

## **Chapter 1. Introduction**

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Composites are defined as materials formed by macroscale combination of two or more chemically distinct phases exhibiting the best and superior qualities of their constituents and often some qualities that neither constituent possesses. The stiffer and stronger constituent is usually discontinuous and called reinforcement phase, and the one in which it is embedded is called matrix. Matrix is less stiff and weaker phase, but it is continuous. The different materials work together to give the composite unique properties, but within the composite the different materials are apart and keep their physical identity, but they do not dissolve or blend into each other. Composite materials are found to have widespread applications in industries like aircraft, automobiles, sporting goods, biomedical sciences, electronics and defence due to their high strength and stiffness as well as low weight, enhanced fatigue properties, insulating properties, workability in different environmental conditions and low cost of mass production. Unlike traditional materials, composites can have their strengths oriented to meet specific design requirements of an application.

However, laminated composites exhibit relatively poorer resistance to impact loading, poor strength in transverse direction, and difficulties in machining and joining. Eventually failure due to one of the modes such as, matrix micro cracking, fiber breakage, ply overlapping, delamination at free edge and from areas of stress concentrations, inclusions, micro-voids and interfacial debonding/delamination restricts their usability. Real composite structures consist of multidirectional laminates. Such laminates will have complex failure modes such as fiber fracture, splits, debonding, delamination and interface cracks between plies of different orientation. All of them reduce to the simple damage modes of fiber fracture, matrix cracks and interlaminar/intralaminar delamination or interplay cracking and cause severe degradation to the structural integrity and load carrying capacity of composite structures. Most of the time these damage mechanisms do not appear independently of each

other. In many cases matrix cracks initiate other damage mechanism like delamination. These can, together with fiber fracture led to final failure. Durability and damage tolerance criteria require composite structures containing undetected damage to be acceptable to operate satisfactorily and safely for high-end advanced threshold structures such as spaceships and aircrafts.

### **1.1. Composite Constituents**

Figure 1.1 describes various types of composites depending upon the reinforcement and matrix configurations. Plastics and alloys should not be confused as composites. Majority of the plastics like toys and soda bottles are pure plastic. In composites, however the constituents keep their physical identity and are not soluble in each other. Lightweight structures use composite materials due to their superior specific stiffness and modulus properties. The basic constituents of composite material system are as follows.

- Reinforcement
- Matrix
- Coupling agents (coatings/fillers)

Over recent decades many new composites have been developed, some with very valuable properties. By carefully choosing the reinforcement, the matrix, and the manufacturing process that brings them together, engineers can tailor the properties to meet specific requirements. They can, for example, make the composite sheet very strong in one direction by aligning the fibers that way, but weaker in another direction where strength is not so important. They can also select properties such as resistance to heat, chemicals, and weathering by choosing an appropriate matrix material. Specific fillers, additives and core materials are also sometimes added to enhance and modify the final product. Structures can be partially or completely pre-fabricated at the manufacturer's facility, delivered on-site and installed in hours.

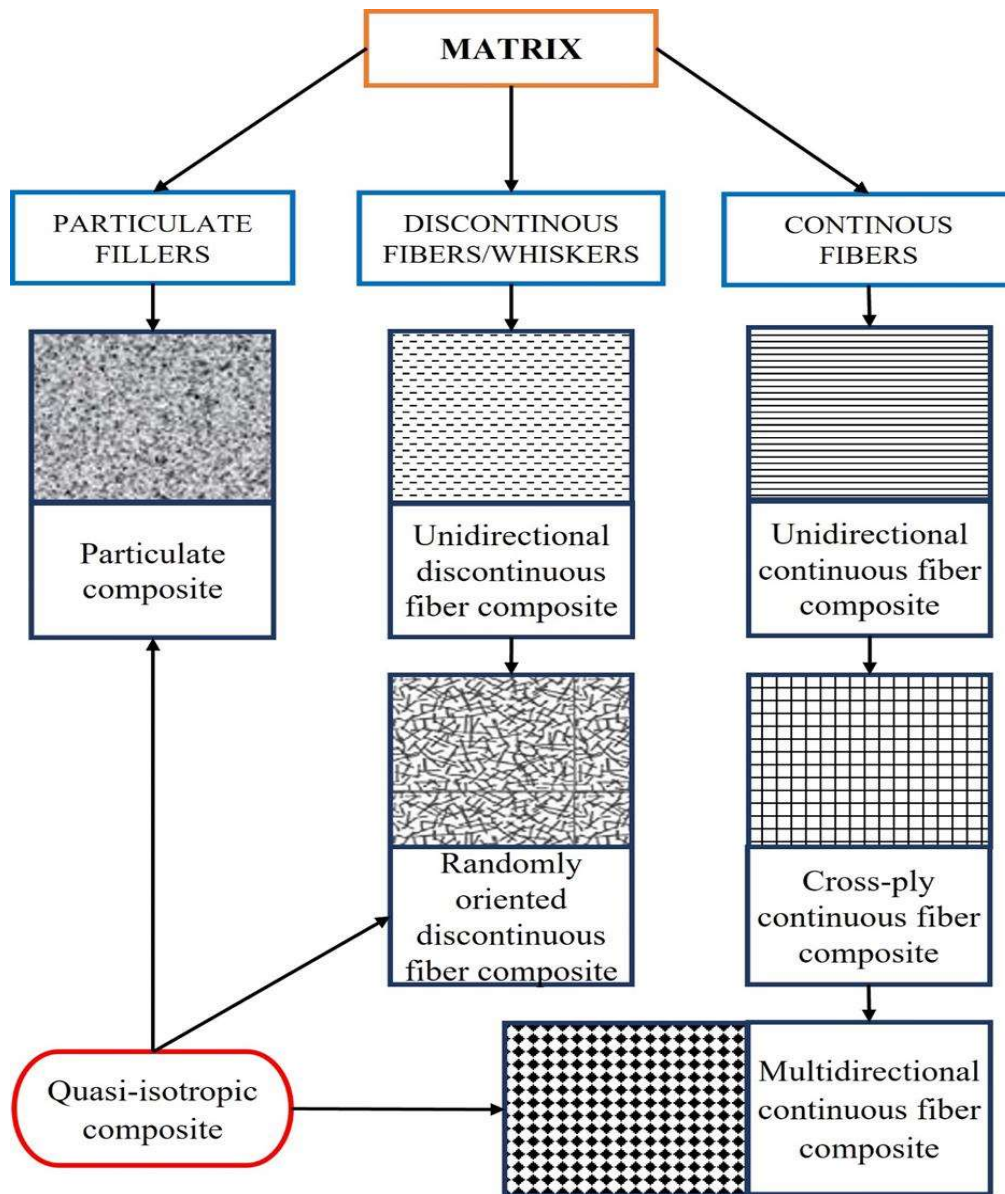


Figure 1.1 Classifications of composites

## 1.2. Characteristics of Laminated FRP Composites

Fiber-reinforced polymer (FRP) composite is a material system of discontinuous phase of fibrous form of reinforcing agents such as glass, carbon, aramid or other reinforcing materials embedded in a continuous phase of polymer (plastic) matrix (either a thermoplastic or thermosetting resin, such as polyester, isopolyester, vinyl ester, epoxy, phenolic). In general, materials in fibrous form have higher strength along their lengths, as the flaws or

discontinuities in the bulk form are eliminated due to the small cross-sectional dimensions of the fibers. Fiber-reinforced laminated composites are a hybrid class of composites involving both fibrous composites and lamination techniques. Such notable features of laminated composites are that the strength and stiffness can be tailored to the specific design requirements of the structural element being built. Apart from high specific strength and stiffness retention, composite can also be shaped into one complex part, replacing the cumbersome aspect of assembling of several parts and fasteners. All these features have resulted in FRP composites as the most sought after and attractive material for structural applications. No wonder that modern day fighter jets and stealth bombers are almost entirely made of composite material. Composite materials are strong, wear and corrosion resistant, and can handle high loads and impact. Hand layup technique, spray up, compression molding, injection molding, filament winding, pultrusion etc. are some of the production processes generally employed for manufacturing of composites.

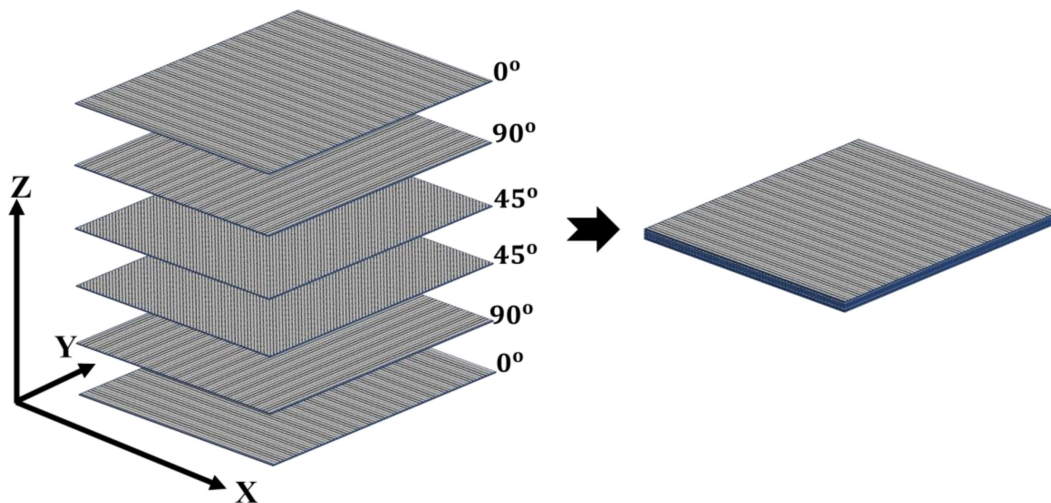


Figure 1.2 Schematic of a symmetric and balanced composite laminate.

The idea of manufacturing composites did not arise in modern times. Millennia ago, man tried to improve the strength of bricks by adding chopped straw or other vegetable fibers to the mass of clay. A cake of dried mud is easy to break by bending, which puts a tension force

on one edge, but makes a good strong wall, where all the forces are compressive. A piece of straw, on the other hand, has a lot of strength when stretched but when it is crumpled it has far less resistance. When pieces of straw are embedded in a block of mud and dried hard, the resulting mud brick resists both squeezing and tearing and makes an excellent building material. Precisely, it has both good compressive strength and good tensile strength. A typical man-made composite is reinforced concrete, but also such familiar objects as a candle, a lead pencil, or the wall of a frame house represent composites. Man, alone does not necessarily produce composites. Nature itself is lavish in creating composites, for example, it is worth mentioning that the limbs of animals, in which a hard bone is combined with hard muscles in order to make a single working element. Composites exist in nature. A piece of wood is a composite, with long fibers of cellulose (a very complex form of starch) held together by a much weaker substance called lignin. Cellulose is also found in cotton and linen, but it is the binding power of the lignin that makes a piece of timber much stronger than a bundle of cotton fibers. Another well-known composite is concrete. Here aggregate (small stones or gravel) is bound together by cement. Concrete has good strength under compression, and it can be made stronger under tension by adding metal rods, wires, mesh or cables.

Nowadays, the manufacture of composites is prompted by the unceasing trend to produce industrial materials with continually better and better mechanical, thermal or other properties. The progress in this direction has been so great that it is now possible to obtain new material of a very high quality. By choosing an appropriate combination of reinforcement and matrix material, manufacturers can produce properties that exactly fit the requirements for a particular structure for a particular purpose. In general, fibers are the principal load carrying members, while the surrounding matrix keeps them in desired location, acts as a load transfer medium between them and protects them from environmental

damages due to elevated temperatures and humidity. The matrix protects the surface of the fibers also. In a typical composite the materials joined together have, as a rule, properties that complement each other. For example, in fiberglass, one material is constituted by fine glass filaments of a very high tensile strength, but of low transverse stiffness. To prevent buckling and secure the concerted working of the individual fibers, the later are imbedded in a binder (matrix) of low strength, but capable of providing adequate protection for the flexible load-carrying filaments. Lamina (or Ply) is a single layer (plane or curved) of unidirectional or woven fabric in a matrix. Laminate: The laminae (plies) can be of various thicknesses and may consist of different or same materials. Figure 1.3 delineated the various lamina configurations with different fiber orientations and alignments to obtain unidirectional or bi-directional continuous and discontinuous or random ply lay-ups.

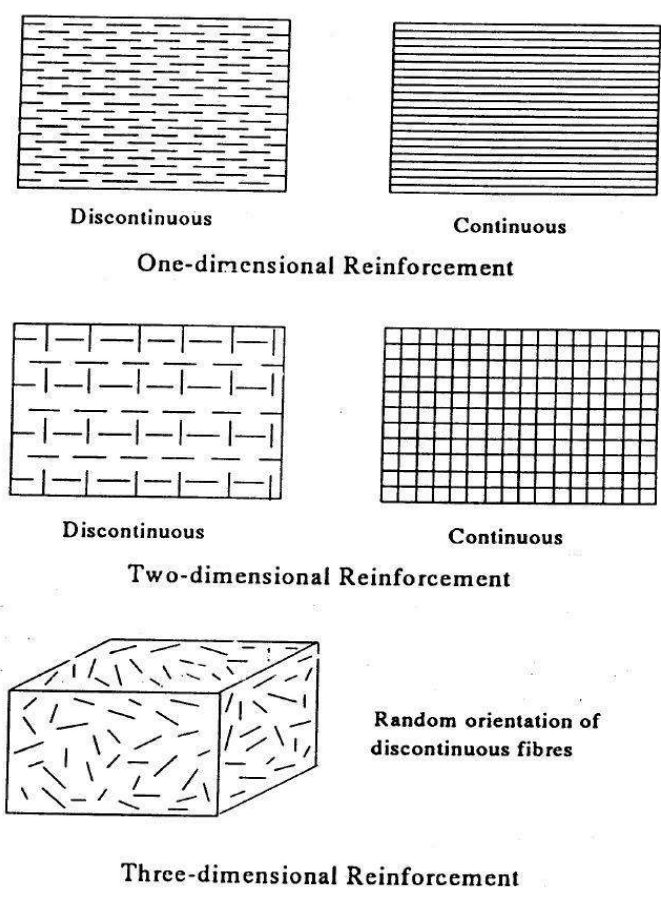


Figure 1.3 Schematic of fiber orientations in FRP composites.

The fibers in the early twentieth-century composites were made of glass. Today the filaments are readily made of metals and minerals, such as boron, beryllium, steel, aluminum, silicon carbide, graphite, asbestos and others. Materials used for the matrix include epoxy, polyester and phenolic. The strength of the fibers- whose diameter is frequently of the order of  $10^{-3}$  cm for glass, graphite, steel and aluminum and of the order of  $10^{-2}$  cm for boron, beryllium and silicon carbide oscillates about the theoretical molecular value of the order of  $10^9$  - $10^{10}$  Pa. For example, the strength of glass filaments reaches a value of 3 to  $5 \times 10^9$  Pa: this compares favorably with about 3 to  $10 \times 10^8$  Pa for steel in bulk. Along with enormous strength, a superior ratio of strength to weight singles out the composites from the orthodox materials. Consequently, the use of composites reduces the weight of structures and various other products often by more than one-third. This economy of weight is closely related to the remarkable adaptability of composites, in this series the sandwich composites are introduced by the design engineers. These sandwich composites emerged as solution to the weight critical structural applications.

### **1.3. Construction of Sandwich Composites**

Sandwich composite is the special subset of the composite structure. Sandwich composite are basically consisting of the two thin face sheets separated and clubbed together by a thick material called core which increase the section modulus of the structure assembly. The face sheets are stiffer and stronger than the core material. It is also noted generally the density of the core material is lower than the face sheets. The sandwich composite performs great under flexural loading and impact loading. These sandwich structures enable the design and development of weight-critical components for aerospace, missiles, locomotives, sports equipment, warships structures, and windmill blades.

The sandwich construction is not only restricted to the enhanced load carting capacity under bending. The sandwich construction facilitate radar absorbing materials in the core, which

make USS Radford mast invisible to radar. The sandwich concept is also utilized as packaging in the form of corrugated paper board, and in the nature, it is manifested as bones, skulls and wings of the birds. The simple sandwich construction is shown in the figure 1.4.

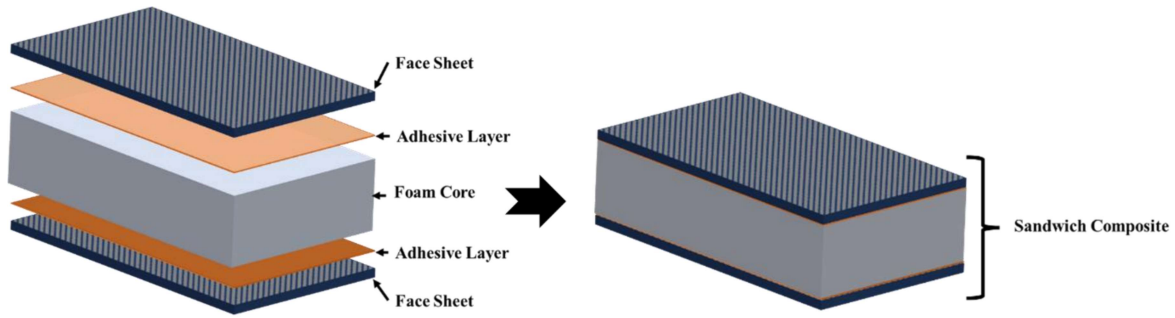


Figure 1.4 Sandwich composite structure

#### 1.4. Classification of Sandwich Composites

Sandwich composites are classified according to the face sheet and more especially the type of core construction is utilized in the fabrication of the sandwich constructions. The classification of sandwich composites is well represented in Fig. 1.5. If the face sheets are made out of the conventional material steel, aluminium and copper alloys are great choices. Because these materials are available in abundance therefore cost effective, high in strength and easy to manufacture in sheet form. While, the face sheets are made of non-metal and unconventional materials also. Here, plywood, reinforced plastics and fiber laminate composites are more prevalent choices. The advanced face sheet composites are used where weight is major criterion in the material selection. This advance fiber reinforced composite is high in stiffness, strength and light in weight than its contemporary materials. The core is also bifurcated in to two categories: cellular and structural as shown in Fig. 1.5. The cellular core is defined as the repetition of the cells in the plane or in the 3-dimensional space. These cells are arranged in organised manner or random manner. In honey comb structure the cells are arranged in plane and well organised. But, in case of natural occurring balsa wood and

foam the cells are arranged in 3-dimensional space and randomly filled the space. Now, the structural core is gaining momentum and competing with the cellular core. Because of the advancement in the manufacturing technology, the structural core specially truss and origami core structure are becoming much easier to fabricate. The structural core has many lucrative advantages and applications. But, as far as fabrication cost is concerned still, the cellular structure is far ahead in this genre to select cost effective core material.

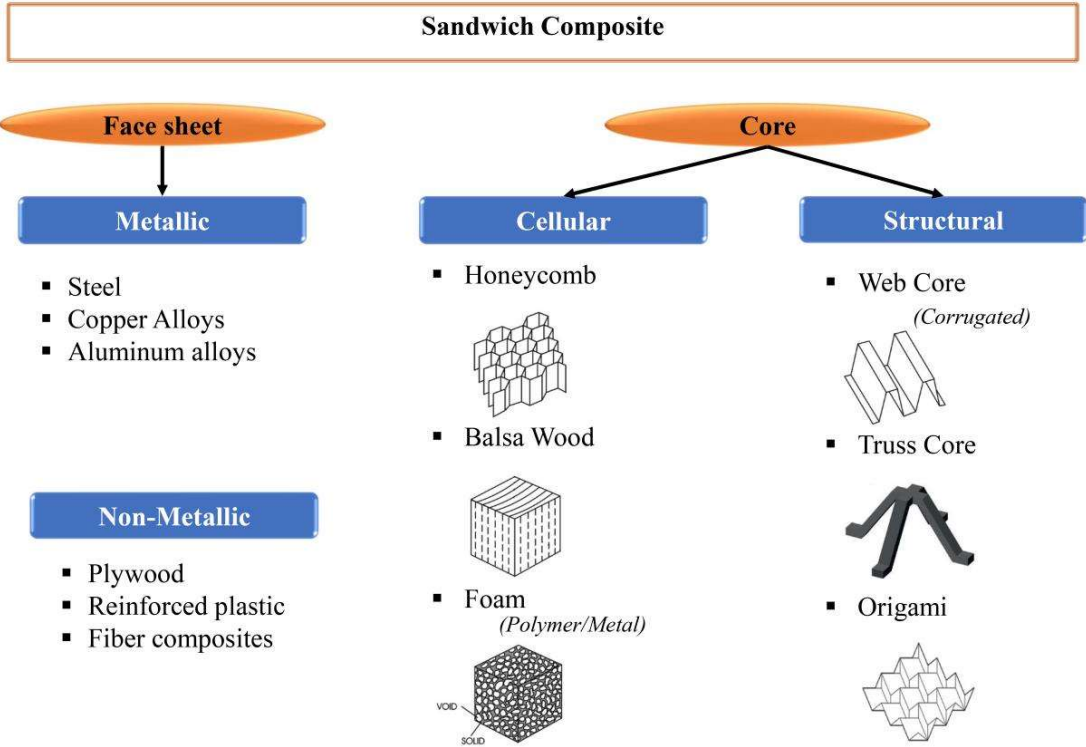


Figure 1.5 Classification of Sandwich composite

**1.5. Design Principle of Sandwich Structure**

A sandwich construction comprises of two face sheets, connected to and separated by a core, as illustrated in Fig. 1.4. The face sheets are stiffer and stronger compared to the low-density core despite their thinness. The face sheets are often constructed of thin, stiff, and sturdy sheets of solid material such as reinforced plastic, alloy, metal, plywood, or cardboard. Carbon filament reinforced epoxy resin composite panels have been more popular for face plates in recent years, notably in the aviation sector. Core materials, on the other hand, might

be very different from those utilised for face sheets. Cores are often made of plastic, fibre, metallic, or felted materials and found in a variety of forms ranging from corrugated to cellular to foamed structures. The idea behind the sandwiched structure is that the facings and core must function in tandem as a highly effective structural element.

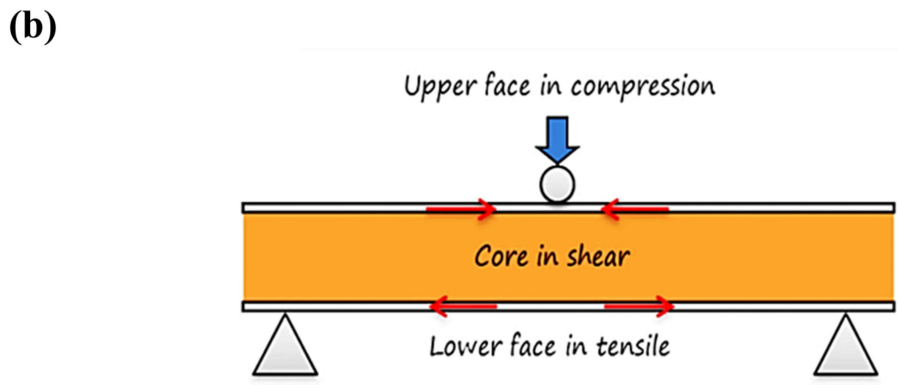
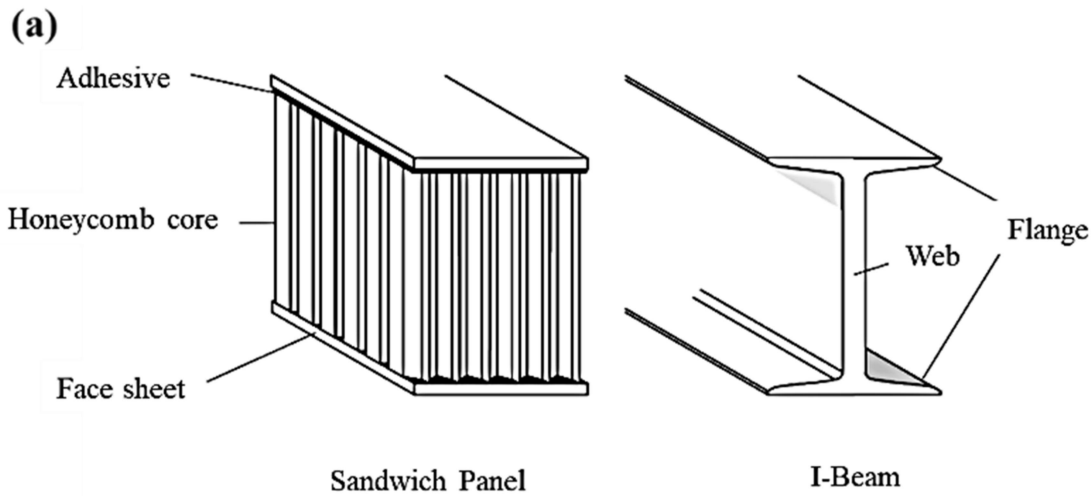


Figure 1.6 Design concept of sandwich composite

The sandwich composite functions similarly to an I-beam (Fig. 1.6 a), which was extensively used in structures for long times. The web of an I-beam bear shear forces efficiently, while the two flanges separated by the web, offer flexure rigidity. Thus, the core of sandwich composite structures and web of I section beam performs the similar function. To obtain greater flexural rigidity from the facings, the core should be sufficiently stiff to make sure

that the facings will remain with proper spacing. The facings must be able to maintain their position relative to each other when the sandwich composite panel is bent, and the core must have sufficient shearing strength to prevent this from happening. If there was insufficient material between the two thin facings to resist shear, they had just been two different beams or panels, and the overall sandwich effect would not work. Finally, the core must be sufficiently strong to keep the face sheets flat or nearly flat when exposed to compressive stresses that may produce buckling or wrinkling effect.

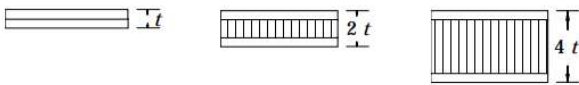
Because of the emergence of new class of core materials as artificial cellular materials, the notion of sandwich composite has grown in popularity among all potential design ideas in composite material field. Sandwich constructions are composed of

1. A pair of thin, resilient, and stiff skins (i.e., faces, facings or covers)
2. A dense, lightweight core that separates the skins and carries the loads from one skin to the next., and
3. An adhesive layer which can transmit shear and axial loads to and from the core

The moment of inertia increases by the core, which separates the facings (or skins) of the composite at the cost of little increment in weight, thereby, producing an effective composite structure to resist the flexure and buckling loads.

Table 1.1 illustrates the flexural stiffness and strength advantage of sandwich panels over solid panels using typical beam theory with typical skin and core density values.

Table 1.1 An example of structural efficiency of sandwich panels in terms of weight



<b>Relative Bending Stiffness</b>	<b>1</b>	<b>7.0</b>	<b>37</b>
<b>Relative Bending Strength</b>	<b>1</b>	<b>3.5</b>	<b>9.2</b>
<b>Relative Weight</b>	<b>1</b>	<b>1.03</b>	<b>1.06</b>

A sandwich panel is created by dividing the solid laminate along the centre and separating them with a core material. The new panel weighs somewhat more than the laminate, but it has substantially better flexural rigidity and strength. The difference is much more apparent when the thickness of the core material is increased. Sandwich composite panels are so common in high-performance applications where weight is limited, such as high-speed marine vehicles, aeronautical structures, and racing automobiles. Composite materials are employed for the skins in the most weight-critical applications, while cheaper alternatives such as steel, aluminium alloy, or plywood are also widely used. Wood, aluminium, polymers, and composites are among the materials utilised for cores. These are employed in the shape of foams, honeycombs, or corrugated structure to save weight (Figure. 1.7).

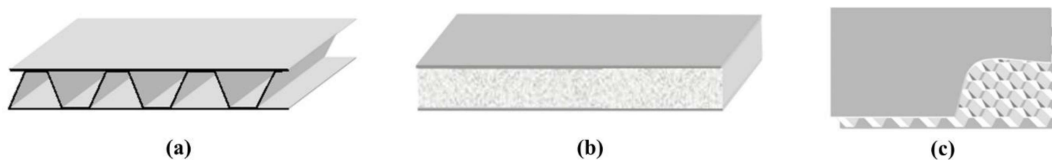


Figure 1.7 Sandwich panels with (a) Corrugated (b) Foam and (c) Honeycomb Core

In addition to mechanical requirements, core materials may be chosen for their fire resistance or thermal properties. Karlsson [1] extensively reviews the most prevalent and

some unconventional procedures used to make sandwich components for structural purposes, as well as current advancements and future prospects in terms of both materials and processing approaches. Sandwich panels must fulfil stiffness and strength requirements. The stiffness of honeycomb sandwich panels is easy to predict, but the strength remains challenging to forecast. Face yielding, face wrinkling, intra-cell dimpling, core shear, and local indentation are common causes of failure. The critical failure load and related failure mode are determined by the characteristics of the face and core materials, the structure's shape, and the loading arrangement.

Sandwich composite structure analysis requires a full knowledge of the mechanical behaviour of both the skins and the core. The skins act in a reasonably straightforward manner, and in the case of composite laminates, the aforementioned methods of analysis (i.e., laminated plate theory) facilitate the modelling approach. However, mechanical modelling of the core material is more challenging, especially for foams or honeycombs. The core's response to loading normal to the plane of skins or shear loading from the skins is needed. The nature of response is affected by both materials employed in the core and the relative density of core. The relative density of core is the ratio of the core density to the density of the solid material that makes up the core. Gibson and Ashby [2, 3] provide an extensive review of the literature on cellular materials, including several findings for foam cores.

## **1.6. Failure of Sandwich Structure**

Sandwich composite materials may fail under the action of external loads. The main failure modes of sandwich structures are:

- Failure of the adhesive bond (delamination). When a sandwich column is subjected to peel loading the adhesion between the face and the core may fail (Figure 1.8 a) [4]
- Face failure. When a sandwich column undergoes tensile loading, if the normal tensile stress in the face equals the yield strength for ductile skin materials and fracture strength for brittle face materials, the face or skin sheet may yield or fracture respectively, (Figure 1.8 b) [5]
- Euler macro buckling, core shear, micro-buckling and face sheet wrinkling failure modes occur when a sandwich column is subjected to end compression [6].
  - Euler macro-buckling, is a type of failure in which a column subjected to compression loading, becomes unstable and pass instantaneously into a curved axis configuration, the column being said to have "bent". It is known simply as buckling, and it occurs because the compression level on the element reaches a certain value for which it is easier to "jump" to another configuration, even if much more deformed (curved). In forging operations buckling is a term used to describe the wavy condition of the workpiece caused by compressive stresses (Figure 1.8 c).
  - Core shear is a failure mode occurring when the principal stresses in the core combine to exceed the yield criteria (Figure 1.8 d).
  - Micro-buckling of composite face sheets occurs when the axial stress within the compressive face sheet attains the face sheet micro-buckling strength, treated as an intrinsic material property (Figure 1.8 e).
  - Face wrinkling is a local instability of the faces involving short wavelength buckling of the face sheets, resisted by the underlying elastic core. It occurs when the normal stress in the compression face of the beam reaches the level of instability (Figure 1.8 f).

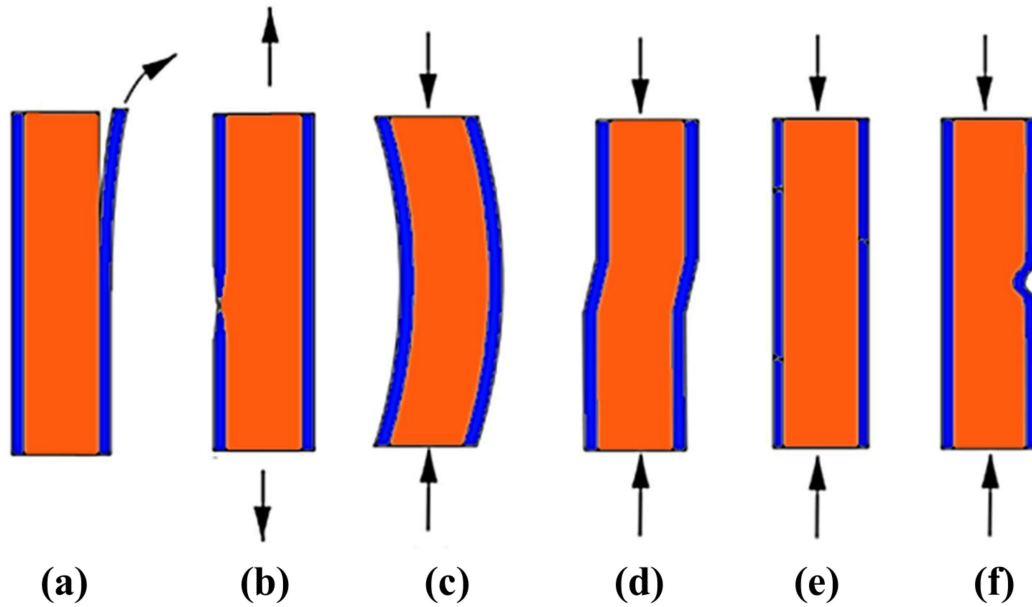


Figure 1.8 Failure modes in sandwich columns according to three types of external loading: a) Delamination failure (peel loading); b) Face yielding failure (tensile loading); c) Euler macro-buckling (compressive loading); d) Core shear macro-buckling (compressive loading) e) face sheet micro-buckling (compressive loading) and f) face sheet wrinkling (compressive loading)

### 1.7. Fly Ash as Sustainable Particulate Reinforcement

Fly ash is a fine, powdery by-product generated from the combustion of pulverized coal in thermal power plants. Fly ash is predominantly composed of silicon dioxide ( $\text{SiO}_2$ ), aluminum oxide ( $\text{Al}_2\text{O}_3$ ), iron oxide ( $\text{Fe}_2\text{O}_3$ ), and calcium oxide ( $\text{CaO}$ ). Traditionally, fly ash has been considered a waste material and posed significant environmental challenges due to its disposal requirements. However, recent research has revealed its potential as a sustainable reinforcement material, offering a promising solution for both waste management and improving material properties. It can enhance the mechanical properties of different materials when used as a particulate reinforcement. It can contribute to improved strength, stiffness, durability, and resistance to cracking. Additionally, fly ash can modify the microstructure of matrices, leading to enhanced performance and extended service life. The availability of fly ash in large quantities and its relatively low cost make it an

economically attractive option for reinforcement applications. By incorporating fly ash as a reinforcement material, project costs can potentially be reduced, offering economic benefits to various industries

### **1.8. Scope of the Present Work**

The present study focuses on using Fly Ash (FA) as a potential particle reinforcement to fabricate a PUF core reinforced with Fly Ash. Then, the improved mechanical characteristics of the PUF core are evaluated under compression, shear, and indentation loading. These cores are then used to fabricate GFRP/CFRP sandwich panels. The better characteristics of these FA-reinforced PUF core sandwich composites compared to those of the unreinforced PUF core sandwich composites under flexural and indentation loading are next studied.