Chapter 1

FIBRE REINFORCED COMPOSITES

1.1 General

Concrete is one of the most widely used building materials in construction industry. Although most of the structures which surround us are made of concrete, there are still some serious problems related to the utilisation of this material, like low tensile strength, low energy absorption capacity and low ductility. Advances in modern technology allowed the designers to reinforce concrete with steel with or without pre-stress, to overcome its inherent weakness in tension. Ductility is the ability of a material or structural member to undergo large inelastic deformations without distress. In the extreme event of a structure loaded to failure, it should be able to undergo large deflections at or near its maximum load carrying capacity. This will give forewarning of failure and prevent total collapse and may save lives. In statically indeterminate concrete structures, ductility of the members at the critical sections is necessary to allow moment redistribution to take place. Ductility and energy absorption capacity can be enhanced by incorporating fibres in concrete (ACI Committee 544, 1996).

1.2 Fibre Reinforced Concrete

Fibre Reinforced Concrete (FRC) can be defined as a composite material consisting of a mixture of cement mortar or concrete and discontinuous, discrete, uniformly dispersed suitable fibres. Various types of fibres like steel, carbon, glass, galvanised iron, polypropylene, asbestos, plastic etc., can be added to produce fibre reinforced concrete (FRC). It is now well established that one of the important properties of FRC is its superior resistance to cracking and crack propagation. As a result of this ability to arrest cracks, fibre composites possess increased extensibility and tensile strength, both at first crack and at
ultimate; and the fibres are able to hold the matrix together even after extensive cracking. The net result of all these is to impart to the fibre composite pronounced post-cracking ductility which is unheard of in ordinary concrete. The transformation of concrete from a brittle to a ductile type of material would substantially increase the energy absorption characteristics of the fibre composite and its ability to withstand repeatedly applied, shock or impact loading. These enhanced properties can be made use in the construction of airport and highway pavements, earthquake resistant and blast resistant structures, mine and tunnel linings etc.

1.2.1 Classification of fibre reinforced concrete

Classification of FRC according to volume fraction of fibres used is given below.

- **Low volume fraction (fibre content <1%)**: Fibres at this volume fraction are used to reduce high shrinkage cracks. Such FRC is used in slabs and pavements that have large exposed surface leading to high shrinkage cracks.

- **Moderate volume fraction (between 1% and 2%)**: The presence of fibres at this volume fraction increases the modulus of rupture, fracture toughness and impact resistance. Such FRC are used in construction methods such as shotcrete and in structures that require energy absorption capability, improved capacity against delamination, spalling and fatigue.

- **High volume fraction (>2%)**: The fibres used at this level lead to strain hardening of the composites. Because of this improved behaviour, these composites are often referred as high-performance fibre reinforced composites (HPFRC). In the last decade, even better composites were developed and are referred as ultra-high-performance fibre reinforced composites (UHPFRC). These are used in blast resistant structures, nuclear installations etc.
1.2.2 Types of fibres used in fibre reinforced concrete

Depending upon the parent material used for manufacturing, fibres can be broadly classified as follows.

- Metallic fibres (e.g. Low carbon steel, Stainless steel, Galvanized iron, Aluminium)
- Mineral fibres (e.g. Asbestos, Glass, Carbon)
- Organic fibres or Polymeric or Plastic or Synthetic fibres (e.g. Cotton, Resin, Polyester, Nylon, Polypropylene, Polyethylene)
- Inorganic or Natural fibres (e.g. Akwara, Bamboo, Coconut, Flax, Jute, Sisal, Sugarcane, Wood, Coir and others)

1.2.3 Steel fibre reinforced concrete

For most of structural and non-structural purposes, steel fibre is the most commonly used of all the fibres. Steel fibres have been used in concrete since the early 1900s. The early fibres were round and smooth and the wire was cut or chopped to the required lengths. The use of straight, smooth fibres has largely disappeared and modern fibres have either rough surfaces, hooked ends or are crimped or undulated through their length (Fig. 1.1). Modern commercially available steel fibres are manufactured from drawn steel wire, from slit sheet steel or by the melt extraction process, which produces fibres that have a crescent-shaped cross section. Typically steel fibres have equivalent diameters (based on cross sectional area) from 0.15mm to 2 mm and length from 7 to 75mm. Aspect ratios of steel fibres generally range from 20 to 100.

Steel fibres have high tensile strength (500 -1800 MPa), modulus of elasticity (200 GPa), a ductile / plastic stress strain characteristic and low creep. Steel fibres have been used in conventional concrete mixes, shotcrete and slurry infiltrated fibrous concrete (SIFCON). Typically, the content of steel fibre in FRC ranges from 0.25% to 2.0% of volume fraction. Fibre contents in excess of 2% by volume generally result in poor workability and
distribution, but can be used successfully where the paste content of the mix is increased and the size of coarse aggregate is not larger than about 10mm. Steel fibre reinforced concrete containing up to 1.5% fibre by volume has been pumped successfully using pipelines of 125mm to 150mm diameter. Steel fibre contents up to 2% by volume have been used in shotcrete applications using both the wet and dry processes.

![Shapes of steel fibres](image)

Fig. 1.1 Shapes of steel fibres

1.2.4 Hybrid fibre reinforced concrete

Most of the fibre reinforced concrete used in practice contains only one type of fibre. It is known that failure in concrete is a gradual, multi-scale process. The pre-existing cracks in concrete are of the order of microns. Under an applied load, these cracks grow and eventually join together to form macro cracks. A macro crack propagates at a stable rate until it attains conditions of unstable propagation and a rapid fracture is precipitated. The gradual and multi-scale nature of fracture in concrete implies that a given fibre can provide reinforcement only at one level and within a limited range of strains. For an optimal response, different types of fibres may be combined. In hybrid fibre technology, two or more types of fibres can be rationally combined to produce a composite that derives the benefits from each individual fibre and exhibit synergistic response. In first type of hybrids, one type of fibre is stronger and stiffer and provides adequate first crack strength and ultimate
strength, while the second type of fibre is relatively flexible and leads to improved toughness and strain capacity in the post-crack zone. Another combination has one type of fibre that is smaller, so that it bridges micro cracks and therefore controls their growth, which leads to a higher tensile strength of the composite, and the second fibre is larger and is intended to arrest the propagation of macro cracks and, therefore, results in a substantial improvement in the fracture toughness of the composite (Banthia et al., 2005).

Best composite properties can be obtained from the use of hybrid fibres, which can enhance the flexural toughness and post peak strength of concrete by the synergistic interaction between the two reinforcing fibres. Some of the advantages are listed below.

1. To provide a system in which one type of fibre, which is stronger and stiffer, improves the first crack stress and ultimate strength, and the second type of fibre, which is more flexible and ductile, leads to improved toughness and strain capacity in the post cracking zone.

2. To provide a hybrid reinforcement, in which one type of fibre is smaller, so that it bridges micro cracks of which growth can be controlled. This leads to a higher tensile strength of the composite. The second type of fibre is larger, so that it can arrest the propagating macro cracks and can substantially improve the toughness of the composite.

3. To provide a hybrid reinforcement, in which the durability of fibre types is different. The presence of the durable fibre can increase the strength and/or toughness retention after age while another type is to guarantee the short – term performance during transportation and installation of the composite elements.
1.2.5 Toughness characterisation of fibre reinforced concrete

The energy dissipated in concrete cracking is the property most benefited from the addition of fibres to concrete. The enhanced performance of fibre reinforced concrete compared to its unreinforced counterpart comes from its improved capacity to absorb energy during fracture (Gopalaratnam V.S. et al., 1991). While a plain unreinforced matrix fails in a brittle manner at the occurrence of cracking stresses, the ductile fibres in FRC continue to carry stresses well beyond matrix cracking, which helps maintain structural integrity and cohesiveness in the material. Further, if properly designed, fibres undergo a pullout process, and the frictional work needed for pullout leads to a significantly improved energy absorption capability. This energy absorption attribute of FRC is termed as toughness. The actual degree to which toughness can be improved will depend on fibre type, dosage, material properties, and bonding characteristics between fibres and the concrete matrix (ACI Committee 544, 1997). While flexural toughness has been widely accepted as the means of quantifying FRC performance, there have been many developments over the years toward devising methodology that reliably measures flexural toughness. Each proposed test method is a variation of the same basic concept: Develop the load-deflection plot for a given flexural specimen and then interpret that data to arrive at the value of toughness. Following paragraphs highlight the standard test methods that are used for evaluation of toughness characteristics.

1.2.5.1 ASTM C 1018 method

The ASTM C 1018 was first published in 1984. Moulded or sawn beams of fibre reinforced concrete are tested in flexure as per ASTM C 78. Load and beam deflection are monitored either continuously by means of an X-Y plotter, or incrementally by means of dial gauges read at sufficiently frequent intervals to ensure accurate reproduction of the load-deflection curve. A point termed first crack which corresponds approximately to the onset of cracking
in the concrete matrix is identified on the load deflection curve. The first-crack load and deflection are used to determine the first-crack flexural strength and to establish end-point deflections for toughness calculations. This test method provides a value of relative flexural toughness, which relates the area under the load-deflection curve at first crack to the area under the same curve at a deflection that is a multiple of the first crack deflection. These values are known as toughness indices $I_N$ (namely, $I_5$, $I_{10}$, and $I_{20}$). The subscript $N$ in these indices is based on elasto-plastic analogy such that for a perfect elasto-plastic material, the index $I_N$ would have value equal to $N$. (Here, the given FRC is compared with a conceptual material that behaves in an ideally elasto-plastic manner. The scheme also assumes that plain concrete is ideally brittle and the various toughness indices in this case assume a constant value of unity). From these toughness indices, residual strength factors ($R$), can be determined by relating various toughness indices, for example, $R_{5,10}=20(I_{10}-I_5)$.

Interpretation of the load-deflection plot to determine toughness and residual strength is shown in Fig. 1.2. In the graph $\delta$ is the first-crack deflection.

Critiques of ASTM C 1018 published by Chen L. et al. (1995) and Johnston (1995) scrutinize the fact that the test method relies on being able to properly determine the first
crack deflection at the mid-span of the specimen. Determining this value properly is extremely difficult because it is dependent on both the physical setup of the testing apparatus as well as the interpretation of the load-deflection plot. It has been well established that the net deflection (the deflection at mid-span minus the deflection at the end supports), and not the nominal mid-span deflection, must be calculated to derive the load-deflection plot. Research conducted by Banthia and Trottier (1995) and Chen L. et al. (1993) has documented that there can be significant differences in net deflection and nominal mid-span deflection if the testing apparatus is not sufficiently rigid to control its own deflections or if the concrete at the end supports begins to crush from continued loading. Care must be taken to ensure that the test setup at a given laboratory is able to accurately determine the net deflection of the specimen, which often leads to setups that are too expensive or complex for most typical laboratories to obtain. The recommended experimental setup is shown in Fig. 1.3. Another issue in determining first-crack deflections is interpreting when the first crack is initially formed. ASTM C 1018 describes first crack as “the point at which the curvature first increases sharply and the slope of the (load-deflection) curve exhibits a definite change”. While this definition may seem simple enough, most concrete, especially concrete with large amounts of fibre reinforcement, will not have one clearly defined moment when the specimen cracks but rather a series of micro cracks that finally combine to lead to more significant macro cracking and energy dissipation. Chen et al. (1995) discussion of ASTM C 1018 provides an excellent example of how variations in the interpretation of first crack can lead to significant deviation in the calculated values of toughness indices and residual strength factors for the same load-deflection plot. The ASTM C 1018 Standard was withdrawn in May 2006 and no replacement for the same is suggested immediately, due to lack of interest and support for its continued use.
1.2.5.2 JSCE Standard SF-4 method

The Japanese method of measuring toughness, JSCE-SF4, obtains the load-deflection curve in the exactly same manner as that of ASTM C 1018; therefore, the same issues in regards to the test apparatus and data acquisition must also be addressed when conducting a JSCE-SF4 test. The critical difference between JCSE-SF4 and ASTM C 1018 is in the interpretation of the load-deflection curve. The Japanese method is an absolute method of determining flexural toughness, as opposed to the relative method used in ASTM C 1018. In JSCE-SF4, toughness is defined as the area under the load-deflection curve to a deflection value that is the length of the specimen divided by 150. A flexural toughness factor, or equivalent flexural strength, is also calculated, which is a function of the specimen’s geometry and its calculated toughness. This toughness factor was created in response to criticisms that the toughness value calculated using the Japanese method was completely dependent on the geometry of the specimen being tested (Chen et al., 1995). JSCE-SF4 interpretations are shown in Fig. 1.4. The technique may be criticised for failing to distinguish between the pre-crack and post-crack behaviours by using the total area under the curve for calculating flexural toughness.
1.2.5.3 Banthia and Trottier's method

In order to simplify the approach, Banthia and Trottier (1995) proposed a method wherein identification of first crack is not required. The procedure suggested by them is as follows.

- Obtain the load-deflection curve with accurate deflection measurements.
- Locate the peak load and divide the curve into pre-peak load region and post peak load region. Measure the area under the curve up to the peak load and denote this value as $E_{pre}$.
- Locate points on the curve in the post peak region with specimen deflections equal to various fractions of the span $L/m_1$, $L/m_2$ etc. The suggested fractions are between $L/3000$ and $L/150$. Measure the areas under the curve up to these deflections, denoted as $E_{total,m}$ (measured at a deflection of $L/m$).
- Subtract the pre-peak energy $E_{pre}$ from the various values of $E_{total,m}$ to obtain the post-peak energy values $E_{post,m}$ to a deflection of $L/m$.
- Calculate the post-crack strength ($PCS_m$) in the post-peak region at the various deflections, using the expression given below.

$$PCS_m = \frac{(E_{post,m}) L}{L - \delta_{peak}} bh^2$$

where $b$ and $h$ are c/s dimensions of specimen.
Nataraja M.C. et al. (2000) have carried out toughness characterization of steel fibre reinforced concrete by JSCE approach. They have discussed the various methods for toughness measurements namely, ASTM C 1018 standard method, JSCE standard SF-4 method, Banthia and Trottier’s (1995) proposed method. They have concluded that if one is interested in the total energy of material, JSCE toughness factor is quite meaningful. Another advantage of the JSCE method is that the value of toughness is not affected much by the deflection measuring technique as observed in their investigation. They have concluded that the characterization of flexural toughness based on the JSCE approach is very simple and is independent of the type of deflection measurement technique. No sophisticated instrumentation is required to determine the toughness factor. The determination of first crack, which is very difficult to identify, is not required in this method.

1.2.5.4 Three point beam test according to RILEM TC-162-TDF (2002)

According to the RILEM standard the toughness characteristics of SFRC is evaluated from simply supported beams exposed to a mid point load. The beams, as shown in Figure 4.6, are provided with a notch in mid-section to enable measurements of the crack mouth opening displacement (CMOD). The depth of the notch should be 25 mm thus leaving an un-notched height of 125 mm.

The results of the tests may be represented in terms of the load versus CMOD or load versus deflection response. In situations where only the mid point deflection $\delta$ is measured, the
following formulation can be used to convert the results to CMOD according to Vandewalle and Dupont (2003):

\[ \text{CMOD} = 1.18 \delta - 0.0416 \]

The evaluation is initiated by finding the limit of proportionality \( F_{\text{fc,l}} \), which is defined as the maximum load recorded within the first 0.05 mm of CMOD, and the corresponding ultimate strength is calculated as:

\[ f_{\text{fc,l}} = \frac{M_{\text{L}}}{W} = \frac{3 \cdot F_{\text{L}} \cdot L}{2 \cdot b \cdot h_{sp}^2} \]

where \( L \) is the span, \( b \) is the width and \( h_{sp} \) is the un-notched depth of the beam.

The residual flexural strength \( f_{R,i} \) is determined from the residual loads \( F_{R,i} \) at CMODs of 0.5, 1.5, 2.5 and 3.5 mm as,

\[ f_{R,i} = \frac{3 \cdot F_{R,i} \cdot L}{2 \cdot b \cdot h_{sp}^2} \]

The strength at a CMOD of 0.5 mm is defined as \( f_{R,i} \) while the corresponding value at a CMOD of 3.5 mm is referred to as \( f_{R,4} \).

1.3 Fibre Reinforced Plastic Composites

Another breakthrough for civil engineering field is the invention of fibre reinforced plastic (polymer) composites. Fibre reinforced plastic (FRP) composites is defined as a polymer matrix, either thermoset or thermoplastic, that is reinforced with a fibre or other reinforcing material with a sufficient aspect ratio to provide a discernable reinforcing function in one or more directions. Issues of corrosion and deterioration of steel reinforcement have led to the use of FRP composites in structures. FRP composite made with resin-impregnated fibres is considered a promising alternative to the traditional steel reinforcements because of its inherent corrosive resistance. Other appealing characteristics of FRP include high tensile strength, good fatigue and damping response, high strength-to-weight ratio, and electromagnetic transparency. The wide-ranging application of FRP reinforcements,
especially as a main reinforcement, however, has been rather limited. This may be partially attributed to the high initial cost of materials and the lack of design guidelines, but more essentially can be attributed to two major engineering drawbacks of FRP materials; low modulus of elasticity and the lack of ductility of fibre reinforced plastics.

Fibre reinforced plastics generally exhibit a linear elastic tensile stress-strain relationship up to failure which, in comparison to steel reinforced members, may result in poor structural ductility even in properly designed FRP reinforced members. Essentially, ductility is the ability of inelastic energy dissipation. For conventional steel-reinforced concrete members, ductility is primarily achieved by the yielding of steel reinforcement, thus consuming a substantial amount of energy while allowing the full compressive strain capacity of the concrete to develop. For an FRP-reinforced concrete member such an inelastic energy consumption mechanism does not exist. The main source of inelastic energy dissipation therefore comes from the cracking and crushing of the concrete matrix. Since the structural failure due to FRP reinforcing bar rupture is rather catastrophic, the over-reinforced design concept that ensures that compressive failure of concrete takes place prior to the tensile failure of FRP has been well accepted (ACI Committee 440, 1996, Sonobe Y. et al.,1997, Theriault M et al., 1998). Nanni (1993) pointed out that, for FRP-reinforced concrete beams, the balanced reinforcement ratio, which is defined as the reinforcement ratio producing a condition for simultaneous failure of the concrete and the FRP reinforcing bar, is much lower than the practically adopted reinforcement ratio if the concrete is unconfined. To fully develop the strain capacity of FRP reinforcement and also to gain plastic deformability, high strength concrete and effective confinement at the compressive zone such as intensive stirrups or spirals should be used. Efforts were also made to develop new types of ductile hybrid FRP composites with deliberately designed fibre architecture (Tamuzs V. et al., 1996, Harris H.G. et al., 1998, Alae F.J. et al., 2003, Maheri et al., 2004).
1.3.1 Types of fibres used

The most common types of fibres used in advanced composites for structural applications are glass (GFRP), aramid (AFRP) and carbon (CFRP). Fibre is an important constituent in composites, occupying 30-70% of the matrix volume.

1.3.1.1 Glass fibres

Glass fibres exhibit the typical glass properties of hardness, corrosion resistance, and inertness. They are flexible, lightweight, and inexpensive. These properties make glass fibres the most common type of fibre used in low cost industry applications. Because glass has an amorphous structure, its properties are the same along the fibre and across the fibre. Glass fibres are useful because of their high ratio of surface area to weight. High strength of glass fibres is attributed to the low number and size of defects on the surface of the fibre. Tensile strength of glass fibres reduces at elevated temperature but can be considered constant for the range of temperature at which polymer matrices can be exposed (up to 275° C depending on the matrix type).

Glass fibres are divided into three classes: E-glass, S-glass and C-glass. E-glass is the most widely produced fibreglass in the world. The letter E is used because it was originally for electrical applications. S-glass is a high strength formulation for use when tensile strength is the most important property. C-glass was developed to resist attack from chemicals and for high corrosion resistance and it is uncommon for civil engineering applications. The E-glass is the most common reinforcement material used in structures. It is produced from lime-alumina-borosilicate, which can be easily obtained from abundance of raw materials, like sand. The fibres are drawn into very fine filaments with diameters ranging from 2 μm to 13 μm. The strength and modulus of glass fibre can degrade with the increase in temperature. Although the glass material creeps under a sustained load, it can be designed to
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perform satisfactorily. The fibre is an isotropic material and has a lower thermal expansion coefficient than that of steel. Properties of E and S glass fibres are given in Table 1.1.

Table 1.1 Properties of E and S glass fibres

<table>
<thead>
<tr>
<th>Typical Properties</th>
<th>E-Glass</th>
<th>S-Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm(^3))</td>
<td>2.60</td>
<td>2.50</td>
</tr>
<tr>
<td>Young's modulus (GPa)</td>
<td>72.00</td>
<td>87.00</td>
</tr>
<tr>
<td>Tensile strength (GPa)</td>
<td>1.72</td>
<td>2.53</td>
</tr>
<tr>
<td>Tensile elongation (%)</td>
<td>2.40</td>
<td>2.90</td>
</tr>
</tbody>
</table>

1.3.1.2 Aramid fibres

These are synthetic organic fibres consisting of aromatic polyamides. The aramid fibres have excellent fatigue and creep resistance. Although there are several commercial grades of aramid fibres available, the two most common ones used in structural applications are Kevlar\(^\text{®}\) 29 and Kevlar\(^\text{®}\) 49. The Young's Modulus curve for Kevlar\(^\text{®}\) 29 is linear to a value of 83 GPa, becomes slightly concave upwards to a value of 100 GPa at rupture. Whereas, for Kevlar\(^\text{®}\) 49 the curve is linear to a value of 124 GPa at rupture. As an anisotropic material, its transverse and shear modulus are of order of whose magnitude is less than those, in the longitudinal direction. The fibres can have difficulty in achieving a chemical or mechanical bond with the resin. Properties of Kevlar\(^\text{®}\) 29 and Kevlar\(^\text{®}\) 49 fibres are given in Table 1.2.

Table 1.2 Properties of Kevlar\(^\text{®}\) 29 & Kevlar\(^\text{®}\) 49

<table>
<thead>
<tr>
<th>Typical Properties</th>
<th>Kevlar(^\text{®}) 29</th>
<th>Kevlar(^\text{®}) 49</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (gm/cm(^3))</td>
<td>1.44</td>
<td>1.44</td>
</tr>
<tr>
<td>Young's modulus (GPa)</td>
<td>83 to 100</td>
<td>131</td>
</tr>
<tr>
<td>Tensile strength (GPa)</td>
<td>3.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Tensile elongation (%)</td>
<td>4.0</td>
<td>2.80</td>
</tr>
</tbody>
</table>
1.3.1.3 *Carbon fibres*

Graphite or carbon fibres are made from three types of polymer precursors: polyacrylonitrile (PAN) fibre, rayon fibre, and pitch. The tensile stress-strain curve is linear to the point of rupture. They have lower thermal expansion coefficients than both the glass fibres and aramid fibres. The carbon fibre is an anisotropic material, and its transverse modulus is an order of magnitude less than its longitudinal modulus. The material has a very high fatigue and creep resistance. Properties of carbon fibres are given in Table 1.3.

<table>
<thead>
<tr>
<th>Typical properties</th>
<th>High strength</th>
<th>High modulus</th>
<th>Ultra-high modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>1.80</td>
<td>1.90</td>
<td>2.00 - 2.10</td>
</tr>
<tr>
<td>Young's modulus (GPa)</td>
<td>230.0</td>
<td>370.0</td>
<td>520.0 - 620.0</td>
</tr>
<tr>
<td>Tensile strength (GPa)</td>
<td>2.48</td>
<td>1.79</td>
<td>1.03 - 1.31</td>
</tr>
<tr>
<td>Tensile elongation (%)</td>
<td>1.10</td>
<td>0.50</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Glass fibre is the least expensive and carbon fibre being the most expensive. The cost of aramid fibre is about the same as lower grades of the carbon fibre. Also the glass fibre has stiffness, $1/5^{th}$ as that of mild steel. The reduced stiffness often causes serviceability criteria (deflections and crack widths) to control the design of FRP-reinforced concrete members.

1.3.2 Properties of composite materials

- Light weight
- High Strength-to-weight ratio
- Corrosion resistance
- Weather resistance
- Dimensional stability
- Low thermal conductivity and low thermal expansion
- Radar transparency
• Non-magnetic
• High impact strength
• High dielectric strength (insulator)
• Low maintenance
• Long term durability
• Small to large part geometry possible
• Tailored surface finish

1.3.3 Benefits of using fibre reinforced plastic composites
• Faster construction
• Reliability of pre-engineered systems
• Enhanced durability and fatigue characteristics
• Innovative and efficient installation
• Increase in the service life of the structures
• Environmental friendly

1.3.4 Applications of fibre reinforced plastic composites

For years, civil engineers have been in search for alternatives to steels and alloys to combat the high costs of repair and maintenance of structures damaged by corrosion and heavy use. Composite materials have gained increasing popularity in the engineering field due to FRP’s high strength properties, ease of installation, versatility, electromagnetic neutrality and excellent durability. There are three broad divisions into which applications of FRP in civil engineering can be classified:

- Applications for new construction,
- Repair and rehabilitation applications, and
- Architectural applications
FRP’s have been used widely by civil engineers in the design of new construction. Structures such as bridges and columns built completely out of FRP composites have demonstrated exceptional durability, and effective resistance to effects of environmental exposure. Prestressing tendons, reinforcing bars, grid reinforcement and dowels are all examples of the many diverse applications of FRP in new structures.

One of the most common uses for FRP is in the repair and rehabilitation of damaged or deteriorating structures. In this case, the FRP composite is used to retrofit an existing and deteriorated structure to bring its load carrying capacity or ductility back to the level for which it was designed. FRP retrofitting to improve the performance of a structure when subjected to blast and impact loading has become a matter of interest of late. Bridge piers are wrapped with FRP to prevent collapse and steel-reinforced columns are wrapped to improve the structural integrity and to prevent buckling of the reinforcement.

Architects have also discovered many applications for which FRP can be used. Cornice mouldings, columns, balustrades, and baluster systems, have become one of the most popular uses of fibreglass. Cornices manufactured with FRP do not require heavy steel supports or structural rehabilitation of the attachment areas on a building. Fibreglass cornice is very practical when compared with the material, maintenance and installation cost of other traditional materials. Columns, balustrades and baluster systems are now manufactured load-bearing to hold substantial weight.

1.4 Glass Fibre Reinforced Plastic
Among the fibre composites, glass fibre reinforced plastics (GFRP) is more popular due to ease of construction, ease of availability of all ingredients and cost effectiveness. One of the greatest advantages of GFRP is its high strength to weight ratio. Not only it has tensile strength but also it is highly corrosive resistant. GFRP is a structural material that incorporates the versatile chemical, electrical and other properties of plastic with mechanical
strength, chemical inertness and electrical resistance of glass fibres to create a synergistic material, which can be engineered for specific applications.

The tensile strength of GFRP can be varied from 34 to over 220 MPa. The standard properties of GFRP like, low maintenance cost, lightweight, high strength, translucency, good resistance to chloride, chemical attack, transparent to magnetic fields and radio frequencies, good impact, compression strength, fatigue and electrical properties make it an ideal material for use in constructions (Saadatmanesh, 1997).

1.4.1 Materials used in preparation of GFRP

Glass fibre reinforced plastic composites are made of resins, reinforcements, fillers, and additives. Each of these constituent materials or ingredients play an important role in the processing and final performance of the end product. The resin or polymer is the “adhesive” that holds the composite together and influences the physical properties of the end product. The reinforcement provides the mechanical strength. The fillers and additives are used to impart special properties to the end product.

1.4.1.1 Resin

The primary functions of the resin are to transfer stress between the reinforcing fibres, act as an adhesive to hold the fibres together, and protect the fibres from mechanical and environmental damage. Resins are divided into two major groups known as “thermoset” and “thermoplastic”. Thermoplastic resins become soft when heated, and may be shaped or moulded while in a semi-fluid state and become rigid when cooled. Thermoset resins, on the other hand, are usually liquids or low melting point solids in their initial form. When used to produce finished goods, this thermoset resin is cured with the help of catalyst or heat, or a combination of the two. Once cured, solid thermoset resins cannot be converted back to their original liquid state. Unlike thermoplastic resins, cured thermoset resin will not melt and flow but will soften when heated (i.e. it loses hardness) and once formed, they cannot be
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reshaped or remoulded. Heat Distortion Temperature (HDT) and the Glass Transition Temperature (Tg) are used to measure the softening characteristics of a cured resin. Both these test methods (HDT & Tg) measure the approximate temperature at which the cured resin will soften significantly to yield (bend or sag) under load.

The most common thermosetting resins used in the composites industry are unsaturated polyesters, epoxies, vinyl esters and phenolics.

1.4.1.2 Catalyst

A catalyst can be defined as a chemical, which initiates a reaction without itself taking part in the reaction. Thus, the chemical composition of a catalyst remains unchanged after the completion of the reaction. The catalyst mostly used with polyester resin, are peroxide compounds, which helps in breaking down complex organic compounds in the polymerization process. A better term to describe catalyst would be “initiators”. During polymerization, catalyst (peroxide compounds) helps in breaking down complex organic compounds into “free radicals”. The following are peroxide catalysts generally used: Benzyol peroxide, Tertiary butyl perbenzoate, Ditertiary butyl peroxide, Methyl ethyl ketone peroxide, and Cyclohexanone peroxide. These substances promote and control curing, and are added to increase the hardness of the resin.

1.4.1.3 Accelerator

Accelerators are chemical compounds, which increase the rate of decomposition of catalysts. This effect is made use of, in cooled curing process for polyester resins thereby enabling curing at temperature as low as 15° C. For practical purpose, the accelerators used are normally of two types: i) Cobalt compounds (e.g. Cobalt naphthenate and Cobalt octate) and ii) Tertiary amines (e.g. Dimethyl aniline, Diethyl aniline, Dimethyl-P-Toluidine).
The cobalt accelerators are extremely effective for polyester resins and are normally used in conjunction with methyl ethyl ketone peroxide and cyclohexanone peroxide but not with benzoyl peroxide. Tertiary amine accelerators are effective with benzoyl peroxide but not with methyl ethyl ketone peroxide or cyclohexanone peroxide.

1.4.1.4 Fillers

Fillers are inert materials and they impart strength, hardness and other properties to plastic. Since resins are very expensive, it will not be cost effective to fill up the voids in a composite matrix purely with resins. Fillers are added to the resin matrix for controlling material cost and improving its mechanical and chemical properties. The three major types of filler used in the composite industry, are calcium carbonate, kaolin, and alumina trihydrate. Other common fillers include mica, felspar, wollastonite, silica, talc and glass. When one or more fillers are added to a properly formulated composite system, the improved performance includes fire and chemical resistance, high mechanical strength, and low shrinkage. Other improvements include toughness as well as high fatigue and creep resistance. Fillers should not be used with fibre volume greater than 50% for the sheet moulding composite production method.

The chief function of filler in reinforced plastic laminate is to impart special properties either to processing characteristics of the material or to the moulded product in its final form. Where a colouring agent is used inert filler such as Calcium carbonate incorporated in the resin, will greatly increase the capacity of the finished moulding and also the density and depth of colour.

For structural applications, it is mandatory to achieve some degree of flame retardance. Fire retardants are usually incorporated in the resin itself or as an applied gel-coat. Fillers and pigments are also used in resins for a variety of purposes. The former to improve the mechanical properties and the latter improves the appearance and the protective action.
1.4.2 Manufacturing processes of GFRP

The mechanical properties and composition of GFRP composites can be tailored for their intended use. The type and quantity of materials selected in addition to the manufacturing process to fabricate the product, will affect the mechanical properties and performance.

Manufacturing processes used to fabricate GFRP includes Pultrusion, Resin Transfer Moulding (RTM), Vacuum-Assisted Resin Transfer Moulding (VARTM), Hand lay-up (open moulding), Compression moulding, and Filament Winding.

1.4.2.1 Pultrusion

Pultrusion is a continuous moulding process that combines fibre reinforcements and thermosetting resin. The pultrusion process is used in the fabrication of composite parts that have a constant cross-section profile. Typical examples include various bar section, ladder side-rails, tool handles, and electrical cable tray components and row bridge beams and decks. Most pultruded laminates are formed using roving aligned to the major axis of the part. Various continuous strand mats, fabrics (braided, woven and knitted), and texturized or bulked roving are used to obtain strength in the cross axis or transverse direction.

This process is continuous and automated (Fig. 1.2). Reinforcement materials, such as roving, mats or fabrics are positioned in a specific location using performing shapers or guides to form the profile. The reinforcements are drawn through a resin bath or wet-out, where the material is thoroughly coated or impregnated with a liquid thermosetting resin. The resin-saturated reinforcements enter a heated metal pultrusion die. The dimensions and shape of the die will define the finished part being fabricated. Inside the metal die, heat is transferred by precise temperature control to the reinforcements and liquid resin. The heat energy activates the curing or polymerization of the thermoset resin changing it from a liquid to a solid. The solid laminate emerges from the pultrusion die to the exact shape of the die cavity. The laminate solidifies when cooled and it is continuously pulled through the
pultrusion machine and cut to the desired length. The process is driven by a system of
caterpillar or tandem pullers located between the die exit and the cut-off mechanism.

1.4.2.2 Resin transfer moulding (RTM)

Resin transfer moulding or RTM as it is commonly referred to as a “Closed Mould Process”,
in which reinforcement material is placed between two matching mould surface (one male
and other being female). The matching mould is then closed and clamped and a low viscosity
thermoset resin is injected under moderate pressures (0.35–0.7 MPa) into the mould cavity
through a port or series of ports within the mould (Fig.1.3). The resin is injected to fill all
voids within the mould and thus penetrates and wets out all surfaces of the reinforcing
materials. The reinforcements may include a variety of fibre types, in various forms such as
continuous fibres, mat or woven type as well as, hybrid of more than one type of fibre.
Vacuum is sometimes used to enhance the resin flow and reduce void formations. The part is
typically cured with heat. In some applications the exothermic reaction of the resin may be
sufficient for proper curing.

RTM as a process, is multi-compatible with a variety of resin systems including polyester,
viny ester, epoxy, phenolic, modified acrylic and hybrid resins such as polyester and
urethane.
1.4.2.3 Vacuum assisted resin transfer moulding (VARTM)

In conventional RTM process; a matched set of moulds or "closed mould" is used. Resin is injected at high pressure and the process is sometimes assisted with vacuum. However, vacuum assisted resin transfer moulding (VARTM) is different for many reasons. Firstly, the fabrication of parts can be accomplished on a single open mould. Secondly, the process uses the injection of resin in combination with a vacuum and captured under a bag to thoroughly impregnate the fibre reinforcement (Fig.1.4). This process has been used in many new and large applications ranging from turbine blades and boats to rail cars and bridge decks. This manufacturing method allows the efficient processing of VARTM to produce large structural shapes that are virtually void-free, which makes it unique. This process has been used to make both thin and very thick laminates.
1.4.2.4 Hand lay-up (open moulding) process

Hand lay-up is the oldest and simplest method used for producing reinforced plastic laminates. Capital investment for hand lay-up process is relatively low. The most expensive piece of equipment is a spray gun for resin and gel coat application. Some fabricators pour or brush the resin into the moulds so that a spray gun is not required for this step. There is virtually no limit to the size of the part that can be made. The moulds can be made of wood, sheet metal, plaster, and FRP composites.

In hand lay-up process, high solubility resin is sprayed, poured, or brushed into a mould pre-placed with GFRP reinforcement. Chopped strand mat is the cheapest reinforcement used in wet lay-up. It also provides equal reinforcing strength in all directions due to the random orientation of the fibres that form the mat. Woven roving is especially suitable for thick laminates requiring greater strength. Woven fabric and braid fabric can also be used. Complex shapes can be easily formed with this process.

1.4.2.5 Compression moulding

Compression moulding is the most common method of moulding thermosetting materials such as SMC (Sheet Moulding Compound) and BMC (bulk moulding compound). This moulding technique involves compressing materials containing a temperature-activated catalyst in a heated matched metal die using a vertical press. The moulding process begins with the delivery of high viscosity uncured composite material to the mould. Mould temperatures typically are in the range of 350°-400°F. As the mould closes, composite viscosity is reduced under the heat and pressure approximating 7MPa. The resin and the isotropically distributed reinforcements flow to fill the mould cavity. While the mould remains closed, the thermoset material undergoes a chemical change (cure) that permanently hardens it into the shape of the mould cavity. Mould closure time varies from 30 seconds up to several minutes depending on material formulation. When the mould opens, parts are
ready for finishing operations such as deflashing, painting, bonding and installation of inserts for fasteners. By varying the formulation of thermoset material and reinforcements, various types of elements can be produced as per requirements.

1.4.2.6 Filament winding

The filament winding process is used in the fabrication of tubular composite parts. Typical examples are composite pipes, electrical conduits and composite tanks. Glass fibre roving strands are impregnated with liquid thermosetting resin and wrapped onto a rotating mandrel in a specific pattern. When the winding operation is completed, the resin is cured or polymerized and the composite part is removed from the mandrel.

1.4.3 Properties of GFRP

- Aesthetics: It gives a finish of high quality, thus enhancing aesthetics of the structure.
- Weight: It has higher strength to weight ratio compared to steel or aluminium.
- Dimensional stability: It holds its form and shape even under severe mechanical stress and severe environmental conditions.
- Durability: Its performance under corrosive environment is superior.
- Design flexibility: It allows freedom in designing complex and artistic constructions.
- Insulation properties: It has non-conductive, non-corroding and non-magnetic properties, which makes it a sound insulating material.
- Thermal stability: It can withstand wide range of temperature variations.
- Light transmission: In thinner section, it gives a great deal of transparency.
- Lightweight: It is 30% less than aluminium and 60% less than steel, in weight, bearing same loads. Due to the lightweight of the elements, it is easy to assemble.
- Energy saving: It requires far less energy for production, e.g. it requires only 2/3\textsuperscript{rd} and 1/3\textsuperscript{rd} of energy required to make identical steel and aluminium elements respectively.