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# FIBER REINFORCED POLYMER COMPOSITES, A NOVEL WAY FOR STRENGTHENING STRUCTURES

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## ABSTRACT

To meet up the requirements of advance infrastructure, new innovative materials/ technologies in Civil engineering industry has started to make its way. Any technology or material has its limitations and to meet the new requirements new technologies have to be invented and used. With structures becoming old and the increasing bar for the constructed buildings the old buildings have started to show a serious need of additional retrofits to increase their durability and life.

Use of FRP for confinement has proved effective in retrofitting and strengthening applications. The Confinement in seismically active regions has proven to be one of the early applications of FRP materials in infrastructure applications. Confinement may be beneficial in non-seismic zones too, where, for instance, survivability of explosive attacks is required or the axial load capacity of a column must be increased due to higher vertical loads, e.g. if new storey's have to be added to an existing building or if an existing bridge deck has to be widened. In any case, confinement with FRP may be provided by wrapping RC columns with prefabricated jackets or in situ cured sheets, in which the principal fiber direction is circumferential. Beams, Plates and columns may be strengthened in flexure through the use of FRP composites bonded to their tension zone using epoxy as a common adhesive for this purpose. The direction of fibers is parallel to that of high tensile stresses. Both prefabricated FRP strips, as well as sheets (wet-layup) are applied. Hence, FRP composites are finding ways to prove effective and economical at the same time.

## INTRODUCTION

In today's growing economy, Infrastructure development is also raising its pace. Many reinforced concrete and masonry buildings are constructed annually around the globe. With this, there are large numbers of them which deteriorate or become unsafe to use because of changes in use, changes in loading, change in design configuration, inferior building material used or natural calamities. Thus repairing and retrofitting these structures for safe usage of these structures has a great Market.

There are several situations in which a civil structure would require strengthening or rehabilitation due to lack of strength, stiffness, ductility and durability. Some common situations where a structure needs strengthening during its lifespan are

- Seismic retrofit according to current code requirements.
- Upgraded loading requirements; damage by accidents and environmental conditions.
- Initial design flaws
- Change of usage.

Depending on the desired properties, usage and level of damage involved members can be repaired and/or strengthened by several widely used methods. Some of widely used repair techniques are presented below.

Concrete jacketing can be applied to locally damaged or heavily damaged structures. When concrete is slightly damaged, the loose concrete is removed the surfaces are roughened and the dust is cleaned. Now depending on the amount of concrete removed, some additional ties or reinforcement can be added and jacketing is carried out i.e. new concrete is filled. Non shrinkage concrete or concrete with low shrinkage properties should be used. Special attention is paid to achieve a good bond between old and new concrete.

Jacketing should be also applied in cases of heavy damaged columns or in cases of insufficient column strength. This is actually a strengthening procedure but can be used for repair purposes. The additional concrete and reinforcement added contribute to strength increase.

Concrete jacketing has a lot of limitations. The jacket should be of minimum thickness 100mm. The sizes of members are increased and the free available usable space becomes less also adding a huge dead mass and increasing the stiffness which reduces the efficiency of the structure. Its durability has also often found to be limited. Furthermore the whole process is slow and takes lot of time for completion.

Jackets may also be made of steel. It is a popular technique to use steel plates bonded with epoxy to external surfaces of beams and slabs. This technique is simple and effective as far as both cost and mechanical performance is concerned, but suffers major disadvantages. Corrosion of steel plates hurdles its use in structures in/near river, lake and sea. Furthermore difficulty in manipulating heavy steel plates in tight construction sites, need for scaffolding, and limitations in available plate lengths which results in need of joints. Sometimes steel’s high young’s modulus causes it to take large portion of axial load resulting in premature buckling.

The conventional jackets, sheets, plates may be replaced with FRP fabrics, sheet and laminates in view of above limitations.

A Fiber Reinforced Polymer (FRP) composite is defined as a polymer (plastic) matrix, either thermo set or thermoplastic, that is reinforced (combined) with a fibre or other reinforcing material with a sufficient aspect ratio(length to thickness) to provide a discernable reinforcing function in one or more directions. FRP composites are different from traditional construction materials such as steel or aluminium. FRP composites are anisotropic (properties apparent in the direction of the applied load) whereas steel or aluminium is isotropic (uniform properties in all directions, independent of applied load). Therefore, FRP composite properties are directional, meaning that the best mechanical properties are in the direction of the fiber placement.

**Composites are composed of:**

- Epoxy - The primary functions of the resin are to transfer stress between the reinforcing fibers, act as a glue to hold the fibers together, and protect the fibers from mechanical and environmental damage. The most common resins used in the production of FRP grating are polyesters (including orthophthalic-“ortho” and isophthalic-“iso”), vinyl esters and phenolics.
- Reinforcements - The primary function of fibers or reinforcements is to carry load along the length of the fiber to provide strength and stiffness in one direction. Reinforcements can be oriented to provide tailored properties in the direction of the loads imparted on the end product. The largest volume reinforcement is glass fiber.
- Fillers - Fillers are used to improve performance and reduce the cost of a composite by lowering compound cost of the significantly more expensive resin and imparting benefits as shrinkage control, surface smoothness, and crack resistance.
- Additives - Additives and modifier ingredients expand the usefulness of polymers, enhance their processability or extend product durability

The following are major pros and cons of using Composites

**Advantages**

1. Corrosion proof
2. Easy in transportation, can be easily rolled
3. Higher UTS and young’s modulus
4. High fatigue resistance
5. Light weight. Hence, very high strength to weight ratio
6. Joints can be easily avoided as they are available in desired length.

**Disadvantages**

1. Low ductility value and fickly plastic behaviour
2. Susceptible to local unevenness.
3. High cost.

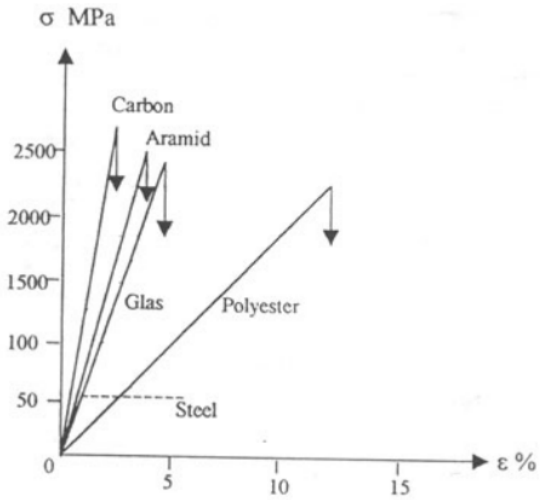


**Fig.1 Comparative strength of different materials**

FRC's can be used in the concrete structures in following forms.

1. Plates- at the face to improve the tension capacity.
2. Laminates- below beams and slabs to improve load taking capacity.
3. Bars- as reinforcements in beams and slabs replacing the steel bars
4. Cables- can be used as tendons and post- tension members in suspension and bridge girders.
5. Wraps- around concrete members i.e. columns, beams, slabs etc for confinement.

## STRENGTHENING BY FRP COMPOSITES

### The concept strengthening of RC Columns by FRP Composites

As concrete is uniaxially compressed due to load, Poisson's effect induces transverse strains that result in radial expansion of the concrete. This increase in transverse strain results in volumetric expansion. By confining the concrete using a continuous FRP jacket, i.e. wrapping of RC columns by high strength-low weight fiber wraps to provide passive confinement, the fibers resist the transverse expansion of the concrete and provide passive confinement which increases both strength and ductility. FRP sheets are wrapped around the columns with fibers oriented perpendicular to the longitudinal axis of column, and are fixed to the column using epoxy resin. The wrap not only provides passive confinement and increases the concrete strength, but also provides significant strength against shear. Since, FRP jacket acts to contain damaged sections of concrete, the maximum usable strain level in the concrete is limited only by the ultimate strain obtainable in the FRP jacket and not by concrete crushing. To increase the effectiveness of wrap, the sharp edges of the rectangular sections must be rounded.

**Design of fiber reinforced strengthening.**

The design of FRP strengthening is performed on the well established principles of mechanics. Most major codes like ACI, CEB-FIP, Euro Code, Japanese code, Swedish bridge code, Chinese Standard, Turkish code etc give guidelines for the design of FRP system for wrapping of concrete columns to increase their capacity. Various institutes like NCHRP, Caltrans, CPWD, etc. recommend the use of FRP Composites for strengthening of concrete structures. For design of strengthening, a composite action is assumed between fiber and existing concrete. The design is based on following assumptions -

- No slip between FRP and Concrete.
- Shear deformation within adhesive layer is neglected.
- Tensile strength of concrete is neglected.
- FRP jacket has a linear elastic stress-strain relationship up to failure.

Fiber wrapping is done on RC members in many different ways

1. Strengthening of junction area by means of L-Wrap:- It is done at the beam- column joint to strengthen the joint.
2. Strengthening the junction area by flat wrap:-
3. Strengthening of the junction area by means of U-Wrap.
4. Column confinement by fully covering the column or beam with fiber wrap.

In actual real life cases a mix of all these techniques is used to attain the designed strengthening requirements.

Confinement effectiveness of externally bonded FRP jackets depends on different parameters namely

- Type of concrete,
- Steel reinforcement,
- FRP jacket stiffness (type of FRP, number of plies and design of wrap),
- Shape of cross section,
- Radius of corners, for non-circular sections, and loading conditions.

Uniaxial compression tests on RC columns confined with CFRP jackets have shown that the increase of ultimate strength is highly influenced and increases with the radius of the corners of square sections. Hence it gives better results for columns with circular cross sections than those with Square/Rectangular cross- sections. For achieving better results in case for effectiveness of FRP confinement with Square/Rectangular cross-sections, the sharp edges are given some curvature to increase FRP wrap more effective.

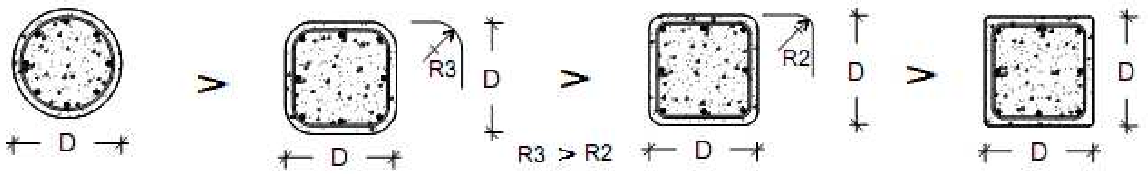


**Fig.2 Cross-section effect on FRP strengthening of columns**

**Methodology for fiber wrapping Beams and columns**

**Grinding and surface preparation**:- for round columns sharp corners are negligible except junctions. For square columns apart from the grinding the plane surface it is also necessary to remove all the sharp corners with grinder and form at least a minimum of 20 mm radius for smooth functioning. For surfaces with unevenness putty is used to make is even.

**Fig.3 Surface grinded and prepared for fiber wrapping**

**Marking and drilling**:- The centre of column width is marked and drilled at points to the depth of 50-60mm to put anchors.

**Primer Coating**:- After making sure that all water has evaporated and moisture is minimal a primer coat is applied to make surface very smooth epoxy application and fiber adhesion. It takes some hours for primer to cure depending on the ambient conditions. It is important to alienate the concrete from the fiber- wrap system so that moisture and other impurities may not affect the process. It also makes the surface very smooth so that the epoxy sticks to the surface nicely and there is no loosening, or layer formation which might make the process less effective.

**Fig.4 Surface Primer applied on the column**

**Epoxy Coating and Wrapping of fiber**:- After Primer coating the surface is perfect for epoxy application. There are two techniques employed for wrapping fiber.

1. The 2- component epoxy adhesive is mixed properly in required proportion and is applied throughout the surface where fiber is to be put. Immediately after epoxy application fiber is wrapped around the column or as per the design proposed. After which a second coat of epoxy is applied.
2. It is also sometimes pre- wetted with epoxy with the help of wet-layup machine and then applied to the surface of application. The fabric is checked again for any air bubbles trapped and roller is rolled over wherever required, which is important as it hampers in functioning of the fiber wrap.

**Fig.5 Cutting and applying of fiber sheet on the column**

**Anchoring and Sand Sprinkling**:- A second coat of epoxy is then applied over which anchors are put into the previously drilled holes so that it holds the ends of fiber wrap and does not allow it to peel off. After which sand sprinkling and a minimum layer of 12mm thickness of polymer modified mortar covering is done. This is done to enhance the life of fiber wrap system. Now the whole system is safe and active.

**Fig.6 Final look of column after plastering**

**Comparison between different types of fibres for use as wraps for strengthening**

Comparison for choosing the best products is necessary. If economical factors are kept aside for some cases, it is found that carbon FRP have a lot of advantages over other types of FRP. This paper aims in presenting the major points which makes Carbon –FRP better solutions for design and execution.

The following are the reasons for Superior properties of Carbon- FRP than that of A-FRP and G-FRP

1. Modulus of elasticity: For the same Fibre Wt., the strength and Modulus of Carbon Fibre Wrap is far more superior to that of Aramid (75% higher) and Glass (150% higher).
2. The Design Strength is considerably higher for carbon than that of aramid and glass fibre wrap. The strains achieved are also lower in case of carbon. This gives a higher Design capacity and range with carbon fibre wraps for strengthening. Below is the graph showing the Design strength vs. the strains developed in wraps of all kinds.
3. At the maximum design strength the modulus of elasticity is higher in Case of carbon than aramid and glass. This shows superior properties in carbon than the other two. This also show that carbon goes to a higher value of both modulus and design strength hence giving a sense of better material property and better design limit for carbon than the other two.
4. The durability with time of Carbon Fibre Wraps is far better than that of Aramid and glass. There are two important points to be considered.
   a. Carbon does not show any loss in tensile strength in rapid Exposure test. Whereas both Aramid and glass loose their strength i.e. 35% and 30% respectively after 10000 hr of rapid exposure which is in principle equivalent to 30 years.
   b. Comparing the rate of deterioration Aramid fibre looses more than 80% of its strength in half of the time, whereas glass fibre deteriorates almost linearly. Showing better functionality of glass than aramid fibres.

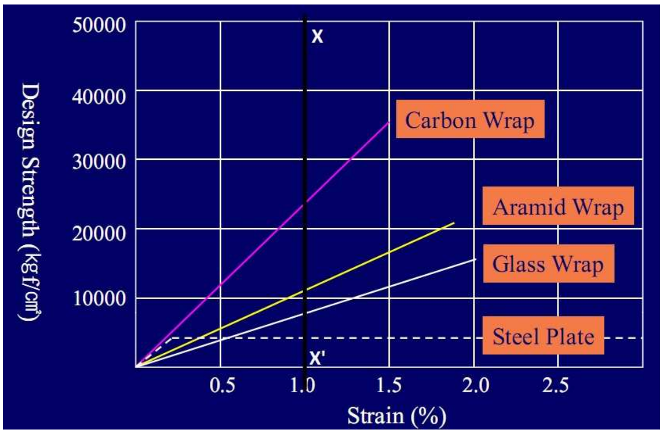


**Fig.7 Graph showing Design Strength vs. Strain Graph for all three Fibre wraps**

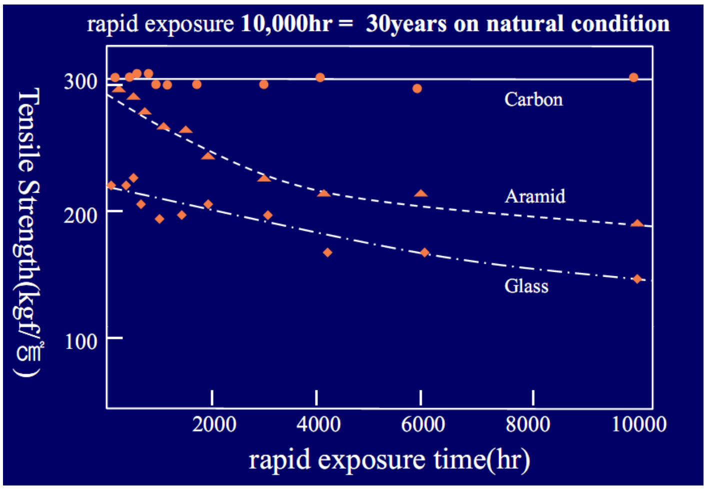


**Fig.8 Graphs showing deterioration with time in rapid exposure test**

5. Comparing the fatigue Characteristics by cyclic loading of the fibre sheets. Again Carbon Fibre shows high performance than both aramid and glass wraps. For the same amount of stress carbon takes fairly high amounts of loading for failure. Fig.9 shows the fatigue characteristics of commercially available Fibre wraps.

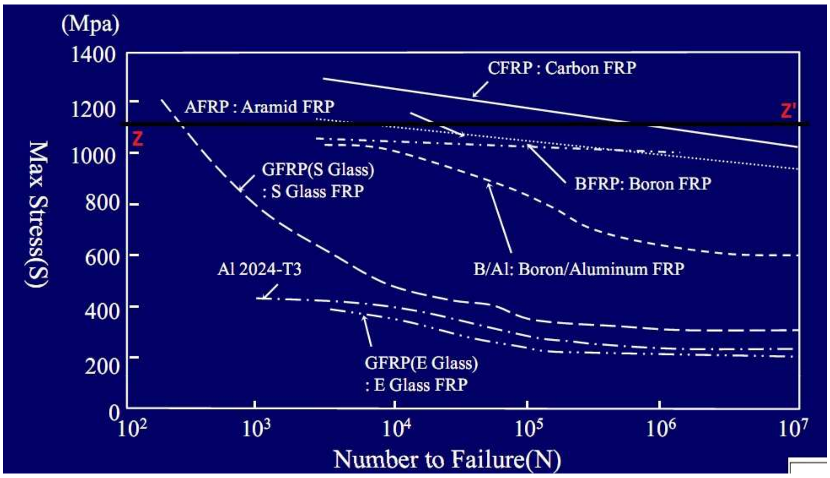


**Fig.9 Graph showing fatigue characteristics of different fibres**

**Strengthening by Carbon Fiber Laminates**

Carbon Fibre laminates can be very effective in strengthening because of their ease for usage and high strength to weight ratio.

Popular method adopted is bonding them adhesively to concrete structures. In this method the laminates are bonded with the structure adhesively so that if any deflection is caused due to extra load on the member it transfers that load on itself.

But this only strengthen the structure passively i.e. becomes active only when some deformation happens. To overcome this, a new technique of pre-stressing these composites before bonding them to concrete surface is employed. It is discussed in next section.

Pre- stressing of concrete is a very effective way of using the high compressive strength property to much greater extend. Moreover, permanent deformations in the structure can be recovered by this technique. This technique of prestressing concrete is possible only in new structures. External prestressing with other materials of the existing structures have always been difficult especially in view of the materials to be used, reinforcement corrosion, lateral instability, end anchorages and of course space constraints. The advantages of resistance to corrosion and high specific strength make these materials ideal for reinforcing existing structures with minimum intrusion. Popular method adopted is bonding them adhesively to concrete structures. However, we can seldom fully use the superior strength properties of these FRC's due to poor capacities of concrete and interfaces formed. Pre-stressing of these materials allow us to better utilization of its properties.

**Fig.10 Slab after strengthening by carbon fibre laminates**

External Pre-Stressing is done in following two ways:

a. Using Fibre reinforced composite Laminates. This includes externally reinforcing beams and slabs from below with laminates giving the members extra flexural and shear strength. The Pre-Stressing gives the members an active upward force even when no live load is given.
b. Column Pre-stressing:- An innovative technique and machinery for retrofitting of columns and joints of a RCC structure have been developed by us. It involves confining of column with Carbon/Epoxy or Aramid/ Epoxy Composite-Belts and Pre-Stressing it, so that it confines the column in stressed position. This is new and exclusive technique which enhances the capability of FRP to confine the columns.

**CASE STUDIES**

**Jawaharlal Nehru Port Trust (JNPT), Navi Mumbai**

JNPT decided to take up the rehabilitation work of the Karal Railway over Bridge (ROB). It got functional in 1991. There are 36 spans of varying lengths having 37 expansion joints in this bridge and the length is 700m. During the heavy rains in July, 2005 the wearing coat and expansion joints were severely damaged. These damaged coats and joints were subsequently repaired and re-laid. But the bridge was still not working satisfactorily. The vibrations of bridge during the vehicle movement were becoming more and more noticeable.

**Fig.11 JNPT Rail over bridge at Karal**

The major observations during the site visit are as follows.

1. Expansion joints were not functioning properly. In the original design there was no provision of appropriate expansion joint.
2. Slab area of expansion joint was found to be damaged severely due to heavy vehicular movement. The gap between two spans has become significant and concrete had deteriorated.
3. The neoprene/elastomeric bearings provided in bridge were inadequate for heavy vehicle movements. They appear to be bulging out and damaged.
4. There was a visible sag in the superstructure in many spans. The typical structural failure cracks in the girders were observed.
5. The new expansion joints could not last long due to excessive vibrations and the poor quality of deck concrete at the end of span.
6. The substructure/piers appeared to be sound.

**Fig.12 Cracks present on the JNPT bridge**

**Fig.13 Distressed slab from below**

In view of above observations it seemed that the structural health of the bridge was not very good. The proposed strengthening measures by the consulting team are as follows.

1. Strengthening of girder by steel truss system-

The girders and slabs are to be strengthened by placing additional steel truss systems which will support the bridge deck/slab/girders with M32 high strength bolts. This was designed to take about 50% of load carrying capacity of girders.

2. Replacement of bearings-
The existing neoprene/elastomeric bearings should be replaced by new elastomeric bearings. Shore-a-hardness hardness of rubber material used should be 60.

3. Provision of new expansion joints-
It was recommended to replace the expansion joints with Wabocrete Strip Seal Expansion Joint System. It is a superior joint system which can be rapidly installed in failed expansion joints and also is suitable for heavy vehicle bridges.

4. Pre-Stressing and Carbon fibre wrapping of girder and slab-
To further increase the structural strength of the bridge, it was recommended to strengthen the bridge using the carbon fibre composite wrapping around the girder and slab. At the bottom of each girder 3 Pre-stressed Carbon Fibre Composites (CFC) laminates i.e. 2- 80/1.4mm and 1- 50/1.4mm was proposed to be placed. The load to be given to prestressed laminates should be 8-9 tons. The deck slab was also recommended to be strengthened by putting CFC laminates 80/1.4 at 50 mm c/c at the bottom. The properties of required laminates and wrap were specified.

**Fig.14 Steel Trusses being fabricated at site**

**Fig.15 Slab Casted at the site over the bridge at the approach**

**Fig.16 Pre-stressing in process and the finished laminate with anchor plates at end**

**Fig.17 Encasing the girders with Carbon Fiber Wrapping**

**Fig.18 Linear Potentiometer's, Accelerometers and Strain Transducers in place for testing under the bridge**

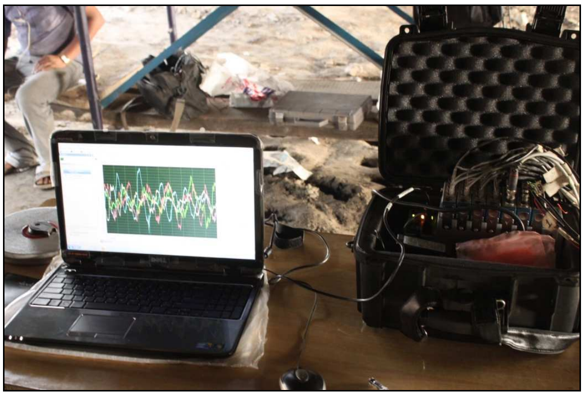

**Fig.19 Data Acquisition System for recording and analyzing testing data**

Tests were conducted before and strengthening for confirming the results of the strengthening process. The initial testing of bridge was conducted which consisted of NO LOAD, STATIC and DYNAMIC LOAD TEST. These were also conducted after the completion of strengthening work. The results showed that the vehicle carrying capabilities of bridge has increased.

Hence the girders were treated with pre-stress technology which gave a back uplift force to girders at a load of 8-9 tons using CFK laminates and high tensioned non corrosive end anchor plates.

After prestressing of laminates, the girders were fully confined with C- Fiber UD-300 & G-Fiber BD-80 as per the specified design for better strength and the ends were locked with fiber anchors to avoid peeling and long lasting.

**Flyover at NH 7, strengthening of over pass Skew Slab**

The two flyovers of around 800m each, originating from National Highway 7, were constructed in record time of 6 months.

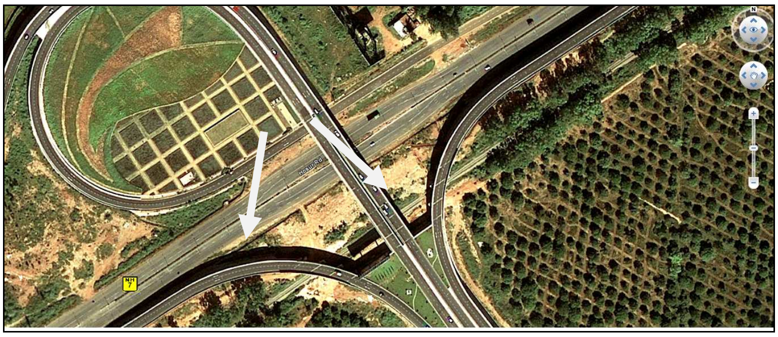

**Fig.20 NH 7 Highway Site**

After a few months, the slab developed sag and on inspection hair cracks were observed. The cracks were inserted with glass pieces to check whether the cracks were live or stable.

After some days it was observed that many glass pieces had fallen down and many have become loose. Hence, it was inferred that the cracks were live and need to be taken care immediately.

The following was proposed as repair and strengthening measures.

For repairing the slab, epoxy grouting with Teflon nozzles was proposed to close the cracks. For strengthening of slab, following two techniques were proposed:

- Full concrete jacketing of the slab by removing the existing loose concrete and encapsulating it with new layer of concrete and reinforcement.
- Strengthening of slabs using CFK laminates with non- pre-stressing and pre-stressing technology according to the design submitted by the consultant.

Finally it was decided to go with CFK laminates using Prestress and Non- prestress technology to rehabilitate the bridge.

a) b) c)

**Fig.21 a) Markings and anchor bolts at place b) Prestressing of Slabs in "Cross-Traffic movement" direction with C-fiber Laminate c) Prestressing in the "Traffic movement" direction**

**Fig.22 Final view of the two Skew Slab of two Bridges**

**Commercial Complex in a SEZ, Navi Mumbai**

This building had beams which were deficient in its shear and flexural capacity for its use as a commercial complex. These beams were strengthened using Carbon Fiber Laminates for flexural enhancement, Glass and carbon fiber wrapping on beams for shear enhancement of these beams.

**Fig.23 D-block of SEZ Commercial complex**

1.Drilling and fixing of Bolts | 2. Laminate laying | 3. Fixing laminate to Adhesive Machine

4. Adhesive Application on laminate | 5. Laminate fixing to the beam | 6. Roller application and Anchor plate fixing.

**Fig.24 Laminate fixing on the beams**

 

a) b)

**Fig.25 a) Fiber Wrapping of beams in progress b) View of beam after fiber wrapping**

**Fig.26 Final view of the building after strengthening of beams by using FRP Wrapping. It is visible on the beams as blue color.**

**Conclusion, Challenges, Technical Issues and Future of FRP**

The main concern with FRP composites is long-term durability because the materials do not have sufficient historical performance data in bridge applications. There is a concern among bridge engineers for the long-term integrity of bonded joints and components under cyclic fatigue loading. There are concerns with improper curing of the resins and moisture absorption and/or ultraviolet light exposure of composites that may affect the strength and stiffness of the structural system. Certain resin systems are found ineffective in the presence of moisture. In the case of a glass fibre composite, moisture absorption may affect the resin and allow the alkali to degrade the fibres.

The high strength, high fatigue resistance, lightweight, and corrosion resistance of composites are highly desirable characteristics for bridge applications. Currently, these new materials are a direct technology transfer from the aerospace industry, and they are far more advanced than those required by civil applications. Most of the advanced composite materials that are cured at high temperature produce high quality components and possess excellent characteristics. In bridge applications, resins as the binders for the fibre and adhesives for joints and connections that can adequately cure at ambient temperature and still offer comparable quality and characteristics are more desirable and practical. More research is needed to develop the most effective and durable resin formulations. More efficient manufacturing and effective production methods for large volume panels and higher modulus materials are needed to make it more cost effective for composites to compete in the civil infrastructure. At the present time, the direct use of fibre composites from the aerospace industry is not cost effective as compared to conventional materials in bridge applications.

If the cost constraint is kept aside, the fiber wrapping system has been proved to be a system which has many added advantages over conventional strengthening processes. It has been proved in laboratory as well in real civil projects that this system is effective and is useful in real life. As the economy is moving ahead and infrastructure development is catching its pace, demand for fiber reinforced polymer in civil construction is slowly increasing and becoming acceptable.

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