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Carbon Fiber: The Future of Building Materials

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Abstract: ***The need for rehabilitation, repair and strengthening of concrete structure has increased worldwide with a growing number of systems employing concrete jacketing, various retrofitting techniques, externally applied fiber-reinforced polymer (FRP) composites, etc. For applications of structures, an overview of different FRP composites is provided by various polymer composites and in civil structures FRP composites are used for reinstatement or firming up the elemental constituent. In our project we have examined the ability of a woven carbon fiber reinforced fabric wrapping to enhance the strength of various building components. For this purpose few concrete cubes were casted and were carbon wrapped to check the increase in strength. The strengths of cubes with carbon fiber wrapping and without carbon fiber wrapping were compared and the results were observed to have increased in strength for the carbon fiber wrapped cubes. Along with these cubes a column at a building site was also examined whose compressive strength was found to be less than design strength. Non – destructive test of Rebound Hammer was conducted on this column and later it was wrapped with carbon fiber fabric to increase its strength. Also, the expenses of both the methods i.e. concrete jacketing and carbon fiber wrapping were compared and the carbon fiber wrapping was found to be economic than the other method. In both cases the strength was found to be increased than the initial strength. Hence, the carbon fiber was found to be effective both***

Keywords: Carbon Fibre, Carbon Fibre Reinforced Fabric, Strengthening of members

1. Introduction

A large number of existing reinforced concrete (RC) infrastructure in developed countries including bridges, municipal buildings, transportation systems and parking facilities are suffering from distress due to overuse or inadequate maintenance. Demolition and building a new structure is very costly and time consuming. Structural strengthening is more economical solution and hence frequently required to extend the functional service lives of deficient RC structures. Reinforced concrete and grout-injected steel jacketing systems are the most common methods developed in past to upgrade RC columns. Although both methods are effective in increasing the structural capacity, they are labor consuming and sometimes difficult to implement on site. In addition, the RC jacketing system would result in substantial increase in the column's cross-section. A steel jacketing system is often heavy and performs poorly in resisting adverse environmental conditions. Hence, an innovative, durable, easy-to-install and cost effective strengthening system is required to replace outdated techniques.

Carbon fiber fabric has emerged as promising alternative strengthening material for upgrading deficient RC infrastructure. This fabric can be easily wrapped around the column's cross-section with a high-strength adhesive to provide a confining. "Carbon fiber and other composite materials are highly per formative; they have a very small weight but can take enormous loads, because carbon fiber has such unique properties, which makes it an ideal building material. Composites represent a very interesting opportunity for rapid fabrication and customization; it would take just weeks to build the enclosure for a small house out of carbon fiber, versus months with conventional materials. Composite structures can be erected rather quickly and do not require much in terms of specialized labor and work flows from general contractors and subcontractors, to material supplies, for example. We can therefore go faster, the delivery chain is shorter, the amount of material is reduced, and it's less expensive."

Thanks to its flexibility and light weight, carbon fiber can be easily moved. Modules can be picked up, taken elsewhere, and chained together to produce larger assemblies as needed, that makes composite structures far more flexible than traditional buildings, where there's an assumption of permanence that is not always a good thing." says Architect Simon Kim, principal at Ibañez Kim, an architecture and design firm in Cambridge, Massachusetts.

1.1 Carbon Fiber

Carbon fibers are fibers about 5–10 micrometers in diameter and composed mostly of carbon atoms. Carbon fibers have several advantages including high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion. These properties have made carbon fiber very popular in aerospace, civil engineering, military, and motorsports, along with other competition sports.

To produce a carbon fiber, the carbon atoms are bonded together in crystals that are more or less aligned parallel to the long axis of the fiber as the crystal alignment gives the fiber high strength-to-volume ratio (making it strong for its size). Several thousand carbon fibers are bundled together to form a tow, which may be used by itself or woven into a fabric.

1.2. Problem Statement

The problem with steel jacketing and retrofitting is that it is a time consuming process and also incurs huge costs, whereas, the use of externally bonded FRP composites for repair can be a cost-effective alternative for restoring or upgrading the performance of existing concrete columns. However, previously the CFRP confining procedures and models were developed for circular columns and could not be used in the case of rectangular columns. Our research aims to enhance the limited data on rectangular columns retrofitted by FRP wrap and also to provide an insight into the behavior of rectangular columns confined with an FRP jacket.

1.3 Objectives

a) To study the life cycle of carbon fibers for light weight engineering Structures.
b) To study the behavior of various types of carbon fiber sheets, carbon fiber reinforced polymers, carbon fiber strands, etc. that can be used for various Civil Engineering works and problems..
c) To study the strengthening of axially and eccentrically loaded Reinforced Concrete Columns with Carbon Fiber Reinforced Polymer wrapping Systems.

2. Methodology

2.1 Research Methodology

In our research we, firstly studied the different properties of carbon fiber an how is it manufactured, the faults that might be generated while the manufacturing of carbon fiber that may lead to failure in its characteristics and results in the carbon fiber being week. Carbon fiber and other composite materials are highly per formative; they have a very small weight but can take enormous loads, because carbon fiber has such unique properties, which makes it an ideal building material.

2.2 Our Approach to the Material

We found that the carbon fibers applications are very large in the automobile industry, in the aerospace industry but very less development so far has been there in the construction industry, so we researched and found out about retrofitting with carbon fiber reinforced fabric to columns and beams, to increase their strength and load carrying capacity. For this we approached many of our faculties regarding the same topic and we were lucky enough that there was a site in Vani, Nashik, Maharashtra whose columns failed due to lack of care after the construction and were needed to be retrofitted.

So, instead of regular retrofitting with steel jackets or with concrete retrofitting, we suggested a solution for Carbon wrapping of the failed columns in the building. And then we went to Vani, for recording the failure of the columns.

We conducted a Non-Destructive Testing on the columns using a rebound hammer and recorded the failure of the columns. The site in-charge over there was generous enough to permit us to wrap a column using Carbon Fiber Reinforced Fabric.

Figure 3.3: Building whose columns failed

After testing the columns using Rebound hammer, we found that most of the columns failed and were having compressive strength less than 20N/mm^2. There were a few columns whose compressive strength even came out to be less than 10N/mm^2, and required urgent retrofitting.

Following is the tabular data of the rebound hammer test that we conducted on the columns.

3. Test Report for NDT

A) Rebound Hammer Test

Rebound Hammer Test	Date of Testing	12/ 09/2018
Executed for Client		
Site Address	Vani, Nashik, Maharashtra.	
Structure	R.C.C. Framed Structure.	
Instrument Details	Schmidt's Rebound Hammer.	
Code of Reference	IS13311 Part (1) : 1992, BS1881 : Part 203 : 1986	

Table1: Rebound Hammer Test Results on Failed Columns for Ground Floor.

Sr. No	Member	Rebound Number							Avg.Char. Comp. Strength. (MPA)
	Ground Floor	1	2	3	4	5	6	Avg.	
1	Column C1	22	19	26	24	26	21	23	14
2	Column C2	24	24	20	26	26	-	24	16
3	Column C3	20	18	18	21	23	22	20.33	10.5
4	Column C4	19	19	24	20	16	18	19.33	*fail*
5	Column C5	26	22	24	24	24	-	24	16
6	Column C6	24	24	22	25	20	-	21.8	12
7	Column C7	37	33	34	34	36	36	31.5	28
8	Column C8	27	25	26	26	28	28	26.67	19.5
9	**Column C9**	**18**	**14**	**18**	**19**	**15**	**14**	**16.33**	***Fail (less than 10)***
10	Column C9(A)	20	20	28	22	24	28	23.67	15.5
11	Column C10	29	35	28	30	30	28	29	24
12	Column C10(A)	22	21	25	25	26	26	24.2	16
13	Column C11	27	31	28	31	28	26	28.5	25
14	Column C11(A)	28	29	30	18	24	28	26.2	19
15	Column C12	28	27	26	24	31	28	27.33	20.5
16	Column C12(A)	26	26	25	24	23	29	25.5	18
17	Column C13	26	24	28	27	24	26	25.83	18.5
18	Column C13(A)	26	26	27	26	28	-	26.6	19.5
19	Column C14	28	26	24	24	25	-	25.4	18
20	Column C14(A)	26	23	24	28	24	26	25.2	17.5
21	Column C15	33	34	36	40	32	-	35	34
22	Column C15(A)	32	34	30	32	32	28	31.33	27.5
23	Column C16	24	24	22	22	26	24	23.67	15.5
24	Column C16(A)	32	30	32	28	26	32	28.33	22
25	Column C17	20	18	16	17	16	12	16.5	*Fail*
26	Column C18	23	18	24	26	25	23	23.2	14.5
27	Column C24	22	20	18	24	22	21	21.2	11.5
28	Column C25	27	26	24	28	24	30	26.5	19
29	Column C26	23	26	23	20	19	27	23	14
30	Column C31	25	22	20	18	25	22	22	13
31	Column C32	21	22	18	22	24	19	21	11

Table 1: Rebound Hammer Test Results on Failed Columns for First Floor

Sr. No	Member	Rebound Number							Avg.Char. Comp. Strength. (MPA)
	First Floor	1	2	3	4	5	6	Avg.	
1	Column C1	22	20	23	24	20	21	21.67	11.5
2	Column C2	28	24	23	25	23	20	23.83	15.5
3	Column C3	22	20	20	20	20	26	21.33	11
4	Column C4	22	26	26	24	24	-	24.4	16.5
5	Column C5	24	23	20	21	22	23	22.2	13.5
6	Column C6	26	25	24	23	24	21	23.83	15.5
7	Column C7	31	30	30	28	30	-	29.8	24.5
8	Column C8	28	26	27	26	24	-	26.2	19
9	Column C9	29	25	24	22	26	28	25.67	18
11	Column C10	30	28	29	30	30	32	29.83	24.5
13	Column C11	24	26	26	26	25	24	25.2	17.5
15	Column C12	28	24	23	26	27	23	25.2	17.5
17	Column C13	23	20	22	19	22	17	20.5	11
19	Column C14	22	23	24	25	25	24	23.83	15.5
21	Column C15	24	26	25	26	25	26	25.33	17.5
23	Column C16	34	28	28	25	30	28	28.83	23
25	Column C17	30	29	28	29	-	-	29	*24*
26	Column C18	26	25	24	28	26	25	25.67	18
27	Column C19	32	33	32	30	28	27	30.33	25.5
28	Column C20	26	22	24	20	20	22	22.33	13
29	Column C21	20	24	27	23	20	25	23.2	14.5
30	Column C22	19	18	22	17	20	19	19.2	*Fail*
31	Column C23	24	21	17	22	22	22	21.33	11
32	Column C24	20	20	20	20	20	22	20.33	10.5
33	Column C25	16	20	19	21	-	-	19	*Fail*
34	Column C26	22	22	24	20	26	23	22.83	13.5
35	Column C27	23	22	22	26	23	22	23	14
36	Column C28	21	20	19	23	20	22	20.67	10.5
37	Column C30	23	26	30	26	24	24	25.5	18
38	Column C31	24	30	28	28	26	-	27.2	20.5
39	Column C32	20	18	22	22	20	18	20	10
40	Column C33	18	16	18	14	18	14	16.33	*Fail*
41	Column C34	14	13	14	13	16	13	13.83	*Fail*
42	Column C35	17	16	17	17	17	15	16.5	*Fail*
43	Column C36	22	22	24	22	24	25	23.2	14.5
44	Column C37	26	25	24	20	18	19	22	13
45	Column C38	24	23	24	22	23	21	22.83	13.5
46	Beam B47	28	28	32	28	30	-	30.83	26
47	Beam B56	39	30	38	32	34	40	35.5	35
48	Beam B66	22	26	26	30	28	32	27.33	21
49	Slab S5	41	39	44	38	42	37	40.2	35
50	Slab S10	44	48	44	45	43	40	44	42
51	Slab S12	42	38	38	38	46	34	39.33	33

3.1 Expected Outcomes

1) Carbon fiber, being the material mostly used in engineering fields such as Automobile and aerospace engineering, or in sports sector, etc. would have increased applications in Civil engineering industry as well.
2) Steel Retrofitting and Reinforced Concrete Retrofitting might get an Economically stable alternative.
3) Till now only structures made of steel were seen, our research might be a starting step to the start of an era with carbon fiber r/f structures or Carbon fiber Structures.
4) An alternative to steel might get available soon with less space occupancy and much greater strength.

4. Research Elaborations

4.1 Experimental Program

Test Specimen - Concrete Cubes

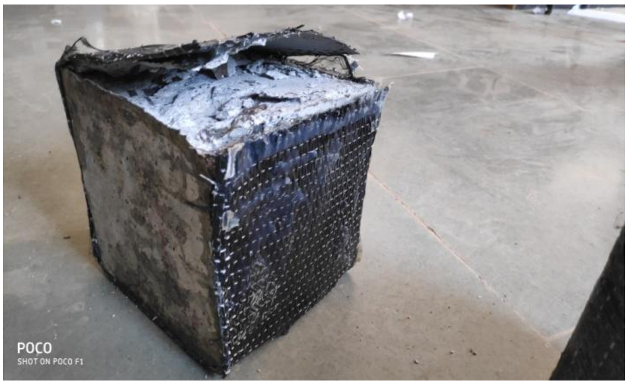
The test specimens were six square concrete cubes of M20 grade of size 15cm x 15cm x 15cm. Proper curing of 7 days for three cubes and 28 days for another three cubes was done. Later on compressive tests were carried out on these cubes using standard compression testing machine until the first crack appeared. The cubes were then wrapped with the carbon fiber fabric of 300 GSM 12k unidirectional. After wrapping the increase in the size of the cubes was negligible. For wrapping purpose the araldite solution was used. The araldite and hardener were mixed in the suitable proportion and applied on the surface of the cubes with the help of spatula. Immediately after applying the solution on four sides of the cube the carbon fiber fabric was applied and another coat of the araldite solution was applied over the fabric. The cubes were then allowed to dry and strengthen for two days and again the same compression test was carried out on the cubes. The test matrix is given in table no. 1 and 2. The parameters included in the test were specimen, compressive strength.

Table 1: Strength before carbon wrap

7th day reading		28th day reading	
Specimen	Compressive strength (KN/m^2)	Specimen	Compressive strength (MPa)
Cube 1	20.06	Cube 1	27.09
Cube 2	19.10	Cube 2	29.31
Cube 3	15.18	Cube 3	25.12
Cube 4	18.69	Cube 4	28.54
Cube 5	19.27	Cube 5	28.59
Cube 6	22.27	Cube 6	29.94
Cube 7	21.29	Cube 7	28.46
Cube 8	17.70	Cube 8	31.60
Cube 9	18.34	Cube 9	29.76

Table 2: Strength after carbon wrap

7th day reading		28th day reading	
Specimen	Compressive strength (MPa)	Specimen	Compressive strength (MPa)
Cube 1	19.64	Cube 1	19.36
Cube 2	17.18	Cube 2	37.78
Cube 3	23.86	Cube 3	48.02
	21.70		36.06
	22.74		32.14
	25.30		38.71
	19.56		35.23
	18.28		31.59
	17.83		28.90



4.2 Column of the Building

A building was found in Vani, a village near Nashik city. It is a government building built about four years ago which components failed due to inadequate maintenance. Non-destructive test was carried out on all the columns, beams and slab. A column which was completely failed was selected for carbon fiber wrapping. The selected column was wrapped with carbon fiber fabric and was allowed to dry and gain strength for 2 days. After 2 days the non-destructive test was performed again and the readings were recorded as follows-

Table 3: Readings before carbon wrap

Column No.	Rebound Number.						Average	Result
	1	2	3	4	5	6		
C9	18	14	18	19	15	14	16.33	Less than 10 MPa (Fail)

Table 3: Readings after carbon wrap

	No.	Face 1	Face 2	Face 3	Face 4	Average	Average Rebound No.	Compressive Strength (KN/mm2)
Rebound Numbers	1.	28	26	34	30	29.5	30.33	25.45
	2.	36	34	34	32	34		
	3.	26	26	28	28	27		
	4.	30	28	28	28	28.5		
	5.	28	24	26	26	26.5		
	6.	38	30	38	40	36.5		

Material Properties
Weight – 300 g/sqm
Thickness – 0.167 mm
Density – 1.8 g/cm3
Packing – 100 m/roll
Width – 100 mm, 200 mm, 300 mm, 500 mm or to be customized

4.3 Carbon Fiber Reinforced Fabric (CFRF) Wrapping System

Full wrapping system is used in the resent study. For full wrapping scheme, one layer of continuous CFRF laminate was wrapped around the column's section in the test region with fibers oriented in longitudinal direction along the loading axis of the column. To avoid premature failure of at the ends of the test region, the strip width was increased to 125mm at each end. The CFRF laminates had an overlap of 50mm in transverse direction.

The CFRP wrapping included surface preparation and CFRF application. The concrete surface was ground to remove any dust and loose particles from the concrete surface. The epoxy resin was them applied directly onto the prepared surface using trowels. The CFRF fabrics, precut in desired dimensions, were then placed onto the resin coating and smoothen out with gloved hands. Adequate pressure was applied until the resin was squeezed out between the fabric's ravings. A final sealer coat of resin was then applied onto the exposed surface.

The carbon fiber reinforced fabric takes almost forty-eight hours to gain complete strength. After a period of twenty-four hours from applying the fabric to the column, we visited the site and again applied a layer of sealer coat on the wrapped column. Then after a period of forty-eight hours, NDT test using a Schmidt's Rebound Hammer were conducted on the same wrapped column. A total of six readings on each of the four surfaces at different location on the column were taken. The readings showed a significant increased value of strength in columns after the carbon wrapping.

5. Results and Conclusion

The construction industry is ever lasting and ever expanding without any break. The need of shelter, buildings, roads, airports, etc. is never ending. In the same way renovation, innovation and creation of new techniques, new infrastructure is also continuous. There is a constant need of correction, rebuilding, improvement in all kinds of structure.

So as to cope up with this need, we have tried to implement another new, innovative and easy method to correct and rectify the failed structures or those in need of renovation.

During our testing we observed that the loading patterns and the direction of the woven fiber plays an important role in the strength results of the Carbon fiber reinforced Fabric. The fabric gives out more strength if it is applied with its fibers longitudinal to the axis of loading of the member.

During the testing of the cubes, it was observed that if the cubes were loaded in the direction perpendicular to the fibers, the carbon fiber reinforced fabric failed to give strength, as in the case of the following cubes.

Table 5.1: Readings of Cube that were tested in direction perpendicular to that of the fibers; before and after carbon wrap

Description	Cubes	Compressive Strength without Carbon Fiber Fabric Wrapping.(KN/m^2)	Compressive Strength with Carbon Fiber Fabric Wrapping.(KN/m^2)
7 Days.	Cube 1	20.06	19.64
	Cube 2	19.10	17.18
	Cube 7	21.29	19.56
	Cube 9	18.34	17.83
28 Days.	Cube 1	27.09	19.36
	Cube 8	31.60	31.59
	Cube 9	29.76	28.90

We have found very amazing results with very less efforts. In comparison with other methods like steel-concrete jacketing and retrofitting, Carbon Fiber Fabric Wrapping has proven to be better in almost all the aspects. As stated earlier, Carbon Fiber Reinforced Fabric has several advantages over conventional methods of retrofitting, like:

1) Thickness of the repaired member does not increase.
2) Initial Cost required is less comparatively.
3) No skilled labor is required.
4) Time required for carbon fiber reinforced fabric wrapping is less.
5) Handling of the material is easier, etc.

Based on the experiments and tests conducted and mentioned above, it can be inferred that the carbon fiber material increased the strength of the specimens effectively.

6. Comparative Study

Carbon Fiber Reinforced Fabric has the following advantages over the conventional Reinforced Cement Concrete Jacketing:

	CARBON FIBER REINFORCED FABRIC	REINFORCED CEMENT CONCRETE JACKETING
Initial Cost.	The initial cost or the cost of wrapping the column required for the carbon fiber fabric used by us i.e. 300 GSM, Unidirectional woven Carbon fiber fabric as compared was less. The following rates as applicable real time were quoted by us for unit column, Total Surface Area of Column: 3.333m^2 Rate of Carbon Fiber Fabric: Rs. 1200 per m^2 Cost of Fabric Required : Rs. 4000/- Cost of Resin and	The Initial Cost required for Reinforced Cement Concrete Jacketing as the quote given by the contractor on the site is comparatively more. The price breakdown is as follows. Total cost required for the material of one column: Rs. 2800/- Scaffolding Rate: Rs 450/- Labor required: 2@400/day: Rs. 800. Bar-bender: Rs. 600/day. Cement Grouter: Rs.

	Hardener: Rs 700/Kg. required. Labor required: 2 @400/day: Rs. 800/day. Total Cost required for one Column: Rs. 4900/-	500/day. Thus, Total cost required by one column for Reinforced Cement Concrete: Rs. 5150/-
Thickness.	Negligible increase in thickness is seen in this method as only two layers of resin and hardener are applied as well the thickness of the Carbon Fiber Reinforced Fabric is also less. Approximately 2-3 mm increase in thickness is observed.	Reinforced Cement Concrete Jacketing consists of jacketing the column with further steel Reinforcement and concreting. This increases the column size many folds thus reducing the usable area in buildings.
Labor Required.	No Skilled Labor is required as it consists only of applying layer of resin and hardener using a spatula and applying the fabric over it and sticking it, to the surface of the failed column.	Skilled labor is required in this case for bar bending, erecting formwork, cement grouting, etc.
Time	Time required by this technique is less as compared. After applying the sealing layer of the epoxy hardener, approximately only 48 hours time is required for the material and the member to gain strength.	Time required in this case is more. As drilling of holes, erecting of formwork, concreting, etc and then the curing of concrete to attain its strength requires more time and efforts.
Handling	Due to light weight of the Carbon Fiber Reinforced Fabric, it is easier to handle. Being a fabric, its application to the member is also effortless.	As mentioned earlier Skilled labor is required, this, in turn, makes the handling and completion difficult.

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