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Tensile Strength of Adhesively Bonded and Hybrid (Bonded/Riveted) Dissimilar Single-Lap Joints

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Abstract

Glass fiber-reinforced composites are commonly employed as structural materials in many fields. In addition, glass fiber-reinforced composites are frequently used with metals, particularly in the automotive and aerospace industry. In this context, the tensile strengths of simple and hybrid single-lap joints having similar (i.e., aluminum/aluminum and composite/composite) and dissimilar (i.e., aluminum/composite) plates were investigated experimentally in this study. At this point, 6061 aluminum alloy and E-glass/epoxy composite plates were used as the adherends and Araldite 2014-1 was used as the adhesive. The composite adherends produced using the vacuum infusion technique consist of E-glass/epoxy laminates with $[0°/90°/+45°/−45°]_6$ stacking sequence. Two different types of joints (i.e., adhesively bonded and bonded/riveted) were employed for similar and dissimilar joints. In addition, both 3-rivet and 4-rivet joints were used in bonded/riveted joints. The results revealed that the strength of the joints could be considerably increased with the addition of rivets to the adhesively bonded joints. In particular, the results showed that the strength value of the bonded/4-riveted joint is 5.7 times higher than the adhesively bonded joints.

Keywords: Simple joints; Hybrid joints; Dissimilar plates; Adhesively bonded joints; Bonded/riveted joints

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1. Introduction

One of the most frequently utilized joining techniques in advanced structures (like aerospace and automotive) is structural adhesive bonding [1–5]. However, the strength of the adhesive joint can be affected by many parameters such as environmental conditions [6–8]. One of the best ways to overcome such problems is to combine adhesive bonding with other joining techniques, thus, another type of joining technique (e.g., riveted joints) can compensate for the disadvantage of adhesive joining such as lack of strength. On the other hand, there are many applications where different types of materials are used together and in such cases using adhesive bonds alone can be a problem. For instance, metal and composite materials are often used together in the automotive and aerospace industries [9–12]. For these reasons, different joining methods are used to bring together different types of materials. Some of these techniques are adhesively bonding [9,13–15], welding [16,17], mechanically fastening [18,19] and a combination of different types of techniques called hybrid joints [20]. Among these methods, hybrid joints obtained by combining mechanical fastening (e.g., riveted joints and bolted joints) with conventional adhesive joints have become very popular in recent years [20–28]. Fu and Mallick [22] investigated the fatigue life of hybrid joints in the composite. They observed that hybrid joints (adhesive/bolted) have more static loading capacity and fatigue life in comparison with adhesively bonded ones. In another similar study, Cat-Tan Hoang-Ngoc and Eric Paroissien [27] simulated the fatigue life of the adhesively bonded and hybrid joints with a flexible adhesive. The results showed that the fatigue life of hybrid joints is longer than that of simple joint. Moroni et al. [20] conducted an experimental analysis of static strength, stiffness and energy absorption of the simple and hybrid joints under various conditions. The results showed that the usage of the hybrid joints can be adjusted according to needs such as cost reduction and mechanical behavior improvement.

Unlike the literature, this study aims to investigate the tensile strength of simple and hybrid single-lap joints with similar and dissimilar plates were investigated experimentally. In this context,three different structures (i.e., aluminum/aluminum,aluminum /composite and composite/composite) were considered by using Al6061 aluminum alloy and E-glass/epoxy composite plates. In addition, two different joints type (i.e., adhesively bonded joints and bonded/riveted joints) were employed for similar and dissimilar plates. Moreover, both 3-rivet and 4-rivet joints were used in bonded/riveted joints, and the tensile strengths of the simple and hybrid joints were compared for each case.

2. Materials and Methods

2.1. Test specimen

The composite adherends were manufactured via vacuum-assisted resin transfer molding (VARTM), which is also known as vacuum infusion (VI). The manufacture of glass fiber reinforced plastic (GFRP) composite using the vacuum infusion technique is shown in Figure 1.

The composite plates consist of E-glass/epoxy laminates with $[0°/90°/+45°/-45°]_6$ stacking sequence. The GFRP composite adherends have E-glass fibers with a density of 640 gr/m^2 and epoxy resin (Araldite LY1564) with a hardener (Aradur 3487) in a mixture ratio by weight of 100:34. The GFRP plates were cured at 100°C for 2 hours on a specially designed heating table and then kept at room temperature [29]. The composite plates have approximately 44% of fiber volume fraction. The mechanical properties of the cured epoxy resin with hardener are given in Table 1. After the production process, the composite adherends were cut using a table saw to a size of 110x40x3mm.

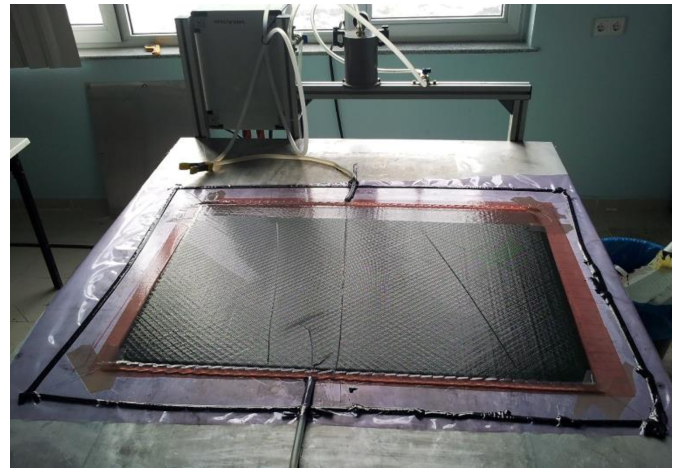

Fig.1 Manufacture of GFRP plate using vacuum infusion technique

Table 1. The mechanical properties of the cured epoxy resin with hardener [29,30]

Components	Mixing ratio	Density	Glass transition temperature	Tensile Strength	Ultimate Strength
Epoxy Resin (Araldite LY 1564)	100	1.1-1.2 g/cm^3	81-86 °C	70-74 MPa	60-64 MPa
Hardener (Aradur 3487)	34	0.94-0.95 g/cm^3			

As metal adherends, the 6061 aluminum alloy plates having 2000x1000x3mm were supplied and the adherends were cut using laser cutting with the same size of GFRP plates. The bonded/riveted specimens have a square array configuration of 3 holes with 120° between them and a triangle array configuration of 4 holes with 90° between them. As the mechanical fastener, an aluminum-magnesium alloy 5154A rivets 3mm in diameter were used. The bonded/riveted joints were drilled and then riveted via a rivet gun prior to the curing process. Two-component Araldite 2014-1 was used as the adhesive. The components are mixed homogeneously before bonding by means of the tip attached to the end of the adhesive tube. This mixture was applied by means of a gun, taking care that the relevant surfaces were completely wet. The properties of Araldite 2014-1 adhesive are shown in Table 2. It should be noted that bonded and bonded/riveted joints require a suitable surface treatment to ensure high bond strength. The bonding region for the adherends was sandpapered using sandpaper and cleaned with acetone before bonding. The adhesively bonded and bonded/riveted joints were cured for 1 week at room temperature. It should be noted that in order to avoid cracks in the adhesive area, the bonded/riveted joints were riveted with a rivet gun without waiting after the bonding process.

Table 2. Properties for Araldite 2014-1 adhesive [31,32]

	Viscosity (MPas)	Tensile strength (MPa)	Tensile Modulus (GPa)	Shear Modulus (GPa)	Strain (%)	G_I (kJ/m^2)	G_{II} (kJ/m^2)	G_{III} (kJ/m^2)
Araldite 2014-1	100	26	2	4	2.4	3	6	1

The bonding region is 40x40mm, and the thickness of the adhesive layer is 0.1 mm [33–35]. A fixture was used to ensure keeping the adhesive thickness constant for all adhesively bonded samples. The samples were placed in the relevant fixture and bolted from 4 sides to ensure a homogeneous thickness of all surfaces. On the other hand, there was no need for a fixture for bonded/riveted joints since the rivets would serve as centering. The drilling and bonding process of the adhesively bonded and bonded/riveted joints are shown in Figure 2.

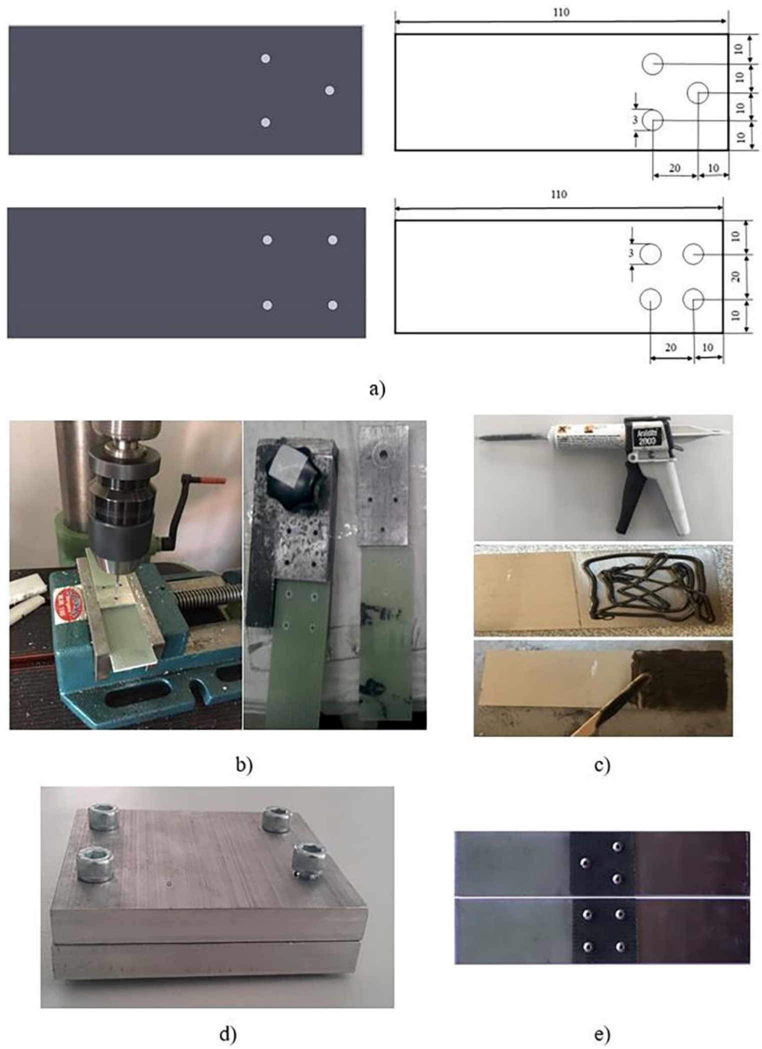

Fig. 2. The dimension of the samples and their preparation process; a) dimensions of 3 and 4-hole plates, b) drilling process, c) adhesive process, d) fixture for adjusting adhesive thickness and e) bonded/riveted dissimilar single-lap joints

2.2. Experimental procedure

The quasi-static tensile tests of bonded and bonded/riveted joints were performed using the Shimadzu Autograph AG-IS universal tester with 100 kN capacity. The tensile tests were carried out at a speed of 1 mm/min according to the literature [36,37]. Each configuration of the joints was tested with at least three samples, and then average values were calculated for each configuration. The load and displacement data were collected at a sample rate of 20 points/sec.

3. Results and Discussion

The typical force-displacement curves of the adhesively bonded and bonded/riveted joints having similar and dissimilar plates are shown in Figures 3-4. In addition, the average tensile test results of these joints having different adherend types are presented in Table 3.

According to the figures, after a linear increase at the beginning of the load-displacement curves, the force values increase to continue non-linearly and the curves reach the maximum point. After the maximum point, the joints are damaged and broken. Here, in adhesively bonded joints, the adhesives carry the load on the joints and after a short displacement value, the joints are damaged. On the other hand, in hybrid joints, initially, both the adhesive and the rivets carry the applying load on the joints, next the adhesive failure occurs after a certain displacement, after the adhesive failure, only the rivets carry the load until they break.

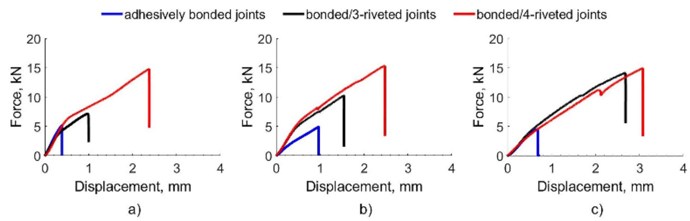

Fig. 3. Typical force-displacement curves of simple and hybrid joints with a) aluminum + aluminum plates, b) aluminum + composite plates and c) composite + composite plates

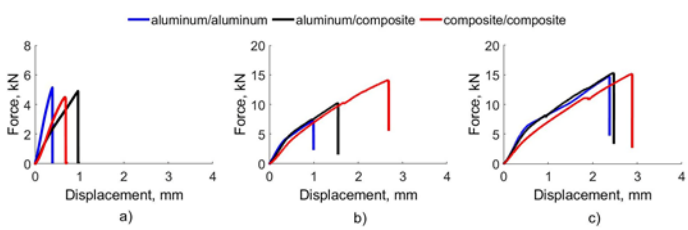

Fig. 4. Typical force-displacement curves of similar and dissimilar plates for adhesively bonded and bonded/riveted joints a) adhesively bonded joints, b) bonded/3-riveted joints and c) bonded/4-riveted joints

It is clearly seen from Figure 3 that, for all cases, the joints with the highest strength are the bonded/4-riveted joints while the joints with the lowest strength are the adhesively bonded joints. In particular, the bonded/4-riveted joints have 2.91 times more strength value than the bonded joints for aluminum/aluminum plates. These values are respectively 5.63 and 3.17 for aluminum/composite and composite/composite plates. Similarly, 3-rivet hybrid joints have strength values of 1.47, 4.34 and 2.95 times greater than adhesively bonded joints for aluminum/aluminum, aluminum/composite and composite/composite plates, respectively. Besides, when hybrid joints having 3 and 4 rivets are compared among themselves, unsurprisingly, it is seen that the 4-riveted-joints carry more load than the 3-riveted-joints due to the high number of rivets. In addition, the displacement value at failure depends on the joint type, and the figure shows that adding the rivets to the simple joints allows the hybrid joints to be failure later. Similar to the maximum force values, bonded/4-riveted joints have the highest displacement values at failure while adhesively bonded joints have the lowest values. As mentioned above, these results are due to the fact that rivets continue to carry loads after adhesive failure in hybrid joints. Consequently, these results reveal that hybrid joints have higher reliability during long-term working. In addition, it is clearly observed from Figure 4 that the displacement value at failure is below 1 mm for bonded joints while this value can be up to 3 mm in bonded/riveted joints. In addition, maximum strength and displacement at failure values of composite/composite plates are higher than aluminum/aluminum and aluminum/composite ones. According to Table 3, the bonded/4-riveted joints have the most displacement values at failure for each adherend type. This is followed by bonded/3-riveted joints and adhesively bonded joints, respectively. Similarly, when the joints are compared according to their maximum strength values, the same ranking is also seen. On the other hand, the joints with dissimilar plates (i.e., aluminum/composite) have generally relatively lower strength values compared to similar plates (i.e., aluminum/aluminum and composite/composite). This can be explained by the poor adhesion of the interface between aluminum and composite.

Table 3. Average tensile test results of simple and hybrid joints having different adherend types

Adherend type	Joint type	Max. Force (N)	Max. Stress (MPa)	Disp. at Failure (mm)
Aluminum/ aluminum	Adhesively bonded joints	5182.82	3.24	0.37
	Bonded/3-riveted joints	7618.75	4.76	0.94
	Bonded/4-riveted joints	15106.25	9.44	2.54
Aluminum/ composite	Adhesively bonded joints	2406.25	1.50	0.36
	Bonded/3-riveted joints	10419.79	6.51	2.02
	Bonded/4-riveted joints	13502.09	8.44	2.23
Composite/ composite	Adhesively bonded joints	4748.44	2.97	0.76
	Bonded/3-riveted joints	14004.70	8.75	2.68
	Bonded/4-riveted joints	15053.15	9.41	2.99

4. Conclusion

This paper investigates the tensile strength of adhesively bonded and hybrid (bonded/riveted) single-lap joints, experimentally. At this point, Al6061 alloy and E-glass/epoxy composite plates manufactured by vacuum infusion technique were utilized as adherends, and Araldite 2014-1 was utilized as adhesive. Composite and aluminum plates were combined as similar and dissimilar joints, and these structures were also joined in two different ways as simple (i.e., adhesively bonded) and hybrid (i.e., bonded/riveted) joints. Moreover, the strength values of hybrid joints were also studied as bonded/3-riveted and bonded/4-riveted. The main findings are summarized as follows:

- The tensile strengths of bonded/riveted joints are considerably higher than the adhesively bonded joints. The main reason for this is that after the adhesive fails under load and the rivets continue to carry the load for a while.
- The bonded/4-riveted joints have the most displacement value at failure compared to bonded/3-riveted and only bonded joints.
- The strength values of similar plates (i.e., aluminum/aluminum and composite/composite) are generally higher than the dissimilar plates (i.e., aluminum/composite). This is due to the lack of good adhesion between the aluminum and composite interface.

More studies are needed to investigate their strength and other mechanical properties before these types of joints can be widely used in industries such as automotive. In this context, future studies are planned to focus on the strength of riveted and bonded/riveted joints with different geometric patterns.

Conflict of Interest Statement

The author declares that there is no conflict of interest in the study.

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