Chapter 7

Summary and Conclusions

7.1. Overview

The aim of the present study is to study the buckling and postbuckling responses of functionally graded hybrid composite plates with and without cutouts under various loading and boundary conditions. In this study, influence of curing temperature such as 80^{o}C, 120^{o}C and 160^{o}C and curing duration (1, 2 or 3 hours) on tensile, compressive, shear and flexural strengths, stiffness and failure strain of plain and hybrid specimens are examined experimentally. Also, a novel functionally graded hybrid laminate made of carbon and glass fibers is fabricated. Tensile, compressive, and flexural responses of the functionally graded hybrid laminate are compared with that of conventional sandwich and alternate layers hybrid laminates. The existence of positive or negative hybrid effect in hybrid specimens with respect to strength and stiffness predicted from the ROM (Rule of Mixtures) is demonstrated. Furthermore, the buckling and postbuckling responses of hybrid and functionally graded hybrid composite plates have been determined under uniaxial compressive, in-plane shear, and combined in-plane loads experimentally and numerically. The effect of cutout shape, size, layup sequences and boundary conditions are also examined. Numerical analysis of the composite plates has been performed using a finite element-based software ABAQUS.

7.2. Conclusions

The following concluding remarks are made based on the results presented in the thesis.

1. CFRP specimens aligned in 0^{o} fiber direction cured at 80^{o}C temperature for 3-hour duration, achieved maximum tensile strength and stiffness. Moreover, specimen cured at 160^{o}C temperature for about two hours, has transverse tensile strength equivalent to room temperature cured specimen while maximum stiffness is obtained at 80^{o}C for 1-hour duration which is higher than that of room temperature cured specimens.
2. GFRP 0^{o} fiber aligned specimens cured at 80^{o}C for 3-hour duration is predominant in tensile strength while stiffness is dominant in case of 120^{o}C temperature cured specimens for 3-hour duration. For 90^{o} fiber aligned GFRP tensile specimens, tensile strength is high for 160^{o}C

temperature cured specimens for 1-hour duration, while stiffness is dominant at 160^{o}C temperature curing for about three hours.

3. Shear modulus of CFRP laminates decreases, if specimens are cured at elevated temperature. In case of GFRP laminates, shear modulus depends upon the temperature and duration of curing. The laminate which is cured for three hours at temperature of 160^{o}C gives the highest shear modulus which is 27% higher than that of room temperature cured specimens.
4. CFRP laminate cured at 80^{o}C temperature for 3-hour curing duration has higher longitudinal compressive strength than that of room temperature cured specimen, while the maximum transverse compressive strength of CFRP laminates can be obtained if laminate is cured at 160^{o}C temperature for two hours.
5. Longitudinal and transverse compressive strength of elevated temperature cured GFRP laminates is higher than laminates cured at room temperature. The laminates cured at temperature of 80^{o}C for 1-hour have higher strength than that of room temperature or other oven cured laminates.
6. Tensile and compressive failure strains of GFRP laminates are higher at elevated temperature than at room temperature, while the longitudinal failure strains of CFRP laminates is lower at elevated temperature. The transverse compressive failure strain of CFRP laminates at elevated temperature is higher than that at room temperature, while the transverse tensile failure strain depends upon temperature and curing time.
7. Flexural strength of specimens cured at 160^{o}C for 1-hour duration is predominant for both CFRP and GFRP specimens. Maximum flexural modulus in CFRP specimens is obtained at 120^{o}C temperature for 1-hour curing while in the case of GFRP specimens, maximum modulus is obtained at 120^{o}C temperature for 3-hour curing.
8. Flexural failure strain of temperature cured CFRP specimens is lower than room temperature cured CFRP specimens. The flexural failure strain of GFRP laminates is higher for temperature curing than room temperature curing for specific temperature and curing duration such as 80^{o}C temperature for three hours, 120^{o}C for two hours and 160^{o}C for one hour. Maximum flexural failure strain of GFRP laminate is obtained at curing temperature of 160^{o}C for 1-hour duration.
9. Functionally graded hybrid laminate (FH-$(CG)_s$-II) specimen has the highest tensile strength amongst all sandwich and alternate layer hybrid specimens. The tensile strength of this specimen shows the existence of positive hybrid effect since its strength is higher than plain

GFRP laminate. Alongwith, modulus of elasticity of functionally graded hybrid specimen (FH-$(CG)_s$-I) is higher than all specimens including plain CFRP and GFRP.

10. Functionally graded hybrid specimens also show more progressive failure than sandwich and alternate layer hybrid specimens in tension. Functional gradation of carbon fiber around glass fibers, i.e., glass fibers in the core, is proved to be better than functional gradation of glass fibers around carbon fibers, because of its higher strength and stiffness.
11. The maximum total energy and inelastic energy have been absorbed by functionally graded hybrid specimen T-FH-$(GC)_s$-III. Therefore, this specimen T-FH-$(GC)_s$-III have the highest ductility. Furthermore, the highest elastic energy was obtained by sandwich hybrid specimen T-SH-$(GGCC)_s$ in which glass fiber acts as the surface layer.
12. Functionally graded hybrid laminate (C-FH-$(CG)_s$-III) has peak compressive strength among the sandwich and alternate layer hybrid laminates. Nevertheless, these specimens exhibit less compressive strength when compared with plain CFRP specimens. Sandwich hybrid laminate (SH-$(CCGG)_s$) exhibits highest failure strain than all other hybrid laminates.
13. Flexural strength of the alternative layer hybrid specimen (F-AH-$(GCGC)_s$) is higher than the sandwich and functionally graded hybrid specimens. Moreover, functionally graded hybrid specimen (F-FH-$(GC)_s$-II) has 10% lesser flexural strength than F-AH-$(GCGC)_s$ specimen and 18% lower strength than CFRP specimens. Flexural modulus of sandwich hybrid specimens is similar to the CFRP specimens, while the flexural modulus of F-FH-$(GC)_s$-II is 7% lesser than that of CFRP.
14. The functionally graded hybrid specimens proved to be better in the uniaxial tension and compression, while its flexural stiffness is equivalent to the stiffness of CFRP. Therefore, the functionally graded hybrid can replace conventional hybrids such as sandwich and alternate layers hybrids.
15. The tensile, and compressive strengths of FH-$(CG)_s$-I specimen obtained from analytical equations are closer to that obtained from experimental tests. FH-$(CG)_s$-III specimen has 2.8% higher experimental elastic modulus than the value obtained from analytical equation which is considered as a minor deviation. Hence, it’s been stated that the analytical equations used in this study can be used to determine the strength and stiffness of the functionally graded hybrid specimens.

16. Among the composite plates tested experimentally, CFRP plates have better performance in terms of buckling load due to their high material stiffness while GFRP plates ended up with lower buckling load due to their low material stiffness compared to CFRP plates.
17. The out-of-plane displacements are high on an average in case of GFRP plates as well as glass fiber surfaced hybrid plates such as functionally graded and sandwich hybrid due to their lower stiffnesses.
18. The buckling loads obtained from experimental and numerical studies are in good agreement.
19. Among the hybrid plates, functionally graded hybrid plates have higher buckling, first failure, and ultimate failure loads when compared with the sandwich hybrid plates. The FH plates with stacking sequence of $(-45/+45/0/90)_{2s}$ outperform other fiber stacking sequences as far as buckling and first failure loads are concerned.
20. Amongst functionally graded composite plates analyzed with various sized cutouts, plates with smaller size cutouts have higher critical buckling and first failure loads. Hence, the usage of smaller size cutouts in the composite plates is recommended for practical purposes.
21. From the experiment and numerical studies, it is shown that the hybrid and non-hybrid composite plates can withstand the loads of about four times the buckling loads and about 2.5 times the first failure load on an average of all the specimens.
22. The carbon surfaced functionally graded hybrid composite plates with elliptical cutout (aligned horizontally) at the center stacked in $(-45/+45/0/90)_{2s}$ sequence have the highest buckling, first failure, and ultimate failure loads.
23. The functionally graded composite plates with elliptical cutout aligned vertically have the lowest buckling loads in all the plates with various shaped and sized cutouts.
24. The functionally graded hybrid composite plates aligned with $(-45/+45/0/90)_{2s}$ stacking sequence are highly recommended through this study to use in practical applications especially where the thin walled structures are subjected to uniaxial compressive loads.
25. The maximum critical buckling and first ply failure loads are observed in functionally graded hybrid (FH) composite plates subjected to negative in-plane shear load than FH plates subjected to positive in-plane shear load. The response is poor in plates under positive in-plane shear.

26. The FH plates with fiber aligned in (+45/-45) direction are observed to have highest critical buckling loads in comparison to the plates with fibers aligned in (0/90) and (+45/-45/0/90) directions.
27. The FH plates having stacking sequence of $(+45/-45)_{4s}$ has the highest maximum first ply failure loads when the plates are subjected to negative in-plane shear load.
28. In case of FH plates subjected to negative in-plane shear load, the FPF loads are higher in fibers aligned in (+45/-45/0/90) direction except the plate without cutout. The highest FPF load of plate without cutout is observed in plate with fiber aligned in (+45/-45) direction.
29. Amongst the plates with different shaped cutouts, FH plates with diamond shaped cutouts perform better irrespective of directions of in-plane shear loads and fiber directions.
30. FH plates with small sized cutouts perform better in terms of critical buckling and first ply failure loads. Also, the FH plate with small sized cutout outperforms irrespective of fiber direction, shape of cutout, and direction of applied in-plane shear loads.
31. The functionally graded hybrid composite plates without cutouts has the higher buckling and first failure loads with FBC3 (all four edges clamped) flexural boundary condition.
32. Among the FH plates with different shaped cutouts, diamond shaped cutout plate with FBC3 boundary condition show better performance irrespective of the directions of applied shear loads. Hence, the cutout shape has significant effect on the buckling and postbuckling responses of composite plates.
33. Amongst all the flexural boundary conditions considered in this study, FH plates with all four edges clamped (FBC3) has better buckling and failure loads irrespective of the directions of shear load. It has been concluded that boundary conditions have a major effect on the buckling and postbuckling strengths of composite plates irrespective of the cutout shapes and directions of applied shear loads.
34. In plates with FBC1 and FBC2 boundary conditions, initial buckling and failure loads are higher for negative in-plane shear loaded plates. In case of FH plates with FBC3 boundary condition, ultimate failure loads are higher for positive in-plane shear load. Therefore, effect of direction of in-plane shear is significant in plates with FBC3 boundary conditions.
35. In case of functionally graded hybrid composite plates without cutouts and with in-plane boundary conditions, PBC1 has better buckling and postbuckling strengths irrespective of the presence of cutout and applied shear load directions.

36. Amongst the plates with PBC2 and PBC3 boundary conditions, the plate with PBC2 boundary condition is having maximum buckling and first failure loads. However, the postbuckling strength is higher in plates with PBC3 boundary condition since it has peak ultimate failure load compared to plates with PBC2 boundary condition.
37. Critical buckling, first ply failure and ultimate failure loads are higher in functionally graded hybrid composite plates subjected to in-plane shear loads with respect to uniaxial compressive loaded plates. However, the critical buckling, first ply failure and ultimate failure loads of the similar plates are decreased when they are subjected to combined in-plane loads, i.e., in-plane uniaxial compression (N_x) and in-plane positive and negative shear loads (N_{xy}).
38. Functionally graded hybrid composite plates with smaller cutout size have better buckling and postbuckling responses under the application of combined loads irrespective of in-plane shear load directions, cutout shapes and layup sequences. The response of plate with small size cutout is very close to that of plate without cutout especially in case of combined compressive load with negative in-plane shear.
39. Composite plates with diamond shape cutout have best performance amongst the considered cutout shapes irrespective of the type of layup sequence and direction of shear loads.
40. FH plates under combined compressive load with negative in-plane shear with fiber aligned in (+45/-45) direction have higher critical buckling and first ply failure loads. Ultimate failure loads are higher in FH plates with fiber aligned in quasi isotropic fiber direction under combined compressive load with negative in-plane shear.
41. Effective utilization of plate stiffness until the ultimate load bearing capacity is seen in most of the FH plates subjected to combined compressive load with negative in-plane shear load irrespective of stacking sequences.
42. As expected, increase in ratio of compressive load to in-plane shear load results in decrease in critical buckling, and postbuckling strengths of the composite laminates especially the first ply failure loads.

7.3. Future scope of the present investigation

The outcomes of the present study will have an impact on the construction sector, especially in structural applications. The material used in this study is highly applicable for analysis, design and fabrication of stuctural components as replacement of steel used for reinforment purpose, which will increase the efficiency and lifecycle cost of structures with economy. The functional gradation used in this study is a novel technique which is implemented on composite plates. Also, in place of carbon and glass fibers, composite plates can be made using natural fibers like jute fiber, hemp fiber, bamboo fiber etc. which inturn reduces the cost of the material. Epoxy resin acts as the bonding agent in combining fibers. Therefore, organic epoxy can be replaced with epoxy resin and it can be used in the future. The potential limitations of the present research include whether these structures can be sustained at very high temperatures. This condition is a major challenge for the researchers.

The following research could be done in the future.

a. "Effect of elevated temperatures on postbuckling response of fiber reinforced composite plates"
b. "Effect of elevated temperatures on postbuckling response of functionaly graded hybrid composite plates"
c. "Buckling and Postbuckling response of composite plates made of natural fibers", are some of the studies which can be done in the future to use these materials as fire resistant structural members.