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Strengthening of Reinforced Concrete Beams using Near-Surface Mounted Fiber Reinforced Polymer Rods

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Abstract: In most cases, buildings are constructed from reinforced concrete (RC) as a major structural component. Through time, these structures tend to deteriorate due to the poor technique at the early stage of construction, aging, over loading, bond degradation of the constituent materials and environmental factors. For durable and effective usage of structures to continue functioning as designed, repairing and strengthening of members becomes a necessity. Near Surface Mounted (NSM) Glass Fiber Reinforced Polymer (GFRP) is an emerging technique for increasing the flexural and shear strength of RC members. This study aimed to investigate the effectiveness and enhancement in flexural capacity of RC beams strengthened with NSM-GFRP rods. The experimental study was conducted by loading the beams under center-point loading and instrumented with linear variable displacement transducers (LVDT) and strain gages. The test results confirmed that the flexural performance of NSM GFRP strengthened beams increased by 10 to 35%. This technique can be used for rehabilitation of RC members. For a better result, further study on bond anchorage and pull out tests on FRP GFRP is recommended.
Keywords: Retrofit, Near surface mounted, Glass fiber reinforced polymer, LVDT, strain gages, RC beam.

I. INTRODUCTION

A concrete structure may have to carry large loads at a later date, or fulfil new standards. In extreme cases, a structure will have to be repaired once their load carrying capacities have been reduced due to sudden accidents. If any of these situations should arise, it needs to be determined whether it is more economical to strengthen the existing structure or to replace it. In comparison to constructing a new structure, strengthening of an existing structure is often more complicated and requires an extensive design since the conditions are already set [1]. A more recent method of repairing is the use of fiber reinforced polymers (FRP) because o f their excellent mechanical properties, corrosion resistance, durability, light weight, ease of application, reduced construction time, efficiency, and low life cycle cost [2]. Mostly, the damage on structural members due to poor construction, repeated loading or sudden impacts on the structural members leads for failure of the structures before their predicted age. To enhance performances of structures, repairing and strengthening for damaged reinforced concrete structures is done frequently. The usual method of repairing or rehabilitation of concrete structures is concrete jacketing or any other external strengthening methods.

Near Surface Mounted (NSM) Fiber Reinforced Polymer (FRP) rods is becoming an attractive method for increasing flexural strength of deficient reinforced concrete members due to the fact that NSM system requires less amount of site installation work, less prone to debonding from the concrete substrate and the NSM bars can be more easily anchored into adjacent members. Moreover, NSM bars are protected by the concrete cover and so are less exposed to accidental impact and mechanical damage [3].

In this study, experimental investigations on NSM GFRP strengthened RC beams were carried out. Moreover, replacement of FRP rods in the deficient and damaged bottom (tensile) side of RC beam members was also made.

The experimental study was done to provide solutions for repairing and rehabilitation for the current problems in the construction industry. These common problems include:

1) Deteriorating and damaged RC beams and columns in buildings,
2) Old and damaged bridges in need of repairing and strengthening due to design age or overloading on the bridges which are expected to transport heavy equipment.

The main objective of this research is to investigate an increment in load carrying capacity of FRP strengthened RC beam member as compared to the non-strengthened RC beam. This study is significant to provide a new and effective method of repairing and rehabilitation of deteriorated reinforced concrete structures. In the experimental study, the beam sections were designed and controlled to fail in flexure. Based on this study, about 10-35% increments were achieved.

A. *Strengthening of Reinforced Concrete Members*

The usual method of repairing or rehabilitation of concrete structures is concrete jacketing, plate jacketing or any other external strengthening methods.

Nowadays, the use of Near Surface Mounted (NSM) Fiber Reinforced Polymer (FRP) rods is becoming an attractive method for increasing flexural strength of deficient reinforced concrete (RC) members. This is mainly because the NSM system is preferable and has a number of advantages [3]:

1) The amount of site installation work may be reduced, as surface preparation other than grooving is no longer required;
2) NSM reinforcement is less prone to debonding from the concrete substrate;
3) NSM bars can be more easily anchored into adjacent members to prevent debonding failures;
4) NSM reinforcement can be more easily pre-stressed;
5) NSM bars are protected by the concrete cover and so are less exposed to accidental impact and mechanical damage, fire and vandalism;
6) The aesthetic value of the strengthened structure is virtually unchanged.

To design the member to be strengthened, the American Concrete Institute (ACI) 440.1R-15, "Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars" [4] is used as the design guidance to calculate the design criteria for FRP bar reinforced concrete members.

Near-surface mounted (NSM) fiber-reinforced polymer (FRP) reinforcement is a latest and most promising strengthening techniques for reinforced concrete (RC) structures. Issues raised by the use of NSM FRP reinforcement include the optimization of construction details, models for the bond behavior between NSM FRP and concrete, reliable design methods for flexural and shear strengthening. In line with this, a very important issue in the manufacture of composites is the selection of the optimum matrix (Resins) because the physical and thermal properties of the matrix significantly affect the final mechanical properties as well as the manufacturing process. In order to be able to exploit the full strength of the fibers, the matrix should be able to develop higher ultimate strain than the fibers. The matrix not only coats the fibers and protects them from mechanical abrasion and chemical attack, but also transfers stresses between the fibers [5].

Traditional methods of repairing of concrete structures with concrete and steel jacketing or any other external strengthening methods using steel materials have been used for some time. These methods often only restore a portion of the ultimate capacity of the damaged member and are left vulnerable to corrosion [6].These methods also are time consuming and labor intensive. They also increase the cross-sectional area of the structural members [2].

II. MATERIALS AND METHODS

A. *Material Property*

The total quantities of component materials for concrete used in this study are shown in Table 1.

TABLE 1
Component materials for concrete

Material	Quantity (kg)	Weight (%)
Water	3.91	7.87
Cement	8.28	16.66
Fine aggregate	17.44	35.09
Course aggregate	20.07	40.38

B. *Mechanical Properties of Materials*

Concrete with an average compressive strength of 33MPa was used. For the reinforcing steel bars deformed, high-yield strength bars were used. Based on uni-axial tension test, the average ultimate and yield tensile strength of the specimens for 8 mm steel bar is 559MPa and 430.89MPa respectively. And for that of 10mm are 520.09MPa and 369.04MPa, respectively. Wrapped surface Glass FRP rods of diam.10mm (#3) and 13mm (#4) were used for flexural strengthening of beams. Their nominal areas are 86 mm^2 and 139 mm^2, respectively. According to the manufacturer data, the effective yield strength and ultimate tensile strength for #3 is 800MPa and 1000 MPa, respectively. And for that of #4 Glass FRP is 965MPa and 772MPa respectively. Fig. 1 shows the wrapped surface GFRP rod with vinyl-ester resins.

Figure 1 Wrapped Surface GFRP rod with Vinyl-ester resins

For the experimental investigation, a commercial available epoxy resin was used. The epoxy resin is generally available in two parts, a resin and a hardener. According to manufacturer data, its compressive strength (ASTM C 579) of 72MPa, flexural strength (ASTM C 580) of 32MPa, and tensile strength (ASTM C 307) of 18MPa were used.

C. *Test Specimens*

A total of ten small scaled reinforced concrete beams were investigated using a standard beam size of 150x150x750 mm with different reinforcement bars. Fig. 2 shows the longitudinal profile of the control beam specimen (Bo-1). Two groups of beam specimens were prepared. For the first group of specimens, Glass FRP rods of #3 (Ø10mm) and #4 (Ø13mm) were embedded in the grooves cut into the bottom concrete surface and then filled with viscous epoxy-resin paste. For the second group of specimens, only Glass FRP rods of #3 (Ø10mm) was inserted into the bottom concrete surface and then filled with cement mortar. Detailed description of beam specimens of groups one and two are shown in Tables 2 and 3, respectively.

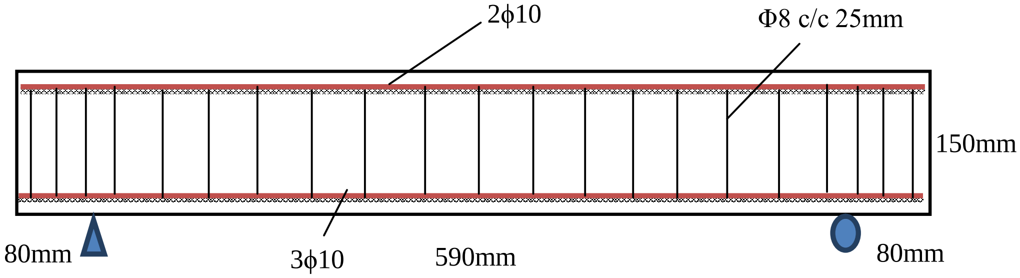

Figure 2 Longitudinal section of RC test beam Bo-1

TABLE 2

Details of group 1 beam specimens

Beam Name	Bottom bars	Top bars	FRP
Bo-1	3Ø 10	2Ø 10	-
B-1	3Ø 10	2Ø 10	2 Ø 10
B-2	3Ø 10	2Ø 10	2 Ø 10
B-3	3Ø 10	2Ø 10	2 Ø 13
B-4	3Ø 10	2Ø 10	2 Ø 13
B-5	3Ø 10	2Ø 10	1 Ø 10

TABLE 3

Details of group 2 beam specimens

Beam Name	Bottom bars	Top bars	FRP
Co-1	2Ø 8	2Ø 8	-
C-1	2Ø 8	2Ø 8	1 Ø 10
C-2	2Ø 8	2Ø 8	1 Ø 10
C-3	2Ø 8	2Ø 8	1 Ø 10

D. Flexural Testing Procedures

To test the flexural strength of the RC specimens, the beams were loaded under center-point loading test with 590 mm distance between supports following standard test method for flexural strength of concrete beams of ASTM C293 [7] and as per the recommendation of ACI 440.3R-04 "Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures" [8]. Each beam was instrumented with two LVDTs placed at mid-span on both sides of the beam. Stain gauges were also attached at the mid-span on the bottom steel rebars and FRP rods. The loading arrangement was the same for all cases. Test setup of RC beam specimens is shown in Fig. 3.

Figure 3 Test Setup of RC beam specimen

E. Strengthening of Specimens with GFRP Rods

The strengthening activities were executed with the beams in the hardened state. For the first group of specimens, installation of the NSM FRP rods began by making a series of grooves with specified location at its tension side. For the second group of specimens, prior to casting of concrete, pipes were inserted within its tensile zone, which was used for the insertion of FRP rods after the concrete has been hardened. Preparation of grooves and insertion of FRP rods are shown in Figs. 4 – 6.

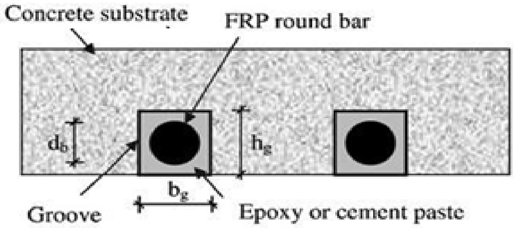

Figure 4 NSM system

Figure 5 Groove preparation

Figure 6 FRP rod inserted into the beam

III. RESULTS AND DISCUSSIONS

Based on the experimental data and measurements, the load displacement curves of the test beam specimens are shown in Figs. 7 and 8, respectively.

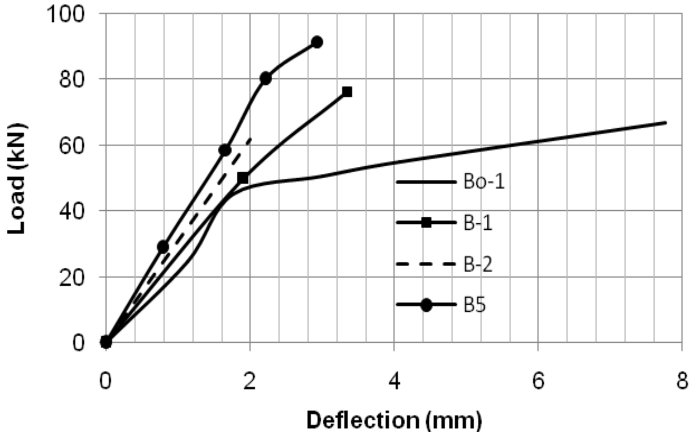

Figure 7 Load- Deflection Curves of RC beams (group 1)

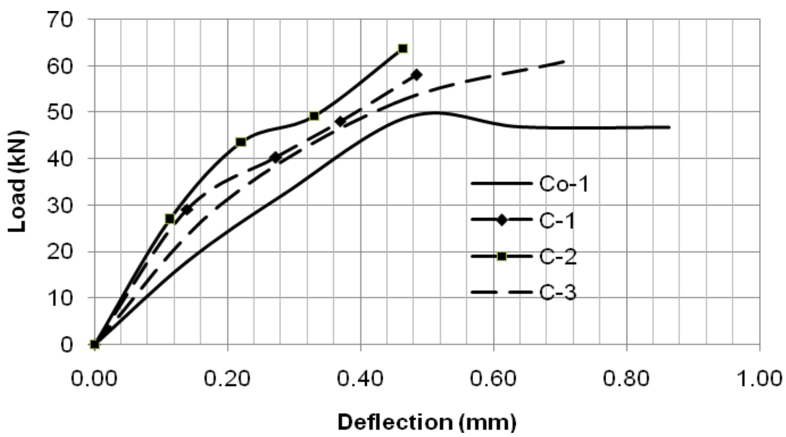

Figure 8 Load- Deflection Curves of RC beams (group 2)

Summary of test results of groups 1 and 2 of test beams are presented in Table 4 and Table 5, respectively. In the tables, increments in section capacity of strengthened beams are also presented. The control beams (Bo-1 and Co-1) have reached failure upon yielding of the reinforcing bars. After yielding, the control beams had a flat load-deflection behavior, whereas in the strengthened beams, yielding of the steel rebar led to a reduction in slope, but the GFRP rods allowed the beams to withstand additional load.

TABLE 4
Summary of results (group 1 beams)

Beam Name	Ultimate Load (kN)	Increment (%)	Remarks
Bo-1	82.1	-	Flexural failure
B-1	97.1	18.27	Flexure and debonding of the GFRP
B-2	93.8	14.25	Flexure and debonding of the GFRP
B-3	103.1	25.58	Shear before yielding of reinforcing steel
B-4	98.3	19.73	Shear before yielding of reinforcing steel
B-5	90.86	10.67	Flexure and debonding of the GFRP

Table 5. Summary of results (group 2 beams)

Beam Name	Ultimate Load (kN)	Increment (%)	Remarks
Co-1	45.4	-	Flexural failure
C-1	56.7	24.89	Flexural failure
C-2	59.3	30.62	Flexural failure
C-3	61.6	35.68	Flexural failure

As shown in Figs. 7 and 8, due to the NSM FRP strengthening, a moderate increase in stiffness was achieved on the region between cracking of the concrete and yielding of the steel bars. In terms of strength and stiffness, the strengthened beams with NSM bonded FRP system performed significantly better than the control (un-strengthened) beam. The strength of RC beams reinforced with NSM FRP system is influenced by the concrete strength of the beams, the amount of NSM FRP rods used and the adhesion used between the concrete and the FRP.

The attached GFRP rods worked as a tensile reinforcement and shared the applied load with the internal steel reinforcement. The load at which the FRP yielded was higher for the strengthened beam, proposing that internal resistance forces were shared between the steel and FRP. Most of the increase in load-carrying capacity was obtained after the rebar yielding point, indicating that GFRP rod works efficiently in tension after yielding of the rebar.

Failure, cracking patterns of different beam specimens are shown in Figs. 9-10. The load-rebar strain responses are shown in Figs. 11 and.12. These strain data were recorded using the electrical resistance strain gauges and these data terminated at the points where the gauges lost their effectiveness.

Figure 9 Failure and cracking pattern of specimen

Figure 10 Debonding of GFRP rod

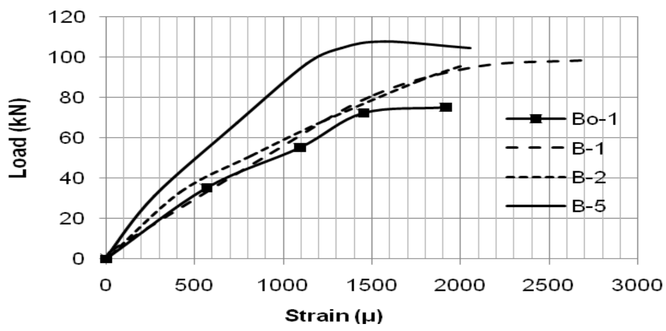

Figure 11 Load- Strain Curves of RC beam specimens (group 1)

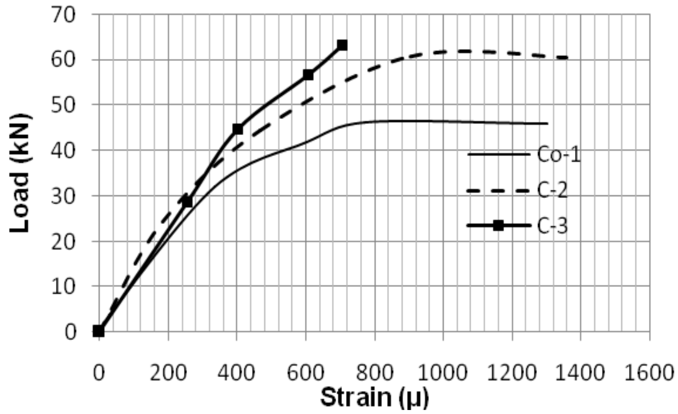

Figure 12 Load- Strain Curves of RC beam specimens (group 2)

IV. CONCLUSIONS & RECOMMENDATIONS

A. Conclusions

An experimental investigation on the performance of RC beams strengthened with NSM GFRP was carried out. The test results confirmed that an increment in flexural capacity of the RC beams was achieved after the beams have been strengthened with NSM GFRP rods. These results showed that NSM GFRP rods can be used to significantly increase the flexural load carrying capacity of RC elements which implies that this technique can be applied for repairing and strengthening of damaged RC beams.

B. Recommendations

From the study that has been carried out, the following recommendations are drawn:

1) Full scale beam specimens to check the actual behavior for the NSM FRP retrofitted or repaired RC member properties.
2) Cost analysis on the different methods of maintenance of structures to be done.
3) Usage of advanced chemical bonding epoxy adhesive filler material can give better results and should be considered.
4) Further tests on pullout tests are recommended.
5) Further study on anchorage systems to minimize debonding effects.
6) Proposing the idea of leaving space within the structural member for further maintenance and repairing.

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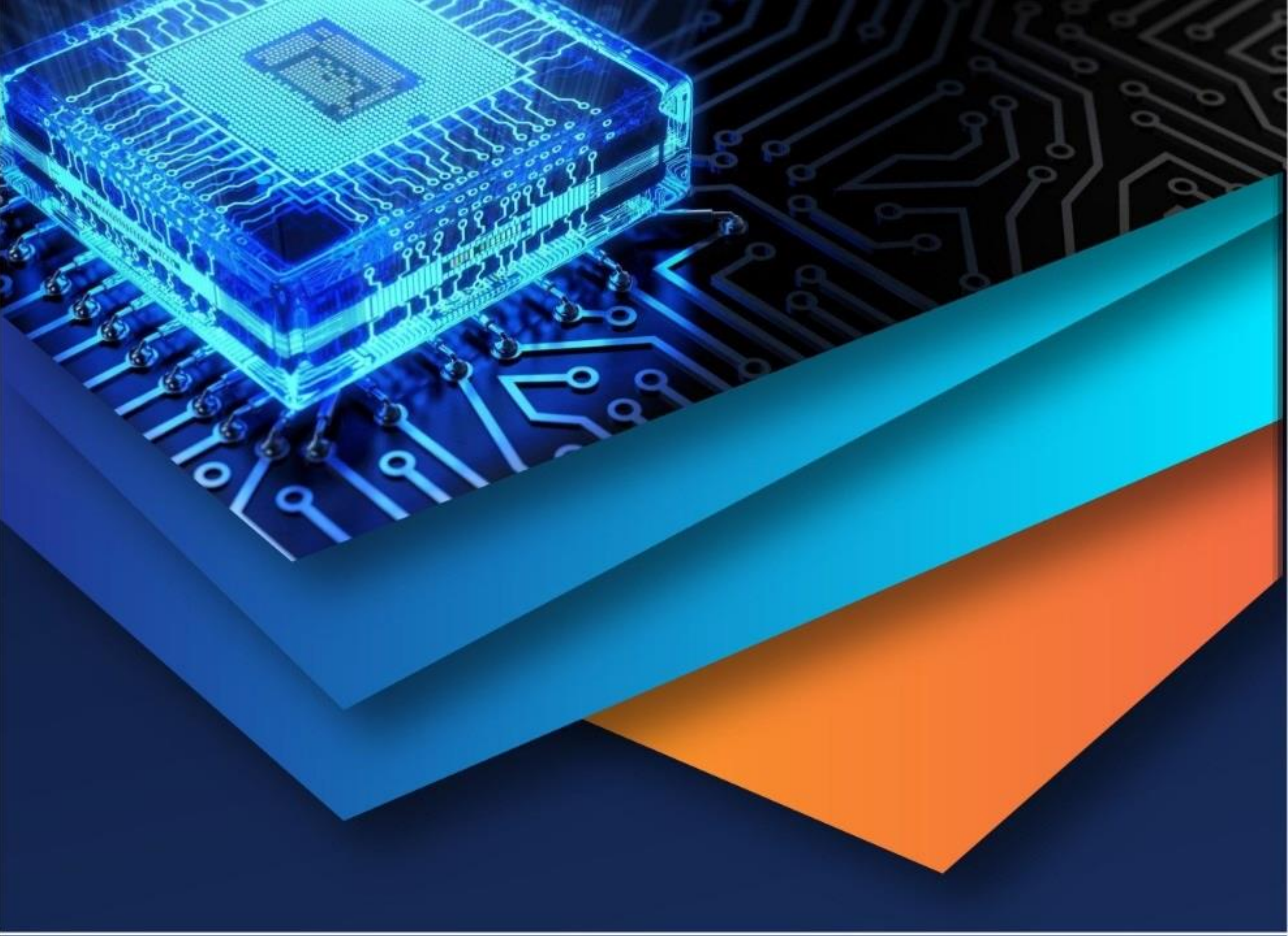

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