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Application of Multi-layer Composites in Construction and their Future Challenges

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Abstract

A concise state-of-the-art survey on fiber-reinforced polymer (FRP) composites for civil engineering towards construction applications is presented. It is an emerging trend in construction field, since it is one of the main repair and retrofitting material, in general and has profound applications in aerospace and marine construction in particular. FRPs are well known for enhancing the mechanical and durability properties of concrete. The paper is organized into separate sections on the various mechanical properties like compressive strength, bond strength, flexural strength; durability properties like chloride ion penetration, elevated temperature, freeze thaw cycle, corrosion resistance, seismic behavior of FRP wrapped structural concrete members proposed by various authors are also discussed. Each of these sections is segmented into a short review and future challenges including problem identification based on literature review as well as authors view point. Based on the experimental investigations of various authors, it can be concluded that FRP wrapping on concrete members increases the strength, ductility and also durability of concrete. However, the associated problems due to continuous exposure of moisture at the concrete-epoxy interface need to be addressed in detail. The problem identification and the methodologies for rectification are also discussed in this paper. Functions of epoxy and scope on functional modification for better bonding between the multi-layer composites i.e, concrete-epoxy-(fiber wrap)$_n$-epoxy-(fiber wrap)$_n$, where n - no. of layers are discussed.

Keywords: CFRP, GFRP, Functional epoxy, multi-layer composites, strength, durability.

Introduction

Composite materials offer many advantages over the conventional civil engineering materials due to their combination of high-strength, high-stiffness structural fibers with low-cost, lightweight, environmental friendliness and better mechanical properties and durability than either of the constituents alone. Fiber materials with higher strength, higher stiffness, and lower density, such as boron, carbon, and aramid, have been commercialized to meet the higher performance challenges of space exploration and air crafts in the 1960s and 1970s (ASCE Review)[1]. A detailed state-of-the review and future of these promising construction materials on fiber-reinforced polymer, also known as fiber-reinforced plastic composites for construction applications in civil engineering was presented[1]. This extensive review attempts to the many potential applications of FRP composite materials in construction and it was concluded that, the amount of experience with various forms of FRP construction materials varies in accordance with the perceived near-term economic and safety benefits.

FRP composites are organized in a laminate structure such that each lamina (or flat layer) contains an arrangement of unidirectional fibers or woven fiber fabrics embedded within a thin layer of light polymer matrix material. The mechanical characteristic of FRPs mainly depends on the quality of fiber and also high performance thermosetting resins. This matrix will have high stability at elevated temperature, low water absorption, good chemical resistance, high mechanical strength, excellent stiffness and also high compressive strength[2]. Epoxy binds and protects the fibers from damage and transfers the stresses between fibers. FRP can be applied for strengthening the beams, columns and slabs of buildings as well as bridges. The strength of the deteriorated concrete or damaged structural members can also be enhanced. FRPs are manufactured from fibers and resins and have proven efficiency and economically feasible for the development and repair of new and deteriorating structures in civil engineering. They are found to enhance the mechanical and durability properties of concrete.

The present study mainly aims to produce a review, which is required to understand the current applications of FRP in construction field along with the future challenges. The review includes mechanical and durability characteristics of FRP composites. Only important and very relevant literatures to focus on problem identification towards epoxy modifications are discussed, as the details on FRP composites are very vast and widely published. A detailed survey will be presented elsewhere in future. Moreover, many reports are available on the use of FRP in construction applications in the report form and journal publications etc and will not be dealt in detail here.

Mechanical Characteristics

Various mechanical characteristics such as compressive strength, flexural strength, bond strength and load-deflection properties studied by various authors are well documented [3-14]. A brief review on these aspects is presented below.

Compressive Strength

The compressive strength of the control specimens and FRP concrete specimens were found and compared in several studies.

Carbon Fiber Reinforced Polymer (CFRP) wraps enhanced the strength and ductility of concrete. This was due to the curtailment of lateral dilation of concrete. The fiber was wrapped for different length as 100mm, 200mm and 300mm and also the layers of CFRP wraps were one, two and three. The strength was higher, when the wrap width was large and thicker[3].

In order to avoid the air voids between the concrete and the CFRP wrap that lead to debonding, the use of CFRP as narrow strips with spacing was proposed. The wrapping thickness on the concrete was also varied. It was found that narrow strips of CFRP were easy to apply and the air voids were removed due to the spacing between the wraps. The stress and strain capacities of the specimen were also found to have increased. Even though the thickness was increased further, the maximum strength of 1.54 times could be obtained[4].

The strength and modulus of elasticity of concrete compression member increased even at elevated temperatures. ASTM C-469-2495-01 was used to evaluate the modulus of elasticity of FRP wrapped concrete. It is reported in this study that 90% of strength increment is possible for the specimens having one layer of CFRP wrapping, when compared to control[5].

The number of layers of Glass Fiber Reinforced Polymer (GFRP) wraps and the aspect ratio of the fiber also has impact on compressive strength. The compressive strength was increased and better confinement resulted with increase in number of layers of GFRP. Load carrying capacity and ductility of the compression member were also found to have increased. But the load carrying capacity decreased with increase in aspect ratio[6].

The specimens were wrapped with CFRP composite of various layers such as 0, 1, 2 and 3 layers. The orientation of fiber was varied such as 0º, 90º, +45º and -45º with respect to hoop direction. It was concluded that the compressive strength increased from about 39MPa to79 MPa for one layer of CFRP, if fibers are oriented in transverse direction[7].

The compressive strength of concrete specimens wrapped with CFRP composites in the weaker part of the concrete was examined. It was concluded that CFRP wrapping increases the strength of the deteriorated portion and the load capacity of the entire column. The greater the number of CFRP layers, the greater the gain in load capacities were achieved[8].

Flexural Strength: The flexural strength of the concrete beams were casted with NSM (Near Surface Mounted) CFRP rebar, NSM CFRP strips, NSM GFRP thermoplastic strips, externally bonded CFRP strips and externally bonded GFRP thermoplastic strips. It was found that the beams strengthened with NSM FRP reinforcement achieved higher ultimate load than beams strengthened with externally bonded FRP reinforcement[9].

The reinforced concrete rectangular beam with epoxy bonded CFRP laminate were studied. CFRP laminates were bonded to the soffit of the beam as one, two and three layers. The strengthened beams failed by crushing, but there was significant increase in flexural capacity. Maximum of 92% increase of flexural capacity was obtained with 3 laminates of CFRP. The ductility and flexural stiffness were also increased with increase in number of laminates. The stress-strain curve was found to be linear upto fracture[10].

Bond Strength: The experimental results on environmentally conditioned CFRP reinforcements bonded to concrete was studied. The Young's modulus and tensile strength of fiber were according to ASTMD 3039. The concrete specimens were subjected to external CFRP wraps. The concrete specimens were conditioned by freeze thaw cycles and its bonding was determined. Some specimens that were conditioned before fiber wrapping showed decrease in compressive strength. Debonding tests were discussed in terms of bonding length. It was observed that the debonding force was higher for the specimen having reinforcing length 400mm and debonding is not majorly affected by freeze-thaw cycles[11].

The efficiency of CFRP strengthening to maintain and enhance the bond between corroded steel reinforcement and concrete was studied. This was conducted by pull out test. The ultimate bond strength increased when the reinforcement steel in the specimen was corroded. The failure mode was changed from brittle failure to ductile failure. The confining effect increased with increase in cover depth to steel rebar diameter ratio only upto 2.3. Even though there was progressive corrosion upto 15%, the ultimate bond strength increased[12].

The changes in bond strength of reinforcing bars due to external confinement were studied[13]. The specimens were designed such that there were insufficient anchorage length and small cover thickness equal to bar diameter. FRP were wrapped on the specimen and tested. The bond strength of the specimen subjected to FRP wrap increased. The increase in number of layers of CFRP and increase in modulus of elasticity of fiber increased the bond strength.

Load-Deflection Properties: The reinforced concrete beam strengthened with GFRP laminates were examined[14]. The flexural and load-deflection properties were studied. The beams were subjected to various environmental conditions such as controlled laboratory environment, outside environment, wet-dry normal water environment, wet–dry saline water environment and wet–dry alkaline (NaOH) environment. The deflection due to loading decreased due to GFRP wrap, when compared to control specimen.

Based on ideas of various authors, the research can be further extended to increase the strength and reduce the deflection. This can be achieved by wrapping FRP on concrete in various orientations and also by increasing the layer of FRP sheets.

Durability Characteristics

Although the term 'durability' is widely used, its meaning and implications are very much ambiguous[15]. Various durability characteristics such as chloride ion penetration, freeze thaw cycles, fire resistance etc., were studied in different exposure conditions by several authors[16-23]. A brief review on these aspects is presented below.

Chloride Ion Penetration: The resistance of chloride ion penetration in concrete specimens with FRP wrapping were discussed[16]. The various specimens such as corroded specimen, FRP wrapped and then subjected to corrosion, one and two layers of CFRP and GFRP wrapped specimen were examined by subjecting it to corrosion by using NaCl solution. Full wrapping of CFRP laminates reduced 70% of chloride ion penetration. The beams strengthened with FRP achieved the unsalted original strength even in corrosive environment.

The effect of chloride content on the bond behavior between concrete and FRP plate were discussed[17]. The FRP strengthened concrete specimens were subjected to corrosion by immersing it in NaCl (3% to 15%) and Direct Shear Test was conducted. It was found that there was a small decrease in the debonding load due to degradation of adhesive. But then, the load increases when the immersion time increases due to the hydration of cement. But finally there was decrease in the debonding load.

The effect of FRP wraps on corrosion of concrete and also cracking of concrete specimens that were chloride contaminated were experimentally studied[18]. The specimens wrapped with FRP were subjected to accelerated corrosion for 80 days. The specimens were regularly monitored for their concrete expansion throughout the corrosion exposure. The reinforcement bars from the specimen were extracted, rust was cleaned and its mass was found. Due to the FRP wrap and increase in concrete cover to bar diameter, the mass of the reinforcement did not vary and the concrete expansion was less.

Elevated Temperature: The variation in modulus of elasticity and the behavior when subjected to elevated temperatures were examined. It was found that the pre-curing of the specimen to high temperatures within the transition temperature of FRP increased the strength and modulus of elasticity of concrete[5].

FRP composite behavior at elevated temperature and freeze thaw exposure were investigated by various mechanical tests[19]. The FRPs were wrapped to the concrete specimen with epoxy and nano-composite materials and were subjected to uniaxial compression test at high temperatures. It was found that the concrete specimens with FRP wrap by using epoxy resin showed increase in strength and axial strain at elevated temperature. Use of nano-composite improved the mechanical properties even without the curing process at elevated temperatures.

The compressive strength was found for the specimen with 1, 2 and 3 layers of GFRP wrap and in various exposure conditions[20]. It was observed that the strength increased as 67%, 129% and 150% when compared to control concrete. When the specimens were exposed to high temperature, the strength decreased to 6% for 3 layers of fiber wrap.

Freeze Thaw Cycles: The FRP composite behavior during the freeze thaw exposure was investigatedl[19] by conducting various mechanical tests. The FRPs were wrapped to the concrete specimens with epoxy resin. Also nano-composite materials were used instead of epoxy resin and were subjected to uniaxial compression test after freeze thaw cycles. It was found that the concrete specimens with FRP wrap by using epoxy resin showed increase in strength and axial strain at freeze thaw exposure. Use of nano-composite improved the mechanical properties even without the curing process at freeze thaw exposure.

The mechanical behavior of CFRP concrete specimens under heating-cooling cycles (-10ºC to 50ºC) were studied[21]. The specimen was subjected to uniaxial compression test after 200 cycles of heating and cooling. It was found that the strain reduced by 5% when exposed to heating-cooling cycles. The strength increased under sustained loading which caused CFRP to be active. The lateral expansion was also reduced.

Corrosion: The structural performance of the corroded concrete specimens wrapped with CFRP were discussed[22]. Concrete specimens that were wrapped with CFRP and unstrengthened specimen were subjected to various corrosion level as 0%, 5%, 10% and 15%. The U-shaped wrapping of the specimen with CFRP sheets were more effective even during high corrosion rates. The strength was more and the deflection was less than the control specimen.

The corrosion progress of steel were investigated after the rehabilitated concrete specimen treated with FRP composites[23]. The concrete with embedded steel bar were wrapped with CFRP and GFRP and subjected to accelerated corrosion. Pull out strength and mass loss were calculated. The test results showed that wrapping of FRP composites slowed down the corrosion process. There was increase in pull out strength and decrease in mass loss. GFRP resisted corrosion more than CFRP wrapped concrete.

The corrosion resistance of concrete specimens with FRP wrapping was examined[16]. The various specimens such as corroded specimen, FRP wrapped and then subjected to corrosion, one and two layers of CFRP and GFRP wrapped specimen were examined by subjecting it to corrosion by using NaCl solution. Full wrapping of CFRP laminates reduced 70% of chloride ion penetration. The corrosion of reinforcement decreased the ultimate strength of control beams up to 13.6%. The ultimate strength of CFRP post-strengthened beams decreased, when compared to CFRP pre-strengthened beams.

Further studies can be carried out in order to improve the durability properties of concrete. This can be achieved by introducing nano composites, so that it prevents the ingress of water molecules and also other aggressive ions like chloride etc.,

Seismic Behaviour

The seismic performance of CFRP strengthened reinforced concrete frames were examined under low cyclic lateral loading[24]. Two specimens out of which one was reinforced with CFRP at beams, columns and at joints and the other without reinforcement. The information about the crack development, the damage characteristics, the hysteretic curves of the steel bar and CFRP sheets were found. It was indicated that the CFRP sheet reinforced frame showed a good hysteretic energy capacity and higher ductility that indicated a good seismic behavior of CFRP composites.

CFRP's contribution to mechanical and energetic performance and to the modification of the cracking pattern on short columns were evaluated[25]. Short columns undergo shear stress due to low resistance to higher lateral displacements during earthquake. The columns were tested and found that brittle failure changed to ductile failure. The ductility was also found to have increased.

The confinement in columns is necessary and beneficial in both seismic and non-seismic regions[1]. Proper confinement prevents the debonding of internal reinforcement in lap splices. This confinement is provided by wrapping the columns by using FRP composites in which the fiber direction is circumferential. In circular columns, FRP wrap curtails the lateral expansion. The ultimate state (f_{cc} and ε_{cu}) is characterized by tensile failure of the wrap (figure-1).

MULTI-LAYER COMPOSITES: concrete-epoxy-(fiber wrap)n-epoxy-(fiber wrap)n
As discussed in the prior sections, it is understood that FRP composite such as concrete-epoxy-FRP, is having the schematic representation of FRP composites as shown in figure-2.

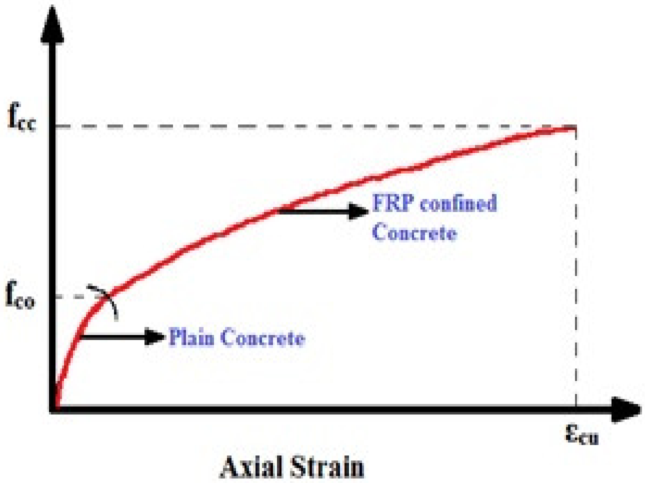

Figure-1
Axial Stress-Strain response of FRP confined concrete Vs Plain Concrete

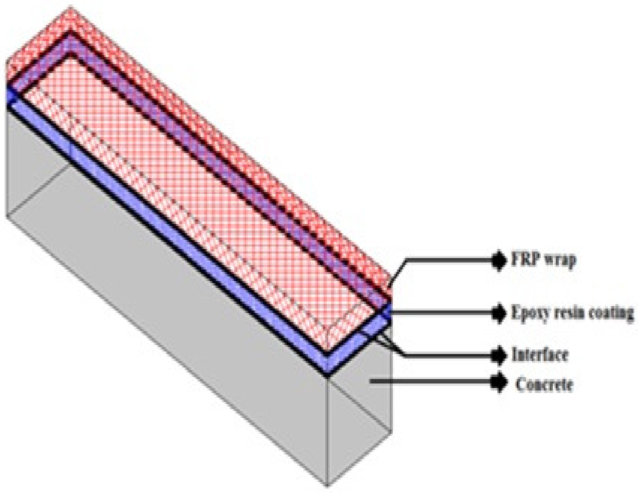

Figure-2
Schematic representation of FRP composites on concrete

Based on the review by various authors, the strength, durability and also seismic behavior have found to be improved. FRP wrapping has been proven to be effective in repair of concrete structural elements. According to some of the authors view point[11-14], proper care must be taken while application of epoxy and fiber sheet. No air voids must be present because it can lead to delamination leading to ingress of aggressive ions and also decrease in strength.

The durability of the polymer is a function of aggressive environment where the polymer is placed. Moisture diffuses into all organic polymers leading to change in their mechanical and chemical characteristics. This moisture absorption may cause reversible and irreversible changes in the structure of the polymer. When the FRP wrapped at the repaired portion of the concrete is exposed to moisture for a long period, the FRP delamination occurs. The continuous exposure of moisture on FRP wrapped concrete leads to weakening of epoxy bonds. Thus leading to the entry of water molecules and aggressive ions, which further may cause delamination of FRP from concrete. The schematic illustration of damage in multi-layer system due to epoxy is shown in figure-3. This problem will be polymerized, if the no. of layers of fibers as shown in figure-4 are used while wrapping the concrete. Hence, an immediate attention has to be paid towards developing a functionally active epoxy.

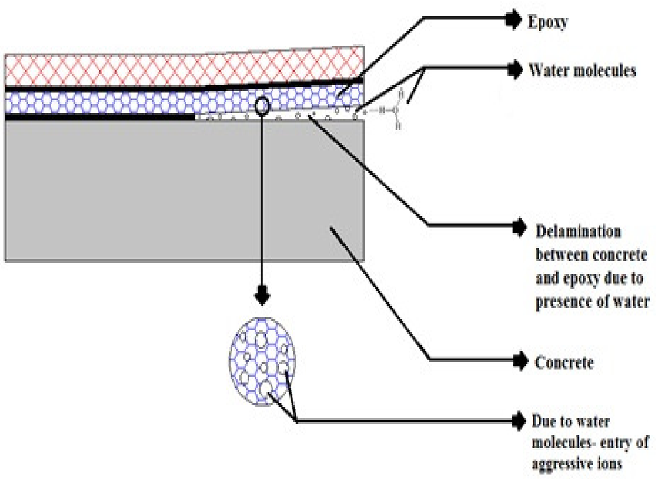

Figure-3
Schematic damage (delamination) representation of epoxy in FRP-Concrete system due to moisture

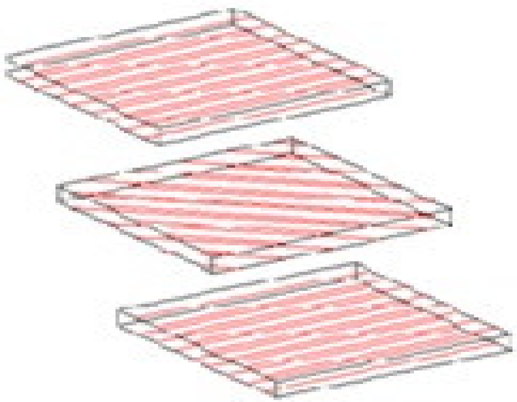

Figure-4
Multi Layer of FRP sheet in 0º and 45º orientation

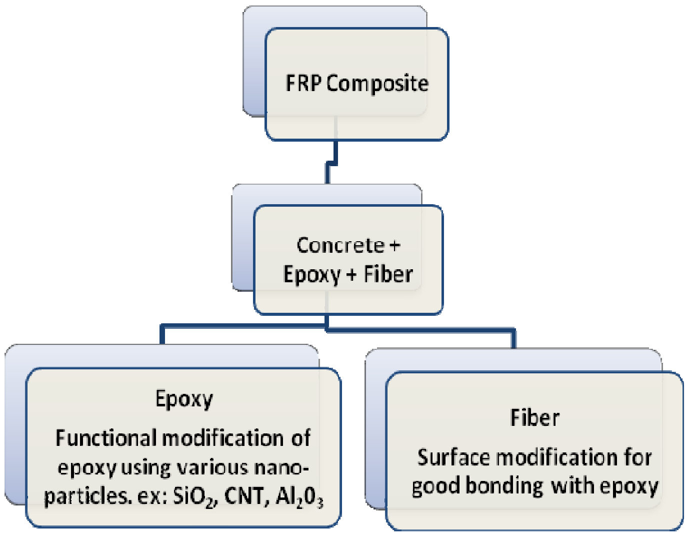

Figure-5
Flow chart on work started at CSIR-SERC towards future challenges on FRP

The application of an additive to the polymer matrix while manufacturing decreases the moisture diffusion into the polymer[26]. By introducing epoxy layered silicate nano-composite into the polymer resulted in lowering the permeability and improved the mechanical properties[27]. The tensile behavior of GFRP composite in which the epoxy was modified by using nano silica particles was studied. The fatigue life of GFRP composite was found to have increased by about 3 to 4 times due to silica nano-particles[28]. Various authors[27,29] experimentally studied the modification of epoxy by using clay and also by fumed silica SiO_2 and multi-wall carbon nanotubes (MWCNT). It was found that clay increased the strength, fire resistance and decreased the permeability. Use of silica and CNT improved the fatigue behavior of FRP composites. Epoxy modification with various nano particles and their tensile, fatigue and also durability characteristics were discussed[30].

Work under Progress in SERC-CSIR: The problem that was identified based on the current research reports, has to be rectified to gain the full benefit of FRP composite application in construction. Towards this, the research work at CSIR-SERC, focuses on functional modification of epoxy inorder to prevent the moisture ingress, bond weakening and also to enhance the mechanical and durability characteristics of FRP composites, since these properties are also associated with the characteristics of epoxy-fiber bonding nature. The flow chart of the work started is shown in figure-5.

Conclusion

The following conclusions are arrived based on the short review on FRP composites application in construction field. i. The compressive strength of concrete with FRP wrapping increases with increase in number of layers of wrapping. ii. The load-deflection behavior of the concrete specimens decreased in FRP concrete and the flexural strength increased. iii. The debonding load required was higher due to the effective bond between the concrete and FRP composite. iv. The penetration of chloride ion in the concrete specimen, due to FRP confinement decreased thus causing the reduction of corrosion thereby increasing the strength. v. FRP concrete specimen has good resistance to high temperatures and also freeze thaw exposure. vi. FRP concrete specimen also shows good hysteretic curves, modulus of elasticity and ductility which shows that it has good seismic behavior. vii. The problem occurring in concrete-epoxy-fiber interface is identified and its rectification by using chemicals SiO_2 and CNT in epoxy treatment is under progress.

To conclude overall, though the application of FRP composites are gaining importance in construction field, certain limitations such as improper bonding between the concrete/epoxy or fiber/epoxy are prohibiting to get the best credit Authors believe that the problem identified based on the survey conducted and the future challenges identified, will definitely play role as an elevator towards promoting FRP in construction field.

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