Investigation of Corrosion Damage and Repair System to Strengthen the Critical Infrastructure

Maruthachalam D., Sugunadevi M., Sowmiya A. B., Sushmithaa P.

***Abstract:** This project provides a detailed study on the repair and strengthening of beams made up of concrete by Carbon Fiber Reinforced Polymer [CFRP] sheets. Mostly, structures fail due to the steel corrosion in the concrete. Corrosion remains primarily owing to the chloride ion intrusion in aggressive environment. The defected concrete will affect the strength of the structures. They can be treated with CFRP sheets so that the strength of the structure could be improved to withstand the design loads. The defects of the structures include - spalling of concrete, cracking, honey- combing etc., resulting in the reduction of strength. To strengthen the defected structure, we have implemented an idea of wrapping the corroded concrete with CFRP sheets. Reinforced concrete prisms will be casted and they will be grouped under four categories. First category of specimens will be kept as control specimens and another two groups of concrete specimen will be subjected to accelerated corrosion initiation test. The range of corrosion will be monitored through Half Cell Potential Mapping, after the crack formation on the surface of the specimens. Third group of prisms will be treated with CFRP sheets in one, two and three layers of the sheets. The last set of prisms will be treated with the CFRP sheets in one, two and three layers of the sheets without giving any chloride intrusion. Finally, the comparative study will be made on the strengths of all the three category specimens. We have selected M30 concrete grade and OPC53 grade of cement. All values are based upon IS 456:2000 and IS 10262:2009.*

***Index Terms:** CFRP sheets, Chloride intrusion, Corrosion, Repair, Strengthening, Half Cell Potential Mapping*

I. INTRODUCTION

Over the ages as we have evolved to form a sustainable future through our revolutionizing technologies. During the course of this progression, on the way to optimally manage the performance cost trade off in the construction sector, engineers and researchers make sure themselves in persistent examination for enhanced materials. Recently, in the civil engineering field, retrofitting is one of the most significant challenges in addition to repair of existing structures. The structure must be strengthened to resist the underestimated loads in addition to overcome the premature failure.

Manuscript published on 30 December 2018.
***** Correspondence Author (s)

Maruthachalam D., Professor, Department of Civil Engineering, Sri Krishna College of Engineering and Technology, Coimbatore (Tamil Nadu), India.

Sugunadevi M., Assistant Professor, Department of Civil Engineering, Sri Krishna College of Engineering and Technology, Coimbatore, Tamil Nadu, India.

Sowmiya A. B., Under Graduate Students, Department of Civil Engineering, Sri Krishna College of Engineering and Technology, Coimbatore, Tamil Nadu, India.

Sushmithaa P., Under Graduate Students, Department of Civil Engineering, Sri Krishna College of Engineering and Technology, Coimbatore, Tamil Nadu, India.

Severe deteriorations are occurred in existing structures made up of reinforced concrete owing to carbonation, attack due to chloride intrusions, construction faults, live load increment and steel reinforcement corrosion. One of the most common repair techniques involves covering the Reinforced Concrete steel or timber members with the help of Fiber Reinforced Polymer (FRP) using epoxy resins. Premature failure and severe damage are occurred in RC structures because of chloride penetration which leads to corrosion in reinforcement access from sea water otherwise from de-icing salts. Depassivation and localized disruption of rebars takes place when the chloride concentration is high in the concrete cover. This circumstance exemplifies an astonishing corrosion risk in the entire structures. Alternating drying-wetting cycle results to severe oxidization. High degree of protection is given by concrete against corrosion to steel, by means of providing pH value more than 13.5 in the solutions present inside the pores. Because of this high alkalinity, passivated condition is developed in steel. The corrosion rate affects the service life of Reinforced Concrete Structure because as soon as the corrosion is commenced, it develops almost at stable rate and decreases the strength by causing cracks on the surface and consequently expansion of corroding steel leads to spalling of concrete cover. This corrosion rate affects the service life of structure. When the structural members like beams, slabs, and columns are strengthened by Fibrous composite materials such as CFRP (Carbon Fibre Reinforced Polymer) has increased extensive recognition for past dualistic periods because of its easiness in installation and corrosion resistance as related to other materials. It's installation property reduces the labour cost at the site and disruptions to prevailing amenities, whereas the second thing make certain long-lasting performance. Prevailing distressed bridges are strengthened using Carbon Fiber Reinforced Polymer composites. FEM analyses were performed in a cylindrical specimen reinforced using a single bar with the purpose of pretend corrosion due to pitting or wide-ranging corrosion intended to establish the option to extend the outcomes to extra multifarious RC members in terms of geometry and reinforcement. Further a systematic prototypical is proposed mechanically to estimate the stresses around steel bars placed inside concrete. When the reinforcement bars are begins to oxidize, stresses are developed in non-linear manner which leads to the crack formation. A refined model is offered to estimate these stress inside concrete which provides a relationships between the development of cracks and steel section reduction [1].

Experimental work was performed on the way to examine the consequence of flexural Carbon Fibre encloses on shear resistance of reinforced concrete beams. Thirteen numbers of beams were manufactured with different steel reinforcement ratio and split into three different groups.

These beams were casted without reinforcement in the transverse direction of shear span. Due to the formation of tension crack in diagonal direction, the verified samples failed in shear. Strengthened specimen's shear capacity upsurges in the sequence of 10% to 70% in associated with control specimens. From the results it is concluded that flexural ratio of longitudinal reinforcement takes a substantial influence in the shear strength of Reinforced Concrete beams [2]. Numerical framework studies deliberate the effects of location and rebar size on the progression of chloride access into concrete. This study helps to estimate the non-uniform corrosion which occurs due to corrosion of segment besides irregular corrosion laterally on the rebar perimeter. Comparison of the estimated non - identical corrosion was carried out between obtainable laboratory and field data illustrates virtuous agreement [3].

Experimental tests were conducted on Reinforced Concrete beams retrofitted by alternatively organized CFRP covering and on a non-retrofitted one. The investigational results verify that this CFRP bands scattering can progress the load carrying capacity of retrofitted beams, on condition that that the diagonal strips are lengthy enough and that the longitudinal reinforcement is organized laterally on the whole beam [16].

II. MATERILS USED AND METHODOLOGY

A. Materials Used

Cement:

Ordinary Portland cement (53 grade) was used in the study. The cement properties are presented in Table 1.

Fine Aggregate:

Locally available **r**iver sand which stand clean and dry transient through sieve size of IS 4.75mm were taken as fine aggregate. Fine aggregates properties are given in Table 1.

Coarse Aggregate:

Crumpled limestone was recycled as coarse aggregate and their properties are tabulated in Table 1.

Water:

Curing and casting of specimens were completed with the clean well water as well as bore water at in the vicinity presented as per IS 456 -2000.

CFRP:

Carbon Fiber Reinforced Polymer sheets has been used as repairing material in order to strengthen the corroded structures. They are made up of carbon atoms. Carbon fiber possesses a 5 -7 microns diameter. It is smaller than the 'human hair 'for about 10 times.

Table 1 Material Properties

Sl. No	Material	I.S. Code Provision	Physical Properties		
			Size	Specific gravity	Fineness
1.	OPC-53 grade	IS12269-2004[11]	12 µm	3.15	7.5
2.	Fine aggregate	IS 383-1970[8]	Finer than 4.75 mm	2.67	2.25
3.	Coarse Aggregate	IS 383-1970[8]	12.5 mm	2.60	5.96
4.	CFRP	ASTM C-94[2]	5 – 7 micron	0.91	-

B. Mixture Details:

The mix design has been adopted using the properties of materials as listed above from IS 10262-2009 (2009). Based on the numerous design specifications, the mix ratio was obtained and tabulated in Table 3. Control Specimen is designated as CSP and concrete beam without fibre is labeled as CFRP00, whereas beam with CRFP in one, two besides three are designates as CFRP01, CFRP02 and CFRP03 respectively. The details of the mix proportions are shown in Table 2

Table 2 Mix Proportional Details

Mix	Number of CFRP Layer	Cement (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Water (Lit/m^3)
Control Specimen	-	438	637	1161	188
CFRP00	-	438	637	1161	188
CFRP01	1	438	637	1161	188
CFRP02	2	438	637	1161	188
CFRP03	3	438	637	1161	188

III. EXPERIMENTAL METHODOLOGY

A. Methodology

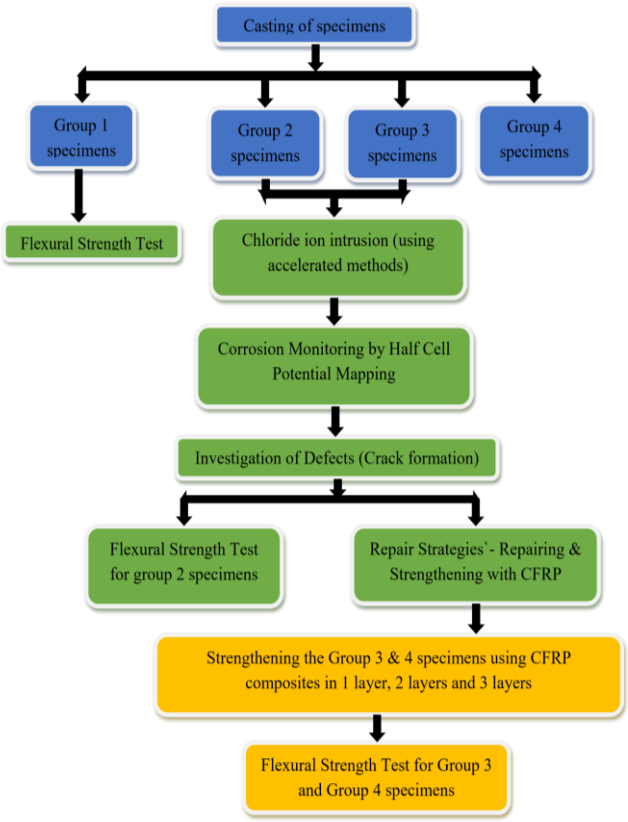

Fig1 Methodology

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

B. Specimen preparation and Curing:

The concrete specimens utilized in the study were six number of PCC and 24 number of Reinforced cement concrete of dimensions 500 x 100 x 100mm and they are categorized into 4 groups which are given in Table 3.
Specimen casting was carried out with the help of vibration table which ensures good compaction and reduce the air voids. Freshly prepared concrete was transferred into oiled steel moulds and concealed with wet burlaps for 24 h. Concrete specimens were then demoulded, labelled as to the date of casting and mix type, and stored in a water tank for initial moist curing period of 28 days.

Table 3. Details about number of specimen and their size

Details	Number of Specimens		Size of Specimen
	PCC	RCC	
Group 1	6	3	500 x 100 x 100mm
Group 2	-	3	
Group 3	-	9	
Group 4	-	9	

Fig 2 Preparation of moulds and pouring of concrete

C. Experimental Methods

a. Compressive Strength Test

The sample is positioned in the Compressive strength testing device in such a way that the applied load is acting in the opposed sides of the prism as per casted. One after the other load is applied in an increasing manner approximately at an amount of 140 kg/sq./min till the resistance to the applied load breaks down and further increment is not possible. The applied ultimate load and any unusual behavior in the concrete specimens are recorded. The results are compared with the design strength computed in the mix calculations.

b. Impressed Current Technique

The test is performed by applying an external potential axially across the saturated specimens through the reinforcement bar. 15 V DC / 1-2 A were applied to all prisms using variable DC power supplies. In DC power supply, positive portion is associated towards the reinforcement bar (anode) and the negative terminal is linked to the stainless harden plate or nickel-chromium wire mesh (cathode). And here, we used the nickel-chromium wire mesh. The surface area of the mesh should be equivalent or larger than the surface area of bar made up steel to be corroded. Electrolytic solution is make ready by adding Sodium Hydroxide, Calcium Hydroxide and Potassium Hydroxide, in the concentration of 0.3 gm / litre, 10.4 gm / litre and 23.23 gm / litre respectively. Apart from these chemicals, additionally Sodium Chloride was added 3.5% per litre, i.e. 35 grams of Sodium Chloride and 965 grams of water per litre of water. This mixed salt solution reflects the composition of marine conditions. So, the corrosion process happens in the marine structures could be replicated in our laboratory prisms. Solutions are filled in the tubs and then the prisms (Group -1 & 2) and the required wire mesh is kept inside the tubs. Electrical connections were made using multi-core electrical wires. 15 V DC power was applied through the bars. Corrosion products started to leach out from the concrete cover after 12 – 15 hours of application of voltage. Test set up is diagrammatically represented in the figure 6.

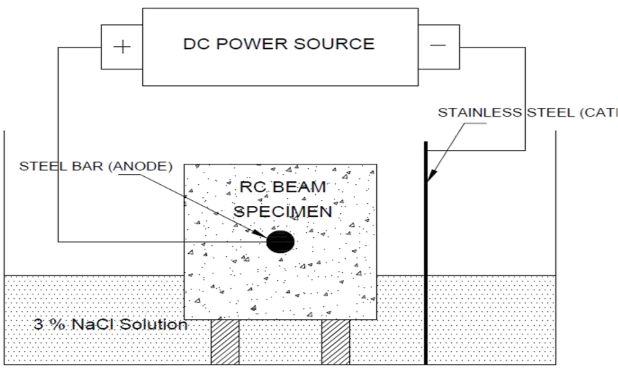

Fig.3 Accelerated Corrosion Initiation Test set up

Current is allowed to pass through the specimens until the crack formation is seen on the surface of the concrete. Longitudinal cracks were formed in 22-27 hours of application of voltage. Even the transverse cracks were formed in some of the specimens. If the specimens are kept allowing the current through the reinforcement after the crack formation, then the crack would widen and finally get opened and collapsed.

c. Half Cell Potential Mapping

Metal tendency to be respond with an environment is frequently designated by the potential it develops when it comes in contact with the surroundings. In case of structures made up of reinforced concrete elements, Concrete performances as an electrolyte and the reinforcement will develop a potential depending on the concrete environment. This potential may vary from place to place. The main principle of this technique is basically measuring the amount of corrosion potential with respect to a standard reference electrode. The reference electrodes are silver/ silver chloride electrode, SCE (saturated calomel electrode), CSE (copper/copper sulfate electrode), etc. It is essential to detect and measure the amount of corrosion in the RC Structures. Several methods are available for detection, measurement and diagnosis of corrosion in steel reinforcement, Half-cell potential meter provides information in a perfect manner. ASTM C876 Standard Test Method describes the uses and interpretation for Half-Cell Potential of Reinforcing Steel in Concrete.

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

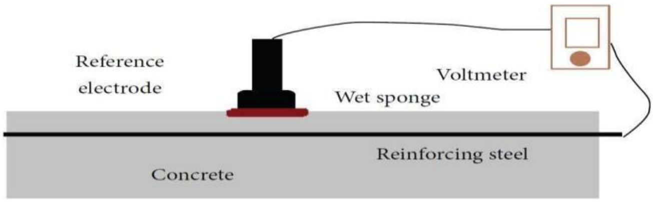

Fig 4 Half-Cell Potential Testing

If the steel potential becomes more than -276mV vs. SCE in concrete then as per this method the corrosion occurrence probability is about 90%. This non-destructive test can accumulates a vast amount of data from a huge structural zone.

d. Flexural Strength test

As per IS: 516-19595, Flexural strength test is carried out the casted specimens. Universal testing machine which possess capacity of about 100 kN is used to test prisms for their flexure capabilities. The concrete beams are positioned in such a way that the applied load must placed 13.3 cm apart on the external surface. The loading device alignment is in line with the specimen axis. Then at a amount of 180 kg/min deprived of astonishment the load is applied to the specimen. The test is continued without any interruptions until the failure of prism occurs then the ultimate load (P) applied to the specimen for the duration of test is taking down. Distance in the middle of the crack and nearest support is dignified as (a) after fracture. The specimen's flexural strength is provided in the form of modulus of rupture.

$f_b = (P\times L) / (b\times d^2)$,

when 'a' is greater than 13.3 cm or

$f_b = (3P\times a) / (b \times d^2)$,

when 'a' is in between 11.0 cm and 13.3 cm.

If 'a' is a smaller than 11.0 cm the test result is discarded.

where, a = the distance between the line of fracture and the nearest support, b = measured width in cm of the specimen, d = measured depth in cm of the specimen, P = maximum load in kg applied on the specimen.

Fig. 5 Test set up **Fig. 6 Breaking of specimen**

Fig. 7 Specimens strengthened with CFRP sheets

IV. RESULTS AND DISCUSSION

A. Hardened Properties of Concrete

The concrete prisms were tested for their compressive and flexure strength then their results was provided in the graphical custom from Fig.1 to Fig. 4.

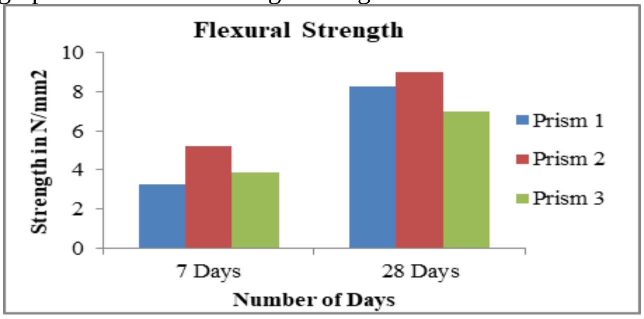

Fig.8. Results of flexural strength test at two different Curing Period

Increasing the age of concrete strength increases concrete strength. This is due to the fact that formation of cracks in the interfacial zone at lower stresses and then it gets propagated into mortar matrix at high stresses.

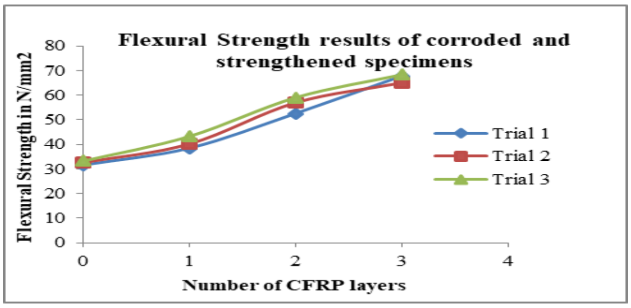

Figure 2. Flexural Strength results of corroded and strengthened specimens

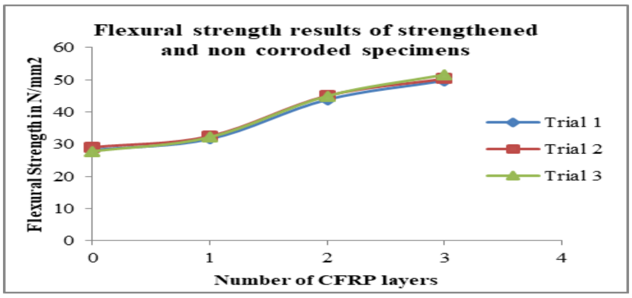

Fig.9. Flexural strength results of strengthened and non-corroded prisms

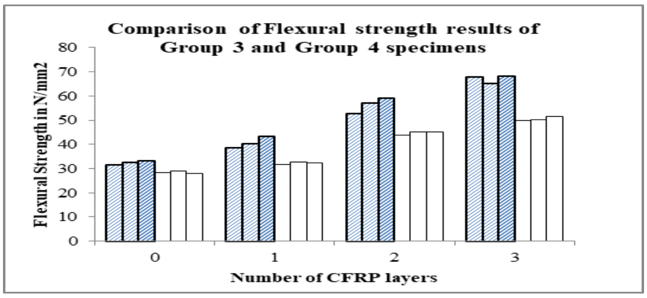

Fig.10. Comparison of Flexural strength results of group 3 and Group 4 specimens

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

Group 1 Specimens

- From the result we have obtained, the concrete compressive strength is greater than the theoretically designed concrete mix.
- And the flexural strength of the prisms is also higher than the designed mix at both 7 days and 28 days of testing.
- The one of the reasons for the above mentioned results is 10 percentage replacements of 20 mm coarse aggregates by 12.5 mm coarse aggregates.
- Flexural strength of conventional RCC prisms are in the range of 32 N/mm2 and the strengths of strengthened RCC prisms are much higher than the conventional prisms.

Group 2 and 3 Specimens

- While considering the strength of corroded concrete prisms (group 2), it got reduced by 1.5 % and the concrete prisms repaired with 1 layer of CFRP Sheet achieved the strength of conventional RCC prisms.
- While strengthening the corroded concrete prisms with 2 and 3 layers of CFRP Sheets, strength was increased around 4% (by its strength before corrosion) and 6.5% (by its strength before corrosion) respectively.

Group 4 Specimens

- As the layer of CFRP Sheets increases, the strength also gets increased in the strengthening of non-corroded specimens.
- For one layer application of CFRP Sheet on tensile side, flexural capacity increased around 3%.
- While strengthening the concrete prisms with 2 and 3 layers of CFRP Sheets, strength was increased around 8% and 12% respectively.

Findings

- Strengthening the concrete before attack of any aggressive elements from the environment or other deteriorations, with one and two layers of CFRP Sheets are considered to be effective in economical wise and also in durability.
- One layer application is more economical and two layer of application is more durable and the three layers of application is much more good in strength wise and in durability but then the material cost is very high.

V. CONCLUSION

Concrete structures durability and higher strengths, are the major demands in construction industries, can be obtained using Carbon Fibre Reinforced Polymer composites. Since this CFRP composite is highly impermeable, further ingression of chloride, carbon di oxide or any other aggressive substance cannot be transported in to the concrete. Chloride ion penetration is mainly due to alternative drying and wetting cycles. Even though the CFRP sheets concrete is subjected to alternate wetting and drying, strength of the structure will not get affected since the sheets provide high strength to the concrete. The structure need not be repaired again, once it is repaired with this material. So, the repairing costs can be reduced and avoided. And also the strength of the concrete structure can be obtained greater than its original design strength.

ACKNOWLEDGEMENT

The authors of current work desire to acknowledge the management and each individual who stood with us and extended their support in the process of getting approval from **"DST (Department of Science and Technology, Government of India)",** as a funded research work. The authors would also like to acknowledge the amenities provided by Sri Krishna College of Engineering and Technology for this project. The involvement and investigation done by the leading author is also greatly valued and appreciated.

REFERENCES

1. Kasimzade A. A. and Tuhta S., Analytical, Numerical and Experimental Examination of Reinforced Composites Beams Covered with Carbon Fiber Reinforced Plastic, Journal of Theoretical and Applied Mechanics, Sofia, 42(1), 2012, 55–70.
2. ACI Committee 440, ACI 440.2R-08. Guide for the design and construction of externally bonded FRP systems for strengthening concrete structure, 38800 Country Club Dr., Farmington Hills, MI 48331-3439, USA. American Concrete Institute, 2008.
3. Ahmed Shaban Abdel-Hay, Partial Strengthening of R.C Square Columns using CFRP, HBRC Journal, 10, 279–286, 2014.
4. Aitcin P.C., The durability characteristics of high performance concrete: a review, Cement & Concrete Composites, 25, 409–420, 2003.
5. Andrade C, Alonso C, On-site measurements of corrosion rate of reinforcements, Construction and Building Materials, 15, 141-145, 2001.
6. Antonio Bossio, Tullio Monetta, Francesco Bellucci, Gian Piero Lignola, Andrea Protaio Bossio, Modeling of Concrete Cracking due to Corrosion Process of Reinforcement Bars, Cement and Concrete Research, 71, 78–92, 2015.
7. ASTM C876, Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete, West Conshohocken, United States; American Society for Testing & Materials, 2009.
8. Dias S.J.E., Barros J.A.O., NSM Shear Strengthening Technique with CFRP Laminates Applied in High-Strength Concrete Beams with or without Pre-Cracking, Composites: Part B 43, 290–301, 2012.
9. Hawileh R.A., Nawaz W., Abdalla J.A., Saqan E.I., Effect of Flexural CFRP Sheets on Shear Resistance of Reinforced Concrete Beams, Composite Structures, 122, 468–476, 2015.
10. Hui Yu, Xianming Shi, William H. Hartt, Baotong Lu, Laboratory investigation of reinforcement corrosion initiation and chloride threshold content for self-compacting concrete, Cement and Concrete Research, 40, 1507–1516, 2010.
11. IS: 10262 – 2009, Concrete Mix Proportioning – Guidelines, Manak Bhavan, New Delhi 110002. Bureau of Indian Standards.
12. IS: 456 – 2000, Plain and Reinforced Concrete Code of Practice, Manak Bhavan, New Delhi 110002. Bureau of Indian Standards.
13. IS: 516 – 1959 (Reaffirmed 2004), Methods of Tests for Strength of Concrete, Manak Bhavan, New Delhi 110002. Bureau of Indian Standards.
14. John P. Broomfield, Kevin Davies, Karel Hladky, The use of permanent corrosion monitoring in new and existing reinforced concrete structures, Cement & Concrete Composites, 24, 27–34, 2002.
15. Kesavan K., Ravisankar K., Senthil R., Farvaze Ahmed A.K., Experimental Studies on Performance of Reinforced Concrete Beam Strengthened with CFRP under Cyclic Loading using FBG Array, Measurement, 46, 3855–3862, 2013.
16. Massimiliano Bocciarelli, Christian di Feo, Nicola Nisticò, Marco Andrea Pisani, Carlo Poggi, (2013), Failure of RC Beams Strengthened in Bending with Unconventionally Arranged CFRP Laminates, Composites: Part B 54, 246–254, 2013.

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

17. Mohamed H. Mahmoud, Hamdy M. Afefy, Nesreen M. Kassem, Tarek M. Fawzy, Strengthening of Defected Beam–Column Joints using CFRP, Journal of Advanced Research, 5, 67–77, 2014.
18. Mohammad Ismail, Bala Muhammad, Mohamed El Gelany Ismail, Compressive strength loss and reinforcement degradations of reinforced concrete structure due to long-term exposure, Construction and Building Materials, 24, 898–902, 2010.
19. Murad M. Bhunga, Dr. N. K. Arora, Comparative Study of ER-FRP Laminated Beam Design with ACI-440-2r-08 and IS Method, International Journal of Advanced Engineering Technology, E-ISSN 0976-3945, 2012.
20. Muralidharan S, Saraswathy V., Madhavamayandi A, Thangavel K, Palaniswamy N, Evaluation of embeddable potential sensor for corrosion monitoring in concrete structures, Electrochimica Acta, 53,7248–7254, 2008.
21. Muthulingam S., Rao B.N., Non-uniform Corrosion States of Rebar in Concrete under Chloride Environment, Corrosion Science, 93, 267–282, 2015.
22. Norazman Mohamad Nor, Mohd Hanif Ahmad Boestamam, Mohammed Alias Yusof, Carbon Fiber Reinforced Polymer (CFRP) as Reinforcement for Concrete Beam, International Journal of Emerging Technology and Advanced Engineering, 3(2), 2013.
23. Oral Buyukozturk, Oguz Gunes, Erdem Karaca, Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites, Construction and Building Materials, 18, 9–19, 2004.
24. Priyanka Sarker, Mahbuba Begum and Sabreena Nasrin, Fiber reinforced polymers for structural retrofitting: A review, Journal of Civil Engineering (IEB), 39 (1), 49-57, 2011.
25. Ratan Kharatmol, Pankaj Sananse, Rohit Tambe, Ms.Raksha J.Khare, (2014), Strengthening of Beams Using Carbon Fibre Reinforced Polymer International Journal of Emerging Engineering Research and Technology, 2(3), 119-125, 2014.
26. Shamsad Ahmad, Reinforcement corrosion in concrete structures, its monitoring and service life prediction—a review, Cement & Concrete Composites, 25, 459–471, 2003.
27. Szweda Zofiaa, Zybura Adam, Theoretical Model and Experimental Tests on Chloride Diffusion and Migration Processes in Concrete, Sciverse Science Direct, Procedia Engineering, 57 1121 – 1130, 2013.
28. Tara Sen, H.N. Jagannatha Reddy, Strengthening of RC Beams in Flexure using Natural Jute Fibre Textile Reinforced Composite System and its Comparative Study with CFRP and GFRP Strengthening Systems, International Journal of Sustainable Built Environment 2, 41–55, 2013.
29. Van der Zanden A.J.J., Taher A., Arends T., (2015), Modelling of Water and Chloride Transport in Concrete during Yearly Wetting/Drying Cycles, Construction and Building Materials, 81, 120–129, 2015.
30. Wonga H.S, Zhao Y.X, Karimi A.R, Buenfeld N.R, Jin W.L., On the penetration of corrosion products from reinforcing steel into concrete due to chloride-induced corrosion, Corrosion Science 52, 2469–2480, 2010.
31. Xianming Shi, Ning Xie, Keith Fortune, Jing Gong, Durability of steel reinforced concrete in chloride environments: An overview, Construction and Building Materials, 30, 125–138, 2012.
32. Yinzhi Zhou, Hualin Fan, Kebin Jiang, Mingkang Gou, Ning Li, Pengcheng Zhu, Yiqiang Tu, Experimental Flexural Behaviors of CFRP Strengthened Aluminum Beams, Composite Structures, 116, 761–771, 2014.

AUTHORS PROFILE

Dr. D. Maruthachalam, Published 14 papers in International Journals

<u>Professional body membership details</u>

1) Institution of Engineers
2) Indian Society for Technical Education
3) Association of Consulting Civil Engineers (India)
4) Indian Concrete Institute

Ms. M. Sugunadevi

<u>Professional body membership details</u>

1) Indian Geotechnical Society
2) International Society of Research and Development
3) Institute of Research Engineers and Doctors

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)