FRP STRENGTHENING OF CONCRETE STRUCTURES – DESIGN AND PRACTICAL EMPHASIS IN SRI LANKA

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Abstract: FRP Strengthening has been developed worldwide as a mean of strengthening and retrofitting concrete structures throughout past few decades. The ever increasing loads on structures and change of use demands higher load carrying capacities. The use of FRP strengthening methods has enabled the use of existing structures thus saving millions, valuable material and valuable time will otherwise be spending on demolition and reconstruction. However lack of design guidance has been a critical issue in this area. The authors have carried-out a design and implementation of FRP strengthening of an existing two storey building to accommodate two more floors and a light weight roof. This paper discusses the design method, testing carried out and practical implications in FRP strengthening of concrete columns.

Keywords: FRP, Strengthening

1. Introduction

The strengthening of reinforced concrete structures is a topic of ever increasing popularity. The change of use of the structures, load increment and bad design and construction practices require remedial measures. The use of Fibre Reinforced Polymers (FRP) to strengthen the concrete structures is rapidly gaining appeal under these circumstances.

FRP has many advantages over conventional strengthening methods such as light weight, high strength-to-weight ratio, ease of handling and application, lack of requirement for heavy lifting and handling equipment and corrosion resistance, etc. The lack of design guidance and standards can be stated as the major problem encountered by practicing engineers using FRP to strengthen the structures.

The case study, noted in this paper discusses the method of testing used to identify the increment of the load carrying capacity of the FRP bonded concrete elements and how the design and construction was carried out.

2. Types & Properties of FRP

The main types used are carbon (CFRP), glass (GFRP) and aramid (AFRP). The typical properties of the FRP materials are given in the Table 1.

Table1: Typical FRP Properties[1]

	Elastic Modulus (GPa)	Ultimate Strain (%)	Ultimate Tensile Strength (MPa)
CFRP (laminate)	165 - 215	1.3 - 1.4	2500 - 3000
CFRP (sheet)	240 - 640	0.6 - 1.6	2650 - 3800
GFRP (sheet)	65 - 75	4.3 - 4.5	2400
AFRP (sheet)	120	2.5	2900

The governing factor for the design of FRP is the allowable strain at the ultimate limit state. It can be seen from the Table 1 that the strain capacity is ranging from 0.6% to 4.5% and thus it is of great importance for the design to select correct material to the correct application.

The CFRP can be stated as the best option in terms of durability and capacity while it is the most expensive material. In usual practice CFRP sheets are used for shear and axial strengthening while CFRP laminates are used for flexural strengthening.

3. Constituent Materials

There are several constituent materials used with FRP fibres available commercially such as resins, primers putties, saturants and adhesives.

It is necessary for those constituent materials to have the following characteristics;

- Compatibility and adhesion to concrete substrate and FRP composite system.
- Resistance to environmental effects.
- Filling ability.
- Pot life consistent with the application.
- Workability.
- Development of appropriate mechanical properties for the FRP composite.

4. Design Considerations

As FRP strengthening is a fairly new system compared to conventional systems, design guidance is lacking. In fact no country has yet developed a design code for FRP composite systems. However there are several national guidelines available for this and what is concentrated in this paper is ACI 440.2R-02: Guide for the Design and Strengthening of Externally Bonded FRP Systems for Strengthening Concrete Structures.

The design method is based on limit state philosophy in compliance with most of the design codes used. In limit state design, the variability in material properties is taken into account by assuming a characteristic strength. Characteristic strength usually is taken as the value below which not more than 5% of test results. A similar approach is used to define characteristic strength of FRP, but the acceptable failure rate may be reduced to 1%.(2)

The ACI 440.2R-02 recommends a limit for the strengthening. These limits are imposed to guard against collapse of the structure should bond or other failure of the FRP system occur due to fire, vandalism or other causes.
The ACI committee recommends that the existing strength of the structure be sufficient to resist a level of load as described by Equation (1). (3)

$$(\varphi R_n)_{existing} \geq (1.25 S_{DL} + 0.85 S_{LL})_{new} \qquad (1)$$

φ – Strength reduction factor
R_n – Nominal strength of a member
S_{DL} – Dead load effects
S_{LL} – Live load effects

The FRP composite system for flexure is designed so that the ultimate strain at the extreme concrete compression fibre is 0.003.

In practical applications prior to and during strengthening, self weight and part of live load of the structure is likely to exist. Therefore the effect of the pre loading has to be considered in the structural analysis and strengthening of the member. The effect of pre-loading is significant and detrimental if the element fails by concrete crushing and should be investigated in the design calculations. As the service moment is typically larger than the cracking moment, the calculation will be based on a cracked section.

A strength reduction factor for the flexural contribution of FRP alone, i.e. $\psi_f = 0.85$, is used in calculation of flexural strength of the composite section. Apart from this an overall strength reduction factor of $\varphi = 0.8$ is used to account for possible slip between FRP membrane and the concrete surface.

Several failure modes under flexure are identified by ACI 440.2R-02, and limitations to prevent these are given in the report itself. To name a few, limiting the concrete strain, limiting the stress and strain levels in FRP and limiting the number of FRP layers used can be noted. Service stress for the steel reinforcement used are limited to a value of $0.8f_y$ while the service stress of the FRP laminates are limited to $0.20f_{fu}$,$0.30f_{fu}$ and $0.55f_{fu}$ for GFRP, AFRP and CFRP respectively where f_{fu} is design ultimate tensile strength of FRP. The service stresses are obtained using cracked section properties and the method is described in ACI 440.2R-02.
The shear strengthening is carried-out using FRP sheets by wrapping the element partially or fully. A strength reduction factor of ψ_f is used for the shear strength enhancement from FRP alone and $\psi_f = 0.85$ is used for partially wrapped sections while $\psi_f = 0.95$ is used for fully wrapped sections. Overall strength reduction factor of φ= 0.8 is also used.

The axial strengthening is also done using FRP sheet wrapping. The FRP sheets, through axial tension stresses, confine the lateral expansion of the axially loaded member thus enhancing the axial loading capacity. These stresses are shown in Figure 1.

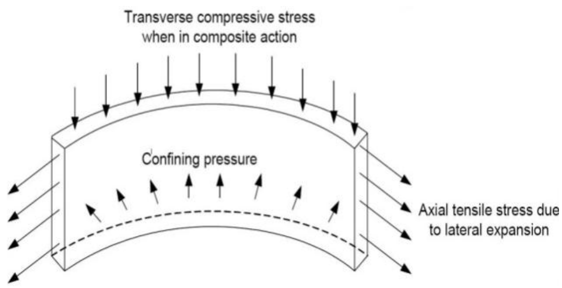

Figure 1: Triaxial State of Stress in FRP

The axial strengthening is more or less used for compression members where the use of confinement can be used. However this can also be used for tensile strengthening provided that stresses can be transferred to the substrate from FRP satisfactorily. (2)

The calculation of strength enhancement is based on a modified compressive strength of the confined concrete. This apparent compressive strength depends on an efficiency factor, κ_a. This efficiency factor is based on the geometry of the structure. Efficiency factor is 1.0 for circular sections and reduces drastically for rectangular sections with the increase of aspect ratio. Efficiency factor also depends on the radius of the edge chamfer of a rectangular section. This chamfering is of great importance to the increment of load carrying capacity as if not done properly stresses can be concentrated at the edges of the section thus reducing the area of concrete effectively confined.

5. Case Study

An FRP strengthening was carried-out under the supervision of Design Consortium Limited for the Proposed Queensway Building Project at R A De Mel Road, Colombo 03.
The building was a two story building with one basement and the client required to add two additional floors. The existing building which was 30 years old needed to check the suitability of carrying the additional load. The structural evaluation revealed that, five ground floor to first floor columns were required strengthen to carry the additional load. Due to the restrictions to the column sizes imposed by the intended use of first floor, it was not possible to increase the size of the column to accommodate excess load carrying capacity. Thus it was decided to use FRP to strengthen the columns.

The flexural capacity was increased using MBrace CFK 150/2000 carbon fibre laminates and axial capacity was increased using MBrace CF 240 430gsm carbon fibre sheets.

Prior to carrying out the strengthening, it was important to find out the actual increment of load carrying capacity through testing. 15 number of 150mm diameter; 300mm high standard cylinders were cast to carry out the testing to evaluate the performance of the FRPs. The test samples were categorized as follows;

- 3 reference cylinders
- 3 cylinders with a single CFRP sheet
- 4 cylinders with two CFRP sheets
- 5 cylinders with two CFRP sheets and 3 CFRP laminates (combine wrap)

The testing was carried out in the laboratories of Department of Civil Engineering, University of Moratuwa. The outcome is shown graphically in Figure 2.

On average, the capacity was enhanced by 32.6%, 82.3% and 73.9% for single wrap, double wrap and combine wrap respectively.

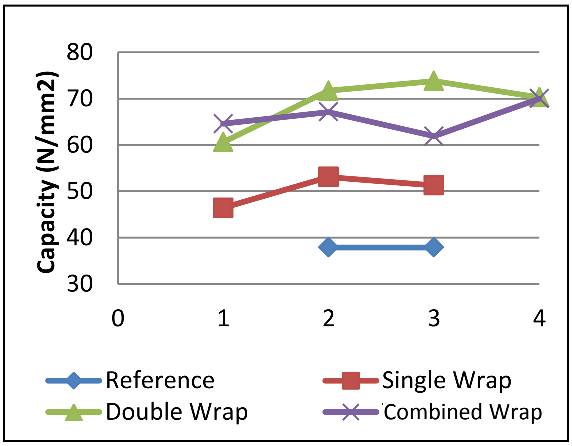

Figure 2: Test Results

The reduction of strength in the combine wrap with respect to the double wrap could be due to the poor bonding of FRP sheets in the total wrap due to FRP laminates which makes the section to deviate from its original circular shape irrespective of the epoxy filling around the laminates.

The Figure 3 shows the failure pattern of a test specimen.

Figure 3: Failure Mode

The failure occurred by splitting of FRP jacket and even after the failure the concrete substrate was attached to the FRP jacket which implied the capability of epoxy resin to make FRP and concrete to act as a composite material. Further it was evident that the resin is capable of keeping layers of FRP jackets together as the failure was due to splitting of FRP jacket as opposed to the de-lamination of FRP sheets. The failure however was a brittle failure in nature and gave no initial warnings before failure occur.

The strength increments of actual columns were significantly lower basically due to the shape and aspect ratio. Two CFRP laminates were used on each face of the column and two CFRP sheets were wrapped around the entire length of the column. The flexural capacity increment was quite significant with 54% while the compressive capacity increment was only a mere 6.6%. This increment was achieved with a corner chamfer of 30mm radius.

One of the practical problems encountered was to get the corner chamfer. As the building was 30 years old, the concrete could not be handled with ease thus the concrete surface was rectified with an epoxy putty to get the corner chamfer and to make the substrate to a suitable condition to apply FRP materials. A primer was applied to the prepared surface and the FRP laminates were applied using an epoxy adhesive. It was required to provide temporary supports to the FRP laminates until the adhesives hardened. As the site was situated adjacent to a congested road, it was very important to take special precautions to prevent dust mixing with the saturant. This was done by temporarily covering the area surrounding the column while providing enough working space.

The substrate was then filled with epoxy putty again to make an even surface. The epoxy resin (saturant) was used to apply the CFRP sheets to the substrate. An overlap of 150mm in the circumferential direction was provided to the CFRP sheet while an overlap of 25mm was provided in the longitudinal direction. An intermediate step in application is shown in Figure 4.

As the purpose of the CFRP sheet was to confine the concrete, it is very importance to make sure there are no air bubbles between the substrate and the sheet. This was achieved by using a rubber roller during the application of CFRP sheets. However it should be noted that the rolling should only be done in one direction as otherwise the fibres in the sheet might be damaged.

Figure 4: Application of CFRP Sheets

Due to hot climatic conditions and inadequate skills of labourers, primers and resins were hardened prematurely and wasted. However this problem was quickly arrested with labourers gaining experience. The primers and resins were mixed in halves and in smaller containers to avoid the premature hardening. The smaller containers meant smaller contact area and smaller amount meant the application can be done quickly.

Finally on top of final saturant coating is applied, sand was sprayed in order to provide with the required key to subsequent plastering. The finished column is shown in Figure 5.

Figure 5: Finished Column before applying plaster

A part of the connecting beams were also strengthened to maintain the continuity as shown in Figure 5.

After strengthening was carried out, a certain portion of a column was found to be delaminated from the CFRP sheets. It was rectified removing the entire section of the rapping and reapplying the sheets as per the previously noted method.

6. Conclusions

As it is important to increase the load carrying capacity of the existing structures to match the increasing loads, the use of FRP is a convenient option. It is believed that FRP is now going through the same process as pre-stressed concrete in 60's and 70's. Thus it is important to recognize this rapidly growing technology.

By the testing carried out, it was evident that there is a significant increase in the increment of load. However it is important to identify understand the uniqueness of the martial and its applications as the installation procedure play a vital role on the amount of increment in the capacity. In the Sri Lankan context, it is required to look at the prevailing climatic conditions and local conditions prior to application to make sure the strengthening is done with minimum losses and maximum gains.

7. References

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