CHAPTER -2
LITERATURE REVIEW
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Usage of composites in defence and space applications is increasing day by day with new materials and methods of manufacturing composites. But the major factor which needs to be looked into is the performance of these composites when distress or damage due variety of reasons occurs in the systems where they are used. All aircraft and aerospace vehicles during their service life are subjected to severe structural and aerodynamic loads, which may result from repeated landings and take-off, manoeuvring, ground handling and environmental degradation such as stress corrosion. These loads can cause damage or weakening of the structure especially for an aging aircraft thereby affecting its load carrying capabilities and safe life. Strength and stiffness of composite materials are two favourable properties that are used full extent in various structural applications under different kinds of loading. First the ‘long term’ behaviour that involves extended exposure of the component to applied condition that may include mechanical, thermal, chemical environment. Second, ‘failure of the composite’ which is defined by the reduction or depletion of strength or by performance reduction in terms of large deformations can result in damage intolerance and can be discussed in terms of strength , or more precisely in terms of remaining life either with damage or some times after repair and rehabilitation, for further effectiveness in service.

Literature on composites is quite voluminous as materials, manufacturing and testing are being updated every now and then for newer composites developed. A comprehensive review of these is taking place annually or bi-annually in conferences on fracture from 1965 with the recent one ICF-13, held in 2011 [1]. In addition, an update of materials manufacture and applications of composites is held frequently, with the upcoming one on Composites-Europe [2] to be held in Sept., 2013 at Stuttgart, Germany. In addition many text
books—Baker [3] for example—and compilations—like Mallik [4]—are available on variety of composites and their usage. Works specifically related to carbon fibre composites are also available like Daborah Chuang [5]. So the review presented in this chapter is focussed on general references on composites, followed by reported experimental studies on damaged composites and later analytical results on estimation of remaining life after damage in composites. This will enable one to see the need for defining the scope and objectives of the proposed work. The works relating to different kinds of composites used in aircraft and space structures can be in terms of materials, development, manufacturing, testing both at material level and system level.

Abraham and Singh [6] focused on damage effects in composites and finding the residual life and performance assessment. Experimental tests were conducted on composite coupons with and without damage so that both stiffness and material modeling are possible to reflect the current status of the composite component. The composite laminate was made up with zero degree unidirectional carbon fibre and cracks were introduced in different angles and tests were conducted. This result was help to find out the decrement of tensile strength of coupons with damages when compared to a virgin coupon.

Arief et al [7] performed an experimental investigation of open hole fatigue characteristics of plain weave carbon/epoxy laminates. Fatigue life and damage growth of stitched and unstitched laminates under T–T and C–C fatigue were explored. It has been found in their study that the round stitch reduces fatigue limit of carbon/epoxy plain weave laminates under tension–tension fatigue loading. Round stitch accelerates the damage growth emanating from the hole rim, and directs the damage towards the edge of specimen. This damage was relatively unstable when the specimen was subjected to $S_{\text{max}}$ above 83% $S_{\text{OHT}}$. Under C–C fatigue loading, parallel stitch imparts some advantages in impeding the delamination emanating from the
hole. As a result, the parallel stitched specimen can withstand compressive fatigue stress beyond 5.3 million cycles, while the specimen without stitch failed at 2.97 million cycles.

Awerbuch et al [8] monitored Acoustic Emission during quasi-static loading-unloading cycles of filament-wound graphite-epoxy laminate coupons and assessed the validity of the Kaiser and Felicity effects. They concluded that the Felicity ratio could be an indicator of damage severity and/or material quality, and ultimately used as an acceptance/rejection criterion.

Having understood the progression of damage qualitatively, researchers began developing models to predict damage in a quantitative manner. Many of the models follow the stiffness reduction models closely and attempt to relate stiffness change and damage (crack density). Badaliance and Dill [9] formulated a model based on an experimentally observed fatigue damage mechanism and a damage parameter based on intra-laminar resin cracking. Spectrum life was predicted using a damage mechanism and a linear residual strength reduction fatigue damage model.

Bakuckas, Jr. et al [10] first used model specimens of titanium matrix composite system exhibiting dominant failure mechanisms and established correlations between the observed damage mechanisms and the AE amplitude. These correlations were then used to monitor the damage growth process in titanium matrix composite laminates exhibiting multiple modes of damage.

Bussiba et al [11] reported that also for C/C composites tested under quasi-static loading with AE monitoring, three stages in damage progression to fracture could be observed. During stage I, no AE activity was detected, during stage II, the gradual growth of AE counts led to a rapid increase with the formation of knee and stage III, sharp increase in AE counts. Moreover, the similarity in the profile between the cumulative AE counts versus strain data and the predicted crack density versus strain by the micro mechanical model suggested for interlaminar cracking indicates the importance of AE in
monitoring the damage evolution in composites in terms of AE counts. Fast Fourier Transform analysis of the AE waves revealed three characteristic frequencies in Stage III, which is a sign of three main micro-mechanisms simultaneously controlling the failure progress: these appear to be fiber fracture, debonding and matrix cracking.

Experimental characterization of the quasi static tensile behavior and the fatigue behavior of a non-crimp structurally stitched carbon/epoxy composite vs. the unstitched composites was investigated by Carvelli et al [12]. The stitching sites played a role of stress concentrators and trigger damage (higher stitching density results in earlier damage onset) but the general effect was positive, e.g. in the present case, the acoustic emission reveals that the tufted specimens show larger crack energy index and event count under moderate load than the unstitched specimens. On the contrary, under higher loads both criteria indicate lower crack development in the tufted specimens. It was also found that the AE data recorded during tension on fatigued specimens, showed a limited number of AE events up to the load corresponding to the maximum stress in the fatigue loading. When the maximum stress in the fatigue loading was reached, the cracking was re-started.

Chevalier et al [13] performed the series of experiments to study the crack propagation behavior of zirconia-based composites. Slow crack growth under static loading in zirconia ceramics was attributed to stress corrosion by water molecules at the crack tip. Also, slow crack growth under static loading reported in terms of a stress intensity factor caused the net reduction in driving force for crack propagation. Slow crack growth under cyclic loading was also reported and mechanical degradation of all zirconia-based composites was observed by a decrease of crack shielding. The mechanical degradation in samples leads to increased velocities as compared to the static fatigue case.
Composite usage on the current generation of commercial aircraft is largely confined to sandwich construction. For example, control surfaces and fairings are thin skin sandwich structures with a honeycomb core. Due to in-service durability problems with sandwich composites, most notably moisture adsorption and susceptibility to impact damage, future generations of commercial transport aircraft will instead use greater quantities of thick monolithic carbon/epoxy structure.

Researchers have studied a vast number of approaches to obtain level 2 diagnostics (damage detection and location) of CFRP composite systems using guided ultrasonic waves. An unsupervised approach based upon triangulation of impacts or acoustic emissions has been extended to anisotropic composite plates. This was achieved by utilizing genetic algorithms to perform optimization routines Coverly [14].

Triangulation methods in composites have their limitations as well. These include the types of damage it is capable of detecting, as well as the associated increase in complexity and corresponding decrease in accuracy for complex structures which may be highly anisotropic, non-prismatic sandwich type systems connected to stiffening elements. For such systems, error in triangulation based methods results from the large variation in wave speed as a function of propagation path.

In practice, a composite material will contain flaws and variances throughout the structure which will influence deformation and failure of the sample. In order to simplify the ultimate strength prediction most theories have been developed to determine macro-mechanical failure by Daniel and Ishai [15]. The maximum strain, maximum stress and the quadratic failure criterion, compare under loading conditions relative to the principal fibre directions. These theories commonly agree when loading is in the fibre and transverse direction but show variations when other loading directions apply.

Eric et al [16] proposed the aircraft structural life prediction process to fully exploit advances in very high performance digital computing. This proposed
process were utilized an individual aircraft by tail number, a Digital Twin, to integrate computation of structural deflections and temperatures in response to flight conditions, with resulting local damage and material state evolution. The test results are concluded that predicting the life of aircraft structure and assuring its structural integrity was presented and also briefly discussed the technical challenge to developing and deploying a digital Twin.

Gamby [17] recently proposed a numerical model for the accumulation of transverse cracks in a composite laminate subjected to tensile fatigue loading. He found that his damage growth rate equation predicted transverse ply cracking as long as it was the only damage accumulation mechanism. Recently, Ghasemi-Nejhad et al [18] proposed three techniques for embedding active piezoceramic actuators and patches within the woven carbon/epoxy material. Their study mainly focused on the material fabrication process.

Ghosh [19] described the basic principles behind remaining life assessment of engineering components. He has examined a structure component specific function for a minimum specified duration of time. It gives a remaining life of the component which was essential to plan future. The author has concluded that some of experience in real life.

Crack compliance method was used to measure the residual stresses in two Ti/SiC unidirectional composite panels with thick cladding by Gungor [20]. Also, using a matrix etching method, the longitudinal fibre strains were measured from the relaxation of fibres upon dissolving the matrix in a part of the composite. The results showed that the additional HIP treatment indeed reduced the in-plane residual stress levels, with the penalty of increased out-of-plane stresses.

Hillger et al [21] used non contact ultrasonic imaging techniques with air coupling for testing a sandwich test specimen. The sandwich test specimen with CFRP skins (each side 1.25 mm thickness) and two different foam core
materials (different densities) were used for examination with burst excitation. The dimensions of the specimen is 487 mm x 171 mm x 35.7 mm containing several artificially inserted flaws, i.e., two debonding of width 10 mm on the left hand side between the upper and the lower skin, three bore holes of diameter 8 mm and a bore hole of 10 mm in diameter on the right hand side. For the tests, a pair of transducers with a nominal frequency of 200 kHz is used. For the excitation, a burst of 5 cycles with a centre frequency of 166 kHz is used.

The analytical approach presented by Hoyt et al [22] for composite bonded joint scan used for predicting critical failure modes, damage initiation loads and locations, static strength, residual strength, and fatigue life. The analysis approach was applied to two different joint configurations. Only a single delamination location was analyzed for each configuration, in order to demonstrate the analysis approach. A fracture mechanics approach was used to predict damage growth and failure under static and cyclic loads based on test data for static fracture toughness (GIc, GIIc) and crack growth rate (da/dN). The results demonstrate that the proposed approach can be used to predict critical failure modes, damage initiation loads and locations, crack and/or delamination stability, static strength, residual strength, and fatigue life.

The initiation and propagation of damage in composite laminates generate Acoustic Emission. The use of real time AE monitoring has been quite extensive for in-service composite structures. Experimental and numerical studies have been performed to characterize the acoustic wave propagation in thin glass/epoxy composite plates by Huang et al [23]. Experimentally obtained and simulated emission signals were used to identify and locate the source of the acoustic wave. Signal processing algorithms and a passive damage diagnosis system based on AE techniques were proposed for continuously monitoring and assessing the structural health of composite laminates. The local sensing and distributed processing features of the sensor
system result in a decreased demand for bandwidth and lower computational power needed at each node.

**Jae et al [24]** studied the Failure process; mode and strength of unidirectional composite single lap bonded joints were investigated experimentally with respect to bonding methods, which is, co-curing with or without adhesive and secondary bonding. The co-cured joint specimen without adhesive had the highest failure strength. Progressive failures along an adhesive layer occurred in the secondary bonded specimen. In the co-cured specimen with adhesive film, delamination failure occurred and the joint strength was lower than that of secondary bonded specimens. Delamination failure did not occur in the secondary bonded specimen because of early crack growth and progressive failure in the adhesive layer. Therefore, the failure strength of composite bonded joint is not always proportionate to adhesion strength of adhesive due to the weakness of delamination in composite materials.

Design and experimental fatigue analysis of composite multi leaf spring using glass fibre reinforced polymer were carried out using life data analysis by **Kumar [25]**. Compared to steel spring, the composite leaf spring was found to have 67.35 % lesser stress, 64.95 % higher stiffness and 126.98 % higher natural frequency than that of existing steel leaf spring. The conventional multi leaf spring weighs about 13.5 kg whereas the E-glass/Epoxy multi leaf spring weighs only 4.3 kg. Thus the weight reduction of 68.15 % was reported. Besides the reduction of weight, the fatigue life of composite leaf spring was also predicted to be higher than that of steel leaf spring.

**Ladevéze and Le Dantec [26]** investigated and developed laws governing the damage properties of a composite when loaded in tension, compression and in-plane shear failure mechanisms, such as matrix cracking, fibre failure and debonding. To determine the progressive effect of damage, a cyclic loading procedure is conducted on a sample with fibres orientated at 450 to the load
direction. Each cycle is analyzed to establish the change in shear modulus and the onset of inelastic deformation through the shear loading process.

Lee et al [27] presented the results of an experimental investigation conducted to characterize the joint strengths, peel strengths and failure modes in adhesively bonded double-strap and supported single-lap glass fiber-reinforced polymer (GFRP) joints. The joints were composed of pultruded GFRP adherents having the same stiffness as the member that would be used in FRP bridge deck. The FRP plates were made of vinyl ester and fibers, and the surfaces of the plate were sand-blasted before bonding with adhesives. The ration of fibers embedded in the vinyl ester resin was 0 °, 90 °, 45 °,-45 ° =3:1:1:1 and with two different thickness h=4 and 8mm. The design parameters investigated in the study were adhesive type, adhesive layer thickness and overlap length. The load displacement response and joint strength of double-strap joints. It was shown that the joint strength was almost independent of adhesive type, decreased with the adhesive layer thickness and increased with overlap length to clearly define how design parameters affecting the joint geometry influence the joint strength and other mechanical characteristics of the joints.

Liu and Wang [28] developed a more sophisticated progressive damage FE model for external patch repairs which used the Tsai-Wu failure criterion (commonly employed for composite laminates) to detect fibre breakage and matrix cracking in repair and parent material with additional shear failure and stiffness degradation criteria applied to the adhesive. Presented predictions failures reportedly showed good agreement with experimental findings. Fatigue of fiber reinforced laminated composites is also a very important issue for a reliable and durable design. Since the load level threshold at which composites become sensitive to cyclic loading is a very high fraction of their static failure load, composite structures are considered not fatigue critical by McCarty [29]. However, composite components with holes, cutouts, impact
damage, or geometry discontinuity (joint) are more susceptible to fatigue due to the brittle character of fiber reinforced composites. Fatigue damage in composite materials consists of various combinations of matrix cracking, fiber-matrix debonding, delamination, void growth and local fiber breakage. The mechanism, type and distribution of damage depend upon the material system (combination of fiber and matrix materials), stacking sequence, fabrication techniques, geometry of the component, stress state and the loading history.

Marco et al [30] investigated about fatigue behaviour of damaged structural components under cyclic loads constant amplitude and load spectrum. In this investigation for residual life estimation and crack growth analysis Strain Energy Density (SED) method was used. The approach SED method uses the low-cycle fatigue (LCF) properties of the material in crack growth analysis. In this approach experimentally results are obtained dynamic properties of the material such as Forman’s constants are not required when this method is concerned.

Murthy et al [31] presented the methodologies for damage tolerant evaluation of stiffened panels under fatigue loading. They are discussed two major objectives of life prediction and residual strength evaluation of stiffened panels. The author was described various methodologies for residual strength evaluation, namely, plastic collapse condition, fracture toughness criterion and remaining life approach and also compared with other methods of plastic collapse condition and fracture toughness criterion. The analysis results are concluded that residual strength increases with the increase of stiffener size.

First-ply failures in composites typically do not affect their residual capability and useful life, and damage progression to significant (detectable) size was required for life assessment. A comprehensive fatigue structural analysis methodology that captures multi-stage failure modes and their interaction in composites, and predicts initiation and progression of structural damage to
detectable size without a priori assumptions of the initial damage or the damage path was required. The structural analysis methodology being developed by Nikishkov [32] attempted to satisfy these requirements to successfully predict life of aircraft composite parts.

Ogin et al [33] quantized experimentally the relationship between fibre/matrix adhesion with the compressive properties and failure modes of unidirectional carbon-fibre/epoxy composites. They used three identical sets of composites differing only in their fibre/matrix interfacial shear strength. The interfacial shear strength was altered by using the same carbon fibres with different surface treatments. They found that fibre surface treatment affects only slightly the compressive modulus. The compressive strength and maximum compressive strain, however, according to these authors, are highly sensitive to the fibre surface treatment. Both strength and strain increase with increasing the interfacial shear strength.

Three point bend tests were conducted by Plumtre and Ostgathe [34] on 45° off-axis 60% volume carbon fibre reinforced polymer composites under stress control (stress ratio, R=1) and frequency of 4Hz. They carried out these tests to explore the continuous damage accumulation in the matrix without the influence of delamination. Permanent bending was observed at all stress levels and found to be cycle dependent, increasing with longer lives. Bending resulted from matrix debris collecting in cracks on the tensile side of the specimen and preventing them from closing. Bending occurred rapidly during the first (Stage I) 20% of life, then continued to develop at a slower rate over the remaining life (Stage II). This characteristic behaviour was followed by the development of transverse cracks which were monitored during the bending tests. The amount of cyclic bending was found to remain constant, whereas statically bent specimens relaxed.

Rotem and Nelson [35] conducted tests in which tension-compression (T-C) fatigue behavior was compared to tension-tension (T-T) and compression-
compression (C-C) behavior. Tension-compression behavior was found to be the severest loading case as either tension or compression failure can occur. A fatigue failure envelope was proposed and demonstrated. Prediction of fatigue life in GRP unidirectional composites was reported by Salmalian [36]. Evolutionary Algorithms (EAs) are used for multiobjective Pareto optimal design of Group Method of Data Handling (GMDH) type neural networks that have been deployed for fatigue life modeling of unidirectional GRP composites using some input-output experimental data. Multiobjective EAs (non-dominated sorting genetic algorithm, NSGA-II) with a diversity preserving mechanism are used for Pareto optimization of such GMDH type neural networks.

Schulz et al [37] used an advanced waveform-based acoustic emission system to study the initiation of transverse matrix cracking in cross-ply graphite/epoxy composites. It found that transverse matrix cracks initiated at the specimen edge rather than within the interior of the specimen for cross-ply laminates; the stress required to initiate cracking was a function of the thickness of 90 degree layer in the middle of a cross-ply composite. They also brought an important outcome of these tests that the same source mechanism in a composite such as transverse matrix cracking produced a wide range of signal amplitudes depending on the thickness of the middle 90 degree layer and also the length of propagation of the crack across the width of the specimen.

Shivakumar et al [38] have studied the effect of the impact on an ‘eye’-shaped resin pocket defect produced by embedding a fiber-optic sensor perpendicularly to the reinforcing fibers. The fiber waviness due to the embedment of the sensor is represented in their finite-element study by using a local element coordinate system parallel to the distorted fibers. Based on the computed stress concentration factors and residual curing stresses, the fracture stress was calculated using the maximum stress criterion. Their results indicate
that, under a tensile loading, the initial failure is by transverse matrix cracking at the resin pocket root, which then leads to a final fracture by fiber breakage. The model accurately reconstructs damage processes occurring within a loaded unidirectional elastic fibre-reinforced composite. Uniaxial loading of the composite was shown to induce random fibre failures that affect neighboring fibres. Tensile loading produces an increasing number of fibre breaks, controlled by the random nature of defects on or in the fibres. The damage rate and ultimate failure were influenced by several mechanisms at the level of individual fibres around fibre breaks. The load originally supported by the broken fibre was distributed to its neighbors, which locally experience an increase in load. The broken fibre debonds from the matrix over a length that determines the limits of the effects of the break. The composite failed when a sufficient concentration of fibre breaks occurs in a particular section.

The fatigue crack-growth life and the crack-front configuration of centrally cracked aluminum panels in mode-I condition with various single-side repairs of glass/epoxy, graphite/epoxy and boron/epoxy composite patches were investigated by Toudeshky and Mohamm [39]. They found that low curing temperatures with long curing cycles have not a considerable effect on fatigue crack-growth life of the repaired panels with glass/epoxy patch. Also it was observed that considering the thermal residual stresses, the obtained FEM fatigue life and crack-front shapes of the repaired panels using glass/epoxy patch were in good agreement with those obtained from the experiments.

Tsamtsakis et al [40] investigated the behavior of quasi-isotropic carbon fiber reinforced epoxy laminates under monotonic tensile loading using several nondestructive techniques such as acoustic emission, X-ray radiography, the edge replica technique and optical microscopy techniques. They concluded that lower amplitude events were produced when the crack propagation occurred in a stable way and delamination covered the medium range of amplitudes.
The ultimate aim of fatigue crack growth models is to establish a suitable means to predict the residual fatigue life of engineering structures. Usually, the experimental test results in fatigue are noisy and random in nature, although repeated trends are observed. A good prediction of the fatigue crack growth behavior can only be obtained by a stochastic rather than a deterministic differential equation model of Virkler [41]. However, the very purpose of a scientific model is that it must be simpler and faster to apply with some physical meaning during its solution process.

Yang et al [42] carried out for the failure prediction of the composite single lap bonded joints considering both the composite adherend and the bondline failures. An elastic-perfectly plastic model of the adhesive and a delamination failure criterion were used in the methodology. The failure predictions using the finite element analysis and the proposed methodology were performed. The failure prediction results such as failure mode and strength showed very good agreements with the test results for the joint specimens with various bonding methods and parameters. Based on the numerical investigation, the optimal joint strength condition was found and a new joint strength improvement technique was suggested. The suggested technique was verified to have a significant effect on the joint strength improvement.

Ziehl [43] reported that AE technique can be used to evaluate the integrity of a structure. The time of flight of the stress wave can also be used to identify the location of the source. AE can also be used to indicate the level of strain when a specific material becomes significantly damaged, which is useful for design criteria.

Some recent studies with specific reference to damage analysis are done by Bogetti et. Al [46] where nonlinear analysis for predicting response and progressive failure is used for a specific type of composite having layers as laminate and three dimensional modeling was adopted. Hart, D.C.[47]has presented an FEM approach to predict the failure of fuselage frame and uses
braided composite as the material in the study. Recent numerical approaches look into micro and nano levels on damages in composites and the study by Mishnaevsky et al [48] discusses modeling mechanical behaviour, deformation and damage of unidirectional fiber reinforced composites, development of computational tools for the automatic generation of 3D micromechanical models of fiber reinforced composites, and micromechanical modelling of damage. A very recent publication Volume 5 of the ASC series on Damage in Composites[49] and Volume 4 on Failure of composites[50], contain original and path-breaking recent work on composite damage analysis, using empirical test methods and computational models.

Based on the literature survey presented, it is very clear that damage, cracking, progress under different kinds of loadings, different modes of failure progressing towards failure all play a role in affecting the performance a composite damaged during its design life. Both static and fatigue type of loadings can contribute to failure and the role of time and testing means for fatigue loading can be prohibitively costly both in terms of duration and cost, more approximate and effective analytical means to find the performance and remaining life of damaged composites are needed particularly when new composites are evolved. Keeping this in view, scope and objectives of the proposed study for a locally made carbon fibre composite-INDCARF- are defined as follows:

1. As new composites are being evolved, material testing followed by analytical studies need to be done for design inputs and this aspect gets a new dimension when damages occur in the composites for which a hybrid approach using experimental and analytical studies is to be developed which is the first objective of this study.

2. Assessing performance of damaged composites and later the remaining life under static or fatigue loading is important and here the role of
fatigue testing and its cost and time involvement many times leads to testing coupons at different damaged conditions and using the inputs for developing an analytical model using non-linear finite element technique is the best possible and economical and least time consuming solution. This will be developed in this study.

3. Damage parameters relating to initiation, location, spread and types are chosen to envelope all possible damage aspects.

4. Nonlinear finite element analysis accounting for local behavior near the crack is accounted for in assessing the performance of damaged systems and later used for remaining life assessment.

5. A comprehensive design curve for estimating remaining life for different design parameters will be the final result of the study.