CHAPTER 1
INTRODUCTION

1.1 MOTIVATION

The use of fiber reinforced composites is extending beyond the initial applications in aerospace and military fields, driven by the advances in manufacturing technologies which made the production process more cost effective. Fiber reinforced composite materials offer excellent mechanical properties, while being much more lightweight than metallic alloys. However, their processing technology is still in the incipient stage with many restrictions in shape and structure forming, all these restrictions making the part design and manufacture more difficult and expensive. Extensive research and development is currently undergoing to overcome such restrictions and difficulties in various stages of their production. Our work is aiming to bring contributions in the machining processes of these types of materials.

As fiber reinforced composites parts are usually integrated in a mechanical assembly, drilling is the most often encountered machining process in the production of such parts. Drilling carried out during the last stages of the manufacturing process in order to create fixing features like holes. Drilling of fiber reinforced composites is governed by different physical laws than drilling of metals (brittle chip formation in opposition to plastic deformation) – this being the reason that current industrial practice are not fully understood and optimized.

Delamination defect and excessive tool wear are the two major problems highlighted in the drilling process of fiber reinforced composites. Delamination (and overall hole quality) is a critical aspect of the drilling process, as it can lead to failure
in use and parts with such defects are usually discarded. Furthermore, delamination is usually not detectable for the eye and special inspection process is necessary. The excessive tool wear make the drilling process of fiber reinforced composites very expensive as only a limited number of holes can be drilled with one particular drill.

From the process planning point of view, delamination defect was found to be related to the thrust force generated during drilling, force which for a given work-piece and material combination depends on the drill geometry and the cutting conditions. Tool wear is believed to be related to both cutting forces and thermal loads with more complex material properties dependence.

Composite materials are anisotropic in nature. Hence drilling in composite components is not similar to drilling in metallic components. In metallic materials all the structure will respond in a similar manner under the machining loads but the composite structure will have localized responses from the same loads, leading to defects in the internal structure of the remaining work-piece material (i.e. delamination) due to which the rejection of the components is increased. Therefore, we find important for studying the influence of various process parameters on the hole quality (delamination and surface roughness) and optimization of those parameters to enhance the quality of holes. From the available literature it is evident that many optimization methods are in use (Taguchi method, Response Surface Methodology etc.). In this research work, for the first time we have introduced System Dynamics as a novel approach for the optimization and simulation of drilling parameters. The simulation was developed with the help of VENSIM® and MATLAB® software. Additionally, the experimental analysis of the drilling process has to be extended to study effect of process parameters on various responses and to collect essential data to develop simulation.
1.2 COMPOSITE MATERIALS

The use of a combination of different materials, which results in the creation of superior products, started very early. It has been used continuously down to the present day. Several composites used today are at the leading material technology, with performance and costs appropriate to ultra-demanding applications like spacecraft. However, heterogeneous materials which combine the most effective aspects of dissimilar constituents have been used by nature for millions of years. Ancient society as such imitated nature and used this approach further. The Book of Exodus reveals the facts that people used straw to reinforce mud in brick making, without which the bricks wouldn't have left with any strength [1].

Composites of matrix reinforced with fibers are being used to build airframe structures. Modern composites owe abundant to glass fiber-polyester composites developed since the 1940’s to wood work over the centuries, and man imitated nature over millions of years. Numerous examples of composites exist in nature, like bamboo, which is a filamentary composite. Through the years, wood has been a commonly used as natural composite whose properties with and against the grain vary considerably. Such directional or isotropic properties have been mastered by design approaches, which build advantage of the superior properties while suppressing the undesirable ones through the use of lamination. For example Plywood is made with a number of lamina. Such a stacking arrangement is important in order to prevent distortion. Within the language of modern composites, this is referred to as the symmetric lay-up or zero extension flexure coupling (orthotropic) [2].

A composite material can be defined as a mixture of two or more materials that leads to better properties than those of the individual components used alone
having a discrete and recognizable interface between them. In distinction to metallic alloys, every material retains its separate chemical, physical, and mechanical properties. The two constituents are reinforcement and a matrix. The main advantages of composite materials are their high strength and stiffness, combined with low density, when compared with bulk materials, it allows for a weight reduction in the finished part [3]. Comparison of strength vs. density for various materials is shown in figure 1.1.

![Figure 1.1: Comparison for various engineering materials with respect to strength vs density](image)

High performance composites offer combinations of engineering properties which cannot be achieved using homogeneous metallic alloy structural materials like aluminum, titanium and steel, and may provide a higher level of these properties. The largest volume usage of structural composites in industrial, aerospace, commercial and military applications relies upon resin matrix fiber reinforced composites. Thus, these composites are emphasized throughout this volume. Comparison of composite properties with metals is shown table 1.1 [5].
Table 1.1 Properties of composite materials [5]

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $(10^3 \text{kg/m}^3)$</th>
<th>Ultimate Tensile strength (Mpa)</th>
<th>Tensile Modulus (Gpa)</th>
<th>Specific strength (Mpa)</th>
<th>Specific modulus (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Glass</td>
<td>2.08</td>
<td>1103</td>
<td>44.8</td>
<td>0.53</td>
<td>0.022</td>
</tr>
<tr>
<td>S-Glass</td>
<td>1.99</td>
<td>1931</td>
<td>51.7</td>
<td>0.97</td>
<td>0.026</td>
</tr>
<tr>
<td>Kevlar-49</td>
<td>1.38</td>
<td>1448</td>
<td>75.8</td>
<td>1.05</td>
<td>0.055</td>
</tr>
<tr>
<td>Type HMS Graphite</td>
<td>1.63</td>
<td>1172</td>
<td>206.8</td>
<td>0.72</td>
<td>0.127</td>
</tr>
<tr>
<td>Type AS Carbon</td>
<td>1.55</td>
<td>1724</td>
<td>137.9</td>
<td>1.11</td>
<td>0.089</td>
</tr>
<tr>
<td>Emerging High Strain</td>
<td>1.63</td>
<td>2413</td>
<td>310.3</td>
<td>1.48</td>
<td>0.190</td>
</tr>
<tr>
<td>Graphite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum (7075-T6)</td>
<td>2.77</td>
<td>572</td>
<td>68.9</td>
<td>0.21</td>
<td>0.025</td>
</tr>
<tr>
<td>Titanium (6A1-4V)</td>
<td>4.43</td>
<td>1103</td>
<td>113.8</td>
<td>0.25</td>
<td>0.026</td>
</tr>
<tr>
<td>Steel(4130)</td>
<td>8.00</td>
<td>1379</td>
<td>200.0</td>
<td>0.17</td>
<td>0.025</td>
</tr>
</tbody>
</table>

The narrower definition of composites becomes a lot of specific and can be restricted to those combinations of materials that contain high strength/stiffness fiber reinforcements supported by a high performance matrix material. Fibers and matrix materials may be organic or inorganic in chemical makeup. Commonly the fibrous reinforcement material is referred to as the discontinuous phase and the matrix material as the continuous phase. The primary engineering properties of the composite are derived predominantly from the mechanical and physical properties of the discontinuous phase, the fiber reinforcement. These are the fiber-dominated properties of the composite. Increasing the fiber volume fraction leads to increasing in the levels of mechanical properties up to the point where there is insufficient matrix material to support the fibers and to transfer load within the composite. The matrix is the adhesive binder that supports the fibers under compressive loads, provides shear capabilities in two dimensional fiber lay-ups, and transfers loads internally within the composite among the numerous fibers and fiber bundles that comprise the load carrying portions of the composite material. In two dimensional composites the matrix provides the fundamental resistance to impact damage and
delamination. Matrix materials may be selected from metallic, ceramic and organic resin materials and the reinforcement from fibers, particles, flakes, and/or fillers [6].

1.2 Classifications of composite materials:

1.2.1 Classification based on the matrix material

The first level of classification is typically made with respect to the matrix constituent as shown in figure 1.2. The major composite classes include metal matrix, ceramic matrix, and polymer matrix, carbon-Graphite matrix composites.

![Figure 1.2: Classification of composites based on matrix materials](image)

a) **Polymer matrix composites:**

A polymer matrix composite is the material consisting of a polymer (resin) matrix combined with a fibrous reinforcing dispersed phase. Polymer matrix composites are very popular as a result of their low cost and simple fabrication strategies. Polymer matrix may either be thermosetting or thermoplastic that is reinforced with mainly fiber material with sufficient volume fraction, aspect ratio to suit the application purpose.

b) **Metal matrix composites:**

The properties like high strength, fracture toughness and stiffness are offered by metal matrices than those offered by their polymer counterparts. They can
withstand elevated temperature in corrosive environment than polymer composites. Titanium, aluminum and magnesium are the popular matrix metals currently in vogue, which are significantly useful for aircraft applications. If metallic matrix materials have to provide high strength, they require high modulus reinforcements. The strength-to-weight ratios of resulting composites can be higher than most alloys. The melting point, physical and mechanical properties of the composite at various temperatures determine the service temperature of composites. Most metals, ceramics and compounds can be used with matrices of low melting point alloys. The selection of reinforcements becomes more stunted with increase in the melting temperature of matrix materials.

c) Ceramic matrix composites:

Ceramic matrix composites are material consisting of a ceramic matrix combined with a ceramic (oxides, carbides) dispersed phase. Ceramic matrix composites are designed to enhance toughness of conventional ceramics, the main disadvantage of it is brittleness. Ceramic matrix composites are reinforced by either continuous fiber or discontinuous fiber. Ceramics can be described as solid materials that exhibit very strong ionic bonding in general and in few cases covalent bonding. High melting points, good corrosion resistance, stability at elevated temperatures and high compressive strength, render ceramic-based matrix materials a favorite for applications requiring a structural material that does not give way at temperatures above 1500ºC. Naturally, ceramic matrices are the obvious selection for high temperature applications.

d) Carbon-Graphite composites:

Carbon graphite composites are composite materials consisting of a carbon matrix material reinforced by carbon fibers. Carbon and graphite have a special place
in composite material choices, both being highly superior, high temperature materials with strengths and rigidity that are not affected by temperature up to 2300ºC. This carbon-carbon composite is fabricated through compaction of carbon or multiple impregnations of porous frames with liquid carboniser precursors and subsequent pyrolysis. They can also be manufactured through chemical vapor deposition of pyrolytic carbon. Carbon-carbon composites are not be applied at elevated temperatures, as several composites have proven to be far superior at these temperatures. However, their capacity to retain the properties at room temperature as well as at temperature in the range of 2400ºC and their dimensional stability make them the obvious choice for the applications related to aeronautics, military, industry and space.

1.2.1. 2 Classification based on the reinforcement form:

The second level of classification refers to the reinforcement form- fiber bolstered composites, stratified composites and particulate composites. Fiber reinforced composites can be further divided into those containing discontinuous or continuous fibers as shown in figure 1.3.

![Figure 1.3: Schematic of different reinforcement arrangements in composites](image)

Figure 1.3: Schematic of different reinforcement arrangements in composites [8]
a) Particulate composites:

A particle by definition is non-fibrous and usually has no long dimension with the exception of platelets. The dimensions are approximately equal in all directions. The shape of the reinforcing particles may be spherical, cubic, platelet or any irregular geometry. The arrangement of the particulate reinforcement may be random or with a preferred orientation. In the majority of particulate reinforced composites, the orientation of the particles is taken into account for practical purposes to be random. In general, particles are not very effective in improving fracture resistance. However, particles of rubber-like substances in brittle polymer matrices improve fracture resistance by promoting and then arresting crazing in brittle matrices. Alternative types of particles like ceramic, metal or inorganic particle produce reinforcing effects in metallic matrices by different strengthening mechanisms. Particles during a particulate composite place constraint on the plastic deformation of the matrix material between them due to their inherent hardness relative to the matrix. Particles are effective in enhancing the stiffness of composites but do not offer the potential for much strengthening. The particles and matrix material in any composite material can be of any combination of metallic and non-metallic materials. Particles of many brittle materials like tungsten, molybdenum and chromium are incorporated into ductile metals to improve their elevated temperature performance while maintaining ductile characteristics at room temperature.

b) Fiber reinforced composites:

Fiber Reinforced Composites (FRPs) are composed of fibers embedded in matrix material. Such a composite is considered to be a discontinuous fiber or short fiber composite if its properties vary with fiber length. On the other hand, when the length of the fiber is such that any further increase in length does not increase the
elastic modulus of the composite therefore the composite is considered to be continuous fiber reinforced. Fibers are small in diameter and when pushed axially, they bend easily although they have excellent tensile properties. These fibers must be supported to keep individual fibers from bending and buckling.

c) Laminar composites:

Laminar composites are found in as many combinations as the number of materials. They can be described as materials comprising of layers of materials bonded together. These may be of several layers of two or additional metal materials occurring alternately or during a determined order more than once, and in as many numbers as required for a specific purpose. Several combinations of metal-plastic, vinyl-metal laminates, organic films and metals, account for up to 95% of metal-plastic composites best-known and they are made by adhesive bonding processes.

1.2.2 Fiber Reinforced Polymer composites:

Polymer Matrix Composite (PMC) is the material consisting of a polymer (resin) matrix combined with fibrous reinforcing dispersed particles. Polymer Matrix composites are very popular as a result of their low cost and easy fabrication methods. Fibers are the principal constituents during a fiber reinforced composite material. They occupy the largest volume fraction in a composite laminate and share the major portion of the load acting on a composite structure. Correct selection of the fiber kind, fiber volume fraction, fiber length, and fiber orientation is extremely important, since it influences the following characteristics of a composite laminate.

- Density
- Tensile strength and modulus
- Compressive strength and modulus
• Fatigue strength yet as fatigue failure mechanisms
• Electrical and thermal conductivities
• Cost

a) Glass fibers:

Glass fibers are the most common of all reinforcing fibers for Polymeric Matrix Composites (PMC). The principal benefits of glass fibers are low cost, high tensile strength, high chemical resistance, and excellent insulating properties. The disadvantages are relatively low tensile modulus and high density (among the commercial fibers), sensitivity to abrasion during handling (which frequently decreases its tensile strength), relatively low fatigue resistance, and high hardness (which causes excessive wear on molding dies and cutting tools). The two varieties of glass fibers commonly used in the fiber-reinforced plastics (FRP) industry are E-glass and S-glass. Another kind, called C-glass is employed in chemical applications requiring greater corrosion resistance to acids than is provided by E-glass. E-glass has the lowest value of all commercially available reinforcing fibers, which is the reason for its widespread use in the FRP industry.

b) Carbon fibers:

Carbon fibers are commercially available with a variety of tensile modulus values ranging from 207 GPa on the lower aspect to 1035 GPa on the higher aspect. In general, the low-modulus fibers have lower density, lower cost, higher tensile and compressive strengths, and higher tensile strains-to-failure than the high-modulus fibers. Among the benefits of carbon fibers are their exceptionally high tensile strength–weight ratios as well as tensile modulus–weight ratios, very low coefficient of linear thermal expansion (which provides dimensional stability in such
applications as space antennas), high fatigue strengths, and high thermal conductivity (which is even more than that of copper). The disadvantages are their low strain-to-failure, low impact resistance, and high electrical conductivity, which may cause “shorting” in unprotected electrical machinery. Their high cost has so far excluded them from widespread commercial applications. They are used principally in the aerospace industry, wherever saving weight is considered a lot of crucial than the price.

e) Aramid fibers:

Aramid fibers are highly crystalline aromatic poly amide fibers that have the lowest density and the highest tensile strength-to-weight ratio among the current reinforcing fibers. Kevlar 49 is the trade name of one of the Aramid fibers available in the market. As a reinforcement, Aramid fibers are used in many marine and aerospace applications where light-weight, high tensile strength, and resistance to impact damage (e.g., caused by accident ally dropping a hand tool) are important. Like carbon fibers, they also have a negative coefficient of thermal expansion in the longitudinal direction, which is employed in designing low thermal expansion composite panels. The main disadvantages of Aramid fiber-reinforced composites are their low compressive strengths and issue in cutting or machining [9].

In general, compressive strength of fibers is lower than their tensile strength, as is shown in figure. The compressive strength of boron fibers is higher than that of carbon and glass fibers. All organic fibers have low compressive strength. This includes Kevlar 49, has a compressive strength nearly 10 times lower than its tensile strength [10]. The mechanical and physical properties of some reinforcement fibers are given in the table 1.2.
Table 1.2: The mechanical and physical properties of some reinforcement fibers [11]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>PAN based carbon</th>
<th>Kevlar-49</th>
<th>E-Glass</th>
<th>S-Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HM</td>
<td>HS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter(μm)</td>
<td>5-8</td>
<td>6-8</td>
<td>8-14</td>
<td>10-20</td>
</tr>
<tr>
<td>Density(Kg/m³)</td>
<td>1.18</td>
<td>1.78</td>
<td>1.44</td>
<td>2.62</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel to fiber axis</td>
<td>400</td>
<td>230</td>
<td>131</td>
<td>80-81</td>
</tr>
<tr>
<td>Perpendicular to fiber axis</td>
<td>12</td>
<td>20</td>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td>Tensile strength (GPa)</td>
<td>2.5-4.5</td>
<td>3.8-4.2</td>
<td>3.6-4.1</td>
<td>3.1-3.8</td>
</tr>
<tr>
<td>Strain to failure (%)</td>
<td>0.6</td>
<td>2.0</td>
<td>2.8</td>
<td>4.6</td>
</tr>
<tr>
<td>Co-efficient of thermal expansion(10⁻⁶K⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel to fiber axis</td>
<td>-0.5</td>
<td>-0.6</td>
<td>-4.3</td>
<td>6.0</td>
</tr>
<tr>
<td>Perpendicular to fiber axis</td>
<td>7.0</td>
<td>10.0</td>
<td>41</td>
<td>-</td>
</tr>
<tr>
<td>Thermal conductivity (W/m K)</td>
<td>70</td>
<td>11</td>
<td>0.04-1.4</td>
<td>10-13</td>
</tr>
<tr>
<td>Specific heat (kJ/kg K)</td>
<td>0.7-0.9</td>
<td>0.769</td>
<td>0.45</td>
<td>0.41</td>
</tr>
</tbody>
</table>

PAN - Polyacrylonitrile
HM-High modulus composites, HS-High strength composites.

1.2.3 Glass Fiber Reinforced Polymer (GFRP) composites:

Fiber glass is a common name of polymer Matrix Composite materials reinforced by fine glass fiber. The reinforced dispersed phase is also in form of either continuous or discontinuous glass fibers.

Glass is widely used as a material for reinforcing fibers due to its properties such as:

- Readily out there and cheap material;
- Simple and inexpensive technology of preparation of continuous fibers from molten glass;
- High tensile strength, which can reach 4100 MPa.
- High corrosion resistance.

Glass is by far the foremost widely used fiber, because of the combination of low cost, corrosion resistance, and in several cases efficient manufacturing potential. It has comparatively low stiffness, high elongation, and moderate strength and weight, and generally lower cost relative to different fibers. It has been used extensively where corrosion resistance is vital, like in piping for the chemical industry and in marine applications. Their use is restricted in high-performance applications owing to their comparatively low stiffness, low fatigue endurance, and
rapid degradation in properties with exposure to moisture. Glass fibers are produced by drawing a liquefied mixture of silica (SiO₂) and other oxides through tiny holes in a platinum-alloy bushing. The fibers rising from the bushing are drawn to size at constant speed and then quenched by air or water spray. A protecting coating, or size, is applied to the fibers to shield their surface and to enhance their bonding to the polymer matrix. Fiber diameters for composites applications are in the range from 10 to 20µm. The fibers are gathered in a collimated assembly called a yarn or a tow, or a strand. A group of collimated yarns is called a roving. Glass is thus amorphous material, and therefore does not develop a preferred orientation in microstructure once drawn. It’s therefore considered isotropic. Glass is also highly abrasive, that poses a significant challenge when machining glass-fiber-reinforced composites [12].

1.2.3.1 Glass fibers used:

Glass fiber comes in several sorts, with E (electrical) and S (high strength) being the most common. E-glass offers excellent electrical properties and durability, is a cheaper general-purpose reinforcement. S-glass offers improved strength, stiffness, and high temperature tolerance. They are significantly more expensive than E-glass. The chemical compositions and properties of E and S glass fibers are shown in tables 1.3 and 1.4.

Table 1.3: Typical compositions of Glass Fibers (in wt%) [13]

<table>
<thead>
<tr>
<th>Type</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>B₂O₃</th>
<th>Na₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Glass</td>
<td>54.5</td>
<td>14.5</td>
<td>17</td>
<td>4.5</td>
<td>8.5</td>
<td>0.5</td>
</tr>
<tr>
<td>S-Glass</td>
<td>64</td>
<td>26</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 1.4: Properties of glass fibers [13]

<table>
<thead>
<tr>
<th>Property</th>
<th>E-Glass</th>
<th>S-Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.54</td>
<td>2.49</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>3450</td>
<td>4590</td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>72</td>
<td>86</td>
</tr>
<tr>
<td>Diameter range (microns)</td>
<td>3 to 20</td>
<td>8 to 13</td>
</tr>
<tr>
<td>Co-efficient of Thermal Expansion</td>
<td>5</td>
<td>2.9</td>
</tr>
</tbody>
</table>

The mechanical properties of glass fiber composites depend on the following factors:

**a) Role of fiber architecture:**

The geometry and arrangements of fibers are important in controlling the mechanical properties like shear stress of a fiber reinforced composites. These factors are normally referred as fiber architecture.

**b) Aspect ratio:**

In fiber reinforced composites, both short and long fibers are used. Their dimension is frequently characterized by the aspect ratio l/d where l is the length and d is diameter of fiber. Concerning the mechanical properties, a large aspect ratio is preferred. It is necessary to have critical length to get reinforcement effect. If the fiber is too short it cannot carry load. In practice, aspect ratios between 10 and 1000 are typical. Arranged fibers can have excellent strength if the load is parallel to the direction of fibers. Such composites have very anisotropic behavior and their modulus depends on direction of load and fibers.

**c) Orientation of fiber:**

Short fibers are usually randomly oriented and result in isotropic behavior but the optimum mechanical properties cannot be achieved. Unidirectional arranged
fibers can have excellent strength if the load is parallel to the fibers. Such composites have very anisotropic behavior and their modulus depends on direction of loads and fibers. In order to overcome this problem, fibers are arranged organized in layers are laminae stacked in an exceedingly predetermined orientation. In the laminae, the fiber may be continuous or in short lengths and can be aligned in one or more directions [14].

d) **Volume fraction and mass fraction of fibers:**

Volume fraction of a reinforcement material or constituent in a composite is simply the ratio volume fraction of glass to the total volume of composite.

Volume fraction = volume of the constituent / total volume of the composite.

Mass fraction of the reinforcement material or constituent in a composite is that the ratio of the mass of the constituent to the total mass of the composite.

Mass fraction = mass of the constituent / mass of the composite.

**1.2.4 Matrix materials for Glass Fiber Reinforced Polymer (GFRP) composites:**

The roles of the matrix in a fiber-reinforced composite are:

- Holds the fibers together.
- Protects the fibers from environment.
- Distributes the loads evenly between fibers so that all fibers are subject to an equivalent amount of strain.
- Enhances transverse properties of a laminate.
- Improves impact and fracture resistance of a component.
- Helps to avoid propagation of crack growth through the fibers by providing alternate failure path along the interface between the fibers and the matrix.
- Carry interlaminar shear.
The matrix plays a minor role in the tensile load-carrying capability of a composite structure. However, choice of a matrix encompasses a major influence on the compressive, inter laminar shear as well as in-plane shear properties of the composite material. The matrix provides lateral support against the chance of fiber buckling under compressive loading, thus influencing to a large extent, the compressive strength of the composite material. The interlaminar shear strength is a vital design consideration for structures under bending loads, whereas the in-plane shear strength is important under torsional loads. The interaction between fibers and matrix is also important in designing damage-tolerant structures. Finally, the processing and defects in a composite material depends powerfully on the process characteristics of the matrix. As an example, for epoxy polymers used as matrix in several aerospace composites, the process characteristics embrace the liquid viscosity, the curing temperature, and also the curing time.

Various matrix materials that have been used commercially are in research. Among these, thermosetting polymers, like epoxies, polyesters, and vinyl esters, are more commonly used as matrix material in continuous or long fiber reinforced composites, mainly because of the ease of processing due to their low viscosity. Thermoplastic polymers are more usually used with short fiber reinforced composites that are injection-molded; but, the interest in continuous fiber reinforced thermoplastic matrix is growing. Metallic and ceramic matrices are primarily considered for high temperature applications.

a) **Polymer matrix:**

A polymer is outlined as a long-chain molecule containing one or more repeating units of atoms joined together by strong covalent bonds. A polymeric material (commonly referred to as a plastic) is a collection of a large range of
polymer molecules of similar chemical structure (but not of equal length). Within the solid state, these molecules are frozen in space, either in a random fashion in amorphous polymers or in a mixture of random fashion and orderly fashion (folded chains) in semi crystalline polymers. However, on a submicroscopic scale, various segments in a polymer molecule may be in a state of random excitation. The frequency, intensity, and number of these segmental motions increase with increasing temperature, giving rise to the temperature-dependent properties of a polymeric solid.

b) Thermoplastic and thermosetting Polymers:

Polymers are divided into two broad categories: thermoplastics and thermosets. In a thermoplastic polymer, individual molecules are not chemically joined together. They are held in place by weak secondary bonds or intermolecular forces, like Vander Waals bonds and H bonds. With the application of heat, these secondary bonds in a solid thermoplastic polymer can be temporarily broken and the molecules can now be moved relative to each other or flow to a new configuration if pressure is applied on them. On cooling, the molecules are often frozen in their new configuration and the secondary bonds are restored, leading to a new solid shape. Thus, a thermoplastic polymer can be heat-softened, melted, and reshaped (or post formed) as many times as desired. In a thermosetting polymer, on the opposite hand, the molecules are chemically joined together by cross-links, forming a rigid, three-dimensional network structure. Once these cross-links are shaped during the polymerization reaction (also referred to as the action reaction), the thermosetting polymer can't be melted by the application of heat. However, if the number of cross links is low, it may still be possible to soften them at elevated temperatures.

The following polymeric matrixes are majorly employed in fiber reinforced composites:
• Epoxies
• Polyesters
• Vinyl esters
• Polyurethanes
• Phenolics

c) Polyesters:

It is made by the condensation polymerization of dicarboxylic acids and dihydric alcohols. The formulation contains an unsaturated material like maleic anhydride orfumaric acid which may be a part of the dicarboxylic acid component. The formulation affects the viscosity, reactivity, resiliency and heat deflection temperature (HDT). The viscosity controls the speed and degree of wet-out (saturation) of the fibers. The reactivity affects cure time and peak exothermic (heat generation) temperatures. High exothermic is needed for a skinny section curing at room temperature and low exothermic for a thick section. Resiliency or flexible grade composites have a higher elongation, lower modulus, and HDT. The HDT is a short term thermal property which measures the thermal sensitivity and stability of the resins.

The advantages cited in the unsaturated polyester are its dimensional stability and cheap cost. Other advantages embrace ease in handling, processing, and fabricating. Some of the special formulations are high corrosion resistant and fire retardants. This resin is probably the best value for a balance between performance and structural capabilities [15].
d) Epoxies:

The epoxies used in composites are mainly the glycidyl ethers and amines. The material properties and cure rates can be formulated to meet the required performance. Epoxies are generally found in marine, automotive, electrical and appliance applications. The high viscosity in epoxy resins limits its use to certain processes like molding, filament winding, and hand lay-up. The right action agent should be carefully chosen as a result of it will have an effect on the sort of chemical process, pot life and final material properties. Although epoxies may be expensive, it should be definitely worth the value once high performance is needed [16].

e) Vinyl esters:

The vinyl ester resins were developed to take advantage of both the workability of the epoxy resins and the curing action of the polyesters. The vinyl ester has higher physical properties than polyesters but costs less than epoxies. The acrylic esters are dissolved in a styrene monomer to produce vinyl ester resins which are cured with organic peroxides. A composite product containing a vinyl ester resin can withstand high toughness demand and offer excellent corrosion resistance.

f) Polyurethanes:

Polyurethanes are made by combining polyisocyanate and polyl in a reaction injection molding process or in a reinforced reaction injection molding process. They cured into very tough and high corrosion resistance materials which are found in several high performance paint coatings.

g) Phenolics:

The phenolic resins are made of phenols and aldehyde, and that they are divided into resole and novolac resins. The resoles are prepared under alkaline
conditions with formaldehyde/phenol (F/P) ratios greater than one. On the contrary, novolacs are prepared beneath acidic conditions with F/P ratios less than one. Resoles are cured by applying heat and/or by adding acids. Novolacs are cured once reacting chemically with methylene groups in the hardener. The phenolics are rated for good resistance to extreme temperature, good thermal stability, and low smoke generation. Properties of some polymer resins are given in table 1.5.

Table 1.5: Properties of polymer resins

<table>
<thead>
<tr>
<th></th>
<th>polyester</th>
<th>epoxy</th>
<th>vinyl esters</th>
<th>phenolics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>1.1 to 1.4</td>
<td>1.2 to 1.3</td>
<td>1.1 to 1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Tensile modulus (Mpa)</td>
<td>2000 to 4400</td>
<td>2500 to 4500</td>
<td>3000 to 3700</td>
<td>2700 to 4200</td>
</tr>
<tr>
<td>Tensile strength (Mpa)</td>
<td>33 to 104</td>
<td>50 to 150</td>
<td>70 to 81</td>
<td>50 to 60</td>
</tr>
<tr>
<td>CTE (per million per C)</td>
<td>55 to 100</td>
<td>45 to 70</td>
<td>50 to 55</td>
<td>45 to 120</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>0.15 to 0.65</td>
<td>0.05 to 0.15</td>
<td>0.20</td>
<td>0.10 to 0.20</td>
</tr>
</tbody>
</table>

1.2.5 Manufacturing methods of GFRP composites:

Hand layup technique has been used since 80s for GFRP composites. To reduce the time and labor more emphasis has been on the development of manufacturing methods that can support rate of mass production. Compression molding, pultrusion and filament winding are best example for these. To provide complicated shapes at high production rate resin transfer manufacturing method is employed. Here, hand layup, filament winding, pultrusion and resin transfer molding methods are mentioned.

a) Hand layup:

Manual lay-up process which is given in figure 1.4 involves cutting the reinforcement material to size employing a sort of hand and power-operated devices. To the wet matrix these cut items are impregnated, and arranged over a mould.
surface that has been coated with a release agent and then typically a resin gel-coat. Hand rolled technique is employed on the impregnated reinforcement material to confirm uniform distribution and to get rid of unfree air. Till the specified part thickness has been built-up more reinforcement material is added to that. Manual lay-up also can be performed using pre impregnated reinforcement material, referred to as 'prepreg' the utilization of separate handling of the reinforcement and resin is eliminated by the utilization of prepreg material, and it can improve part quality by providing additional consistent control of reinforcement and resin contents. To prevent premature curing prepreg should be kept cold [17].

![Figure 1.4: Schematic of hand lay-up process](image)

**b) Filament winding:**

Filament winding method that is shown in figure 1.5 refers to wrapping a narrow fiber tow or band of tows of resin impregnated fiber around a shaft of the form to be made. Hollow form is made once shaft is removed. Uses for filament winding embrace pipe, tubing, pressure vessels, tanks and things of comparable form. Hoop or helical winding is employed to use filament winding. In hoop winding, the tow is sort of perpendicular to the axis of the rotating shaft. Every shaft rotation advances the material-delivery supporting carriage one band width, butting the edge
of one band next to the previous band. In helical winding, deposition takes place in helical pattern in one direction that turns around on finish and returns during a helical path in the wrong way. Filament winding mandrels may be metallic or non-metallic and they are designed in such a way to either collapse or felicitate part removal [18].

![Schematic of filament winding process](image)

**Figure 1.5: Schematic of filament winding process [18]**

c) **Resin transfer molding:**

Large, complicated things like bathtub and shower enclosures, cabinets, aircraft parts, and automotive components are made using resin transfer moulding or ‘RTM’. During this method, a collection of mould halves are loaded with reinforcement material then clamped along. Resin is then wired or gravity fed into the mould infusing the reinforcement material. Once the mould is full of resin, it is blocked and allowed to cure. The mould halves are separated and also the part removed after curing for final trimming and finishing [19]. The schematic illustration of the method is given in figure 1.6.
d) **Pultrusion:**

To produce long, straight shapes of constant cross-section, pultrusion method is employed. Pultrusion is analogous to extrusion except that the composite material is pulled, instead of pushed, through a die. Longitudinal reinforcement is provided using pultrusion, and the transverse reinforcement in the style of mat or cloth materials. These reinforcements are resin impregnated by drawing through a resin wet-out station, and generally shaped within a guiding, or preforming system. They are then cured through a preheated die or set of dies and then later on reshaped. Once cured, the pultrusion is saw-cut to length. Pultrusions can be hollow or solid, and applications include bar and rod, pipe, tubing, ladder rails and rungs, and supports of the many sorts, they will be hollow or solid. The method is depicted schematically in Figure 1.7.
1.2.6 Applications of Fiber Reinforced Polymer composites:

Fiber reinforced plastic (FRP) is a composite material consisting of a base matrix (polymer) material that is reinforced by addition of fibers (of glass, carbon, Kevlar) to improve the mechanical strength and heat resistance. Composites have several excellent structural qualities and some examples are high strength, material toughness, fatigue endurance, and light weight. Other extremely fascinating qualities are high resistance to elevated temperature, abrasion, corrosion, and chemical attack.

As a result of this reason, it is extensively employed in aerospace, automobile, marine, sports and construction industries. A number of the benefits within the use of composite structural members embrace the convenience of manufacturing, fabrication, handling, and erection. Project delivery times are often short. Composites are often developed and designed for the high performance, durability and extended service life. They have excellent strength-to-weight ratios.

Advance fiber reinforced polymer composites is made of fiber reinforcements, resin, fillers and additives. The fibers provide increased stiffness and tensile capability. The resin offers high compressive strength and binds the fibers into a firm matrix. The fillers serve to scale back price and shrinkage. The additives facilitate to improve not only the mechanical and physical properties of the composites however also workability [21]. Applications of fiber reinforced polymer composites in numerous field are listed in table 1.6 [22], and a few are conferred within the form of image from figures 1.8-1.12.
Table 1.6: Applications of composites [22]

<table>
<thead>
<tr>
<th>Application area</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace</td>
<td>Space structures, satellite antenna, rocket motor cases, high pressure fuel tanks, nose cones, launch tubes</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Fairings, access doors, stiffeners, floor beams, entire wings, wing skins, wing spars, fuselage, radomes, vertical and horizontal stabilizers, helicopter blades, landing gear doors, seats, interior panels</td>
</tr>
<tr>
<td>Chemical</td>
<td>Pipes, tanks, pressure vessels, hoppers, values, pumps, impellers</td>
</tr>
<tr>
<td>Construction</td>
<td>Bridges and walkways, handrails, cables, frames, grating</td>
</tr>
<tr>
<td>Domestic</td>
<td>Interior and exterior panels, chairs, tables, baths, shower units, ladders</td>
</tr>
<tr>
<td>Electrical</td>
<td>Panels, housing, switchgear, insulators, connectors</td>
</tr>
<tr>
<td>Leisure</td>
<td>Tennis racquets, skis, golf clubs, protective helmets, fishing rods, playground equipment, bicycle frames</td>
</tr>
<tr>
<td>Marine</td>
<td>Hulls, decks, masts, engine shrouds, interior panels</td>
</tr>
<tr>
<td>Medical</td>
<td>Prostheses, wheel chairs, orthofies, medical equipments</td>
</tr>
<tr>
<td>Transportation</td>
<td>Body panels, dashboards, frames, cabs, spoilers, bumpers, leaf springs, drive shafts</td>
</tr>
</tbody>
</table>

Figure 1.8: Components of composites in airbus 380 [23]
Figure 1.9: Standard solar car which is made with monocoque chassis using fiber composites [24]

Figure 1.10: Glass fiber-reinforced vinyl ester pultruded sections in the construction of a bridge deck system [25]
Figure 1.11: Typical fighter aircraft applications [26]

Figure 1.12: Boeing 787 Dreamliner commercial airplane [26]
1.2.7 Machining of Glass Fiber Reinforced Polymer composites:

Despite the very fact that fiber-reinforced polymer parts are largely created to close net form. However machining is commonly needed so as to bring the part into dimensional necessities and prepare it for assembly. Machining of cured FRPs is carried out by conventional or nonconventional material removal methods. The conventional ways that are used most often are edge trimming, milling, drilling, countersinking, turning, sawing, and grinding.

1.2.8 Need for drilling of composite materials:

In fact, drilling represents one of the foremost necessary machining operations that are applied on composites. Drilling, counter boring, and countersinking are typically needed processes for making ready composite parts for joining and assembly. Drilling is the commonest material removal operation in metals and composites machining. It is used for making holes required for assembly. Drilling is done on conventional upright drilling machines, milling machines, and numerous specialized machines. In fact, drilling is one of the foremost common manufacturing processes employed in order to put in fasteners for assembly. Conventional drilling remains one of the foremost economical and normally used machining process for drilling the components and has caused a need for an understanding of their machining characteristics.

In drilling on a vertical drill press, the spindle provides the primary rotational motion to the drill bit and the feed into the work piece is provided through the spindle axis. The most common drill bit is a two flute twist drill, which has two major cutting edges forming the drill point angle. Each one of the major cutting edge acts like a single point cutting tool. The lead angle for the cutting edge is half of the
drill point angle. The flute provides a way for the chip to clear the cutting zone and for coolant to be supplied to the cutting tip. Despite its extensive use, drilling also remains as one of the foremost challenging machining operations.

Among the key issues to be considered are thermal management, tool wear, surface roughness, fracture and delamination. Poor thermal conductivity of the fiber and the matrix favors heat buildup at the cutting region and majority of the heat generated has to be conducted away through the tool. Because the heat generated during drilling is affected by the cutting speed and the feed rate, FRPs are machined only in a limited range of process parameters so as to avoid heat damage. In some cases, approved coolant are often employed in order to scale back the cutting temperatures and management machining dirt. Furthermore, different thermal expansion coefficients between fiber and matrix make it difficult to attain dimensional accuracy of the drilled holes. The holes may shrink after drilling causing poor assembly tolerance. Reinforcement fibers cause severe wear by abrasion of the cutting edges. Wear of the cutting edge in turn increases the thrust force. Thrust force was found to be the most controlling factor of the onset of delamination [27].

1.2.9 Mechanism of drilling:

The machining action of the chisel edge is a lot of like extrusion than cutting, significantly at the middle of the edge. The chisel edge makes vital contribution to the overall thrust force at full engagement of the drill. The cutting edges take away the majority of the fabric within the hole. For a drill with web length equal to 18 percent of its diameter, the cutting edges take away 97% of the outlet material. The nomenclature of the standard bit is conferred in figure 1.13.
In the figure 1.14, the line BC is a simplified chisel edge. The important chisel edge is slightly convex and has an obtuse center point. The straight lines AB and CD are the simplified cutting edges. These real cutting edges are twisted, the projection of those elements for the real drill are usually convex, and the angles at A, B, C, D are more obtuse. The point length P is outlined as the distance between the lines AD and the line BC. The point length is often exactly measured and the value varies among drills, sometimes they need same diameter and products number.

Figure 1.14: Simplified two dimensional representation of two flute twist drill

1.2.10 Delamination in drilling of composites:

Since the quality of the drilled hole in composite material is outlined in terms of the delamination damage, it is considered as one of the vital process parameter. The delamination damage caused by the tool thrust has been recognized as one of the
main problem during drilling. A lot of reference of the drilling of fiber-reinforced plastics reports that the standard of the cut surface is strongly dependent on drilling parameter. As early as 1967, the fact that a rapid increase in feed rate at the end of drilling will cause the cracking around the exit edge of the hole was found. It was also stated that the larger the feeding load, the more serious the cracking. The drill geometry is also considered as the most important factor that affects drill performance. Delamination is considered as the principal failure model in drilling of composite materials. It is analyzed using classical plate bending theory and linear elastic fracture mechanic. Delamination will be developed when the thrust force exceeds the critical thrust force which can be calculated using the following equation which is given by Hocheng and Dharan.

\[ F_{crit} = \pi \left[ \frac{8G_{IC}E_1h^3}{3(1-\nu^2)} \right]^{\frac{1}{2}} \]  

Where: \( F_{crit} \) = The critical thrust force [N].

\( E_1 \) = Elastic modulus of the composite [Mpa].

\( \nu \) = Poisson ratio.

\( G_{IC} \) = Interlaminar fracture toughness in mode I.

\( h \) = Un-cut plate thickness [mm].

There are two distinguishable mechanisms which are responsible for delamination, peel up at the entrance and push down at the exit during drilling.

**a) Peep up delamination:**

Peel up happens because the drill enters the laminate. The drill cutting edge first abrades the laminate, so by moving forward, tends to pull the skinned material away along the flute. Therefore the fabric can spiral up before it machined fully as
shown within the figure 1.15. This action introduces a peeling force upwards to separate the upper laminate from the uncut portion which was held by the down ward cutting thrust force. The cutting force acting in the peripheral direction is the driving for delamination. Normally a reduction in feed rate will reduce this delamination.

![Peeling Action](image)

Figure 1.15: Peel up delamination [27]

**b) Push out delamination:**

Push-out delamination is a damage that happens in interlaminar regions, thus it depends not solely on fibre nature however conjointly on resin kind and several properties. This damage could be a consequence of the compressive thrust force that the drill tip invariably exerts on the uncut laminate plies. There is a precise purpose at that the cutting forces exceed the interlaminar bond strength and therefore delamination happens. The push down delamination is shown in figure1.16. Generally, push out delamination is often larger than peel up delamination in drilling. Hence, within the present study emphasis is given to push out delamination.

![Push down delamination](image)

Figure 1.16: Push down delamination [27]
When the drilling process is divided into 3 phases, 1, 2, and 3, push down delamination may be careful as follows:

During phase one, due to the strong “pushing” action of the chisel edge of the twist drill, the composite specimen merely undergoes deflection and no cutting happens. Throughout section two, the drill starts to penetrate the fabric and therefore the actual feed rate depend upon the elastic force of the composite specimen and therefore the thrust force the drill. In phase 3, when chisel edge exists the fabric, the pushing component is eliminated and suddenly thrust force decreases. The elastic force of the deflected specimen acts on the drill which is not any longer balanced by the thrust force. Hence, the component suddenly returns to undeflected position, with an actual feed rate which is higher than the nominal one. Such a high actual feed rate implies that the effective back rake angle of the twist drill is negative and therefore the twist drill acts like piercing punch over the previous couple of laminae. This punching action generates a bigger push down delamination.

1.2.11 Factors influencing the delamination:

The delamination during drilling in influenced by many parameters which can be grouped as:

a) Machining parameters:

Machining at higher cutting speed and feed rates will reduce the machining time and increases the productivity. On the other hand, because of increasing thrust force, torque and cutting temperature many defects are observed. During drilling the chisel edge provides more than 50% of the drill and this fraction increasing drastically with increasing in feed rate. Since the thrust force and torque generated
during drilling have a greater influence on the overall productivity of the composite material, cutting speed and feed are selected as machining parameters.

\textit{b) Cutting tool parameter:}

Drill geometry plays an important role over the damage occurred in drilling of composites. A typical drill has several design parameters such as drill diameter, drill point angle, chisel edge length, cutting lip length and helix angle etc. each of these parameters affects the cutting forces and quality of the drilled hole in various ways.

\textit{c) Specimen parameter:}

Literatures regarding quality of the drilled hole in composite materials reveal that the specimen variables such as fiber volume fraction, fiber orientation, type of matrix material, material thickness are having the significant effect on the quality of the drilled hole [46, 50, 58, 60].

1.2.12 Surface roughness:

For designing mechanical components surface designing is an important aspect and is also presented as a quality and precision indicator of manufacturing processes. It is also a characteristic that could influence the quality of a component and hence the production cost. Various failures, sometimes catastrophic, leading to high costs, have been attributed to the surface finish of the components. For these reasons, there have been research developments with the objective of getting good surface finish by optimizing the drilling conditions. In drilling of composite materials, roughness is dependent upon many independent variables such as fiber orientation, speed, feed, drill material and drill diameter. Surface roughness is one of the major consideration parameters when the composite materials are used for the
applications like, containers for storing gases, chemical liquids and in other high end
applications like in aerospace industry.

1.3 SYSTEM DYNAMICS (SD)

System dynamics is a method for studying the world around us. It helps us for
the better understanding of the causes of interesting or surprising behavior, weather
social, technological, or the both.

System dynamics helps us to find solutions to persistent problems. If the
behavior under study is not only interesting or surprising, but also undesirable, system dynamics can be used to find ways to improve that behavior.

Jay Forrester from Massachusetts Institute of Technology, Cambridge is the
founder of the field of system dynamics. In the year 1940s he was associated with the
Servo-Mechanics Laboratory at MIT, where, during WWII, he developed
servomechanisms for the control of radar antennas and gun mounts on naval vessels.
In the later 40s and early 50s he became involved with the development of aircraft
flight simulators which led to design of the WHIRL WIND digital computer and
eventually the SAGE air defense system for system for North America. During this
period he invented magnetic core memory, which was the primary mainframe
computer memory system for decades. Probably magnetic core memory is the most
lucrative patent in MIT’s history. In 1996, Forrester joined the Sloan School of
Management at MIT where he began to apply feedback control theory to social
systems (the social system at that time was business management). This evolved into
the field of system dynamics.

Mathematical modeling of dynamic systems and response analyses of such
systems comes under system dynamics with a view of understanding the dynamic
nature of each system and improving system performance. Response analyses are frequently made through computer simulations of dynamic systems.

1.3.1 System:

A system is defined as a combination of components (elements) which performs certain objective by acting together. A composite is a single functioning unit of a system. By no means limited to physical ones, the concept of a system can be extended to abstract dynamic phenomena.

**Static Systems**: Have an output response to an input that does not change with time.

**Dynamic Systems**: Have a response to an input that is not instantaneously proportional to the input or disturbance and that may continue after the input is held constant. Dynamic systems can respond to input signals, disturbance signals, or initial conditions. The constituent of a dynamic system is presented in figure 1.17.

![Figure 1.17: Excitation and response of a system](image)

Dynamic Systems may be observed as common devices employed in every living such as shown in figure 1.18, as well as in sophisticated engineering systems such as those in spacecraft that takes astronauts to the moon. Dynamic Systems are found in all major engineering disciplines and include mechanical, electrical, fluid and thermal systems.
a) **Mechanical Systems:** Systems that possess significant mass, inertia and spring and energy dissipation (damper) components driven by forces, torques, specified displacements are considered to be mechanical systems. For dynamic mechanical system automobile is a good example. It has a dynamic response as it speeds up, slows down, or rounds a curve in the road. The body and the suspension system of the car have a dynamic response of the position of the vehicle as it goes over a bump.

b) **Electrical Systems:** Resistive capacitive and inductive circuits excited by voltage and current come under electrical systems. Electronic circuit can include transistors or amplifiers. A television receiver has a dynamic response of the beam that traces the picture on the screen of the set. Dynamic response also includes TV tuning circuit.

c) **Fluid systems:** Fluid system employ orifices, restrictions, control valves, accumulators (capacitors), long tubes (inductors), and actuators excited by pressure or fluid flow. A city water tower has a dynamic response of the height of the water as a function of the amount of water pumped into the tower and the amount being used by the citizens.
d) **Thermal systems:** Thermal systems have components that provide resistance (conduction, convection or radiation) and a capacitance (specific heat) when excited by temperature or heat flow. A heating system warming a house has a dynamic response as the temperature rises to meet the set point on the thermostat. Placing a pot of water over a burner to boil has a dynamic response of the temperature.

e) **Mixed system:** Some of disciplines, with energy conversion between various components. Figure 1.19 shows several examples the more interesting dynamic systems use two or more of the previously mentioned engineering.

![Figure 1.19: Examples of mixed systems](image-url)

**Electro-Mechanical Systems:** Dynamic response is used for the Systems employing electromagnetic component that converts into a force. Loudspeaker in a stereo system, a solenoid actuator and electric motors are some of the examples. Electrical current from the amplifier is transformed into movement of speaker cone and the subsequent air pressure fluctuations that cause us to hear the amplified sound in a load speaker.

**Fluid-Mechanical Systems:** Hydraulic or pneumatic systems with fluid-mechanical conversion components exhibit dynamic behavior. Examples are a hydraulic pump, a valve controlled actuator, and a hydraulic motor drive. A hydraulic
servo system used for flight control in an airplane is a good example of a common
electro-fluid-mechanical dynamic system.

c) **Thermo-Mechanical Systems:** A thermo fluid mechanical device converts
thermal energy into fluid power and then to mechanical power and is used in car,
truck, ship, airplane combustion engine Thermodynamics, fluid dynamics, and
mechanical dynamics are all involved in the process.

d) **Electro-thermal Systems:** A space heater that uses electric current to heat
filament, which in turn warms the air, has a dynamic response to the surrounding
environment. An electric water heater is another common example of an electro-
thermal system.

1.3.2 Mathematical modeling of dynamic systems:

A mathematical model typically describes a system by means of variables.
Typically physical laws are applied to get mathematical model. Sometimes
experimental procedures are necessary. However no mathematical model will
represent a physical system completely. Approximations and assumptions limit the
validity of the model.

1.3.3 Developing of system dynamics models from causal loop diagrams:

Causal Loop diagrams (CLDs) have long been utilized in standard system
dynamics practice for functions connected with simulation modeling. They are today
principally used before simulation analysis, to depict the essential causal mechanisms
hypothesized to underlie the reference mode of behavior over time, that is, for
articulation of a dynamic hypothesis of the system as endogenous consequences of
the feedback structure. It conjointly forms a connection between structure and
decisions that generate system behavior. Later, CLDs have begun to be used for purposes not essentially related to model building, namely, for detailed system description and for stand-alone policy analysis.

The other common notation for system dynamics and system thinking are Stock-and-Flow diagrams (SFDs). Proponents of CLDs laude their accessibility to non-experts and claim that SFDs are helpful only for people who the ambiguity how they work. Proponents of SFDs criticize the ambiguity and lack of detail in CLDs that prevents simulation of the modeled systems and prefers a minimum of to start with stocks first and others propose to use CLDs for brainstorming and then to switch to an SFD which models the system precisely. This quickly raises the question how CLDs can be used as a base for an SFD.

CLDs can be a decent begin for system modeling. However, the transition to SFDs isn't straightforward. The knowledge on SFDs is hidden within the CLDs, collapsed into links and factors. Extracting stocks, flows and auxiliaries from the CLDs require further investigation of the links and what they represent. This process may increase the amount of factors within the system. So as to develop the CLD further, the modeler is therefore to have to own in-depth knowledge regarding the system considered.

1.3.4 Approaches to modeling:

Process models are very helpful. They can be used for operator training; safety analysis and design of safety systems; process design and process control systems design. There are two main approaches to developing process models:

a) Empirical or information primarily based modeling.

b) Building models supported the underlying physics and chemistry that govern the behavior of the process.
The following can discuss variations between the two approaches.

### 1.3.5 Development of Empirical models:

Development of empirical modeling follows the subsequent common procedure.

1. Collect information from the process.
2. Specify the correlation structure between variables, example polynomials; time-series; artificial neural networks.
3. Use a numerical to search out parameters for the structure such the correlation between the information is maximized.
4. Validate the model against an ‘unseen’ data set.
5. If model isn’t satisfactory, attend step (2).

Thus, we can see that in empirical modeling,

- The model is much depends on the availability of representative data needed for building validation.
- Apart from cause and effect between variables, not a lot of else is required in terms of process knowledge.
- A trial and error approach is adopted.

### 1.3.6 Development of Mechanistic models:

Development of mechanistic models follows a special procedure.

1. Use fundamental knowledge of the interactions between process variables to define the model structure.
2. Perform experiments to work out the parameters of the model.
3. Collect data from the process to validate the model.
4. If the model isn’t satisfactory, attend step (1) and pre examine process knowledge.
Mechanistic model therefore

- Does not need much data for model development, and thus is not subject to idiosyncrasies in data.
- Requires an elementary understanding of the physics and chemistry governing the process.
- Can be sometimes time consuming.

As the alternate to step (2), once the structure of the model is outlined, numerical techniques is applied to parameterize the model. During this case, although the structure has been determined from process knowledge, the modeling procedure becomes an empirical one. The numerical techniques that are used are also very different from those usually encountered in strictly empirical modeling. They have a tendency to iterative, and are more complex.

1.3.7 Empirical versus Mechanistic models:

When available, mechanistic models can provide additional realistic predictions and more can be done with it in terms of analyses. For instance, the details contained within a mechanistic model provide the chance to check the sensitivities of the process to significant entities like heat transfer coefficients; activation energies; catalyst poisoning, etc. With very few exceptions, the parameters of data primarily based models are simply numbers encapsulating combined effects. This it is very troublesome to connect physical meaning to them, and hence such sensitivity studies cannot be performed.

Thus, whereas mechanistic models are accustomed design process, empirical models are often used because the bases for process controller design. The argument here is that model based controllers solely need the models to represent with some accuracy, that the trends in process behaviour. Conservative tuning, at the side of the
feedback mechanism are typically sufficient to overcome any inaccuracies. Even so, if a mechanistic model is offered, it is fascinating to adopt it.

Another comparison that is invariably made between the two modeling approaches is that of cost. As a result of complexity of the many processes, mechanistic modeling is indeed very expensive in terms of human effort and expertise. As the mechanistic modeling approach forces an in depth examination of fundamental process behavior, a number of the cost is recovered in terms of increased ‘deep’ knowledge of process behavior. Though such benefits are intangible, they are often discounted. In apply, empirical modeling can be expensive moreover. It requires great amount of ‘representative’ data and in several instances, these will solely be acquired by perturbing the process via planned experiments. Inevitably production will be non-continuous, and the lost revenue can exceed the value of hiring someone to develop a mechanistic model. The advantage with empirical modeling lies within the proven fact that empirical modeling can deliver some sort of operating model during a shorter time.

The consequence of this is often that we have to question what the model is to be used for. If it is to design management algorithms, then empirical models can do. However, if we need a model to design a new process; or one that may be accustomed trouble-shoot a process that is behaving poorly; or a model that is capable of pointing towards fundamental enhancements is process operability, then, it is best to develop a mechanistic model [29,30,31].

1.4 DESIGN OF EXPERIMENTS (DOE)

Experimental design is a statistical technique that enables an investigator to conduct realistic experiments, analyze data with efficiency, and draw significant conclusions from the analysis and the original objectives of the investigation.
Experimental methods are widely used in research as well as in industrial applications. The aim of scientific research is usually to point out the statistical significance of an effect that a specific factor exerts on the dependent variable of interest. From the industry perspective the experimentation is employed to know and to improve a product or process. Specifically, the goal of these methods is to spot the optimum settings for the various factors that have an effect on the production process. The primary reason for using statistically designed experiments is to get a maximum amount of data from a minimum amount of resources being utilized.

Investigators perform experiments in all fields of inquiry, usually to find something about a process or system. An experiment may be outlined as a test or series of tests during which purposeful changes are made to the input variables of a process or system in order that the possible reasons for the changes within the output/response could be known. Experimentation plays a vital role in product realization activities that consists of new product design and development of manufacturing process. A well designed experiment is vital as a result of the results and conclusions that can be drawn from the experiment that depend on an oversized extent on the manner in which the data were collected. Many methods viz. theoretical, simulation and experimental are used arrive at helpful conclusions regarding the process.

In theoretical approaches, mathematical equations are developed using appropriate assumptions that represent the process. Simulation is employed when the mathematical cannot completely describe the process. The method uses random numbers and tries to simulate the actual process using different simulation algorithms. When the results obtained by the mathematical or simulation models cannot completely represent the process, experimental methods are used. These
methods are either exhaustive experiments or statistical methods to attain the desired conclusions. Statistical methods arrive at the solution in fewer experiments. In the engineering and scientific research environment, an experiment is usually a test or a series of tests. The intension of the experiment could also be either to verify the knowledge about the system or to study the effect of new conditions on the system.

A scientific approach to planning an experiment must be used in order to carry it out efficiently. Statistical design of experiments is the process of planning an experiment in order that data will be collected and analyzed by statistical methods leading to valid and objective conclusions. When the problem involves data that is subject to experimental errors, statistical methodology is the solely objective approach for analysis. Consequently, there are two aspects to any experimental problem: the design of the experiment, and the statistical analysis of the data. To design an experiment, it is necessary to know the product/process or system.

1.4.1 Classifications of process parameters: P Diagram:

The response of the product/process may be the output or some other suitable quality characteristic which is denoted by y. The parameters that influence the response of the process may be classified as Signal, Noise and control factors as shown in figure 1.20.

![Figure 1.20: Block diagram of a product/process: P Diagram.](image-url)
a) Signal factors (M):

These are the product/process parameters set by the user or operator to get the intended value for the response of the product. The signal factors are selected by the design engineer based on the engineering knowledge of the product/process is developed. Sometimes two or additional signal factors are used in combination to precise the desired response.

b) Noise factors (z):

Certain parameters cannot be controlled by the designer and are known as noise factors. Parameters whose settings (also known as levels) are difficult to manage in the field or whose levels are pricey to manage are also considered noise factors.

c) Control factors (x):

Those process parameters that can be specified freely by the designer are known as control factors. In fact, it is the designer’s responsibility to determine the best values of these factors. Each control factor can take multiple values known as levels.

1.4.2 Strategy of experimentation:

Usually the objective of a person conducting the experiment is to determine the influence of these factors on the output/response of the system. the general approach to designing and conducting the experiment is called the strategy of experimentation. This strategy of experimentation could also be of the subsequent types:
1.4.2.1 Best-guess approach:

This approach is employed often in practice by the industries due to its simplicity. The factors and their levels which control the process may be guessed by the engineer, as a result of the prior knowledge regarding the factor settings and process response. The best-guess approach has major disadvantages.

- It is unscientific and iterative process. Suppose the initial best-guess does not turn out the desired results, the experimenter needs to take another guess at the right combination of factors and their levels. This might continue for a long time, with none guarantee of success.
- The best-guess approach may not attain the optimum factor settings.

1.4.2.2 One factor at-a-time approach:

This approach is also used extensively in practice, which consists of selecting a starting point, or baseline set of levels for each factor, then successively varying each factor over its range with the other factors held constant at the baseline level. after all the tests are performed, a series of graphs are usually made that show the response variation caused by the modification within the particular factor levels with all other factors held constant.

The major disadvantage of this strategy is that, it fails to consider any possible interaction between the factors which affect the response. An interaction is the failure of one factor to produce the same effect on the response at different levels of another factor. One factor at a time experiments are always less efficient than the other statistical methods of design.
1.4.2.3 Factorial designs:

This is an experimental strategy, in which all the factors of study are varied together, instead of one at a time. If the factorial experiment has two factors at 2 levels, all attainable combinations of the two factors across their levels are employed in the design. This explicit type of factorial experiment is called a $2^2$ factorial design. Generally, if there are “k” factors, each at 2 levels, the factorial design would require $2^k$ runs (experiments). As the number of factors of interest increases, the number of experiments increases rapidly. Though this method is efficient, it is not feasible from the point of view of time and resources, when the number of factors and their levels are relatively large.

1.4.2.4 Fractional factorial designs:

Fractional factorial experiment is a variation of the basic factorial design in which solely subsets of the runs are considered for experimentation. These designs are widely used in industrial research for problem finding during which the factors that are responsible for the product defects (factor that have large affect on the response) are known. They are generally used as screening experiments in the early stages of a project to sort those factors which have very little or no result on the response. The factors that are identified as important are then investigated thoroughly in subsequent experiments.

1.4.3 Applications of experimental design:

Experimental design is an important tool in the scientific and engineering world for the product realization, improvement and defect finding process. The employment of experimental design in product realization ends up in products that
are easy to manufacture at low cost within a short time, products that have enhanced field performance and reliability.

The application of experimental design techniques could result in:

- Improved process yields.
- Reduced variability and nearer agreement to nominal or target necessities.
- Evaluation and comparison of basic design configurations.
- Evaluation of material alternatives.
- Formulation of new products.
- Selection of design parameters in order that the product can work well under a wide variety of field conditions i.e. robust product.

1.4.4 Basic principles of experimental design:

The three basic principles of experimental design are randomization, replication and blocking. Randomization means, the allocation of the experimental material and the order during which the individual runs or trials of the experiment are to be performed are indiscriminately determined. Randomization is the cornerstone underlying the use of statistical methods in experimental design. Statistical methods require that the observations are independently distributed random variables. Randomization makes this assumption valid.

Replication suggests that the repetition of the basic experiment. There are two important properties of replication. First, it helps to get an estimate of the experimental error. This error becomes a basic unit of measurement for determining whether observed differences in the data are statistically different. Second, if the sample mean is employed to estimate the effect of a factor in the experiment, the replication assists in obtaining a more precise estimate of this effect.
Blocking is a design technique used to improve the precision with which comparisons among the factors of interest are created. Often interference is employed to scale back or eliminate the variability transmitted from noise factors. A block is a portion of the experimental material that ought to be more homogeneous than the entire set of material.

1.4.5 Guidelines for designing experiments:

To use the statistical approach in designing and analyzing an experiment, it is necessary for everyone involved in the experiment to have a clear idea in advance regarding what is to be studied, how the data are to be collected, and how these data are to be analyzed. An outline of the suggested procedure is as follows:

a) Recognition and statement of the problem.

b) Selection of the response variable.

c) Choice of factors levels and ranges.

d) Choice of experimental design.

e) Performing the experiment.

f) Statistical analysis of the data.

g) Conclusions and suggestions.

a) Recognition and statement of the problem:

In practice, development of the statement regarding an identified problem is not so easy. It is necessary to come up with numerous ideas so that significant objectives of the experiment can be framed. Usually, it is vital to solicit input from all concerned parties viz: engineering, quality assurance, manufacturing, marketing, management, the client and operating personnel. For this reason, a team approach to designing experiments is recommended. A transparent statement of the problem often
contributes to better understanding of the phenomenon being studied and the final solution of the problem.

**b) Selection of the response variable:**

In selecting the response or dependent variable, the experimenter must be certain that the measured response really provides useful information regarding the process beneath study. Thought should also be given to how the response will be measured, and the probable accuracy of those measurements. In some situations where gauge capability is poor, the experimenter may decide to measure each experimental response several times and use the average of the repeated measurements as the observed response.

**c) Choice of factors, levels, and ranges:**

The choice of factors or independent variables, that may influence the performance of a process or system, may be classified as either potential design factors or noise factors. The design factors are the factors actually selected for study in the experiment. The potential design factors are often arrived from the cause and effect diagrams or from knowledge and skill of the experimenter. The factors in the experiment could also be either quantitative or qualitative. If they are quantitative, thought must be given for selecting the ranges over which these factors will be varied, and the specific levels at which runs will be created. Importance should even be given to how these factors are to be controlled at the desired values and how they are to be measured.

If objective of the experiment is factor screening or process characterization, it is usually best to keep the number of factor levels low, and conjointly the region of interest should relatively giant. When the levels are wide apart, the factor effects are
giant compared to the experimental errors. As a result, the factor effects can be identified without several repetitions.

**d) Choice of experimental design:**

This involves consideration of sample size (number of replicates), selection of a suitable run order for the experimental trials, and determination of whether or not blocking or other randomization restrictions are involved. In selecting the design, it is important to stay the experimental objectives in mind. The appropriate sample size may be chosen based on the difference in true response that will be detected and the magnitude of the risks concerned. It is necessary to take care of a balance between statistical accuracy and cost that should be considered while choosing the experimental design.

**e) Performing the experiment:**

This is the actual data collection process. When running the experiment, it is vital to monitor the process carefully to ensure that everything is being done consistent with the plan. Errors in experimental procedure at this stage can usually destroy experimental validity. Explicit attention ought to be paid to randomization, measurement, accuracy and maintaining as uniform experimental environment as possible.

**f) Statistical analysis of the data:**

Statistical methods ought to be used to analyze the data so that results and conclusions are objective rather than judgmental in nature. If the experiment has been designed correctly and performed according to the design, the statistical methods required are not elaborate. It is conjointly usually very helpful to present the results of many experiments in terms of an empirical model that expresses the relationship
between the response and the important design factors. Statistical methods cannot prove that a factor (or factors) has a particular effect. They solely offer guidelines as to the reliability and validity of results.

g) Conclusions and recommendations:

Once the data are analyzed, the experimenter could draw sensible conclusions regarding the results and advocate a course of action. Graphical ways are often helpful during this stage, particularly when presenting the results to others. Follow-up runs and confirmation testing should even be performed to validate the conclusions from the experiment.

1.4.6 Full factorial designs:

In experimental design researchers measure responses at all combinations of the factor level. During a full factorial experiment, responses are measured at all combinations of the experimental factor levels. The combinations of factor levels represent the conditions at which responses are measured. Each experimental condition is named a “run” and therefore the response measurement an observation. The complete set of runs is the “design”.

1.4.7 Main effects and main effects plot:

The amendment in the average response produced by a amendment in the level of the factor is called “Main Effect” of that factor. These plots are used in conjunction with an analysis of variance (ANOVA) and design of experiments to examine variations among the level means for one or more factors. A main effect is present when different levels of a factor affect the response differently. In the main effects plot graphs, the response mean for each factor level is connected by a line.

General patterns to look for:
• When the line is horizontal (parallel to the x-axis), then there is no main effect present. Every level of the factor affects the response within the same manner, and therefore the response mean is that the same in the least factor levels.

• When the line is not horizontal, then there is a main effect present. Different levels of the factor affect the response differently. The steeper the slope of the line, the greater the magnitude of the main effect [32].

1.4.8 Analysis of variance (ANOVA):

ANOVA is a statistical decision making tool, used to analyze the experimental data, for detecting any differences in the response means of the factors being tested. ANOVA is also needed for estimating the error variance for the factor effects and variance of the prediction error. In general, the purpose of analysis of variance is to determine the relative magnitude of the effect of each factor and to identify the factors significantly affecting the response under consideration (objective function). The name "analysis of variance" is based on the manner in which the procedure uses variances to determine whether the means are different. The procedure works by comparing the variance between group means versus the variance within groups as a method of determining whether the groups are all part of one larger population or separate populations with different characteristics.

1.4.8.1 Components of an ANOVA table:

The outputs of an analysis of variance study are arranged in a table. They are: the sources of variation, their degrees of freedom, the total sum of squares, and the mean squares. The analysis of variance table also includes the F-statistics and p-
values. These are used to determine whether the predictors or factors are significantly related to the response.

ANOVA tables are also used in regression and DOE analyses.

The components of an ANOVA table are:

- **DF** - degrees of freedom from each source. If a factor has three levels, the degree of freedom is 2 (n-1). If we have a total of 30 observations, the degrees of freedom total is 29 (n - 1).

- **SS** - sum of squares between groups (factor) and the sum of squares within groups (error).

- **MS** - mean squares are found by dividing the sum of squares by the degrees of freedom.

- **F** - Calculated by dividing the factor MS by the error MS; we can compare this ratio against a critical F found in a table or we can use the p-value to determine whether a factor is significant.

- **P** - Use to determine whether a factor is significant; typically compare against an alpha value of 0.05. If the p-value is lower than 0.05, then the factor is significant.

**Source:** Indicates the source of variation, either from the factor, the interaction, or the error. The total is a sum of all the sources.

For a two-way ANOVA, there are two factors and an interaction term. For DOE and regression applications there are several factors, or sources of variation.

**Degrees of freedom:** It is the number of independent parameters associated with an entity like a factor, or an error, or the mean, or the total number of all observations.

\[ V_T = \nu_m + \nu_A + \nu_e \] (1.2)
Where $v_T$ - Total degrees of freedom which is equal to total number of observations (N)

$v_m$ - Degree of freedom associated with the mean (always 1)

$v_e$ - Degree of freedom associated with error

$v_A$ - Degree of freedom of factor A which is equal to ($k_A - 1$), where $k_A$ is the number of levels of factor A.

**Total Sum of Squares (SST):** It is the sums of squared deviations of the response data from data mean which include deviations due to individual factors and error deviation.

$$SS_T = \left[ \sum_{i=1}^{N} y_i^2 \right] - \frac{T^2}{N} \hspace{1cm} \text{...............(1.3).}$$

Where, $y_i$ – is the response, observation, data

$N$ – total number of observations, $T$ – Sum of all observations

**Sum of squares due to factor A (SS$_A$):** It is the sum of squared deviations of the factor means at different levels from the overall mean. It can be expressed as:

$$SS_A = \left[ \sum_{i=1}^{k_A} \frac{A_i^2}{n_{A_i}} \right] - \frac{T^2}{N} \hspace{1cm} \text{...............(1.4).}$$

Where $A_i$ - sum of observations under $A_i$ level.

$n_{A_i}$- number of observations under $A_i$ level.

**Sum of Squares due to error (SS$_e$):** It is the sum of the squares of the error terms. It can also be expressed as the difference between the total sum of squares and sum of squares due to the factors and their interactions, given by the equation:
\[ SS_e = SS_T - SS_A - SS_B - SS_{AxB} \] 

**Mean square of factor A**, 
\[ MS_A = \frac{SS_A}{v_A} \] 

**Mean square of error**, 
\[ MS_E = \frac{SS_E}{v_E} \]

**Variance Ratio (F0):** The ratio of the mean square is due to a factor and the error mean square. A large value of \( F_0 \) means the effect of that factor is large compared to error variance. 
\[ F_0 = \frac{MS_A}{MS_E} \]

Also, the larger the value of \( F_0 \) (greater than 4), the more important that factor is in influencing the process response, hence used to rank the order of the factors. Statistically, there is a tool which provides a decision at some confidence level as to check these estimates are significantly different or not.

**Confidence level (\( \alpha \)) and the P-value:** Alpha is frequently referred to as the level of significance. Its value is to be set before beginning the analysis and then compare p-values to determine significance. The most commonly used \( \alpha \) -level is 0.05. At this level, the chance of finding an effect that does not really exist is only 5%. P-value is used to determine whether a factor is significant; and is compared to an alpha value of (confidence level) 0.05. If the p-value is lower than 0.05, then the factor is significant [33].

**1.4.9. Process optimization:**

There are 3 signal-to-noise ratios of common interest for optimization of static problems.

**a) Smaller-the-better.** Here, the quantity characteristics continuous and nonnegative that can take any value from 0-\( \infty \). Its most desired value is zero.
n=1og (mean of sum of squares of measured data)

This is usually chosen S-N ratio for all undesirable characteristics like defects; etc. for which the ideal value is zero. Also, when ideal value is finite and its maximum or minimum value is defined, then the difference between measured data and ideal value is expected to be as small as possible. The objective function to be minimized for such problems and S-N ratio is given by:

\[ n = -10 \log_{10} \left[ \text{mean of sum of squares of measured \{ideal\}} \right] \]

Note how this S/N ratio is an expression of the assumed quadratic nature of the loss function. The factor 10 ensures that this ratio measures the inverse of “bad quality”, the more flaws in the paint, the greater is the sum of the squared number of flaws, and the smaller (i.e, more negative) the S/N ratio. Thus maximizing this ratio will increase quality.

b) **Nominal-the-best.** Here, as in smaller the better type, the quality characteristics is continuous and non-negative that can take any value from 0-\(\infty\). Its target value is non zero and finite. For these problems when the mean becomes zero, the variance also becomes zero. The objective function to be maximized for such problems and the S/N ratio is given by:

\[
\frac{\text{square of mean}}{\text{variance}} = 10 \log_{10} \]

This case arises when a specified value is MOST desired, meaning that neither a smaller nor a larger value is desirable. This signal-to-noise ratio could be used whenever ideal quality is equated with a particular nominal value.

c) **Larger-the-better.** Here, the quality characteristic is continuous and nonnegative and that takes value as high as possible. This problem can be transformed into a smaller-the better type problem by considering the reciprocal of the quality
characteristics. The objective function to be maximized in this case and the S/N ratio is given by:

\[ n = -10 \log_{10} \text{[mean of sum of squares of reciprocal of measured data]} \]

This case has been converted to smaller-the-better by taking the reciprocals of measured data and then taking the S/N ratio as in the smaller–the-better case.

1.5 ARTIFICIAL NEURAL NETWORKS (ANN)

Artificial Neural Network (ANN) is considered as a robust modeling tool that can perform non-linear mapping (transformation) from a multi-dimensional input space to a multi-dimensional output space. The feed forward ANNs like the Multi-Layer Perceptron Neural Network (MLPNN) find vast application in different engineering and non-engineering domains. Generally, an ANN consists of three layers of neurons (nodes): one input layer, one or more hidden layers and one output layer. Each neuron is a computational unit. The number of neurons in the input and output layers are equal to the number of inputs and outputs respectively, of the system to be modeled. The nodes of the layers are linked through weighted connections: \(w_{ij}\) between input and hidden layer and \(w_{jk}\) between the hidden and the output layer. The response of the hidden and the output layers are generally obtained through some transfer functions like sigmoid and tan sigmoid functions \([34, 35]\).

The implementation of an ANN is carried out in two phases: training and testing. Before commencing with the training phase, the data available is paired as input-output. It is then thoroughly mixed and a subset of it (50 to 70%) is used in the training phase and the remaining (30 to 50%) is used in the testing phase. In the training (learning) phase, the connection weights of the neurons are all initialized to small arbitrary values. The training inputs are fed one after the other and the ANN output obtained is compared with the actual output. The error between the two
outputs is back-propagated so as to adjust the weights on the connections. This continues iteratively until the error between the two outputs is acceptably low. Then, the ANN is said to be trained. In the testing phase, the connection weights established in the training phase are used to compute the ANN output for the testing data set. Since the testing data has not been used in the training phase, the trained ANN is expected to give the desired output for the test data inputs.

There are various types of neural networks available such as feed forward neural network with single and multi perception, Adaline, radial basis function and Kohonen self organizing map. Out of them the feed forward networks are the most simple and are used in prediction by training input data to obtain the desired output. The basic structure of feed forward networks with multi layer perception is shown in figure 1.21. The first layer is called the input layer and the last layer is the output layer. The intermediate layer is called the hidden layer and it can be more than one. The information is fed forward from the input layer to output layer through the hidden layers in a simple feed forward neural network model. Where as in the back propagation model the output value is compared to the desired value and the difference is back propagated through the network. The back propagation adjusts the weights of the neural network such that the output of the network matches the desired output. This cycle is repeated until the desired value is obtained with the minimum root mean square error and is basically called training the neural network.
Input Layer — A vector of predictor variable values \( (x_1,...,x_p) \) is presented to the input layer. The input layer (or processing before the input layer) standardizes these values so that the range of each variable is -1 to 1. The input layer distributes the values to each of the neurons in the hidden layer. In addition to the predictor variables, there is a constant input of 1.0, called the bias that is fed to each of the hidden layers; the bias is multiplied by a weight and added to the sum going into the neuron.

Hidden Layer — Arriving at a neuron in the hidden layer, the value from each input neuron is multiplied by a weight \( (w_{ji}) \), and the resulting weighted values are added together producing a combined value \( u_j \). The weighted sum \( (u_j) \) is fed into a transfer function, \( \sigma \), which outputs a value \( h_j \). The outputs from the hidden layer are distributed to the output layer.

Output Layer — Arriving at a neuron in the output layer, the value from each hidden layer neuron is multiplied by a weight \( (w_{kj}) \), and the resulting weighted values are added together producing a combined value \( v_j \). The weighted sum \( (v_j) \) is fed into a
transfer function, $\sigma$, which outputs a value $y_k$. The $y$ values are the outputs of the network.

If a regression analysis is being performed with a continuous target variable, then there is a single neuron in the output layer, and it generates a single $y$ value. For classification problems with categorical target variables, there are $N$ neurons in the output layer producing $N$ values, one for each of the $N$ categories of the target variable.

1.6 RESPONSE SURFACE METHODOLOGY (RSM)

During experimentation, researchers want to determine the levels of the design parameters at which the response reaches its optimum. The optimum could be either minimum or maximum of a function of the design parameters. Response Surface Technique (RSM) is one of the methodologies for obtaining the optimum. RSM is a collection of statistical and mathematical methods that are useful for the modeling and analyzing engineering problems. In this methodology, the main objective is to optimize the response that is influenced by various process parameters. RSM also quantifies the relationship between the controllable input parameters and obtained response surfaces. This tool produces maps of product performance similar to topographical display of elevation, as a function of the input variables. The objective is to optimize a response (output variable), which is influenced by several independent variables (input variables) by careful design of experiments.

In RSM, if all variables are assumed to be measurable, the response surface can be expressed as:

$$y = f(x_1, x_2, \ldots, x_k)$$

The goal is to optimize the response variable $y$. In RSM it is assumed that, the independent variables are continuous and controllable by experiments with negligible
errors. Hence, it is necessary to find a suitable approximation for the true functional relationship between independent variables and the response surface. Generally, a second order model is utilized in response surface methodology.

\[
y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i^2 x_i^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \varepsilon \text{ ..................(1.10)}
\]

Where \( \varepsilon \) is a random error. The beta coefficients, which should be determined in the second order model, are obtained by the least square method.

### 1.7 OBJECTIVES OF THE PRESENT RESEARCH WORK

The objectives for the present research work are as follows:

- To select the process variables based on drill geometry, machining conditions and material properties.
- To design the systematic experiments using full factorial Taguchi design.
- To conduct the experiments to obtain the necessary data for analysis and to develop the simulations.
- To investigate the individual and combined significance level of each process variable on the process parameters.
- To analyze and optimize the process parameters in order to obtain good quality holes using Taguchi, RSM and SD methods.
- To develop the simulations for the considered process responses through System Dynamics approach.
- To compare the SD results with experimental results.
- To compare the SD results with ANN and RSM simulated results as a part of validation.
- To estimate the acceptance level of SD simulated result.
1.8 ORGANIZATION OF THE THESIS

In chapter 1 introduction to composites, DOE, ANN, RSM and System Dynamics have been provided. It also consists of classification of composites, types of reinforced polymer composites, fiber reinforced polymer composites and their applications and manufacturing methods. Objective of the present work and organization of the thesis are also discussed. In chapter 2, previous literatures regarding evolution of thrust force and torque, estimation of delamination, effects of surface roughness, application of DOE, ANN and RSM were presented. In chapter 3, composition of test specimen and its manufacturing method, methodology of the experimentation, equipments used to carried out the experiment, instruments used to measure the response parameters, factors and levels considered for the experimentation, drilling tools used, data acquisition methods, process responses evaluation methods have been discussed. In chapter 4, methods adopted for analysis, optimization and simulation of response parameters, such as thrust force, torque, surface roughness and delamination are discussed. Also, comparisons between various simulation methods have been done. In chapter 5 conclusions regarding the work carried out and further scope for future work has been presented. References and paper published based on this research work have been listed in the end which is followed by the Appendix.