8.1 Conclusion

This thesis deals with the evaluation of fracture behavior of graphite/epoxy composite specimen with bimodular material property under thermo-mechanical coupled field. The Finite Element (FE) based software COMSOL-multiphysics model is used to determine the stress distribution and shifting of neutral axis/ surface. The interface delamination fracture parameter is also investigated due to the influence of bimodulus behavior of graphite and curing stresses by conducting a sequential thermal and geometrically non-linear finite element analysis (FEA) iteratively for evaluating strain energy release rate along the delamination front. The stress dependent elasticity problem of interface fracture has been studied based on the concepts of Modified Crack Closure Integral (MCCI) for different numerical specimens with tension compression bimodulus ratio R varying from 1 to 5 along the bond line for the respective functionally graded bimodular property of the specimen. It is illustrated that the variation of bimodularity index has a strong influence on the interface delamination crack propagation characteristics apart from the other aspects of functionally grading and thermo-elastic anisotropy. The influence of bimodularity in comparison to functionally grading is found to be much more significant on mixed-mode fracture behavior as observed by the dissimilar variation of G_I, G_{II} and G_{III} along the interface failure front, even indicating retardation of the interfacial failure propagation rate over certain zones of structure.

Though most materials exhibit bimodulus behavior at elemental scale, for practical design purposes, the problem are treated as unimodular to get rid of the complexity of the stress dependent elasticity phenomena. However, this makes the high risk aerospace and avionics structure more susceptible to such failure mechanism, which cannot be explained with an application of the classical elasticity theory. In retrospect, consideration of bimodulus elasticity not only invokes the uncertainty of stress field as a priori, but also it necessitates iterative evaluation of state of stress resulting significant computational effort and novel modeling procedures. Now, behavior of laminated structures containing such defects as delaminations are very difficult to predict in those circumstances, as other experimental or analytical procedures render grossly inefficient or illogical to exactly quantify the fracture phenomena. These delaminations are most often very small and embedded in nature, which cannot be detected even with the latest advent of non-destructive technology.

Therefore, numerical procedures as an alternative are found to be effective for quantifying the interface mixed-mode fracture behavior, though the rigors for such iterative computation are only well known. The present work endeavors to study the fracture behavior of delaminated composite specimens with bimodular material properties under thermo-mechanical loading.

8.1.1 General conclusion

Strain energy release rate as the characterizing fracture parameter has been computed for tee-joint and skin-stiffener laminated composites having bimodular material property in thermo-elastic condition based on the concepts of modified crack closure integral. General conclusion has been summarized from the present research work as follows.

1. The bimodular behavior causes the neutral axis shifting on the application of flexural load and affects the state of stress under tensile and compressive loadings.

2. In a multi-lay up laminate, the thermo-elastic properties put a restraining effect on the adjacent plies at the interface. The residual thermal stresses evolved may retard or magnify the mechanism of delamination growth depending upon the loading type.

3. A functionally graded bimodular property of the specimen has revealed significant reduction in damage growth driving forces compared to a composite with unimodular property.

4. The asymmetries in the interface fracture behavior are reasoned to be the effect of anisotropy ratio of thermal expansion coefficients and influence coefficients of the multi-directional laminates with bimodular interfaces.

5. Strain Energy Release Rate is more when coupling effect of curing stress is present than the elastic loading.

8.1.2 Specific conclusion

Following are the specific conclusion that has been procured based on the different analyses from each chapter.

8.1.2.1 Influence of bimodularity on structures

1. The bimodular material exhibits two different stress-strain plots for tension and compression.

2. The bimodular behavior causes the neutral axis shifting on the application of flexural load and affects the state of stress under tensile and compressive loadings.

3. Maximum value of stress in compression zone is quite high in comparison to tension zone, due to material bi-modularity. Young's Modulus of elasticity in tension (E_T) is quite high in comparison to compression (E_C) for graphite composite.

8.1.2.2 Effect of curing stresses on adhesively bonded joints and stiffened panel

1. Multi-lay-up laminate, the varying orientation and stacking sequences along with the heterogeneity of thermo-physical properties affect the distribution of stress, flux and gradient along bond length in case of adhesively bonded tee joints.

2. The asymmetry in angle ply orientation $[0]_8$, $[0/45]_4$, $[0/90]_4$ decreases the von-Mises stress in tee joint.

3. First mode of energy release rate is the most dominant component of the total energy release rate and plays a salient role in characterizing the delamination crack growth behavior and failure of composite laminates for both three point bending and tensile loading in stiffened composite panel.

4. The asymmetries in strain energy rate plots for stiffened composite panel obtained with and without considering the thermo-elastic superposed effect of residual stresses is due to the anisotropy ratio of thermal expansion.

8.1.2.3 Effect of bimodularity on adhesively bonded joints

1. The plot of G_T distribution along the Interfacial failure front, it has been seen that the peak of the distribution pattern is occurring at the center of the delamination front with an asymptotic variation at both the ends. This has been in contrast to the belief of constant strain energy release rate along the interface for self-similar crack front propagation. This uneven energy distribution pattern might lead to interfacial failure propagation characteristics which are geometrically non-self-similar for each subsequent interface delamination progression.

2. Mode I is the most dominant component of the total energy release rate and plays an important role in characterizing the delamination crack growth behavior and failure of composite laminates.

3. A functionally graded bimodular adhesively bonded tee joint has revealed significant reduction in damage growth driving forces compared to a unimodular adhesive. It has been concluded that the bimodularity and gradation of adhesive considerably reduces the failure propagation rate but as we vary the bimodularity index from R =1 to 5, the bimodular effect is found to be more pronounced upon fracture energy distribution in comparison to functionally graded property. Therefore, the difference in tension and compression behavior of adhesive joints has to be appropriately calibrated for a more reliable fracture resistance design.

4. Damage is more pronounced along the interface of the main plate and adhesive compared to the adhesive and substrate interface.

8.1.2.4 Effect of bimodularity on skin-stiffener

1. Strain energy release rate is more when coupled effect of thermal residual stress is considered in comparison to the elastic loading is applied alone.

2. Functionally graded bimodularity significantly reduces the damage growth driving force compared to the unimodular material properties but it is significant that bimodular effect is more pronounced in comparison of functionally graded property.

3. The dominance of failure of structure is when residual thermal stresses have been applied in comparison to the mechanical loading.

4. Coupling effect of thermal residual stresses in some cases, enhances the mixed mode interlaminar delamination crack growth, whereas in others, it also opposes the interface

crack growth mechanism depending the location of the delamination front in between skin and flange.

It has been concluded that the bimodularity and gradation considerably reduces the failure propagation rate but as the bimodularity index vary from R =1 to 5, the bimodular effect is found to be more pronounced upon fracture energy distribution in comparison to functionally graded property. Therefore, the difference in tension and compression behavior of structure has to be appropriately calibrated for a more reliable fracture resistance design.

The desirable intention of the laminated composite designer is to retard interfacial failure propagation rate in order to intensify the structural integrity of the component. As a result, the strength and lifetime of the specimen can be significantly upgraded. In the present research, efforts are made to retard interfacial failure propagation rate by employing functionally graded bimodular material property.

8.2 Future scope

This work is limited to results estimated through simulation procedure only. The results can be evaluated and demonstrated by analytical and experimental work also. Further, there are many scopes for extending the work of this thesis. This section presents some of these directions.

- Weibull distribution parameter can be used for analysis of damages in FRP composite laminates (Ref. Appendix A). Shape and scale parameters of Weibull distribution can be estimated by different methods to analyze the fracture characteristics of composite laminates. Further it can be extended to three parameter Weibull distribution for more precise results.

- Fracture analysis of laminated composite can also be carried out in hygrothermal environment and analyze its effect on strain energy release rate. This thesis includes only the effect of residual thermal stresses. Further effect of hygrothermal can be examine and compared it with thermo-mechanical loading for strain energy released rate.
- Effect of porosity on bimodularity can also be computed for studying the fracture characteristic of laminated structures. Equation of variation of elastic modulus with the effect of porosity along with functional gradation can be implemented and assessed its consequences on strain energy release rate.
- Delamination damage propagation behaviour with different non-linear behaviour of each composite layer with bimodular functionally graded adhesive layer.