2.1 Introduction

This chapter presents detailed literature review based on fracture behavior and delamination of laminated composite structures. Damage mechanism of tee joint structures and skin-stiffener under thermo-mechanical loading is presented. Also, the detailed objectives are listed of present investigation.

2.2 Bimodular material property

According to Classical Elasticity Theory, it is assumed that materials have the same elastic properties in tension and compression, but this interpretation is only for simplicity and it does not account for material non-linearity. Studies [19] have indicated that material such as concrete, ceramics, graphite, and some composites, shows different tensile and compressive strains even when the same stress is applied in tension or compression. The materials which exhibit different elastic moduli in tension and compression are known as bimodular materials [20,21].

There are two basic material models widely used in theoretical analysis within the engineering profession. One model is based on the criteria of positive-negative signs in the longitudinal strain of fibers proposed by [22]. This model is widely used for laminated composites [23-28]. Another model is the criterion of positive-negative signs of principal stress proposed by Ambartsumyan [29] and is applicable to isotropic materials.

The proposal of the stress analysis for bimodular solids were given by Ambartsumyan [29] and Medri [30]. The stress analysis of bimodulus materials is complex because of the elastic constants involved in the governing equations. The bimodular materials model proposed by Ambartsumyan asserts that Young's modulus of elasticity depends on material properties and the state of stress at that point. Except in particularly simple problems, it is difficult to estimate a priori the state of stress at a point in the deformed body. Medri concluded through experiments that the stress-strain curve at the point of origin of material with different moduli is non-linear. In complex problems, it is necessary to resort to FEM based on an iterative strategy [31,32]. Generally, iterative methods based on an incrementally evolving stiffness have been adopted by many researchers [33-41] to calculate the state of stress at a point.

Analytical solutions are available in a few cases, all involving simple bending of bimodular beams, bending-compression columns and thin plates. When analyzing these components, a simplified mechanical model based on subarea in tension and compression is adopted. For the bending problem of thin plates, He *et al*. [42,43] used the Kirchhoff hypothesis to judge the existence of the elastic neutral layers of bimodular thin plates in small-deflection bending. The analytical solutions of a bimodular bending-compression column and a lateral force bending beams considering the neutral axis shift have been derived by Yao and Ye [44,45]. In case of bending of beams, to simplify the derivation, the bimodular beams may be turned into classical beams by an equivalent section method [46] and the approximate elasticity solution of a bimodular deep beam under uniformly-distributed loads has been obtained [47]. Yang *et al.* [48] considered functionally graded cantilever bimodulus beam for evaluating elastic solutions by using semi-inverse method. The series of variational principles and related bounding theorems have been established for bimodulus materials including bimodulus beam [49]. Ye *et al*. [50] and Jadan [51] used the concept of neutral axis shift in case of bimodular beam and developed the formulation for neutral axis shift of bimodular beam. Kamiya [52] has given the concept of transverse shear effect in case of bimodulus beam.

2.3 Application of composites in aerospace structure

Emergence of strong and stiff reinforcements like carbon fiber or graphite fiber along with advances in polymer research to produce high-performance resins as matrix materials have been useful in meeting the challenges posed by the complex designs of modern aircraft. The large-scale use of advanced composites in current programmes for the development of military fighter aircraft, small and big civil transport aircraft, helicopters, satellites, launch vehicles and missiles all around the world is perhaps the most radiant example of the utilization of potential of such composite materials. The current generation military aircraft have about one-third of the structural weight of the aircraft built with advanced fiber-reinforced polymer composites which includes such critical and primary structures as wing, fin, control surfaces and radome. Most aerospace composites use prepregs as raw materials with autoclave moulding as a popular fabrication process. Filament winding is popular with shell like components such as rocket motor casings for launch vehicles and missiles. Oven curing or room temperature curing is used mostly with glass fiber composites used in low speed small aircraft. Resin injection moulding also finds use in special components such as radomes[53].

2.4 Interlaminar delamination in composite structures under mechanical loading

Composite stiffened panels are being predominantly used as aerospace structures due to their outstanding weight/ stiffness and strength ratio and also ease of repair and assembly under in-situ loading conditions. However, these composite structures are susceptible to interfacial or interlaminar damage mechanisms such as delamination, debonding or such other involvement like matrix crack and fiber breakage due to defects or flaws arising even during manufacturing stages, service or maintenance induced damages, or from low-velocity impact damage or from operational malfunctioning. Among, all these damage mechanisms delamination mode of failure is being considered as most critical failure mechanism because in most of the cases, they are embedded in the structure and not visible from outside, and their initial size are very small even for detection by traditional non-destructive testing methodology. Apart from this, during curing stages of multiply stiffeners, residual thermal stresses are induced due to the asymmetric thermal expansion coefficients between differently oriented layers even when the skin-stiffener panels are free from any mechanical loading. Initial prediction of the location and size of such delaminations are almost impossible leading to such unpredictability in failure behavior of aerospace and avionics structures made up of composite stiffened panels. Anisotropy of thermoelastic properties and mismatch of expansion coefficients might be coupled detrimental phenomena, which can induce all of a sudden a very small interlaminar damage to promptly evolve and propagate to catastrophic structure failure, especially under the severity of tensile and bending loading conditions during its structural application. Rice [54] reexamined the elastic fracture mechanics concepts for a crack on the interface between dissimilar solids. Also, the function theory has been given in the form of stress and displacement fields at the vicinity of the crack tip. Many authors have investigated the debonding mechanism and damage propagation of skin/stiffener panels and failure analysis using shell models [55-57] without consideration of manufacturing stage stresses such as thermal residual stresses. These studies focused on the development of step-wise approach to detect the failure mechanism, computational stress analysis to determine the location of first matrix cracking and computational failure mechanics to investigate the potential for delamination growth with the use of numerical and experimental testing activities.

In aerospace application, nuclear reactors and chemical plants, the plates/panels made up of polymer based fiber reinforced composite materials are often subjected to hostile environment conditions during their operational life. In addition to the mechanical loading, these structures are frequently subjected to hygroscopic as well as destabilizing thermal loading. Lekhnitskii [7,8] introduced the complex variable formulation for the problems of two-dimensional linear anisotropic elasticity. Also, Amartsumyan [9] illustrated the fundamental theory and equations based on the anisotropic laminar shell. According to the theory of thermo elasticity, there are basically three reasons of the occurrence of thermal stresses: first, if the specimen experiences a non-uniform temperature field, secondly, if the displacements are obstructed from occurring freely because of the constraints placed on the boundary even with a uniform temperature, and thirdly, if the materials displays anisotropy, even with uniform heating [58]. Composite materials have layer-wise inhomogeneity behavior, thermal stresses usually occur at interfaces between layers with dissimilar fiber orientation and thermal expansion coefficients, causing distortion and stretching of normal to mid-surface. Due to inter-laminar stresses, severe warping and stretching of cross-section may occurred which results in delamination of layers, fiber fraction or debonding of matrix. So, accurate prediction of thermally induced deflection and stress becomes important for the analysis of laminate composite in thermal environment. Hahn and Pagano [59] determined the curing stresses in resin matrix composite laminates over a large temperature range for the appreciable variation of elastic moduli. A method based on total stress-strain-temperature relations is formulated and applied to determine the curing stresses in boron/epoxy composite laminates. Three-dimensional non-linear finite element analyses have been carried out for graphite/epoxy laminated FRP composite single and double lap joints to study the onset and growth of adhesion failure and delamination induced damages

[60-62]. It can be concluded that the positions of the through-the-width delaminations significantly influence the delamination damage propagation behavior viz-a-viz the performance of the composite joint.

2.5 Thermo-elastic damage evaluation using plate theory

Tungikar and Rao [63] obtained three dimensional elasticity solutions for temperature distribution and thermal stresses in simply-supported rectangular laminates. According to the three dimensional elasticity solution given by Pagano [64] and Noor *et al.* [65], three dimensional thermo-elasticity closed form solution is obtained. Usually Classical Laminated Plate Theory (CLPT), First-order Shear Deformation Theory (FSDT) and Higher-order Shear Deformation Theory (HSDT) have been used as solution of thermal problems in composites to minimize computational cost of three dimensional theories, and to reach acceptable accuracy in the field of application. Earlier many authors studied thermal deformation and stresses in symmetric and anti-symmetric laminates using CLPT and FSDT. Ninth order theory was proposed by Matsunaga [66,67] for the analysis of thermal behaviors of laminated composites and sandwiched plates, in which in-plane displacement field composed of a ninth order polynomial in global thickness coordinate z, whereas transverse deflection is represented by an eighth-order polynomial of global coordinate z. Kant and Shiyekar [68] used higher order theory to predict the thermal stresses of laminated composite plates. Global higher order theory is used by Zenkour [69] to present the analytical solutions of cross-ply laminated plates.

2.6 Delamination phenomena based on VCCT under mechanical loading

During the last decades, the delamination growth phenomena of complex composite structures, such as stiffened composite panels, become the main area of research activities.

Many researchers [70-73] have performed experimental and numerical activities on stiffened composite panels containing delamination to investigate the effect of delamination position, depth and size on the panel compressive behavior. Kuriakose and Talreja [74] presented the approximate analytical solutions based on a variational approach for stresses in two cross-ply laminates, $[90_m/0_n]_s$and $[0_m/90_n]_s$, with matrix cracks in the 90° layers, subjected to bending. Suemasu *et al.* [75] have been developed the advanced numerical models, based on the Virtual Crack Closure Technique (VCCT) and on the fail release approach, for the simulation of delamination growth in stiffened composite panels and used for the numerical analysis of the debonding across stringer and skin and for the bay delaminations growth. Pietropaoli and Riccio [76] demonstrated that the delamination growth predictions, obtained with these numerical models, are highly dependent on the finite element size at the delamination front and on the load step size which can be correctly set only with the aid of a large amount of experimental data. Krüeger and Minguet [77] analyzed the debonding behavior of skin-stiffener specimen subjected to tension and three-point bending under mechanical loading. In this paper, total energy release rate and mixed mode ratio have been computed by using VCCT technique. In other paper Krüeger *et al.* [78], authors studied skin/stringer separation of a graphite/epoxy composite panel subjected to shear loading that causes the panel to buckle and resulting out-of-plane deformation. Cetkovic [79] analyzed the thermo-mechanical bending of laminated composite and sandwich plates subjected to mechanical load and linearly varying through the thickness temperature field. A MATLAB program has been used to investigate the impact of plate geometry and degree of material orthotropy on thermo-mechanical response. In other paper, Springer and Tsai [80] analyzed composite thermal conductivities of unidirectional composites and expressions have been obtained for predicting these conductivities in the directions along and normal to the filaments. Also, thermal expansion coefficient of the composite has been analyzed and determined by the method of energy principles [81]. Riccio *et al.* [82] used standard VCCT based approach for the numerical study of skin-stringer debonding growth in stiffened composite panel under compressive load. Three-dimensional thermo-elastic analysis of the composite under residual thermal stresses has been done for the determination of fracture mechanism of imperfect interfaces and cracks [83].

2.7 Damage mechanism in adhesively bonded joints with unimodular material properties

The structural integrity of adhesive bonded joints made of laminated fiber-reinforced composite material is greatly hampered due to the presence of interlaminar embedded delaminations or debonding along the adherend interface. The alternating ply sequence and clustering ply sequence affect differently to the mixed mode interlaminar fracture characteristics and strength of FRP laminated composites due to the mismatch of influence coefficients and Poisson's ratio. For such interface studies, classical laminated plate theories cannot be applied, as in this case the stresses σ_{ZZ}, τ_{zx} and τ_{zy} are not zero, and rather they govern progressive propagation of crack front. So the studies of interlaminar stresses become important for proper characterization of joint failure. These interlaminar stresses are due to the mismatch of Poisson's ratio and influence coefficients between two consecutive layers. Classical lamination theory assumes a plane stress state involving σ_{xx}, σ_{yy} and τ_{xy} but the existence of interlaminar stresses have been recognized for many years. The interlaminar stresses σ_{zz}, τ_{zx} and τ_{zy} are known to be responsible for debonding and delamination at the interface of laminated composites [84-87]. The fundamental reason for the presence of interlaminar stresses in laminated composites is the existence of a mismatch in engineering properties between layers. The two most important lamina properties, which signify this aspect, are Poisson's ratio and the coefficient of mutual influence [88,89]. The Poisson's ratio in this context is defined as the ratio of orthotropic lateral in-plane transverse strain to the in-plane longitudinal strain, whereas the coefficient of mutual influence is defined as the ratio of in-plane shear strain to longitudinal strain. It is to be noted that, if there is no mismatch of Poisson's ratio or influence coefficients between layers then there will be no interlaminar stresses regardless of the mismatch in elastic and shear moduli. In fact, the mismatch of Poisson's ratio between adjacent layers gives rise to dissimilar lateral strains in free boundary (unbonded layers), but induces identical strains at the layer interfaces with accompanying interlaminar stresses in perfectly bonded laminates. As such, the influence coefficients mismatch results in non-zero interlaminar shear stresses in bonded laminates. The moment due to in-plane transverse stresses are balanced by the interlaminar normal stresses. However, the magnitude of the interlaminar stresses developed is dependent upon the magnitude of mismatch in Poisson's ratio and influence coefficients, the elastic and shear moduli of the material, stacking sequence and fiber orientation of the composite laminate.

2.8 Thermal characteristics of adhesive joints

The use of adhesively bonded joint technology has been growing in many structural components to improve the joint performance due to inherent advantages. Adhesively bonding techniques has been widely used due to its ability to distribute a load over a larger area [90,91]. When the adhesive joints undergo thermal load as well as structural load, stress and deformation fields play an important role in the strength of the adhesive joints.

Kim and Lee [92] determined thermal characteristics of tabular single lap adhesive joints under axial loads and investigate the effects of environmental temperature and filler on the tensile modulus and failure strength of the epoxy adhesive. The results show that the average tensile strength of the tabular single lap adhesive joint does not decrease much compared to adhesive properties because the tensile residual thermal stress in the joint decreases as the environmental temperature is increased, and the mechanical properties of the epoxy adhesive decreases sharply in the vicinity of glass transition temperature. Apalak *et al.* [93] conducted three dimensional thermal residual analysis of an adhesively bonded functionally graded tubular single lap joint for a uniform temperature field throughout the joint and two edge conditions.

Adhesive bonding technology has also found a good place in joining advanced composite materials. One method of joining composites is through tee-joints. These joints are typical type of connections and are commonly used in many structural applications such as in skin stiffened panel of aerospace structures, ship hulls of marine machineries, etc. Apalak *et al.* [94,95] analyzed two types of tee joints: with double support and with single support plus angle reinforcement under different loading and two boundary conditions. They showed that the bending load resulted in the higher stress levels in the joint and in the adhesive layer for both the boundary conditions. Li *et al.* [96,97] performed stress and stiffness analyses of simple tee-joint by assuming adhesive and adherends linearly elastic and also investigated the effects of overlap length, thickness of adhesive and adherends on the stress distribution of the joint. Composite tee-joints of sandwich structures subjected to out-of-plane loading was analyzed by Theotokoglou [98] and found that geometric non-linearities were caused by out-of-plane loading of right angled plate. Hu *et al.* [99] analyzed that by increasing the bond line length, the energy absorbed capacity of tee joints increased significantly. Prevost and Tao [100] analyzed the coupled thermo-elastic problem.

2.9 Concept of mixed adhesive technique

Li *et al.* [101] conducted finite element analysis using VCCT for the investigation of the fracture behavior of tee joint structure. The analyzed structure contained initial disbond at various locations and the strain energy released rate (SERR) at the disbond tips is used to predict the failure loads and crack growth mechanism of the structure. Fitton and Broughton [102] investigated the behavior of a variable modulus bond line by the help of numerical and experimental techniques. Da Silva and Lopes [103] found that the mixed adhesive technique provides joint strength improvements in relation to a brittle adhesive alone. Neves *et al.* [104] studied a mixed adhesive single and double lap joint at low to high temperatures using analytical model. Mixed adhesive consists of a high temperature adhesive in the middle of the overlap and a low temperature adhesive at the ends of overlap. Then the results of this analytical model are compared with that obtained from finite element analysis and excellent agreement is ensured between the results. Temiz [105] investigated the application of two adhesives possessing different stiffnesses along the overlap length in double strap joint subjected to bending moment and the possible gains in joint strength through the use of bond line with graded stiffness. A hard adhesive is applied in the middle portion of the overlap, while a softer adhesive is applied towards the edges prone to stress concentrations. The same author carried out non-linear FE analyses to predict failure loads by which effective ratios of properties are identified for maximum joint strength. Halil and Ozkan [106] have carried out 3D FE analyses of bi-adhesively double lap joint considering various bond-length ratios and determined the influence of hybridadhesive bond line on peel and shear stress distributions. They have suggested appropriate bond-length ratios for improved joint strength based on FE analyses. Kumar and Pandey [107] performed 2D and 3D FE analyses of adhesively bonded single lap joints having modulus-graded bond line under monotonic loading conditions. The adhesives are modeled as an elasto-plastic multi-linear material, while the substrates are considered as both linear elastic and bilinear elasto-plastic material. Stress and strain distributions studied at mid-plane as well as at the interface of bond line. It has been noticed that the static strength is more for the joints with bi-adhesive bond lines compared to those with single adhesives in bond line.

Two-dimensional analytical solutions for cylindrical bonded joints, mainly related to the joint overlap, have been proposed by many researchers to ensure that the stress free boundary conditions would be satisfied at the free end. Shi and Cheng [108] developed approximate closed form solutions for cylindrical single-lap joints employing the variational principle of complementary energy with similar boundary conditions and assumptions to those of Allman. Nemes *et al.* [109] proceeded further, employing the same methodology as that of Shi and Cheng [108] to provide a statically determinate elastic solution for the same cylindrical lap-joint by omitting radial stress component in the joint. Various techniques have been employed for the reduction of stress concentrations at the ends of the overlap of single lap joints and hence to improve structural capability [110-112]. These include modifying the adherend geometry [113-115], the adhesive geometry [116] and the spew geometry [117], Tsai and Morton [118]. This technique further advances to functionally modulus graded bondline (FMGB) adhesives to reduce stress concentration and to achieve higher joint strength [119]. These studies mostly concentrated on geometrical aspect of constituent components of joint to maximize joint performance.

Kumar and Khan [120] determined the complete stress field in the whole assembly with a specific concentration on shear and peel adhesive stresses including the axial stress in the adhesive layer, while exactly satisfying traction and traction-free boundary conditions. Therefore, in this study, a stress function approach is adopted in combination of the principle of minimum complementary energy (PMCE) to develop a tractable analytical model for cylindrical joints experiencing axial tension.

2.10 Functionally graded adhesive joints

Carbas *et al.* [121] developed a functionally graded adhesive joint having mechanical properties that vary gradually along the overlap. The functionally graded joint is found to have a higher joint strength compared to the cases where the adhesive is cured uniformly at low temperature or at high temperature. Analytical models have been developed to predict the failure load of the joints with graded cure and isothermal cure. Carbas *et al.* [122] also established an analytical model of functionally graded adhesively bonded single lap joint. The differential equation of this model is solved by a power series. Numerical modeling by finite element analysis is carried out in order to validate the analytical model. The considered graded joint with functionally modified adhesive is found to have a higher joint strength compared to cases where the adhesive has homogeneous properties along the overlap.

Kumar and Scanlan [123] presented improved analytical model in order to perform stress analysis of interface stiffness graded axi-symmetric adhesive joints. They have considered continuous variation of elastic properties of bond line by using suitable modulus functions. These authors also showed significant reduction in peak values of peel and shear stress through parametric study with an appropriate combination of geometrical and material properties of joint system. Stapleton and Waas [124] have addressed practical concerns regarding the use of functionally graded adhesive (FGA) which includes manufacturing complications, alterations to grading due to adhesive flow during manufacturing and impact of loading conditions on effectiveness of grading. These practical concerns are addressed by the same researchers through analytical study. All the investigators have used functionally graded bond line for in-plane joints. Zhan *et al.* [125] have examined the five different types of adhesively bonded T joints through experimental and numerical analysis. It is explained that the variation of the geometry of the bond line has a strong influence on the stress distributions, stress concentrations and the load bearing capacity of the adhesively bonded tee joint. Nimje and Panigrahi [126] improve the strength of out-of-plane joint by employing functionally graded adhesive along the bond line. Two material gradation function profiles (linear and exponential) are used to grade the bond line. The same researchers have performed parametric study with varied modulus ratios to show their influence on out-of-plane and von-Mises stresses along the bond length. These authors [127] also deal with the three dimensional failure analysis of functionally graded adhesively bonded tee joint of laminated FRP composite plate under mechanical loading. Based on the fracture mechanics principles, damage propagation analyses have been studied using the SERR values along damage front.

2.11 Failure of composite skin-stiffener with unimodular material properties under mechanical loading

In recent years, aerospace industries mostly use composite skin-stiffeners due to their outstanding specific strength and stiffness compared to the other metals and alloys. In aircrafts, post-buckling structures are intentionally designed for significant reduction in weight and to withstand the loads. But due to the unavailability of complete and validated methodologies to analyze the structural collapse accurately, there is a very limited application of post-buckling design with composite structures. The most complex failure mechanism of stiffened composite structure includes skin-stiffener debonding or inter-laminar damages under compression loading which ultimately results in complete failure of structure. Such Co-bonded structures are cured for several hours from a higher temperature to lower temperature during manufacturing stages. The difference in thermal expansion coefficients among neighboring plies induces curing stress or residual thermal stress in such stiffened composite structures. This residual thermal stress also plays an important role in deformation and subsequent failure and fracture of stiffened composite panel. Quantifying exactly these induced residual thermal stresses through state of the art experimentation have been either near impossible or much more prone to errors. This renders standard design procedures susceptible to uncertainty in high risk composite panel aircraft structures. Hence in order to increase the life of composite stiffened panels, efficient and accurate numerical tools are required to access the effects of damages on the load carrying capability of structure.

2.12 Study of embedded delamination

In real structures, the embedded delaminations are of very small dimension to be detected by existing non-destructive techniques for detecting flaws [128-132]. Laboratory scale experimentation of inserting teflon sheets between adjacent plies for replicating such delamination behavior fail to address this delamination progression behavior properly [133-135]. The mechanical behavior of composite structures due to inter-laminar damages has been widely investigated by many authors. Experiments on delamination presented by the authors [136-139] have been considered as a contribution in improving the knowledge of defects in composite. Initially, two-dimensional numerical delamination model based on energy release rate calculations [140-142] has been used to simulate the post-buckling behavior of plate while later it has been found that full three dimensional approach [143-145] produces better results. Numerical analyses by means of realistic modeling of delamination have been used to investigate the influence of the geometrical parameters of embedded delaminations on the buckling modes of composite plates [146-148].

2.13 Analysis of delamination growth phenomena using VCCT in skin-stiffener

Composite plates with single delamination [149-153] and multiple embedded delaminations [154] have been studied to find out the problems of initiation and propagation of delaminations using the Virtual Crack Closure Technique (VCCT) and fail release approach. During the last decades, the improved knowledge of delamination growth phenomena accelerates the research activities on delamination which helps in solving complex composite structures like stiffened composite panels. Stiffened composite panels have been analyzed by experimental and numerical approach to investigate the influence of panel compressive behavior on delamination position, depth and size. The delamination growth phenomena based on VCCT is highly dependent on the finite element size at the delamination front and on the load step size which can be correctly set only with the aid of a huge amount of experimental data.

To conquer this problem, a novel and improved numerical approach is introduced [155] by which iterations at the delamination front can be correctly predicted without load step dependency even in coarse finite elements discretization. Riccio *et al.* [156] enhanced the previously mentioned novel numerical approach to simulate the mechanical behavior of delamination positioned beneath the stiffener foot and to investigate the delamination size and position on its evolution. The novel numerical approach has been applied on stiffened composite panels under compression to monitor the delamination growth phenomena [157-160] and inter-laminar and intra-laminar damage mechanism [161]. This novel method is also tested for circular delamination to manage the defect shapes characterizing a skin-stiffener debonding. Post buckling damage growth and collapse analysis of stiffened panels has been done for the next generation composite aircraft designs [162,163] by use of fracture mechanics approach (VCCT). Riccio *et al.* [164] introduced and demonstrated the novel numerical procedure based on VCCT and Cohesive Zone Model (CZM) to study the skin-stiffener debonding growth in composite panels under compressive load. This method is able to overcome the difficulties in setting the cohesive elements parameters.

2.14 Concept of Weibull distribution

The theory of statistical extremes, that is, extreme value of a random variable is used for prediction of integrity and life of individual components. One of the extreme value distributions for smallest values is the Weibull distribution. Weibull [10] developed this distribution to study fatigue and fracture of materials. The Weibull distribution is defined by a few parameters and estimation of these parameters for a given data set is necessary to describe the data set by the Weibull distribution.

2.15 Research gap

1. Evaluation of strain energy release rate of laminated composites has been done under mechanical loading but not under coupling effect of thermal and mechanical loading.

2. Comparison of delamination rate under mechanical and thermo-mechanical loading has not been discussed in case of composite laminates.

3. Effect of bimodularity on delamination of inter-laminar composite laminates has not been studied so far.

4. Comparison of strain energy release rate for different values of bimodular ratio in case of tee-joint and skin-stiffener has not been reported in literature.

5. Effect of functionally graded bimodular material properties on interlaminar delamination has not been done till now.

2.16 Objectives

The main objective of the present work is:

- To study the fracture behavior of graphite/epoxy laminated composite with functionally graded bimodular material properties under thermo-mechanical loading.

The specific objectives of this work include:

- Interlaminar delamination of composite skin-stiffener under thermo-mechanical loading.
- Comparison of SERR values for mechanical and thermo-mechanical loading of skin-stiffener.
- Interlaminar delamination of tee joint with functionally graded bimodular adhesive.
- Comparison of SERR values for mechanical and thermo-mechanical loading of tee joint.
- Comparison of energy release rate for different values of bimodular ratio in case of tee-joint.

- Interlaminar delamination of skin-stiffener composite with functionally graded bimodular material properties.
- Comparison of SERR values for mechanical and thermo-mechanical loading of skin-stiffener.
- Comparison of energy release rate for different values of bimodular ratio in case of skin-stiffener.

2.17 Summary

In this chapter, state-of-the-art literatures have been included for the study of work already done in this area. Review study has been done and written in different sections. In the starting sections, papers based on bimodularity and applications of composite have been incorporated. Then, further literatures related to damage mechanism of composite materials have been comprised. Failure of composite in adhesive bonded joints and skin-stiffeners under mechanical loading and effect of temperature on composite has been investigated. As a future work emanating from the present study, Weibull distribution theory for the calculation of life prediction of component related literature has been included. An outline has also been delineated in Appendix-A for the procedure of developing Weibull model and relevant results has been demonstrated for further study. Based on these literatures, research gap and objectives of the thesis has been given in the last section.