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Comparative Analysis of Adhesive Effectiveness in Kevlar/Aluminum 6061-T6 Hybrid Double-Strap Joints: A Study on Static and Fatigue Strength †

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Abstract: This research work experimentally investigates the effectiveness of various adhesives in bonding Kevlar fiber-reinforced polymer with aluminum alloy 6061-T6 in a hybrid double-strap joint. Hybrid double-strap joints were developed using thermosetting epoxy Araldite LY5052 with Aradur H5052 and thermoplastic epoxy polyurethane mixed with tetrahydrofuran. These specimens were prepared using a hand layup method. Both adhesives were used to make eighty samples: forty for thermoplastic epoxy polyurethane with tetrahydrofuran and forty for thermosetting epoxy Araldite LY5052 with Aradur H5052. In order to determine the static strength of joints, tensile tests were conducted using a universal testing machine (UTM) where a tension–tension fatigue test was carried out on 50%, 70%, and 80% of the static load at which the joint failed. In the thermosetting double lap strap joint, the findings of both the elongation and fatigue tests showed an increase in strength throughout both the elongation and fatigue cycles. Thermosetting Kevlar hybrid joints have a high static and fatigue strength. Based on the results, thermosetting hybrid joints using Aradur H5052 and epoxy Araldite LY5052 had a static strength of 20.67 KN, whereas a thermoplastic adhesive joint had a static strength of 11.93 KN. Furthermore, the microscopic failure modes revealed that the mode of failure for the joints was cohesive and mixed-mode failure.

Keywords: double-strap hybrid joint; araldite LY5052; polyurethane; static strength; fatigue strength

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1. Introduction

Double lap joints (DLJs) between metal and the composite materials are extensively used in engineering and construction for connecting different components with effectiveness and reliability. These joints provide superior stress distribution and structural integrity which makes these joints ideal for applications where high strength and durability are required. Furthermore, Kevlar fiber-reinforced polymers are being used in aviation components and automobiles as an alternative to steel due to their strength and lightweight characteristics. Kevlar fabric bonded joints with polyester resin are used extensively in aerospace owing to their improved structural stability, low density, and high flexural and static strength [1–3]. Different adhesives can bond metals, ceramics, polymers, rubber, and a combination of these materials [4]. These materials need to be connected to their properties [5,6]. Fiber metal laminates are being widely used for the fabrication of wings and fuselage in the aerospace industry due to their low cost and weight-to-fuel ratio [7,8]. Adhesively bonded joints have been receiving huge attention due to their advantages over traditional joining methods due to their ability to achieve uniform stress distribution [9–11].

The strength of the adhesively bonded joint depends on the selection of adhesive, patch length, fiber patch thickness, and adherent strength. Suthan, R., et al. investigated the effects of different thicknesses of epoxy adhesive on the interfacial fracture toughness of Kevlar fiber-reinforced adhesive joints with and without short aramid-fiber toughening and compared the results with aluminum composites. The results showed that Kevlar composites have higher static strength than aluminum composites [12]. Nallamuthu, Ramasamy, et al. proposed the tensile strength of similar and dissimilar hybrid Kevlar joints using different chemical processes and epoxy matrices with nanofiller. These treatments were examined in depth and it was found that the treated Kevlar joints had much higher tensile shear strength and Weibull modulus values than the untreated joints and similar nanocomposite joints [13]. The tensile, flexural and impact strength of glass/hybrid, Kevlar/hybrid and composite resin joints were investigated and it was concluded with the help scanning electron microscopy and Fourier-transformation infrared spectroscopy that Kevlar/hybrid joints have higher tensile and bending strengths than epoxy composites [14]. Kim, Sanghyun, et al. proposed a comparison of the mechanical properties of carbon fiber and Kevlar fiber-reinforced polymer composites with aramid fiber-reinforced polymer and ABS plastics using simple cross-ply and vacuum-assisted resin transfer molding techniques. Heat resistance and mechanical characteristics including impact, tensile, bending, and interlaminar shear strength were examined by thermogravimetric analysis. It was concluded that carbon and Kevlar fiber composites showed high static, impact, and heat resistance compared to ABS plastics [15]. A comprehensive study has been conducted to investigate hybrid bolted-bonded joints, with an emphasis on the distribution of stress between the adhesive and bolt that affects their performance. This research examines the performance of joints with multiple bolts under static loads. It examines the behavior of joints with hybrid bolted-bonded joints and bolted joints using one, two, and three bolts. The study of load distribution in multi-bolted joints continues to be a significant focus of research; hybrid bolted-bonded joints have high stress concentrations around holes compared to bolted joints [16]. Davies et al. proposed a comparison between adhesive bonding and fusion bonding for joining thermoplastic composites. Epoxy adhesives are utilized in adhesive bonding where fusion bonding has been achieved using a number of outlined local melting procedures. The analysis includes fatigue behavior, static strength, moisture impact, and fracture resilience. It was concluded that adhesive bonding has higher static and fatigue strength than fusion bonding [17]. This study investigated the relationship between shear behavior and fatigue performance for cleaned aramid fiber and hydrolyzed aramid fibers for rubber materials. The finding revealed that fracturing occurred at 30,000 cycles for hydrolyzed aramid fibers, indicating higher shear and fatigue strength [18].

The tensile, fatigue, impact and flexural strength of Kevlar composites joints, including thermosetting adhesive hybrid adhesive joints has been extensively reported on in the literature [12–18]. However, there is no published research available focused on finding the static and fatigue strength of hybrid double-strap joints between aluminum alloy 6061-T6 and Kevlar fiber-reinforced polymer using thermosetting (Araldite 5052 with Aradur 5052 hardener) and thermoplastic polyurethane (mixed with tetrahydrofuran) adhesives. These two different adhesives were used for the preparation of specimens. The shear strength and fatigue life of hybrid double-strap joints were determined using tensile and fatigue tests. An optical microscope was also used in order to carry out a fractographic investigation on these hybrid joints.

2. Experimental Procedure

2.1. Materials

Hybrid double-strap joints were prepared using a high-strength aerospace-grade aluminum alloy plate with a 5 mm thickness that was purchased from Aeromotive Technologies (Islamabad, Pakistan). The chemical composition of 6061-T6 aluminum alloy is shown in Table 1.

Table 1. Chemical properties of 6061-T6 alloy.

Element	Mg	Cu	Si	Cr	Mn	Fe	Zn	Ti	Al
Weight %	1.26	0.4	0.8	0.38	0.15	0.8	0.25	0.15	Bal

This research used woven Kevlar 49 (968 TG) (purchased from Aeromotive Technologies) with a high stiffness and strength-to-volume ratio. This research used two different adhesives for bonding adherends (6061-T6) and Kevlar fiber-reinforced polymer (968 TC), which are often used in aircraft manufacture and repair. The first comprises of Araldite LY5052 epoxy resin and Aradur 5052 hardener [19]. The second was polyurethane combined with tetrahydrofuran resin [20]. Table 2 displays the mechanical characteristics of Al 6061-T6 alloy and Kevlar fiber [21].

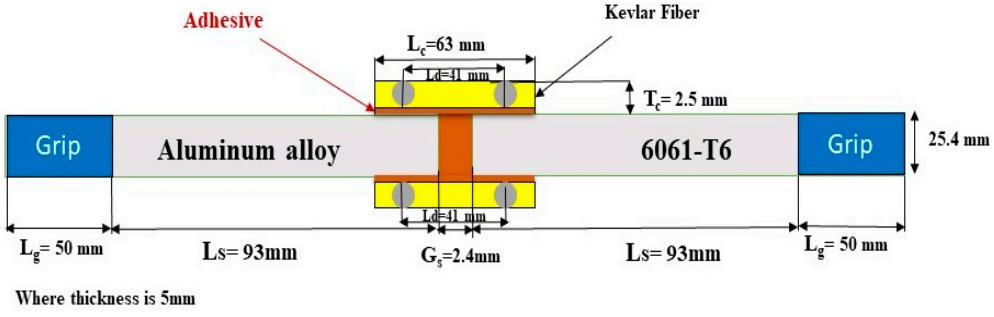
Table 2. Mechanical properties of 6061-T6 alloy and woven Kevlar 49 (968 TG).

Materials	Ultimate Tensile Strength (MPa)	Elastic Modulus (GPa)	Poisson Ratio
Aluminum 6061-T6	310	69	0.33
Woven Kevlar Fiber 49 (968 TG)	3600	125	0.36

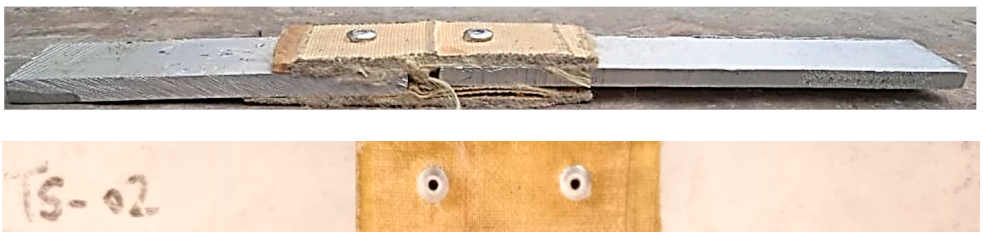
Furthermore, the ultimate tensile strengths of Araldite 5052 and polyurethane are 102 MPa and 42 MPa, respectively.

2.2. Preparation of Specimens

The hand layup process was used to fabricate the laminates using Al 6061-T6 and Kevlar 49 (968 TG) using Epoxy Araldite LY 5052 and Aradur 5052, as well as polyurethane combined with tetrahydrofuran resin. The hybrid double-strap joints with one bolt were developed and manufactured in accordance with ASTM-D 3528-96 [22], as shown in Figure 1a,b.



(**a**)



(**b**)

Figure 1. (**a**) Schematic of Kevlar hybrid double-strap joint; (**b**) final machined-out hybrid double-strap joint of KFRP/aluminum alloy.

Stainless steel SS 304 rivets were used to start the fastening process. For the aluminum adherend, the bonding surface was blasted at a 3-bar pressure, then polished with emery

paper ranging in mesh size from 180 to 2000 and cleaned with acetone. The hybrid joints were developed using rivets, Araldite epoxy 5052 and polyurethane. The stepwise methodology of the specimens' preparation is presented in Figure 2.

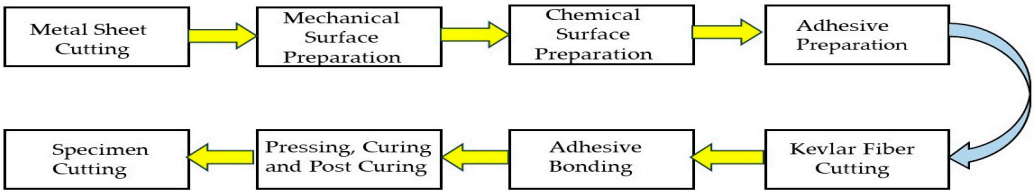
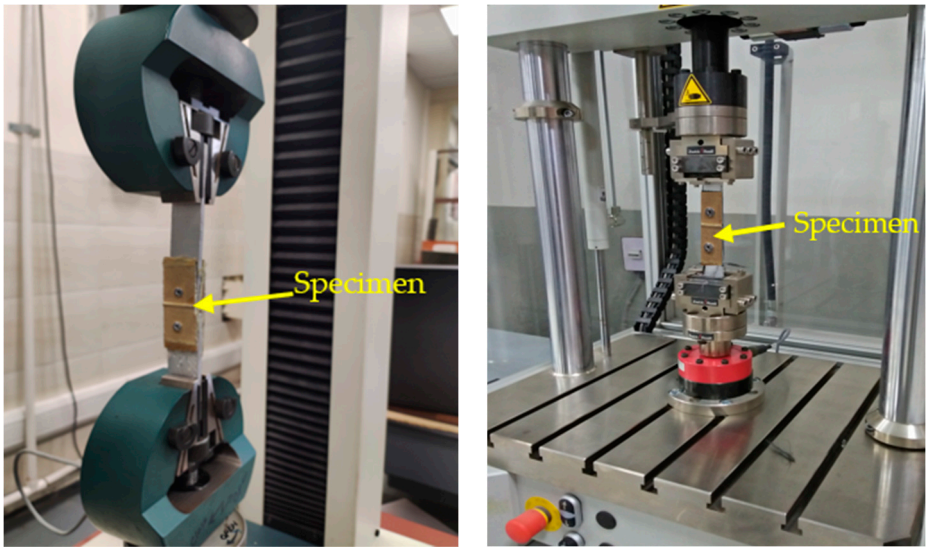


Figure 2. Stepwise procedure for hybrid joint preparation.

3. Test Procedure

3.1. Tensile Testing

Static tests were carried out using the UTM (model: SJ-10T) in accordance with ASTM standards to determine the static strength of thermosetting and thermoplastic specimens [23]. Every specimen was clamped on a machine that moved at a rate of 1.27 mm/min. For tensile testing, five repeats were performed for each configuration of double-strap joint. Furthermore, the tensile strength of the specimens was determined using load and extension curves. The UTM with a test specimen is shown in Figure 3.



(**a**) (**b**)

Figure 3. Experimental setup for (**a**) tensile testing; (**b**) fatigue testing.

3.2. Fatigue Testing

Tension–tension fatigue testing was conducted at room temperature using a Zwick Fatigue tester, using ASTM D 3166-99 [23]. Using varied stress amplitudes, the specimens' performance was examined for all samples under both low- and high-cycle tensile loading. For fatigue testing, five repeats were performed for both thermosetting and thermoplastic double-strap joints. For every specimen, the loading frequency was kept constant at 10 Hz. For every joint combination, the fatigue test was performed at 50%, 70%, and 80% static joint strength. The results were presented in the form of S–N curve, which shows the number of cycles with respect to failure.

4. Results and Discussion

In this study, for the static strength, the investigation and evaluation were performed by comparing the failure load and extension. A nearly linear correlation between the load

and displacement for both adhesives can be observed from Figure 4a. The thermosetting adhesive joint showed a maximum average bonding strength of 20.67 kN and stretched a maximum extension of 1.07 mm, whereas the thermoplastic adhesive joint attained values of 11.93 kN for bonding strength and 0.81 mm for extension. Araldite LY 5052 exhibits higher tensile strength than polyurethane (TPU) in hybrid joints. The results given in Figure 4b show that the thermosetting hybrid double lap strap joints exhibited 42.2% higher failure strength than the thermoplastic joints. The experimental results are given in Table 3.

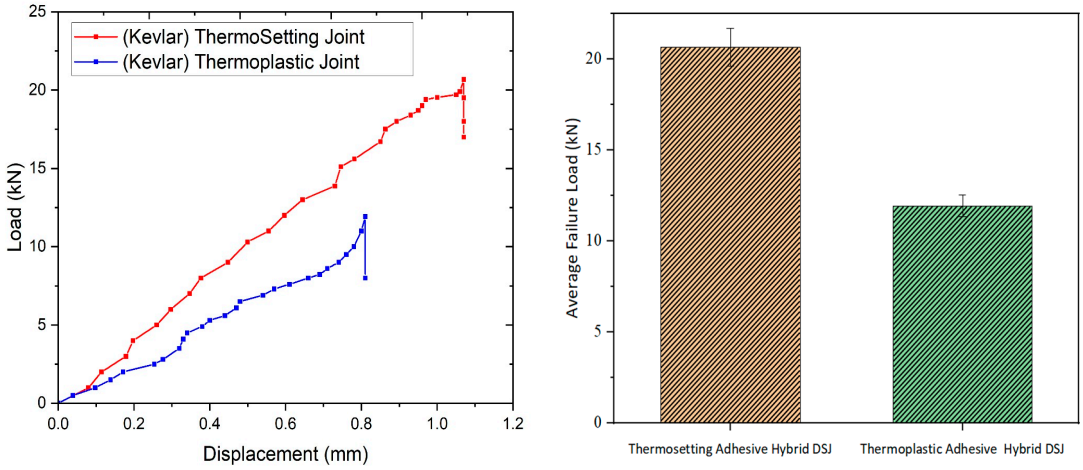


Figure 4. (**a**) Load–extension curve for tensile testing; (**b**) average failure load for thermosetting and thermoplastic hybrid double lap strap joints.

Table 3. Failure load and extension of different adhesives joints.

Type of Specimen	Avg. Failure Load (KN)	Avg. Deformation (mm)
Thermosetting Adhesive Hybrid DSJ	20.67	1.07
Thermoplastic Adhesive Hybrid DSJ	11.93	0.81

The life span and behavior of the hybrid adhesively bonded joints under cyclic stress have been determined using fatigue tests. A relationship between stress and the number of cycles was used to analyze the strength of thermosetting Araldite LY5052 with Aradur H5052 and thermoplastic polyurethan (TPU) hybrid joints, as shown in Figure 5. The strength of thermosetting and thermoplastic hybrid joints is correlated with the average number of failure cycles. Therefore, thermosetting and thermoplastic hybrid joints tested at 50% and 70% of their tensile strength for fatigue testing did not fail up to 1,10,000 and 43,000 cycles. However, at 80% of the tensile strength, both the joints failed at 35,197 and 12,503 cycles at 10 Hz, as shown in Table 4. The results show that the thermosetting hybrid joint exhibited 64.5% higher fatigue strength than the thermoplastic hybrid joints. Furthermore, the fracture of the hybrid joint indicated that the mode of failure was mixed-mode failure, as shown in Figure 6.

The apparent separating of KFRP at the bonded area in Figure 6 shows cohesive and mixed-mode failures in thermosetting hybrid joints. The adherends' surface preparation was suitable; however, a separation occurred between the KFRP and the adhesive due to an ineffective connection between the aluminum and Kevlar/epoxy laminates. As the joints were created by hand layup, air bubbles and adhesive shrinkage may have caused cracks in the KFRP layers. These cracks propagate from the KFRP layers to the adhesive between the aluminum sheets, ensuring joint failure. The results of the fractography analysis indicated that the failure was cohesive and mixed mode.

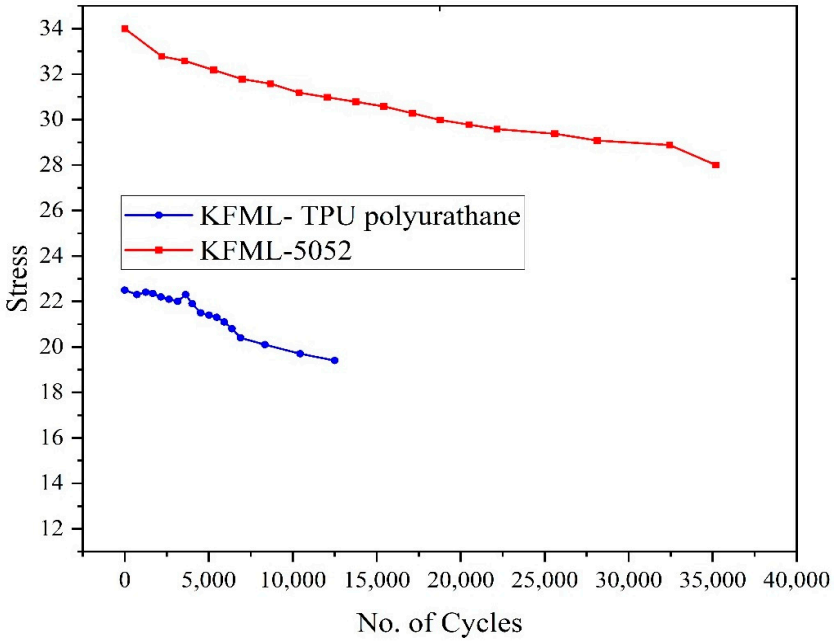


Figure 5. Number of cycles of KFML for Araldite 5052 and TPU.

Table 4. Experimental results of fatigue testing.

Type of Joint	Number of Cycles			Mode of Failure
	50%	70%	80%	
KFML's with 5052	≥110,000	≤110,000	35,197	Mixed-mode Failure
KFML's with TPU	≥43,000	≤43,000	12,503	Mixed-mMode Failure
Joint Behavior	Safe	Safe	Failure	

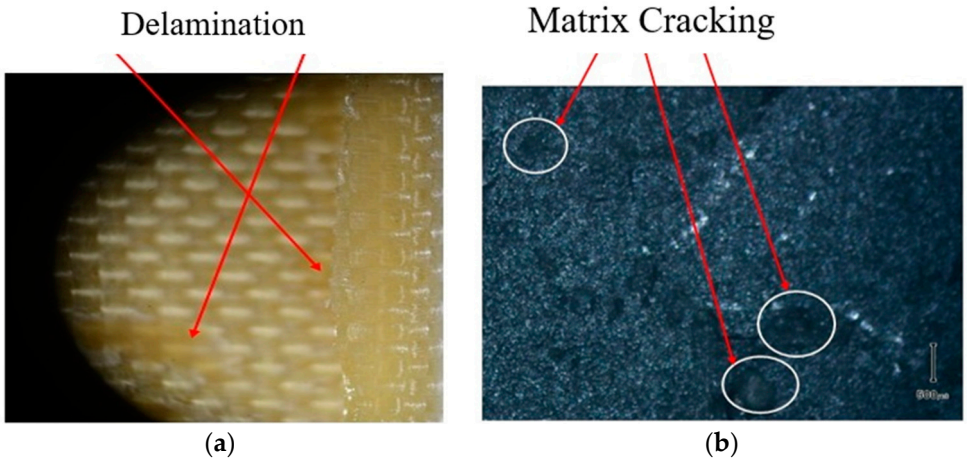


Figure 6. Failure modes observed in the specimen after testing (**a**) KFRP delamination on the fracture surface of joint; (**b**) matrix cracking.

5. Conclusions

This study examined the static strength of hybrid double-strap connections between aluminum alloy 6061 and Kevlar fiber using Araldite 5052 and TPU polyurethane epoxy adhesives. Tensile, fatigue and fractographic tests examined static and fatigue strength and failure modes. The experiments showed that Kevlar fiber-reinforced polymer hybrid joints bonded with Araldite 5052 had a 32% higher elongation capacity than polyurethane epoxy hybrid joints, due to proper thermosetting adhesive hybrid joint curing. Thermosetting

hybrid joints had 73% higher static strength than thermoplastic joints. All samples failed at 35,197 cycles for thermosetting joints and at 35,197 for thermoplastics adhesives at 80% of the static load owing to the fatigue strength of the joint. Furthermore, due to passive crack propagation in the thermoplastic glue, thermoplastic hybrid joints had 24% less elongation showing adhesive and mixed-mode failure of the joints.

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