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A Comparison of Different Joining Options of Hybrid Composite Joints for Improved Fatigue Life

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ABSTRACT

The use of composite materials has increased rapidly in the last couple of decades especially in the aerospace industry due to its lighter weight, higher stiffness and better fatigue properties. The fiber metal laminates (FML) assemblies design normally involves an interaction between composites (carbon fiber) and metallic parts (AA 6061 T6) and these interfaces often prove to be the weakest portions of the structures. This research has therefore focused on carrying out a comparison of different joining techniques of composites with metals keeping in view the tensile and fatigue properties of double lap joint configuration. For this purpose simple adhesive joints, hybrid joints (adhesive +rivets) and joints having adhesive pins in metal plate were prepared and tested. The research also involves finite element modeling of these joints and their subsequent experimental validation. The results showed higher strength of hybrid joint, in which a combination of fasteners and adhesive was used; however, the novel idea of using adhesive pins could not be successful.

1. Introduction

Composite materials are increasingly being used for light weight and high strength applications. These are now used in various applications including aerospace, naval, military sectors, automotive, rail industry and turbines [1]. Now, composite materials are replacing aluminum alloys due to their lower weight, higher fatigue strength and better corrosion resistance properties. These are mostly being used in commercial aircrafts for the fuselage, wings and various other structural components [2]. The composite assembly design normally involves an interaction between composites and metallic parts and the interface generally proves to be the weakest part of the structure. The two popular options for joining composites with the metal counterpart are the use of fasteners and permanent adhesive bonding. According to Ali et al. [3] adhesive joining technique is used extensively in many industries because adhesive improves the strength to weight ratio, provides resistance to corrosion, heat, sound isolation, damping and sealing. More importantly this option overcomes problems such as stress concentration around hollow cavities and thermal effects.

However, there is a need to enhance the shear and fatigue properties of these joints without weakening of the parent materials. In the last several years, hybrid joints have attracted the attention of many industries such as automotive, aerospace and transportation. This is due to their better performance compared to simply fastened or bonded joints [4]. Mazumdar & Mallick [5] studied the adhesively bonded single lap joints (SLJs) in Sheet Molding Compounds (SMC) under static and fatigue response. The authors investigated the effects of overlap length, adhesive thickness, surface preparation, test speed, and water exposure on the joint performance. From the results, it was concluded that ratio of fatigue to static strength is merely affected by the overlap length and thickness of adhesive. Moreover, it was also noticed that fatigue strength is nearly 50 - 54% of static strength and the water immersion for 214 hours did not affect the static as well as fatigue failure load. Azari et al. [6-7] studied the effect of bond-line thickness in the range of 0.13mm to 0.79mm on the fatigue and quasi static fracture behavior of Al joints adhesively bonded. The static and fatigue performance of hybrid joints in a structural reaction injection molded composite was studied by Zeng and Sun [8].

It was observed using finite element analysis (FEA) that the hybrid joints have a higher static failure load and longer fatigue life than the adhesive. Makqto Imanaka et al. [9] performed fatigue tests on the rivet, adhesive and hybrid single lap joints with different lap widths, adhesive and rivet strengths. The authors found that the fatigue strength of hybrid joint was higher in comparison with adhesive joint. It was concluded that by the increase of

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lap width fatigue strength of adhesively bonded joint will also increase whereas riveted joint is independent of lap width. Kelly [10] investigated the strength and fatigue life of hybrid bonded/bolted joints with carbon fiber reinforced plastic (CFRP) substrates through experimentation. It was determined that the hybrid joints had greater strength, stiffness, and fatigue life when compared to adhesively bonded joints for adhesives with lower elastic modulus. Kweon et al. [11] tested the composite-to-aluminum double lap joints (DLJs) to get the failure load and mode for adhesively bonded joints, bolted joints and hybrid joints. It was noticed that the strength of hybrid joint increased when the strength of fastener was stronger than the paste type adhesive and when the strength of film type adhesive was stronger than the fastener strength. Kwakernaak and Hofsiede [12] showed that combining mechanical fastening and a structural adhesive improved the fatigue strength of the riveted joint.

Ngoc and Paroissien [13] studied adhesively bonded and hybrid bolted/bonded SLJs using FEA. Two-dimensional and three dimensional analyses was carried out taking into account geometrical and material nonlinearities. It was concluded that hybrid bolted/bonded joints have a longer fatigue life than bolted joints. Bond-line thickness has a significant effect on static and fatigue behavior of adhesively bonded joints. It should be optimized in order to maximize the fatigue strength of a joint. Du and Shi [14] studied the static and fatigue performance on steel/Al components mixed hybrid joints. The use of the adhesive increased the press-fitted joint performances, with respect to its release force. Yogesh and Arunkumar [15] compared three types of joining techniques for SLJs, namely adhesive joining, mechanical fastening and hybrid joining. Tensile testing was used to evaluate the joint strength and failure modes and adhesive bonding was found suitable for acrylic type adhesive and the for the rubber type adhesive.

1.1 Objectives of the Research

It is apparent from the literature review that the hybrid joints generally show better static and fatigue properties, however, there is a lack of experimental data on static and experimental behavior of double lap joint of CFRP (woven carbon fiber) with aluminum alloy(AA 6061 T6) and a potential new joining technique of adhesive pins needs further research.

2. Experimental Procedure

In order to conduct a thorough investigation of the fatigue life in the CFRP laminates with the hybrid double lap joints, there are two types of tests that need to be carried out. It is necessary to perform static tests to determine the ultimate static strength of the material under consideration that sets the upper range of the stress amplitude for fatigue tests. Also finite element modelling and experimental solutions would be developed during this research.

2.1 Material

The carbon reinforced laminates (manufactured from 8 layers plain weave 3K carbon) and aluminum 6061-T6 was used for experimental work of double lap adhesive and hybrid joints. Epoxy resin Araldite LY5052 along with Aradur H5052 was used as an adhesive for the joining of these two different materials. The same adhesive was used for adhesive pins in double lap configurations. The rivets SS 304 aerospace grade was used for testing of fasteners only and fasteners and adhesive combined joints. The summarized information about the mechanical properties of adherend and adhesive is prescribed in table 1 [16-17].

Table 1: Mechanical properties of different materials

Aluminum Alloy 6061-T6 Properties		
Tensile Yield Strength (KPa)	Ultimate Tensile Strength (KPa)	Poisson Ratio
276000	310000	0.33

Carbon Fiber	
Tensile Modulus (KPa)	Poisson Ratio
230000000	0.35

Araldite LY 5052	
Poisson ratio	Tensile Strength (KPa)
0.35	59.98

2.2 Test Specimens Preparation

The test specimen adherends were prepared according to the ASTM D 3528. For aluminum alloy thickness of the sheet is 5 mm and thickness of the carbon fiber composite sheet is 2.5 mothers recommended lap length is 19.05 mm which is half of the width of the specimens [18]. The adhesive thickness of 0.2 mm was selected referring to Azari et al. [6-7]. The stainless steel SS 304rivet was used for initial fastening. The bonding surface of aluminum adherend was prepared by sand blasting at a pressure of 3 bar followed by the polishing of aluminum surface through 180 grade mesh emery paper and acetone cleaning/skimming. The double lap joints were made by the use of adhesive and combination of adhesive and rivet are shown in Fig. 1 and Fig. 2.

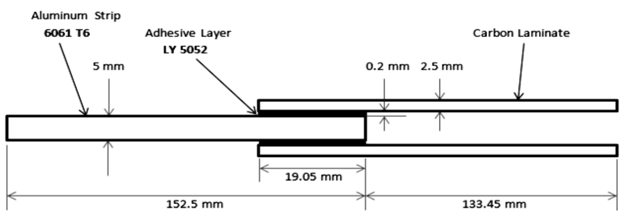

Fig. 1: Schematic representation of adhesive joint

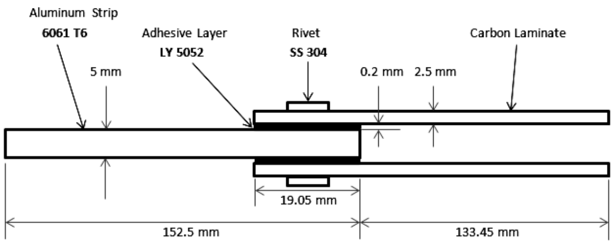

Fig. 2: Schematic representation of hybrid joint

Adhesive pins were introduced in the joints by drilling holes for rivets and filling them with adhesive only instead of rivets during the bonding process. Curing was performed under clamp pressure for 1 day at room temperatures shown in Fig. 3. The post curing was performed in an incubator for 4 hours at 100^{o}C.

Fig. 3: Test specimens preparation

2.3 *Tensile and Fatigue Tests*

Tensile as well as fatigue testing of specimens was carried out using material testing system (810 MTS)having stress ratio of 0.1, loading frequency of 10 Hz and applying 100 kN static and 120 kN dynamic load.16 samples were tested for tensile as well as for fatigue tests. The fatigue test was conducted at 50%, 60% and 80% of the ultimate static strength of the hybrid joints. A photograph of the MTS with specimen is presented in Fig. 4.

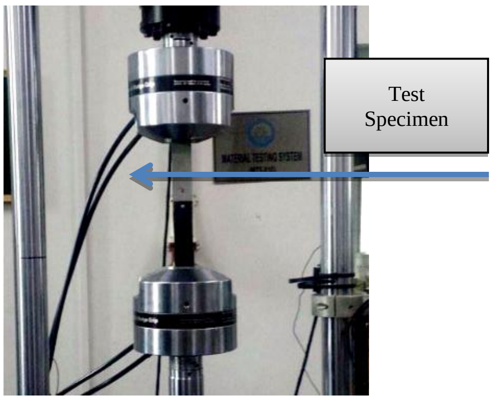

Fig. 4: Material testing system (810 MTS) with specimen

2.4 *Finite Element Analysis*

For the comparison of results finite element analysis of adhesive and hybrid joint was done on ABAQUS. Cohesive zone technique (CZT) is used for modeling the joint. The composite was assumed to be orthotropic carbon/epoxy of 9-ply laminates. Classical laminate plate theory was used for the material properties using bi-directional laminates [19]. Aluminum 6061-T6 material is an isotropic material, with perfectly elastic and plastic deformation behavior. After damage properties were assigned using damage for traction separation law in the form of maximum stress damage which is dependent on the stiffness of the bulk material [20-23].

One edge of the specimen is fixed in the jaw of machine and load is applied at the other end as a displacement of 2e^{-5} m/s. Finite element model with boundary conditions of double lap adhesive as well as hybrid joint is shown in Fig. 5. The adhesive only and hybrid joint were independently meshed as shown in Fig. 6. In adhesive joint aluminum and carbon epoxy laminates were meshed using structure hex, 3D stress element referred to Abaqus as C3D8R element. Adhesive was meshed using sweep hex, cohesive element COH3D8 through element deletion. In hybrid joint aluminum and carbon epoxy were meshed using sweep hex, 3D stress element C3D8R element; rivet was meshed using Free Tet, 3D stress element C3D10 with element deletion.

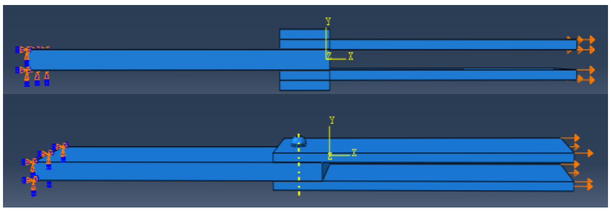

Fig. 5: Boundary conditions of adhesive and hybrid joints

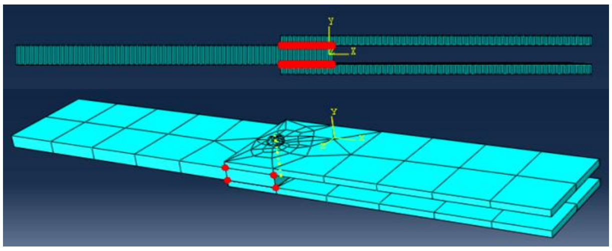

Fig. 6: Element meshes of adhesive and hybrid joints [24]

4. Results and Discussions

4.1 *Adhesive Joints*

The objective was to determine the bonding strength and fatigue life of adhesive only and the hybrid joint of adhesive and fasteners. The maximum average bonding strength of adhesive joint was measured as 24.5 kN and maximum displacement was 1.45 mm.

The results from the finite element model are shown in Figs. 7-10.

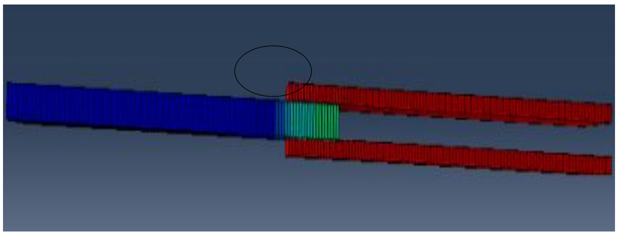

Fig. 7: Transfer of shear from carbon fiber to aluminum through adhesive

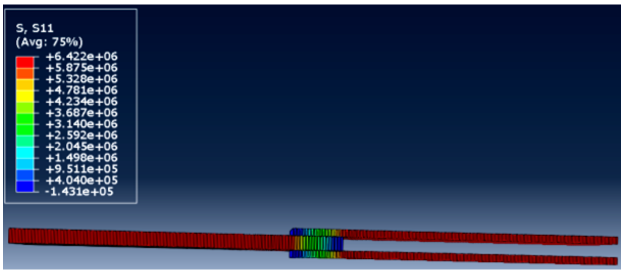

Fig. 8: Shear in X- direction

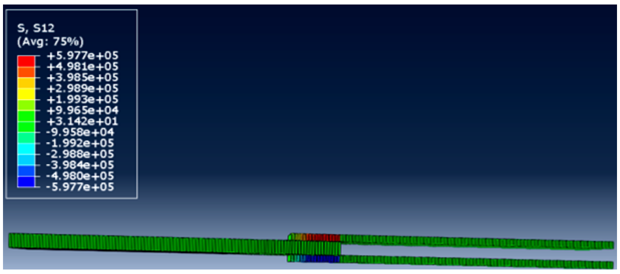

Fig. 9: Shear in Y- direction

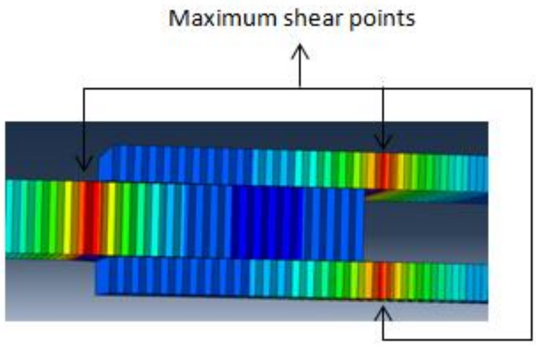

Fig. 10: Maximum shear at the end of joint

The maximum value of force is 24.9 kN and maximum displacement is 1.47 mm. The force displacement relationship comparison between experimental and simulation results are shown in Fig. 11. When applying a load 50% & 60% of the tensile strength the joint did not fail up to 30,000. But when apply a load 80% of the tensile strength the joint breaks at 22,255 cycles with the frequency of 10 Hz. The mode of failure of adhesive joint after fracture is mixed mode failure shown in Fig. 12.

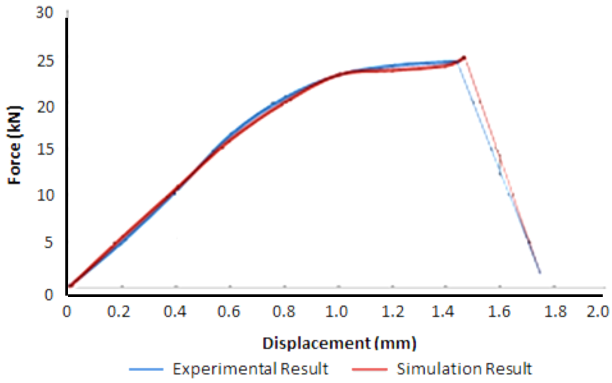

Fig. 11: Force-displacement relationship comparison between experimental & simulation results of adhesive joint

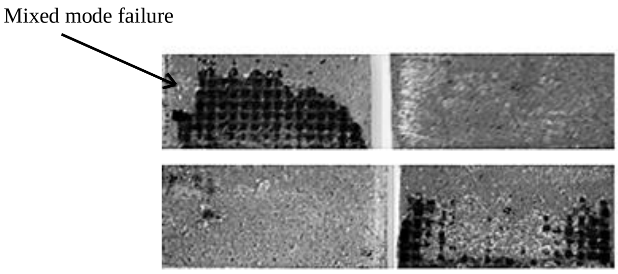

Fig. 12: Mode of failure of adhesive joint after fracture

4.2 Hybrid Joints

When a combination of adhesive and rivet is used as a bonding material then strength of the joint is 25.5 kN and maximum displacement is 1.4 mm at which the joint fracture experimentally. Similar to adhesive joint for the validation of experimental data finite element analyses of hybrid joint was carried out that provides information about deformation, strain, stress distribution and load value till the joint breaks shown in Fig. 14.In Fig. 14 it is shown that maximum stress generated in carbon fiber sheet through rivet because after generating hole discontinuity developed in carbon fiber. By finite element analyses the joint strength is 25.8 kN and maximum displacement is 1.42 mm. The force displacement relationship comparison between experimental and simulation results are shown in Fig. 15. Comparison of experimental as well as finite element analyses values of both adhesive and hybrid joints for tensile test is shown in table 2. Fatigue test of hybrid joint was done similarly as the fatigue test of adhesive joint. For fatigue testing apply a load 50 & 60% of the tensile strength the joint didn’t fail up to 30,000 cycles. But when we apply a load 80% of the tensile strength the joint breaks at 24,059 cycles with the frequency of 10 Hz. The mode of failure of hybrid joint after fracture is mixed mode failure shown in Fig. 16.

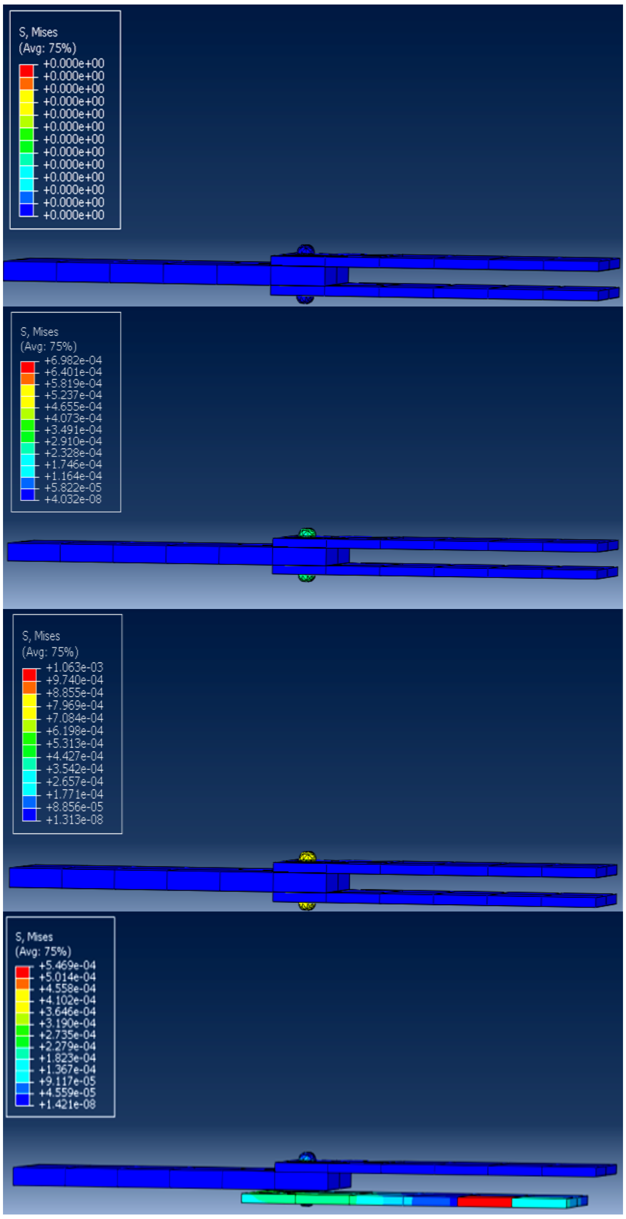

Fig. 14: Different Stress levels in hybrid joint till the fracture happens

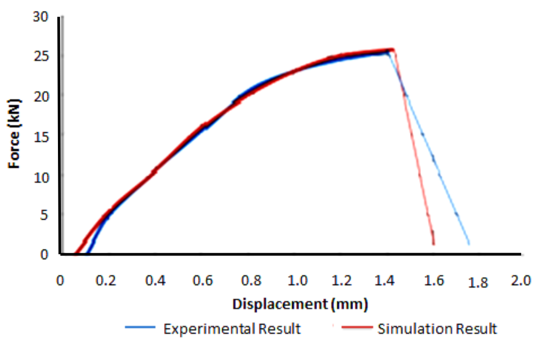

Fig. 15: Force-displacement relationship comparison between experimental & simulation results of hybrid joint

Mixed mode failure

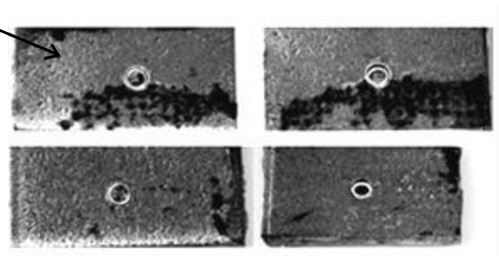

Fig. 16: Mode of failure of hybrid joint after fracture

Table 2: Tensile Test Comparison of Experimental and FEA of adhesive joint

Type of Joint	Failure Load (KN)				
	Experimentally			FEA	% Difference
	Sample #1	Sample # 2	Average Value		
Adhesive Joint	25	24	24.5	24.9	1.63
Hybrid Joint	25	26	25.5	25.8	1.17
Adhesive Pins	17.3	16.5	16.9	N/A	N/A

Comparison of experimental values of adhesive and hybrid joints for fatigue test is shown in Table 3.

Table 3: Experimental results of fatigue tests

Type of Joint	No. of Cycles			Mode of Failure
	50%	60%	80%	
Adhesive Joint	30,000	30,000	22,255	Mixed mode failure
Hybrid Joint	30,000	30,000	24,059	
Adhesive Pins	30,000	30,000	12,725	
Safe/Failure	Safe	Safe	Failure	

5. Conclusions

Tensile and fatigue tests were performed to investigate the strength of CFRP to Aluminum double lap adhesive and hybrid joints. After experimentation and FE analyses it is concluded that strength of hybrid joint is more than that of adhesive joint both in case of tensile as well as in case of fatigue testing. The mode of failure in both adhesive and hybrid joint is mixed mode failure. FE analyses showed that maximum shear stresses are developed at the start and at the end of the adhesive joint but in case of hybrid joint maximum stress generate in carbon fiber through hole because of discontinuity in carbon fiber laminate.

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