Chapter 1
Introduction

1.1 Overview of composites

Composites, as the name suggest is the cumulation of two or more materials, whose mechanical properties and performance are superior to its constituents. Generally, composite materials have two phases, where one of the phases is continuous, less stiff and weaker than another phase is called matrix (continuous phase), while the other phase is discontinuous and is called reinforcement (dispersed phase) as shown in Fig. 1.1. Mechanical properties of composites depend on distribution of fibers, i.e., orientation of fibers and volume fraction of fibers. Alongwith, it is highly dependent on the properties of reinforcing fibers and matrix. Ancient man-made composites were mud brick and wall, which were made from mud (clay) and straw. In 3400 B.C., ancient Mesopotamians used to make the plywood with different angle of ply, and properties was better than natural wood. Wood of Palam and Bamboo trees is a natural composite which is still used in construction such as scaffolding and load carrying members as beams and columns for low cost construction. Composites are classified in three sub-categories as shown in Fig. 1.2.

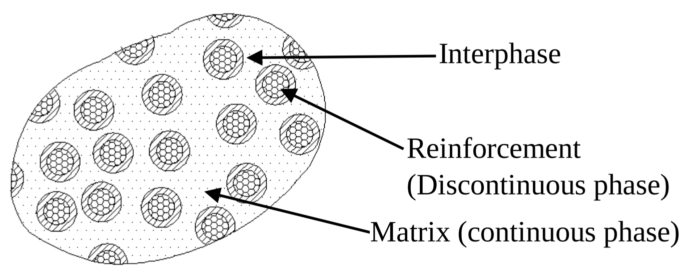


Fig. 1.1. Phases in a typical composite

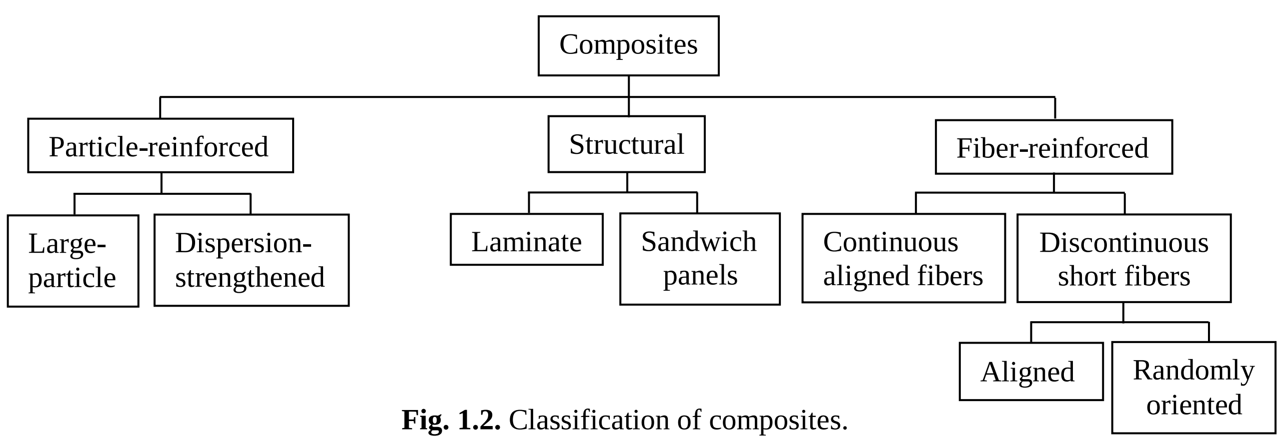


Fig. 1.2. Classification of composites.

1.1.1 Particle-reinforced composites

This class of composites is most widely used, because they are easily available, and economical. Further, this composite is divided in two categories based on the sizes of particles, such as composites with particles size in between 0.01-0.1μm are known as dispersion-strengthened composites, while those with particles size larger than 0.1 μm is known as particulate composites and are discussed in following sections:

1.1.1.1 Dispersion-strengthened composites

In this type of composite, very fine particles (dispersed phase) are used for strengthening of the metals (matrix phase) and its alloys, and matrix is the main load carrying element. This strengthening technique is similar to precipitation hardening. In dispersed phase, metallic, non-metallic and oxides materials are used.

1.1.1.2 Large-particle reinforced composites

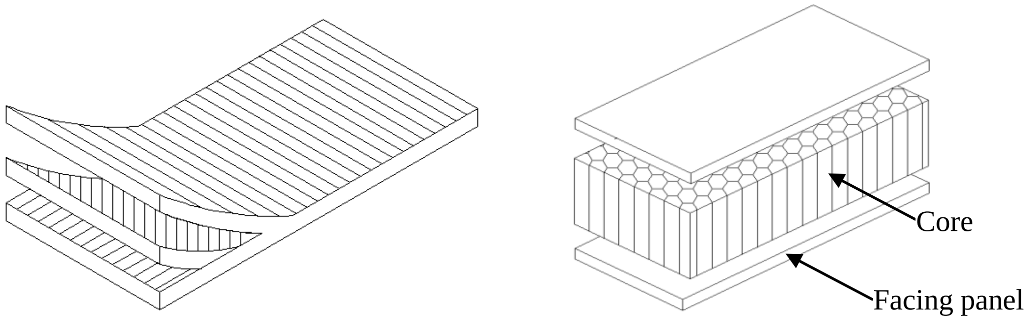
This category of composite contains large amount of coarse particles, which reinforce the matrix phase. The mechanical behavior of composites depends on the properties of constituents as well as on the degree of bonding at the matrix-reinforcement interface. Concrete is most commonly used particulate composite. It consists of cement as binding medium (matrix phase) and finely dispersed particulates such as coarse and fine aggregates as reinforcement phase. Polymers are also reinforced with various particulate materials such as carbon black. For example, when carbon black is added to vulcanized rubber, it enhances the toughness and abrasion resistance of the rubber. Aluminum alloy castings contain dispersed SiC particles, which is widely used for automotive applications including pistons and brake applications.

1.1.2 Structural composites

This type of composite generally consists of homogeneous and composite materials. Properties of these composites depend not only on the properties of the constituents but also on geometrical design of various structural elements. There are two sub categories of structural composite such as:

1.1.2.1 Laminates structures

Sheets (panels) with different orientations of high strength directions are stacked and glued together, producing a material with more strength than strength of each isotropic lamina. Materials used in their fabrication include metal sheets, cotton, paper, uni-directional fibers, woven glass fibers embedded in plastic matrix, etc. Many laminar composites are designed to increase corrosion resistance while retaining the low cost, high strength and low weight properties. Examples are plywood and modern skis. A typical laminated composite having different angle of fiber orientation is shown in Fig. 1.3 (a).



(a) Laminated (b) Sandwich

Fig. 1.3. Structural composites.

1.1.2.2 Sandwich structures

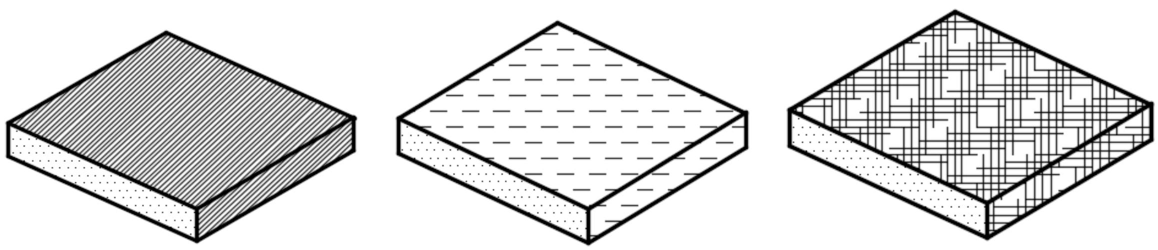
Sandwich structures consist of thin layers of facing material and the gap between facing material is filled with light weight filler material which is known as core as depicted in Fig. 1.3(b). Neither the filler material nor the facing material is strong or rigid, but the composite possesses high stiffness and strength than its constituents. Filler material can be honeycomb, fine or coarse particles such as foamed polymers, synthetic rubbers, inorganic cements, balsa wood. Faces of sandwich structures generally bear the tensile or compressive stress and bending stress, while the core provides the shear rigidity to the panel and resist the deformation perpendicular to the face of the plane. Face of sandwich structures are generally made from Al-alloys, fiber-reinforced plastics, titanium, steel and plywood, while the core materials are foamed polymers, synthetic rubbers, inorganic cements and balsa wood. Sandwich structures are used in roofs, floors, walls of building, and in wings, fuselage, tail and skins of aircraft.

1.1.3 Fiber-reinforced composite

Fiber-reinforced composite consists of fibers embedded in matrix material. Fibers carry the load and the matrix transfer the load to the fibers as well as protect the fibers from external load and atmosphere such composites are called as fiber reinforced polymer (FRP). The key role of the fibers is to provide strength and stiffness to the composite. The bond strength of fiber and matrix depends on the fiber length, surface characteristics, and kind of fiber. Hence, mechanical properties of composites mainly depend on properties of fibers, fiber length and kind of fibers. Fiber-reinforced composites are classified based on length of fibers. Fibers whose length is more than critical length is known as continuous fiber and when length is lesser than critical length (Monette et al., 1993) is called as discontinuous fibers. The critical length of fiber is calculated as,

$$l_c = \frac{\sigma_f d_f}{2\tau_c} \tag{1.1}$$

where, σ_f is the tensile strength of the fiber, τ_c is the interface bond strength of the fiber and d_f is the diameter of the fiber. Discontinuous fiber composites are further classified as aligned and random oriented discontinuous fibers as shown in Fig 1.4.



(a) Continuous (b) Discontinuous aligned (c) Discontinuous random

Fig. 1.4. Schematic of fiber reinforced composites.

1.2 Introduction to fiber reinforced polymer

Fiber reinforced polymers are one of the high strength composite materials, which earn its extraordinary strength capabilities through the synergistic combination of fibers in a polymer resin matrix, wherein the fiber reinforcements carry load and matrix transfers the load to the fibers. Firstly, fiber reinforced polymer (FRP) composites were developed for aerospace and defense applications (Fletcher, 1994), but due to high performance over the other competitive materials, it is growing highly in civil engineering sector also. In fact, with respect to traditional materials, FRP components offer significant advantages in assembling, transporting and launching large parts of structures. Moreover, strong resistance to chemical attacks makes them particularly suitable for aggressive environments. FRP has immense potential as a construction material, therefore it is used in strengthening of existing structures and new construction. FRP encompasses a wide variety of composite materials with different orientations and types of fibers and matrix. Strength of FRP depends on the type of fibers, matrix, fiber orientations, and manufacturing process. The different manufacturing process of FRP are as follow:

1. Hand-layup
2. Filament winding
3. Autoclave

4. Compression molding
5. Rein-transfer molding
6. Sheet molding
7. Roll-forming
8. Pultrusion

The present work is limited to the fabrication of FRP beams and stiffening elements by pultrusion technique and hand layup method are discussed in the following sections.

1.2.1 Hand layup method

Hand layup technique is the simplest method for fabrication of composites. The infrastructural requirement for this method is also less. In this method, first of all, a releasing agent is applied on the surface of mold to avoid the sticking of matrix to the surface. Reinforcement such as woven fiber mats, stitched fiber or chopped strands mat are cut as per the require dimension of the laminate. The mixture of resin and hardener is prepared in suitable proportions and is sprayed or uniformly spread on the surface of mold using brush. The first layer of fabrics is placed on the polymer (mixture of resin and hardener) surface and again polymer is applied on the surface of the fabrics. A roller is moved on the fabric-polymer layer with a pressure to remove any entrapped air and the excess polymer as shown in Fig. 1.5. Further next layer of fibers as per the stacking sequence is placed above the fabric-polymer layer and the same process is repeated till the required layers are stacked. After placing all layers, a releasing agent is sprayed on the inner surface of the top mold which is then kept on the stacked layers and the pressure is applied for getting the uniform thickness of the laminate. Further the whole assemble is left for curing at room temperature or elevated temperature. After the curing, mold is opened, and the developed laminate is taken out.

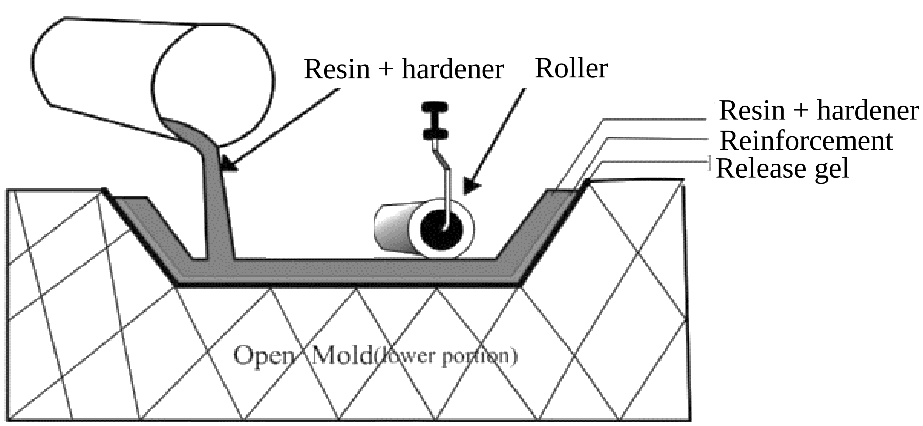


Fig. 1.5. Hand layup process

1.2.2 Pultrusion technique

1.2.2.1 Historical development

From the past few decades, various researchers have shown interest in using the pultruded fiber reinforced polymer (FRP) beams for civil engineering applications. Development of FRP step ladder in late 1970s is the key driver for increasing the interest of researchers in improving the pultrusion technique for low cost manufacturing (Bakis et al., 2002). In early 1980s, the improvement in pultrusion process led to the production of beams and channel for load-bearing applications. Later, a lot of industries started producing standard profiles such as angle, I, H and channel sections, which are used as a part of structural elements as non-load carrying members. These industries provide different layups of fibers in beams, therefore material properties of profiles produced by each industry is different. Hence, they produce their own design manuals such as Fiberline (1995), Creative pultrusions (1999) and Strongwell design manual (1999). Composite Technology, Inc. (Composite Technology, 1991) and Ceramic Cooling Tower Co. used the FRP profiles (I, C or Z-sections) for fabrication of cooling towers (Green et al., 1994). The results of the research efforts in composites are incorporated by various industries for construction of pedestrian bridges and walkways (Bakis et al., 2002).

1.2.2.2 Manufacturing process

Pultrusion is a continuous process for manufacturing of fiber reinforced polymer profiles having constant cross-section. In this process, reinforcements (fibers) like rovings, woven fibers, fabric of chopped strands mat and stitched fibers are impregnated with resin and pulled from heated die for polymerization of resin as shown in Fig. 1.6. After the curing, a rigid cured profile is formed, that corresponds to the shape of the die. The finished profiles can be cut as per the required length using simple hand hacksaw blades. Pultrusion technique is a automatic process which requires low number of labours, and is fast and efficient way to produce FRP profiles such as rods, angle, I-, T-, U- and Z-sections. In this process, designer has flexibility in selection of geometry, properties and design of the finished profile.

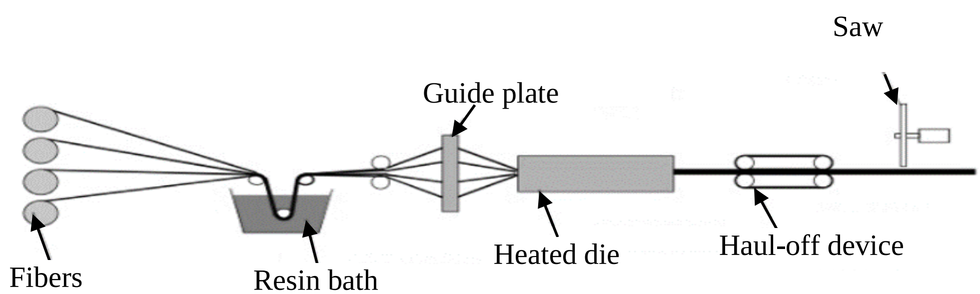
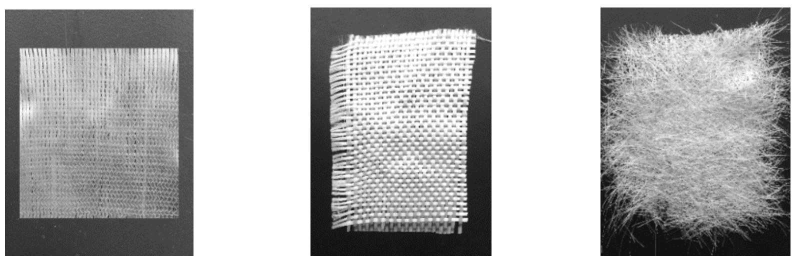


Fig. 1.6. Pultrusion process for manufacturing of FRP profiles.

1.3 Materials used in fabrication of FRP beams

1.3.1 Reinforcement

The main role of the fibers is to carry the load, i.e., to provide the strength and stiffness to the composites. Fibers in composites are in form of bundles or in filaments. Hence, during loading after the failure of fibers, load is transferred to the adjacent fibers. When the fibers are arranged together in a proper fashion it forms fabric. Arrangement of fibers can be in uni-direction, bi-direction, or in random directions which is also known as chopped fibers as shown in Fig. 1.7.



(a) Unidirectional (b) Bidirectional (c) Chopped fibers

Fig. 1.7. Types of fibers.

Fiber used for manufacturing of composite structures can be natural fibers and/or synthetic fibers. Bamboo, jute, rice husk, wheat corn, roots, etc, are the examples of natural fibers, while the synthetic fibers generally used in construction are glass, carbon and aramid fibers. Wrong selection of type of resin and fiber affects the strength, durability, product life and cost of the end products. Brief description of fibers and matrix is given below:

1.3.1.1 Glass fibers

Glass fibers have lower mechanical properties than carbon fibers, but cheaper and more ductile than carbon fibers. Generally, type of glass fibers used in construction are E-glass (E for electrical), S-glass (S for structural), C-glass (C for corrosion) and AR-glass (AR for alkaline resistant). Glass fibers have high surface area-to-weight ratio, which is good for thermal insulation. Glass fibers are most commonly used in construction.

1.3.1.2 Carbon fibers

Carbon fibers are also known as graphite fibers, and are stronger, lighter, conductive and costlier than other fibers. These fibers are mainly used for high strength applications and in important structures in which safety and weight are primary requirements such as rehabilitation of old structures, aircrafts, military equipment's, high-speed vehicles, sports items, etc. Carbon fibers are produced from pitch, polyacrylonitrile (PAN) and rayon $(C_6H_{10}O_5)_n$. Carbon fibers made from rayon are denser than Pan and pitched fibers, while those made from PAN are stronger than pitched and rayon fibers.

1.3.1.3 Aramid fibers

Aramid fibers are in bright golden color. These fibers have high strength-to-weight ratios and heat resistant properties. Therefore, they are mainly used in aerospace, defense and firefighting works. More precise, aramid fibers are used in manufacturing of body armor, bullet-proof vests, fire fighter's uniforms and tyres of high speed vehicles.

1.3.1.4 Veil

Veil is non-load bearing elements in pultruded profiles. It is provided on the outer face of the FRP beams. The main role of the veil is to avoid the display of the internal reinforcement from the surface and it gives resin rich finish to the profile. It gives color to the profiles, resistance for moisture and ease in handling of the products. The most commonly used veils are A-glass and polyester.

1.3.2 Matrix

A composite matrix can be a polymer, ceramic, metal or carbon, but polymer matrices are widely used in laminated and fiber reinforced composites. Composites generally contain 30-40% polymer matrix by weight or volume. Polymer matrix is formed after curing of resin and hardener (catalyst). Resin is further classified in two types such as thermoset and thermoplastics. Thermoset resins are the ones which become infusible and insoluble after hardening, while the thermoplastics resin become softer when subjected to temperature. The most widely used thermoset resin is polyester, vinyl ester, and epoxy. Brief description of each thermoset resin is given below:

1.3.2.1 Polyester resin

This type of resin is a clear liquid, which is mixed with hardener generally 5-20% of the weight of the resin. It is mainly used for coating and fabrication of FRP, and usually used with glass fibers. Polyester resin has two types, i.e., orthophthalic and isophthalic polyester resin. Orthophthalic resin is commonly used resin in fabrication of laminates and cheaper than other polyester resin. On the other hand, isophthalic resin is preferred for marine applications.

1.3.2.2 Vinylester resin

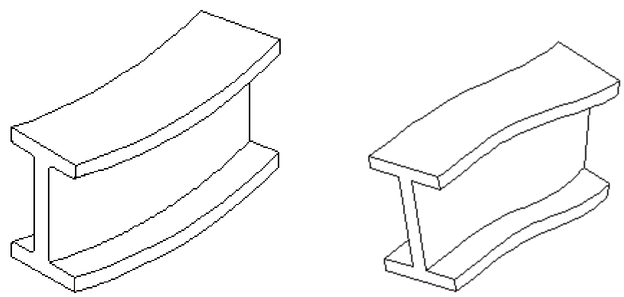
The mechanical properties and cost of vinlyesters are intermediate between epoxy and polyester. The viscosity of vinylester is 0.2 Pa.s, which is lower than polyester (0.5 Pa.s) and epoxy (0.9 Pa.s). Due to high corrosion resistance and resistance to water absorption, it is generally used in marine industries and fabrication of water tanks and vessels. It is more durable than polyester resin but bond strength is lesser than other resins and chances of delamination is more with this type of resin. Hence, this type of resin is not fit for structural strengthening.

1.3.2.3 Epoxy resin

The bond strength of epoxy is 13.8 MPa which is much higher than polyester (3.5 MPa). It is widely used in strengthening purpose, filling the cracks, and for airframe and missile applications. In comparison with other resins, epoxy resin is highly resistant to shrinkage, wearing, peeling, and damage due to chemical degradation, and has higher strength and stiffness. Epoxy resins also offer high resistance to environmental degradation like polyester and vinylester resins when exposed to water.

1.4 FRP I-beams

A thin-walled I-beam is economical and efficient than solid beams, because their bending stiffness per unit cross-sectional area is much higher than that for solid cross-sections such as a rod or a bar. Like steel beams, FRP I-beams also have great potential in carrying the load, as a primary load carrying members in structures. Due to various advantages, some designers have gained interest in the use of FRP I-beams in buildings, bridges and industrial structures for replacement with steel and concrete beams. Researchers have revolutionized the traditional design concepts and shown the possibility of FRP I-beams as viable materials for construction. The design of thin-walled members is governed by stability considerations due to their slenderness as well as failure of the web-flange junction. Thin-walled I-beams are very prone to buckling, in the absence of lateral restraints. Moreover, if the section is slender and the member bends about its strong axis, then it has chances to fail by lateral-torsional or lateral buckling of beams (See Fig. 1.8). Another reason for lateral-torsional buckling of the I-beams is lesser torsional rigidity than bending rigidity. Under the flexural loading, compressive stresses are produced above the neutral axis and tensile stresses below the neutral axis. At a certain load, neutral axis shifts downward, the flange and the part of the web in compression suddenly buckle about its weaker beam axis in the lateral direction, which is known as lateral buckling. Additionally, in pultruded I-beams, the ratio of longitudinal modulus-to-transverse modulus is high, and shear modulus is low, which causes the high shear deformation under service conditions and the beam is susceptible to global and/or local buckling failure. During the local buckling of web of FRP deep beams, high stresses are produced at the web-flange junction, which lead to the tearing of web-flange junction (Borowicz and Bank, 2014). Usually in unstiffened pultruded beams, failure of web-flange junction is the primary failure as shown in Fig. 1.9. (Duggal, 2010).



(a) Lateral buckling (b) Lateral-torsional buckling

Fig. 1.8. Buckling of beams.

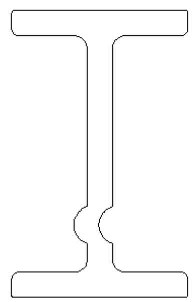


Fig. 1.9. Crippling of I-beam

1.5 The problem in broad-sense

FRP beams are still lagging to replace steel beams in construction due to the deficiency of design guidelines of FRP beams. There is no standard for providing the types and number of fabrics in FRP beams. Leading manufacturers of pultruded beams have produced their own design manuals and guidelines for the production of beams. Moreover, there are lot of experimental and analytical methods to determine the properties of the beams. The elastic and shear moduli play a vital role in the deformation of FRP I-beams. Therefore, for the design prospect and to reproduce the behavior of FRP beams using theoretical or numerical analyses, it is very important to find out the appropriate test method, and analytical methods, which are useful for material characterization of all types of beams.

Generally, I-sections fail by local failure of flanges and web under highly stressed region. Web area of I-section over supports and under concentrated loads behaves like a short column. Therefore, when the stresses produced from reaction or concentrated load is higher than the compressive strength of the web, this leads to the failure at the web-flange junction. This phenomenon is called crushing of web. FRP I-beams have weaker web-flange junction due to the discontinuity of fibers. Even though, high fillet radius is at the junction, but still the beam fails by tearing failure of web-flange junction. This is because extra rovings is required at the web-flange junction, which has very low transverse strength (direction along the height of web). Hence, the failure load of the beams can be enhanced by modifying the layup of the beams, i.e., reducing the amount of rovings and increasing the fabrics at the web-flange junction in transverse direction to the web length. Bearing plate distributes the load over the beams, beams with bearing plate have higher failure load than that of beams in which load is applied using roller. Moreover, failure load of the beams also increases with increase in the width of bearing plate (width is along the length of the beam), but the increase in the load is less in comparison with increase in the cost. Hence, it is important to find out the optimum length of bearing plate for applying the load. Equation to calculate the crushing load of the beam is given in FRP design manual of American Society of Civil Engineering (ASCE, 2011), which is taken from the manual of American Institute of Steel Construction (AISC, 2005). In that equation, effect of the width of the bearing plate (along the width of beam) is also considered, which has significant effect on the steel beams, because bearing plate and steel beams have almost equal stiffness and strength. Therefore, during bending of beams, bearing plate can also deform. In contrast, GFRP pultruded I-beams with steel bearing plates, flexural strength and stiffness of steel bearing plate is much higher than GFRP beams. Therefore, bearing plate does not deform with deformation of GFRP beams. In ASCE formula, the effect of length of the beam is not considered. The crippling load also depends on the length of the beam due to the change in the flexural strength of the beam with length. Hence, a new empirical formula is required, which considers the effect of transverse strength of web, shear strength of web, and flexural strength of the beam.

The high stressed region of the beam can be strengthened with stiffening elements to avoid the failure of web-flange junction. The local failure of the junction can be prevented by various strengthening techniques such as longitudinal stiffener, bearing stiffeners, web plate and cover angle. Further, the dimensions and connection of the stiffening element plays the vital role in enhancing the strength of beams. Again, optimum dimension of stiffening elements and spacing of connection are essential for safe and economical design of the stiffened beams. In industrial structures, openings are essential for service duct and the opening makes the section weaker, especially in FRP beams, where most of fibers are in longitudinal directions. Hence, chances of the failure of the structure become pre-dominant due to shear force and bending moment, which lead to failure of the structures. Design of FRP I-beams with openings is an important structural issue, which can be overcome by proper sizing and positioning of openings in the beam and/or stiffening the edge of the openings with reinforcement.

1.6 Need of this research

In construction, steel is most commonly used metal, especially in buildings, bridges, marine and industrial structures, because of its high stiffness and strength. However, steel has its own weakness such as susceptibility to corrosion when exposed to moisture, salts, and chemicals, which is regarded as its major disadvantage. This problem was solved quite handily about three decades ago by replacing the steel with fiber reinforced polymer (FRP) such as FRP rebar, sheets, ladders, etc. Unlike steel, FRP is resistant to corrosion when exposed to harsh weather and chemicals. Alongwith, it is also nonconductive to electricity and has high impact resistant. The major advantage of FRP is its high strength-to-weight and high stiffness-to-weight ratios. Even though, FRP is used in construction for last three decades, there is no sufficient guidelines available for using FRP beams as a flexural member in buildings and bridges. There are few codes available on FRP beams such as American code, European code, Italian code, and design manuals of FRP production industries. These codes discuss the buckling of FRP beams, but the designing of beams with stiffening elements and guidelines to resist the local failure such as tearing of web-flange junction and crippling failure of web is missing. Hence, in this study flexural response of stiffened and unstiffened beams is investigated. Alongwith, design guidelines of castellated I-beams are described. Design charts of FRP I-beams with and without stiffening elements are made using analytical and numerical models, which can be used to design the beam as a flexural member for buildings and bridges.

1.7 Objectives of the present study

In an effort to fill these apparent gaps, the main objectives of the present investigation are as follows:

1. To experimentally predict the material characteristics of FRP system
2. Experimental as well as numerical investigations of the flexural-torsional and/ or lateral-torsional buckling of self-fabricated FRP laminated beams with different geometric configurations
3. Detailed study on the effect of shape, size and location of cutouts in web on overall response of the FRP laminated beams
4. To study the effect of axial and flexural rigidities of stiffeners on the flexural and shear responses of FRP beams
5. Recommendation of guidelines for cost effective design and section classifications of FRP beams

1.8 Methodology

Based on the objectives of the project, methodology incorporated for executing the research is given as follows:

Stage 1: Material characterization of beams was performed by conducting tests on FRP coupons and beams, and using theories.

Material properties of beams was determined such as Young’s modulus, tensile strength, compressive strength, flexural modulus, flexural strength and interlaminar shear strength.

This preliminary stage aims at determination of material properties, which is used for analytical and numerical modeling of FRP beams.

Stage 2: Flexural test setup is made to experimentally predict the flexural response of FRP I-sections. Structural stability of beams was determined for beams with and without imperfection in the geometry. Further, the effects of layup and sizes of bearing plate on the flexural response of FRP I-beams were investigated using analytical and numerical models.

This stage aims to enhance the flexural strength of beams with different types of layup and sizes of bearing plates.

Stage 3: Mechanism to present the local failure of the beams under the stress concentration is developed by addition of bearing stiffeners. Parametric study is performed to study the effect of different sizes and types of stiffening elements on the failure and service loads of the beams.

This stage aims to develop a design approach for using the FRP beams with different stiffening elements.

Stage 4: Structural responses of FRP castellated I-sections are predicted under three-point bending. The effect of different types of stiffening elements on structural behavior of castellated I-sections is investigated.

The primary aim of this stage is to generate the design guidelines for effective design of castellated I-beams.

Stage 5: Preparation of technical papers, submission of research findings and completion of report.

In this final stage, the findings of the entire research program are reported to research community in the form of technical papers. Further, a detailed report is prepared and submitted to the funding agency for possible research grants.

1.9 Outline of thesis

In order to meet the above mentioned objectives, this thesis is divide into 7 chapters. The outline of the next six chapters is given below

Chapter 2 provides the literature review on material characterization of composite materials, analytical and numerical methods for analysis of FRP beams, and different failure modes of FRP I-beams.

Chapter 3 presents the material characterization of FRP beams using experimental, analytical and numerical methods.

Chapter 4 deals with the experimental study on the flexural behavior of FRP I-sections with and without stiffening elements. Alongwith, flexural response of the FRP I-beams with and without stiffening of cutout is also discussed.

Chapter 5 presents analytical methods to predict the Young's and shear moduli of the beams. It also includes the modeling of FRP beams using self-developed equations for prediction of flexural response and failure modes similar to the experimental response.

Chapter 6 provides the steps-by-step procedure to model the FRP I-beams with and without stiffening elements, and cutouts using finite element software, i.e., ABAQUS.

Chapter 7 discusses the important and useful conclusions based on this study, and recommendations are made for effective design of FRP I-beams for civil engineering applications.

1.10 Scope of the present investigation

The outcomes of this study will have impact on the construction sector of the country, especially in buildings and bridges. This study is highly applicable for analysis, design, and fabrication of the FRP beams as replacement of steel beams, which will increase the efficiency and decreases the life cycle cost of structures with low maintenance cost. All the design charts, tables, and design equations will be directly helpful for fabrication of FRP materials and girders, so that they could be effectively designed as per needed performance, function, and strength requirements. Thus, design recommendations of the study will help in performance based design of FRP girders for buildings and bridges in our country as well as development of Indian standards for designing of FRP beams.

In this study, flexural characteristics of stiffened and unstiffened FRP I-beams are determined analytically and numerically; and verified with experimental results of the present investigations. There are no code provisions for designing the FRP beams with stiffening elements. Hence, equation to calculate the deflection of beams with different stiffening elements are derived using Castigliano's theorem. In order to get the better understanding of failure of FRP beams, various formulae of beams without stiffening elements available in design manuals are incorporated in the analytical model for prediction of failure load and mode. Further, a failure criterion is recommended for prediction of failure load of beams with and without stiffening elements. The numerical model presented in this study can be further utilized for investigation of FRP I-beams with different geometric configurations of beams and stiffening elements such as bearing plates, bearing stiffeners, cover angle, cover plate, and web plates. Alongwith, flexural response of FRP castellated I-beam with different stiffening elements is also investigated. The results obtained from analytical and finite element model show that using failure criteria in analytical and 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 composite FRP beams.