Failure Mode and Analysis of the Bonded/bolted Joints between a Hybrid Fibre Reinforced Polymer and Aluminium Alloy

T. L. Yogesh[a,*], **N. Arunkumar**[a]

[a,] *Department of Mechanical Engineering St. Joseph's College Of Engineering, Chennai, India.*

ARTICLE INFO

Article history:

Received 8 Aug 2014
Accepted 01 Jan 2015
Available online 30 June 2015

Keywords:

Variable substrates
Adhesive Bonding
Mechanical fastening
Hybrid joining
Joint strength
Failure modes

ABSTRACT

Three different joints, namely adhesive bonding, mechanical fastening and hybrid joining were considered for the assembly of variable substrates. Two different types of adhesives, namely high modulus acrylic adhesive and low modulus rubber adhesive, were selected for the study. Tensile tests were performed to evaluate the joint strength and failure modes for different joining techniques.

Adhesive bonding was found suitable for the acrylic type adhesive. Bolting had no significant effect on the joint strength in the hybrid joints for the acrylic type adhesive. For the rubber type adhesive, the hybrid joint shows better performance compared to other types of joints. For rubber type adhesive, bolting in the hybrid joint significantly improved the load carrying ability of the joint.

1. Introduction

Composite materials have high strength to weight ratio when compared to conventional materials such as steel, aluminum, etc. Hence, the application fields for composites are continuously expanding from high tech to common engineering applications. Recently, traditional materials such as steel or metal alloys have been widely used in conjunction with the innovative ones called fibre reinforced polymers in order to obtain hybrid structures. The joints between these materials often represent the weak point of structures. This is why a key challenge is to realize the structural joints able to bear elevated loads. To increase the effectiveness and efficiency, many prehistoric as well as modern devices require the assembly of several components, often involving dissimilar materials. By combining multiple materials, the resulting structure acquires useful features of each constituent, often making the whole greater than of the parts. Joining allows us to fabricate efficient, lightweight, and open structures with tailored properties and performance matched to the intended use. There are three different types of techniques for joining between a composite and metal. They are classified as(a) adhesive bonding, (b) mechanical fastening, and (c) hybrid joining.

Adhesive bonding requires no holes to be drilled which eliminates the stress concentration and provides uniform stress distribution at the joint. Certain brittle or damage prone adherends are difficult to drill and hence mechanical fasteners cannot be used. However, these joints are very sensitive to the environment and have poor heat resistant properties. Kweon et al. [1] suggested that difficult because of its catastrophic mode of failure.

Corresponding author:
E-mail address: tlnyogesh@gmail.com (T. L. Yogesh).

Mechanical fastening involves the use of bolts and nuts in the drilled hole at joint interface. Fastener joints could be of interference, push or clearance fits. A rigid pin of diameter $2a \times (1 + \lambda)$ is introduced into a plate with a hole of diameter $2a$. If λ is positive the fit is of interference, and if λ is negative the fit is of clearance, and $\lambda = 0$ is the case of a push fit. The fit used here was the interference type because it has the maximum fatigue life. Holes drilled in mechanical fastening cause stress concentration which affects the strength of the adherend and hence the joint. However, bolted joints are proved to be more reliable for assembling variable substrates and have been used in many engineering applications. Kweon et al. [1] suggested that strength predictions in the bolted joints are easy and accurate because the mode of failure is progressive, which is a favorable phenomenon. Unlike many adhesives, mechanical fasteners have a very long shelf life. They generally have less environmental concerns and may facilitate repair.

To overcome the potential weakness of adhesive bonding, hybrid joints were proposed [2, 3, 4, 5]. For a hybrid joint, mechanical fastening is added to bonding for improvement in the joint strength. Lee et al. [6] suggested that optimally designed mechanical fastening might induce more progressive induced failure rather than the catastrophic mode of failure. Thus, combination is often employed as a safeguard against defects within the adhesive layer, which may lead to premature or catastrophic failure.

Al-Zubaidy et al. [7] conducted an experiment for double strap joints at four speeds of loading to highlight its effect on the bond strength between the Carbon Fibre-Reinforced Polymer (CFRP) sheet and steel for adhesively bonded joints. Nguyen et al. [8] studied specimens (epoxy adhesive, CFRP laminates and steel/CFRP adhesively-bonded joints) exposed to Ultra Violet (UV) radiation for various time periods and identical reference specimens to only thermal environments without UV exposure. The tensile strength of the adhesive was reduced by 13.9%, while modulus showed a significant increase by 105% after 744 hours of exposure. The tensile modulus of the adhesive exposed to only thermal environment also increased by 38%, considerably less than that induced by UV exposure. The UV exposure also led to a decrease in the joint strength but an increase in stiffness, caused by the temperature effect rather than the UV rays. Sarfarazet al. [9] experimentally investigated the effect of the mean load on the fatigue behavior of the adhesively-bonded pultruded GFRP double lap joints under constant amplitude. Al-Zubaidy et al. [10] examined the bond between steel plates and the CFRP fabrics at different loading rates. Kim etal. [11] Investigated failure process, mode and strength of unidirectional composite single lap bonded joints with respect to co-curing with or without adhesive and secondary bonding. Several strength prediction methods have been proposed for mechanical joints. Hart-Smith [12] used the stress concentration coefficient to predict the strength of a mechanically fastened joint. Ireman [13] studied the non-uniform stress distribution in a composite laminate in the vicinity of a bolt head and hole. Whitney and Nuismer [14, 15] suggested a characteristic length based on an average stress and failure criterion. In addition, Chang and Scott [16, 17] suggested a characteristic curve generated by a combination of characteristic lengths for tension and compression. Choi and co-workers [18, 19] suggested the failure area index method to estimate the average failure index over a certain area. Kelly [20] investigated the strength and fatigue life of the hybrid (bonded/bolted) joints with CFRP adherends. Moroni et al. [21] evaluated to what extent, or under which conditions it is beneficial to use hybrid weld-, rivet- or clinch-bonded joints in comparison with simple adhesive, spot-welded, riveted or clinched joints. Kweon et al. [1] tested the composite-to-aluminum double lap joints to obtain the failure load and mode for three types of joints: adhesive bonding, bolt fastening and adhesive bolt hybrid joining. Kelly [22] predicted load distribution in hybrid composite single-lap joints through the use of a three-dimensional finite element model including the effects of the bolt-hole contact and non-linear material behavior. He investigated the effect of relevant joint design parameters on the load transferred by the bolt through a finite element parameter study. Although research has been carried on adhesive bonding, mechanical fastening and hybrid joining between a composite and metal, there has been lack of knowledge regarding failure modes and its initiation between a natural fibre composite and aluminum alloy. Thus to bridge the gap and enhance knowledge for an environment friendly future, study was carried to understand the phenomenon of adhesive bonding, mechanical fastening and hybrid joining between natural fibre composite and aluminum alloy.

Matsuzaki et al. [23] proposed bolted/co-cured hybrid joining method, and experimentally investigated its joint strength. They also state that most of the composite materials are made out of artificial fibres such as glass or carbon fibre. Carbon fibres have limited applications as they are very expensive and hence glass fibres are used extensively. However, the use of glass fibres has certain limitations. For instance, when exposed to humid environments, the glass fibre-epoxy composites absorb moisture and undergo volumetric expansion degrading the mechanical properties of the structure. Moreover, the manufacture of glass fibres is environmentally harmful compared to natural fibres. To move towards a sustainable and green future, a natural fibre, namely cotton, was used as a reinforcing fibre in the research work. Joshi et al. [24] have reviewed life cycle assessment studies of natural fiber and glass fiber composites, and identified key drives of their relative environmental performance. The advantages of using natural fibres compared to the artificial ones include: 1. Natural fibre production has lower environmental impacts compared to glass production; 2. Natural fibre composites have higher fibre content for equivalent performance, reducing more polluting base polymer content; 3. The light-weight natural fibre composites improve fuel efficiency and reduce emissions in the use phase of the component, especially in auto applications; 4. End of life incineration of natural fibres results in recovered energy and carbon credits.

Lundahl et al. [25] state that natural fibres do not provide the same strength as artificial fibres and hence to obtain higher strength, a layer of iron fibre was used to impart additional strength to the composite. Since a combination of fibres is used in the composite, they are called 'hybrid fibres'. This paper involves fabrication of three different types of joints between a Hybrid Fibre Reinforced Polymer (HFRP) and aluminum alloy 1100 and experimentally investigates the joint strength. From the test results failure modes were identified and analysed by macroscopic visual observation.

2. Experimental procedure

2. 1. Specimen preparation for evaluating the breaking load

HFRP and aluminum alloy were used as base materials for the joining process. ASTM specification D3039/3039M-14 was used as reference for sample preparation. HFRP was prepared using the hand lay-up technique. In HFRP, a combination of cotton and iron fibres were used as reinforcing fibres and the matrix phase was epoxy resin. A total of eight layers of cotton fabric were used and iron fibre was inserted as the center layer. After preparation of the hybrid composite by hand lay-up technique, cutting operation was performed by band saw cutting machine to obtain dimensions of the specimens as per ASTM standards for testing. Aluminum alloy 1100 was cut to the required dimensions of the ASTM standards.

A total of 15 lap joint specimens were prepared for the test. Two different types of adhesives, namely high modulus acrylic adhesive (Three Bond (TB)-3921/3926) and low modulus rubber adhesive (TB-1530) were used. For the joint with high modulus adhesive TB-3951/3956 and low modulus adhesive TB-1530 three specimens of bonded and hybrid joints were prepared, respectively. The design specifications of the bonded joints are:1. Length of the adherends-125mm;2. Width of the adherends-25mm;3. Thickness of the adherends-6mm;4. Area to be assembled-*25mm X 25mm*. Fig. 1 represents three dimensional CATIA model of the bonded joint designed with dimensions of substrates adhering to ASTM standards. A specimen manufactured according to the CATIA model is shown in Fig. 2, which represents a bonded joint to be used in the test.

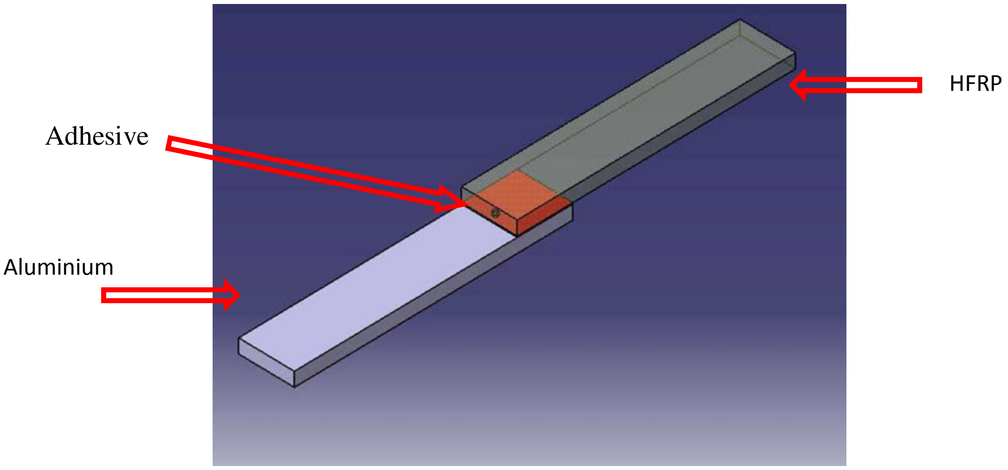

Fig. 1. The CATIA model of bonded joints

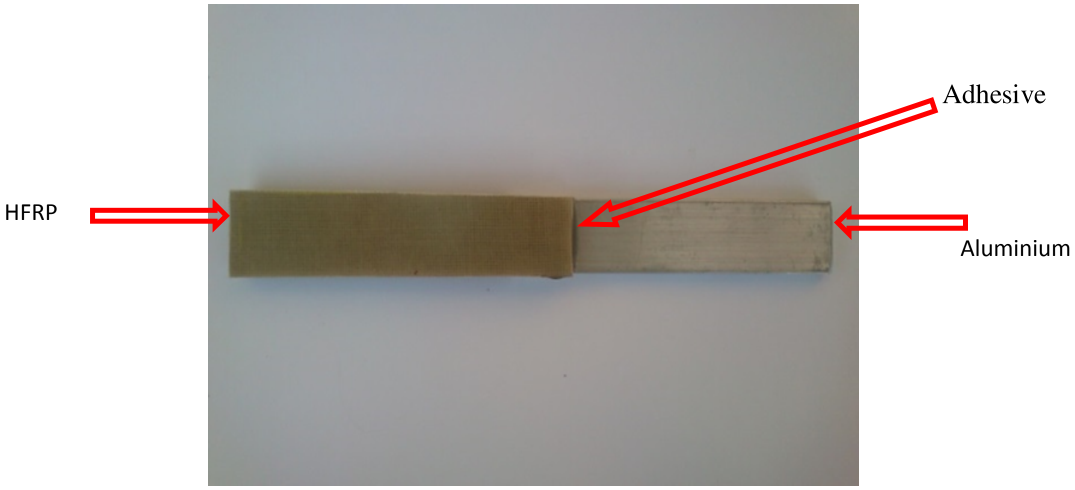

Fig. 2. A bonded joint for use in test

Three bolted joints of 5mm bolt diameter were prepared with dimensions of adherends similar to that of bonded joints adhering to the ASTM standards for comparison purposes. Fig. 3 represents three dimensional CATIA model of the bolted joint. A specimen manufactured according to the CATIA model is shown in Fig. 4, which represents a bolted joint to be used in the test. The bolt used was mild steel.

Again, the dimensions of the substrates for hybrid joints are similar to those of bonded joints and CATIA model of a hybrid joint is shown in Fig. 5. A hybrid joint manufactured according to CATIA model is shown in Fig. 6. This figure represents specimen to be used in the test in order study behavior of hybrid joints.

3. Tensile testing

One of the most common mechanical stress–strain tests is performed in tension. As will be seen, the tension test can be used to ascertain several mechanical properties of materials that are important in the design. For this reason, tension test was chosen in the experiment to find a suitable joint between HFRP and the aluminum alloy. Hydraulic Universal Tensile Testing Machine FIE UTN-10 was used for the test. Test conditions were in compliance to ASTM D3039/3039 M-14 with head displacement rate of 2mm/min at room temperature. Fig. 7 shows tensile test setup of the specimen in universal testing machine during the experiment. The output of the tension tests are usually recorded by computer as load vs. displacement. These load characteristics are dependent on the size of the specimen.

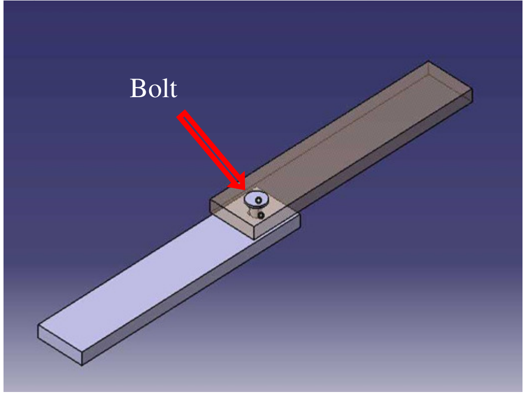

Fig. 3. The CATIA model of bolted joints

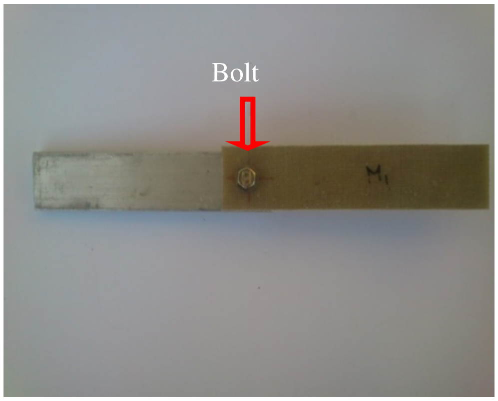

Fig. 4. A bolted joint for use in test

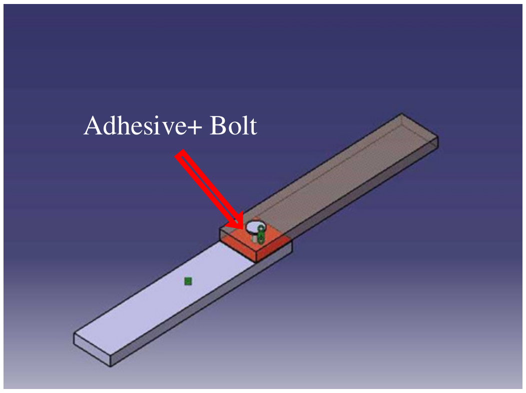

Fig. 5. The CATIA model of hybrid joint

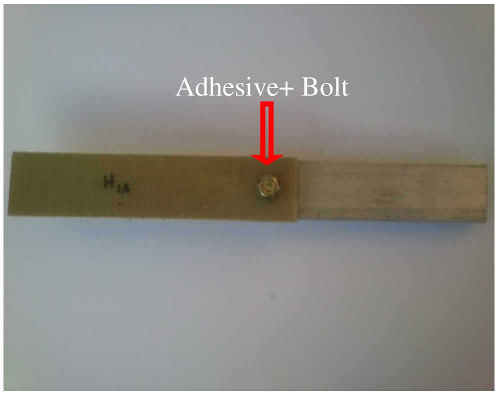

Fig. 6. A hybrid joint for use in test

4. Results and discussion

4. 1. Joints with high modulus adhesive TB – acrylic adhesive 3921/hardener 3926

To investigate the reinforcing effect of bolting on the strength of bonded joints, a test for bonded joints with high modulus adhesive, namely acrylic adhesive, was conducted first. The baseline material properties of the adhesive are generally provided by the manufacturer. These properties, however, can be affected by test conditions such as the temperature, humidity and even the surface treatment. Furthermore, adherend materials can also affect the joints. Composite materials are unlike aluminum and steel. Therefore, it is common to determine the bonding strength of an adhesive for a joint with a test for given conditions. Conventionally, bonding strength of an adhesive is defined as the maximum load carried divided by the bonded area. The method of defining the strength of the joint depends on the type of joint. Certainly, in this type of research, the method of defining the joint strength should be consistent for comparison purposes. Therefore, for convenience and consistency, the strength of the joint, regardless of the joining method, is defined as the maximum load divided by the cross sectional area of the composite laminates. The cross sectional area of the aluminum, which is the other adherend, is not used because initiation of failure in all specimens occurred in the composite laminate. Table 1 shows the test results for a bonded joint with the high modulus adhesive.

In Table 1, P_{max} denotes the maximum load carried by the joint. A_c and A_b represent the cross sectional area and bonded area of single-lap joint, respectively. The joint strength, which is maximum load divided by the cross sectional Area of the composite laminate, is 25.9 MPa, on average. This will be compared with the other two types of joints.

Fig. 7. Tensile test setup

Fig. 8. Joint failed with acrylic adhesive

Table 1. Results of the test on bonded joint with acrylic type adhesive

Result/specimen	B_{1a}	B_{2a}	B_{3a}	Average
Joint strength, P_{max}/A_c(MPa)	29.1	23.4	25.3	25.9
Adhesive strength, $Pmax/A_b$ (MPa)	6.99	5.61	6.07	6.226

All specimens failed in brittle failure of composite laminate while the adhesive sustained the bonding. Fig. 8 shows that failure occurs due to brittle failure of HFRP at the joint interface. The strength of the joint in this case was lower than the shear strength of the adhesive itself. This could be due to the low strength of the composite laminate which involved the use of natural fibres. HFRP was prepared by hand lay-up technique, dynamic crack propagation from the tip of micro voids in the material could have also led to decrease in load carrying ability of the laminate resulting in sudden failure.

Fig. 9 shows the load–displacement curves for the joints that were used to define the maximum carried load. In Fig. 9, no large difference is found in the maximum carried loads.

4. 2. Joints with low modulus adhesive TB – Rubber Adhesive 1530

The test results for composite-to-aluminum bonded joints with low modulus adhesive are given in Table 2. The meanings of P_{max}, A_c and A_b are the same as in Table 1.From Table 2 it can be seen that the joint strength, which is the maximum load divided by cross sectional area of the composite laminate, is 6.44 MPa, on average.

Fig. 10 represents failure of the bonded joint with low modulus adhesive. From Fig. 10 it can be seen that adhesives are found in both the composite and aluminum surfaces, which indicates the mixed mode failure of the bonded surface. This type of failure generally occurs due to improper curing time. Here, HFRP laminate sustained the loading but failure occurred due to the peeling effect of the adhesive. It could be due to low shear strength of the rubber type adhesive arising from its inherent property of high flexibility but lower strength.

Fig. 11 shows the load–displacement curves for the joints that were used to define the maximum carried load. In the figure a large difference is found in the maximum carried loads. The behavior could be attributed to minute differences in thickness of the adhesive layer of which we had little control during preparation of joint.

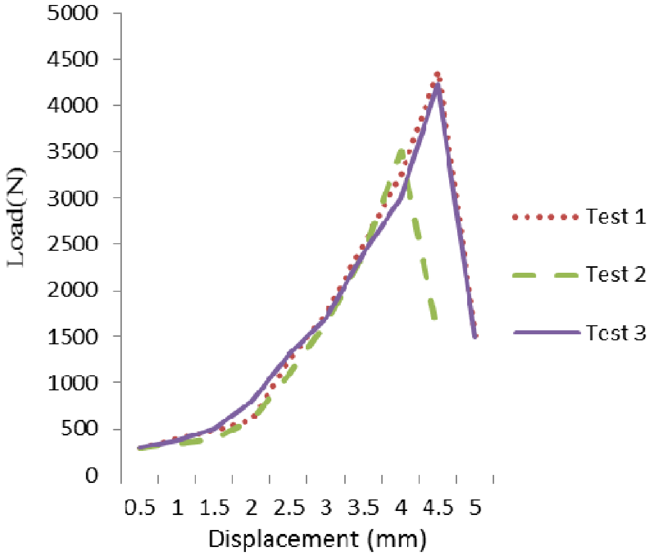

Fig. 9. Relationship between load and displacement of bonded joint from tensile tests with acrylic adhesive.

Table 2. Results of the test on bonded joint with rubber type adhesive

Result/specimen	B_{1r}	B_{2r}	B_{3r}	Average
Joint strength, P_{max}/A_c (MPa)	5.2	8.466	5.66	6.44
Adhesive strength, P_{max}/A_b (MPa)	1.248	2.032	1.36	1.546

Fig. 10. Joint failed with rubber adhesive

4. 3. Bolted joints

Table 3 shows the test results for simple bolted joints without adhesive bonding. From Table 3, the average joint strength of the simple bolted joints is 13.46 MPa, which is 92% of the joint strength with high modulus adhesive and twice the strength of joint with low modulus adhesive. Reasonable decrease in strength of bolted joints compared to high modulus adhesive is observed due to reduction in load carrying ability of the former by stress concentration. Holes drilled in bolted joints could act as favorable sites for crack propagation along with concentration of stress, leading to failure of the joint.

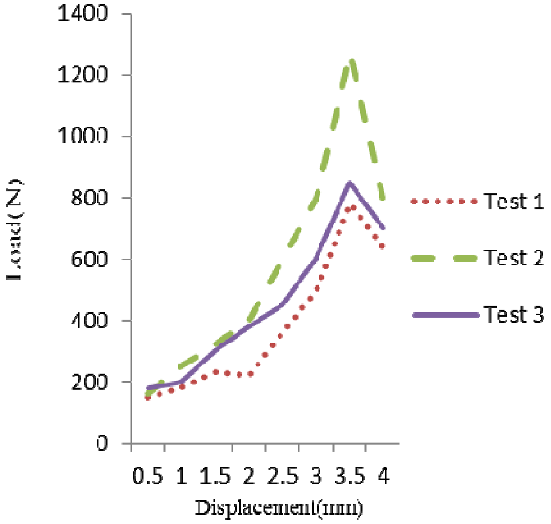

Fig. 11. Relationship between the load and displacement of the bonded joint From tensile tests with rubber adhesive

Table 3. Results of the test on bonded joint with rubber type adhesive

Result/specimen	M_1	M_2	M_3	Average
Joint strength, P_{max}/A (MPa)	13.4	14.33	12.66	13.46

Fig. 12 clearly indicates that specimen failed in the net tension mode at the composite laminate. The net tension failure for bolted joints occurs when there is insufficient material at the joint to carry the load. The curves shown in Fig. 13 indicate typical pattern of the load–displacement curve for the bolted joint.

4. 4. Hybrid joints

Summary of the test results of hybrid joints with the high modulus adhesive are shown in Table 4. The average joint strength, defined as the maximum carried load P_{max} divided by the cross sectional area A, is 22.59 MPa. This is 13% lower than the strength of the simple bonded joint (25.9 MPa). This reduction of strength in the hybrid joint can be attributed to stress concentration that occurs due to drilling operation on the surface of the adherends. Thus, for a joint using high modulus adhesive bonded joints are preferable to the hybrid joints.

Fig. 14 shows failure of the hybrid joint with high modulus adhesive. From Fig. 14 it can be seen that the specimen failed due to brittle failure of the composite laminate. Fig. 15 shows the load–displacement curves for the joints that were used to define the maximum carried load.

The results for the hybrid joints with a low modulus adhesive are given in Table 5. The average strength of the hybrid joints from Table 5 is 15.244 MPa, which is higher than the strength of the simple bonded or bolted joints. In the joint with high modulus adhesive, the bolting did not affect the strength of the bonded joint. On the contrary, in hybrid joints with low modulus adhesive that was cured at room temperature with low bonded shear strength, the effect of bolting greatly increased the strength of the hybrid joints. It should also be noted that the strength of the hybrid joints is even greater than the strength of the simple bolted joint, which means that the adhesive works to strengthen the bolted joint and delay the final failure of the joint.

Specimen failed in hybrid joint with low modulus adhesive is shown in Fig. 16. It can

Fig. 12. Joint failed with mechanical fastening

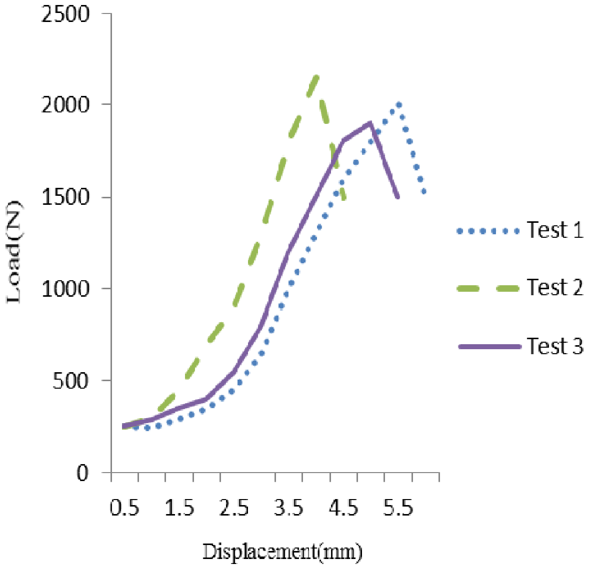

Fig. 13. Relationship between load and displacement of bolted joint from tensile tests

Fig. 14. Joint failed with hybrid joining (Acrylic adhesive)

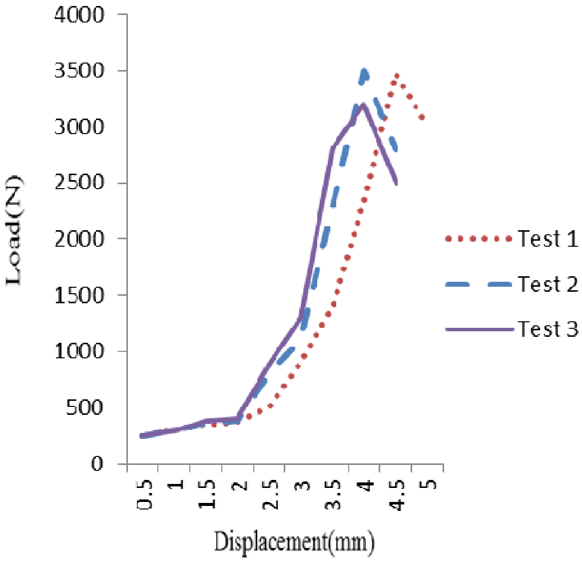

Fig. 15. Relationship between load and displacement of hybrid joint from tensile tests with acrylic type adhesive

Table 4. Results of the test on hybrid joint with acrylic adhesive

Result/specimen	H_{1a}	H_{2a}	H_{3a}	Average
Joint strength, P_{max}/A (MPa)	23.13	23.33	21.33	22.59

Table 5. Results of the test on hybrid joint with Rubber adhesive

Result/specimen	H_{1a}	H_{2a}	H_{3a}	Average
Joint strength, P_{max}/A (MPa)	13.933	16.9	14.9	15.244

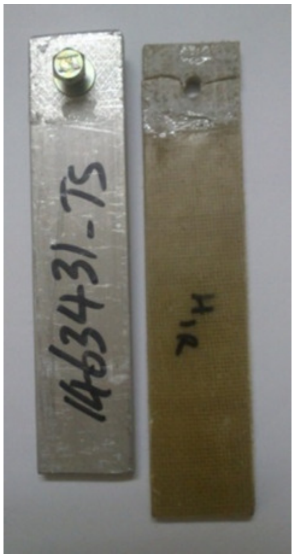

Fig. 16. Joint failed with hybrid joining (rubber adhesive)

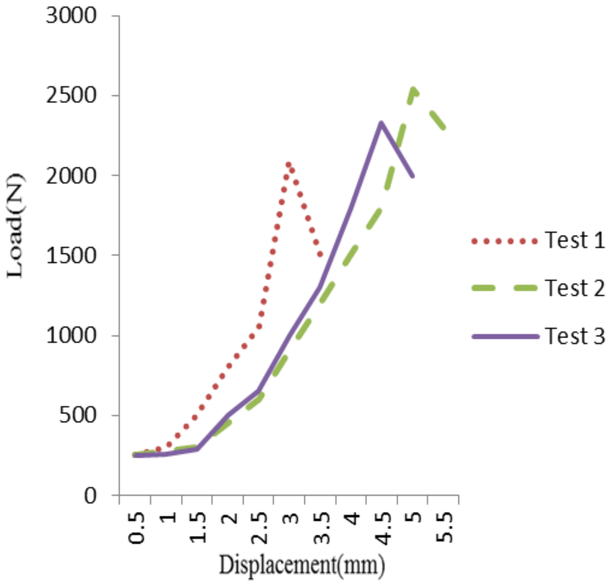

Fig. 17. Relationship between load and displacement of hybrid joint from tensile tests with Rubber type adhesive

be seen from Fig. 17 that initiation of failure in hybrid joints occurs at the adhesive layer and then the bolt takes up the load, after which failure of joint due to composite laminate breakage takes place.

5. Conclusion

Tests were conducted to evaluate the strength of the HFRP-to-aluminum single lap joints with two different adhesive materials: high modulus and low modulus types. Three types of joints were considered: adhesive bonding, bolt fastening and an adhesive-bolt hybrid joint. It was found that the strength of hybrid joints with high modulus adhesive is dominated by the strength of the adhesive itself. On the contrary, the strength of hybrid joints with low modulus adhesive was mainly affected by the bolt joint. In general, it should be noted that hybrid joining is effective when the mechanical fastening is stronger than the bonding. On the contrary, when the strength of the bolted joint is lower than the strength of the bonded joint, the bolt joining contributes little to the hybrid joint strength.

Acknowledgement

This work was supported by Three Bond adhesives, India, through provision of adhesives for the research.

References

1. Jin-Hwe Kweon, Jae-Woo Jung, Tae-Hwan Kim,

Jin-Ho Choi, and Dong-Hyun Kim, “Failure of carbon composite-to-aluminum joints with combined mechanical fastening and adhesive bonding,” Compos Struct, vol. 75, 2006, pp. 192–198.

2. P. P. Camanho, C. M. L. Tavares, R. de Oliveira, A. T. Marques, and A. J. M. Ferreira, “Increasing the efficiency of composite single-Simple mechanical model of a structural hybrid adhesive/riveted single lap joint,” Int J Adhes Adhes, vol. 27, 2007, pp. 263–267.

5. L. J. Hart-Smith, “Bonded-bolted composite joints,” J Aircr., vol. 22(11), 1985, pp. 993–1000,\.

6. Young-Hwan Lee, Do-Wan Lim, Jin-Ho Choi, Jin-Hwe Kweon, and Myung-Keun Yoon, “Failure load evaluation and prediction of hybrid composite double lap joints,” Compos Struct, vol. 92, 2010, pp. 2916–2926.

7. Haider Al-Zubaidy, Xiao-Ling Zhao, and Riadh Al-Mahaidi, “Dynamic bond strength between CFRP sheet and steel,” Compos Struct, 2012.

8. Tien-Cuong Nguyen, Y. Bai, Xiao-Ling Zhao, and Riadh Al-Mahaidi, “Effects of ultraviolet radiation and associated elevated temperature on mechanical performance of steel/CFRP double strap joints,” Compos Struct, vol. 94, 2012, pp. 3563–3573.

9. R. Sarfaraz, P. Anastasios, Vassilopoulos, and T. Keller, “Experimental investigation and modeling of mean load effect on fatigue behaviour of adhesively-bonded pultruded GFRP joints,” Int J Fatigue, vol. 44, 2012, pp. 245–252.

10. Haider Al-Zubaidy, Riadh Al-Mahaidi, and Xiao-Ling Zhao, “Experimental investigation of bond characteristics between CFRP fabrics and steel plate joints under impact tensile loads,” Compos Struct, vol. 94, 2012, pp. 510–518.

11. Kwang-Soo Kim, Jae-Seok Yoo, Yeong-Moo Yi, and Chun-Gon Kim, “Failure mode and strength of uni-directional composite single lap bonded joints with different bonding methods,” Compos Struct, vol. 72, 2006, pp. 477–485.

12. L. J. Hart-Smith, Mechanically fastened joints for advanced composites, phenomenological considerations and simple analysis. Plenum Press, 1980.

13. T. Ireman, “Three-dimensional stress analysis of bolted single-lap composite joints,” Compos Struct, vol. 43, 1998, pp. 195–216.

14. J. M. Whitney and R. J. Nuismer, “Stress fracture criteria for laminated composites containing stress concentrations,” J Compos shear lap joints using bonded inserts,” Compos Part B, vol. 36, 2005, pp. 372–383.

3. Maofeng Fu and P. K. Mallick, “Fatigue of hybrid (adhesive/bolted) joints in SRIM composites,” Int J Adhes, vol. 21, 2001, pp. 145–159.

4. S. Gomez, J. Onoro, and J. Pecharroman, “A Mater, vol. 8, 1974, pp. 253–265.

15. J. M. Whitney and R. J. Nuismer, “Uniaxial failure of composite laminated containing stress concentrations,” Fract. Mech. Compos., vol. 593, 1975, no. 117–142.

16. F. K. Chang and R. A. Scott, “Strength of mechanically fastened composite joints,” J Compos Mater, vol. 16, 1982, pp. 470–494.

17. F. K. Chang and R. A. Scott, “Failure of composite laminates containing pin loaded holes-method of solution,” J Compos Mater, vol. 18, 1984, pp. 255–278.

18. J. H. Choi and Y. J. Chun, “Failure load prediction of mechanically fastened composite joint,” J Compos Mater, vol. 37(24), 2003, pp. 2163–2177.

19. C. O. Ryu, J. H. Choi, and J. H. Kweon, “Failure load prediction of composite joints using linear analysis,” J Compos Mater, vol. 41(7), 2007, pp. 865–878.

20. G. Kelly, “Quasi-static strength and fatigue life of hybrid (bonded/bolted) composite single-lap joints,” Compos Struct, vol. 72, 2006, pp. 119–129.

21. F. Moroni, A. Pirondi, and F. Kleiner, “Experimental analysis and comparison of the strength of simple and hybrid structural joints,” Int J Adhes Adhes, vol. 30, 2010, pp. 367–379.

22. G. Kelly, “Load transfer in hybrid (bonded/bolted) composite single-lap joints,” Compos Struct, vol. 69, 2005, pp. 35–43.

23. R. Matsuzaki, M. Shibata, and A. Todoroki, “Improving performance of GFRP/aluminum single lap joints using bolted/co-cured hybrid method,” Compos Part A, vol. 39, 2008, pp. 154–163.

24. S. V Joshi, L. T. Drzal, A. K. Mohanty, and S. Arora, “Are natural fiber composites environmentally superior to glass fiber reinforced composites?,” Compos Part A, vol. 35, 2004, pp. 371–376.

25. A. Lundahl, R. Fangueiro, F. Soutinho, and F. Duarte, “Waste Fibre Reinforced Ecocomposites,” Mater Sci Forum, vol. 636–637, 2010, pp. 1415–1420.