CHAPTER 1

INTRODUCTION

1.1 HISTORY OF ACOUSTIC EMISSION RESEARCH

Acoustic Emission (AE) and microseismic activity are normally occurring phenomena which man has observed from early times. Although it is not known exactly when the first acoustic emissions were heard, fracture processes such as the snapping of twigs, the cracking of rocks, the breaking of trees, and the breaking of bones were no doubt among the earliest. But the first non-destructive application of acoustic emission can be attributed to the ancient potters. Potters observed the sound of the cracking of clay vessels cooling too quickly in the kiln. Through these audible acoustic emissions, the potter knew that his creation was defective and structurally weak. The oldest variety of hard fired pottery dates back to as early as 6,500 B.C. In metals it would be reasonable to assume that the first true acoustic emission heard was the cry of tin, the audible emission produced by mechanical twinning of pure tin during plastic deformation. This then would have occurred only after tin was smelted, which would be around 2500 BC.

In the 19th and 20th centuries, incidental observations of audible sound emitted by metals during the course of studying metallurgical phenomena, such as twinning and martensitic phase transformation studies, are reported in the literature by Czochralski (1917) and others. Since then, in the period 1923-1950, a number of observations relating to AE release during mechanical testing and deformation has been reported. However, all these
were just passing observations and no detailed investigations had been attempted.

The first systematic studies and the genesis of today’s technology in acoustic emission can be considered to be the outcome of the work of Josef Kaiser at the Technisché Hochschule Munchen in Germany. In 1950, he published his Ph.D thesis, which reported the first comprehensive investigation into the phenomena of acoustic emission (Joseph Kaiser 1950). He made two major discoveries. The first was the near universality of the acoustic emission phenomenon by observing emissions in different materials including dry wood which he studied, and the second was the irreversibility phenomenon which now bears his name. He also proposed a distinction between burst-type and continuous-type emissions.

Following the pioneering work of Kaiser, Schofield H. Bradford (1958) initiated the research program directed towards the application of AE to the field of materials engineering. In the decade of the 1960s, many engineers and scientists became interested in the AE method and utilized it in studies relating to materials research and characterization, non-destructive testing and structural evaluation. By the mid 1960s, Acoustic Emission Testing (AET) started to move out from the laboratory into the field environment, primarily as an NDT tool for the structural integrity evaluation of pressure vessels. The first applications of AE in the aerospace industry were believed to be the efforts of Green Allen, Charles Lockman and Steel Richard in trying to verify the structural integrity of Polaris rocket motor cases, fabricated for the US Navy using contact microphones, a tape recorder and second level analysis equipments in the year 1964. An analysis of AE data clearly showed crack initiation and propagation prior to catastrophic failure at about 56% of proof pressure with a location accuracy of ±0.3m. At the Boeing Scientific Research Laboratories, Pollock (1967) engaged himself on the study of crack growth in titanium and its detection through acoustic
emission. Parry and Robinson (1967) developed an acoustic emission instrumentation system which could detect, locate and characterize incipient failure conditions in the reactor pressure vessels and in the primary pressure system components of a nuclear power plant. Liptai (1968) conducted experiments on martensite phase transformations in single crystals of a gold-cadmium alloy. In 1979, Thomas initiated the first production application of AE at the Rocky Flats Plant. These applications include vessels for crack propagation during pressure testing etc. The AE monitoring of a pressurized system met with varying degrees of success. Generally, thin walled vessels are easier to test than thick walled ones when it comes to locational accuracy. AE techniques are most often used for Nondestructive testing (NDT) of composite pressure vessels and storage tanks in three ways.

1. Quality assurance of new pressure vessels.
2. Intermittent evaluation of vessels after accumulation of service time.
3. Continuous on-line monitoring of vessels.

During quality assurance testing, the proof testing of composite structures is complicated by the fact that most composite structures do not exhibit the same elastic plastic behavior found in metal structures. A significant amount of fiber breakage takes place during proof loading. This means that the common proof testing loads of 70-80 percent of expected failure strength used on metal designs, can significantly damage a composite structure, thereby degrading its structural integrity. To avoid significant fiber breakage and the associated structural degradation during proof loading, a procedure needs to be invented, that uses a much lower proof loading for composite hardware and that would also accurately determine the ultimate failure strength of the structure. Initially this has been demonstrated through a multivariate statistical analysis on graphite epoxy pressure vessels (Kalloo 1988).
The emergence of the Artificial Neural Network (ANN) in the 1990s made the prediction processes faster and more accurate. Hill et al (1996) proved the capability of the neural network in the burst pressure prediction exercise through a series of eleven graphite epoxy pressure bottles. While much work is reported on the online acoustic emission monitoring of composite structures, only limited information is available in the open literature on the prior prediction of failure strength (burst pressure) of composite structures. Moreover, dilation of the pressure vessel during loading, local yielding (strain) and Felicity ratio important parameters closely associated with the ultimate burst pressure were overlooked by researchers. An accurate prediction of burst pressure is contemplated in this research by involving these parameters with AE data through a neural network. The significance of other AE parameters like counts and energy for failure strength prediction are also planned to be examined.

1.2 ACOUSTIC EMISSION PHENOMENON

Acoustic Emission (AE) is the phenomenon, in which transient elastic waves are generated by the rapid release of energy from localized sources within a material, or the transient elastic waves so generated (ASTM-E610 1982). This phenomenon can also be called ‘stress wave emission’, ‘stress waves’, ‘microseism’, ‘micro seismic activity’ and so on. It is well known that when a solid is subjected to stress at certain levels, discrete acoustic waves are generated. This phenomenon of sound generation in metals under stress is termed as acoustic emission.

1.3 SOURCES OF ACOUSTIC EMISSION

Sources of AE include many different mechanisms of deformation and fracture. The largest naturally occurring sources are earthquakes and rock burst, while the smallest sources are dislocations, slips, twinning etc. Other typical sources are the initiation and propagation of cracks, sudden
reorientation of grain boundaries and bubble formation during boiling or martensitic phase transformation. Thus, acoustic emission sources can be classified as macroscopic and microscopic. Apart from these, there are other mechanisms such as leak and cavitations, friction in rotating equipments, growth or realignment of magnetic domains (magnetic barkhausen noise effect) all of which release emissions. These also fall under the definition of acoustic emission. However, such sources are termed as secondary sources or pseudo sources, to distinguish them from the classical acoustic emissions arising due to mechanical deformation of materials that are subjected to stress. While stressing, composite materials also emit acoustic signals just like metals due to failure modes such as matrix cracking, fiber failure, delamination etc. Figure 1.1 summarises the various failure mechanisms which act as sources of acoustic emission signals.

![Figure 1.1 Acoustic Emission sources](image-url)
1.4 ACOUSTIC EMISSION SIGNALS

The emissions from various sources outlined above, are released as acoustic energy impulses. The energy thus released, travels through the structure as spherical elastic waves; normally, a piezoelectric transducer converts these acoustic impulses into electrical signals. This electrical signal is then suitably processed and analyzed to reveal information about the source causing the energy release. Two types of signals can be recognized in general acoustic emission. These are discussed below.

1.4.1 Burst Emission

Burst emissions are discrete types of signals of very short duration (few microseconds to milli seconds), and hence, of the broad frequency domain spectrum. On the screen or monitor, they appear as individual signals or single needles well separated in time. Although these signals are rarely simple needlelike, they usually rise rapidly to a maximum amplitude and decay in an exponential way to the level of background noise. Figure 1.2 shows a typical AE burst signal.

Figure 1.2 Typical AE burst signal
Burst signals are characteristics of crack growth and propagation and are also observed during fiber failure in composite materials.

1.4.2 **Continuous Emission**

If the acoustic impulses are emitted close to one another or if the burst rate is very high, then the signals occur very closely and sometimes even overlap. In such cases, the emissions are termed as continuous. In these types of emissions, one cannot observe the individual signals separately. Matrix crazing in fiber reinforced composites may emit this kind of signals. A typical continuous emission is shown in Figure 1.3.

![Figure 1.3 Typical AE continuous signal](image)

1.5 **AE SIGNAL CHARACTERISTICS**

The purpose of an acoustic emission signal characterization is to detect the presence of the emission sources and provide as much information as possible about the source. The technology for detecting and locating sources is well established and acoustic emission signals can provide a large amount of information about the sources of the emission and the material and structure under examination.
The waveform parameters of an idealized signal as shown in Figure 1.4 are

1. Acoustic emission event
2. Acoustic emission counts (Ringdown count)
3. Acoustic emission signal amplitude
4. Acoustic emission signal duration
5. Acoustic emission event energy
6. Acoustic emission signal rise time.

The cumulative representation of these parameters can be defined as a function of time or test parameter (such as pressure or temperature), including (1) Total event; (2) Total counts; (3) Amplitude distribution; and (4) Cumulative energy. Once a specific parameter is selected, the rate function may be defined as a function of time or test parameter: event rate, count rate, energy rate etc.
1.5.1 Emission Events and Counts

Acoustic emission counts are an individual signal burst produced by local material changes. The emission count is the number of times a signal crosses a preset threshold. High amplitude events of long duration tend to have many threshold crossings. The number of threshold crossings per unit time depends on test parameters like, (i) the sensor frequency; (ii) the damping characteristics of the sensor; (iii) the damping characteristics of the structure; and (iv) the threshold level. The idealized signal in Figure 1.4 can be represented by Equation (1.1) (Harris et al. 1972)

\[ V = V_0 \exp(-Bt) \sin \omega t \]  

(1.1)

where \( V = \) output voltage; 
\( V_0 = \) initial signal amplitude; 
\( B = \) decay constant (greater than 0); 
\( t = \) time; and 
\( \omega = \) angular frequency.

The number of counts ‘\( N \)’ from a given event can be given by

\[ N = \frac{\omega}{\pi B} \ln \frac{V_0}{V_t} \]  

(1.2)

where \( V_t = \) the threshold voltage of the signal.

In spite of the sensitivity of the Ring Down Counts (RDC) to parameters such as system gain and threshold voltage, and the lack of a direct correlation between the count rate and event rate, it has been argued that the RDC is one of the most meaningful measurements of AE activity (Heiple and Carpenter 1983). The RDC is considered a qualitative measure of the energy present in the AE event (Klini 1983).
1.5.2 Acoustic Emission Amplitude

The peak signal can be related to the intensity of the source in the material producing an acoustic emission. The measured amplitude of the acoustic emission waveform is affected by the same test parameters as the event counts. Amplitude distributions have been correlated with deformation mechanisms in specific materials (Nakamura et al 1971; Pollock 1981). For practical purposes, a simple equation can be used to relate signal amplitudes, events and counts.

\[ N = \frac{Pf\tau}{b} \]  

(1.3)

where \( N \) = cumulative counts; 
\( P \) = cumulative events; 
\( f \) = resonant frequency of the sensor; 
\( \tau \) = decay time of the event; and 
\( b \) = the amplitude distribution slope parameter.

The RMS voltage generated by the AE signals is reported as the measure of the AE activity (Heiple and Carpenter 1983). An amplitude distribution analysis of the AE signals is one of the potential methods to characterize the source of acoustic emission (Ono 1975). For example, the high amplitude emissions encountered at lower load level on some of the specimens appear to be the result of the spalling of the surface oxide layer (Kerawalla 1965).
1.5.3 Event Duration

Event duration is the time between the first and the last threshold crossings. This is schematically illustrated in Figure 1.4. The duration can be a useful parameter when measuring the relative durations of the signals from the same test. A change in either the average signal duration or the distribution of durations can indicate either a change in the signal path to the sensor or a change in the generating mechanism. Both can be important in structural tests. For example, in glass fiber composites, matrix cracking generally produces short duration signals, while propagating cracks produce long duration signals (Kalyanasundaram and Mukhopadhyay 2007).

1.5.4 Rise Time and Decay Time

Rise time refers to the time required for the signal to reach its peak amplitude and is normally counted from the time between the first threshold crossing and the peak amplitude, while decay time refers to the time taken by the signal to decay from its peak value to just above the threshold level. Rise time and decay time are illustrated in Figure 1.4. While short rise times are related to crack growth, the longer ones pertain to crack surface interference (Sklarczyk and Waschkies 1989). Rise time between 10 to 60 µsec indicates crack growth on carbon steel (Botten 1989). Very short rise time in the range of 1µsec or less corresponds to microscopic crack growth events (Wadey et al 1981). Rise time can be a useful parameter for studying matrix cracking (Prosser 1995) and fiber failures (Ativitavas 2006) in certain composite materials.
1.5.5 Acoustic Emission Energy

Since acoustic emission activity is attributed to the release of energy in a material, the energy content of the acoustic emission signal can be related to the energy release (Harris and Bell 1977; Beauttie and Jarmaillo 1974). As stated earlier, the energy content depends largely on the source of acoustic emission. For example, while the AE from a deformation source can contain higher energy, the one associated with inclusion and brittle fracture may contain a smaller energy content. The true energy is directly proportional to the area under the acoustic emission waveform. The electrical energy ‘U’ present in a transient event can be defined as:

\[ U = \frac{1}{R} \int_0^t V^2(t) dt \]  

(1.4)

where R = Electrical resistance of the measuring circuit.

A direct energy analysis can be performed by digitizing and integrating the waveform signal or by special devices performing the integration electronically.

1.6 ACOUSTIC EMISSION WAVE PROPAGATION

A short, transient AE event is produced by a very fast release of elastic energy, actually a local dislocation movement. This local dislocation (or change in material) is the source of an elastic wave that propagates in all directions and cannot be stopped anymore. It is similar to an earthquake, with the epicenter at the defect, but in microscopic dimensions. On flat surfaces, the wave propagates in terms of concentric circles around its surface and can be detected by one or more sensors as shown in Figure 1.5. During propagation, the wave is attenuated. The maximum distance, where an AE
event can still be detected, depends on various parameters, e.g. on the material properties, the geometry of the test object, its content and environment, etc. On flat or cylindrical metal surfaces, events can still be detected at a distance of several meters, which is one of the great advantages of this technique. AE testing can reliably cover areas which are not assessable by other testing methods. Depending on the position of the AE source, the wave reaches the sensors with certain delays. The position of the source can be calculated using the different arrival times. This is called ‘location calculation’. Thanks to the high computing power of modern PCs, the location calculation can be done in real-time. ie. during the examination.

Figure 1.5 Propagation of waves
1.6.1 Types of Waves

There are only two distinct types of waves existing in an infinite medium. The waves are called ‘dilatational’ and ‘distortional’. A special kind of dilatational wave is called a ‘plane longitudinal wave’ and the distortional wave can be termed a ‘plane transverse wave’ or ‘shear wave’. A longitudinal wave is a primary wave consisting of a periodic disturbance or vibration that takes place in the same direction as the advance of the wave. The combined motions result in the advance of alternating regions of compression and rarefaction in the direction of propagation. A transverse wave is a secondary wave wherein the particles move back and forth perpendicular to the direction of propagation. When a free surface is present in a medium, a third type of wave may exist in addition to dilatational and distortional waves. It is also called a ‘surface wave’ or ‘Rayleigh wave’. Surface waves may also exist on surfaces that are rigidly constrained in both the tangential and normal directions. Surfaces that have mixed boundary conditions (such as those rigidly constrained from normal motion but with zero in-plane tractions) cannot support surface waves.

1.6.2 Attenuation of Waves

The term ‘attenuation’ is the decrease in amplitude that occurs as a wave travels through a medium. Attenuation has several causes and may be specifically related to the physical parameter used to specify the amplitude of the wave. The mechanical properties of the materials at which the wave propagates, is also an important phenomenon. In isotropic materials the attenuation will be uniform in all directions, whereas in fiber-reinforced composites, attenuation will be more in the transverse direction of the fibers (Kalyanasundaram and Mukhopadhyay 2007). Effective acoustic emission monitoring on fiber-reinforced composites requires much closer sensor spacing than would be the case with a metal component of a similar size and
configuration. With the proper number and location of sensors, the monitoring of a composite structure has proved highly effective for detecting and locating areas of fiber breakage, delaminations and other types of structural degradations.

1.7 ACOUSTIC EMISSION INSTRUMENTATION

The equipment for processing AE signals is available today in a variety of forms, ranging from single or dual channel systems to multi-channel systems. Depending on the need and type of applications, systems can vary from small rugged portable units to large PC-based systems with a variety of software options for R&D applications. The components common to all these systems include sensors, preamplifiers, filters, amplifiers and signal conditioning circuits. Auxiliary instrumentation to assist in displaying the signals, analyzing and recording, vary depending on the application and user. A schematic of a simple and typical four channel system is given in Figure 1.6.

![Schematic diagram of a basic four-channel Acoustic Emission system](image-url)
The various individual subunits of an AE system are discussed as below.

1.7.1 AE Sensor

The heart of the AE system is the sensor. When an acoustic emission wave front impinges on the surface of a test object, very minute movements of the surface molecules will occur. A sensor’s function is to detect these mechanical movements and convert them into specific useable electric signals. The sensors used for acoustic emission testing often resemble an ultrasonic search unit in configuration, and generally utilize a piezoelectric transducer as the electromechanical conversion device. The sensors may be resonant or broadband. The main considerations in sensor selection are (i) operating frequency; (ii) sensitivity; and (iii) environmental and physical characteristics. Figure 1.7 is a typical schematic construction of an AE sensor.

![Figure 1.7 Construction of an AE sensor](image_url)
The AE sensor normally consists of several parts. The active element is the piezoelectric element with electrodes on the top and bottom faces. One electrode is connected to the electrical ground. The entire sensor is appropriately packaged in a metal case, which also acts as a shield to minimize electromagnetic pick-ups. A wear plate is also provided to protect the piezoelectric element. The AE sensor is mounted/attached to the surface of the test object using adhesive tapes, strapons or magnetic holders.

1.7.2 Couplents

The purpose of a couplant is to provide a good acoustic contact between the test object and the sensor. The couplant should have properties like high wettability, corrosion resistance, sufficient viscosity and easy removal. Some commonly used couplants are natural wax, silicone grease, epoxy resin and propylene glycol.

1.7.3 Preamplifiers

The pre-amplifier is the first part of the instrumentation system and its main function is to enhance the signal level against noise. Since the sensor produces a charge proportional to the source intensity, the preamplifier must be located near the sensor. Preamplifiers are used to amplify the small sensor signals so that they can be transmitted over long signal cables. They are also used to match the high impedance of the sensors to the low impedance of the signal cable (typically 20 k ohms to 50 ohms). Low impedance cables pickup less air borne electrical interference. The desirable characteristics for a good AE preamplifier are low noise, moderately high gain, low output impedance, good dynamic range, high stability, good common mode rejection and input impedance matching the sensor. The schematic drawing of a preamplifier is shown in Figure 1.8.
1.7.4 AE Filters

Filters play an important role in allowing the amplified signal from the sensor and attenuating unwanted noise. An ideal filter of a passive or active network allows the desired frequencies with unit gain, and rejects unwanted frequencies. A filter with flat frequency response for desired frequencies and sharp cut off for unwanted noise, is required. Depending upon noise considerations, the operating band width frequency is chosen. So, filters are designed for different band widths and can be plugged to preamplifiers to meet the specific requirements. Low pass, Band pass and High pass filters are the different types of filters. Band pass filters with a band width ranging from 100 kHz - 300 kHz are widely used during AE experimentation.

1.7.5 Amplifier and Measurement Circuitry

The output of the filter is fed to an amplifier where the signal is further amplified. The amplifier gains in the range of 20 to 60 dB are most
commonly used. After amplification, the signal is processed to reveal information about the source and its characteristics, using measurement circuitry and processing software. The level of processing to which the signal is submitted depends upon the size and cost of the system. In small portable instruments, acoustic emission events or threshold crossing may simply be counted and the count then converted to an analog voltage for plotting on a chart recorder. In more advanced hardware systems, provisions can be made for energy or amplitude measurement, spatial filtering, time gating and automatic alarms.

1.7.6 AEwin Software

AEwin is a 32 bit WINDOWS, Data acquisition and replay program capable of running PAC’s (Physical Acoustic Corporation) DiSP, MISTRAS or SPARTAN-based products. AEwin uses full WINDOWS resources including; setting of any WINDOWS available screen resolutions, printing, networking, multi-tasking, multi-threading, etc. It is capable of operating in WINDOWS98 / NT / ME / 2000 / XP operating systems. AEwin is fully compatible with PAC’s standard (DAT) data files. This allows as replaying and analyzing all previously collected AE files. AEwin is easy to learn and it is user-friendly. The software has all the acquisition, graphing and analysis capabilities that have come to be expected in AE systems, plus many more new and enhanced features to make data analysis and visualization tasks easy.

1.8 ARTIFICIAL NEURAL NETWORKS

The development of artificial neural networks started 50 years ago. Artificial neural networks are gross simplifications of real (biological) networks of neurons. The paradigm of neural networks, which began during the 1940s, promises to be a very important tool for studying the structure-
function relationship of the human brain. Due to the complexity and incomplete understanding of biological neurons, various architectures of artificial neural networks have been reported in the literature. Most of the ANN structures commonly used in many applications, often consider the behavior of a single neuron as the basic computing unit for describing neural information processing operations. Each computing unit, i.e., the artificial neuron in the neural network is based on the concept of an ideal neuron. A neuron is assumed to respond optimally to the applied inputs. However, experimental studies in neuro-physiology show that the response of a biological neuron appears to be random, and only by averaging many observations it is possible to obtain predictable results. Inspired by this observation, some researchers have developed neural structures based on the concept of neural populations.

The aim of a neural network is to mimic the human ability to adapt to a change in circumstances and the current environment. This depends heavily on being able to learn from events that have happened in the past and to be able to apply this to future situations (Sivanandam and Sumathi 2007). For example, the decisions made by doctors are rarely based on a single symptom because of the complexity of the human body, since one symptom could signify any number of problems. An experienced doctor is far more likely to make a sound decision than a trainee, because, from his past experience he knows what to look out for and what to ask, as he may have etched on his mind a past mistake, which he will not repeat. Thus, the senior doctor is in a superior position than the trainee. Similarly, it would be beneficial if machines, too, could use past events as part of the criteria on which their decisions are based, and this is the role that an artificial neural network seeks to fill.

An artificial neural network is an information processing system that has certain characteristics similar to biological neural networks. A neural
network consists of a large number of simple processing elements called neurons or nodes as shown in Figure 1.9.

![Diagram of a processing element in a neural network](image)

**Figure 1.9 Processing Element of Neural Network**

Each of these neurons is connected to other neurons by communication links, each with an associated weighting. The weightings represent information being used by the network to solve a problem. A neuron has many input paths and combines the values of the input paths by a simple summation. The summed input is then modified by a transfer function and passed directly to the output path of the processing element. The output path of the processing element can then be connected to the input paths of other nodes through connection weightings. Since each connection has a corresponding weighting, the signals on the input line to a processing element are modified by these weightings prior to being summed. The processing elements are usually organized into groups called layers. Typically, a network consists of an input layer where data are presented to the network, and an output layer which holds the response of the network, and one or more hidden layers for processing, as shown in Figure 1.10.
There are several types of neural networks in supervised learning feed forward nets such as Perceptron, Adaline, Madaline, Back propagation, Cauchy machine, Artmap and Cascad correlation, etc. (Sathish kumar 2008). Only the back propagation neural network is discussed here, because it is found to be suitable for this research work. A feed forward network is one that has no feed back connections from one layer to another or to itself. Information is passed from the input buffer through the hidden layers to the output layers in a straightforward manner using the summation and activation function characteristics of the network. There are two main phases in the operation of a feed forward back propagation neural network: ‘learning’ and ‘recall’ (Fausett 1994). Learning is the process the network goes through to adapt or modify the connection weightings. In supervised learning the desired response or output of the network is given as the target. Recall refers to how the network processes a stimulus presented at its input layer and creates a
response at the output layer. Recall is part of the learning process wherein the desired response of the network is compared to the actual output of the network to create an error signal. The error signal is then used to modify the connection weightings throughout the network or back propagate the error corrections.

The training algorithm used in the back propagation network is as follows.

**Initialization of weights**

**Step 1:** Initialise the weight to small random values.

**Step 2:** While stopping condition is false, do steps 3-10

**Step 3:** For each training pair do steps 4-9

**Feed Forward**

**Step 4:** Each input unit receives the input signal $X_i$ and transmits this signal to all the units in the layer above, i.e. hidden units.

**Step 5:** Each hidden unit $(Z_j, j=1,\ldots,p)$ sums its weighted input signals as

$$Z_{inj} = V_{oj} + \sum_{i=1}^{n} X_i V_{ij} \quad (1.5)$$

Applying the activation function

$$Z_j = f(Z_{inj}) \quad (1.6)$$

And sends this signal to all the units in the layer above, i.e. the output units,
Step 6: Each output unit \((Y_k, k = 1, \ldots, m)\) sums its weighted input signals and applies its activation function to calculate the output signals.

\[
Y_{ink} = W_{ok} + \sum_{j=1}^{p} Z_j W_{jk}
\]  
\[
Y_k = f(Y_{ink})
\]  

\(1.7\)
\(1.8\)

Back propagation of errors

Step 7: Each output unit \((Y_k, k = 1, \ldots, m)\) receives a target pattern corresponding to an input pattern; the error information term is calculated as

\[
\delta_k = (T_k - Y_k) f'(Y_{ink})
\]  
\(1.9\)

Step 8: Each hidden unit \((Z_j, j = 1, \ldots, n)\) sums its delta inputs from units in the layer above as

\[
\delta_{inj} = \sum_{k=1}^{m} \delta_k W_{jk}
\]  
\(1.10\)

The error information term is calculated as

\[
\delta_j = \delta_{inj} f'(Z_{inj})
\]  
\(1.11\)

Updation of weights and bias

Step 9: Each output unit \((Y_k, k = 1, \ldots, m)\) updates its bias and weights \((j = 0, \ldots, p)\)

The weight correction term is given by

\[
\Delta W_{jk} = \alpha \delta_k Z_j
\]  
\(1.12\)

And the bias correction term is given by

\[
\Delta W_{ok} = \alpha \delta_k
\]  
\(1.13\)

Therefore,
\[ W_{jk}(\text{new}) = W_{jk}(\text{old}) + \Delta W_{jk} \]  
\[ W_{ok}(\text{new}) = W_{ok}(\text{old}) + \Delta W_{ok} \] 

Each hidden unit \((Z_j, j = 1, \ldots, p)\) updates its bias and weights \((I = 0, \ldots, n)\)

The weight correction term
\[ \Delta V_{ij} = \alpha \delta_j X_i \]  

The bias correction term
\[ \Delta V_{oj} = \alpha \delta_j \] 

Therefore,
\[ V_{ij}(\text{new}) = V_{ij}(\text{old}) + \Delta V_{ij} \]  
\[ V_{oj}(\text{new}) = V_{oj}(\text{old}) + \Delta V_{oj} \] 

**Step 10**: Test the stopping condition.

The stopping condition may be the minimization of the errors, the number of epochs etc.

### 1.9 NEURAL NETWORK WITH MATLAB

MATLAB is a product of The Math Works, Inc. and is an advanced interactive software package specially designed for specific and engineering computation. The MATLAB environment integrates graphical illustrations with precise numerical calculations, and is a powerful, easy-to-use, and comprehensive tool for performing all kinds of computations and scientific data visualization. MATLAB has proven to be a very flexible and useful tool for solving problems in many areas such as
- Math and computation
- Algorithm development
- Modeling, Simulation and Prototyping
- Data analysis, exploration and visualization
- Scientific and engineering graphics
- Application development, including graphical user interface building.

Data analysis and simulation problems in a neural network can be very quickly and accurately solved by the MATLAB toolboxes. Figure 1.11 shows the main features and capabilities of MATLAB.

![Figure 1.11 Features and capabilities of MATLAB](image)
1.10 FIBER REINFORCED COMPOSITES

Composites are best defined as materials in which two or more constituents have been brought together to produce a new material nominally, at least, of more than one component, with the resultant properties different from those of the individual constituents (Hull and Clyne 1997; Savage 1993). In fiber matrix composites, fibers are the main load carrying members. Matrix resin keeps the fibers in the desired location / orientation, and hence, acts as a load transfer medium between them and protects them from environmental damages. There are many advantages in using the FRP composite material; to name a few, high strength to weight ratio, good corrosive resistance, and fast on-site installation. These qualities make the FRP more attractive for many engineering applications, especially in aerospace industries. Since it consists of more than one material, the failure mechanism can occur in one material or in a combination of materials (Ativitavas 2006). Common failure mechanisms in fiber reinforced composite materials are, matrix cracking, fiber failure and delamination with several subcategories such as matrix splitting, fiber-matrix debonding, fiber pullout etc. as shown in Figure 1.12.

Figure 1.12 Failure modes in composites
1.10.1 Matrix cracking

The initiation of micro cracks in the resin matrix of fiber reinforced composites during loading is called as matrix crazing or matrix cracking. Since the matrix is the binding material for fibers and since it also transmits the loads to the fibers, their cracking usually causes stiffness reduction and thus affects the performance of the composite structure (Prosser 1995).

1.10.2 Fiber breakage

Fiber breakage can even lead to catastrophic failures in composites. This occurs by tensile stress or localized compressive buckling. Discontinuities in a fiber make it weak at that point, and may fracture when stressed. The fracture of a fiber gives additional load to the other fibers, which can lead to the eventual breakage of all fibers, thus weakening the composite structure (Marvin 1986).

1.10.3 Delamination

One of the most commonly observed failures in a composite material is delamination, a separation of the fiber reinforced layers that are stacked together to form laminates. Delamination occurs at stress-free edges due to the mismatch in the properties of the individual layers, at ply drops where the thickness must be reduced, and at regions subjected to out-of-plane loading such as bending of curved beams (Dharan and Kevin 1995). In filament wound composite pressure vessels, delamination is the common failure mechanism.
1.11 SUMMARY

A brief history of the acoustic emission technique has been discussed in this chapter. Various AE parameters, instruments and software associated with AE technique have also been briefly discussed. A short introduction about composite materials is given. Other important terminologies associated with the acoustic emission technique are given in Appendix 1.

1.12 ORGANISATION OF THE THESIS

The thesis consists of seven chapters. A brief introduction to the acoustic emission non-destructive testing and artificial neural network is presented in the first chapter. The characteristics of fiber reinforced composite materials have also been briefly discussed.

A comprehensive literature survey on composite failure characterization, failure strength analysis on composite tensile coupons and composite pressure vessels is given in chapter 2. Based on the review, the need for future investigation is identified. The scope and objectives of the thesis are then laid out.

Chapter 3 presents the experimental work carried out on composite tensile coupons and the AE data acquired from them. The various instruments used for data acquisition are briefly discussed.

Chapter 4 discusses the experimental work (hydrostatic pressure test) carried out on the GFRP composite pressure vessels and the data acquisition. Details of the composite pressure vessels and the hydraulic pump used in the experimental work are also presented.
Chapter 5 discusses the failure strength prediction exercise on composite tensile coupons using the AE data collected during loading the coupons, along with an artificial neural network.

Chapter 6 presents the burst pressure prediction methodology on composite pressure vessels using the AE data acquired from the pressure vessels during proof pressure testing, along with an artificial neural network.

Chapter 7 contains the summary of the results along with the main conclusions arrived at from the study. The scope for further research in the area is also discussed.