Chapter 2

Literature Review

2.1. Overview of the past work

An immense literature review has been conducted on material characterization of fiber reinforced polymer, curing methods incorporated, functional gradation of materials and their characteristics, buckling and postbuckling responses of plates with and without cutouts under various loading conditions and different analytical methods available. The main objective of this chapter is to give an overview of the past research works done related to buckling and postbuckling behavior of functionally graded hybrid composite plates with and without cutouts under various loading conditions. Utilization of composite materials in structural applications is mainly because of their high performance. Other than high performance, composite materials add an advantage of having less weight-to-stiffness ratio and thereby increase the energy efficiency of the components which is an important parameter to be considered in many structural applications. Mechanical behavior of composite materials depend on many determinants such as volume fraction of constituents, orientation of fibers, type of fibers, and most importantly curing technique employed.

2.2 Material characterization

The materials used in this study can be characterized by using different experimental techniques such as uniaxial tensile test, compressive test, shear test, and flexural test using suitable equipment. Before conducting the experiments, fabrication of fiber reinforced polymer coupons is very much important. Various fabrication and curing methods have been proposed by different researchers from decades. A comprehensive review of more than 350 research papers on buckling and postbuckling of orthotropic, anisotropic and unsymmetrically laminated plates without cutouts has been compiled by Lessia (1987). Initially, to know the properties of materials used in the study is of utmost important and how to fabricate them is also significant. Hence, literature review based on material characterization is also included in the chapter.

The mechanical properties of a unidirectional composite system are largely affected by the cure cycle (Esposito *et al.*, 2016) and to obtain the optimum value of a mechanical property, there is an optimum curing time for any given curing temperature (Bang *et al.* 2001 and Olivier *et al.* 1995). There are different curing processes for the fabrication of fiber reinforced polymer (FRP) laminates such as microwave heating, hot air curing, autoclave process, vacuum bagging curing technique, etc. Every method has some advantages and disadvantages. Mechanical properties of laminates also depend upon the saturation and unsaturation of layers with resin. Degree of saturation depends upon the amount of resin flow inside the laminate during manufacturing process (Abrate, 2002; Govignon *et al.*, 2008; Nordlund and Michaud, 2012).

In order to track the resin flow in the laminate, dielectric sensors are used, and results are verified with computational fluid dynamic model (Carlone and Palazzo, 2015). Experimental and numerical models (Carlone and Palazzo, 2015) have shown good agreement of results and these techniques can be used to monitor the degree of saturation during the fabrication of laminates.

Higher tensile and flexural moduli of the composites are gained by the conventional thermal cure process when heated at 70°C temperature for about 80 mins of time period compared to microwave heating cure process (Chaowasakoo and Sombatsompop, 2007).

Quickstep process (Davies *et al.*, 2007) is novel polymer composite manufacturing technique designed for the out-of-autoclave processing of high-quality, low-cost components with a reduction in cure cycle times and resin viscosity facilitating low voids. This method is compared to autoclave curing process (Zhang and Fox, 2007) using carbon/epoxy prepreg. It is observed that the flexural strength obtained from quickstep process shows 10% lower strength than autoclave process whereas other mechanical properties such as interlaminar shear strength performed better when cured under quickstep method than autoclave process (Davies, 2007). Cure cycles in the autoclave process affects the thickness and the void content in the final laminate which can be controlled by varying the pressures applied on the laminate and the duration of pressure applied (Thomas *et al.*, 1997). Degree of cure and gradient change against different thermal influences can be controlled by a neuro-genetic optimization model using genetic algorithms for the autoclave temperature optimization during an imposed thermal cycle (Aleksendri *et al.*, 2016). CFRP and GFRP wrapped specimens experience loss in strength when exposed to high temperatures and this loss increases as temperature increases (Al-Salloum *et al.*, 2011). GFRP material is much more vulnerable under shear and compression than under tension when subjected to elevated temperatures, but at 220 °C the material strength still retains about 54% of its ambient temperature strength (Correia, 2013). Shear and compressive strengths are drastically reduced for elevated temperatures, exhibiting strength retentions compared to ambient temperature i.e., 11% for shear and 5% for compression (Correia, 2013).

In another study, small reduction in the tensile strength of the coupons was noticed in between temperatures 20–150 °C, while at 300 °C the ultimate strength was approximately 50% of the room temperature strength (Wang *et al.*, 2011). Significant change in the mechanical properties was observed in glass fiber reinforced polymer laminates cured under different times and temperatures (Kumar *et al.*, 2015). At elevated temperature, polymer matrix composites show the better chemical properties and amount of cross-linking also increases (Aruniit *et al.*, 2012). It is also noticed that with increase in the temperature and time, material becomes too brittle. Necessary curing time to reach the maximum tensile strength can be significantly reduced from several hours at room temperature to approximately 30 min at 90 °C temperature (Czaderski *et al.*, 2012). With increase in temperature, failure mode changes from fiber pull out to fiber breakage and has significant effect on the impact strength of composites (Badawy, 2012). Flexural strength and modulus increase after exposing to the temperature and with increase in fiber volume fraction (Furtos *et al.*, 2012). However, the temperature and time combination depend on the type of resin system used (Johnson and Owston, 1973). Along with properties of fibers, strength and stiffness of laminates also depend upon the thermal properties of resin (Hogg *et al.*, 1993).

Liu *et al.* (2006) established an optimum cure cycle by altering the cure pressure within the range of minimum viscosity. It can effectively shorten the cure cycle by nearly 1-h if appropriate pressure is applied.

In another study by Li *et al.* (2001), optimization techniques which include design sensitivity methods were utilized to minimize the duration of cure of laminates maintaining thermal degradation and to achieve proper consolidation. Optimum temperature profile was developed using numerical simulation which can be used during curing process and decrease the thermally induced residual stresses produced during the curing of laminates (Gopal *et al.*, 2000). Observing the temperature gradients, which shows the behavior of residual stress in the material. But residual stresses can be reduced by choosing optimal gradients. The loss of strength and stiffness in laminates is due to the lack of load-sharing between individual fiber rovings at the temperature closer to glass transition temperature of resin, which is due to the softening of laminate (Chowdhury *et al.*, 2011). Failure always occurs through fiber fracture and occurs with very little permanent deformation. The stress-strain curve of CFRP remains unchanged as strain rate increases but GFRP has notable changes at low and high strain rates. At low strain rate, fiber breaks while at high strain rate, fiber splits and fiber pullout occur, and hence the serration appears in the stress-strain curve (Babukiran and Harish, 2013). CFRP outperformed GFRP in all respects such as tensile strength, stiffness and specific absorbed energy except in case of transverse tensile strength (Wonderly *et al.*, 2005). Even though the total energy absorbed by GFRP is more than CFRP, but the specific absorbed energy is high in CFRP laminates. Transverse properties of CFRP can be improved by more elaborate joint design (Wonderly *et al.* 2005). Despite all, curing process of these laminates is very crucial because of its high dependence on its engineered/mechanical behavior.

Bai *et al.* (1996) conducted experiments to establish relation between fiber matrix adhesions. They examined the interfacial shear strength with different surface modifications and the values changed from low to intermediate then to high. They also observed that interlaminar shear strength determined from short beam shear strength followed the same trend while the fiber properties remained unchanged. Nightingale and Day (2002) investigated flexural and interlaminar shear properties of specimens cured under autoclave curing and microwave curing as well. They observed that properties were greater for specimens cured under autoclave.

Fan *et al.* (2008) examined the Interlaminar Shear Strength (ILSS) by suspending the multi walled carbon nanotubes into normal glass fiber mats and observed about 33% increase in ILSS. Authors (Fan *et al.*, 2008) concluded that preferential orientation of multi walled carbon nanotubes in the thickness direction contribute to increase in ILSS.

Whitney and Browning (1985) conducted experimental and analytical analysis to examine interlaminar shear strength of unidirectional composites under three-point Short Beam Shear (SBS) test and four-point flexure tests. Authors (Whitney and Browning, 1985) observed complex failure modes under extremely high combined stress gradients. The regions where high shear stress (any direction) exists tend to suppress interlaminar shear failure mode by compression stresses. Finally, they concluded that initial damage in the form of vertical cracks appears to induce mixed mode horizontal interlaminar failure and for specimens without initial damage, the failure mode is a combined compression and shear.

Zhang *et al.* (1986) and Cecen and Sarikanat (2008) illustrated the effects of geometric variables on the structural integrity and ILSS under short beam shear test. Strong correlation between the changes in the interlaminar shear strength values and fiber orientation angle in woven fabric laminates have been observed. Failure of specimen occurs suddenly in a macroscopically brittle mode by crack initiation and propagation. A sharp drop in the load–displacement curves and an audible cracking sound accompany catastrophic delamination. Authors also investigated the interaction between glass fiber and polyester matrix by interpreting experiments in conjunction with scanning electron photomicrographs of fractured surface of composites. Authors concluded that ultimate strength of laminates was lost in the matrix-dominated orientations because of the matrix-controlled failure mode.

Sideridis *et al.* (2004) studied the interlaminar shear stresses of chopped strand mat (CSM) glass fiber reinforced polyester laminates both experimentally and analytically. Lap shear specimens were tested, and they concluded that length of the shear surface have significant effect on results. The cracking mechanism was examined using photomicrographs and observed that the cracks tended to follow the fiber/matrix interface and the distribution of fibers appeared to influence the orientation of the cracks. Authors also determined the shear strength of unidirectional glass fiber reinforced epoxy resin composites in different fiber directions with the short beam three-point bending test. Authors concluded that shear stress highly depends on slenderness ratio of the specimen. Shear fracture occurs at the interface or through the resin but not through the fibers have been observed. Authors prepared resin rich laminates to compare with normal laminates and concluded that these resin rich laminates have severe effect on moduli of the specimens.

Shekar *et al.* (2014) conducted short beam shear test on carbon nanotubes, carbon fiber reinforced epoxy matrix hybrid composite and concluded that orientation was very significant in deciding the interlaminar shear strength.

2.3 Buckling and postbuckling response of composite plates

The references mentioned in foregoing paragraphs primarily deal with buckling and postbuckling responses of plates or laminates. Buckling phenomenon of plates due to mechanical loads is a traditional topic in engineering mechanics. The plates may still sustain additional loads even after buckling occurs (Liew *et al.,* 2006). Therefore, there is a lot of research scope in the mechanical behavior of plates to make full use of their strength.

The different laminated plate theories, such as the classical laminate plate theory (CLPT), First Order Shear Deformation theory (FOSDT), Higher Order Shear Deformation Theory (HOSDT) and layer-wise theories have been employed in numerical studies for failure analysis. Turvey (1980-82, 1987) investigated the failure of laminated plates without cutouts in the early days using analytical solutions. Author considered symmetric and anti-symmetric laminates with simply supported boundary conditions under transverse load. Buskell *et al.* (1985) conducted the tests to investigate the postbuckling behavior and failure mechanisms of rectangular quasi-isotropic panels. Reddy and Pandey (1987) predicted the first-ply failure load of composite laminates, using finite element method (FEM), subjected to transverse and in-plane loading. Kam and Sher (1995) investigated the nonlinear behavior and the first-ply failure strength of centrally loaded laminated plates with semi clamped edges based on von Karman Mindlin plate theory in conjunction with the Ritz method. The first-ply failure of laminated panels under transverse loading was analyzed using an eight-noded isoparametric quadratic shell element by Prusty *et al.* (2001) using various failure criteria and predicted the first-ply failure load of various plates and shells with varying lamination schemes. Buckling and postbuckling responses of composite plates with cutouts have been studied numerically and experimentally by Kong *et al.* (2001). Jain and Kumar (2004) investigated the effect of cutout shape, size and the alignment of the elliptical shaped cutout on the buckling and first-ply failure loads (based on Tsai-Hill failure criterion) of laminates and observed that these parameters have a substantial influence on the reserve strength of composite laminate beyond buckling. Barbero and Lonetti (2001, 2002) and Lonetti *et al.* (2003) proposed a model for damage initiation, evolution and failure of composite structures at critical values of damage based on the concepts of thermodynamics of irreversible processes.

2.3.1 Uniaxial compressive loading

Many researchers (Bisagni, 2000; Xie and Biggers, 2003; Gal *et al.*, 2006; Lopes *et al.*, 2007; Kere and Lyly, 2008; Kumar and Singh, 2012; Reinoso *et al.*, 2012; Boni *et al.*, 2012; Rivallant *et al.*, 2013; Hofmeyer and Courage, 2013; White *et al.*, 2015; Farooq and Myler, 2015) investigated the postbuckling response of composite plates under various loading conditions, boundary conditions, layup sequences, and orientation of fibers. Generally, functionally graded materials are made of ceramic and metal or a combination of metals (Najafizadeh and Eslami, 2002) but in the study by Singh *et al.* (2018), laminates made of carbon and glass fiber are combined and a functionally graded hybrid (FH) laminate is developed. Lee and Hyer (1993) studied the postbuckling failure characteristics of square laminated plates with a circular hole under uniaxial compression using the maximum stress failure criterion.

Vescovini and Bisagni (2013); Soh *et al.* (2000); Kassapoglou (2008) tested and analyzed the composite plates in order to determine the possible buckling load carried by the composite plates and the maximum postbuckling strength of the plate until the ultimate failure is determined. Comparisons between experimental and analytical results have also been done (Pevzner *et al.*, 2008; Yang *et al.*, 2013).

Singh *et al.* (2008) predicted the failure loads of laminated plates under uniaxial compressive loading. Authors concluded that first ply failure and ultimate failure loads depend on the type of laminate layups and first ply failure location lie near the loaded edges of the plate. Also, first ply failure load and ultimate failure load are found to be highest in $(-45/+45/0/90)_{2s}$ quasi-isotropic laminates. Engelstad *et al.* (1992) analyzed graphite-epoxy (GE) panels loaded in compression to determine the postbuckling response and predicted failure using maximum stress and Tsai-wu criterion.

Kumar and Singh (2010) investigated the buckling and postbuckling strengths of composite laminates in addition to the effect of composite layup, i.e., $(+45/-45/0/90)_{2s}$, $(+45/-45)_{4s}$, and $(0/90)_{4s}$. Authors concluded that plate with fiber aligned in $(-45/+45)_{4s}$ directions has maximum buckling strength while $(+45/-45/0/90)_{2s}$ laminate has maximum ultimate failure load.

Namdar *et al.* (2017) studied buckling, postbuckling and progressive failure analyses of composite laminated plates under compressive loading. Authors observed reduction in stiffness of plates after damage initiation. Authors also concluded that composite plates can withstand about four times higher load than their critical buckling loads during postbuckling. When a thin plate is subjected to in-plane compressive loading, it initially doesn’t deform from its original position and stays in equilibrium position. As the application of load increases, it starts buckling in the out-of-plane direction. Further, it will start cracking or failure starts in the plate progressively layer–by-layer and the laminate completely fails which is the ultimate failure.

The effects of geometric imperfections are also considered by Hilburger and Starnes (2004) since the initial buckling of composite plate depends on the plate’s geometrical imperfection. Failure mode of composite plates depends on the rate of crosshead motion (Wang and Cho, 2012) of the actuator, i.e., compressive properties and failure modes were severely affected by strain rates.

Cutouts in fiber reinforced polymer plates are required in construction industry since they have access in the members for passing the cables, hydraulic lines, and for damage inspection (Nemeth, 1995). Singh and Kumar (2008) investigated the postbuckling response of composite laminate with various shaped and sized cutouts and it has been reported that cutout shape has considerable effect on buckling and postbuckling behavior of laminate with small sized square shaped cutout.

2.3.2 In-plane shear loading

The variable angle tow composite plates analyzed under negative shear performed better than plates under positive shear (Raju *et al.*, 2015). With the increased use of plates made of functionally graded materials, it is also important to investigate the buckling and postbuckling behavior of functionally graded hybrid plates (Shen and Leung, 2003).

Cutout size and shape play significant roles in the mechanical responses of composite plates (Jain and Kumar, 2004; Yazici, 2009). Under various loading conditions, cutout shape and size also affect the buckling and postbuckling behavior of composite plates.

Ghannadpour *et al.* (2006) investigated the buckling behavior of square plates with cutouts and concluded that, with the increase in cutout size buckling load decreases. Similar conclusion was made by Kumar and Singh (2010) about the buckling and postbuckling behavior of CFRP laminates with a cutout.

Zhang and Matthews (1984) observed that the direction of in-plane shear load also affects the postbuckling behavior of composite plates. Guo *et al.* (2009) investigated the effect of reinforcements around cutouts on the buckling behavior of the composite panel made of carbon fiber reinforced polymer (CFRP) under in-plane shear load. Stoll and Johnson (2016) investigated in-plane shear strength of FRP sandwich panels configured in a two-picture frame fixture, one is baseline and the other is modified. The baseline configuration initiated early failure and the modified configuration showed a promising outcome.

Similar to the functionally graded hybrid composite plate, Fazilati and Khalafi (2019) fabricated a laminate with variable orientation reinforcements within their geometrical domain. As a result of this, desired directional stiffness through the laminate geometry is obtained.

Lopes *et al.* (2010) investigated the buckling and first ply failure responses of perforated composite panels. Hyer and Lee (1991) studied about the strength and buckling performance of variable stiffness composite plate using finite element method.

Fantuzzi and Tornabene (2014) studied the static and dynamic analysis of composite panels of arbitrary shapes with arbitrary cutouts. Chen *et al.* (2018) studied the buckling response of variational stiffness composite laminated plate with pre-embedded delamination under axial compression using Rayleigh-Ritz method.

Wang *et al.* (2016); Goswami and Becker (2016); Javed *et al.* (2016); Aslami and Akimov (2016) and Neves and Ferrari (2016) dealt with the study of angle-ply and cross-ply laminates under compressive and/or shear loading conditions.

2.3.3 Combined Uni-axial and In-plane shear loading

Buckling and postbuckling responses are important in the analysis and design of composites subjected to in-plane shear load in combination with uniaxial compression such as web panel, shear web with openings, castellated beams, cellular beams, etc. (Oluwabusi, 2020). The first-ply failure of thin laminated composite plates under combined loads including transverse load with uniaxial compression and transverse load with in-plane shear was studied by Jha and Kumar (2002). Investigating the behavior and response of thin plates under in-plane shear and uniaxial compression experimentally is difficult due to the complexity in the problem. Bailey and Wood (1997); Jain and Kumar (2004); Loughlan and Hussain (2016) and Wang *et al.* (2019) used numerical methods and computer programs based on finite element method to solve the problems to determine buckling and postbuckling responses of composite structures with cutouts.

Rockey *et al.* (1967) and Rockey (1979) investigated the effect of buckling coefficient and plate aspect ratio of shear web plate with cutout in their study. Authors also suggested that stiffeners around cutout decrease the circumferential stress significantly. The 7 degree of freedom finite element model was developed by Tolson and Zabaras (1991) to determine the first ply failure and the last-ply failure of laminated composite plates subjected to both in-plane and sinusoidal transverse loads using a progressive stiffness reduction technique.

Garlock *et al.* (2019) studied the postbuckling mechanism in steel square plate and observed that localized compression due to out-of-plane postbuckling deformation had a significant effect on ultimate postbuckling capacity of the plate.

Singh *et al.* (1998) studied the postbuckling responses and various parameters such as effect of boundary conditions, plate lay-ups, fiber orientations and lamina material properties on load-deflection response of composite plates under in-plane shear. Kim and Noor (1996); Singh and Kumar (1999); Iyengar and Chakraborty (2004) and Kumar and Singh (2011, 2012) analyzed the buckling and postbuckling responses of composite plates under combined loading conditions.

Kim and Noor (1996) performed a parametric study on composite panels and discussed the effect of cutout diameter, fiber orientation and stacking sequence on postbuckling response of a composite plate.

Singh and Kumar (1999) determined the postbuckling behavior and progressive failure of thin, symmetric laminates under combined in-plane loads. Authors have presented the critical buckling, first ply failure and ultimate failure loads associated with failure modes and locations at various load ratios.

Iyengar and Chakraborty (2004) tried to incorporate the effect of transverse shear on stability and failure of thick composite laminates. Authors have studied and presented the interaction curves in detail under combined loading conditions.

Kumar and Singh (2011) presented the load interaction curves and postbuckling responses of composite plates showing the effect of ratio of uniaxial compression and in-plane shear loads on the postbuckling response of composite plates.

Kumar and Singh (2012) studied the stability and failure of composite laminates with cutouts under combined in-plane loads and presented the optimized cutout shape and fiber orientation at which the performance of the composite plate is better.

2.4 Boundary conditions

Different parameters affect buckling and postbuckling response of composite plates in the practical applications such as cutout size, cutout shape and its location, as such, boundary conditions are one of the key parameters which will affect the robustness of the structural material under various loads (Singh and Kumar, 1998; Kumar and Singh, 2010; Kumar and Singh, 2013). Boundary conditions are the constraints which specifies the extremes of independent members. They are extremely important in mechanics field as they model a vast number of phenomena and applications. In finite element analysis, a boundary condition is the setting of a known value for a displacement or an associated load. Therefore, it is imperative to have knowledge on effect of boundary conditions on buckling and postbuckling responses of composite plates.

Aboudi *et al.* (1999) presented the use of higher order theory for functionally graded materials with boundary and interfacial conditions by coupling the micro and macro structural responses. The results illustrate the technologically important applications of functionally graded materials.

Mantari *et al.* (2012) also used the higher order theory and presented an analytical solution of functionally graded plates under static loads. Authors also provided a detailed comparisons of higher order theories used in various studies.

A detailed review of structural response of functionally graded materials (FGMs) was given by Gupta and Talha (2015). A modal analysis of composite plate using simply supported and clamped boundary conditions made of functionally graded material was developed by Tabatabaei and Fattahi (2020) using finite element-based software ABAQUS coupled with FORTRAN language.

2.5 Gaps in Present Research

On the basis of literature survey, the following gaps have been identified:

1. There is lack of economical design criteria to process functionally graded composite material (FGCM) plates.

2. Postbuckling response, strength and failure characteristics of FGCM plate with cutouts have not been investigated in detail.

3. Effects of cutout reinforcement including shape, size, aspect ratio and slenderness ratio on the postbuckling response of FGCM & classical hybrid plate needs to be studied.

4. Effects of location, shape, number and size of stiffeners on the postbuckling response of functionally graded composite plates with cutouts needs to be examined in detail.

5. Guidelines for economical and optimal design of FGCM plate are needed.

2.6 Objectives of the present study

Considering the gaps in the research, a detailed list of objectives are made in the present investiation and are described as follows:

1. To develop an optimized curing method for the fabrication of functionally graded hybrid composite plates.
2. Mechanical characterization of functionally graded hybrid composite specimens under tensile, compressive, flexural and shear loading.
3. Experimental verification of postbuckling response of functionally graded hybrid composite plates with and without cutouts under uniaxial compression.
4. Experimental verification and numerical verification of postbuckling response of functionally graded hybrid composite plates with and without cutouts under uniaxial compression, inplane shear, and combined uniaxial compression and inplane shear loading conditions
5. Numerical investigation of the effect of boundary conditions on postbuckling responses and strength of functionally graded hybrid composite plates subjected to inplane shear loading.
6. Recommendations of guidelines for cost effective design of functionally graded composite plates.