Damage Monitoring of Single Lap Bonded Composite Using Acoustic Emission Technique

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Abstract: - Adhesively bonded joints are currently of interest to the aerospace field due to the heavy reliance on bonded composite structures in new aircraft designs. In response, tools for joints analysis have been developed and examined. In this paper, the type of failure involved in single adhesive lap joints of composite has been experimentally investigated. An acoustic emission technique (AET) was used to monitor the pre and post aspects of damage growth in adhesive composite joint in terms of strain energy released rate and sound amplitude dissipated. Criticality of prior to failure was well assessed through acoustic waves monitoring method.

Key words: Composite, Lap joint, Acoustic emission technique, Damage monitoring.

1. Introduction
Most of the airframe structure consists of assemblies of simple elements, which include skins, stiffeners, frames and spars from the major components of wings, fuselage and empennage. An increasing use of bonded composite joints in these applications of aircraft structures in recent years has attracted the attention to assess the bond strength in different loading conditions. Also, it is necessary to identify the factor like stress concentration at bonding areas during operations of aircraft.

In many practical applications in aircraft design, it is virtually impossible to create an entire structure by a single piece because of the cost involvement, design complexity, and geometrical limitations. It can then solved by manufacturing small parts and assembling later as per needs of designer through bonding or jointing by mechanical method. One of these types is an adhesive bonded joint, where the elements are bonded using polymer adhesive. These type joints have substantial advantage due to their lightness, durability and maximum strength.

In this context, it is necessary to assess the load bearing capacity and failure mechanism associated with these types of joints. An acoustic emission technique, a non-destructive testing is almost viable for identification of failure in composite and currently practiced in aircraft industry. Basically, it is a naturally occurring phenomenon within material. It happens due to transient elastic waves, which results from a sudden strain energy release within material due to elastic deformation. In composites, the complexity of damage development starting from matrix cracking, the delamination, debonding, fibre failure and fiber pull out has extended to gross material failure. The failure depends on the composite character like the reinforcement of the matrix material, the ductility or brittle nature, type of reinforcement etc. Over all, this complex nature of composite failure can be monitored through the simple technique of AE, because, energy release during failure quite sufficient to be detected and
acoustic in nature. Thus, AET can be used as a failure-monitoring tool for studying damage sensitivity and material degradation.

The bonded joints are mostly used in critical areas of aero-structures; still it is lacked with perfect non-destructive test evaluation before failure. The certain literatures available relative to non-destructive detection during failure are very few in numbers. Starting Avila and Bueno1 have carried out an experimental and numerical investigation of adhesive joint. They found that 41% variation in load bearing capacity of single-lap and wavy-lap joint. Hanauska et al.2 has studied the double-lap joints with five stage bolts. Their analysis is based on total potential energy including strain energy of the bolts and related shear deformation theory. A few literatures (3-13) are highlighting about the analysis process of bonding strength, and few literatures are relevant to nondestructive analysis of composite bond failure.

In this paper, a study on bonded lap joints of bi-directional glass fiber reinforce composite has been carried out. The acoustic emission technique (AET) has been used for scanning the pre and post failure mechanism involved during tensile loading. The data’s are filtered by application of neural network technique and failure mechanism has been characterized by comparing the strain energy release rate.

1.1 Fundamentals of AE Technique

Basically, the failure of the material is initiated soon after the crack formation, and cracking is accompanied by emission of elastic waves, which propagate within bulk material. These waves can be received and recorded by transducers applied on the surface of the structural element [15]. The AE method, which is called Ring-Down Counting or Event-Counting, considers the number of waves beyond a certain threshold level and is widely used for defect analysis (Fig.1) [16,17]. As a first approximation, in fact, the cumulative number of counts \( N_T \) can be compared with the amount of energy released during the loading process, assuming that both quantities grow proportionally to the extent of damage. The quantity that characterizes the distribution of peak amplitude is the cumulative distribution \( N(v) \), which represents the number of recorded signals with peak amplitude larger than \( v \) (measured in Volt). Similar analyses are commonly carried out, at different scales, in seismology, where it was proved that a larger number of emissions correspond to smaller amplitudes, whereas larger amplitudes are restricted to few events. Therefore, \( N(v) \) can be expressed, with a good approximation, through the constants \( a \) and \( c \), according to the Gutenberg-Richter power-law [14]:

\[
\log N(v) = c - av
\]

2. Experimental Method

2.1 Specimen preparation

An extensive experimental program has been carried out to study the damage detection in single lap jointed bi-directional glass fiber reinforced composite specimens by acoustic emission technique at tensile loading. The specimens were machined from glass fiber epoxy laminated plates manufactured by hand layup technique. A bi-directional woven glass fabric was used together with epoxy resin (Dobeckof 520F and Hardner 758 with 100:27 parts by weight) for fabrication of composite plates. The plate was 2.8mm thickness with nine layers of bi-directional fiber laminate and 55% fiber volume fraction. The fabricated laminates are processed through room temperature and high temperature curing. After verification of hardness testing and homogeneity checking of plate, the tensile tensing specimens were cut from the plate as per ASTM standard D-3039. The specimen dimensions are kept as 228mm x 25mm x 2.8mm for tensile property study. The second group of specimens was prepared with adhesive bonded lap joints. Two sections with 129mm length, 25mm width and 2.8mm thick were cut. A hand abrasion technique was used for surface preparation before bonding. The epoxy has been used as bonding reagent. The specimens were cured in room temperature for 24 hrs. The detailed configurations of fabricated specimen are shown in fig2.

2.2 Tensile Test

Tensile test was conducted using a universal testing machine with a load capacity of 10kN, and as per ASTM Standard D-3039. The machine is hydraulic controlled and electrical configured to measure the data during the testing. The specimens were mounted in the clamp loading fixtures at one end and clamped within the grips of the testing machine at the opposite end. The tests were run in displacement control at a rate of 1mm/min. Loading was stopped after the first significant load drop. Selected
specimens were instrumented with unidirectional strain gauges to determine the strain field around the bonding points. Also, the strain in the laminate was measured using a strain gauge extensometer with a gauge length of 100mm. The tensile test results are presented in table 1 and fig. 3.

2.3 AE Calibration

Before applying the full scale acoustic Emission Technique (AET) for studying the failure mechanism, the acoustic velocity and attenuation of acoustic velocity has been determined. For that, the acoustic emission rate was studied in an aluminium plate and same method was implemented in case of bidirectional glass fiber reinforced plate. Attachment of sensor for studying velocity wave during acoustic emission is shown in photograph2. The velocity has been calculated using simple formulation

\[ V = \frac{\text{Distance between sensors}}{(t_2 - t_1)} \]

Where \( t_1 \) and \( t_2 \) are time interval of traveled acoustic wave from transducer to the receiver. The aluminium plate has been accepted as a reference material for transmission of acoustic wave. The velocity data obtained for aluminum and bi-directional glass fiber reinforced composite plates are presented in table 2 and 3. Also, an attenuation of signal waves have been recorded for both the plates under similar condition and presented in figures 4a and 4b.

2.4 AE Application during Tensile Test

A block diagram of acoustic emission setup is shown in fig. 5. Piezoelectric transducer having capacity of 2 MHz recorded the transient energy generated during tensile loading. These piezoelectric transducers were fixed at two end points of gauge length by the help of couplent. The signal waves were moved in form of spherical waves. To modify the strength of the signal waves, a preamplifier with filter was attached in between source and recorder. Though these pressure waves had undergone through distortion and attenuation due to material continuity, but density and characteristics of the source were amplified and filtered to data acquisition system for analysis. Special precautions were taken to incorporate with initial severity, local microstructure and attenuated version of original signal waves in distorted form during filtering and magnification. Also, sizeable steps like neural network programming were adopted to make the signal wave free from noise.

3. Results and Discussion

All the specimens were tested under tensile loading conditions, and the data are analyzed under the two main headings, i.e,

1. Tensile testing and mechanical properties evaluation, and
2. AE testing for failure analysis.

All specimens fabricated under standard laboratory conditions. Special precautions have been taken for fabrication of joints between two sections. Starting from surface preparation to adhesive bonding, all specimens have gone through water immersed ultrasonic inspection for identification of any crack or flaw development during fabrication.

3.1 Tensile testing and mechanical properties evaluation

Tensile tests have been carried out till the specimens failed at fixture. Figure 3 illustrates typical load displacement curve for specimen failing at point of adhesion. It has been observed that there is a constant rate of deflection till the failure approach. At point of failure of the bond, there was immediate load degradation. For higher loads, a continuous reduction in stiffness was noted as damage developed at the bearing surface of adhesive bonded lap joint. The load continued to increase until the maximum load was attained, and a minor drop in the load characterized failure. This may be attributed to critical strength bearing capacity of adhesive, which is mismatching with strength of joining samples. The failure point of bonding was shown in photograph 2. It has been found that the lap joint failure was occurred either by peeling effect or adhesive breaking. Details of tensile test results of single lap glass fiber bidirectional composite are shown in table.1.

The load displacement behavior was also found to be dependent on the geometry of the test specimen and the resulting failure mode. The specimens of bi-directional glass fiber reinforced composite with single lap joints have shown two types of failure during loading under tensile condition.
Some specimens have failed in adherent point due to high peel stress at bonding juncture. It has been observed that first three layers peeled off from specimen surface and caused the failure. Another type of failure is related to brittle nature of bulk adhesive, and the specimen has failed like brittle material. The cause of adhesive failure is attributed to micro cracking development in adhesive that has further extended to final failure. The adhesive material might nucleate to micro cracks during joining and during thermal curing process. These micro cracks are further aggravated into macro size as external tensile load is applied over specimen and causing complete failure of adhesive.

3.2 AE testing for failure analysis

The acoustic emission study has been carried out for identifying damage initiation, crack propagation and discriminate the difference between damage phenomenon and spatial location of damage. All these observations are studied during application of tensile load over the specimens. The sensors were put at 100mm distance for monitoring the damage location, and kept under 40db threshold condition. Including to AE data recorded there was some unwanted data’s has been input in form of noise, and these were due to the grip noise and signal echo. So, to catch hold the accurate data of time load factor, the filtration of AE signals was processed through neural network programme, which was run in MATLAB platform. Figure 6a to 8d illustrate the typical data obtained through acoustic emission technique (AET) under tensile loading.

In fig. 6a to 6d the load vs. amplitude has been plotted. It has been observed that the concentration of amplitude value is maximum at the failure load. Also, it has been observed that the extension of amplitude density is slightly higher for peeling failures in comparison to adhesive failure. Again, these failure mechanisms are monitored in form of sign waves and compared with linear velocity as shown in figure 8a to 8d. It has been found that the bidirectional tolerance in load carrying capacity of glass fiber reinforced composite bonded adhesive lap joint is started varying after 50% of its original UTS load and extended to peel type failure as shown in figure 7a and 7b, whereas adhesive failure has been started quite before of its 50% loading as shown in fig 7c and 7d. So it implies that the adhesive failure starts prior to peel type of failure.

Figure 8a and 8b illustrate the distribution of acoustic wave density in specimen during peel type of failure. When the damage location has been monitored in terms amplitude density from the center of bi-directional glass fiber/ epoxy adhesive lap joint, it has been observed that there is uniform stress concentration for peel type of failure, and distributed in both direction of entire adhesive length. In adhesive type of failure, a non-uniform stress concentration has been noted at the point of fracture. Maximum failure stress is found at centre point and gradually reduced in both direction of entire adhesive length. This can be well marked from fig 8c and 8d.

So, it has been observed that the energy has been elevated with the amplitude at this region peeling failure, whereas the energy level is low in case of adhesive failure. In other since, an higher strain is required for feel type of failure in comparison to adhesive type. It may be related to involvement of fiber, fracture toughness strength of material, and delamination nature of the composite.

Table 1: Tensile test results of bi-directional glass fibre reinforced composite adhesive lap joint.

| No. | Property                      | Value     |
|-----|-------------------------------|-----------|
| 1   | Ultimate Tensile Strength at break | 4.320 KN  |
| 2   | Displacement at maximum Load  | 2.420 mm  |
| 3   | Maximum Displacement          | 2.710 mm  |
| 4   | Area                          | 150 mm²   |
| 5   | Ultimate Stress               | 0.029 KN/mm² |
| 6   | Elongation                    | 5.420 %   |

Table 2.a Wave velocity study in Aluminum plate

| Time  | Ch | Rise | Counts | Energy | Duration | Amp |
|-------|----|------|--------|--------|----------|-----|
| (Sec) |    | (Sec)|        | (J)    | (Sec)    | (dB)|
Table 2.b Wave velocity studies in glass/epoxy plate.

| Time (sec) | Ch | Rise (sec) | Count | Energy (j) | duration (sec) | Amp (dB) |
|-----------|----|------------|-------|------------|----------------|---------|
| 27.7924670 | 1  | 12         | 67    | 249        | 551            | 97      |
| 27.7925070 | 3  | 73         | 39    | 32         | 349            | 77      |
| 27.7925135 | 2  | 67         | 37    | 19         | 282            | 73      |
| 428.8162708 | 2  | 11         | 57    | 331        | 492            | 98      |
| 428.8163160 | 3  | 65         | 48    | 32         | 386            | 74      |
| 428.8163260 | 1  | 118        | 43    | 32         | 342            | 71      |
| 758.1767307 | 3  | 12         | 65    | 258        | 467            | 97      |
| 758.1767717 | 1  | 70         | 45    | 30         | 388            | 73      |

*Calculated wave velocity in glass/epoxy composite plate = $3.1 \times 10^6$ m/s (aprox.)

Figure 1: Detected signals by AE Technique

Figure 2: Tensile Test Specimen of bidirectional glass fibre reinforced composite with adhesive lap joint

Figure 3: Load vs. Displacement curve of bidirectional glass epoxy composite with adhesive lap joint

Figure 4a: Attenuation of Signal wave during motion with Aluminum Plate
Figure 4b: Attenuation of Acoustic wave velocity in bi-directional glass/epoxy Composite plate.

Figure 5: The complete Layout AE Testing Set-up.

Figure 6a: Amplitude data at different tensile load on bi-directional Glass/Epoxy composite with adhesive lap joint. (Peel type of failure)

Figure 6b: Amplitude data at different tensile load on bi-directional Glass/Epoxy composite with adhesive lap joint. (Peel type of failure)

Figure 6c: Amplitude data at different tensile load on bi-directional Glass/Epoxy composite with adhesive lap joint. (Adhesive type of Failure)

Figure 6d: Amplitude data at different tensile load on bi-directional Glass/Epoxy composite with adhesive lap joint. (Adhesive type of failure)

Figure 7a: Energy data at different tensile load on bi-directional Glass/Epoxy composite with adhesive lap joint

Figure 7b: Energy data at different tensile load on bi-directional Glass/Epoxy composite with adhesive lap joint.
**Figure 7c:** Energy data at different tensile load on bi-directional Glass/Epoxy composite with adhesive lap joint.

**Figure 7d:** Energy data at different tensile load on bi-directional Glass/Epoxy composite with adhesive lap joint.

**Figure 8a:** Amplitude density distribution on both side of centre point at ultimate tensile load on bi-directional glass/epoxy composite with adhesive lap joint. (Peel failure)

**Figure 8b:** Amplitude density distribution on both side of centre point at ultimate tensile load on bi-directional glass/epoxy composite with adhesive lap joint. (Peel failure)

**Figure 8c:** Amplitude density distribution on both side of centre point at ultimate tensile load on bi-directional glass/epoxy composite with adhesive lap joint. (Adhesive failure)

**Figure 8d:** Amplitude density distribution on both side of centre point at ultimate tensile load on bi-directional glass/epoxy composite with adhesive lap joint. (Adhesive failure)
4. Conclusion

Based on above experimental observations, the following conclusions are drawn:

1. Acoustic emission waves have less dense in adhesive failed specimens and these waves have high density during peeling type of failed specimen.
2. Adhesive type of failure started much before compared to peeling type of failure.
3. It can be early forecasted about type of failure through acoustic Emission Technique (AET) application.
4. Also the area of stress concentration can be well monitored prior to failure of joints.
5. A smart character can be developed through AET study.

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