Chapter 1

Introduction

1.1 Overview

Two or more materials are combined to form a single material with properties different from its constituent element is composite material. The final product is made to enhance the performance superior to its constituents. The use of composites has increased considerably to reduce the acquisition and maintenance costs and improve the structural and operational performance. Composite materials have a wide range of novel applications in various industries. The potential use of these materials is in superstructures, bridge decks, propellers, propulsion shafts, pipes, shells, valves, machinery, etc. 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 depends on many determinants such as volume fraction of constituents, orientation of fibers, type of fibers, and most importantly curing technique employed.

1.2 Fibers

Carbon and glass fibers are used in the fabrication of composite plates for civil engineering applications and the literature review on these fibers is explained in detail in the following section.

1.2.1 Carbon fibers

Carbon fibers also known as graphite fiber are fibers about 5-10 micrometers in diameter and composed mostly of carbon atoms. Graphite fiber consists 99% of carbon content while it is 80-95% in case of carbon fiber. Carbon fibers have several advantages including high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion. These properties have made carbon fiber very popular in aerospace, civil engineering, military, and motorsports, along with other competition sports. In 1860, Joseph Wilson Swan created carbon fibers for the first time, for use in incandescent light bulbs. However, they are relatively expensive when compared with similar fibers, such as glass fibers or plastic fibers. To produce a carbon fiber, the carbon atoms are bonded together in crystals that are more or less aligned parallel to the long axis of the fiber as the crystal alignment gives the fiber high strength-to-volume ratio (in other words, it is strong for its size). In 1879, Thomas Edison baked cotton threads or bamboo slivers at high temperatures carbonizing them into an all-carbon fiber filament used in one of the first incandescent light bulbs to be heated by electricity. In 1880, Lewis Latimer developed a reliable carbon wire filament for the incandescent light bulb, heated by electricity. Several thousand carbon fibers are bundled together to form a tow, which may be used by itself or woven into a fabric. In 1958, Roger Bacon created high-performance carbon fibers at the Union Carbide Parma Technical Center located outside of Cleveland, Ohio. Those fibers were manufactured by heating strands of rayon until they carbonized. This process proved to be inefficient, as the resulting fibers contained only about 20% carbon and had low strength and stiffness properties. Carbon fibers are usually combined with other materials to form a composite. When permeated with a plastic resin and baked, it forms carbon-fiber-reinforced polymer (often referred to as carbon fiber) which has a very high strength-to-weight ratio and is extremely rigid although somewhat brittle. Carbon fibers are also composited with other materials, such as graphite, to form reinforced carbon-carbon composites, which have a very high heat tolerance.

In the early 1960s, a process was developed by Dr. Akio Shindo at Agency of Industrial Science and Technology of Japan, using polyacrylonitrile (PAN) as a raw material. This had produced a carbon fiber that contained about 55% carbon. In 1960 Richard Millington of H.I. Thompson Fiberglas Co. developed a process (US Patent No. 3,294,489) for producing a high carbon content (99%) fiber using rayon as a precursor. These carbon fibers had enough strength (modulus of elasticity and tensile strength) to be used as a reinforcement for composites having high strength to weight properties and for high temperature resistant applications. The properties of different carbon fibers obtained from different precursors are presented in Table 1.1. The high potential strength of carbon fiber was realized in 1963 in a process developed by W. Watt, L. N. Phillips, and W. Johnson at the Royal Aircraft Establishment at Farnborough, Hampshire.

During the 1960s, experimental work to find alternative raw materials led to the introduction of carbon fibers made from a petroleum pitch derived from oil processing. These fibers contained about 85% carbon and had excellent flexural strength.

Table 1.1 Properties of carbon/graphite fibers (Tiwari, 2005)

Property	Pan	Pitch	Rayon
Fiber diameter (μ)	5 – 8	10 – 11	6.5
Specific gravity	1.71 – 1.96	2.0 – 2.2	1.7
Tensile modulus (GPa)	230 – 595	170 – 980	415 – 550
Tensile strength (MPa)	1925 – 6200	2275 – 4060	2070 – 2760
Elongation at failure (%)	0.40 – 1.20	0.25 – 0.70	-
Coefficient of thermal expansion (-1^{-06}/C)	0.75 – 0.40	1.6 – 0.90	-
Thermal conductivity (W/m-K)	20 – 80	400 – 1100	-

Also, during this period, the Japanese Government heavily supported carbon fiber development at home and several Japanese companies such as Toray, Nippon Carbon, Toho Rayon and Mitsubishi started their own development and production. Since the late 1970s, further types of carbon fiber yarn entered the global market, offering higher tensile strength and higher elastic modulus. For example, T400 from Toray with a tensile strength of 4,000 MPa and M40, a modulus of 400 GPa. Intermediate carbon fibers, such as IM 600 from Toho Rayon with up to 6,000 MPa were developed. Carbon fibers offer broad range of stiffness and strength as shown in Table 1.2.

Table 1.2 Classification of carbon fibers as per Young's modulus (Barbero, 1999)

Property	Symbol	Young's modulus, GPa
High tenacity	HT	above 3
Super high tenacity	SHT	above 4.5
Low modulus	LM	below 200
Standard modulus	SM	200 – 250
Intermediate modulus	IM	250 – 350
High modulus	HM	350 – 450
Ultra-high modulus	UHM	above 450

Carbon fibers from Toray, Celanese and Akzo found their way to aerospace application from secondary to primary parts first in military and later in civil aircraft as in McDonnell Douglas, Boeing, Airbus, and United Aircraft Corporation planes.

1.2.2 Glass fibers

Glass was manufactured by the ancient Pheonicians and Egyptians, and both civilizations spun glass into fibres or made fibreglass. Glass fibres were available to many other civilizations. Most of these only produced a limited amount of glass fibre at a time, and the fibre they did produce was coarse. They employed this fibre for ornamentation, not realising the possibilities it had. In 1870, a gentleman named John Player invented a method for mass-producing glass strands using a steam jet to create mineral wool. As an excellent insulator, this substance was used. A patent for a sort of fibreglass cloth was granted to Herman Hammesfahr in 1880. Silk was weaved throughout this fibreglass textile. It was both long-lasting and flame-resistant. As with many scientific breakthroughs, the first glass fibres of the type we now know as fibreglass were created by accident. Dale Kleist, a young Corning Glass researcher, was attempting to solder two glass blocks together to create an airtight seal. Unexpectedly, a jet of compressed air collided with a stream of molten glass, resulting in a shower of glass fibres, demonstrating to Dale a simple way to make fibreglass. Glass fibers consists of numerous extremely fine fibers of glass. Glass fibers or Fiber glass was invented by Russell Games Slayter in 1932 – 1933 as a material to be used as thermal building insulation. Glass fibers when used as a thermal insulating material, is specially manufactured with a bonding agent to trap many small air cells, resulting in the characteristically air-flowed low-density “glass wool” family of products. Corning Glass teamed up with Owens-Illinois, another business that had been working with fibreglass, in 1935 to further develop the material. They patented "Fiberglas" with only one "s." in 1936, and the two businesses joined in 1938 to form Owens-Corning, which is still in business today.

Glass fiber has roughly comparable mechanical properties to other fibers such as polymers and carbon fiber. It is not as rigid as carbon fiber; it is much cheaper and significantly less brittle when used in composites. A patent for polyester resin was granted to Carlton Ellis of DuPont in 1936. Polyester resin can be used in conjunction with Fiberglas to create a composite. Owens-Corning began making fibreglass and polyester aeroplane parts for the war effort as early as 1942. These were low-pressure plastic laminates produced from resin-impregnated Fiberglass fabric. Glass fibers are therefore used as a reinforcing agent for many polymer products to form a very strong and relatively light-weight fiber reinforced polymer (FRP) composite material called Glass Fiber Reinforced Polymer (GFRP). This material is denser and is a much poorer thermal insulator than glass wool. Strength of glass fiber further depends on the time for immersion in chemicals, operating temperature, and application of loads. The properties of different fiber types are presented in Table 1.3. The freshest, thinnest fibers are the strongest because the thinner fibers are more ductile. The more the surface is scratched, the less the resulting tenacity (Volf, M.B., 1990). Because glass has an amorphous structure, its properties are the same along the fiber and across the fiber (Gupta and Kothari, 1997).

ASTM D3379 (1989) specifies the procedure for determination of strength of glass fibers. Lee (1990) specifies that strength of the single fiber is not like strength of the fibers in composite. The reduction in strength is attributed to the residual stresses and secondary stresses produced from the matrix.

Table 1.3 Properties of glass fibers

Fiber type	Tensile strength (MPa)	Compressive strength (MPa)	Density (g/cm^3)	Thermal expansion (µm/m·°C)	Softening, T (ºC)
E-glass	3445	1080	2.58	5	846
S-2 glass	4890	1600	2.46	2.9	1056

1.3 Functionally Graded Materials

Over the years, designing and fabrication of laminated hybrid is an active research. Many strategies have been proposed to make the hybrid more durable and ductile. Hybrid laminates have gained the attention of many industries such as aerospace, automotive, construction, composite material industry, etc. These composite laminates replaced the metallic members wherever applicable, especially in the aviation industry. The main significance of hybrid laminates is the enhancement of failure strain of low extension fiber laminates using high extension fibers and economical design of laminated structures.

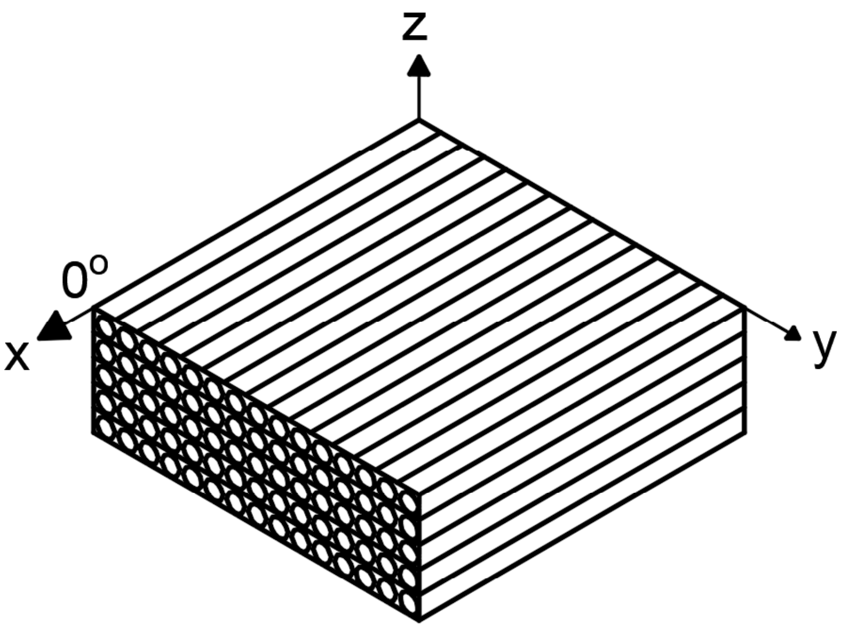
The CFRP has high strength and elastic modulus, but the failure occurs catastrophically (Chawla, 2012) and comparatively GFRP laminate is less strong and stiff than CFRP. But, glass fiber laminates are less brittle and economical than the CFRP in contrast. Hence, the concept of hybridization is applied to these two materials, i.e., CFRP and GFRP to obtain a third useful material specified as hybrid material. Utilization of CFRP laminates solely is not economical since carbon fibers are inherently expensive to produce (Giancaspro, Papakonstantinou and Balaguru, 2010). Hybridization techniques were implemented in 1960's since the carbon fibers were very expensive (Shindo, 2000) and (Tang and Bacon, 1964) and then the focus turned towards the behavior of non-hybrid composites as the price of carbon fibers dropped (Fitzer, 1989). Strengthening of fiber particles may improve the mechanical behavior such as modulus of elasticity, strength, etc. (Bigg, 1987), (Pukanszky *et al.*, 1994), (Ramsteiner and Theysohn, 1984), (Dekkers and Heikens, 1983), (Gupta *et al.*, 1989) and (Joshi *et al.*, 1994) and this combination of fiber particles into a fiber reinforced polymer is also considered as a hybrid composite (Fu and Lauke, 1998). Tensile and compressive testing of hybrid carbon/glass fibers shows that, initial point of fracture of the hybrid system is beyond the breaking point of plain CFRP, i.e., non-hybrid composite (Hayashi, 1972) and (Phillips, 1976), and the behavior of hybrid and non-hybrid materials are not similar after the occurrence of initial fracture (Bunsell and Harris, 1974). Design of new materials is possible to fulfill the specific requirements by tailoring different fiber materials such as carbon and glass fibers (Zweben, 1977), (Fukuda and Chou, 1983), (Fukuda, 1984) and (Pan and Postle, 1996). The elastic modulus of hybrid composites obtained from experimental investigation gives the good comparison of results with that obtained from the rule of mixtures. The limitation of using the rule of mixtures is that this method does not consider the interaction between particles and fibers (Fu, Xu and Mai, 2002).

Fu *et al.* (2002) used the laminate analogy approach to determine the elastic modulus of hybrid composites and the method was in good agreement with the experimental stiffness than the rule of mixtures approach. Also, they (Fu *et al.*, 2002) defined hybrid effect as the deviation of the curve from the linear rule of mixtures which can be positive or negative. Nevertheless, the laminate analogy approach can be applied for short fibers/particulate fibers only, whereas rule of mixtures can be applicable for long fibers also. Hybrid effects are difficult to find when two natural fibers are combined. Combination of natural fibers with glass fiber improves mechanical properties (Pavithran *et al.*, 1991; Pavithran *et al.*, 1991a; Jawaid *et al.*, 2011; De Rosa *et al.*, 2009; Almeida *et al.*, 2013; Devi *et al.*, 2010; Santulli *et al.*, 2005; Sreekala *et al.*, 2002 and John and Naidu, 2004) whereas the cases in which combination of natural fibers with carbon fibers are very rare since its life cycle cost is very high and it is expensive too (Jawaid *et al.*, 2011). The effect of carbon/glass fiber ratio on the stress-strain curve of the hybrid composite was studied and concluded that high modulus of elasticity was obtained due to fragmentation of carbon fibers in the inter-mingled carbon/glass hybrid composites (Yu *et al.*, 2015). It is also observed that hybrid laminates have high failure strain at low carbon/glass fiber ratios (Czél *et al.*, 2015 and Swolfs *et al.*, 2013), due to the high elongation fibers in the laminate (Peijs and de Kok, 1993; Liang *et al.*, 2004 and Pitkethly and Bader, 1987). Failure strain can be increased dramatically, if some low elongation fibers are replaced with high elongation fibers in plain low elongation fibers composite, this change in failure is known as hybrid effect (Swolfs *et al.*, 2014). If the failure strain of hybrid composite is more than that of low elongation fibers, it is known as positive hybrid effect, otherwise, it is known as negative hybrid effect. For a hybrid specimen subjected to tension in the fiber direction, brittle/low elongation fibers fail primarily and give warning before complete failure.

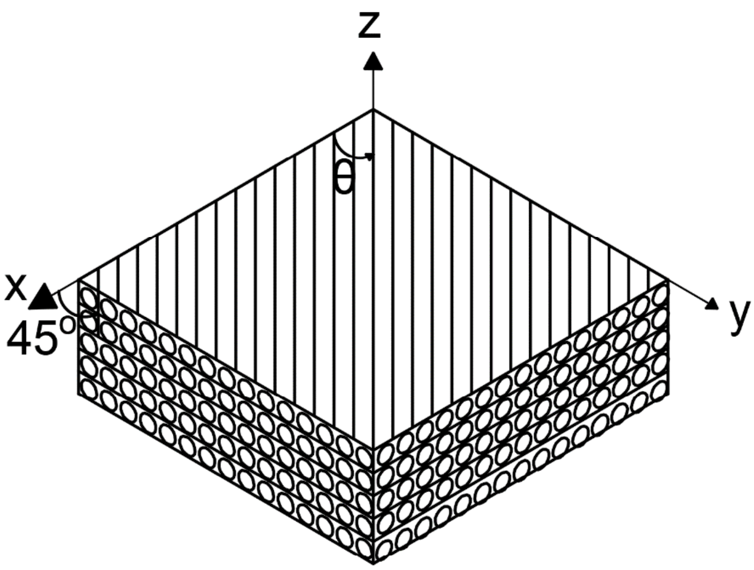
Generally, in hybrid composites, a sudden change in the mechanical properties induces the stress concentration which leads to the delamination or failure at the interface of the different types of fibers. In order to reduce this effect, hybridization of carbon and glass fibers can be made by linear gradation of glass and carbon fibers along the thickness direction. It is also noted that dispersion of fibers has high effects on the tensile, compressive, and flexural characteristics of hybrid laminates. Dispersion of low elongation fibers around high elongation fibers or vice-versa can enhance the material properties which have not been studied yet. In order to fill this gap, the concept of functional gradation is introduced in this study which has novel configurations. Functionally graded hybrid composite of glass/carbon fibers is made having different functional gradations of glass-carbon fibers in a specimen along the thickness direction and this concept is like the dispersion of fibers in a specimen. The significance of functional gradation is to further enhance the mechanical behavior such as strength, stiffness, and failure strain of FRP laminates. Because enhancement of material properties also depends on how well fibers are dispersed (Swolfs *et al.*, 2014). The mechanism implied in functionally graded hybrid composites is the sharing of the load applied among the constituents (glass and carbon fibers) based on the fraction and dispersion of its constituents.

1.4 Orientation of laminates

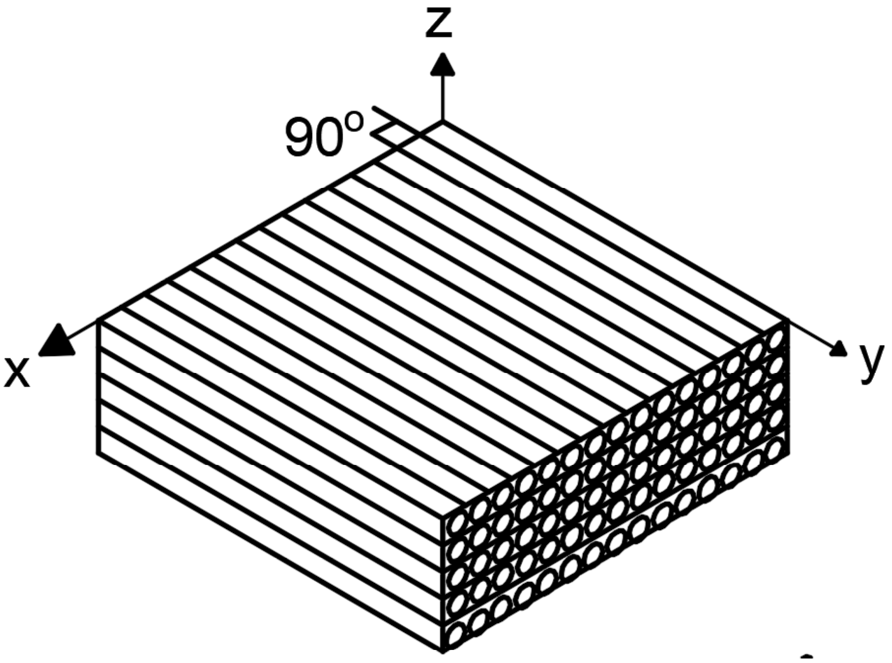
Laminate orientation is used to represent the lay-up or stacking sequence in a laminate. Combination of laminae is a laminate and the orientation of a laminae is specified by an angle (in degrees) with respect to the *x*-axis (with reference to x, y, z co-ordinate system with z-axis being perpendicular to plane of the laminate) as shown in Fig. 1.1. The number of plies within a laminate is specified by a numerical subscript, and if the laminate is symmetrical about the mid-plane, the it is represented by a subscript ‘s’ next to the numerical.



(a)



(b)



(c)

Fig. 1.1. The x, y, z coordinate system representing the ply orientation: (a) 0° aligned fiber (b) 45° aligned fiber (c) 90° aligned fiber

1.5 Applications of composites

The products fabricated from composites are stronger and lighter and it is one of the reasons for the growth in composite applications. Many industries are utilizing and are benefited from the composite materials. There have been substantial changes in the technology, infrastructure and its requirement because of these materials. This created many new needs and opportunities, which are possible only with the advancement in novel materials and manufacturing. To fulfill the need in various market segments, several advanced manufacturing technologies have been developed. Aerospace, automotive, construction, marine, etc., are the various industrial categories where the composites can be utilized broadly. The range of materials that can be classified into different categories such as Metals, Polymers, Ceramics and inorganic glasses and composites. Metals lose their strength at elevated temperatures. High polymeric materials in general can withstand low temperatures. Ceramics have an ability to withstand high temperatures and also, they are better than metals and polymers with respect to their favorable melting points but due to their brittleness they often are unsatisfactory as structural materials. This lead to the exploration of composites.

To meet the challenges imposed by the complex design of architecture, emergence of stronger and stiffer reinforcement has been developed like carbon fiber along with advances in polymer research to produce high performance resins as matrix materials. The potential utilization of composite materials such as development of military housing, fighter aircrafts, small and big civil transport aircrafts, helicopters, satellites, launch vehicles, and missiles all over the world is the example for large scale use of composites.

1.5.1 Aerospace industry

The Aerospace industry was among the first to realize the benefits of composite materials. Three decades ago advanced composite structures made of carbon fiber reinforced polymer, boron fiber reinforced polymer, and aramid fiber reinforced polymer were only being produced for components of military aircrafts due to their high performance characteristics. This situation has changed dramatically during the years and now all airframes are being produced from the composites even for civil aircrafts. The hand layup technique is a common manufacturing method for the fabrication of aerospace parts. Resin transfer molding and filament winding techniques are also being used for the manufacturing purpose. The aircraft composite structural and semi structural components which are currently being produced are wings, fuselages, propulsion systems, vertical stabilizers, door and fairings, tail control surfaces, rotors, fins, etc.

Several features that are offered by composites includes:

(i) High specific strength, stiffness and light in weight.
(ii) High fatigue resistance and corrosion resistance
(iii) Capability of high degree of optimization, tailoring the directional strength and stiffness
(iv) Capability to mold large complex shapes in small cycle time reducing part count and assembly (v) Good for thin walled constructions
(vi) Capability to maintain dimensional and alignment stability in space environment
(vii) Possibility of low dielectric loss in radar transparency
(viii) Possibility of achieving lowrider cross-section

There are some weaknesses in composites which includes

(i) Laminated structure with weak interfaces for resistance to out-of-plane tensile load
(ii) Susceptibility to impact damage and strong possibility of internal damage going unnoticed
(iii) Moisture absorption and consequent degradation of high-temperature performance

(iv) Multiplicity of possible manufacturing defects and variability in material properties

1.5.2 Automobiles

The advanced composite materials, particularly polymer matrix composites (PMCs) are been used widely in automotive industries such as weight reduction for better fuel efficiency, improved ride quality, etc. The performance criteria of composite materials in automotive structural applications are as follows.

(i) Fatigue (durability),
(ii) Energy absorption
(iii) Ride quality in terms of noise, vibration, and harshness (related to material stiffness)

1.5.3 Construction industry

Composites offer the designers a combination of properties not available in traditional materials. They can be used in various architectural applications such as doors, exterior cladding, light panels, sky lights, composite walls, roofing, framing, windows, sliders, structural insulated panels, etc. Pedestrian bridges are also constructed using composite materials. Some luxury components of house are also fabricated using composites such as swimming pool panels, bathtubs, shower stalls, imitation granite, cultured marble sinks, and counter tops.

The main advantages of these materials in construction industry are:

(i) Transportation cost is minimized
(ii) Reduction in quantity of materials
(iii) Manpower utility is reduced
(iv) Enhanced efficiency of construction due to lighter weight

Structural considerations for FRP:

(i) Tensile strength: Their tensile strength can range from about the strength of mild reinforcing steel to stronger than that of prestressing steels. As such, they offer good incentive for use in situations where high tensile strength is an asset. FRP composites generally exhibit linear tensile stress strain behavior throughout their load-carrying range and as such do not change their modulus over their loading history. Since FRP composites are materials

composed of structural fibers in a polymeric matrix, the fibers can be custom-oriented to suit individual needs.

(ii) Fatigue: Research to date indicates that FRP composites exhibit good fatigue resistance in tension cycling. Research has yet to document the effects of temperature, moisture, reverse loading, long-term and compression load cycling, and holes on fatigue resistance. Long-fiber composites generally retain a high proportion of their short-term strength after 107 cycles. Carbon-fiber composites exhibit the highest fatigue resistance, followed by aramid and then glass.

(iii) Low mass: Excessive structural mass is often a reason to consider alternate materials which will provide high load-carrying capacity as well as low density. FRP composites have densities in the range of 1,200 to 2,600 kg/m^3 (75 to 162 lb/ft^3) which make them attractive alternatives to structural materials such as steel with a density around 7,850 kg/m^3.

(iv) Specific strength: The specific strength of materials, defined as the strength divided by the density, is often used to make comparisons between materials on the basis of strength and mass. FRP composites, because of their high strength and very low density, have specific strengths which are up to 60 times that of high strength steels. The high specific strengths associated with FRP composites are very useful in applications such as structural cladding panels, low-density framing materials, and vehicle components. Their low weight makes the assembly and disassembly of temporary structures much easier and less time-consuming than similar structures made of wood or steel. Cost of many of the FRP composites, although higher than conventional construction materials on a pound-per-pound basis, are competitive when the specific strength of the materials is taken into consideration.

(v) Vibration damping: The specific modulus of FRP composites, defined as the modulus of elasticity divided by the density, is also high and provides characteristics such as low vibration in situations where vibration may be a problem (Grace *et al.,* 1991). Steel has a high density, high modulus, and low damping characteristics whereas composites have low densities, moderate moduli, and high damping characteristics. Use of composites in floors and bearing pads where damping of vibration is of concern can reduce these problems.

(vi) Repair using composites: Structural repairs of conventional materials using FRP composites can be advantageous from the standpoint of ease of installation and reduced maintenance costs. Conventional techniques for externally strengthening cracked concrete structures call for steel plates or bars to be installed across the crack to carry the structural loads no longer carried by the concrete. FRP plates can be structurally bonded across such cracks to replace the steel repair components. The low mass of these materials makes their handling more convenient, and their noncorrosive nature eliminates the need to protect them from rusting deterioration.

(vii) Corrosion resistance: One of the most convincing reasons to consider the use of FRP composites is their resistance to corrosive elements. The plastic resins that form the matrix of most composites are resistant to deterioration from many chemicals as well as the effects of acidic, salt, and fresh waters. Acidic, salt, and fresh waters are corrosive to ferrous metals. The benefits of composites over steel in terms of resistance to corrosion are greatest in the areas of maintenance and life-cycle costs. Components in marine construction such as piling, docks, and submerged construction would be applicable uses. Storage structures for corrosive liquids are suited to FRP composite materials. Fiberglass tanks have been used for storage of chemicals for many years.

1.5.4 Marine industry

The first marine application of fiber reinforced polymer (FRP) composite material was in the construction of boats after World War II. Builders of the boats began to use FRP composites instead of timber (traditionally used material), because wood was becoming scarce and expensive. Also, wooden boats were easily degraded by sea water and marine organisms. Therefore, the maintenance cost of the wooden boats is expensive. The application of FRP composites to maritime crafts was initially driven by a need for lightweight, strong, corrosion resistant and durable. Most of these early applications were driven by the need to overcome corrosion problems experienced with steel and aluminum alloys or environmental degradation suffered by wood. The topside weight of the ships must be less in weight. This is one of the reasons in using FRP composites in ships. The acoustic transparency of composites is also high which in turn resulted their use in sonar domes on submarines.

1.6 Manufacturing processes of fiber reinforced polymer materials:

There are different manufacturing processes involved in the fabrication of FRP composites:

1. *Pultrusion*

   Pultrusion is a continuous process for the manufacture of products having a constant cross section, such as rod stock, structural shapes, beams, channels, pipe, tubing, fishing rods, and golf club shafts. Pultrusion process is a commonly followed method in the field of composites in which continuous glass fiber, carbon fiber or basalt fiber are passed through a chamber which consists of resin. After the resin bath, this wet fiber is passed through a heated die where the wet fiber becomes dry and gets cured. In the final step, the hard glass fiber reinforced polymer laminated is obtained and passed through a cutting chamber where a required length of the laminate can be cut and utilized.

2. *Hand layup*

   Hand lay-up is a molding process where fiber reinforcements are placed by hand then wet resin is poured on it and is evenly spread. This manual nature of this process allows for almost any reinforcing material such as chopped strand mat (CSM), uni- and bi-directional mats.

3. *Filament winding*

   Filament winding is a fabrication technique mainly used for cylinder manufacturing or closed end structures such as pressure vessels or tanks. In this process, filaments are wound under tension over a rotating mandrel.

4. *Centrifugation*

   In centrifugal casting of composites, reinforcements (fibers) and resin (epoxy) are deposited against the inside surface of a rotating mold. Centrifugal force holds the materials in place until the part is cured. With centrifugal casting, the outside surface of the part, which is cured against the inside surface of the mold, represents the “finished” surface. The interior surface of centrifugally cast parts can be given an additional coating of “neat” or pure resin to improve surface appearance and provide additional chemical resistance in the part. Large diameter composite pipe and tanks are commercially produced by centrifugal casting. Advantages of centrifugal casting include a finished exterior surface and containment of volatiles during processing. The primary limitations of centrifugal casting are the ability to spin molds of large size and relatively low productivity per tool.

5. *Resin transfer molding (RTM)*

   Resin transfer molding (RTM) is an intermediate volume molding process for producing composites. In RTM, resin is injected under pressure into a mold cavity. This process produces parts with two finished surfaces. The mold is gel coated conventionally, if required. The reinforcement (and core material) is positioned in the mold and the mold is closed and clamped. The resin is injected under pressure, using mix/meter injection equipment, and the part is cured in the mold. The reinforcement can be either a preform or a pattern cut roll stock material. A preform is a reinforcement that is formed to a specific shape in a separate process and can be quickly positioned in the mold. RTM can be done at room temperature; however, heated molds are required to achieve fast cycle times and product consistency. Clamping can be accomplished with perimeter clamping or press clamping.

6. *Resin infusion molding (RIM)*

   Resin Infusion Molding is a double-mold process. First, the dry fibers are laid in a metal mold. A metal counter mold is then hydraulically pressed down over the composite object. Under moderate pressure the resin is pressed into the mold and saturates the fibers. The mold is heated to cut down on cycle time. To further enhance the quality, the mold can be subjected to a vacuum, which minimizes air pockets. The quality of the finished product is high and even. Metal molds are more expensive than ordinary composite molds, but last much longer. Meanwhile, RIM's short process time makes the process perfect for large batch production, in which the surface quality is of paramount importance. The benefits of RIM process include excellent strength, particularly excellent surface quality on both sides of member, highly even quality, and material thickness. The molds have very long service life, short process time and it can be used for sandwich constructions.

7. *Compression molding*

   Compression molding is a high-volume, high-pressure method suitable for molding complex, fiberglass-reinforced polymer parts on a rapid cycle time. The mold set is mounted in a hydraulic or mechanical molding press and the molds are heated from 121° to 204° C. A weighed charge of molding material is placed in the open mold. The two halves of the mold are closed, and pressure is applied. Depending on thickness, size, and shape of the part, curing cycles range from less than a minute to about five minutes. After cure, the mold is opened, and the finished part is removed. Typical parts include automobile components, appliance housings and structural components, furniture, electrical components, and business machine housings and parts.

8. ***Vacuum assisted resin transfer molding (VARTM)***

   Vacuum Assisted Resin Transfer Molding (VARTM) or Vacuum Injected Molding (VIM) is a closed mold, out of autoclave composite manufacturing process. VARTM is a variation of Resin Transfer Molding (RTM) with its distinguishing characteristic being the replacement of the top portion of a mold tool with a vacuum bag and the use of a vacuum to assist in resin flow. The process involves the use of a vacuum to facilitate resin flow into a fiber layup contained within a mold tool covered by a vacuum bag. After the impregnation occurs, the composite part can cure at room temperature with an optional post cure sometimes carried out.

   Typically, this process uses a low viscosity (100 to 1000 cP) polyester or vinyl ester resin along with fiberglass fibers to create a composite. Normally the process can produce composites with a fiber volume fraction between 40-50%. The resin to fiber ratio is important for determining the overall strength and performance of the final part, with mechanical strength being most influenced by the type of fiber reinforcement. The type of resin used will primarily determine the corrosion resistance, heat distortion temperature, and surface finish. Resins used in this process must have low viscosity due to the limited pressure differential provided by the vacuum pump. High performance fibers, such as carbon fiber can also be used. However, their usage is less common and is mainly for the fabrication of high-end parts.

1.7 Mechanical behavior of composite plates

Practically, composite structures are subjected to different types of loads such as wind loads, earthquake loads, gust loads, thermo-mechanical loads, moisture loads, aerodynamic loads, etc. Under the application of such loads, the behavior of composite materials will be different from that of the conventional/traditional materials. This is because traditional materials are homogeneous and isotropic while the composite materials are inhomogeneous and anisotropic.

Therefore, composite materials are assessed from micro mechanics and macro mechanics point of view and it is designed to suit a structural requirement.

> *Micromechanics* of materials is the analysis of composite or heterogeneous materials on the microscopic level of the individual constituents that constitute these materials. Micromechanics allows to predict multi-axial properties that are often difficult to measure experimentally.
>
> *Macromechanics* is the study of composite material behavior wherein the material is presumed to be homogeneous, and the effects of the constituent materials are detected only as averaged apparent macroscopic properties of the composite materials.

Due to the inherent anisotropy of composite materials, there exist a coupling behavior between the type of loading and deformation modes. For instance, an anisotropic material subjected to a normal stress leads not only to extension in the direction of applied stress, but also causes shearing deformation. So, if a metal is to be replaced by a composite material, the designer must have complete knowledge of the mechanical behavior of composite structures under various types of loads.

1.8 Concept of hybridization

In classical hybrid composites, generally high elongation (HE) and low elongation (LE) fibers are provided in different styles such as inter-layer, intra-layer, and intra-yarn random hybrid. Degree of dispersion of glass/carbon fibers have significant effect on the hybrid effect of tensile, compressive, and flexural characteristics of specimens. Using the concept of functionally graded materials in laminated composites HE and LE fibers, i.e., glass and carbon fibers are functionally graded along the thickness direction in a specimen, which is described as functionally graded hybrid (FH) in this study. FH composite is made by linearly varying the width of glass and/or carbon fibers layer in a stacking sequence. The content of fiber in each layer and/or number of layers of FH composite can be increased or decreased.

1.9 Overview of plate theories

Because of the construction of the composite plates (having planar dimensions larger than thickness) and the applications of composite laminates that mostly need membrane and bending strengths, these laminates are analyzed by considering them as plate elements. Several plate theories developed for isotropic materials and then generalized for anisotropic materials.

1) Equivalent single-layer theories (2-D)
    a) Classical laminated plate theory (CLPT)
    b) Shear deformation laminated plate theories
        - The first-order shear deformation theory (FSDT) which is also referred as Mindlin Plate theory
        - Higher-order shear deformation theories (HSDT)
2) Three-dimensional elasticity theory (3-D)
3) Multiple model methods (2-D and 3-D)

Classical laminated plate theory: The classical laminated plate theory (CLPT) is the simplest theory among others and is just an extension of the Kirchhoff's (classical) plate theory to laminated composite plates. The CLPT is based on the *Kirchhoff's-Love hypothesis* i.e., straight lines perpendicular to the midplane after deformation remain straight, inextensible and normal to the midplane before deformation. So, in the case of CLPT, plate is assumed to be infinitely rigid in the transverse direction and hence, transverse shear and normal effects are neglected, and deformation is entirely caused by bending and in-plane loads. This theory gives adequately good results for thin laminated plates.

First order shear deformation theory: The assumption made in CLPT ignores the transverse shear deformation. Consideration of shear deformation results in added flexibility, which becomes significant as the plate thickness increases relative to its length and width. The shear flexibility is particularly important in laminated composite because the moduli of elasticity in transverse shear are typically much less than the in-plane moduli. The first-order shear deformation theory (FSDT) relaxes the restriction of the classical laminated plate theory, and hence allows the rotation of transverse normal during deformation. The transverse shear strains are assumed to be constant through the laminate thickness, and so with the transverse shear stresses. Therefore, the FSDT requires shear correction factors to correct the discrepancy between the actual stress state (i.e., parabolically through the thickness) as predicted by elementary theory and the constant stress state as predicted by the FSDT. The FSDT theory provides a balance between computational efficiency and accuracy for the global structural response of thin and moderately thick laminated composite plates.

1.10 Failure criteria of composite plates

Under service conditions, failure of fiber-reinforced composite structures may be caused by matrix cracks, fiber-matrix debonds, fiber fractures, fiber pull-out, delamination, or by a combination of these factors. These damage effects reduce the stiffness and strength of the laminate which in turn results in the reduction of the load-carrying capacity and the life of the structure. Finally, when the structure or a component ceases to fulfill its intended function, it is said to be failed. For instance, when the damage (such as micro-cracks) grow and number, they merge into each other and develop into debonds, thus results in reduction of the load-carrying capacity of the laminate. To determine the load carrying capacity and service life of a composite structure it is necessary to predict the onset of failure and their progression. Once the mechanical properties are determined whether from Micromechanics approach or experimentally, the initial failure of the ply within a laminate for structure can be predicted by applying an appropriate failure Criterion. The subsequent failure prediction requires an understanding of damage modes and damage accumulation.

There exists several failure criteria in the literature as applied to composite materials as presented by Tsai and Hann (1975) and Tsai (1984). Because of the complexities involved in failure and failure characteristics of composite from micromechanics point of view, the failure criteria predict the number of failures of lamina at macroscopic level. Hence, these criteria are also called as microscopic failure criteria.

Tsai and Wu (1971) represented the failure criterion as a general quadratic in the stresses. According to this criterion, the failure of the lamina is said to have occurred when the following condition is satisfied.

$$\mathbf{F_{ij}s_is_j+F_{ij}s_i=1};\ i,j=1,2,3,4,5,6 \qquad (1.1)$$

where F_i and F_{ij} are the strength tensors of second and fourth ra` nk and '$\mathbf{s_i}$' is the stress component in the principal material co-ordinate system. The foregoing difficulty inspired Hashin and Rotem (1973) to propose a new criterion which can distinguish between fiber dominated failure and matrix dominated failure. It is originally proposed for the problem of fatigue which was later revised by Hashin (1980) for static failure and developed a set of interacting failure criteria involving the general 3-D state of stress that have the ability of predicting modes of failure. In this criterion, each of the failure mode, that is, tensile fiber, compressive fiber, tensile matrix and compressive matrix were modeled separately by a quadratic polynomial containing appropriate stress components resulting in a piece-wise smooth failure surface. Another unique feature of this failure criterion is that, it avoids prediction of multiaxial tensile (or compressive) modes in terms of compressive (or tensile) failures stresses.

Later, Tsai (1984) introduced a general tensor polynomial failure criterion based on the combined effect of stresses on failure. As per this criterion, the failure is defined for the following condition:

$$\begin{gathered}\mathbf{F_1 s_1+F_2 s_2+F_3 s_3+2F_{12} s_1 s_2+2F_{13} s_1 s_3+2F_{23} s_2 s_3+} \\ \mathbf{F_{11} s_1^2+F_{22} s_2^2+F_{33} s_3^2+F_{44} s_4^2+F_{55} s_5^2+F_{66} s_6^2+\ldots \geq 1}\end{gathered} \tag{1.2}$$

where $\mathbf{s_1}$, $\mathbf{s_2}$, $\mathbf{s_3}$ are the normal stress components in three principal material directions while $\mathbf{s_4}$, $\mathbf{s_5}$, $\mathbf{s_6}$ are shear stress components at a point in planes 2-3, 1-3 and 1-2, respectively. Although, the above two criteria are general and versatile to predict initial failures, but without regard to the mode of failure, that is fiber mode, matrix mode and/or delamination mode. It is of prime importance for a designer to know the mode of failure, since this facilitates in predicting the progressive failure response and ultimate failure of the structure, shortcomings of the general quadratic failure criterion is that failure under biaxial tensile stresses depends on the compressive failure stresses and vice versa which seems physically unacceptable.

It is well known fact that final failure of the laminated composite plates does not occur at the load corresponding to the first ply failure, but it is caused by propagation of failures or damage as the load is increased. To model this effect, Engelstad *et al.* (1992) used the tensor polynomial criterion for progressive failure in nonlinear analysis of typical laminates in which failure modes have been predicted by the weightage of the principal stress terms associated with the criterion. At each load step, the selected tensor polynomial failure criterion is checked based on Gauss point stress. If failure occurs at a Gauss point, a reduction in lamina stiffness is introduced in accordance with the mode of failure which causes changes in the overall laminate stiffness. Then failure is checked again at the same load step. If no failure occurs, nonlinear analysis is carried out at next load step. The tensor polynomial failure criterion with its various degenerate cases and other independent criteria have been reported by Reddy and Pandey (1987), Ochoa and Reddy (1992) and Singh *et al.* (1997).

Delamination is another critical mode of failure in composite laminates which causes layers of the laminates to separate. The presence of delamination may reduce the overall stiffness as well as the residual strength leading to structural failure. The most common sources of delamination are material and structural discontinuities that give rise to high interlaminar normal and shear stresses at locations such as free edges and ply drops. There are two basic methods to predict the onset of delamination:

(i) The stress method: This method requires interlaminar shear stresses to be determined at each interface and then to be compared with the material strength characteristics using any of the failure criteria.

(ii) Energy release rate method: Energy method or energy release rate criterion is based on fracture mechanics theory for three fundamental modes of failure (i.e., Mode I, Mode II, Mode III) or mixed modes of failure.

Mode I represent opening Mode, Mode II represents in plane shearing Mode, and Mode III represents tearing or scissoring shearing mode. It assumes that inherent flaws or defects are always present, and failure is due to the propagation of these cracks. The crack will propagate when the strain energy released is enough to create the new fracture surface, that is, when it reaches a critical level.

The important failure criteria used for failure analysis of composites are listed below:

- Hashin criteria
- Tensor polynomial criterion with its degenerate cases as given below:
    - Maximum stress criterion
    - Maximum strain criterion
    - Tsai-Hill criterion
    - Tsai-Wu criterion
    - Hoffman criterion
- Interlaminar shear stress criterion
- Strain energy release rate criterion

1.11 Buckling and Postbuckling response of functionally graded hybrid composite plates

1.11.1 Overview

Most of the composite laminated plates used in various structural applications are thin. These thin plates may be subjected to various in-plane loads such as uniaxial compressive loads, biaxial compressive loads, shear loads, non-uniform uniaxial tensile loads or combination of any of these loading conditions. Under these loads, the thin flat plate initially undergoes in-plane deformations only. As the in-plane load increases, the in-plane deformations increases and a stage is reached when the plate suddenly undergoes a deviation from the flat equilibrium state to another equilibrium state that is bowed out of plane which is characterized by the out-of-plane deflection. The critical quasi-static load at which the sudden bifurcation of equilibrium state takes place is called the buckling load. Schematic of buckling of a plate under uniaxial compression is shown in Figure 1.2.

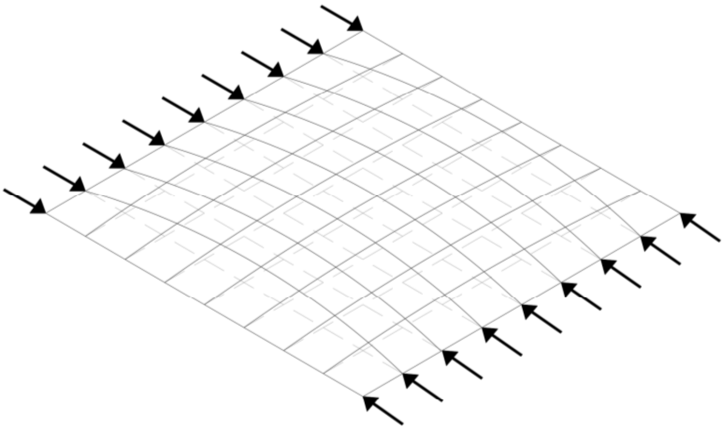


Fig. 1.2. Buckling of a plate under uniaxial compression

Buckling and postbuckling response of any structural elements such as columns, shells and plates may be discussed in terms of a plot of in-plane loading for (P) vs deflection (w) measured at a point on the element as depicted in Fig. 1.3. As shown in the Fig. 1.3, a column, a shell (or a plate) shows no deflection with increased load until a critical value of load (i.e., P_{cr}) is reached. It can also be noted that a column fails immediately after the critical load. So, for a column, critical buckling load is the ultimate failure load. Unlike a column, the plate does not fail immediately after the buckling load and hence, have reserve strength beyond the classical buckling strength in the postbuckling range. Further, it can be noted from Fig. 1.3 that the flexural stiffness (given by the slope of the curve) of the plate after buckling increases with increase in the lateral deflection as against the flexural stiffness of a shell which decreases with increase in the deflection. So, the nature of load deflection response for a plate in postbuckling range is of the stiffness type, whereas it is of the softening type for a shell. Thus, plates are capable of carrying considerable additional load (several times as much as the buckling load) before the ultimate failure occurs. The theoretical analysis of postbuckling behavior of plates is inherently nonlinear, even though the transverse displacement is of moderate level (i.e., of the order of a few times the plate thickness). The initial nonlinearity is caused by additional in-plane strains and stresses because of the displacements. Further, additional geometrical or material nonlinearities may arise during larger deflections after buckling, but these are typically not considered in theoretical postbuckling analysis.

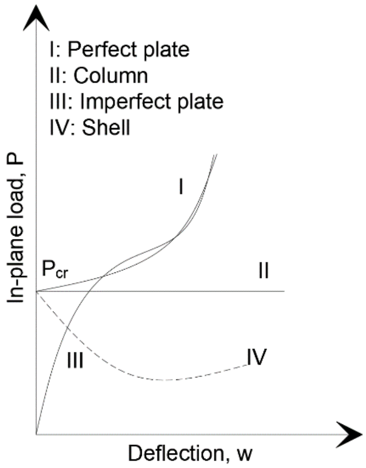


Fig. 1.3. Load-deflection response of various structural elements

In general, no plates are perfectly flat but forces some initial deviation from flatness, usually called as geometric imperfections. These are because of some manufacturing defects. The application of in-plane loads along the midplane of an imperfect plate causes a change in the transverse displacement and its postbuckling behavior deviates from that of a perfect plate as shown in Fig. 1.3. Such a load-deflection response may also be resulted if the load applied is eccentric (i.e., not applied along the midplane of the plate) or if the loads also act simultaneously along with in-plane loads. In case of isotropic plates, the standard procedure for determining theoretical values of buckling loads is eigen value problem, i.e., a problem governed by a differential equation and homogeneous boundary conditions which is also known as linear buckling analysis. In this method, the magnitude of the deformations after buckling cannot be determined, so the postbuckling response of the plate cannot be predicted. Therefore, a non-linear analysis of the plate is carried out with increasing loads for accurately predicting the buckling and postbuckling response of composite plates.

The typical complications involved with the buckling and postbuckling analysis of composite plates are cutouts in the plate, transverse shear deformation, delamination, hybridization with two different materials, local failure, non-linear stress-strain relations, external stiffness and environmental effects. These complications are seen either from geometric complications or from generalization of various developed theories in order to accommodate broader range of problems.

1.11.2 Need for cutouts

Composite plates are used in almost all the applications as mentioned earlier. The cutouts of various shapes are typically required by practical concerns such as cutouts in wing spars, aeroplane windows, cockpit utilities, electrical maintenance, access to hydraulic lines, etc. They are also provided for ventilation, damage inspection, to accommodate bolts, etc. and sometimes to reduce the weight of the structure.

1.12 The problem in a broad-sense

This investigation is carried out based on the following facts.

- Advanced composites are being used increasingly in all the practical applications such as aerospace, automobile, structural, Infrastructure etc., because of their high specific stiffness and strength. During this application, the structural members are subjected to complex loading conditions.
- When thin-plates or laminates are used as structural members, they might be subjected to buckling under various in-plane loads.
- These composite plates can sustain heavy loads beyond buckling and hence possess postbuckling strength. Progressive failure is observed in these types of plates i.e., ultimate failure does not take place at the instant of first-ply failure.
- The failure charcteristics of these composite plates (heterogeneous anisotropic laminated plates) are completely different from isotropic metallic counterparts.
- Complications such as in-plane shear deformations, effects of cutouts, stacking sequence and material non-linearity are involved while studying the response of these composite plates

- A numerical technique is required to accurately predict the buckling, postbuckling, and reserve strength of composite plates by performing a non-linear geometric analysis.

1.13 Outline of the thesis

In order to solve the above mentioned problems, the thesis is divided into six chapters. The outline of the upcoming chapters is gien below.

Chapter 2: A detailed literature review on mechanical characterization of hybrid, non-hybrid, and functionally graded hybrid composite materials, buckling and postbuckling of functionally graded hybrid composite plates with and without cutouts under different loading conditions, different parameters and their effects on postbuckling response is given in this chapter.

Chapter 3: Experimental program for mechanical characterization of materials used in this study and the effect of curing temperature is detailed in this chapter. Mechanical properties of specimens such as carbon, glass, hybrid carbon-glass, and functionally graded hybrid carbon-glass are investigated under tensile, compressive, flexural, and shear loadings.

Chapter 4: Experimental and numerical invesgation is carried out on hybrid, non-hybrid, and functionally graded hybrid composite plates with and without cutouts under uniaxial compressive load to check the effects of buckling and postbuckling.

Chapter 5: Postbuckling response of functionally graded hybrid composite plates with and without cutouts under in-plane shear loads are investigated. Also, the effect of boundary conditions on postbuckling response has been analysed and presented in this chapter.

Chapter 6: Postbuckling response of functionally graded hybrid composite plates with and without cutouts under the combined action of in-plane loads i.e., uniaxial compression and in-plane shear has been investigated and presented in this chapter.

Chapter 7: In this chapter, important and useful conclusions based on this study are explained, and recommendations are made for effective use and cost effective design of functionally graded hybrid composite plates for civil engineering applications are also described.

1.14 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 (*one of the applications*), which will increase the efficiency and lifecycle cost of structures with economy. These materials can also be used for repair and rehabilitation of deterioted structures. The functional gradation used in this study is a novel technique which is implemented on composite plates.

In this study, functional gradation of fibers has been done and functionally graded hybrid plates has been fabricated and the postbuckling response is determined analytically. The main behind using functioanally graded composites is, the obtained laminate or plate will have advantages of both carbon and glass fiber and also the utilization of carbon fiber is reduced to 50%. The results obtained from analytical and finite element model show that using failure criteria in FEM model gives good agreement of results with those obtained from experimental investigation. Further parametric study is performed, which is helpful in developing the design guidelines for performance based design of efficient as well as low cost functionally graded hybrid composite members.