Parametric Study on Bond Strength between Epoxy Coated Steel of Concrete

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Abstract— Epoxy-coated steel reinforcing bars are widely used in concrete construction to improve corrosion resistance. The coating, however, causes a reduction in bond strength between reinforcing bars and concrete. The main objective of this study was to study the bond strength of epoxy coated reinforcement and equivalent uncoated bars. The effectiveness of bond strength between reinforcing steel and concrete is the most important requirement of reinforced concrete as composite building material. Thereby, the bond quality is influenced by a wide range of parameters. The Present investigation, bond strength of the epoxy coated grey colour, green colour and uncoated steel bar with concrete was studied. Tests were conducted on 45 rectangular pullout concrete specimens with compressive strength 25 MPa at an age of 7 days, 14 days and 28 days. The embedded length of steel bars were considered in this test are 400 mm with 24 mm diameter of bar. The accuracy of result obtained from analytical analysis using ABAQUS software is validated by comparing it with previous literature study and experimental work.

Keywords: Epoxy Coated Bars, ABAQUS Software, Embedded Length

I. INTRODUCTION

The bond behavior in reinforced concrete (RC) structures plays an important role in the interaction between the steel reinforcement and the concrete. The bond consists of three aspects: chemical adhesion, friction and mechanical interlock. At a low stress level, the bond strength is assured by chemical adhesion between the reinforcement and the concrete. For this period, the bond strength increases with the concrete compressive strength. Once the slip occurs, bond is mainly provide by mechanical interlock between the ribs and the surrounding concrete, which is dependent on the gripping force between the concrete and the contact surface area. With the load increases, the bond failure may occur due to either the splitting of the concrete wrap or the pull-out of the steel reinforcement. Extensive research on the bond mechanisms of steel reinforcement in concrete has been conducted. The quality of the steel-concrete interface and the state of the steel reinforcement and the surrounding concrete are considered to be critical factors affecting the bond performance in RC structures. [12]

Corrosion of steel reinforcement occurs gradually in RC structures exposed to marine environments or de-icing condition. As a result, the cross-sectional area reduction of the steel reinforcement occurs and the strength of the steel-concrete interface is influenced. Moreover, the volumetric expansion of the corrosion products generates additional stress in the concrete, and finally causes the cracking and even spalling of the concrete cover, inducing the loss of bond performance of the steel reinforcement in the corroded RC structure [12]

A. Usage of Epoxy-Coated Reinforcing Bars

Epoxy-coated bars have been primarily used in bridge decks to stop corrosion due to de-icing salts. They were first introduced in 1973, in a bridge deck in Pennsylvania. Since then, they have been used in nearly all types of structures. In coastal regions all elements of a bridge exposed to sea water or sea spray may be built with epoxy-coated bars to prevent corrosion. Epoxy-coated bars have also been used in structures where concrete is exposed to a corrosive environment. Applications include sewage treatment plants, water-chilling stations, and chemical plants

B. Review of Bond

The bond of reinforcing bars to concrete is critical in the analysis and design of reinforced concrete structures. Inherent in the analysis of a reinforced concrete section is the assumption that the strain in the concrete and steel is equal at the location of the steel. This implies perfect bond between the concrete and steel.[11]

Two modes of bond failure are commonly recognized: a splitting failure and a pullout failure. In both cases, the main component of bond is the reaction of the bar deformations against the surrounding concrete which is at an angle to the axis of the bar as shown in Fig.1. The component of this reaction perpendicular to the axis of the bar exerts a radial pressure on the surrounding concrete. If the cover on the bars or the spacing between bars is relatively small, this pressure will cause splitting (Fig.2). The restraint against splitting is dependent on the tensile capacity of the concrete across the splitting plane. Additional restraint may be provided by transverse reinforcement crossing the splitting plane. If the cover and spacing between bars is great enough, or if enough transverse reinforcement is provided, a splitting failure cannot develop and a pullout failure will occur or the bar will yield. In a pullout failure, the concrete between bar deformations is sheared from the surrounding concrete (Fig 3).[11]

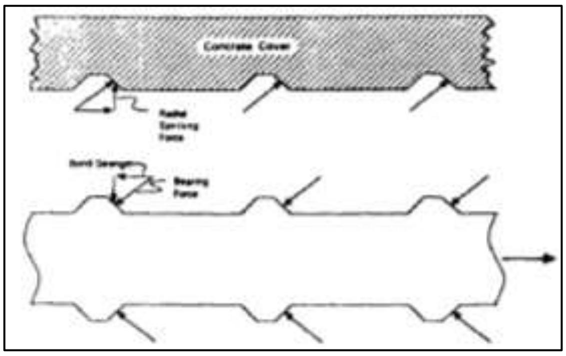

Fig. 1: Inclination of Bond Stress

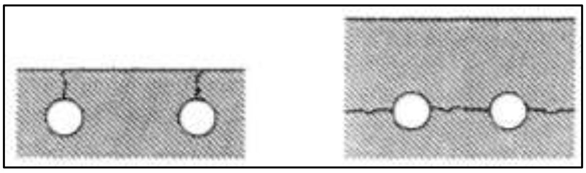

Fig. 2: Splitting Failure

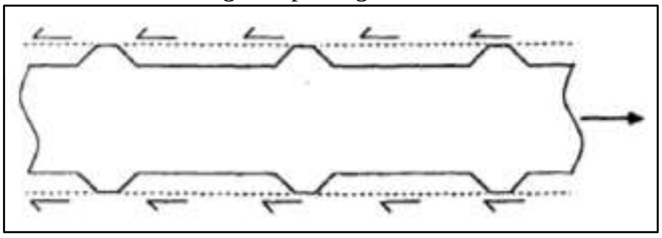

Fig. 3: Bond Stresses in Pullout Failure

II. LITERATURE REVIEW

A. High Performance Epoxy Coating with Cross-Linkable Solvent

Protective coatings are effective to prevent concrete from corrosion and improve its durability. In this study, we report a novel epoxy coating with cross-linkable solvent via Diels-Alder reaction. Such a coating has a low viscosity so it can permeate into the pores or defects of concrete up to 1.5 mm, whereas the solvents cross-link with epoxy resin in-situ at higher temperature, forming a robust root-like coating/concrete composite. The concrete is significantly reinforced in the mechanical strength and corrosion resistance. Moreover, the crosslink able solvents allow the coating to have a low content of volatile organic compound (VOC) (< 2 wt%) so it exhibits less negative impact on environment. The high performance coating can find applications in protection of concrete. [5]

B. Temperature effects on the bond strength between concrete and steel reinforcement bars

The purpose of this study is to investigate the temperature effects on the bond strength between concrete and steel reinforcement bars. For two different steel bars (epoxy-coated and uncoated bars), three experimental parameters (heating rate, target temperature, and cooling condition) are examined. At a target temperature of 200 _C, the epoxy-coated rebar has much higher bond strength than the uncoated rebar. However, in the specimens exposed to target temperatures higher than 200o C, the test results show that the epoxy coated rebar has less bond strength than the uncoated rebar. Also, the test results demonstrated that as the heating rate and target temperature increase the bond strength decreases. [3] The cooling method does not affect the ultimate bond stress of the specimens using uncoated rebar very much but can greatly affect specimens that contained epoxy coated rebar. A more in-depth study can be considered regarding the cooling effect on the bond strength.

C. Effect of Waste Steel Shavings on Bond Strength

The investigation was carried out to know the effect of waste steel shavings on the bond resistance between concrete and steel reinforcement using 16mm and 20mm diameter high-yield reinforcing bars. Eighty (80) RILEM specimens, made up of forty (40) cubes each of 160mm x 160mm x 160mm and 200mm x 200mm x 200mm were cast and tested with varying percentages of waste steel shavings, (0%, 1%, 1.5%, and 2%, by weight of concrete) using pull out arrangement. The normal concrete (with no steel shavings) which are ten (10) in number were used as reference. Also, twelve (12) 150mm concrete cubes were cast to monitor the compressive strength of concrete. The results showed that bond strength increased with the addition of 2%, (by weight of concrete), of waste steel shavings.[7]

III. MATERIAL AND METHODOLOGY

A. Behaviour of Bond

1) Bond Behaviour and Failure Modes

The structural behaviour of reinforced concrete elements basically requires the interaction between steel reinforcement and concrete. Tensile forces in the area of separating cracks and bending cracks are carried by the reinforcement and transferred into concrete by bond action[10] Crack widths and crack spacing are therefore significantly dependent on the bond properties of the applied reinforcement. Thus, stiffness and deformation behaviour of reinforced concrete elements are directly influenced by the bond properties. For activation of the bond mechanism, relative displacements (slip) between steel and surrounding concrete are required. Essentially, bond action is achieved by mechanical interlocking of the steel ribs and the surrounding concrete. With initiating relative displacement, the ribs start to penetrate into the mortar matrix. Compressive stresses in the concrete compression struts additionally induce perpendicular tensile stresses and therefore inclined internal bond cracks starting at the ribs, so-called Goto-cracks, as show in figure[10]

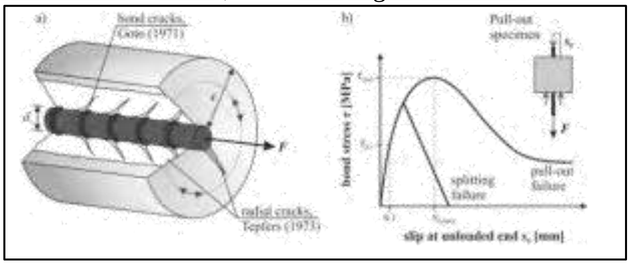

Fig. 4: Failure Mode and Bond Stress-Slip Relationship

In general bond stress-slip relationships are used to describe the bond behaviour, which can be determined on so-called pull-out specimens as shown in figure 3.1b. In real structural elements, bond stresses for large relative displacements are of minor importance. At this, the bond behaviour for small slip values, which correspond to the dimension of limiting crack widths, is relevant. Based on the assumption that the mean crack width in structural elements is approximately consistent with twice the slip at the unloaded bar end in pull-out tests, for the estimation of the bond behaviour in serviceability limit states the bond stresses corresponding to slip values of s0 = 0.1 mm are used.[10]

2) Bond Behaviour under Transverse Tension

Increasing internal pressure causes biaxial tensile loading in the containment wall. Therewith, the embedded reinforcing bars are not only affected by axial loads but also by tensile stresses acting perpendicularly to the bar axis.[10] This so-called transverse tension is superimposed by circumferential tensile stresses around the bar caused through bond action. As a result, deterioration of the bond behaviour is possible, depending on the thickness of the concrete cover and the level of transverse tension.

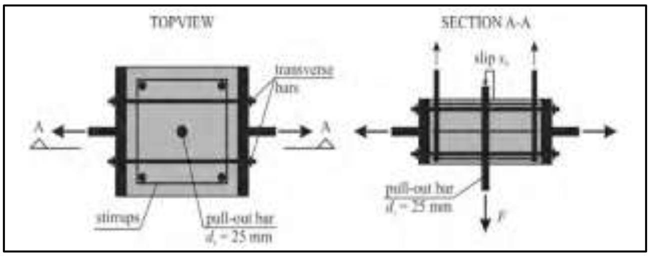

Fig. 5: Transverse Reinforcement

B. *Corrosion Protection Methods for Reinforcing Bars*

Corrosion of reinforcing steel in concrete is the most common cause of premature deterioration of reinforced concrete structures. The corrosion problem continues to drain resources of owners of reinforced concrete structures in both the public and private economic sectors in the United States and throughout the world. Reinforced concrete is inherently a durable and maintenance free material under normal conditions. The calcium hydroxide solution in set cement is an alkaline solution with a pH of 12.5. In this alkaline solution a protective iron oxide film forms over the reinforcing steel rendering it passive and well-protected against corrosion.

1) *Corrosion Mechanism*

Corrosion is an electrochemical process associated with the presence of anodic and cathodic areas arising from in homogeneities in the steel surface or non-uniformities in the chemical or physical environment afforded by the surrounding concrete.

2) *Corrosion Protection Methods*

a) Increased Concrete Cover

The purpose for increasing the depth of the concrete cover over the reinforcing steel is based upon the theory that it takes longer for the chlorides to seep through a greater distance. However, if the chlorides are present in the concrete, then increased depth does not help against corrosion.

b) Membranes and Overlays

The function of membranes and overlays is to provide an impervious layer through which the chlorides cannot pass. The problem with membranes and overlays is that if the concrete contains chlorides, corrosion attack will not be prevented. Also, membranes are installed at the construction site and are weather dependent.

c) Sealers

Sealing the concrete surface by a proper surface coating such as linseed oil or bituminous coating is another method to prevent the absorption of exterior salts and other aggressive substances into the concrete

d) Anodic Inhibitors

Anodic inhibitors contain materials such as alkalies, phosphates and chromates which form either iron salts or a ferric oxide film on the anodic surface of the reinforcing bar thus preventing ferrous ions from entering the solution.

e) Cathodic Protection

Cathodic protection is a preventative maintenance procedure which uses electrochemical principles to reduce the corrosion rate in an existing structure. In cathodic protection an external current is supplied to the corroding metal.

f) Fusion-Bonded Epoxy Coating

Of all the methods of corrosion protection possible, fusion-bonded epoxy coating often offers the best combination of protection, ease of use, and economy. The purpose of the epoxy coating is to prevent chlorides from reaching the steel surface. The material is applied to the reinforcing bar at a coating plant away from the job site.

C. *Material Properties*

1) *Concrete*

Concrete shows different behavior in tension and compression. The ultimate compressive strength can be used to predict the elastic modulus of concrete.

2) *Physical Properties of Steel*

Sr. No	Steel	Value
1	Nominal Diameter of bar	24 mm
2	Yield Stress (MPa)	420
3	Young Modulus (MPa)	$2x10^5$
4	Poisson's Ratio	0.3
5	Density (gm/mm^3)	0.0078
6	Tangent Modulus (MPa)	21
7	Bounded length (mm)	400

IV. EXPERIMENTAL SETUP

A. *Pull out Specimen Fabrication*

Forty five pullout test specimens were produced to determine the bond between high strength concrete and high strength steel bar. All of the pullout specimens were made on the same day. The high strength concrete used in construction was provided by industry. All the steel bars were 500 grade of steel with nominal diameters of 24 mm. For each bar size concrete sizes (100x500 mm) were conducted. Figure 3.4 shows details of the test specimens. Before conducting the pull-out tests, all reinforcing bars were tested for their tensile strength. The experimental results are listed. All the pullout specimens were constructed by using moulds made of steel as shown in the Figure.

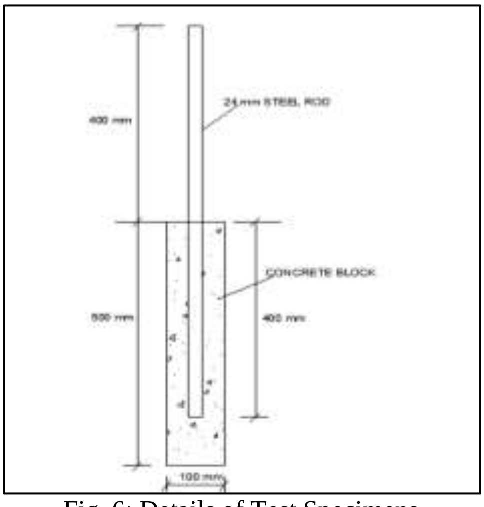

Fig. 6: Details of Test Specimens

Fig. 7: Sample of Mould

B. *Experimental Setup*

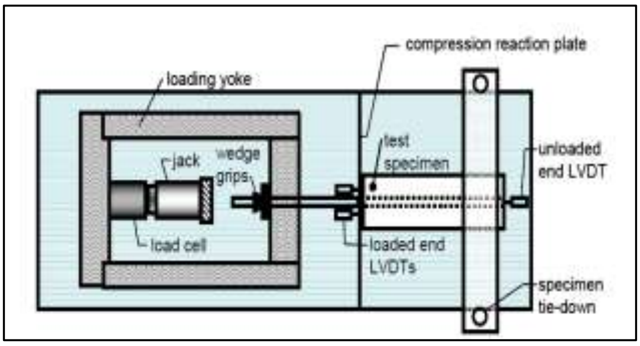

Fig. 8: Setup Plan

V. RESULTS AND ANALYSIS

A. *Analytical Load Carrying Capacity*

Sr. No	Thickness of Coating in mm	Types of coating	Load carrying capacity in KN
1	0	NA	93.985
2	0	NA	93.412
3	0	NA	93.583
4	0.3	Gray	94.013
5	0.3	Gray	93.852
6	0.3	Gray	97.142
7	0.3	Green	94.52
8	0.3	Green	94.073
9	0.3	Green	96.14
10	0.5	Gray	97.168
11	0.5	Gray	98.187
12	0.5	Gray	100.2
13	0.5	Green	101.207
14	0.5	Green	102.22
15	0.5	Green	103.19

Table 1: Load Carrying Capacity of Rectangular Shape Pullout Concrete Section

Sr. No	Thickness of Coating in mm	Types of Coating	Average Load Carrying Capacity in KN
1	0	without	93.66
2	0.3	Gray	95.00
3	0.3	Green	94.91
4	0.5	Gray	98.52
5	0.5	Green	102.21

Table 2: Average Load Carrying Capacity of Rectangular Shape Pullout Concrete Section

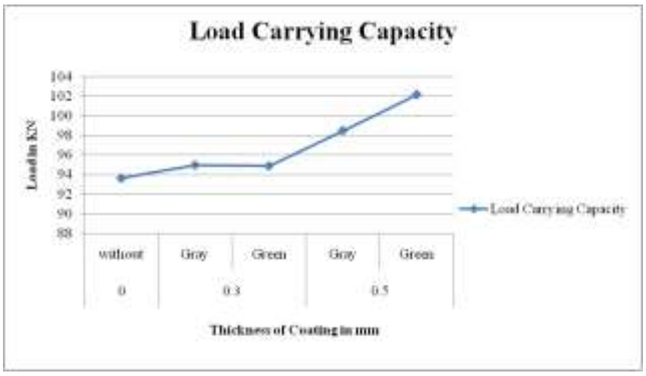

Fig. 9: Average Load Carrying Capacity of Rectangular Shape Pullout Concrete Section

B. *Comparison Percentage Difference W. r. t without Coating*

Sr. No	Thickness of Coating in mm	Types of Coating	Load Carrying Capacity	Percentage Difference W. r. t Without Coating
1	0	without	93.66	-
2	0.3	Gray	95	1.43
3	0.3	Green	94.91	1.33
4	0.5	Gray	98.52	5.19
5	0.5	Green	102.21	9.1

Table 3: Comparison Load Carrying Capacity of Without Coating

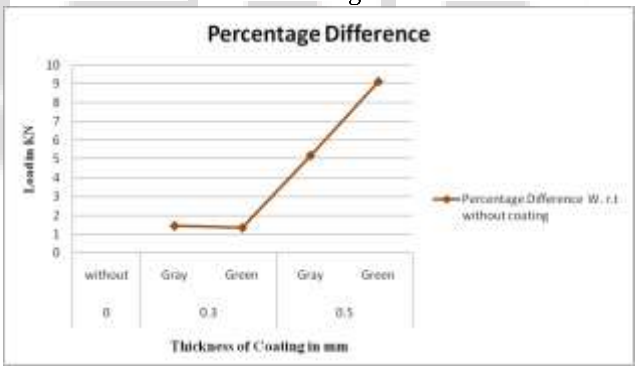

Fig. 10: Comparison Load Carrying Capacity of Without Coating

C. *Experimental Load Carrying Capacity*

Sr. No	Thickness of Coating in mm	Types of coating	7 Days Failure load/ Strength in KN
1	0	NA	26.0
2	0	NA	26.7
3	0	NA	27.5
4	0.3	Gray	29.1
5	0.3	Gray	29.0
6	0.3	Gray	28.8
7	0.3	Green	27.9
8	0.3	Green	28.0
9	0.3	Green	28.2
10	0.5	Gray	30.5
11	0.5	Gray	31.0
12	0.5	Gray	30.2

13	0.5	Green	31.4
14	0.5	Green	30.9
15	0.5	Green	31.2

Table 4: 7 Days Failure Load in KN

Sr. No	Thickness of Coating in mm	Types of Coating	Average Failure load/ Strength in KN
1	0	NA	26.73
2	0.3	Gray	28.97
3	0.3	Green	28.03
4	0.5	Gray	30.57
5	0.5	Green	31.17

Table 5: Average 7 Days Failure Load in KN

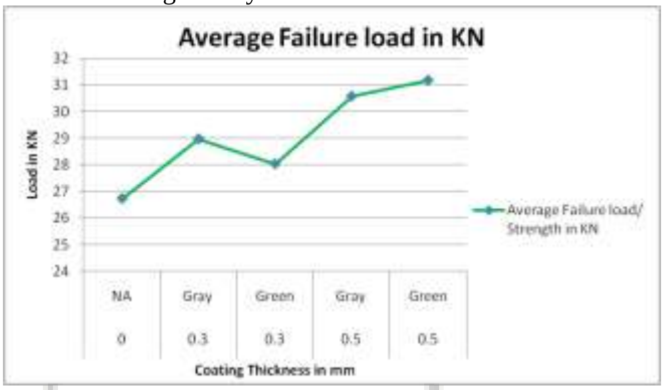

Fig. 11: Average 7 Days Failure Load in KN

Sr. No	Thickness of Coating in mm	Types of Coating	14 Days Failure load/ Strength in KN
1	0	NA	50.9
2	0	NA	50.0
3	0	NA	50.4
4	0.3	Gray	51.9
5	0.3	Gray	52.0
6	0.3	Gray	52.2
7	0.3	Green	52.4
8	0.3	Green	51.0
9	0.3	Green	52.0
10	0.5	Gray	53.0
11	0.5	Gray	53.7
12	0.5	Gray	52.8
13	0.5	Green	52.9
14	0.5	Green	53.0
15	0.5	Green	52.8

Table 6: 14 Days Failure Load in KN

Sr. No	Thickness of Coating in mm	Types of Coating	Average Failure Load/ Strength in KN
1	0	NA	50.43
2	0.3	Gray	52.03
3	0.3	Green	51.8
4	0.5	Gray	53.17
5	0.5	Green	52.9

Table 7: Average 14 Days Failure Load in KN

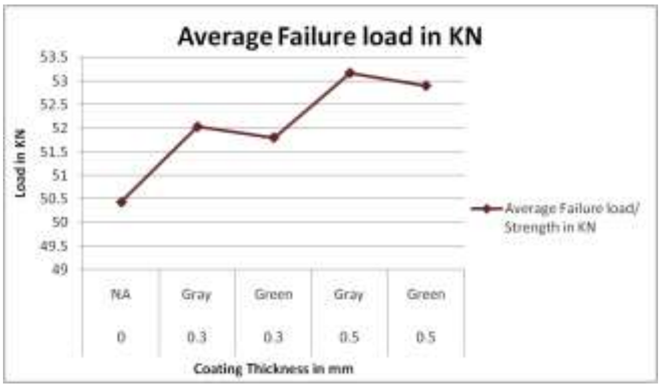

Fig. 12: Average 14 Days Failure Load in KN

Sr. No	Thickness of Coating in mm	Types of coating	28 Days Failure load/ Strength in KN
1	0	NA	90.6
2	0	NA	91.0
3	0	NA	91.8
4	0.3	Gray	90.0
5	0.3	Gray	93.6
6	0.3	Gray	94.0
7	0.3	Green	92.8
8	0.3	Green	94.2
9	0.3	Green	93.8
10	0.5	Gray	95.8
11	0.5	Gray	96.0
12	0.5	Gray	95.2
13	0.5	Green	95.0
14	0.5	Green	96.4
15	0.5	Green	96.8

Table 8: 28 Days Failure Load in KN

Sr. No	Thickness of Coating in mm	Types of Coating	Average Failure Load/ Strength in KN
1	0	NA	91.13
2	0.3	Gray	92.53
3	0.3	Green	93.6
4	0.5	Gray	95.67
5	0.5	Green	96.07

Table 9: Average 28 Days Failure Load in KN

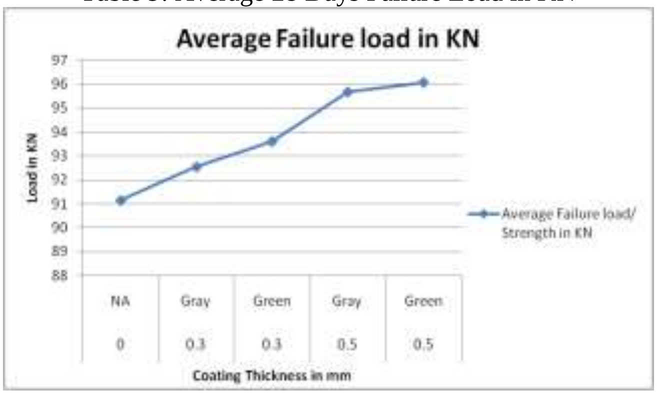

Fig. 13: Average 28 Days Failure Load in KN

D. Comparison of Experimental and Analytical Results

Sr. No	Thickness of Coating	Types of Coatin	Average Failure	Average ABAQUS Load	% Difference

	in mm	g	Load in KN	in KN	
1	0	NA	91.13	93.66	2.78
2	0.3	Gray	92.53	95.0	2.67
3	0.3	Green	93.6	94.91	1.40
4	0.5	Gray	95.67	98.52	2.98
5	0.5	Green	96.07	102.21	6.39

Table 10: Load Carrying Capacity of Analytical and Experimental

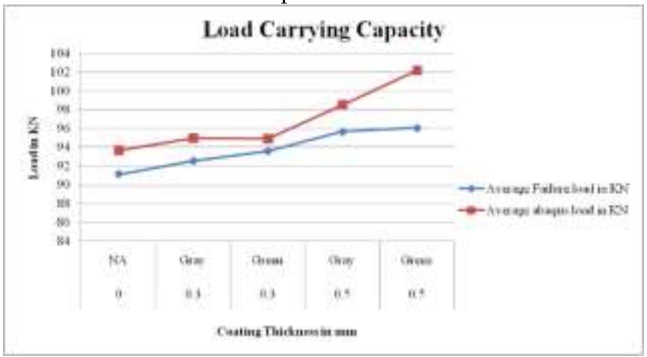

Fig. 14: Load Carrying Capacity of Analytical and Experimental

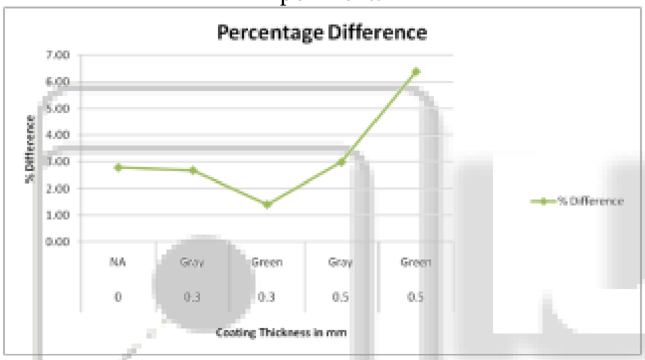

Fig. 15: Percentage difference of Analytical and Experimental

E. Comparison of Software Results with Research Paper Results

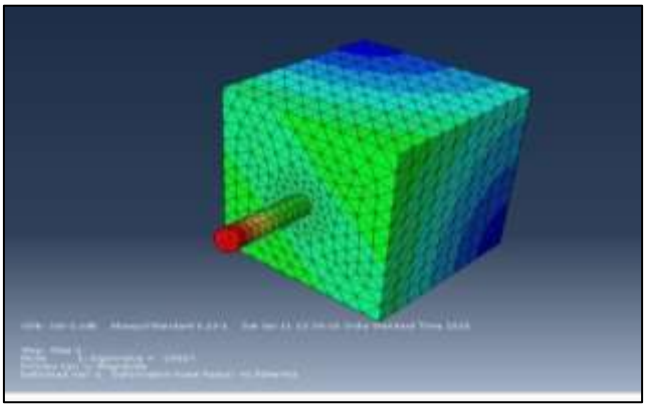

Fig. 16: Results for Load Carrying Capacity of Model in Research Paper

Sr. No	Actual coating Thickness	Xiao-Hui Wang Load	ABAQUS	Percentage error
1	0	22.88	24.827	-
2		22.65	23.2	7.01
3		25.25	23.95	3.23

4		24.03	24.0	0.21
5		19.75	18.3	31.25
6		21.34	19.5	6.56
7		21.86	20.4	4.62
8	200 µm	20.27	21.69	-
9		21.34	22.56	4.01
10		18.26	20.89	7.99
11		20	21.985	5.24
12		17.56	19.4	13.32
13		18.36	18.62	4.19
14		22.77	19.8	6.34
15	600 µm	13.20	15.6	-
16		19.28	18.35	17.63
17		13.23	15.4	19.16
18		18.64	17.65	14.61
19		12.74	13.74	28.46

Table 11: Results for Load Carrying Capacity of Model in Research Paper

Sr. No	Actual coating Thickness	Xiao-Hui Wang Load	ABAQUS Results
1	0	22.54	22.03
2	200 µm	19.79	20.71
3	600 µm	15.418	16.148

Table 12: Average Results for Load Carrying Capacity of Model in Research Paper

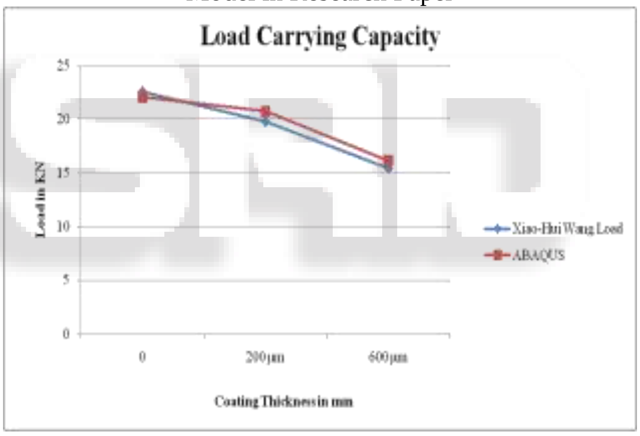

Fig. 17: Average Results for Load Carrying Capacity of Model in Research Paper

VI. CONCLUSION

The bond properties are again directly related to the loading condition of the structural elements. Several parameters of the experiment were chosen in the present study, Experimental tests and finite element analyses conducted in this research program highlighted the effects of natural corrosion, confinement and repeated loading on bond strength between steel rebar and concrete.

Following conclusion can be drawn from the study so far carried out in respect of epoxy coated pullout rectangular shape concrete section with respect to load carrying capacity using ABAQUS software.

1) The analytical results giving load carrying capacities of epoxy coated pullout rectangular shape concrete section is found to be almost similar to that of the results obtained in the research paper using software and percentage variation in load carrying capacity is found to

be approximately same. Hence, it can be concluded that the results of ABAQUS are validated with the results obtained by using software in research paper.

2) The epoxy coated pullout rectangular shape concrete section has been studied. The variation in load carrying capacity as obtained by software is as given below:
   1) Bond strength of epoxy-coated bars decreases with the increase of the coating thickness when both normal uncoated and epoxy-coated reinforcing bars having the same bar parameters, bar size, concrete strength, cover-bar diameter ratio, nominal embedded length and splitting failure modes.
   2) The epoxy coated rectangular optimized pullout column is 0.3 mm grey colour coating is maximum load carrying capacity is 95.00 KN than other and with respect to without epoxy coating.
   3) The epoxy coated rectangular optimized pullout column is 0.5 mm green colour coating is maximum load carrying capacity is 102.21 KN than other and with respect to without epoxy coating.
   4) The epoxy coated rectangular optimized pullout column 0.5 mm green colour coating is maximum percentage difference is 9.1 with respect to without epoxy coating.
3) The epoxy coated pullout rectangular shape concrete section has been studied with respect to load carrying capacity. Specimen tested in 7, 14, 28 days compressive strength. The variation in load carrying capacity as obtained by experimental analysis is as given below:
   1) The epoxy coated rectangular optimized pullout column is 0.5 mm green colour coating is 7 days maximum average load carrying capacity 31.17 KN with respect to without epoxy coating.
   2) The epoxy coated rectangular optimized pullout column is 0.3 mm grey colour coating is 7 days maximum average load carrying capacity 28.97 KN with respect to without epoxy coating.
   3) The epoxy coated rectangular optimized pullout column is 0.5 mm grey colour coating is 14 days maximum average load carrying capacity 53.17 KN with respect to without epoxy coating.
   4) The epoxy coated rectangular optimized pullout column is 0.3 mm grey colour coating is 14 days maximum average load carrying capacity 52.03 KN with respect to without epoxy coating.
   5) The epoxy coated rectangular optimized pullout column is 0.5 mm green colour coating is 28 days maximum average load carrying capacity 96.07 KN with respect to without epoxy coating.
   6) The epoxy coated rectangular optimized pullout column is 0.3 mm green colour coating is 28 days maximum average load carrying capacity 95.67 KN with respect to without epoxy coating.
4) Comparison of Analytical and experimental result proved that the analytical result is increase than the experimental results. The experimental study using epoxy coated pullout rectangular shape concrete section showed comparable results with those obtained in analytical studies.
5) The analytical results, compared with the experimental data, pointed out the important role of confinement as a parameter influencing the bond strength of corroded bars. The bond strength decreased and the slip enhanced with increasing corrosion.

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