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RESEARCH ARTICLE

Crack repair of aluminium components using glass fibre reinforced polymer composite patches: Effect of patch thickness on tensile behaviour

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Abstract - Crack propagation in metallic structures is a critical issue in industries such as aerospace, oil and gas, and automotive, where conventional repair methods such as welding or part replacement are often costly and time-consuming. This study investigates the effectiveness of Glass Fibre Reinforced Polymer (GFRP) composite patches for repairing cracked aluminium sheets. Centre- and edge-notched specimens with crack lengths of 5, 10, and 15 mm were fabricated and repaired using hand lay-up GFRP patches of varying thicknesses (two and four layers). Tensile tests were performed according to ASTM E8 to evaluate the mechanical performance of repaired specimens compared with unrepaired samples. The results demonstrated that composite patches significantly improved the load-carrying capacity of cracked specimens, with thicker patches providing higher strength recovery. Specifically, specimens with four-layer GFRP patches produced the highest maximum stresses of 152.44 MPa and 184.67 MPa for edge and centre cracks of 5 mm, respectively, compared with substantially lower strengths in unrepaired samples. An increase in patch thickness led to greater tensile-strength recovery; however, this improvement must be weighed against weight considerations, particularly in weight-sensitive applications such as aerospace structures.

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1. Introduction

Metallic components play a vital role in critical engineering sectors such as aerospace, oil and gas, transportation, and marine structures [1-5]. However, they are prone to crack initiation and propagation due to cyclic loading, corrosion, high pressure, and environmental degradation. Such cracks can compromise structural integrity and, if untreated, may lead to catastrophic failures. Conventional repair approaches, including welding, grinding, and mechanical fastening, are often costly and time-consuming and may introduce additional stress concentrations or metallurgical defects [6-7]. In recent years, fibre-reinforced polymer (FRP) composites have emerged as effective alternatives for structural repair [8-10]. Composite patching offers several advantages over traditional methods, including corrosion resistance, high specific strength, weight savings, and ease of application on complex geometries. Studies have shown that adhesively bonded FRP patches can reduce stress intensity factors (SIFs) at crack tips, delay crack propagation, and restore the load-bearing capacity of damaged metallic components. Katnam et al. [11] reported significant improvements in fatigue life and tensile strength of aluminium alloys repaired with bonded composite patches. Among FRPs, carbon fibre reinforced polymer (CFRP) is widely studied for its excellent stiffness and fatigue resistance, but its high-cost limits widespread industrial adoption [12-14]. GFRP, on the other hand, offers a cost-effective solution with good mechanical performance and has been successfully applied to repair aerospace, marine, and civil infrastructure. Previous studies demonstrated that the efficiency of composite repair depends strongly on patch configuration, including geometry, fibre orientation, and thickness. For example, Khan Mohammed et al. [15] showed that rectangular patches significantly improved fatigue life compared to triangular patches, while Katnam et al. [11] reported that increasing patch thickness enhanced repair effectiveness by lowering SIF values and extending structural life.

Experimental investigations specifically focused on GFRP repairs on thin aluminium sheets appear limited compared to the extensive research on CFRP. However, studies on GFRP composites provide relevant insights into their mechanical performance and potential applications. GFRP composites exhibit notable mechanical properties, such as good stiffness and strength, corrosion resistance, and reduced weight, making them attractive for structural applications, including when used as reinforcements [16], [17]. Experimental research on GFRP composites addressing mechanical characteristics such as tension, bending, shear, and fracture toughness has shown that their performance can be further enhanced through modifications, such as the inclusion of multi-walled carbon nanotubes, which improve comprehensive mechanical properties [18]. In structural strengthening applications, GFRP sheets have been experimentally investigated for shear strengthening, for example, on masonry walls. Single-sided application of GFRP has demonstrated significant increases in in-plane shear capacity, which indicates the effectiveness of such repairs even when full encasement is impractical [19]. Experimental structural tests on GFRP elements, such as pultruded profiles subjected to vibration and mechanical

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loading, reveal favourable dynamic and load-carrying behaviour compared with metals such as steel and aluminium, suggesting their promise for repairs on thin metal substrates [17]. While there is a notable scarcity of dedicated experimental studies on GFRP patches on thin aluminium sheets per se, the available research on GFRP elements and composites under various mechanical and environmental conditions sets a basis for optimism. These investigations show that GFRP can provide enhanced mechanical performance, good bonding potential, and thermal stability under varying load and temperature conditions, which are critical factors in repair applications on aluminium substrates [20].

Although experimental investigations explicitly examining GFRP patch repairs on thin aluminium sheets are limited, the broader body of experimental work on GFRP mechanical properties, structural applications, and strengthening effectiveness suggests that GFRP is a viable reinforcement material. Despite significant progress in composite patch repair techniques, further experimental validation is required to quantify the influence of GFRP patch thickness on crack repair performance, particularly for thin aluminium sheets commonly used in pipelines, marine structures, and lightweight engineering components. While the effect of composite patch thickness has been widely reported, most existing studies focus on CFRP patches, relatively thick metallic plates, or numerically modelled systems. Experimental investigations of thin aluminium sheets repaired with GFRP, especially those comparing edge- and centre-cracked configurations, remain limited. In addition, few studies have coupled tensile testing with detailed fracture surface observations to correlate mechanical performance with crack-arrest mechanisms directly. To address these gaps, the present study experimentally evaluates the tensile behaviour of cracked Aluminium Alloy 6061-O sheets repaired with GFRP patches of varying thickness. Both edge-cracked and centre-cracked specimens with different crack lengths were tested under tensile loading in accordance with ASTM E8, and the combined mechanical and fractographic analyses provide practical insights into repair efficiency under static tensile loading.

2. Materials and Methods

2.1 Materials and Specimen Preparation

The substrate material selected for this study was Aluminium 6061-O alloy, which is widely applied in structural and piping systems due to its good strength-to-weight ratio and corrosion resistance. It was obtained from Makmal Jentera, Fakulti Kejuruteraan, UPNM. The mechanical properties of the alloy include a modulus of elasticity of 68.9 GPa, a yield strength of 55.2 MPa, and an ultimate tensile strength of 124 MPa. The aluminium sheets were machined into rectangular specimens measuring 150 mm × 50 mm × 3 mm. Two types of crack configurations were introduced using precision waterjet cutting:

a. Single-edge notched specimens with crack lengths of 5, 10, and 15 mm.
b. Centre cracked specimens with crack lengths of 10, 20, and 30 mm.

A water jet cutter (AWC-P50-T1515GS) was used to fabricate the single-edge cracked and centre-cracked specimens. The process uses a high-pressure water jet with abrasive particles, making it suitable for cutting hard materials such as metals. The water jet cutting system is shown in Figure 1.

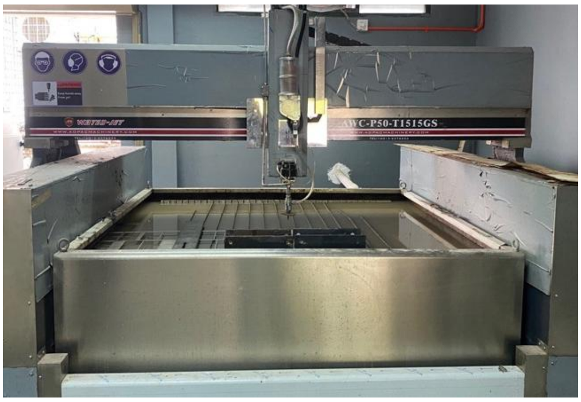
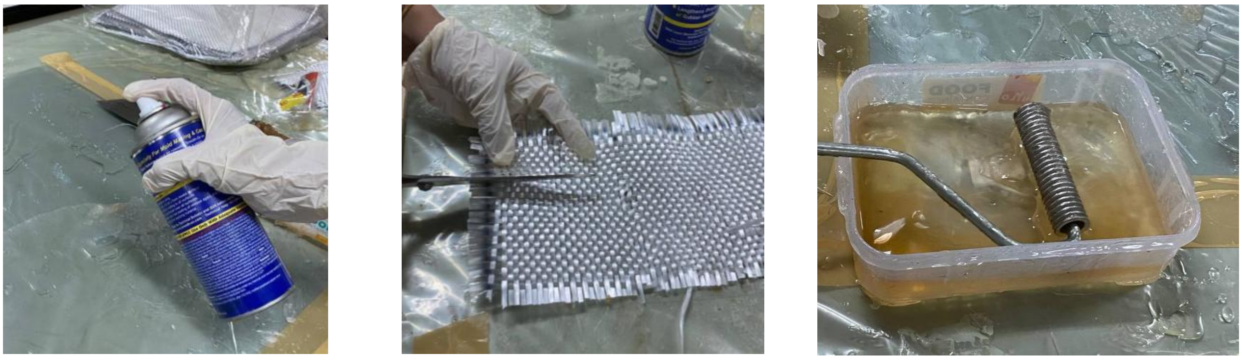


Figure 1. Water jet machine

2.2 Composite Materials

The repair patches were prepared using woven roving E-glass fibres supplied by the UPNM Solid Laboratory. The fibres had a modulus of elasticity of 72 GPa and tensile strength of 1700 MPa. EpoxAmite 100 epoxy resin and 103 slow hardeners were used as the matrix. To prevent the resin from hardening too early in the process, a 103 slow hardener is used at a 3:1 mix ratio (resin: hardener). All materials and equipment were prepared prior to fabrication due to the limited working time caused by the exothermic curing reaction of the epoxy system. The working surface was sprayed with Smooth-On Universal Mold Release to prevent adhesion between the repaired specimen and the working surface during curing (Figure 2 (a)). Glass fiber reinforcement was cut to dimensions of 40 mm × 150 mm according to the required patch geometry using standard cutting tools, as shown in Figure 2(b). The epoxy resin and compatible slow hardener were mixed at a 3:1 ratio (resin: hardener) according to the manufacturer's guidelines. The components were combined in a disposable mixing container and stirred for 3-5 minutes using a stir stick, starting slowly to minimize air entrapment and gradually increasing the mixing speed until a homogeneous mixture was obtained (Figure 2(c)). All mixing was performed at room temperature. The prepared epoxy was applied to the cracked aluminium plate using a brush, and the glass fiber patch was placed over the damaged region with sufficient overlap onto the intact surface (Figure 3). A scraper was used to remove trapped air and ensure proper adhesion. For multi-layer repairs, epoxy resin was applied between successive layers until the required number of layers was achieved. The repaired specimens were cured at room temperature for 24 hours to ensure complete polymerization and bonding of the composite repair.



(a) Spraying process of workplace (b) Cutting process of glass fibre (c) Stirring process of resin and hardener

Figure 2. Sequential steps in the preparation process

Figure 3. Layering process of composite material on a cracked plate

2.3 Characterisation

2.3.1 Tensile testing

Mechanical testing was conducted using a Universal Testing Machine (Instron) 5569A in accordance with ASTM E8 standard. The specimens were mounted using wedge grips, and loading was applied at a constant crosshead speed of 1 mm/min until failure. The parameters recorded were ultimate tensile strength, maximum load, and elongation. For each configuration (unrepaired, 2-layer patch, and 4-layer patch), at least three specimens were tested to ensure repeatability.

2.3.2 Microscopy analysis

Post-test fracture surfaces were analysed using an optical microscope (Dino-Lite AM4113ZT USB Digital Microscope) to examine failure mechanisms. Observations were conducted at magnifications of 15X-30X to examine crack propagation paths, debonding between the patch and the substrate, fibre pull-out, and resin fracture. Comparisons were made between unrepaired and repaired specimens to evaluate the effectiveness of patch bonding and load transfer.

3. Results and Discussion

3.1 Tensile Behaviour of Edge-Cracked Specimens

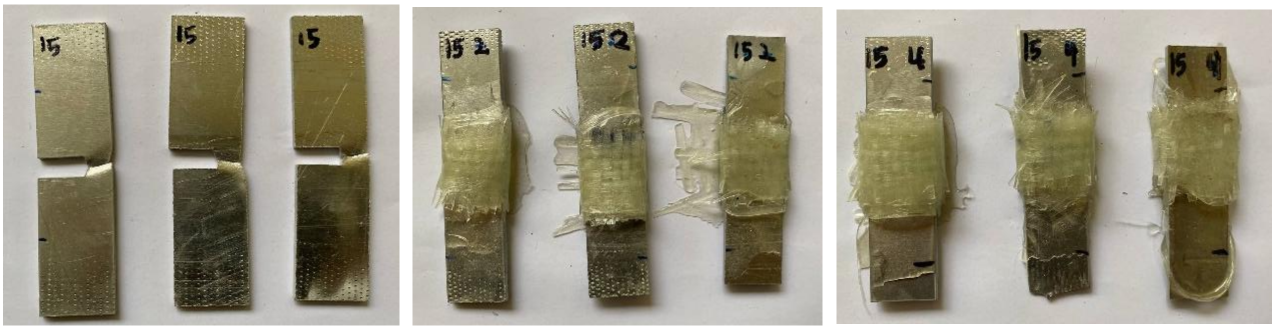
The tensile performance of edge-cracked aluminium specimens revealed a clear distinction between unrepaired and repaired conditions. This study successfully evaluated the effects of varying patch thickness and layer count on the mechanical characteristics and crack propagation of edge-cracked plates. Figures 4-6 show all the edge-cracked specimens with their respective crack lengths. Unrepaired specimens exhibited the lowest strength, failing prematurely due to stress concentration at the crack tip. The stress–strain curves showed a steep linear elastic region with little plastic deformation, followed by sudden fracture (Figure 7). When repaired with GFRP patches, a substantial improvement in load-carrying capacity was observed. For specimens with a 5 mm crack, the two-layer patch increased the maximum stress relative to the unrepaired specimens, whereas the four-layer patch increased the strength to 152.44 MPa, exceeding that of the uncracked specimen (Table 1). This represents a significant enhancement compared to the original uncracked Aluminium Alloy 6061-O, which has an ultimate tensile strength of 124 MPa, thereby confirming the effectiveness of the composite reinforcement.

(a) Unpaired (b) Repaired with 2 layers of GFRP (c) Repaired with 4 layers of GFRP

Figure 4. Edge cracked specimens with a crack length of a = 5 mm: (a) unrepaired, (b) repaired with 2 layers of GFRP, and (c) repaired with 4 layers of GFRP

(a) Unpaired (b) Repaired with 2 layers of GFRP (c) Repaired with 4 layers of GFRP

Figure 5. Edge cracked specimens with a crack length of a = 10 mm: (a) unrepaired, (b) repaired with 2 layers of GFRP, and (c) repaired with 4 layers of GFRP



(a) Unpaired (b) Repaired with 2 layers of GFRP (c) Repaired with 4 layers of GFRP

Figure 6. Edge-cracked specimens with a crack length of a = 15 mm: (a) unrepaired, (b) repaired with 2 layers of GFRP, and (c) repaired with 4 layers of GFRP

Table 1. Variations in the maximum load and stress in edge-cracked aluminium sheets with cracked length a = 5 mm

a (mm)	No of layers	Maximum load (N)	Maximum stress (MPa)
		Average	Average
5	Unrepaired	7860	104.83
	2	10156.67	136.00
	4	11046.13	152.44
10	Unrepaired	5018.96	73.23
	2	5052.65	77.41
	4	6710.78	86.70
15	Unrepaired	3987.59	42.83
	2	3777.15	46.50
	4	4029.59	52.11

The beneficial influence of patching persisted at longer crack lengths (10 mm and 15 mm). Although overall strength declined with increasing crack length, the repaired specimens consistently outperformed the unrepaired ones (Figures 7(a–c), Table 1). For instance, at a 10 mm crack length, a four-layer patch raised the maximum stress to 86.70 MPa, whereas the unrepaired counterpart failed at a much lower stress. Even at a crack length of 15 mm, the four-layer GFRP patch achieved a maximum stress of 52.11 MPa, demonstrating that the repaired specimen retained residual strength despite severe crack propagation. These results can be rationalised using fracture mechanics principles. The presence of a bonded composite patch alters the stress distribution around the crack tip, effectively reducing the SIF and slowing crack propagation. Higher layers of GFRP repair have a higher load-carrying capacity than the two configurations, as compared to the unrepaired edge-cracked sheet, and the findings are supported by [21]. By comparing the patched specimen to the simple edge crack specimen, Maleki and Chakherlou [22] conclude that the fracture strength can be enhanced. Although Kara et al. [23] investigated impact performance rather than tensile behaviour, their findings similarly highlight the importance of patch thickness in enhancing repair effectiveness. However, microscopy later revealed voids and partial debonding in thicker patches, indicating that optimisation of thickness is essential to balance short-term strength gains with long-term durability.

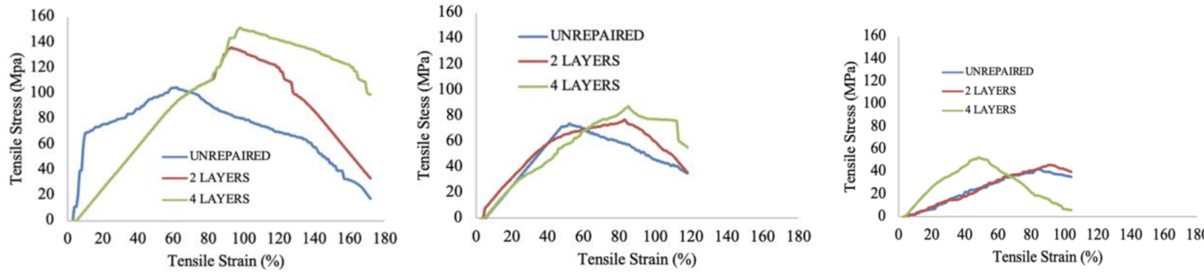


Figure 7. Tensile stress versus tensile strain graph of unrepaired and repaired edge-cracked sheet with crack length (a) a = 5 mm, (b) a = 10 mm, (c) a = 15 mm

3.2 Tensile Behaviour of Centre-Cracked Specimens

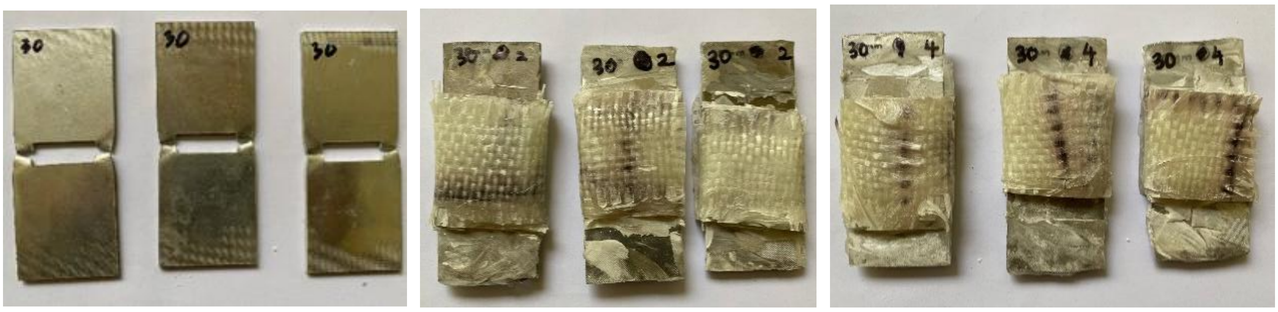
The centre-cracked aluminium specimens exhibited trends similar to those of the edge-cracked ones, but with a more pronounced stress concentration due to the central crack geometry. Figures 8-10 show centre-cracked specimens with varying crack lengths. Unrepaired specimens failed rapidly at relatively low stress levels, exhibiting stress–strain curves with an abrupt fracture immediately after the linear elastic region. In contrast, repaired specimens showed a more gradual failure response due to load redistribution by the composite patch. Repair with GFRP patches significantly enhanced tensile performance. At a crack length of 5 mm, two-layer patches provided noticeable strength recovery, while four-layer patches achieved a maximum stress of 184.67 MPa (Table 2). Remarkably, this value exceeded the maximum stress of the unrepaired specimen with a 5 mm crack length of 165.66 MPa and was approximately 49% higher than the ultimate tensile strength of the original uncracked Aluminium Alloy 6061-O of 124 MPa, indicating that the GFRP patch not only compensated for the crack but also provided additional stiffness and enhanced load-bearing capability.

(a) Unpaired (b) Repaired with 2 layers of GFRP (c) Repaired with 4 layers of GFRP

Figure 8. Edge cracked specimens with a crack length of a = 5 mm: (a) unrepaired, (b) repaired with 2 layers of GFRP, and (c) repaired with 4 layers of GFRP

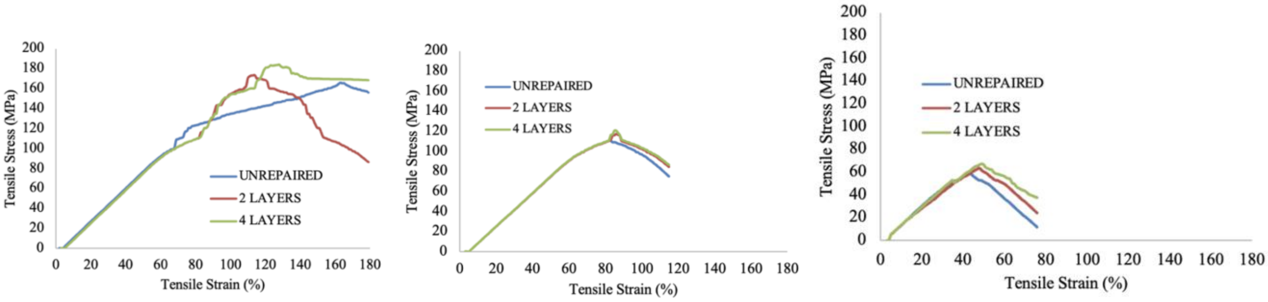
(a) Unpaired (b) Repaired with 2 layers of GFRP (c) Repaired with 4 layers of GFRP

Figure 9. Edge cracked specimens with a crack length of a = 10 mm: (a) unrepaired, (b) repaired with 2 layers of GFRP, and (c) repaired with 4 layers of GFRP



(a) Unpaired (b) Repaired with 2 layers of GFRP (c) Repaired with 4 layers of GFRP

Figure 10. Edge-cracked specimens with a crack length of a = 15 mm: (a) unrepaired, (b) repaired with 2 layers of GFRP, and (c) repaired with 4 layers of GFRP



(a) crack length = 5 mm (b) crack length = 10 mm (c) crack length = 15 mm

Figure 11. Tensile stress versus tensile strain graph of unrepaired and repaired centre cracked sheet with crack length (a) a = 5mm, (b) a = 10mm, (c) a = 15mm

Table 2. Variations in the maximum load and stress in centre cracked aluminium sheets with crack length a = 5 mm, 10 mm, 15 mm

2a (mm)	a (mm)	No of layers	Maximum load (N)	Maximum stress (MPa)
			Average	Average
30	15	Unrepaired	9915.72	58.05
		2	16972.67	63.33
		4	17445.00	68.44
20	10	Unrepaired	12851.43	111.63
		2	18501.63	117.03
		4	20793.71	121.34
10	5	Unrepaired	16955.63	165.66
		2	18165.45	173.99
		4	19329.73	184.67

For longer crack lengths, the maximum stress naturally decreased; however, repaired specimens consistently outperformed the unrepaired ones. At a crack length of 10 mm, the four-layer patched specimen sustained a maximum stress of 121.34 MPa, compared with much lower values for the unrepaired sheet (Figure 11(b), Table 2). At 15 mm crack length, the strength dropped further to 68.44 MPa for the four-layer repair, yet still represented a substantial recovery relative to the unrepaired specimen (Figure 11(c), Table 2). The role of patch thickness was even more evident in centre-cracked specimens. Four-layer patches provided superior strength recovery at all crack lengths, with the most remarkable effect observed at 5 mm, where the repaired specimen exceeded the strength of the uncracked aluminium sheet. This behaviour can be explained by the symmetrical load transfer across both crack tips, which reduced the effective SIF and delayed crack propagation. Similar trends have been reported by Achour et al. [24] and Srilakshmi and Ramji [25], who found that increasing patch thickness or using double-sided repairs substantially improved ultimate load capacity. Nevertheless, microscopy showed occasional interfacial debonding and fibre pull-out in thicker laminates, underscoring the need for careful optimisation of patch design and adhesive bonding.

3.3 Morphology Analysis

Microscopy analysis provided further insights into the failure mechanisms of both unrepaired and repaired specimens. In unrepaired aluminium specimens, cracks propagated rapidly and almost linearly from the notch, resulting in brittle-like failure. The fracture surfaces showed sharp crack tips and minimal plastic deformation, consistent with stress-concentration-dominated fracture (Figure 12). This observation explains the low load capacity of unrepaired specimens under tensile testing.

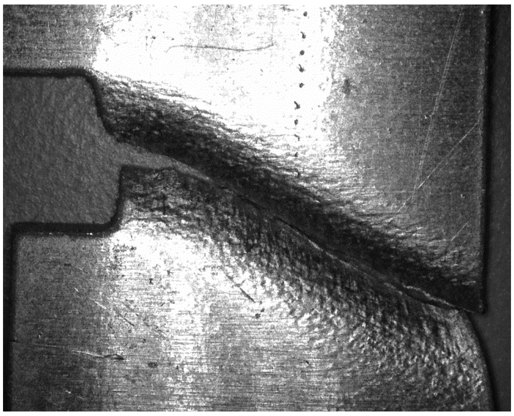


Figure 12. Optical microscope images of a crack in an aluminium sheet

For repaired specimens, the fracture morphology changed significantly. Unrepaired aluminium specimens exhibited relatively straight crack paths, sharp crack tips, and minimal plastic deformation, indicating brittle-like fracture behaviour dominated by stress concentration. In repaired specimens, the interaction between the aluminium substrate, adhesive layer, and GFRP patch produced more complex fracture features (Figure 13). Strong adhesive–substrate bonding was observed in most cases, confirming efficient load transfer across the repair interface. Fibre bridging and fibre pull-out were evident across crack faces, both of which dissipated fracture energy and delayed complete crack opening. Crack deflection at the adhesive–substrate interface was also observed, effectively reducing the crack-driving force and delaying catastrophic failure. The optical micrographs also highlighted localised imperfections such as resin-rich regions and voids, particularly in thicker laminates. Although these defects did not prevent strength recovery in static tensile tests, they may act as initiation sites for debonding or delamination under long-term or cyclic service conditions. The surface morphology confirmed that adhesive bonding, fibre bridging, fibre pull-out, and crack deflection were the dominant mechanisms behind the improved tensile behaviour of repaired specimens, consistent with previous studies [11], [24].

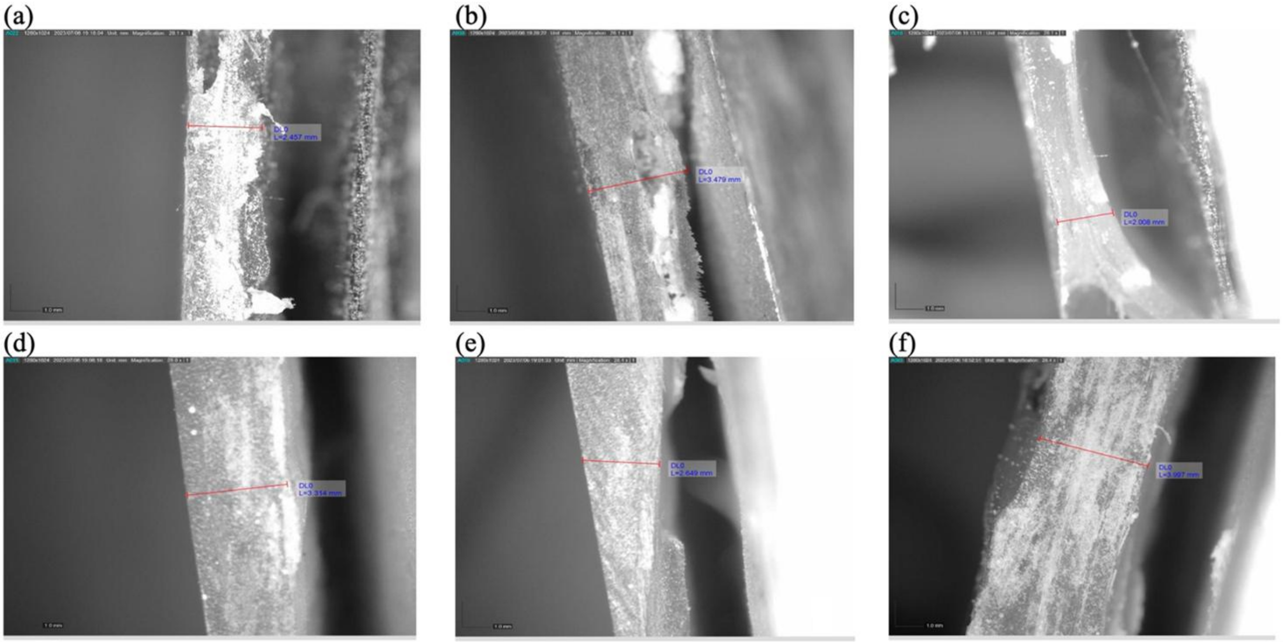


Figure 13. Optical microscope images of GFRP with crack length a = 5 mm with thickness of (a) 2 layers, (b) 4 layers; crack length a = 10 mm with thickness of (c) 2 layers, (d) 4 layers; crack length a = 15 mm with thickness of (e) 2 layers, (f) 4 layers.

4. Conclusions

This study demonstrated the effectiveness of GFRP patches in restoring the tensile strength of cracked aluminium specimens. Both edge- and centre-cracked sheets showed significant improvements after repair, with four-layer patches consistently providing greater strength recovery than two-layer patches. The influence of crack length remained evident: longer cracks reduced overall load capacity, yet repaired specimens still outperformed unrepaired ones. Microscopy confirmed that fibre bridging, adhesive bonding, and crack deflection were the dominant mechanisms contributing to the improved performance, while occasional voids and interfacial debonding in thicker patches highlighted the need for careful optimisation of fabrication and bonding. Overall, the findings suggest that GFRP patching is a cost-effective and reliable technique for extending the service life of metallic components, with patch thickness playing a key role in determining repair efficiency.

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Declaration of Competing Interest
The author declares no conflicts of interest.

CRediT Authorship Contribution Statement
N. N. Shukor (Methodology; Data curation; Formal analysis; Investigation; Visualisation; Writing -original draft)
A. Ali (Supervision; Conceptualisation; Data curation; Investigation; Visualisation; Writing -original draft)
N. A. S. M. Amin (Validation; Writing -review & editing)
H. E. C. Hamid (Data curation; Formal analysis; Investigation; Visualisation; Writing -original draft)
H. Ariff (Data curation; Formal analysis; Investigation; Visualisation; Writing -original draft)
M. N. F. Norrrahim (Methodology; Data curation; Formal analysis; Visualisation; Writing -original draft)

Availability of Data and Materials
The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations
This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations
The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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