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NON DESTRUCTIVE EVALUATION OF ADHESIVELY BONDED CARBON FIBER REINFORCED COMPOSITE LAP JOINTS WITH VARIED BOND QUALITY

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ABSTRACT. Structural adhesive bonding is widely used to execute assemblies in automobile and aerospace structures. The quality and reliability of these bonded joints must be ensured during service. In this context non destructive evaluation of these bonded structures play an important role. Evaluation of adhesively bonded composite single lap shear joints has been attempted through experimental approach. Series of tests, non-destructive as well as destructive were performed on different sets of carbon fiber reinforced polymer (CFRP) composite lap joint specimens with varied bond quality. Details of the experimental investigations carried out and the outcome are presented in this paper.

KEYWORDS: Adhesive Joints, Ultrasonic Testing, Bond Strength, Acoustic Emission Technique

PACS: 68.35.Np, 81.70.Cv, 87.15.Fh, 43.40.Le

INTRODUCTION

Adhesively bonded structural components provide many advantages over conventional mechanically fastened joints in terms of lower structural weight, improved damage tolerance, uniform stress distribution and smooth appearance. This can also avoid undesirable high stress zones as there are no cut outs for protruding fasteners such as bolts, screws, rivets or spot-welding marks [1]. Accordingly, adhesive bonding has found its way in structural applications in various fields of industry such as aerospace, electronics, shipping and automotive as also in construction, sports, health and packaging.

The adhesive bond ought to be one of the strongest aspects of the structure and most certainly should not be the life limiting factor provided that the joint has been correctly executed. The major factors determining the integrity of an adhesive bond are selection of the appropriate adhesive, joint design, preparation of the bonding surfaces, strict quality control in production and condition monitoring in service [2]. Most often these joints are subjected to aggressive environments in service like high temperature and humidity, leading to degradation of the adhesive layer in the joint. In addition, defects also creep in to the joint area during its fabrication [3]. With the increasing use of adhesive bonding, corresponding methods for evaluation and testing of the structural integrity and quality of bonded joints have been widely investigated and developed. Literatures show that work has been carried out previously to identify different types of defects in bonded joints and to characterize them using NDT methods [4-8]. However, a concerted effort to evaluate a composite bonded joint through NDE approach and to correlate the measurements to the bond strength is still on and the goal yet to be achieved. The work presented here is an attempt at non destructive evaluation of bonded joints with varied bond

quality through a series of experimental investigations with an end objective of obtaining a correlation between NDE measurements and the bond strength. Variation in the quality of adhesive layer was induced by adding different quantities of poly vinyl alcohol to the resin system used for the bonded joints. These joints were subjected to NDE using ultrasonic testing and digital x-ray radiography imaging to assess the degradation in bond quality. Standard destructive tests were performed to estimate the actual bond strength of the composite to composite lap joints. The experimental studies have yielded interesting and encouraging results in terms of correlation between the NDE measurements and the bond strength.

MATERIALS AND SAMPLES

The composite strips were cut out from the autoclave cured CFRP laminates fabricated using 18 layers of unidirectional carbon/epoxy prepreg CP150ns. Specimens were prepared according ASTM D 5868 standard for lap shear adhesion for fiber reinforced plastic bonding. These samples were obtained by bonding two composite strips together with an adhesive. The physical dimensions and the appearance of the single lap shear joint specimens are as shown in Fig. 1. One of the basic requirements for a good bond is the roughness and cleanliness of the adherend surfaces. The roughened surface creates better mechanical interlocking between adhesive and adherend. Surface preparation was carried out according to ASTM D 2093 standard for surface preparation of plastics, the adherend surfaces were sanded by using 100 grit size sandpaper, and subsequently cleaned with a cleansing agent. Sanding also removes any surface contaminants which may degrade the quality of the bond.

Bonding was accomplished using a two part epoxy adhesive system; Araldite AV 138M/Hardener HV 998. Adhesive to hardener weight ratio was maintained as 100:40 as per the recommendation of the manufacturer. An area of 25.4mm x 25.4mm was bonded and the bond line thickness was maintained at 0.76mm using a specially designed mold which also helps in maintaining a proper alignment of the CFRP adherend strips during the process of curing. The quality of adhesive was varied using different quantities of poly vinyl alcohol (PVA). This releasing agent does not stick to the epoxy and affects the polymerization process, leading to weak adhesion and cohesion. Five sets of specimen, six samples in each were prepared. The set without any PVA content was presumed as healthy denoted by the symbol 'H', the remaining samples were represented by the symbol 'P'. The PVA content was varied from 10% to 40% by total weight of the resin system with an increment of 10% in each set. The adhesive in the joint was cured at room temperature for 24 hours at atmospheric pressure.



FIGURE 1. CFRP single lap shear joints.

NON DESTRUCTIVE EVALUATION OF BONDED JOINTS

Different non-destructive testing techniques can be used to evaluate adhesive joints but ultrasonic methods have generally been regarded as potentially the most useful techniques for NDE of multilayered composite structures and adhesive joints [9-13]. The joints were tested using time domain ultrasonic testing methods like pulse echo and through transmission to evaluate their bond quality.

Ultrasonic Through Transmission Method

Inspection of the bonded region was performed by using two coaxially aligned 13 mm diameter, 5MHz focused probes with a focal length of 76mm in water. One of the probes (pulser) generate the ultrasonic energy which passes through the specimen, while the other receives (receiver) the transmitted energy across the bonded region. A rectangular pulse, 72ns wide with a pulse repetition frequency of 1000Hz and amplitude of 350 volts was used to excite the pulser, while the receiver had a gain of 8dB arrived at after trial and error method to obtain a clear transmitted signal. The entire arrangement of probes and the specimen was immersed in water which acts as a medium for acoustic wave propagation. The edges of the joints were completely sealed to prevent the ingress of water into the joint area. The amplitude variation of received ultrasonic signal over the bonded area was mapped to obtain a C-scan (Fig.2) which can give a measure of the adhesive quality in the bond line. The average amplitude for each image was computed using an image processing tool and a plot of normalized amplitude versus PVA percentage was plotted as shown in the Fig. 3. During the curing process the adhesive passes from a semi solid to solid state by the formation of intermolecular bonds, with subsequent creation of the branched chains of molecules which give the adhesive its strength. It is therefore logical to think that; the more developed the polymerization process; the smaller is the attenuation of the ultrasonic wave passing through what is now a more elastic medium with lower energy dispersion. Consequently the amount of ultrasonic energy passing through the healthy adhesive joint is much higher owing to less attenuation. Whereas the joints with added PVA suffer from hampered polymerization and leads to more attenuation of ultrasonic energy.

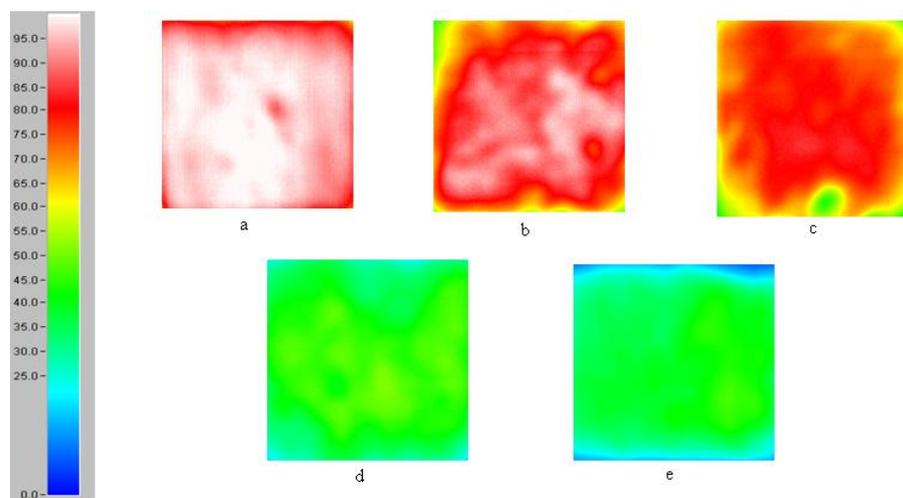


FIGURE 2. Ultrasonic through transmission images for a) Healthy specimen b) 10 % PVA (c) 20% PVA (d) 30%PVA (e) 40% PVA samples.

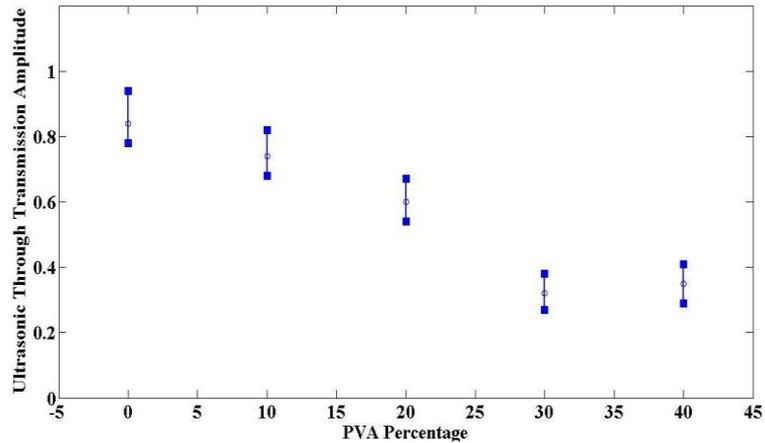


FIGURE 3. Variation of ultrasonic through transmission amplitude with different PVA percentages.

Ultrasonic Pulse Echo Method

Unlike through transmission technique, the pulse echo method uses a single transducer to transmit and receive the ultrasonic energy. The adhesive joint is kept normal to the 5 MHz focused transducer and the incident energy gets reflected from the top surface as well as from different interfaces as illustrated in Fig.4

Ultrasonic C scans were obtained for each sample at different interfaces by setting the gate at the corresponding echo, For instance C-scan image for the interface between the top adherend and the adhesive layer was obtained by setting the gate on first interface echo. The amplitude of reflection at the first interface for a healthy joint is lower than those joints having PVA due to better adhesion between the adhesive and the substrate. The amplitude variation for the first interface reflection was computed for different samples and plotted Fig. 5. The amplitude of reflected signal from an interface depends on the acoustic impedance mismatch between the two surfaces, as the amount of PVA is increased the mismatch becomes more predominant; as such higher amplitude reflections are seen. Contradicting this, the quality of adhesion in case of a healthy specimen is better leading to a low impedance mismatch; as such more energy gets transmitted into the bond line.

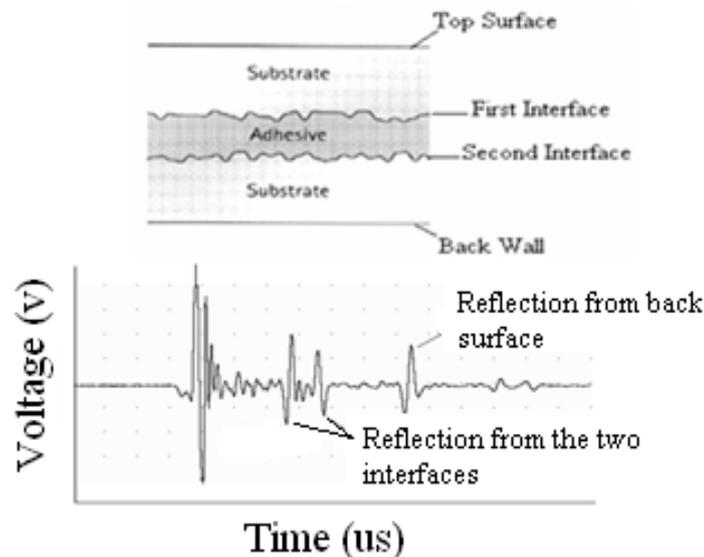


FIGURE 4. Interfaces in an adhesive joint and ultrasonic wave reflections from them.

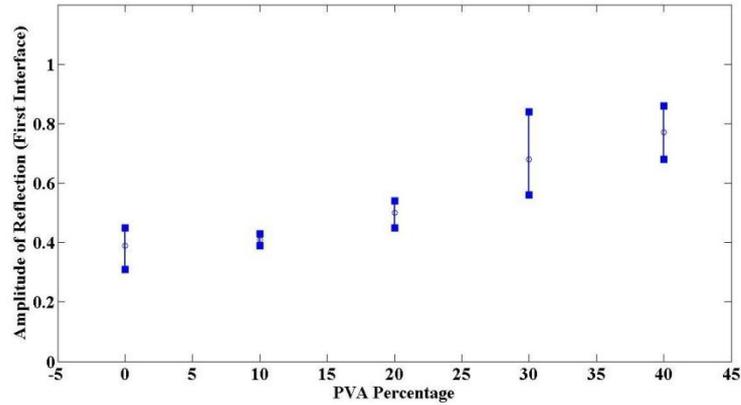


FIGURE 5. Variation of amplitude of reflected signal from the first interface for different samples.

The cumulative effect of all the interfaces can be realized by fixing the gate on back wall echo in the received pulse. It is evident that the amount of energy reaching the back wall depends on the reflection from the first interface, reflection from the second interface and the attenuation of energy by the two substrates and the adhesive in the bond line. Ultrasonic energy reaching the bottom surface of a healthy sample is more owing to weaker reflections and lower attenuation. The variation of amplitude of the back wall echo is plotted against the PVA percentage as shown in Fig. 6

LAMB WAVE INSPECTION

The adhesive joints were also evaluated using lamb wave techniques. To accomplish this two PZT disks were bonded on the either end of the sample as shown in Fig 7. One of the disks acts as actuator (transmitter) while the other receives it. Lamb waves at a frequency of 260 kHz (So mode) was made to propagate through the joint area and the same was received at the other end by the receiver. The received signals were further amplified and processed. Fig. 8 shows the plot of amplitude of the received signal on time axis. It can be seen that the amplitude of a healthy adhesive joint was higher compared to those with different percentages of PVA and the amplitude decreased with increasing percentage of PVA.

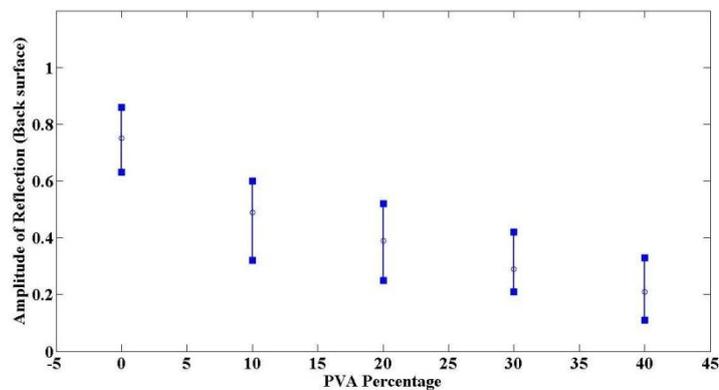


FIGURE 6. Variation of amplitude of reflected signal from the back surface for different samples.



FIGURE 7. CFRP adhesive joints with PZT disks bonded on the either sides for lamb wave inspection.

To validate the experimental results a two-dimensional finite element simulation of the experiment was carried out using ANSYS, a signal similar to that used in experiment was made to propagate through the model and received at the other end. The amplitude of the received pulse was plotted against time and a similar trend was observed (Fig. 9).

REAL TIME DIGITAL X- RAY RADIOGRAPHY

The lap joint CFRP specimens were exposed to low kV X-ray with the plane of the bonded area maintained normal to the X-ray beam. The amorphous silicon flat panel detector converts the transmitted X-rays to light in real time. The intensity of received X-ray energy at the detector depends on three factors - atomic number, density and thickness of the test object. Other two parameters being practically maintained constant, density of adhesive in a healthy sample is higher compared to that in a PVA sample, leading to more absorption of X-rays. Accordingly, the images for healthy samples appear darker. The average intensity of X-rays was plotted for different PVA samples (Fig. 10), it can be seen that the intensity increases with increasing amount of PVA

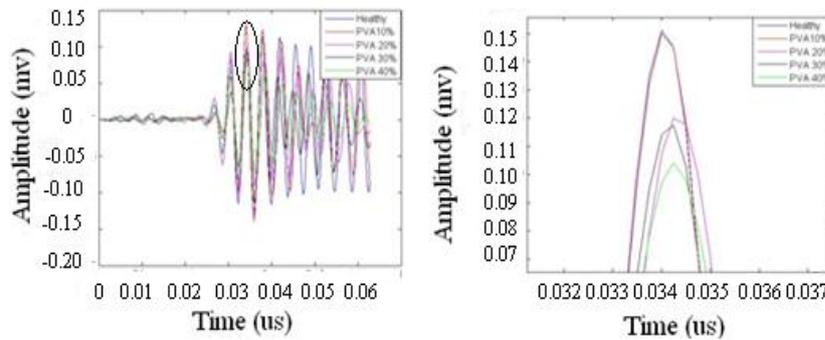


FIGURE 8. Experimental signal received and the magnified view of peaks.

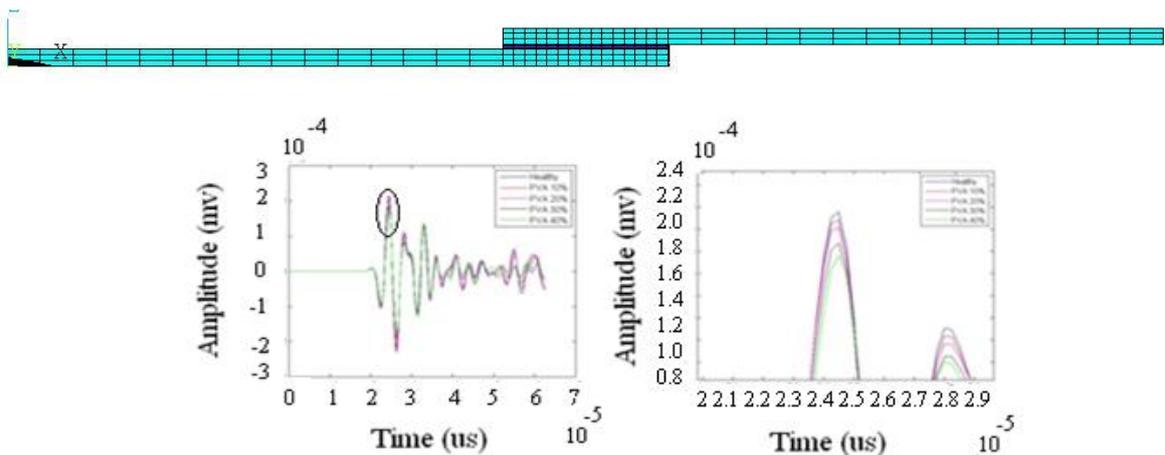


FIGURE 9. Received signal from 2D FEM simulation and the magnified view of peaks.

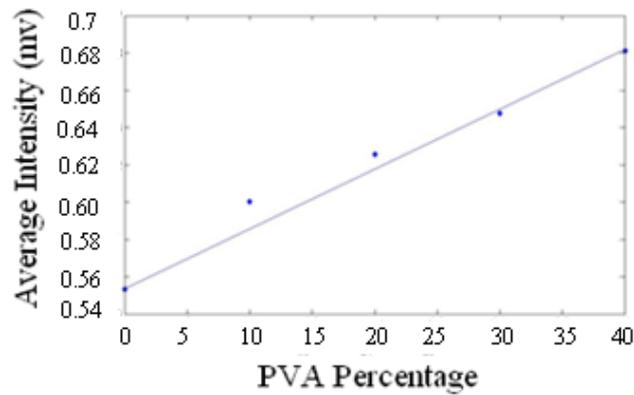


FIGURE 10. Variation of average intensity of X-rays penetrating the adhesive for different samples.

DETERMINATION OF BOND STRENGTH OF ADHESIVE JOINTS

The bonded CFRP samples were subjected to destructive test in an uni-axial loading machine by applying monotonically increasing load till the bonded joints gave away. The failure load for different samples were noted and plotted against the PVA percentage (Fig. 11). It can be seen from the figure that the shear strength of the adhesive joint decreases with increasing orders of PVA. The healthy samples had average shear strength of 10MPa while the joints having 40 percent PVA had an average strength of 5.5MPa. There is a severe degradation of strength for 40 percent PVA samples.

On-Line Acoustic Emission (AE) Monitoring

During the shear strength tests presented above, an acoustic emission sensor was surface mounted in the bonded area to record emissions generated from the joint area during failure. Acoustic Emissions (AE) are the stress waves generated during dynamic processes like fracture. The recorded acoustic emissions during the failure of bonded joints of different sets of samples were compared. Table 1 shows the details of the AE data collected, more number of hits can be seen in case of healthy adhesive joints compared to the samples with different percentages of PVA but emissions were observed much earlier for PVA samples giving an indication of early failure and low strength.

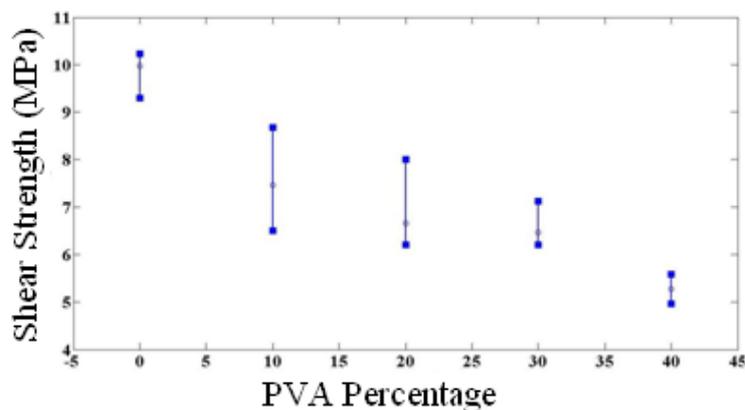


FIGURE 11. Variation of shear strength of adhesive joints for different PVA percentages.

TABLE 1. Acoustic emission data for different adhesive joints.

Sample	Number of Hits	Energy	% failure load at which emission was first observed
Healthy	360	19000	46%
PVA10%	200	7500	25%
PVA20%	160	5800	33%
PVA30%	140	5600	15%
PVA40%	125	5000	05%

Healthy samples also showed higher energy due to higher bond strength which implied that more energy is required to break a healthy sample. It can be seen from the table that Emissions were observed much earlier for PVA samples compared to healthy samples, while emissions were observed at 46% of the failure load for healthy adhesive joints, they were seen at as low as 5% of failure load for adhesive joints with 40% PVA.

CONCLUSION

NDE of single lap joints in composite to composite bonded joints has been attempted. Results from ultrasonic imaging show a clear indication of the bond quality in these specimens. Outcome of X-ray imaging though shows an encouraging trend, the results are not as distinct as UT. The lamb wave technique though has a high potential for many practical applications, further studies are required to arrive at a quantitative correlation. The acoustic emissions gave an early indication of failure for defective adhesive joints.

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