Acoustic Emission Analysis for Damage Mechanism in Fiber Reinforced Polymer Composite under Torsional Behaviour

G. Hemanth Raj, M. Prakash and Abburi Lakshman Kumar
Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamilnadu, India
E-mail: prakashmuniyandi@gmail.com

Abstract. In this study the torsional behaviour of fiber reinforced polymer (FRP) composite rods of different matrix materials like PEEK, Aqua bond, Epoxy are studied and different types of failures are observed. The FRP composite rods are fabricated by using Vacuum Assisted Resin Transfer Moulding (VARTM) method as per the standards. FRP composite rods are tested in the digital torsion testing machine (MTS100NM). The Acoustic Emission (AE) sensors are used to analyse the nature of the cracks. The defects in FRP composite rods are identified, like surface micro cracks, matrix failure and reinforcement failure. After getting AE signals based on different AE Parameters like Time, Frequency, AE hits and AE energy from the obtained results the failure initiation and crack propagation are identified, Hence the AE method is best suitable technique for identify the micro failures.

1. Introduction

Polymer composite materials are being increasingly utilized in many critical engineering applications because of its high strength and stiffness. The stiffness, strength and fatigue properties of laminated composite materials may degrade due to the existence of delamination. This type of damages leads to the catastrophic failure of the polymer composite structured materials [1]. In most of the studies the resin reinforced with fiber laminates was done by hand lay-up with compression molding technique for rectangular plates to test the tensile strength of the composite specimen. The AEWin software along with the data acquisition system with a rate of 40MHz is used to record AE events [2]. Most researchers use polymer composites with different resins and fibers for manufacturing of torsional bar. In this method the liquid composite molding (LCM) technique is used to manufacture structural components and complex shapes with high accuracy. In this technique the voids formation in the specimens is the main difficulty, that depending upon their size of structural composites. In resin transfer molding (RTM) process the resin is transferred by using a mold with a consolidate pressure in the mold after resin injection [3]. Even some studies were focused on impact of plates and cylindrical structures under residual torsional strength (RTS) after the impact strength. Both symmetric and non-symmetric laminated tubes are tested under torsional load to analyse the torsional and impact strength of tubes, the FEM buckling analyses is performed using ANSYS with three degrees of freedom per node [4]. In one of the case the damage monitoring of F82H HIP joints are monitored under the torsional fracture behavior by acoustic emission testing(AE), which is anon-destructive testing method used as appropriate monitor tool in several fields to identify the structural health in a real time for a composite material. The AE elastic waves able to cover a high range of frequency up to 1 MHz. The specimen undergoes the torsional strength where a cyclic load is applied on the manufactured specimens. This test is used to investigate damage mechanism and AE behaviour of the specimen under different loading rate. The torsion tests were performed to investigate the torsion properties of as-prepared specimens, and the AE technique is used to monitor the damage and failure progress [6-8]. All thermoset resins used in this study has high material property strength. The reason behind the
attention of thermoset materials is their thermal and mechanical properties that can handle high temperatures, good process ability and at a low cost, easily available making the most interesting part to utilize these synthetic polymer materials. The resin materials, at high temperature range the porosity in the resin help more to evacuate the carbonization gases from the part during the ablation. The laminates are prepared by hand lay-up method in a rectangular shape with a uniform thickness of 150mm long, 10mm thickness, 25mm width. The tensile tests are performed on the specimens with a speed range of 0.5 to 500mm/min and for all the specimens at a constant load of 2mm/min. The resonant sensors have a frequency range of 513.28 kHz and optimum range of 100-750 kHz [9]. The other polymer materials like polypropylene and high-density polyethylene with the addition is carried out in injection moulding process. All specimens are ‘U’ notched on both the sides and loaded at a speed of 100mm/min. in polymer blends, the mechanical energy is released to identify the micro-failures like inter phase debonding, fiber breakage. To find out the tensile strength of a specimen, the specimen is placed in a test rig under a one point in a fixed position. The load used for tensile strength is around 100 kN. The domains like time and frequency are analysed at four different loads (60.97, 67.75, 74.52, 81.30 MPa). The composite plates have different damage mechanisms in which the AE parameters are named as matrix cracking and matrix debonding and delamination. The statistical method used to identify the difference between unsupervised and supervised data analyses. For most of the other structures like off shore structural applications also we can perform the acoustic emission testing to find out the crack growth in particular structure. In this point the mooring chains are analysed. The mooring chains are commonly observed in offshore structures [10-14]. For metal joints the detailed analysis for damage evaluation through AE by using signal monitoring system is monitored at a lower load cases. The fractographic analysis is performed for maximum and minimum load to explain the damage mechanisms like fatigue, micro cracks formation and river markings. In many analytical methods is used to derive the relation between crack length and bandwidth of the propagated AE waves during crack growth. In this case generally if the crack length increases, the bandwidth of the signal decreases [15-17].

2. Materials and Specimen preparation

In this study the different polymer matrix composite rod used for a typical torsional bar application were examined/tested. Instead of metallic torsional bars the non metallic replacement was studied to observe the mechanical behaviour of the non metallic materials. The polymer materials with a matrix composition of resin material and fiber reinforcement a specimen was prepared as per the ASTM standards to the stipulated the tensile properties of polymer matrix composites. A whole piece of manufactured specimen was reduced to 250mm long and 10mm diameter. The mild steel grippers were manufactured to hold the specimen tight and also help to hold the fixed grip to the testing machine.

The three specimens of polymer resin with fiber reinforcement were manufactured and identified the behaviour of the material at particular load and angle. All the specimens were tested under torsional loading behaviour. The tensile strength of PEEK material is around 90-100MPa. Epoxy has a tensile strength around 65-75MPa, when it comes to the glass filled epoxy the tensile strength increases around 250-300MPa. The epoxy resin has cross-linked chains in themselves through a catalytic homopolymerisation, and this cross-linking reaction is mostly referred as a curing process. Without curing of epoxy it has very poor mechanical and thermal properties. In order to get good properties it has to form three-dimensional cross-linked thermoset structures.

This process usually referred as a curing process or gelation process. The fabricated specimens were cut into the 250 x 10 mm long is the exact measurement of the specimen according to the standards. The extra specimen undergoes a formation of gripper region. The VARTM method consists of successive part manufacturing surface layer for fiber reinforced polymer composite materials. The epoxy resin (LY556) with reinforced glass fiber where total weight of specimen is 12gm approximately.
From the below Fig. 1, the aluminium mold is of 300 x 50 mm with a circular diameter of 10 mm. The fiber was first rolled circularly and then inserted in the aluminium mold and closed with a screws fixed tightly. The aluminium alloy mold is a T6 temper 6063 series, with alloying elements of magnesium and silicon elements. This aluminium mold has a melting point around 615˚C, due to its high melting point the material doesn’t damage or react to the resins that passes from the mold. The mold will be in a closed position after the resin passes from entire material. By using this temper mold the surface finish of the material is also very fine and clean with no damages or surface losses are not observed.

![Figure 1. Aluminium 6063 T6 temper mold.](image1)

From the above fig 2 The VARTM-Vacuum Assisted Resin Transfer Molding setup was placed in the aluminium mold having the fiber and resin inlet valve. The specimen is manufactured by using VARTM Vacuum assisted resin transfer molding process, which is a closed mold composite manufacturing process. This method is a variant of RTM method which replaces the top mold tool with a vacuum bag and by the use of a vacuum assist resin flow. This method has the potential

![Figure 2. Experimental Setup of VARTM method.](image2)
advantages of relatively low cost processing with high volume fractions of reinforcement. The resin to fiber ratio is most important for determining the overall strength and performance of the finished part or final part.

![Manufactured specimens.](image)

**Figure 3.** Manufactured specimens.

This VARTM method is a liquid flow process through a porous media, which has a major effect on the final microstructure and for overall quality of the composite material. Most of all the Liquid Composite Molding techniques have two major processes one resin filling and fiber filling in the mold. This is the best technique for FRP based materials because this technique is best suited for the requirement of high strength and reliability of the material. From the above fig 3 the three specimens A, B, C are epoxy, Aqua Bond, PEEK which are manufactured using VARTM method. This method of specimen is of low cost and can be achieved good surface finishing for complex patterns also.

### 3. Experimentation studies

In this study the main test is torsion tests were performed with an assumed rotation speed, by using digital torsion testing machine (MTT-E-100NM) and the AE sensors are placed on the specimen at both the ends of the specimen with a estimated distance. The resonant transducers are placed on the specimen to identify the acoustic signals. The AE transducer was directly mounted on the surface of the specimen by using plaster and silicon gel to keep it in a fixed position and no chance for any kind of movement in the sensor. The fracture in the material is identified by the sensory signals and differentiated in such a way that the crack initiation, crack propagation and breakage. In this fracture study, the fracture takes place without considerable macroscopic plastic deformation which is generally without a pre-warning. The fracture process takes place in a rapid manner, after initiation there is only a small chance of influencing the fracture.

#### 3.1. Torsion Testing

In the field of solid mechanics, the term torsion is defined as a twisting of a specimen due to an applied torque. It involves in a twisting of a sample along an axis and it is useful to acquire the information about the torsional shear stress, maximum torque, breaking angle of a material. The torsion test was conducted under room temperature in ambient air with implementation of AE monitoring system. The digital torsion testing machine (MTT-E-100NM) was used.
3.2. Acoustic Emission Testing

In this Acoustic emission testing technique is a non-destructive testing method and monitoring method which is used to detect and locate the damages in the material. AE method is a generation of elastic waves produced by a sudden stress in the material. The acoustic emission sensors used to detect the defects in the form of micro cracks obtain in the material. It is also used to identify the micro cracks in the material structures which have low frequencies during micro fracturing. The data that obtain from the acoustic emission is used to distinguish the torsional strength of the composite material. It is also used to analyse the nature of the cracks.

Acoustic emission technique is a phenomenon of ultra wave radiation and sound in materials undergo deformation and fracture process. It is used to track the flaws in mechanically loaded structure by releasing elastic waves through plastic deformation or fracture in the material. In implementing this technique the material undergoes repetitive stress till the material breaks completely. The AE signals are propagated along the surface of the material where the sensor sense those signal continuously along the process. By using the signals, we can able to locate the structural integrity and dislocations in the material. From the below fig.4 it is a digital torsion testing machine (MTT-E-100 Nm) where the specimen is placed in between the cylindrical bars named as channel 1 and channel 2. The rotation starts in opposite directions on both the side of the channel, on channel 1 side rotates in anticlockwise direction and channel 2 rotates clockwise direction.

![Figure 4](image1.png)

**Figure 4.** Digital torsion testing machine (MTT-E-100NM).

![Figure 5](image2.png)

**Figure 5.** Placement of AE sensors on the surface of the specimen.
From the above fig. 5, the AE sensors are located on the surface of the specimen. While performing the AE test, it uses a computer-controlled device known as physical acoustic corporation AE node. Two AE nodes are placed, where two resonant sensors are linked to the AE nodes using cables. The AE nodes have 5volts and 125Ma amps. The resonant sensor has a range of 50-400 KHz. Based on the sensory signals, it gives different parameters like amplitude, rise time, number of counts, duration, AE energy, RMS, signal strength.

4. Results and Discussion

From the above fig. 3, the manufactured specimens are showcased. The three specimens are a) epoxy reinforced glass fiber, b) aqua bond and c) PEEK-polyether ether ketone. VARTM method is used to manufacture the specimen and grippers are arranged at the ends of the specimen to be in a fixed point under twisting mode. The specimens were tested under torsional condition where the specimen undergoes to a twisting moment in opposite directions. The sensors were placed on the specimen with a 15 mm distance from the grippers end on all the three specimens.

The acoustic emission setup was arranged and connected to the computer PC with AE node as a mediator where it generates the sensory signals observed from the specimen. The number of cycles was rotated until the specimen breakage point. The resonant sensor senses the crack signals from a very minor fracture. After the torsional test, the broken specimens were noted where the breakage have occurred on the specimen. From the below fig. 6, the broken specimens are showcased where the specimen a breakage is occurred at the channel 1 and for specimen B breakage is occurred at the nearest place of channel 1 and for peek the breakage is occurred at the channel 2. The torque and angle were calculated using the values obtained from the digital meter on the machine, the graphs were plotted accordingly for every specimen.

Figure 6. Specimens after Torsion Test.
Figure 7(a). Torque vs. Angle for Epoxy Specimen.

Figure 7(b). Torque vs. Angle for Aqua bond Specimen.
Figure 7(c). Torque vs. Angle for PEEK Specimen.

From the above fig 7(a), the graph represents the torque vs. angle of epoxy reinforced glass fiber specimen, the crack initiated at around 30˚ deg angle and continues the propagation. Because of the fiber content in the material the crack propagation line has a wave type of growth. Where the final breakage of the material took place at the angle of 860˚ deg and the pre-breakage point plotted at the angle of 830˚ deg.

From the above fig 7(b), the graph represents the torque vs. angle of Aqua bond specimen, the crack initiated at the angle 20˚ deg and continues propagation. Because of only presence of aqua bond the complete plastic deformation takes place at the angle around 601˚ deg, where the final breakage of the material took place. The continuous signals are been observed by the resonant sensors from the material while the crack propagation takes place in the material. From the above fig 7(c), the graph represents the torque vs. angle of PEEK specimen, the crack is initiated at a starting angle of around 50˚ deg and because of the only PEEK material without any fiber material the material took the highest angle of rotation at 1800˚ deg. The material breakage point took at the highest angle of rotation when compared with other two specimens.
From the above fig 8(a), the graphs are plotted based on the Acoustic emission sensory signal data observed from the specimen while performing the torsional test. The comparison of AE rms value for each material is plotted accordingly based on the signal data obtained from the sensors. The graph represents the rms value of three specimens, from that the peak value of PEEK having around 0.213 to 0.284 for PEEK material, and for epoxy the peak value is around 0.189 to 0.252, and for aqua bond the peak value is around 0.0078 to 0.0104. The signal data obtained from AE sensors will be identified from channel 1 and channel 2. The two sensors are connected to the two channels individually; channel 1 observes some signals obtained in the specimen and similarly from channel 2. The data is characterized accordingly based on the signals which sensor observed the highest number of signals.

**Figure 8(a).** AE rms vs. Angle of Rotation for three Specimens.
From the above fig 8(b), the AE energy (relative unit) of the three specimens is plotted one by one. The comparison of three specimens is represented accordingly. From the graph it represents the peak value or peak point of each material, the highest peak point of AE energy for PEEK material plotted around the range of 8400000 to 11200000 at the angle of rotation 300˚ deg, and for the epoxy material the peak point plotted around the range of 11700 to 15600 at the angle rotation at 200˚ deg, for the aqua bond material the peak point plotted above 159000 at the starting angle of rotation within 50˚ deg.

4.1. Sem Analysis

SEM analysis is used to identify the damages in the materials such as fiber breakage, matrix failures, debonding of fiber and matrix, structure failures, voids. Especially in fiber reinforced structures it is
easy to identify the chemical bonding of each reinforced material respectively. It can generate high resolution imaging and high speed acquisition. The live observation of the specimen with a magnification of around 10x to 50000x within 5-6 orders. The measurement of the specimen is measured in a cross-sectional direction.

Specimen 1: Aqua bond specimen

![SEM image of Aqua Bond](image)

Figure 9. SEM image of Aqua Bond.

From the above SEM image fig 9, in some places we can identify the mirror appearance due to the heat generation effect. On the specimen surface the aqua bond matrix is observed and the circular shapes are noted as scratchy structure while it undergoes the twisting load. From the above fig 9, it is observed that there is no existence of voids in this aqua bond specimen. The nature of crack is appeared from the ductile to brittle nature. The matrix forms a twist fiber structure, which indicates the matrix itself acts as a fiber in reinforced structure [9].

Specimen 2: Epoxy/Glass Fiber

The glass fiber which is used as a reinforced material is a mat glass fiber. From the below SEM image fig 10, we can identify that the fiber are in uniaxial orientation and it is evident. The bonding between the epoxy resin and glass fiber materials is well bonded. In this material the epoxy resin is uniformly distributed throughout the specimen and the transverse fiber of the mat are loosen on break ate damages and rooted deep in the matrix. Due to the well entanglement of epoxy and fibers, the torsional strength of the material increases significantly [6]. The fibers in the material as a reinforced material are arranged in a vertical direction. In this particular material the nature of the fracture is appeared in ductile nature. Mainly there is no much presence of voids in this particular specimen [7].
Figure 10. SEM image of Epoxy/Glass Fiber.

Specimen 3: PEEK-Polyether Ether Ketone

From the above SEM image fig 11, we can say that the ploughing mechanism is observed because of the occurrence of matrix shear, which leads to matrix fracture and rupture. In this particular specimen we can observe that there are no much voids or deeper cracks. The nature of fracture is in the form of brittle nature. The SEM image indicates that the plastic deformation along the fracture surface and no trace of deep cracks are seen, this indicates that there are no propagation of cracks due to torsional load in the material [11].
5. Conclusion

In this study, the crack behaviour of epoxy, aqua bond, and PEEK materials are studied and plotted the graphs accordingly. The Acoustic emission test gives the most detail results of crack behaviour in the material of both inner and outer surface cracks. In most of the other cases it is difficult to identify the inner cracks or micro cracks. It is too difficult to identify the micro-cracks in the material while testing takes place, but by using this non-destructive testing method we can get detail information about the crack behaviour in minor level. The crack propagation events are monitored continuously with the help of sensors. The acoustic events are observed entire the process till the material breakage point. The various data are collected from the acoustic emission data from channel 1 and channel 2, the data we get is rms values, rise time, AE energy, amplitude, signal strength, frequency. From this number of data we concentrated on rms and AE energy at every angle of rotation and the graphs are plotted accordingly based on the supervised data. The supervised data is differentiated from the unsupervised clustered data. In the comparison of the three specimen’s results, the PEEK specimen has highest peak value in rms and also has the highest angle of rotation. Due to the fiber and the epoxy the strength of that material has gained some more elastic properties when compared to the PEEK and Aqua bond. By using the SEM analysis the bonding and the damage mechanism is visualized by the images and concluded that there is no much voids presented in all the three specimens.

6. References

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