composite reinforced with graphene. The image shows that the fibre-matrix interfacial bonding is significantly stronger in the graphene-reinforced composite than in the one without graphene. This enhanced bonding explains why fibre breakage occurred rather than fibre pull-out. The presence of graphene improves the adhesion of the fibres to the matrix, resulting in a more uniform and cohesive interface.

This improvement can be attributed to graphene's unique properties, such as its large surface area and strong intermolecular interactions, which allow for better load transfer and stress distribution within the composite. As a result, incorporating graphene improves not only mechanical performance but also material durability and reliability.

Adding graphene to a PALF/fibreglass composite enhances its suitability for aerospace applications by improving fibre-matrix interfacial bonding. SEM analysis showed stronger bonding, indicated by fibre breakage rather than pullout, crucial for materials facing extreme conditions such as high stress, temperature changes, and impacts. Graphene-reinforced composites offer weight savings without compromising strength, making them ideal for aerospace components like wings and horizontal tails that endure high bending stress. These composites' increased durability and reliability reduce maintenance costs and downtime, representing a significant advancement in materials science for more efficient and high-performing aerospace structures.

4. Conclusion

The purpose of this research is to look into the effect of graphene content on the mechanical properties of PALF/glass fibre composites. It emphasises the benefits of PALF, such as high tensile strength, biodegradability, and renewability, as well as its underutilization due to a lack of awareness. The methodology summarises PALF preparation, graphene functionalization, and the composite sample layup process. It also summarises the mechanical testing procedures and results, which revealed that the addition of graphene had little effect on tensile strength but improved flexural properties in the composites. The strength and flexibility of 50:50 and 70:30 PALF/fibreglass composites were measured using SEM, tensile, and flexural tests, with 50:50 serving as the control. The 70:30 ratio, with higher PALF content, showed greater flexibility and lower Young's modulus compared to the 50:50 ratio. While tensile test results for stress and strain were similar, flexural tests differed due to the varying PALF content. Adding 1% graphene made the 70:30 composite stiffer, as shown by the Young's modulus in tensile tests, but had a slight effect in flexural tests. SEM analysis revealed that graphene strengthened the bonding between fibres and resin, causing fibre breakage, while samples without graphene showed fibre pull-out. The project aims to develop a material suitable for aerospace applications, such as wings or horizontal tails, which require high bending stress resistance.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to this manuscript as follows. ***Study conception and design:*** *Noor Ezzat Nafie bin Noor Azman, Mohd Fadhli Zulkafli and Syafiqah Nur Azrie Safri.* ***Data collection:*** *Noor Ezzat Nafie bin Noor Azman and Syafiqah Nur Azrie Safri.* ***Analysis and interpretation of results:*** *Noor Ezzat Nafie bin Noor Azman, Mohd Fadhli Zulkafli and Syafiqah Nur Azrie Safri.* ***Manuscript preparation:*** *Noor Ezzat Nafie bin Noor Azman, and Mohd Fadhli Zulkafli. All authors reviewed the results and approved the final version of the manuscript.*

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