CHAPTER 3

FABRICATION AND TESTING METHODS

3.1 FABRICATION OF COMPOSITE LAMINATES

3.1.1 Hand Lay-Up Method

The major advantage of hand lay-up manufacturing process is its great flexibility, meaning that it suits most common mould sizes and complex shapes. Although tooling is normally expensive, it can be reused for several runs and the actual cost of the raw materials make this process economically feasible. The simplest manufacturing process (Figure 3.1) adopted involved laying down unidirectional glass roving over a polished mould surface previously treated with a releasing agent (wax): after this, a liquid thermosetting resin is worked into the reinforcement manually with a brush or roller. The fiber is placed over the resin (LY 556 with hardener HY 951) and the resin is squeezed to the top surface by a stippling action using resin-wetted brush. After the first layer is laid up, subsequent layers are laid up in a similar manner. This procedure was repeated till the required thickness (3 mm) has been built up.

Figure 3.1 Hand lay-up manufacturing process
3.1.2 Compression Molding Process

Fabricated laminated composites were then placed in the compression molding for curing. Voids are introduced during the manufacture of composite laminates. The compression molding is used to prevent the voids of specimen in bonded region. The top plate of the compression molding machine is set to a pressure of 100 KPa at an ambient temperature for 24 hours which is used to uniformly apply the pressure in the symmetric ply \([0^\circ/0^\circ]_3\) laminate; whereby voids can be prevented from accumulating in the symmetric ply \([0^\circ/0^\circ]_3\) laminate. If the specimen is cured properly, the strength of the laminates increases.

3.2 SPECIMEN PREPARATION FOR MECHANICAL CHARACTERIZATION STUDIES

3.2.1 Preparation of Tensile and Flexural Specimens from Composite Laminates

GFRP and BFRP laminates of size 300 × 300 mm² are fabricated with required layers of unidirectional glass fibers and unidirectional basalt fibers with LY556 epoxy matrix as the binding medium and cured at ambient temperature for 24 hours as shown in Figure 3.2. After that, the composite laminates were cut according to American society for testing and materials (ASTM) standards and the size of test specimens was verified.

Figure 3.2 Composite laminate: (a) glass fiber reinforced plastics (b) basalt fiber reinforced plastics
ASTM D638-01 standard tensile specimens of size 165 × 18 × 3 mm³, ASTM D3039 standard tensile specimens of size 280 × 18 × 3 mm³ and ASTM D790 standard flexural test specimens of size 130 × 18 × 3 mm³ as shown in Figures 3.3, 3.4 and 3.5, respectively, were cut from the fabricated laminates using a water jet cutting machine to avoid machining defects and to maintain good surface finish. Aluminum tabs of size 25 mm × 25 mm × 3 mm were used in the specimen to reduce the noise produced during testing and prevent damaging the extremities of the laminates with possible unexpected failures external to the grip length.

Figure 3.3 ASTM D638-01 and D3039 standard tensile specimens-GFRP

Figure 3.4 ASTM D3039 standard tensile specimen-BFRP

Figure 3.5 ASTM D790 standard flexural test specimens: (a) GFRP (b) BFRP
3. 2.2 Tension and Flexural Testing Setup

The ASTM standard specimens were cut from the laminates and tested using an INSTRON 3367 universal testing machine (UTM) along with AE monitoring. Figures 3.6(a) and 3.6(b) show the photographs of tensile and flexural test setup.

![Tensile test setup](image1)

![Flexural test setup](image2)

Figure 3.6 (a) Tensile test setup (b) flexural test setup

3.2.3 Impact Test Setup

The specimens are fabricated according to ASTM D5628 standard and were subjected to drop impact at three different temperatures using a fractovis drop impact tower (Figure 3.7). The parameters such as impact energy and velocity are recorded. The specimens were impacted from heights of 250 mm with corresponding energy level.

- Impact specimen dimensions = 60mm × 60mm × 3 mm
- Impact energy = 5 J
- Impact velocity = 2 m/s
- Impact height = 250 mm
- Impacted at different temperature = Ambient/50°C/75°C
3.2.4 Double Cantilever Beam (DCB) Test Setup

GFRP laminates are fabricated with E-glass fiber with standard epoxy as the binding medium containing a Teflon tape in the mid-plane using hand lay-up technique and cured at ambient temperature for 24 hours. Per ASTM D5528, DCB specimens are cut from GFRP laminates as shown in Figure 3.8(b). This Teflon tape serves as an initiator for delamination. The thickness of the Teflon insert is 13µm and 35 mm in width. It should be free from surface wrinkling. ASTM D5528 standard DCB specimens of size 130 mm × 25 mm × 5 mm are cut from the fabricated laminates. Care was taken to ensure that the non-adhesive insert (Teflon) is at one end of the specimen. The bonding surface of the specimen and the loading block or piano hinge are grit-blasted or scrubbed with sandpaper and then cleaned with volatile solvents like acetone or methylethylketone (MEK) to remove any contaminants. The hinges are adhesive-bonded using araldite to keep the loading tabs parallel to the specimen. Figures 3.8(a), 3.8(b) and 3.8(c) show the photographs of DCB specimen with piano hinges.
3.3 SPECIMEN PREPARATION FOR SINGLE LAP JOINTS AND DOUBLE LAP JOINTS

3.3.1 Bonded Joints

ASTM D5868-01 standard tensile specimens of size 100 mm × 25.4 mm × 3 mm were cut from the fabricated laminates. The specimen adherent surfaces cleaned with acetone were bonded to form single and double lap joints as shown in Figures 3.9–3.14. Single and double lap joints with adhesive thickness of 0.2 mm, adherend thickness of 3 mm and overlap length of 25.4 mm were prepared. The adhesive thickness was controlled using four steel needles on the four corners of overlap area and a specially designed fixture, except the riveted joints. The adhesive was applied in the overlap area and was cured in atmospheric air conditions. The minimum weight, normal to the lap area, was placed on the substrate to maintain a uniform pressure during curing stage. The joining areas of few specimens were examined using a low-power magnifying lens (Figure 3.15). After that, they were tested for tensile breaking strength. The lap joints of composite laminate were relatively smooth. All the specimens used in the testing are with aluminum tabs.
Figure 3.9 Photographs of single lap bonded joints: (a) GFRP (b) BFRP

Figure 3.10 Photographs of double lap bonded joints: (a) GFRP (b) BFRP

Figure 3.11 Photographs of single lap joints and double lap pure resin bonded joints
Figure 3.12 Photographs of single lap bonded joints: (a) single layer specimen (0.8 mm) (b) double layer specimen (2 mm)

Figure 3.13 Photograph of double lap bonded joints: (a) Single layer specimen (b) double layer specimen

Figure 3.14 Photographs of the lap joints: (a) front view (b) top view
3.3.2 Riveted Joints

Aluminum rivets were used quite successfully on laminates up to 4 mm thick and also were a tight fit, called interference fit. The choice lies between solid and hollow types and whichever is chosen, care must be taken to minimize the damage to the laminate during hole-drilling and closing of rivet as shown in Figures 3.16 and 3.17. The rivet holes are made using a drilling machine with a diameter of 2.5 mm, then the rivet was inserted into the hole and a hammer tool was used to shape the rivet head. The surfaces of the aluminum rivet are polished and are wiped off with acetone.

Figure 3.15 (a) INSTRON 3367 Universal Testing Machine with AE setup (b) specimen with AE sensor using magnifying lens

Figure 3.16 Photographs of single lap riveted joints: (a) GFRP (b) BFRP
3.3.3 Hybrid Joints

The rivet was placed adjacent to the rivet hole and at the overlap ends. Hybrid joint is similar to the riveted joint, except that a thin layer of adhesive bond exists between the laminates. In the manufacturing of hybrid joints (bonded–riveted), rivets are inserted in the composite laminate after the curing process. This rivet inserting process utilizes the space between centre points of the overlap area of composite laminates and the fibers are continuous even around the rivet holes. In addition, the rivets are covered with adhesive (epoxy-filled) after the curing process; this method has better sealing performance and corrosion resistance. Thus, the method is suitable for joints in structural applications (Sadowski et al 2012). The single and double lap joints with hybrid joints were made from the cut specimens as shown in Figures 3.18 and 3.19.
3.4 AE MONITORING

3.4.1 A Generic AE Setup

A schematic arrangement of an AE system and its detection procedure is represented in Figure 3.20. The process chain basically consists of the following stages, which take place in a very short time, so that all stages can be perceived as simultaneous for testing purposes.
An 8-channel AE system (supplied by Physical Acoustics Corporation [PAC], Princeton, NJ, United States) was used for this study. AE measurements were performed using two PAC wideband (WD) sensors (dimensions of 18 mm × 17 mm) with a frequency range of 100–1000 kHz. The sensors are positioned with high-vacuum silicone grease as a coupling agent. With two piezoelectric transducers, the sources of AE signals were located in the test specimen and the background noise was eliminated. The ambient noise was filtered using a threshold of 45 dB_{AE}. Signals detected using the transducers were passed through preamplifiers of 40 dB_{AE} gain with a bandwidth of 10 kHz–2 MHz. After mounting the transducer, AE signals were generated repeatedly using a pencil lead break procedure for checking the sensor coupling (ASTM E976, Nielsen 1980). Wave velocity and attenuation studies were performed on the laminates. AE hardware settings are as follows: peak definition time (PDT) = 32 µs, hit definition time (HDT) = 160 µs and hit lockout time (HLT) = 300 µs. The pre-trigger value and the hit length values are estimated as 26 µs and 4 K, respectively.

3.4.2 Pencil Lead Break Test

Among the characteristics of the AE instrumentation system, sensitivity needs to be considered. Of all the parameters and components contributing to the sensitivity, the piezoelectric sensor is the one subjected to variation. This variation can be a result of damage or aging, or there can be variations between nominally identical sensors (ASTM E1781). To detect such variations, it is desirable to have a method for measuring the response of a sensor to an acoustic wave. Specific reasons for checking sensors include: (1) checking the stability of its response with time and (2) checking the sensor for possible damage after accident or abuse. A recommended method to check the sensitivity of the sensor is the response of the system to pencil lead break
test (EN 13477 NDT, ASTM E976). In this test, a repeatable acoustic wave can be generated by carefully breaking a pencil lead against the test panel. When the lead breaks, there is a sudden release of stress on the surface of the panel where the lead is touching. This stress release generates an acoustic wave. The Hsu (NDT.net, 2007) pencil source uses a mechanical pencil and the Nielsen shoe can be used to aid in breaking the lead consistently. The pencil lead break test was performed to obtain the actual AE source for this research. The test scheme is shown in Figure 3.21 (Nielsen 1980). This test consists of breaking a 0.5 mm diameter (2H) pencil lead approximately 3 mm (± 0.5 mm) from its tip by pressing it against the surface of the piece. This generates an intense acoustic signal, quite similar to a natural AE source that the sensors detect as a strong burst. The purpose of this test is two-fold. First, it ensures that the transducers are in good acoustic contact with the part being monitored. Generally, the lead breaks should register amplitudes of at least 80 dB$_{AE}$ for a reference voltage of 1µV and a total system gain of 80 dB. The recorded AE signals amplitude from a Hsu-Nielsen source depend on the distance between the location where the pencil lead break is applied and the sensor, on the coupling of the sensor to the test piece (sensor mounting), on the test piece material (attenuation properties) and on the coupling agent used. The dB scale used for AE signals is different from the conventional dB scale in the electronics (e.g., amplification by 80 dB). The largest voltage peak in the AE signal waveform customarily expressed in decibels relative to 1 µV at the preamplifier input. For this case, 0 dB corresponds to a 100 µV peak at an output of 40 dB preamplifier. For example, the amplitude distribution covers the range 0–80 dB$_{AE}$ (0 dB corresponds to 1 µV at the transducer output). Second, it checks the accuracy of the source location setup. This purpose involves indirectly determining the actual value of the acoustic wave speed for the object being monitored.
3.5 INPUT PARAMETERS TO AE WIN SOFTWARE

3.5.1 Wave Velocity

The Hsu–Nielsen pencil lead break procedure method is used to calculate the wave velocity as shown in Figure 3.22. The pencil tip is broken at a known distance from the sensors and the corresponding time difference at which the signal is captured by the two sensors is noted down. The acquisition system is calibrated before each test using a pencil lead break procedure to estimate the wave velocity and the attenuation of the acoustic waves (Marec et al 2008). For this study, the two sensors were located on the specimens at a mutual distance of 40 mm centre-to-centre, and also trace the waves to a specific zone for localization of the detected signals. The location method used in this study is linear location and the wave propagation in two sides of the joint for lap bonded, riveted and hybrid joints was taken care by the estimation of the wave velocities which are different for the three cases. Attenuation effects are not predominant as the sensors were placed close to the lap region as shown in Figure 1.8(b). Wave dispersion is a serious concern only in large structures where geometric discontinuity, scattering mechanism at structural boundaries affects the frequency content of an AE signal. Wave dispersion effects are not predominant in coupon-level testing. The influence of dispersive signal propagation and attenuation are considered in the larger structures (Sause & Horn 2010a). The average wave velocity has been
measured from GFRP and BFRP laminates as shown in Table 3.1. The timing parameters in the hardware settings are calculated for different lap joints. The standard deviation values of wave velocity are plotted for different lap joints as shown in Figure 3.23. The HDT is calculated by trial and error method. Proper setting of the HDT ensures that each signal from the structure is reported as one signal only.

![Image](image.png)

**Figure 3.22 Wave velocity using pencil lead break test**

**Table 3.1 Wave velocity for composite lap joints**

<table>
<thead>
<tr>
<th>Material</th>
<th>Types</th>
<th>HDT (µs)</th>
<th>PDT (µs)</th>
<th>HLT (µs)</th>
<th>Joints</th>
<th>Wave velocity m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass fiber/epoxy laminate</td>
<td>Single lap joints</td>
<td>160</td>
<td>32</td>
<td>300</td>
<td>Bonded</td>
<td>3212</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Riveted</td>
<td>3375</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Hybrid</td>
<td>3489</td>
</tr>
<tr>
<td></td>
<td>Double lap joints</td>
<td>160</td>
<td>32</td>
<td>300</td>
<td>Bonded</td>
<td>3278</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Riveted</td>
<td>3389</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Hybrid</td>
<td>3636</td>
</tr>
<tr>
<td>Basalt fiber/epoxy laminate</td>
<td>Single lap joints</td>
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<td>32</td>
<td>300</td>
<td>Bonded</td>
<td>2596</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Riveted</td>
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<td></td>
<td></td>
<td></td>
<td>Hybrid</td>
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<td>Double lap joints</td>
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<td>32</td>
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<td>Bonded</td>
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</tr>
</tbody>
</table>
Figure 3.23  Standard deviation values of wave velocity for different single lap joints (SLJ)

3.5.2  Hit Definition Time (HDT)

The function of HDT is to enable the system to determine the end of the hit, close-out the measurement processes and store the measured attributes of the signal. Proper setting of HDT ensures that the AE signal from the structure is reported as the one and only signal. The recommended range for the composites is 100–200 µs (SAMOS AE user manual, Rev: 2).

3.5.3  Hit Lockout Time (HLT)

The function of HLT is to inhibit the measurement of reflections and late-arriving parts of the AE signal. With proper settings of the HLT, spurious measurements during the signal decay are avoided and data-acquisition speed can be increased.

3.5.4  Peak Definition Time (PDT)

The function of PDT is to enable determination of the time of true peak of the AE waveform. A proper setting of the PDT ensures correct identification of the signal peak from rise time and peak amplitude
measurements. The formula yields a range of PDT between 20 and 50 µs (using 80 mm sensor distance and maximum and minimum values of 3600 m/s and 2400 m/s measured wave velocity, respectively). PDT is calculated using the following relation (3.1).

\[
PDT = \frac{\text{Distance between the sensors}}{\text{Wave Velocity}}
\]  

(3.1)

3.5.5 Sample Rate

This is the rate at which the data-acquisition board samples the waveforms on a per second basis. A sample rate of 1 MSPS (mega sample per second) means that one waveform sample is taken every µs.

3.5.6 Pre-Trigger

This value tells the software how long to record (in µs) before the trigger point (the point at which the threshold is exceeded). The user may enter a value in the pre-trigger edit box. The minimum allowable pre-trigger value is zero. The maximum allowable pre-trigger value is calculated by dividing the hit length by the sample rate in MHz.

3.5.7 Hit Length

This determines the size of a waveform message. The available hit length is in the range of (1–4 k). At a 4 MSPS sampling rate, a hit length of 1k will allow up to 256 µs of data, a hit length of 2 k will allow 512 µs of data (2 × 256) and so on.

3.6 SUMMARY OF EXPERIMENTAL PROCEDURE

Fabrication of composite laminate and specimen preparation per ASTM standards for given loading conditions is also discussed in this chapter. The tensile test equipment was described; one 30 kN load cell Instron 3367
universal testing machine was used for all the tests. Drop impact test was conducted using fractovis drop impact tower.

All the equipments to conduct an AE investigation have been described along with the terminology of the standard data processing associated with AE. The wideband sensors used in this research and their technical specifications are also presented. The simplest way of analyzing AE results is by counting the number of hits that are detected by the sensors. The number of hits acquired per unit of time is generally called the AE activity. The total number of hits acquired during a certain period of time is called the cumulative number of AE hits. An activity analysis in its basic form is used to study the initiation and propagation of damage in composite laminates. A common way of calibrating an AE test to ensure some repeatability is described in detail. There are also several other parameters that need to be defined prior to experimentation to make the best of the recording system and obtain sensible data. The procedure involved in the selection of these AE hardware parameters for different materials are presented in this chapter. All the input parameters for the experimentation purpose are also presented in this chapter.