J. Basic. Appl. Sci. Res., 3(4)386-393, 2013

ISSN 2090-4304
Journal of Basic and Applied Scientific Research
www.textroad.com

Identification of Failure Mechanisms in Glass /Polyester Composites under Buckling Loading by Acoustic Emission testing

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ABSTRACT

The objective of this study is to investigate the damage mechanisms in glass/polyester composite laminates under buckling loading by the acoustic emission (AE) technique. Delamination and Fracture are the most common failure mode in composite materials, since they will result in the reduction of stiffness and can grow throughout other layers. When a solid material is stressed, imperfections within the high-frequency sound waves are created. The waves in the material released by the sensors can be certain they will receive and analyze these waves can fault type, location and severity to be determined. Acoustic Emission testing is a novel method of non-destructive testing. This method can detect various errors and positioning components and structures under load and use them. Rapid depletion of energy from a localized source within the body, causing a transient elastic wave propagation in the material, This phenomenon is called Acoustic Emission. In this study, the Acoustic Emission method for flaw detection in composites has been created. These defects include: matrix cracking, fiber pull-out and breakage, fiber-matrix deboning and delamination. These drawbacks reduce the stiffness and hardness of the composite. Used in the testing of composite glass / polyester is., Three types of composite glass / polyester $[0^0/90^0]6_s$, $[\text{Woven}]6_s$ and $[0^0]6_s$ has been used. All composites have 12 layers and the thickness of each layer is about 0.416 mm .Everyone composites have been buckling under test. During their experiment different defects are created. While these flaws, the composite sounds are produced. These sounds are received by acoustic sensors. The analysis of these sounds, different faults can be classified in the composite. Buckling of a composite is consisted of two main stages including delamination and fracture. The complex failure mechanisms that are commonly considered as the distinctive characteristic of composites are being amenable to nondestructive test advance. Moreover, Using electron microscopy(SEM), the sections of damaged in the composite, has photographs, Thereby creating better and more precisely the nature of the damage in the composite realized. the microscopic properties of different composite specimens after fracture are watched and analyzed by scanning electron microscope (SEM). In this study, Effect of two lay-up patterns: energy, count, amplitude are explored. The results of this study indicate that: Although the controlling failure modes can be identified, the complete separation of all appearing failure mechanisms is not easily realized because of the complex interactions among them. . Here, we summarize the amplitude range for each failure mode. The amplitude of the matrix cracking, fiber/matrix interface deboning, delamination, and fiber pull-out and breakage are about 40-60 dB, 50-70 dB, 60-80 dB and 80-100 dB, respectively. However, the amplitude range varies from different composites, sizes and lay-up patterns even for the same failure mode. Also compare some of the different parameters of the samples we tested.
KEYWORDS: Acoustic Emission, Buckling, Damage Mechanisms, SEM, glass/polyester composite.

INTRODUCTION

Glass fiber polymer composites have been increasingly use in areas, and wind-power electricity generation because of their advantages such as high strength and stiffness to weight ratios.

The design ability is an outstanding advantage for laminated composites, linking the physical with the mechanical performance flexibly. By design, the stiffness and strength of composite mechanics, two points characterize the designability of composites: (1) Since the stiffness and strength of an individual layer are much higher in the fiber principal direction than in the transverse directions, the load-bearing ability in the fiber principal directions is fully displayed, and severe stress concentrations are avoided by placing different lay-up angles for different layers; (2) The weak shear strength of such as the polyester easily lead to the delamination since different layers are bonded only by the matrix.

If intralaminar cracking for some layer appears, other layers may not be much affected because of the delamination. Thus, the damage and failure properties between two neighboring separated layers keep independent [1-2].

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However, the laminated properties of composites also bring about some negative influence that may restrict the application of composites. An important factor lies in the complex failure mechanisms: intralaminar and intralaminar failure as well as their interactions. Intralaminar failure includes the matrix cracking, the fiber/matrix debonding, and the fiber pull-out and breakage [3-4].

Sincethe composites are microscopically inhomogeneous represented by spatially irregular array of fiber and matrix, statistical distributions of fiber strength as well as the defects arising mainly from the manufacturing, the progressive failure properties will result in the decrease of stiffness and strength of composites. This shows hunting advanced test approaches to analyses the damage and monitoring failure properties of composites in significant.

Currently, there are some advanced nondestructive inspection technique including the X-ray, ultrasonic and acoustic emission inspection which are being increasingly applied to the research on the failure mechanisms of composite structures. All of the them show high sensitivity, rapid response speed and high precision.

However, the main advantage of the acoustic emission technique over other two techniques is the acoustic emission can acquire the evolution information of defects dynamically. The basic principle of acoustic emission technique is to convert the mechanical vibrations in to the electrical signals, and to analyze the acoustic response in terms of the evolvement of the energy, count, peak frequency and amplitude. Research on the acoustic response law of composites is worthwhile to further insight into the failure mechanisms and damage evolution of composites. Williams and Lee [5],early introduced the acoustic emission to monitor the failure of composites. Groot et al [6],and Yu et al [7].

Preformed the failure detection of composites by determining the real-time acoustic frequency. Woo and Choi [8], explored the failure process for the single-edge-notched laminated composites by studying the high-amplitude acoustic emission events. Giordano et al [9],performed the quantitative failure analysis on the polymer composites by acoustic emission. M izutania et al [10], Boshse [11], Zhuang and Yan [12], Bussiba et al [13], and Ramirez-Jimenez et al [14], studied several typical microscopic damage and failure mechanisms of composites using acoustic emission. Particularly, Benmedakhene et al [15], Hill et al [16], Johnson and Gudmundson[17], BakhtiaryDavijani et al [18], Scholey et al [19], and Gutkin et al [20] explored the failure mechanisms including the matrix cracking and delamination of composite laminates using acoustic emission. Loutas and Kostopoulos [21], Sasikumar et al [22],and Oliviera and Marques [23], performed the health monitoring research of composites using acoustic emission and artificial neural network. Czigany [24],proved it possible to correlate the acoustic emission features such as the number of events, the amplitude and energy to the physical properties. Recently, Rosa et al [25], gave a literature review on the application of acoustic emission for the natural fiber composites including the damage evolution and failure mechanisms detection.

However, little research is concentrated on the failure mechanisms of multidirectional composite laminates with crack in surface using acoustic emission tests with different lay-up angle arrangements in a true way. The mapping is expected to promote understanding of critical failure mechanisms of composites whereas it lessens the cost of inspection .The main difference between this study and previous study in type of test samples and set up. In terms of test samples: type of layering, angle of fibers and fabrics used in previous study are different. Samples used in this study are symmetric, the type of fabric used is plain fabric. The set-up: Using Universal compression machines and equipment used in the acoustic frequency range up to 1 MHz sensor is different from the previous study.

The main goal of this study is to obtain online load critical, energy critical, and also get a domain of damages, These damage include fiber breakage, fiber pull-out and breakage, matrix cracking, fiber-matrix debonding, and delamination. also, Introduction to the acoustic emission method, as a new leader in online damage detection during testing of composites and other materials. In this study, the acoustic emission tests are performed for the glass/polyester composite laminates with different lay-up and crack surface arrangements. Some representative features such as the energy, count and amplitude examine the frequency distribution are extracted with the buckling load to study the controlling failure mechanisms of composites. By test and analysis, the mapping laws for different specimens are obtained, which provides helpful references to unveil the progressive failure properties of composite.

In the following, at first we introduce composite used in the experiment. Then, equipment used for acoustic emission of this research are presented. Acoustic emission testing approach and Buckling tests on test samples is explained. Finally, the output graph of the test and SEM photographs analysis are discussed. Based on test results, a description of results of this study will be discussed.

MATERIALS AND METHODS

Material Specimens

The tested glass/polyester composite specimens include four lay-up patterns: $[0^0/90^0]_{6s}$, and $[\text{Woven}]_{6s}$. The woven fabric and unidirectional fibers material are as follows: density of 195 g/m2, tensile strength warp: 386 n/cm weft: 486 n/cm, thickness 0.28 mm and weave is plain. The properties of the polyester resin as a matrix material is density of 1020-1040 kg/m3. The laminates were prepared by hand lay-up. To prevent slip during loading, end tabs in 20mm X 30 mm length were glued at the same ends of specimens.

The composites specimens are shown in Fig. 1, Alsodimension and lay-up of 2 specimens are listed in Table 1. Each specimen includes 12 layers, and the thickness of each layer is about 0.416 mm.

Table.1.Sizes and lay-up patterns for 2 specimens.

Number	l×w×t (mm)	lay-up patterns
1	220×20×5	$[0/90]_{6s}$
2	220×20×5	$[\text{Woven}]_{6s}$

Where the subscript " s" denotes the symmetry.

Test Equipment

The aim of this experimental، study of the signals emitted from the damage caused by the composite buckling tests, and found that the relationship between the mechanical and acoustic data._For this purpose, the mechanical behavior of composite acoustic behavior of glass / polyester under buckling is desired._Buckling load testing was done by Universal compression machine. The machine is equipped with a Ball Screw system. This machine is a constant displacement rate of jaw movement. The motion range from 2 mm/min to 300 mm/min and a load cell capacity, 50,000 N .speed in this experiment is equal to 5 mm/min._Detection of acoustic signals induced buckling load on Acoustic Emission systems by using of two channels modern sensors with frequency range from 100 to 750 kHz. Signals are amplified by the amplifier, and the signal using the filter passes the threshold of 30 dB, are filtered. In This test has been used in AEWin software, the software is built by the Corporation Physical Acoustics company.Data collection system, in the long process of testing data capture, and then the software will extract the individual signals and on the display shows._The acoustic equipment intended for both sensing threshold 30 dB and Threshold frequency 1 MHz is set.

The tests were carried out in a universal test machine with the load cell capacity of 50000 N at the cross head speed of 5 mm/min. Figure 2 shows the composite specimen positioned for acoustic emission test.

For every specimen that was tested, four different graphs are provided, namely:

- Amplitude of AE hits versus test time.
- Count and Load of AE hits versus test time.
- Cumulative AE Energy and Load of versus test time.
- Energy and Load of AE hits versus test time.

Fig1 Composite samples of glass / polyester before buckling test.

RESULT AND DISCUSSION

The accurate of the acoustic emission response plays an important role in explaining the failure mechanisms and damage evolution of composites. The mapping appears between the acoustic emission features and failure mechanisms of composites. Williams and Lee5 summarized the main acoustic emission source mechanisms during the failure of composites, which includes (1) the fracture of fiber and matrix, (2) the fiber-matrix debonding, (3) the relaxation of fibers if they fracture and (4) the fiber pullout against friction during composite rupture. Furthermore, the interlaminar delamination is also an important failure source besides, Yang et al [29].

The deep exploration of the true mapping laws by the acoustic emission features contributes to promoting insight into the failure mechanisms of composites. The schematic description of typical acoustic emission signals is shown in Figure 3, including mainly three features: energy, count and amplitude [26,27,28]. The following discussion concentrates on the failure analysis for two representative composite specimens 1 and 4.

Acoustic Emission Representation for Composite Specimen $[0/90]_{6s}$.

Figure 3shows the acoustic emission response about the evolvement of energy, count and amplitudes for the $[0^0/90^0]_{6s}$ specimen. Figure 4 shows the microstructure of the $[0^0/90^0]_{6s}$specimen after fracture by SEM.

The damage evolution includes three stages: (1) at the early stage (0-10s), the energy, the number and amplitude of acoustic emission signals are small, corresponding to a roughly linear deformation behavior.

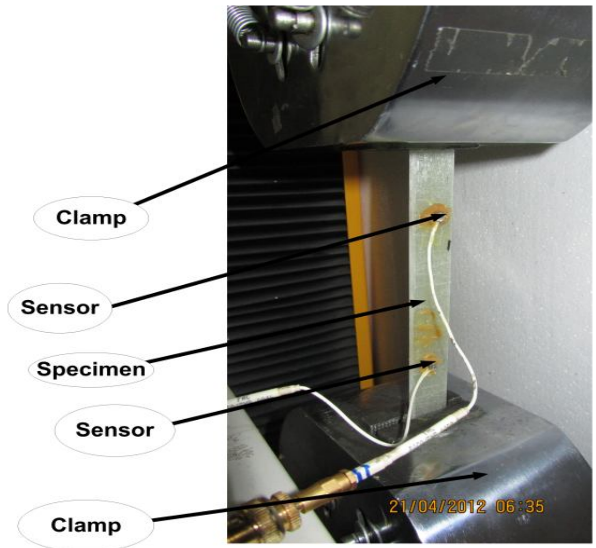


Fig 2 Test equipment including acoustic test equipment, Buckling test equipment and Composite sample

The mechanical properties of composites are stable because of few signals. Because the properties of composite materials Mechanical (strength, hardness, resistance to change shape, etc.) are high. The initial load, the amount of force (load) is low, the devastation caused by the load will be less, and As a result, the signal will be less damages .The second stage, the load more. This causes overcoming the mechanical properties of the composite and the damage is increased. The signals resulting from the failure of phase 1. In phase 1, due to the low damage resulting from loading the signal received from the failure rate is too low. Consequently, based on graphs drawn, the greater applied load is increased, resulting in the failure rate of the received signal will be more. In general, we can conclude that the value of the load is higher, resulting in more damage and more signals, and vice versa. So in general it can be said ,the high mechanical strength of materials, so the first step, the number of signals under load is low. The longitudinal matrix cracks with the 30-40 dB amplitudes other than fiber breakage first appear. As the tensile stress increases, some longitudinal and transverse fiber/matrix interface crack with 40-60 dB amplitudes also spring up. The main failure is still in the forms of the matrix cracking, the interface failure, and little longitudinal fiber breakage with about 60-70 dB amplitude. This speeds up the no uniform redistributions and variation of stresses as well as the progressive failure of neighboring matrix and interface. At the same time, the transverse 0^0fibers shear some redistributed stress due to the interlaminar shear, which prevents the damage evolution of 0^0longitudinal fibers. However, this also results in the progressive transverse failure and delamination and buckling. (2) At the middle damage stage (10-40 s), the amplitude range of signals increases, and the high-amplitude signals especially those beyond 80 dB increase remarkably, and the energy slightly increases, marking more failure points and more severe damage areas.

The energy reaches about $3*10^8$attoJoul (aJ) and the event count reaches about 15at 35 s though the force-time-energy curve shows a small fluctuation due to the fracture localization [7]. (3) At the stage of fracture (40-90s), the amplitudes of signals keep the same, but the energy increases remarkably and the number adds continually, represented by more longitudinal fiber breakage with the 60-80 dB amplitudes. The low interlaminar shear strength and transverse fibers have small effects on the longitudinal tensile properties, which are yet determined by longitudinal fibers.

Thus, the high-amplitude signals beyond 80 dB representing the longitudinal fiber breakage are also mixed with the middle and low-amplitude signals showing the progressive matrix cracking and interface failure. The controlling failure mechanisms include the matrix cracking, fiber/matrix interface debonding, delamination and fiber breakage.

Similarly, Yu et al [7], described the energy, count and amplitude using the crack propagation lengths for the notched 0^0, 90^0 and cross-ply composite specimens under static and impact loads.

The edge notch has a large effect on inducing the initial crack similar to the designed by us, and they designed an acoustic emission signal analyzer and use the optical microscope to measure the effect of the microscopic crack length on the acoustic emission response. Besides, Cox and Yang [1], performed the virtual numerical simulation using finite element analysis and Mizutania et al [10], performed the acoustic emission test on the $[0^0/90^0]_{6s}$specimen, and they further classified the matrix cracking into the transverse matrix cracks, and longitudinal splitting crack in the 0^0 layer that develops as shear failure.

Acoustic Emission Representation for Composite Specimen $[\text{Woven}]_{6s}$.

Figure 5 shows the acoustic emission response about the evolvement of energy, count and amplitude. In general, the high-amplitude signals for the $[\text{Woven}]_{6s}$specimen are fewer than those for the $[0^0/90^0]_{6s}$specimen, In contrast with the specimen-1, the energy reaches just about $3*10^8$attoJoul (aJ) at 90s and shows more fluctuation for the specimen-2, but the event count reaches about 1500 which shows more complicated damage process and fracture localization then the specimen-2. The damage evolution in clues also three stage: (1) at the early stage (0-20s) , the energy, number and amplitude of acoustic emission signals are small, corresponding to the elastic deformation. The longitudinal matrix cracks with the 30-40 dB amplitude other than fiber breakage first appear.

Some longitudinal and transverse fiber/matrix interface cracks with 40-60 dB amplitudes also spring up. (2) At the middle stage (20-25s), the amplitude range of signals increases, the energy reaches about $12*10^8$attoJoul (aJ) and the event count reaches about 60 at 70 s though the force-time-energy curve shows a small fluctuation due to the fracture localization [7]. The main failure is still in the forms if the matrix cracking, the interface failure, and little fiber breakage with about 70 dB amplitude. (3) At the stage of fracture (25-40 s), the amplitude of signals keep the same, but the energy increases and the number adds continually, represented by more fiber breakage with the70-80dB amplitudes.

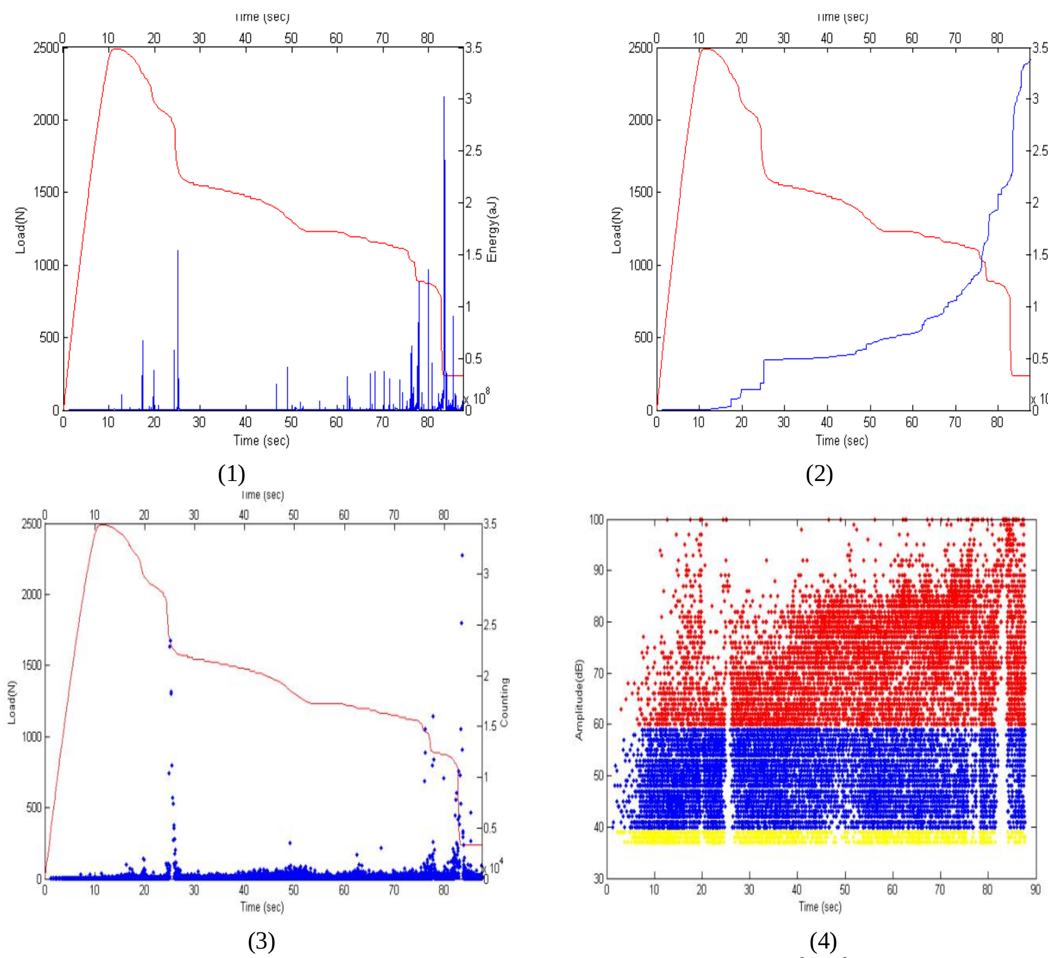
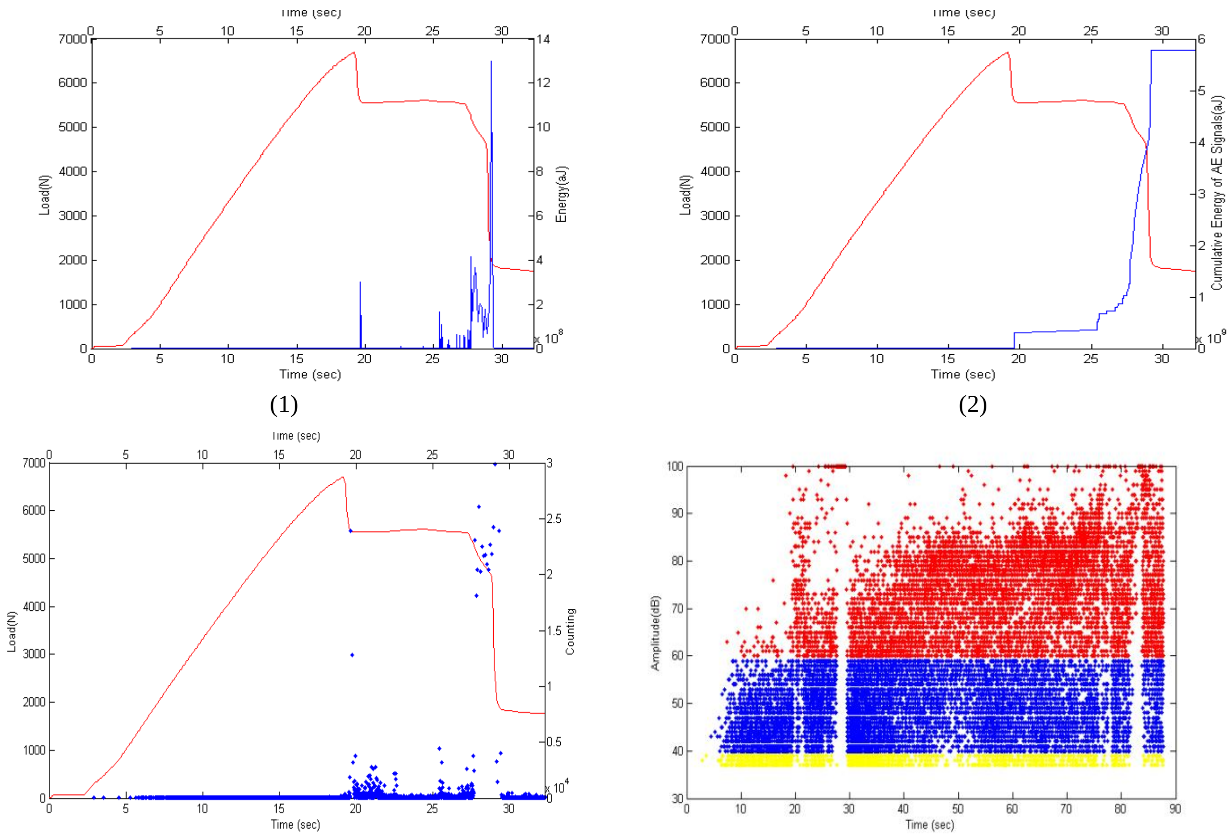


Fig 3. Output curve of acoustic emission tests on composite specimen $[0^0/90^0]_{6s}$ type: (1) Load-time-energy curve, (2)Load-time-cumulative energy curve, (3) Load-time-count and (4) time-amplitude curve.



(1) (2)

(3) (4)

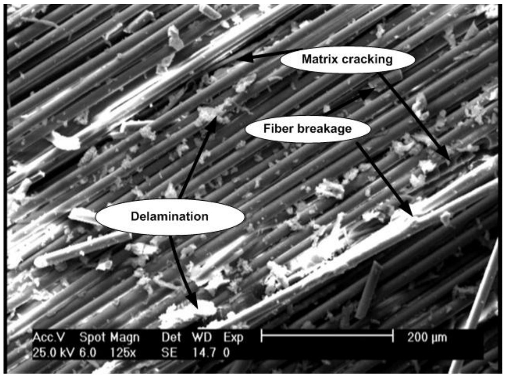
Fig 4. Output curve of acoustic emission tests on composite specimen $[\text{Woven}]_{6s}$ type: (1) Load-time-energy curve, (2)Load-time-cumulative energy curve , (3) Load-time-count and (4) time-amplitude curve.

Table 1 . A comparison of acoustic emission representation for composite specimen [Woven]6s and [0/90]6s

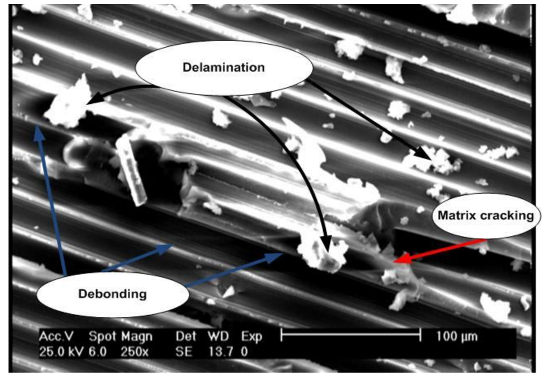
	$[0/90]_{6s}$	$[\text{Woven}]_{6s}$
Critical Load	2500 N	7000 N
Critica Energy	3×10^{8} atto Joul	12×10^{8} atto Joul
Amplitude Matrix Cracking	30-40 dB	30-40 dB
Amplitude Delamination	40-60 dB	40-60 dB
Amplitude Fiber Breakage	60-100 dB	60-100 dB

Scanning Electron Microscopy (SEM)

A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with electrons in the sample, producing various signals that can be detected and that contain information about the sample's surface topography and composition. The electron beam is generally scanned in a raster scan pattern, and the beam's position is combined with the detected signal to produce an image. SEM can achieve resolution better than 1 nanometer. Specimens can be observed in high vacuum, low vacuum and in environmental SEM specimens can be observed in wet condition. For more comprehension of fracture mechanisms, have been observed by SEM. For interpretation of the damage mechanism occurred during loading, the fractured surface is chosen for SEM. In this way, the specimens are coated in gold, having been prepared for viewing fracture surface with a scanning electron microscope. The primary modes of damage observed in the specimens tested are illustrated in the photomicroscographs of the fracture surfaces as shown in Fig. 5 (a) shows matrix cracking, fiber pull-out and breakage, fiber-matrix debonding and delamination in a $[0/90]_{6s}$ specimen. In a $[\text{Woven}]_{6s}$ specimen, fiber breakage, fiber pull-out and breakage, matrix cracking and delamination were observed as shown in (b). Those mentioned above, such as fiber breakage, fiber pull-out and breakage, matrix cracking, fiber-matrix debonding, and delamination are well visible in Figure 4. As this figure is quite clear: Delamination occurs when the composite of two layers are separated, this phenomenon arises hole between the two layers of the composite, fiber-matrix debondin occurs when the fibers are separated from the matrix in place of the phenomenon as a longitudinal slot in the space between the fibers and the surrounding matrix is seen, matrix cracking into cracks and holes will appear in the matrix, fiber pull-out and breakage into rupture of fibers and fiber splitting and cracking appears.



(1)



(2)

Fig 5. (1) Scanning Electron Microscopy (SEM) images taken from breakdown cross section of the composite specimen $[0^0/90^0]_{6s}$ after buckling test. (2) Scanning Electron Microscopy (SEM) images taken from breakdown cross section of the composite specimen $[\text{Woven}]_{6s}$ after buckling test

CONCLUSION

In this study, we investigated the failure mechanisms of the three different types of composite glass / polyester are discussed. The composites were buckling under test and failure mechanisms created to assist in their identification and classification is Acoustic Emission testing. In this study, Effect of two lay-up patterns: energy, count, amplitude are explored. The results of this study indicate that: Although the controlling failure modes can be identified, the complete separation of all appearing failure mechanisms is not easily realized because of the complex interactions among them. Also compare some of the different parameters of the samples we tested. The comparison for all samples:

- The amplitude of Matrix cracking, mostly between 40 - 60 dB.
- The amplitude of fiber-matrix separation (debonding), is mostly between 50 - 70 dB.
- The amplitude of delamination, mostly between 60 and 80 dB.
- The amplitude of fiber pull-out and breakage mostly between 80 - 100 dB.

The results can be understood that various failure mechanisms are different features. If done correctly, acoustic testing and analysis of the data from the tests are good, Thereby can cause all the failures in composite classification and detected with high accuracy.

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