CHAPTER 2

LITERATURE REVIEW

Composites are now used in many applications like the automobile, aerospace, marine industries, civil infrastructure and domestic applications. The assessment of damage to composites due to impact load during in-service conditions is important for the prevention of failure as discussed in chapter 1.

2.1 REVIEW OF EARLIER WORK ON DROP IMPACT DAMAGE

The drop impact damage induced in composites produces defects without leaving any visible mark or indication on the surface, which in turn, causes the failure of composite. Many research works have been carried out in the field of composite damage and monitoring the impact loading conditions. A few research works, related to finite element modelling, impact damage tolerance and some work related to the detection of damage, and wear rate were carried out. Mechanical properties by Artificial Neural Network (ANN) model have been studied. Many works towards impact damage in comparison are related to the impact damage characterisation of the composite material, but only a few have focussed on composite damage analysis by the Ultrasonic Technique (UT). Furthermore, only a few research works have been focussed on post impact characterisation, using the Acoustic Emission Technique (AET) by studying the impacted specimen to tensile or compressive load. Brief reviews of earlier literature in this area, are discussed in this chapter.
2.1.1 Drop impact damage

Drop impact damage induced in composites produces invisible defects, which results in the reduction of the load carrying capacity. Finite Element Modelling (FEM) is carried out to simulate drop impact damage and compared with the experimental result. FEM saves material and time spent for the experimental investigation of the drop impact damage.

Cantwell (1988) reported that the flexural stiffness of a target is increased by varying the fibre stacking sequence or increasing its thickness. The mode of initial fracture changes from a lower surface flexural failure to a top surface contact failure. Increasing the surface area on the target by varying its length or width does not alter the amount of damage incurred from high velocity impact loading.

Ghalmminejhad & Parvizi-Majidl (1990) demonstrated that the effect on the impact velocity was insignificant and the impact energy appreciably affects the impact performance of the panels. Below the perforation energy, the damage areas were increased by the increase in the incident impact energy up to a threshold energy beyond which the trend was reversed. The basic failure modes observed within the damage zone were delamination, fibre breakage, matrix cracking, fibre matrix debonding and pull-out.

Robinson & Davies (1992) demonstrated that for a given specimen size of the materials, the damage varied only according to the magnitude of the impact energy and not according to impactor mass or velocity. Hull & Shi (1993) suggested that the damage tolerance of the composite depends upon the properties of the resin and the fibre-resin interface.
Zhou (1998) reported that an experimentally determined impact force is a well proven method for impact resistance measurement. The ratio of measured threshold impact force is a useful alternative to residual compressive strength usually used for damage tolerance assessment.

Benmedakhene et al (1999) suggested that at low velocity impact test, failure propagates primarily in the matrix. As the velocity increases, the failure propagates in the fibre/matrix and interply interfaces. Tai et al (1999) suggested that low-energy impact had a more considerable influence on the tensile strength, for thinner than for thicker laminates.

Anderson & Madenci (2000) reported that the increase in the impact energy produces a tear or crack from the centre of the laminate to the edge. Sohn and Walker (2000) reported that fibre breakage, matrix cracking, delamination, intra-ply cracking and translaminar fracture are the common damage modes induced by impact loading.

Mizutani et al (2000) reported that the internal damage evolution of the composite specimen determines the fibre fracture in the front lamina, transverse cracks in the mid-lamina and delamination and splitting in the back surface.

Yang et al (2000) demonstrated that increasing the density of Z-directional stitching of fibre will moderately increase the delamination resistance of the composites. Delamination followed by micro-buckling and global buckling was the failure observed in woven fabric composites.

Iannucci et al (2001) demonstrated that the composite damage model can correctly predict the matrix micro-cracks in the weft and warp directions of the composite beams being simulated. The predicted fibre fracture in the numerical simulations were in good agreement with the

Prasse et al (2001) reported that the electrical resistance method was able to differentiate earlier strained and damaged laminates, from those stressed for the first time. Acoustic Emission (AE) is better to explain the damage growth. Melin et al (2002) reported that the compressive loads have a larger effect than the tensile load. This is because to the compressive load creates local buckling around the damage zone. Belingardi et al (2002) found that in the glass fibre reinforced epoxy matrix, the strain rate effect is not sensitive to its mechanical properties.

Greenhalgh & Hiley (2003) stated that impact resistance deals with the capability to sustain a given impact risk with the minimum amount of damage and a given level of damage with the least effect on the residual performance.

Shyr et al (2003) reported that fibre breakage occurred prior to the major damage during the impact testing of a laminate. The threshold force and energy for greater damage require further study.

Elder et al (2004) proposed that the Linear Elastic Fracture Mechanics (LEFM) has been used broadly in the Finite Element Analysis. The Cohesive Fracture model solves some of the limitations of the Linear Elastic Fracture Mechanics model. Marshall et al (2004) presented that the pre-stress does not significantly affect the peak force, absorbed energy and penetration depth. The impact energy of the test and the absorbed energy by the composite materials are independent of the pre-stress.
Mitrevski et al (2004a) inferred that the energy absorbed by the specimen was the largest for the conical impactor, which created the biggest indentation/penetration depth. The peak force was the greatest for the hemispherical impactor, which has also created the shortest contact duration.

Riccio & Tessitore (2005) reported that a variation of the local stiffness can cause a variation to absorbance of the impact energy, which results in a change in the damage resistance. Brian Freeman et al (2005) reported that the amount of damage and delamination area increases by an increase in the impact energy.

Zenkert et al (2005) investigated the damage tolerance assessment of composite sandwich panels in a ship’s structural components. It is found that many components in ship structures are not utilised fully. Therefore, in ship structures, components can be allowed to run with damage.

Hosur et al (2005) demonstrated that there is a substantial development in the load carrying capability of hybrid composites as compared to carbon/epoxy laminates. The damage tolerance of structures can be greatly enhanced by hybrid combinations. Sanchez-Saez et al (2005) reported that a woven laminate was found to offer the maximum residual strength under all the impact energies. Shim & Yang (2005) reported that the residual strength and stiffness of the impacted laminates decrease with the increase in the area of the impact damage.

Baucom et al (2006) reported that the energy dissipated during low velocity impact damage is primarily through several interacting damage modes, rather than elastic deformations. The principal dissipative mechanisms are delamination and matrix cracking.
Mitrevski et al (2006) reported that the impact damage modes in a composite laminate are fibre breakage, matrix cracking and delamination. The blunt hemispherical impactor produced the largest damage area followed by the ogival and conical, for all impact conditions.

Feraboli & Kedward (2006) reported that the aperture shape has little effect upon the impact response of a composite target. On the other hand, the support span and laminate thickness have a considerable effect on the impact event.

Hosseinzade et al (2006) concluded that the glass fibre reinforced plates failed under 30 J of impact energy. At higher energies, the damage diameter increased significantly but no disintegration occurred in the plates, whereas in carbon fibre reinforced and carbon / glass fibre reinforced plates, there is no significant damage under 30 J impact energy. However, the structure collapsed unpredictably at the impact energy passed at 50 J.

Atas & Sayman (2007) concluded that impact parameters, such as the absorbed energy, velocity versus deflection or time may give beneficial information on the damage process in laminates. The ‘radius of the impactor nose-to-plate thickness’ ratio may be measured as a parameter in determining the penetration threshold, penetration range, and perforation threshold.

Schubel et al (2007) suggested that the impact damage consists of delamination and permanent indentation in the impacted face sheets. Delamination reduced the compressive strength of the sandwich column to less than half the original strength.

Berketis et al (2008) reported that impacting after the conditioning phase for various immersion time intervals did not increase the damage size
considerably, but produced a larger density of through thickness damage, which resulted in a lower Compression After Impact (CAI) strength.

Hulsenberg et al (2008) suggested that the difference in the thermal expansion coefficients of the fibres and the matrix affects the mechanical as well as damage tolerance properties of the composite.

Philippidis & Theoni Assimakopoulou (2008) concluded that a substantial degradation of residual strength was affected up to 40%, which was a function of the stress ratio, maximum stress and life fraction spent under cyclic loading.

Ballere et al (2009) reported that the empirical relationships were arrived between the impact parameters and residual properties, using the experimental design. There was no considerable decrease in the residual tensile strength below the yield energy level and above this yield energy level, the tensile strength decreases drastically and fracture instabilities occur.

2.1.2 Application of ANN in monitoring damage of composite

ANN is one of the soft computing techniques. ANN was used to train with the help of the real time damage variables. The damage characteristics were determined by the simulation of the ANN, with the help of Non-Destructive data obtained from the damage source.

Sung Choi (2003) reported that the ANN models would be able to capture more of the non-linear characteristics and work well with the linear cumulative damage rule.

Chakraborty et al (2005) reported the use of the Neural Network (NN) in detecting the embedded delamination size, shape and location in the Fibre Reinforced Polymer (FRP) composite laminated structure from the...
simulated data. The actual efficiency of the ANN model will be better when the network is modelled with real time data. Reda Taha & Lucerob (2005) proposed that the method of pattern recognition and damage detection is increased by fuzzy sets.

Leone et al (2006) reported that the Artificial Neural Network was an effective model for the interpretation of the Acoustic Emission signals generated by the pre-fatigued composite, allowing for a quite accurate prediction of its residual strength.

Lin Ye et al (2006) reported that damage characteristics such as delamination, matrix crack and fibre breakage were fed into the ANN, as a damage pattern which is termed as ‘‘Digital Damage Fingerprints’’ (DDF), and were used as the identification of the actual damage in carbon fibre/epoxy matrix laminates.

Just-Agosto et al (2008) reported the Bayesian probabilistic neural network used in the detection of the type, location and extent of the damage of composite materials with data from vibration or thermography.

Bassir et al (2009) reported that the ANN is created in such a way as to relate the mechanical parameters of the material between the true and simulated values. The ANN model simulated the different mechanical behaviours related to the non-linear properties of the composite laminate, including elasticity, plasticity and viscoelasticity.

Bilgehan (2011) reported a comparative study of the neural nets and neuro-fuzzy techniques. The ANFIS (Artificial Nero Fuzzy Inference System) architecture with Gaussian membership function is found to perform better than the multilayer feed forward ANN learning, by a back propagation algorithm. ANFIS modelling may represent an efficient tool for elastic
buckling analysis. These model architectures can be used as a Non-Destructive procedure for the health monitoring of the structural elements.

Jiang et al (2011) presented the first stage of damage detection based on Fuzzy Neural Network (FNN) models, while in the second stage they used both data fusion and FNN models. The proposed method of FNN and data fusion was superior, in structural damage detection with enhanced accuracy.

Beriha et al (2012) found that the fuzzy logic helps to map inputs and outputs for building the inference engine, so that the database model can be used for the prediction of various types of accidents. The prediction of different types of accidents helps the managers to formulate organisational policies for increasing the safety.

Sanza et al (2012) proposed that the multilayer perceptron Neural Network feed with statistical parameters obtained from the wavelet coefficients, was derived for the most sensitive levels of damage for gear condition monitoring. The proposed algorithm was allowed for a suitable scheduling of timely diagnosis at early stages of damage and repair actions necessary for the component.

2.1.3 Impact damage and Non-Destructive Technique

Most of the previous research works were carried out to monitor the damage on the composite material with the help of the Non-Destructive Technique (NDT). The characteristics of damage induced in composite materials are well understood by the Ultrasonic Technique and AET. Many research works were carried out, using UT for the assessment of impact damage during post impact characterisations. Some focussed on AET for the post impact characterisation of composite materials. A few research works
were carried out with Infra Red Thermography, Scanning Electron Microscopy (SEM) and Scanning Acoustic Microscope (SAM).

Scott & Scala (1982) observed that the use of several NDT techniques in combination gives better defect location and extent of damage, than would result from using one technique in isolation. Radiographic and acoustic techniques are best applied to materials in sheet or laminar form of the composite material. Both vibration and acoustic emission techniques appear to possess the potential for predicting failure composite materials.

Challenger (1986) stated that the primary purpose of NDT is to ensure that defects will not become critical before the next inspection. As the size of the damage increases, the residual compressive strength decreases to a constant value. The Need-to-repair criteria must be developed. The Reject-repair criteria should be established for thermoplastics and new tougher thermosets.

Bhat & Murthy (1993) reported that AET has good potential as an online NDT tool for monitoring fatigue damage in composites. Matrix cracking generates lower-amplitude AE events, fibre fracture gives rise to high-amplitude signals. Interface debonding gives out lesser AE events, whose peak amplitude values fall in between matrix and fibre failure mechanisms.

Kaczmarek & Maison (1993) observed that the ultrasonic method supplies a detailed analysis of damage. It can be applied for the investigation of compression fatigue delamination threshold detection on delaminated plates and more generally in post-impact studies.
Dai & Harris (1998) demonstrated that the micro-structural damage due to impact damage resulted in a reduction of the load bearing ability and related increase in AE activity.

Dong & Mistry (1998) reported that the AE monitoring system could be used to detect the first failure sign of the Glass Reinforced Plastic (GRP) material. Aymerich & Meili (2000) reported that the conventional time of flight and amplitude C-Scan at normal incidence was used to check for the presence of delamination, while back scattering C-Scan allows the detection of matrix crack through the laminate thickness.

Mouritz et al (2000) reported that the de-bonding of the surface together with complex arrays of cracks and delamination can be detected by the ultrasonic pulse echo technique. Short cracks can also be detected within the resin rich region.

Ravishankar & Murthy (2000) stated that the AE generated during the drilling of composite laminates carries valuable information on the state of the material being cut. The resulting frictional AE signal was highly dependent upon the type, the nature and surface characteristics of the tool and the laminate. Scarponi & Briotti (2000) reported that the ultrasonic method had capabilities in terms of damage detection, location and evaluation in glass fibre polyester resin systems.

Huguet et al (2002) suggested that during acoustic emission monitoring, a high duration–low/intermediate amplitude (45 to 75dB) event is related to delamination and debond. On the other hand, a high duration–high amplitude event is associated with fibre fracture.
Hosur et al (2003) stated that the general procedure for repair were evaluation and removal of damage, condition of the surface of repair, cutting patches, lay-up of repair patches, curing and assessment of repair.

Quispitupa et al (2004) reported that AE yielded very accurate information on the extent and location of damage in various constituents of the composite. Hosur et al (2004) demonstrated that the ballistic limit was higher for the unstitched laminates. The Ballistic limit was increased by the increase in the thickness of the laminate.

Imielinska et al (2004) proposed that the air-coupled ultrasonic C-scan technique can be used for defect size estimation, during the impact and post impact study. Further, they reported that the carbon fibres partly replaced by glass fibres, and Kevlar/carbon woven fabric laminates may be beneficial with improved damage tolerance and corresponding cost saving. Park et al (2004) suggested that the shear stress and mechanical properties of composites can be measured non-destructively using the AET.

Kawaguchi et al (2004) studied the impact fatigue properties of glass fibre reinforced thermoplastics. They found that the numbers of cycles to failure were strongly dependent upon the duration of the interval time. The results of the AE measurements were in good agreement with the results of the cycles to failure in the fatigue test.

Rojek et al (2005) proposed that it is necessary to know diagnostic dependences individually identified for each test material. Nageswaran et al (2006) reported that delamination and porosity can be effectively detected by the 32 elements ultrasonic phased array technique.

Shoukai Wang et al (2005) stated that electrical resistance was sensitive to even minor impact damage, which was associated with stated
negligible indentation by stated drop impact. The depths of damage induced in the composite material can be measured by the UT.

Angelidis & Irving (2007) reported that impact damage caused significant changes in the local value of the electric potential. Furthermore, there was an excellent correlation between a region of electric potential change and impact damage, as measured by the ultrasonic C-scan.

Arul et al (2007) suggested that the power of AE signal monitored, progressively increases with the number of holes drilled, as indicated by the increased amplitude of the dominant peaks. Park et al (2008) related the AE energy and AE counts with the micro failure process of the composites.

Woo et al (2008) reported that the strong emissions with high frequencies correspond to fibre breakages, whereas a high event rate was induced by the process of delamination and matrix micro fracturing.

Sarasinia et al (2009) reported that the composite materials allow a more effective distribution of impact damage by Acoustic Emission (AE) monitoring, during the flexural test carried out after the impact test.

Rosa et al (2009) suggested that using Pulse Infra Red Thermography the modes of failure were identified in the impact tested composite materials.


Loutas & Kostopoulos (2009) concluded that the analysis of AE hits associated with the damage mechanisms of the material, activated at the
different load levels. The damage evolution and its identification based on the different fibre/matrix interfaces were extracted.

Wang et al (2009) reported that the polymer matrix may be used on the battle field for repair, due to its better properties such as high strength and stiffness, long fatigue life and low density. It has the advantage of easy storage, portability and the ability to be processed on the field using the least equipment. It can also be used to repair flat or curved surfaces.

From the SEM analysis, Arun et al (2010) reported that the nature of fracture and the strength of the composite are dependent upon the type of loading and the environmental conditions. Savage & Oxley (2010) reported that the repair of major damage to complex components is possible, to restore the structural integrity of the polymer composite.

Reyes & Sharma (2010) claimed that the repaired samples show a considerable recovery of stiffness and flexural strength. The maximum recovery of the flexural strength was limited by the fibre breakage damage induced during low velocity impact.

Wang et al (2010) claimed that repair could sufficiently restore the stiffness and static strength of composite parts. The repair design consists of a laminate patch, Aluminium angle bracket and adhesively bonded and riveted joints for the helicopter’s external surface.

Atas et al (2010) reported that the flexural and bending strengths of the repaired samples developed by the vacuum assisted resin infusion moulding process are approximately 54% higher than those obtained by the hand lay-up method.
2.2 GAPS IDENTIFIED IN THE LITERATURE SURVEY AND SCOPE OF THE PRESENT RESEARCH

Drop impact damage initiates an invisible damage in the composite laminate, which affects its residual properties, as reported by Mitrevski et al (2006). Manabendra Das et al (2009) proposed that impact damage should be repaired properly; otherwise, it may trigger extensive damage to airplane structures and disruptions to airline operations. Drop weight (low velocity) impact causes three principle types of damage in laminated polymer composites, namely, matrix cracking, delaminations and fibre breakage, which together can seriously degrade the laminate’s monotonic compressive strength, as reported by Souti & Curtis (1996). Demuts et al (1985) demonstrated that the low velocity impact damage is more severe, and produces delaminations or porosity in composites, since such impact may cause internal damage in a laminate without leaving externally visible marks on the surface. Therefore, further experimental study is needed to monitor the drop impact damage on the composite laminate. Hence, there is a need to monitor the drop impact damage by the Non-Destructive method, and this will help us to know about the damage induced in a composite without any breaking or destructive testing of the composite under investigation.

Many works were carried out to study the post impact damage and the residual properties of composites using Destructive Testing methods. Some research works were carried out using Impact Damage Tolerance (IDT) detection. The Ultrasonic Technique and Acoustic Emission Technique were used for post impact characterisation of composite material. The research works related with IDT analysis by UT are not reported in any of the literature. None of the research works have reported the relation of the online monitoring of impact damage by the AET and IDT of composite materials.
In the present research, an experimental investigation of the drop impact damage on a woven Glass Fibre reinforced Polymer (GFRP) composite laminate is carried out, using the AET and UT. The UT was used to assess the drop impact damage on the GFRP composite laminate as an offline inspection method. The online monitoring of the drop impact damage was carried out through AET using the AE system, by conducting drop impact tests. The significant AE parameters for impact damage were determined.

The compressive strength of the composite decreases considerably, due to drop impact damage, which will affect the load carrying ability and the performance of the material. The effect of impact damage of the specimen can be characterised, by finding the Compression After Impact strength of composite material. The IDT of the impact damaged composite is the measure of the residual Compressive strength After Impact test. The significant AE parameters and ultrasonic parameters for impact damage were related with Impact Damage Tolerance. The above correlation will be used for online and offline monitoring of drop impact damage on the GFRP composite through AET and UT respectively, in real time applications. A separate ANN models were developed for prediction of the IDT value, using AE and ultrasonic parameters. Based on the IDT value, suitable decisions can be taken, and safety can be ensured without destruction to the material.