ABSTRACT

The applications of fiber reinforced polymer (FRP) products are increasing in the construction sectors due to its versatile properties such as lightness, resilience to corrosion and ease of installation. They have been found to have almost unlimited usefulness in all segments of the construction industries such as FRP structural elements which includes beams, plates, shells and membranes; bridge repair, cable-stayed bridge, structural strengthening, etc. The FRP products has attracted great attention due to its high specific stiffness, specific strength, non-corrodible characteristics, and chemically inert properties. Incorporating more than one type of fiber in a laminate results in hybrid FRP material. Depending on the location and stacking sequence of the fibers used in the laminate different names are proposed. Also, the fibers considered are functionally graded throughout the thickness of the plate and these are called functionally graded hybrid plates. Since usage of plain FRP became conventional and in-order to reduce the cost maintaining the same strength and stiffness, responses of these materials are investigated in this study. Experimental and numerical analysis have been carried out in this study to understand the nature and behavior of these plates.

Initially, coupons are fabricated made of plain carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) materials to determine the Young's modulus, tensile strength, compressive strength, flexural strength, and flexural modulus of the material. Carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) laminates are used in different structural elements of buildings such as beams, columns, floor slabs, hand railings and for the strengthening of structures. Strength and stiffness of CFRP and GFRP laminates are highly dependent on curing temperature and time. Therefore, it is important to study the influence of temperature and duration of curing on the strength and stiffness of laminates. This study deals with the influence of curing duration and temperature of CFRP and GFRP laminates on the tensile, compressive, and flexural characteristics. Laminates were cured at temperatures of 80°C, 120°C and 160°C for different time periods such as 1, 2 and 3 hours in a hot air oven and another laminate cured at room temperature for 15 days as a reference. It is observed that the mechanical properties of the CFRP and GFRP specimens have better performance when cured under oven heating than being fabricated at room temperature. Conclusions have been drawn that longitudinal tensile strength of CFRP and GFRP laminates is better at 80°C temperature curing for three hours and the

maximum Young's modulus of CFRP and GFRP laminates was achieved at 80°C and 120°C temperature for 3-hour curing, respectively. Similarly, peak longitudinal compressive strength for CFRP specimens was obtained at 80°C temperature cured for three hours and GFRP specimens cured at 80°C temperature for 1-hour. The flexural strength of CFRP and GFRP specimens was highest at 160°C temperature cured for 1-hour. However, the flexural stiffness of CFRP and GFRP specimens was dominant at a temperature of 120°C cured for 1-hour and 3-hours, respectively.

Later, functionally graded hybrid (FH) laminates are developed using carbon and glass fibers dispersed layer wise in proportions throughout the laminate. The properties of the FH laminate have been evaluated under tensile, compressive, and flexural loading conditions and are compared with sandwich and alternate hybrid laminates. Two types of FH specimens are fabricated, one with glass fiber in the core and the other with carbon fiber in the core among which specimens with glass fibers embedded in the core region performed better in terms of strength and stiffness. Analytical equations are developed based on the power law and the results obtained are in good agreement with experimental results. It has been concluded that FH laminates have better performance in tension and compression. Therefore, it is noteworthy that FH laminates can replace conventional hybrids as far as uniaxial tensile or compressive strength is concerned.

Further, experimental, and numerical investigations of buckling and postbuckling responses of square symmetric plates configured with innovative layup sequences have been conducted under uniaxial compressive loading. Effect of stacking sequences and orientation of fibers on buckling and postbuckling responses of fiber reinforced polymer (FRP) plates made of unidirectional carbon and glass fibers are investigated. Initially, plates with fiber aligned in (0/90) directions are fabricated and tested under uniaxial compressive loading, with simply supported boundary conditions. Later, the plates are modeled and analyzed with FEM based software ABAQUS, and a parametric study is performed with various fiber orientations. The plates considered are plain CFRP, plain GFRP, functionally graded hybrid (FH) and sandwich hybrid (SH). Amongst the stacking sequences, such as $(0/90)_{4s}$, $(-45/+45)_{4s}$, and $(-45/+45/0/90)_{2s}$, the functionally graded hybrid (FH) plate with fiber stacked in $(-45/+45/0/90)_{2s}$ directions showed highest buckling and postbuckling strengths. First ply failure was predicted by incorporating the Tsai-hill failure criterion in the numerical analysis. It is observed that plates with glass fibers in the core region have high strength, and the strength significantly depends on the type of plate and fiber orientation. This type of strength enhancement has been observed in all the plate types, i.e., functionally graded hybrid and sandwich hybrid plates. It is further observed that the numerically investigated results are in good agreement with experimentally obtained values. Buckling and postbuckling responses are also investigated for functionally graded hybrid plates with various shaped and sized cutouts, using similar loading and boundary conditions. Circular, diamond, horizontal ellipse, vertical ellipse, and square shaped cutouts were considered in three different sizes (small, medium, and large). It is observed that plates with a smaller size elliptical shaped cutout aligned horizontally and located at the center of the plate have highest buckling, first failure, and ultimate failure loads.

Later, investigation of buckling and postbuckling responses of functionally graded hybrid square plates which are symmetric about its mid plane have been performed under uniaxial in-plane shear load. The cutouts of various sizes and shapes located at the center of the plate are considered. The plate is subjected to positive and negative in-plane shear loads. The boundary conditions used are simply supported on all the four edges of the plate. Three stacking sequences are considered to investigate the optimum stacking sequence at which the critical buckling and first failure loads are highest. Functionally graded hybrid plates (FH) subjected to negative in-plane shear load is more effective compared to plates subjected to positive in-plane shear load. Diamond shaped cutout with small sized perforation has the highest critical buckling and first ply failure loads amongst the FH plates with cutouts. It is observed that the direction of applied in-plane shear load, fiber stacking sequence; cutout shape and size substantially influence the strength and failure characteristics of functionally graded hybrid composite plates.

Boundary conditions are one of the key parameters that have a significant effect on postbuckling response. Flexural and in-plane boundary conditions are considered to study their effects on buckling and postbuckling responses of functionally graded hybrid plate with and without cutouts subjected to positive and negative in-plane shear loads. The quasi-isotropic $(\pm 45/0/90)_{2s}$ layup sequence is considered in the plate for the numerical investigation with various shaped cutouts. The flexural boundary conditions include all four edges simply supported, two edges simply supported, and two edges clamped, and all four edges clamped while the in-plane boundary conditions are simply supported on all edges with different in-plane boundary restraints. The analysis is based on finite element method-based software ABAQUS. Postbuckling strength is predicted by non-linear analysis static-riks method in which geometric imperfections are incorporated and the first failure is predicted by Tsai-Hill failure criterion. The effect of flexural and in-plane boundary conditions on postbuckling strength of composite plates is explained distinctly. Buckling and postbuckling strengths are observed to be higher in plates with all edges clamped while it is lower in case of plates with all edges simply supported in case of flexural boundary conditions. PBC1 in-plane boundary restraint is having high buckling and postbuckling strengths amidst all in-plane boundary conditions. Though plates without cutout have higher buckling capacity, it is worth noting that functionally graded hybrid composite plate with diamond shaped cutout can resist higher in-plane shear buckling load than other shaped cutouts for both flexural and in-plane boundary conditions.

Further, postbuckling response of functionally graded hybrid composite plates subjected to combined uniaxial and in-plane shear loading conditions is numerically investigated. The finite element formulation-based software ABAQUS has been used for the numerical study. Eigen buckling analysis and Tsai-Hill failure criterions are used to determine critical buckling and first ply failure loads, respectively. Functionally graded composite plates with and without cutouts are considered for the study. Five different shapes and three different sizes of cutouts at the center of the plate have been taken to examine the response under the combined in-plane loads. Effect of $(0/90)_{4s}$, $(+45/-45)_{4s}$, and $(+45/-45/0/90)_{2s}$ fiber stacking sequences are also examined. It is shown that, diamond-shaped cutout of small size among the cutouts performs better in terms of buckling and first ply failure loads of the plates under compressive loads combined with negative in-plane shear load. The $(+45/-45)_{4s}$ stacking sequence has the highest buckling and failure loads in comparison to other layup sequences.