Effect of Adhesive Types and Fiber Orientation on Mechanical Properties of Single Lap Joint Composite Using Vacuum-Assisted Resin Infusion Manufacturing Method

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Abstract. Composite materials have been widely used in various industries due to their high specific strength and stiffness. Although composite materials have the flexibility to create designs with good integrity, connections between structures may have to be made due to the design of the structure and the cost of the manufacturing process. This paper will evaluate especially the shear strength of composite joints using the single-lap joint method with various adhesive types and ply stacking orientation face of the joint. The composite was made using a vacuum-assisted resin infusion manufacturing technique using carbon fiber and chempoxy resin with specific unidirectional, orthotropic, and quasi-isotropic arrangement orientations. The results showed that the using of the same adhesive as the composite resin type, chempoxy adhesive had the highest value a lap shear strength of 11,43 MPa compared to other adhesives with tested interface layer 0°. The variation of the direction interface layer is a variable that has a significant effect on lap shear strength. The results showed that the quasi-isotropic with interface layers 0°, 90°, and +45 ° has lap shear strength of 7.42 MPa, 6.34 MPa, and 5.46 MPa respectively. The difference in shear strength values in lap joints with variations direction of stacking ply in the interface layer of the adhesive is also evident from the failure modes that occur in the specimens.

Keywords: Composite carbon Unidirectional, Adhesive, Single Lap Joint, Quasi-isotropic

1. Introduction

Composite structures, used to meet the demands of lightweight materials, high strength, stiffness, and corrosion resistance in the aircraft industry and engineering composite fields, have become one of the materials used to repair existing structures due to their superior mechanical properties [1].

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Composite materials are easy to mold in their application into a structure with mutual integrity. It can reduce the connection and weight effectively. However, in manufacturing processes with limitations on manufacturing large components, jointing of parts in an aircraft structure is unavoidable and critical to maintaining structural integrity. A composite structure is usually assembled after the production of certain parts during the manufacturing process, so it is important to consider the strength of the joints between the parts of the component laminates. Compared with other mechanical joints, the adhesive joint provides the advantages of light structural weight for material connection, such as high joint efficiency, vibration reduction, good insulation, smooth aerodynamic shape, and avoidance of drilling holes and fasteners [2]. An important advantage of adhesive joints is the uniform stress distribution at the joint interface, which reduces stress concentrations [3]. In contrast to adhesive joints, fastening holes can cause peeling of plies and matrix degradation in composite materials and can reduce compressive residual strength [4].

There are many types of adhesive bonding on composites. In this case, the influence of adhesive, as well as the sequence of arrangement on bonded joints, has been extensively investigated by many researchers. However, the bonding is still considered unreliable in critical bonding due to concerns such as fatigue, long-term behavior uncertainty, and significant load variation failure [5]. In addition, the resin infusion process has become a popular choice in manufacturing polymer-based composite structures. The resin infusion process is more economical than the conventional autoclave technique. For example, through the resin infusion process, we can produce complex and thick components with excellent mechanical properties while reducing the amount of waste generated, in contrast to traditional methods [6]. Therefore, the research on adhesive joints using vacuum infusion has attracted much attention in the development field.

There have been many studies of adhesive joints in composite plates. T. Dhilipkumar et al. [7] A study comparison of single lap joints with various bonding techniques such as co-curing, co-bonding, and secondary bonding can be seen in Fig. 1. Research comparing the shear strength of co-curing, co-bonding, and secondary bonding joint types shows that the co-curing technique can provide higher shear strength and the strength of the joint against shear loads can also be improved by adding multi-wall carbon nanotubes (MWCNTs). Research related to modeling adhesive joints using the cohesive zone model has also been conducted on single-lap joints to evaluate each parameter that affects the strength of the joint [8].

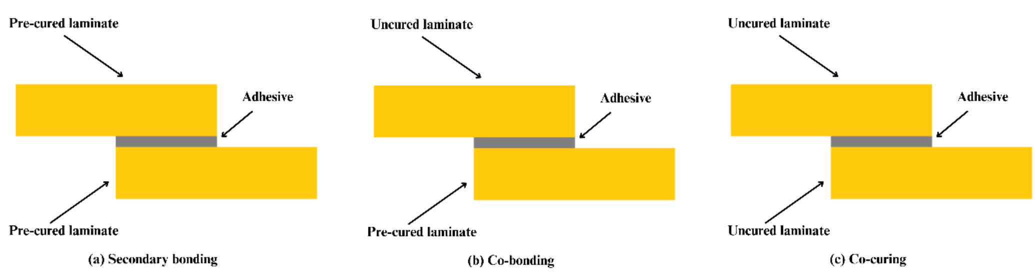

Fig. 1. Various adhesive bonding techniques

Each joint has its advantages and disadvantages. Secondary bonding has the advantages of repairability, cost-effectiveness, flexibility, minimized material waste, reduced downtime, consistent material properties, and good versatility. Although it is not an adhesive type of joint that can provide high strength, there is a lot of research on this joint. Research on the effect of fiber orientation on composite lamina in single-lap joints has been conducted and shows that the orientation at the joint interface has an important role in the rupture but does not have a significant effect [9]. F. `L. Matthews et al. [10] Investigation of the static properties of CFRP single-lap joints made of UD lamination with several layer combinations of 0°, 45° and -45° showed that the bonding strength increases with the increasing layer ratio of 0°, with the highest values found on bonding with the entire layer 0°. In addition, layer arrangement and overlap length also affect failure mode. E. Ziane et al. [11] study was conducted on single-lap joints using an epoxy-type layered substrate, with variations in layer orientation consisting of unidirectional at angle 0°, and multidirectional specimens at 45/0/45/0. The observed failure mode differs between the two cases, with cohesive failure on glue occurring in the first case, and intralaminar failure occurring on the first layer of lamination in the second case.

There are many types of adhesive bonding on composites. In this case, the influence of adhesive, as well as the sequence of arrangement on bonded joints, has been extensively investigated by many researchers, but the bonding is still considered unreliable on critical bonding due to concerns such as fatigue, long-term behavior uncertainty, and significant load variation failure. To improve the strength of the adhesive connector, several tests on the influence of the glue type and sequence of arrangement on bonded joint behavior have been investigated. This study will examine the influence of the orientation of layers of interfaces and adhesives with different characteristics on the strength of single lap joints on the composite. The lap joint adhesive bonding technique uses a secondary bonding joint in which pre-cured composite laminates are made separately and then bonded with adhesive. The specimens used unidirectional carbon fiber composites with various adhesive types. The experiment is performed to test the shear strength of the adhesive bond is a critical parameter used to assess the performance and integrity of adhesive joints. The bonding area is denoted as S, the thickness of the adhesive layer as h, and the displacement as x. Here, the adherends are assumed to be rigid bodied that do not deform. The shear stress σ is expressed as $\sigma = P/S$, while shear strain ε is expressed as $\varepsilon = x/h$ as well as the failure mode is analyzed after a series of tensile tests are performed. The influence of the interface orientation layer and the type of adhesive on the strength of the adherend was then inferred from the experimental results.

2. Methods

In this study, UD-CFRP composite specimens were treated, bonded, and shear tested to assess the effect of adhesive type and fiber orientation on the strength of single-lap shear joints. Specimens were made at BRIN's Research Center for Aeronautics Technology (PRTP) using the Vacuum Assisted Resin Infusion (VARI) method. Unidirectional carbon fiber and chempoxy resin were the materials used to make the laminate composite specimens. As a manufacturing process, the VARI method was to make 12 layers of UD-CFRP composites. A chempoxy resin concoction with a resin and catalyst ratio of 2:1, with a fiber mass fraction of 40% and a resin mass fraction of 60%. The composite plates were made at room temperature with a vacuum pressure of -100 KPa. A vacuum machine from VacMobile New Zealand was used to induce vacuum conditions in the bag. Then, chempoxy resin is flowed into the vacuum bag until the entire UD-CFRP is wet. The VARI process was then allowed to stand for 24 hours (see Fig. 2).

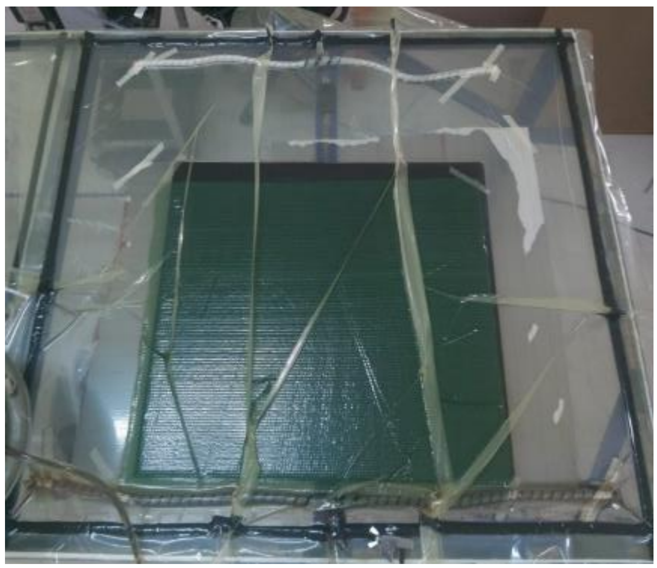

Fig. 2. The Process for VARI Method

Specimens were cut from composite panels according to ASTM D 5868-01 standard [12] with a substrate length and width of 101.6 mm x 25.4 mm. The substrate-cutting process is performed using an NRT-Pro table saw machine operating at 2950 rpm. Next, 1x1 $inch^2$ patches were marked on one side of the thin plate for abrasive treatment. The plate was then subjected to abrasive treatment using a Rockwell belt sander machine with constant speed at 1700 fpm. The abrasive treatment of the belt sander machine uses 800-grid sandpaper. The abrasive treatment technique can be used to improve the joint strength. Based on the review, the most effective surface treatment for single-lap joints is the abrasive type treatment method [13]. After abrasive treatment, the specimens were cleaned with acetone to prevent contaminants from entering the adhesive area. The specimens were firmly bonded to the treated surface using six different adhesives applied specifically to the 0° unidirectional specimens. The best adhesive was applied to quasi-isotropic (with interface orientation of 0°, +45°, and 90°) and orthotropic (with fiber orientation of ±45° and 90°) configuration specimens, with each variation of five samples. To ensure that the specimen sticks well, pressure is applied to the secondary bonding adhesive area, and then the curing process is allowed to stand for 24 hours. The picture of the single lap joint test specimen can be seen in Fig. 3.

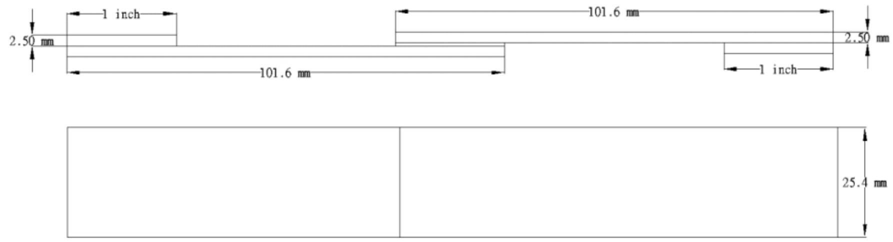

Fig. 3. Single-lap joint specimen scheme scale 3:1

Secondary bonding between two pre-cured laminated composites was performed using different types of adhesives. The adhesives used included Ripoxy R-800 EX (VI), Epoxy Adhesive Bisphenol A, Chempoxy Resin, Aerospace Grade Epoxy Adhesive B/A, Acrylic Adhesive 1, and Acrylic Adhesive 2. These six adhesive types were evaluated in a 0° unidirectional configuration to determine the highest lap shear strength value. After identifying the adhesive with the highest lap shear strength, it was applied to configurations with varying orders of fiber directional arrangement to determine its effect on different interfaces, according to Table 1.

Table 1 shows a list of six laminated composites with different stacking order configurations that will be investigated using the adhesive with the highest lap shear strength value. The composite panel is represented by a quasi-isotropic stacking sequence with 0°, 45°, and 90° as the outer layer in contact with the adhesive. The other two configurations are unidirectional and orthotropic, with 90° and ±45° interfaces.

Table 1. Layup configurations.

Fiber Orientation	Stacking sequence
Unidirectional 0°	$[0°]_{12}$
Unidrectional 90°	$[90°]_{12}$
Orthotropic	$[+45°/-45°]_{3S}$
Quasi-isotropic first ply of 0°	[0/90/+45/-45/0/90/90/0/-45/+45/90/0]
Quasi-isotropic first ply of 45°	[+45/-45/0/90/+45/-45/-45/+45/90/0/-45/+45]
Quasi-isotropic first ply of 90°	[90/0/+45/-45/90/0/0/90/-45/+45/0/90]

Tensile tests were carried out using the RTF Universal Testing Machine (UTM). The purpose of the test was to obtain elasticity and strength with various types of adhesives when receiving shear loads. Data taken from UTM includes load and elongation measurements to calculate stress and strain values. Tensile tests on the material are used to determine the lap shear strength of the various types of adhesives tested in the 0° unidirectional fiber direction and the effect of the orientation of the interface layer on the strength of the adhesive connection in the composite material against the tensile load (see Fig. 4).

Fig. 4. Tensile testing process of test objects using UTM.

3. Result and Discussion

The results of the single-lap joint shear test with a variation of 6 types of adhesives in the 0° unidirectional orientation have been carried out. From these results, it can be seen that the chempoxy adhesive type has a high stiffness and shear strength value compared to other adhesives. The single-lap joint specimen with chempoxy adhesive has a shear strength value of 11.43 MPa. Meanwhile, single-lap joint specimens with other adhesives, namely epoxy bisphenol A, acrylic adhesive 1, aerospace grade epoxy adhesive B/A, ripoxy R-800 EX (VI), and acrylic adhesive 1 which has a shear strength value of 11.07 MPa, 10.66 MPa, 9.25 MPa, 8.42 MPa, and 3.09 MPa, respectively. The experimental results of the shear test with various adhesives are shown in Fig. 5. The test results show that the best adhesive material is a material similar to the resin used in composite manufacturing. This is because there will be a perfect chemical bond between the resin in the composite and the adhesive. After all, they are similar. This perfect bond causes the shear strength of the joint to be better than other adhesives that are different in type from the resin in the composite.

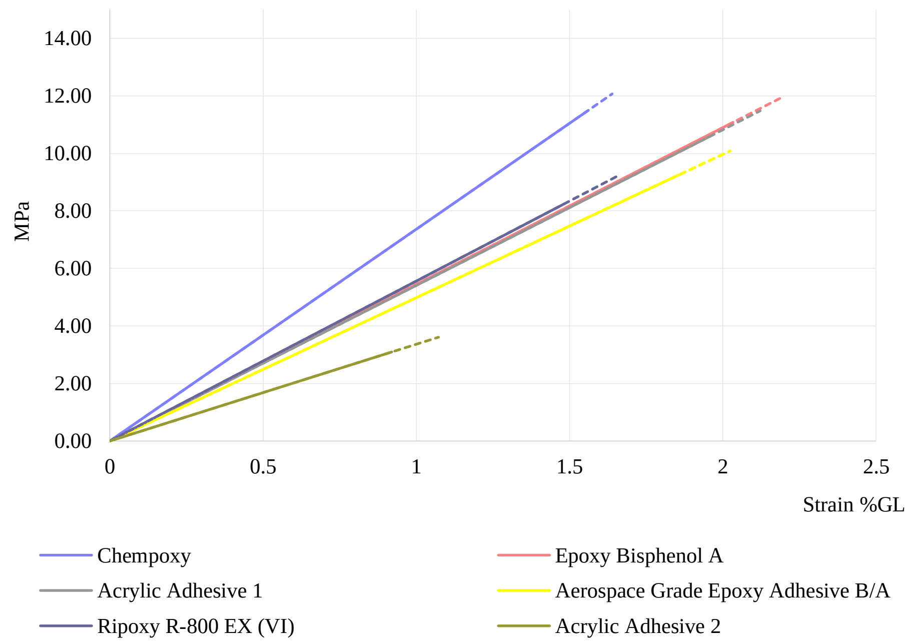

Fig. 5. Stress-strain curve of six adhesive types

The failure modes for each type of adhesive tested in the 0° unidirectional direction showed different damage results (see Fig.6a). Failure modes using Chempoxy, Epoxy Bisphenol A, and Ripoxy R-800 EX (VI) adhesive types experienced substrate or adherend failure. Adherend failure is failure that occurs in adherends which are characterized by the appearance of fibers that are attracted to the surface during testing on the ruptured area. This failure occurs when the mechanical strength understands the uncertainty in the adhesively bonded joint [14]. Aerospace Grade Epoxy Adhesive B/A, Acrylic Adhesive 1, and Acrylic Adhesive 2 had adhesion failure (see Fig. 6b). Adhesion failure is the failure mode that occurs when minimal adhesive is present on one or both sides of the surface bonding. It is characterized by the absence of adhesion on one of the surfaces due to the hydration of the chemical bond formed [15]. This can occur when the adhesive dries before a bond with the adhesive is created. Apart from the direct impact of the manufacturing process, the environment can also contribute to adhesive failure [14].

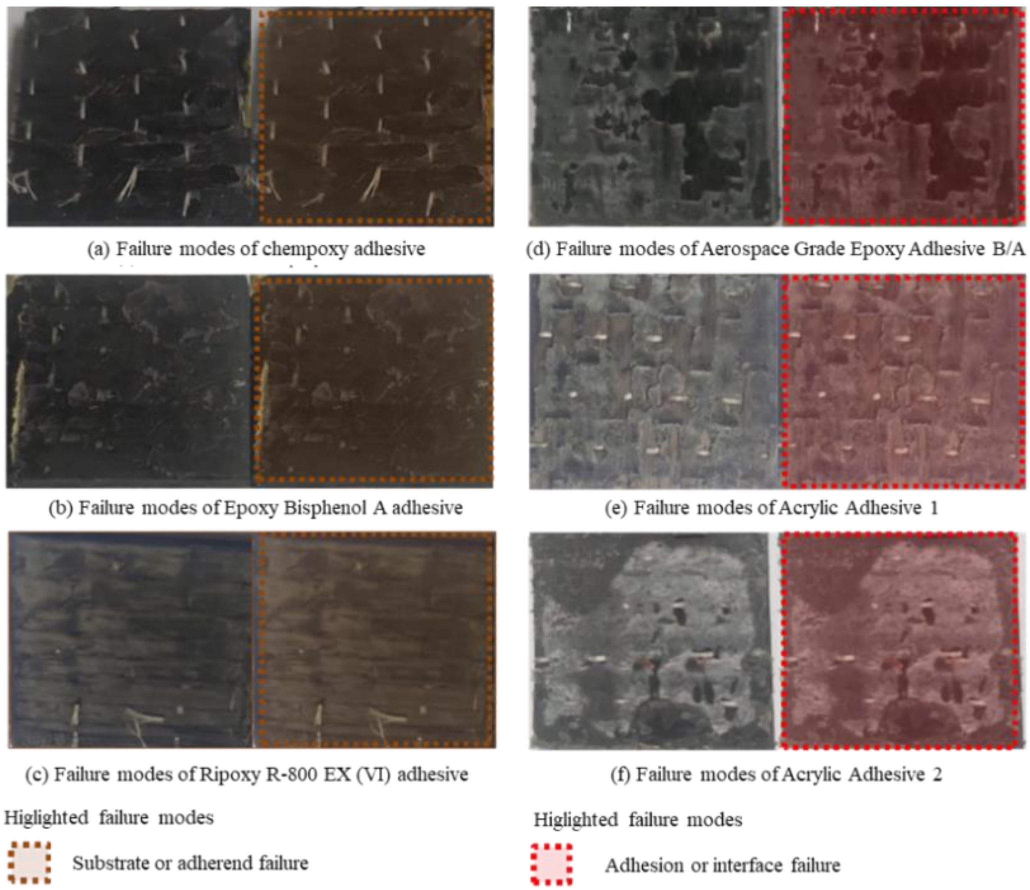

Fig. 6. Failure mode of adhesive single-lap joint due to shear stress

The results showed that chempoxy adhesive has the highest lap shear strength value of 11.43 MPa compared to other adhesives with the order of 0° unidirectional arrangement with a vacuum-assisted resin infusion method. Layup configuration is a variable that significantly affects the lap shear strength tested using chempoxy adhesive because it has the highest lap shear strength value. Due to its high shear strength value, chempoxy adhesive is applied to quasi-isotropic and orthotropic single-lap joint specimens. The results of the single lap shear adhesion test of quasi-isotropic and orthotropic specimens can be seen in Fig. 7.

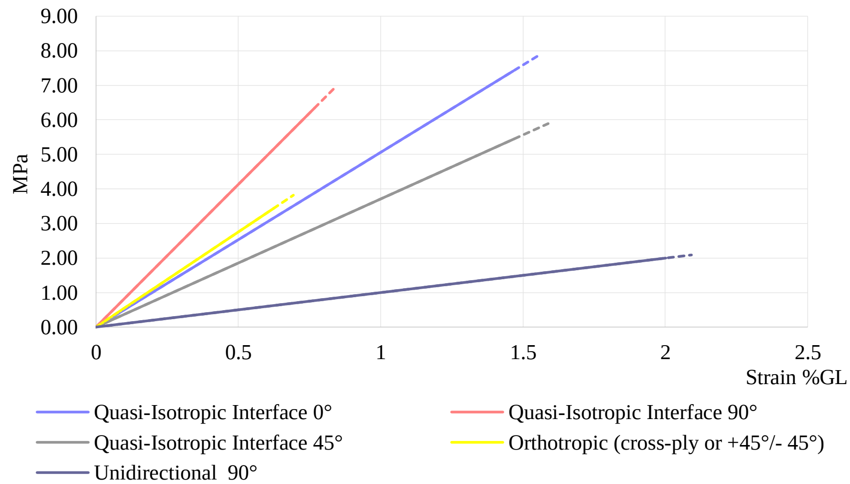

Fig. 7. Stress-strain curve of interface configuration

The quasi-isotropic configuration with 0° interface ply has the highest lap shear strength value of 7.42 MPa, better than that produced by unidirectional 90°, which only has a shear strength of 1.99 MPa. In comparison, the other quasi-isotropic configuration with 90° interface ply has a shear strength of 6.34 MPa. The quasi-isotropic interface ply +45° showed a lap shear strength of 5.46 MPa, and the orthotropic configuration (cross-ply or +45°/- 45°) had a tensile strength of 3.52 MPa (see Fig.7). The results of similar studies also show that the 0° layer as the interface layer in contact with the adhesive will produce a higher load strength[16]. This happens because ply orientations in composite materials significantly influence their mechanical properties, including lap shear strength when bonded with adhesive. A 0° interface ply possesses the highest lap shear strength due to the direct alignment of the fibers along the applied force. In this configuration, the load is primarily carried by the fibers, resulting in efficient stress transfer between the adhesive and the material. This alignment minimizes the shear stress within the adhesive bond, maximizing the overall strength of the joint. In contrast, other stacking sequences like interface 45° and 90° have lower lap shear strengths due to their fiber orientations. In a interface 45°, the fibers are oriented diagonally concerning the applied force. This orientation leads to a combination of tension and shear stresses within the adhesive, reducing the overall lap shear strength compared to the 0° ply where the fibers are directly aligned with the force. Similarly, in a interface 90°, the fibers are perpendicular to the applied force. This arrangement results in higher peel stresses and lower shear stresses within the adhesive joint, leading to decreased lap shear strength compared to the 0° orientation. Ultimately, the variation in fiber orientation directly affects the distribution of stresses within the adhesive joint, influencing its shear strength. The 0° orientation offers the highest lap shear strength due to the alignment of fibers directly along the applied force, maximizing stress transfer and minimizing shear stress within the adhesive bond.

Failure modes of each sequence configuration with different interface variations have been tested using chempoxy adhesive as an adhesive. Specimens with quasi-isotropic sequence configuration interfaces 0°, +45°, and 90° predominantly experience substrate or adherend failure (see in Fig. 8a, 8b, 8c). The orthotropic interface (cross-ply or +45°/- 45°) predominantly experienced cohesive failure (see Fig. 8d). Cohesive failure occurs when there is damage along with the adhesive layer, failure occurs due to shear stresses or peel stresses, which occurs due to the design of the joint such as too much peel stress [14]. The failure does not propagate deeply into the composite until the first layer. Showing a similar trend investigated the impact of interface layer orientation on the fatigue behavior of bonded CFRP-SLJ. The experimental findings revealed that the use of a 45° layer at the adhesive-composite interface significantly improved the resistance to crack propagation. [17]. The 90° unidirectional layup configuration experienced stock-break failure when one of the adherents broke (see Fig. 8e). The matrix can withstand the shear force received but cannot transmit it to the surrounding fibers because the orientation direction of the 90° unidirectional fibers is opposite to the direction of the tensile test load. The failure mode is strongly influenced by the orientation of the interface lamina in contact with the adhesive, such that a 0° interface layer causes failure within the bond line, while a 90° interface layer causes failure within the composite binder [18].

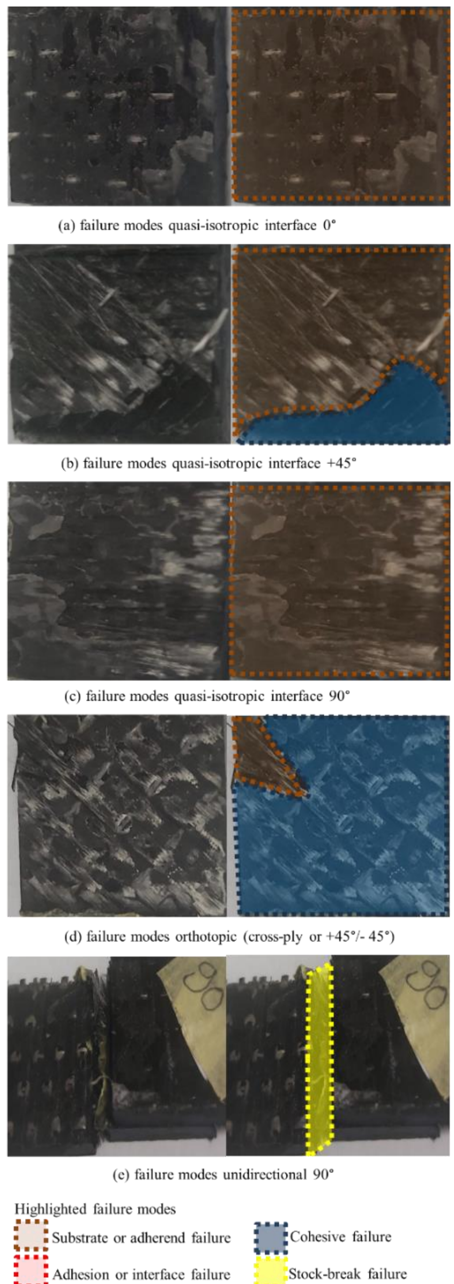

Fig 8. Failure modes of various stacking sequence interfaces

4. Conclusions

A study of the effect of adhesive types and fiber orientation on mechanical properties of single lap joints has been carried out, evaluation of the performance of various adhesives in shear tests of single lap joints, particularly focusing on 0° unidirectional orientation, underscores the critical role of adhesive selection and layup configuration in determining joint strength and failure modes in composite structures. The chempoxy adhesive emerged as a superior choice, showing very high shear stress values compared to other alternative adhesives as the adhesive material is a material similar to the resin used in composite manufacturing due to a perfect chemical bond between the resin in the composite and the adhesive. In addition, this study highlighted the significant influence of layup configuration on the shear strength of bonded joints, with the 0° interface layer displaying the highest lap shear strength attributed to the direct alignment of fibers along the applied force, allowing efficient stress transfer and minimal shear stress in the adhesive bond.

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