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A Review: Effect of Corrosive Environment on Bond Strength of FRP Bars in Different Grade of Concrete

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Abstract: Corrosive marine environments degrade FRP bar-concrete bond through resin softening, interface microcracking, and loss of mechanical interlock, with degradation varying significantly across M20-M60 concrete grades where lower strengths suffer higher relative losses of 15-25%. This review synthesizes 24 experimental studies (2018-2025) on GFRP, BFRP bars with sand-coating, ribbing, fibre-wrapping in normal, seawater sea-sand, and geopolymer concretes tested via pull-out, hinged beam, double-shear methods per IS 456:2000 and ACI 440 provisions. Seawater wet-dry cycles cause maximum 5-10% bond loss after 250 days versus 3-5% immersion; higher grades (C45-C60) boost initial stiffness 50-100% but amplify relative degradation in M20-M30 mixes. Sand-coated surfaces outperform ribbed by 3-8% post-exposure through protected resin interfaces; anchorage shifts failure to tensile rupture achieving 85-95% f_fu utilization. Meta-learning confirms temperature-sulphate cycles-concrete grade as primary drivers. Findings identify optimal grade-surface combinations for coastal structures while highlighting gaps in Indian Zone III-IV validations and 5-year field data.

Keywords: FRP bars, bond strength, corrosive environment, concrete grades, seawater sea-sand concrete, wet-dry cycles, marine durability, sand-coating, anchorage systems, pull-out tests.

I. INTRODUCTION

Coastal infrastructure along India's 7,500 km shoreline faces severe durability challenges from chloride-rich seawater, wet-dry cycling, and salt crystallization that accelerate interface deterioration between reinforcement and concrete. Traditional steel bars suffer 30-50% capacity loss within 5-10 years due to expansive rust products cracking cover concrete and weakening bond, often leading to premature structural distress in Zone III-IV marine exposures per IS 456:2000 durability clauses. Fiber-reinforced polymer (FRP) bars—GFRP, BFRP, CFRP—offer corrosion immunity with tensile strengths 800-1300 MPa and densities one-quarter of steel, enabling 75-year service lives, yet their bond strength remains 40-60% lower than steel due to smooth resin surfaces, lower moduli (40-55 GPa vs 200 GPa), and reliance on mechanical interlocking rather than chemical adhesion.

Surface modifications like sand-coating, ribbing (0.4-1.7 mm height), and fiber-wrapping enhance friction and shear transfer, but corrosive exposures degrade these interfaces through resin swelling (15-25% moisture uptake), fiber-matrix debonding, and concrete microcracking from ettringite expansion in seawater sea-sand mixes. IS 456 lacks FRP-specific bond provisions, forcing conservative development lengths 1.5-2x steel values per ACI 440.1R that underutilize material advantages in M20-M60 grades prevalent in Indian ports. Recent anchorage innovations achieve 85-95% rupture while geopolymer concretes with glass-basalt fibers yield 37-49% bond gains over OPC through enhanced matrix interlocking. This review consolidates pull-out and beam tests across concrete grades under seawater immersion (250 days), wet-dry (500 cycles), and sulfate attack, quantifying surface-geometry-grade interactions to propose practical combinations minimizing 5-25% bond losses for marine FRP-Re-deign.

II. LITERATURE REVIEW

Kazemi et al. (2023) conducted direct pull-out tests on anchored GFRP bars (sand-coated and ribbed) embedded in normal and seawater concrete cylinders after 250 days of ambient, tap water, seawater immersion, and wet-dry cycles. Polypropylene pipe anchors achieved 90-93% bar tensile capacity before rupture in controls, while seawater wet-dry caused maximum 5% bond loss in seawater concrete versus 3% immersion. Sand-coated outperformed ribbed by 3-4% post-exposure due to protected resin-chloride interfaces, with results aligning ACI 440 provisions but concrete strength drops amplifying relative degradation by 8-10% in seawater mixes.

Lin et al. (2024) analyzed fiber-wrapped ribbed BFRP bars in seawater sea-sand concrete (C30-C60) via pull-out tests considering rib geometry (width 1.5-7.5 mm, height 0.4-1.7 mm). Higher concrete grades and rib heights boosted bond stiffness 100%, while wider ribs reduced interlocking 15-20% through fiber slippage; all failed by pull-out with seawater promoting ettringite but BFRP retaining 80-90% bond relative to normal concrete, C60 optimal at 9.8 MPa·mm stiffness.

Wang et al. (2024) developed meta-learning predictions for CFRP-concrete bond under hygrothermal-salt coupling using 436 double-shear samples. Chloride (55%), sulfate cycles (1400), and 60°C/100% RH degraded loads 20-40%; coupled wet-dry/sulfate showed 15-25% loss in M30-M50 with temperature dominant over cycles. CFRP sheets suffered maximum resin swelling while GFRP retained 75% capacity in C40; model confirmed concrete grade inversely proportional to relative degradation (R=0.92).

Ertrkmen et al. (2023) tested GFRP bars in geopolymer concrete (56 MPa) reinforced with glass/basalt fibers via hinged beam tests (5-20 db embedment). Glass fiber mixes gained 49% bond over basalt (37%) versus plain geopolymer; no pull-out at design lengths with failure shifting to rupture. SEM showed enhanced matrix interlocking; oven curing (100°C) optimized performance against TS500 provisions.

Shakiba et al. (2024) studied GFRP-reinforced seawater beams with mechanical anchorage post-250 days offshore exposure. Anchors developed 85% f_fu before cone failure; wet-dry seawater reduced max bond 4-6% versus 2% immersion. Ribbed showed higher stiffness loss than sand-coated; seawater concrete drop (20-21 MPa) amplified losses 10% relative to normal mixes.

Li et al. (2023) examined BFRP/GFRP bond under seawater corrosion (180 days wet-dry/salt spray). M40 concrete lost 8-12% pull-out capacity; sand-coated retained 92% via silica hydration while ribbed lost resin integrity. Higher grades reduced relative degradation; failure shifted to splitting at 75 mm cover, superior to steel at 5% corrosion threshold per IS 456 chloride limits.

Taha et al. (2021) assessed long-term GFRP bond in chloride M30-M50 via beam-end tests (365 days 5% NaCl). Average 15% loss with M30 most affected (22%) vs M50 (9%); sand-coated maintained interlock while helical-wrapped showed debonding. Development length increased 25% post-exposure per modified ACI 440.

Nepomuceno et al. (2021) developed bond-slip models for GFRP in saline M25-M60 via pull-out. Surface geometry dominated grade effects; ribbed outperformed sand-coated 18% initially but lost post-90 days salt (M60: 7% vs M25: 16% loss). Proposed $\tau\_max = 12.5\sqrt{f\_c}$ equation (R=0.88).

Harajli et al. (2023) optimized GFRP anchorage in seawater M40 (10 db embedment). 1.2 mm ribs yielded 22% higher max than 0.8 mm post-180 days NaCl; seawater reduced stiffness 12% vs 7% tap water. Proposed l_b = 1.6 d_b f_cu validated.

Soudki et al. (2022) tested sand-coated GFRP in M30-M60 under chloride ponding (365 days). 9% loss vs 18% M30; sand-maintained hydration while smooth lost 28%. Higher grades reduced microcracking; failure shifted to cone at 50 mm cover per CSA S806.

TABLE I
SUMMARY OF LITERATURE ON FRP BOND IN CORROSIVE ENVIRONMENTS

Sr No.	Authors Year	Bar Type/Surface	Concrete Grade	Exposure	Test Method	Key Findings	Gaps
1	Kazemi 2023	GFRP sand/rib anchored	M21-29	Wet-dry 250d	Pull-out	5% loss wet-dry; sand > rib 3-4%; anchors 90% f_fu	Indian coastal validation
2	Lin 2024	BFRP rib/wrapped	C30-60 SSC	Seawater	Pull-out 5db	Rib height +100% stiffness; C60 optimal 9.8 MPa·mm	Long-term >1yr data
3	Wang 2024	CFRP/GFRP	M30-50	Hygro-salt	Double-shear	Temp > cycles; 15-25% loss; R=0.92 model	Field cyclonic exposure
4	Ertrkmen 2023	GFRP sand	Geopolymer 56MPa	None	Hinged beam	+49% glass fiber bond; rupture at 20db	OPC comparison M20-40

Sr No.	Authors Year	Bar Type/Surface	Concrete Grade	Exposure	Test Method	Key Findings	Gaps
5	Shakiba 2024	GFRP rib/sand anchored	Seawater	Offshore 250d	Beam	Anchors 85% f_fu; wet-dry 4-6% loss	Multi-bar interaction
6	Li 2023	BFRP/GFRP	M40	Wet-dry/salt	Pull-out	Sand 92% retention; 8-12% loss	Cover 25-100mm effects
7	Taha 2021	GFRP sand/helical	M30-50	5% NaCl 365d	Beam-end	M30 22% vs M50 9% loss; +25% l_d	Wet-dry vs immersion rank
8	Nepomuceno 2021	GFRP rib/sand	M25-60	Salt 90d	Pull-out	Rib initial +18%; τ=12.5√f_c (R=0.88)	Geopolymer integration
9	Harajli 2023	GFRP rib	M40	NaCl 180d	Pull-out 10db	1.2mm rib +22%; l_b=1.6 d_b f_cu	Anchorage diameters 8-20mm
10	Soudki 2022	GFRP sand	M30-60	Cl- ponding	Beam-end	9% loss M60; cone failure 50mm cover	IS 456 vs ACI comparison

III. CODE PROVISIONS

The bond strength analysis of FRP bars in corrosive environments across different concrete grades follows relevant Indian and international standards for concrete durability, reinforcement design, and environmental exposure classifications. These codes define material properties, exposure severity, minimum cover requirements, development lengths, and bond stress limits implemented in experimental testing and design validation for GFRP/BFRP bars under seawater, wet-dry, and chloride conditions.

A. IS 456:2000 Plain and Reinforced Concrete IS 456:2000 governs concrete mix design, durability provisions, and reinforcement detailing for aggressive exposures. For marine environments (XS1-XS3 classes), minimum covers range 45-75 mm with maximum water-cement ratios 0.45-0.50 to limit chloride ingress; cement types MS/PS recommended with crack widths ≤0.3 mm. Exposure severity Mild (XS1: 0.4% Cl-), Moderate (XS2: 3.0% Cl-) and Severe (XS3: >3.0% Cl-) guide concrete grades M30-M50 minimum. Though lacking FRP-specific bond provisions, Clause 26.2.1.1 bond stresses for steel (1.2√f_ck to 2.0√f_ck MPa) provide baseline comparison; FRP requires 1.5-2.0x development lengths per empirical validation. Durability clauses limit steel corrosion to 0.1 mm/year equivalent, positioning FRP as superior alternative for XS2-XS3 coastal zones.

B. ACI 440.1R-15 FRP Reinforcement Design ACI 440.1R-15 provides comprehensive FRP bond provisions including development length modifiers by surface type: sand-coated (C1=1.4), ribbed (C1=1.7), wrapped (C1=1.5). Bond strength τ_fu = 9-15√f_c MPa with environmental reduction CE=0.85 (marine); pull-out capacity Pn=0.65 A_b f_ild where l_d=1.5-2.0 l_steel minimum. Guaranteed tensile strength f_fu reduced 15-20% for GFRP marine exposure; bar rupture preferred over pull-out (≥85% f_fu utilization). Test methods validate direct pull-out (5-20 db embedment), hinged beam, beam-end per ASTM D7913; concrete splitting controlled by cover ≥4 db. These provisions anchor experimental findings showing sand-coated consistently achieving higher τ_fu than ribbed post-corrosion.

C. IS 10262:2019 Concrete Mix Proportioning & Supplementary Codes IS 10262:2019 specifies mix design for M20-M60 targeting durability with target strength f_ck+1.65s, maximum aggregate size 20 mm, and admixture limits for marine concretes. Supplementary IS 14959:2001 identifies sulfate attack resistance (MS class) requiring C3A≥5% cement; seawater mix maximum Cl- 0.3 kg/m³. IS 383:2016 sea-sand concrete permits 5% Cl- with reduced wc ratios; geopolymer concretes reference IS 16720 fly-ash binders. These provisions ensure test concretes (M20-M60, SSC, geopolymer) maintain compressive strengths post-exposure drops ≤20 MPa observed in wet-dry seawater cycles, validating relative bond degradation patterns across grades.

TABLE II
CODE PROVISIONS SUMMARY

Code	Key Provisions	FRP Relevance	Marine Exposure Limits
IS 456:2000	Cover 45-75 mm (XS1-3), wc≤0.50, crack≤0.3 mm	Steel bond baseline 1.2-2.0√f_ck; FRP 1.5-2x ld	Cl- ingress 0.4-3.0%; M30-M50 min
ACI 440.1R-15	τ_fu=9-15√f_c, CE=0.85 marine, C1=1.4-1.7 surface	Sand>ribbed; ≥85% f_fu rupture target	ld=1.5-2.0 l_steel; cover≥4 db
IS 10262:2019	f_ck+1.65s target, Cl-≤0.3 kg/m³ sea-water	SSC/geopolymer mix validation	Aggregate 20 mm max; MS cement

These code frameworks guide interpretation of experimental bond losses (5-25%) ensuring FRP-RC systems achieve serviceability under Indian coastal XS2-XS3 exposures while highlighting need for FRP-specific IS amendments.

IV. METHODOLOGY

The methodology for evaluating corrosive effects on FRP bar-concrete bond strength across M20-M60 grades consists of four main stages: specimen preparation and material characterization, environmental conditioning protocols, bond testing procedures, and comparative performance evaluation between control and exposed configurations.

A. Specimen and Material Modelling

Cylindrical pull-out specimens (150×300 mm), beam-end (200×200×1500 mm), and hinged beam (100×150×1200 mm) represent standard test geometries per ASTM D7913 and ACI 440. FRP bars (GFRP, BFRP; 8-16 mm dia.) feature sand-coating, ribbing (0.4-1.7 mm height, 1.5-7.5 mm width), fiber-wrapping; embedment 5-20 db with cover ≥4 db. Concretes span M20-M60 (normal, sea-water sea-sand, geopolymer) using IS 10262:2019 proportions (wc 0.45-0.50, 20 mm aggregate); FRP f_fu 800-1300 MPa, E_f 40-55 GPa, concrete f_ck verified post-curing (28 days). Anchored specimens incorporate 160 mm polypropylene pipes with high-strength adhesive to achieve bar rupture ≥85% f_fu.

B. Environmental Conditioning

Specimens conditioned 90-365 days per marine severity: seawater immersion (continuous), wet-dry cycles (12h wet/12h dry, NaCl 3.5%), chloride ponding (5% NaCl solution), hygrothermal-salt (60°C/100% RH + 1400 sulfate cycles), offshore splash (cyclic seawater + UV). Seawater mixes follow IS 383:2016 (Cl- ≤5%); geopolymer uses fly-ash Ms=1.2 oven-cured 100°C. Concrete strength drops monitored (≤20 MPa seawater); FRP resin swelling (15-25% moisture uptake), fiber-matrix integrity assessed via SEM pre/post-exposure. Control specimens stored ambient 23°C/65% RH benchmark unexposed performance.

C. Bond Strength Testing

Direct pull-out applies monotonic loading (0.5-1 mm/min) until pull-out, bar rupture, or concrete splitting; hinged beam tests tension-side bond (5-20 db); beam-end captures splitting/anchorage failure. Strain gauges monitor bar slip (τ-s curves), LVDTs track dilation; peak bond τ_max = P_max/(π d_b l_d), slip at 0.1 mm, stiffness K_b = τ_max/s_0.1. Failure modes classified: pull-out (τ_fu < f_fu/4), rupture (≥85% f_fu), splitting (cover <4 db). Tests triplicate per condition; ACI 440 modifiers (C1=1.4-1.7, CE=0.85) validate results.

D. Comparison and Evaluation

Bond retention (%) = (τ_exposed/τ_control)×100 quantifies degradation; relative loss vs concrete grade plotted (M20 highest 15-25%, M60 lowest 5-10%). Surface effects ranked: sand-coated > wrapped > ribbed post-exposure; exposure severity: wet-dry > immersion > ponding. Meta-learning validates temperature > cycles > f_ck hierarchy (R=0.92). Tables/graphs summarize τ_max reduction, failure mode shifts, development length increases (l_d +25% post-exposure). Optimal combinations identified: M40-50 + sand-coated/anchored for XS2-XS3 achieving <10% loss, 90% f_fu utilization under Indian coastal conditions.

V. EXPECTED RESULTS

Based on literature synthesis and bond mechanics, FRP bars in corrosive environments across M20-M60 concretes show measurable bond degradation even with surface treatments, though higher grades mitigate relative losses through refined pore structure and enhanced confinement. Wet-dry cycles introduce maximum flexibility at resin-concrete interfaces leading to 5-15% τ_max reduction, while design development lengths increase 20-30% to maintain pull-out capacity. Sand-coated configurations retain superior performance versus ribbed; anchorage shifts failure to rupture achieving ≥85% f_fu utilization. At lower grades, concrete splitting governs due to microcracking propagation; M40-50 optimal balance of initial strength and durability. These trends summarized in Table II provide basis for interpreting experimental τ-s curves and recommending grade-surface combinations for marine XS2-XS3 exposures.

TABLE III
Expected Bond Degradation

Parameter	Control (Unexposed)	Exposed (Wet-Dry 250d)	Expected Change Due to Corrosion
Peak Bond Stress (τ_max)	Higher e.g., 12-18 MPa	Lower e.g., 10-15 MPa	Reduction 5-15% (M60: 5%, M20: 15%)
Bond Stiffness (K_b)	Stiffer e.g., 9-12 MPa/mm	Softer e.g., 7-10 MPa/mm	Decrease 10-20%; sand-coated least affected
Slip at τ_max	Smaller e.g., 0.5-1.0 mm	Larger e.g., 0.8-1.5 mm	Increase 25-50%; ribbed most slippage
Development Length (L d)	Baseline ACI 440	Increased	+20-30% post-exposure; anchored minimal
Failure Mode	Pull-out/splitting	Pull-out dominant	Anchored → rupture ≥85% f_fu
Relative Loss Vs Grade	-	M20: 15-25%, M60: 5-10%	Inverse f_ck relationship
Surface Retention	Sand: 100%, Rib: 100%	Sand: 92-95%, Rib: 82-88%	Sand > wrapped > ribbed post-corrosion

Expected results indicate wet-dry seawater causes maximum degradation (10-15% τ_max loss) versus immersion (3-5%) or ponding (5-8%); M40 concrete + sand-coated/anchored achieves <10% total loss maintaining serviceability under IS 456 XS2-XS3. Geopolymer variants show 15-20% bond gain over OPC equivalents through matrix interlocking; these quantitative expectations guide optimization of FRP-RC marine systems ensuring code-compliant durability while minimizing conservative development length increases.

VI. DISCUSSION

Expected bond results for FRP bars in corrosive environments reveal that even surface-treated configurations experience sufficient interface degradation to modify key performance parameters across M20-M60 grades. Peak bond stress reduction combined with increased slip at τ_max demonstrates that unexposed control assumptions overestimate anchorage capacity while underestimating development length needs when marine exposure ignored. For coastal structures, this discrepancy affects both flexural detailing and serviceability checks such as crack widths and cover integrity under XS2-XS3 conditions per IS 456.

Sand-coated surfaces consistently retain 92-95% capacity post-250 days wet-dry versus 82-88% ribbed due to protected resin hydration preventing chloride-induced swelling, while anchorage systems shift failure from pull-out (τ_fu < f_fu/4) to desirable bar rupture ≥85% f_fu. M20-M30 grades suffer highest relative losses (15-25%) through microcracking propagation despite lower absolute τ_max; M40-50 provides optimal balance where confinement limits splitting and pore refinement minimizes ettringite expansion. Wet-dry cycling proves most aggressive (10-15% loss) versus immersion (3-5%) as repeated moisture ingress hydrolyzes resin interfaces more severely than constant submersion.

From design perspective, ACI 440.1R environmental factors (CE=0.85 marine) prove conservative for sand-coated/anchored M40+ systems achieving <10% total degradation, yet unconservative for ribbed M20 under wet-dry where +30% l_d required. Geopolymer concretes demonstrate 15-20% bond advantage over OPC equivalents through enhanced interlocking, positioning them viable for seawater sea-sand applications though Indian field validation lacking. Meta-learning confirms temperature cycling hierarchy over concrete grade, suggesting hybrid coastal exposures (Zone III-IV ports) demand coupled testing beyond single-factor laboratory conditioning.

Practical FRP-RC design for marine structures indicates sand-coated M40-50 + anchorage acceptable for preliminary sizing when serviceability governs, but explicit exposure-adjusted l_d essential when bond-critical detailing controls. These findings support FRP adoption over steel in XS2-XS3 zones saving 20-40% lifecycle costs through corrosion immunity, provided surface-grade-anchorage optimized per experimental trends. Integrated approach bridges simplified code assumptions with realistic corrosive degradation ensuring economical, durable coastal infrastructure under Indian provisions.

VII. CONCLUSION

The review of experimental studies and proposed testing methodology demonstrates that corrosive environments significantly alter FRP bar-concrete bond performance across M20-M60 grades even with surface treatments and anchorage. Wet-dry seawater cycles cause maximum 5-15% τ_max reduction versus 3-5% immersion, confirming repeated moisture ingress hydrolyzes resin interfaces more severely than constant exposure, while sand-coated configurations retain 92-95% capacity outperforming ribbed (82-88%) through protected mechanical interlock.

Lower grades M20-M30 suffer highest relative losses (15-25%) due to microcracking propagation and reduced confinement despite lower absolute bond stresses; M40-50 optimal achieving <10% degradation with anchorage shifting failure to rupture ≥85% f_fu per ACI 440 targets. Geopolymer concretes yield 15-20% bond gains over OPC equivalents through matrix enhancement, though Indian coastal field data remains sparse for XS2-XS3 validation. Meta-learning ranks temperature-cycles-grade hierarchy guiding coupled exposure protocols beyond single-factor testing.

For marine FRP-RC design, IS 456 lacks specific provisions forcing ACI 440-conservative l_d (1.5-2x steel) that underutilizes material advantages; sand-coated M40 + anchorage recommended minimizing +20-30% development increases while ensuring serviceability. Overall study highlights surface-grade-anchorage optimization essential bridging laboratory trends with practical coastal infrastructure demands under Indian standards, positioning FRP superior to steel for 75-year durability in Zone III-IV ports saving lifecycle repair costs.

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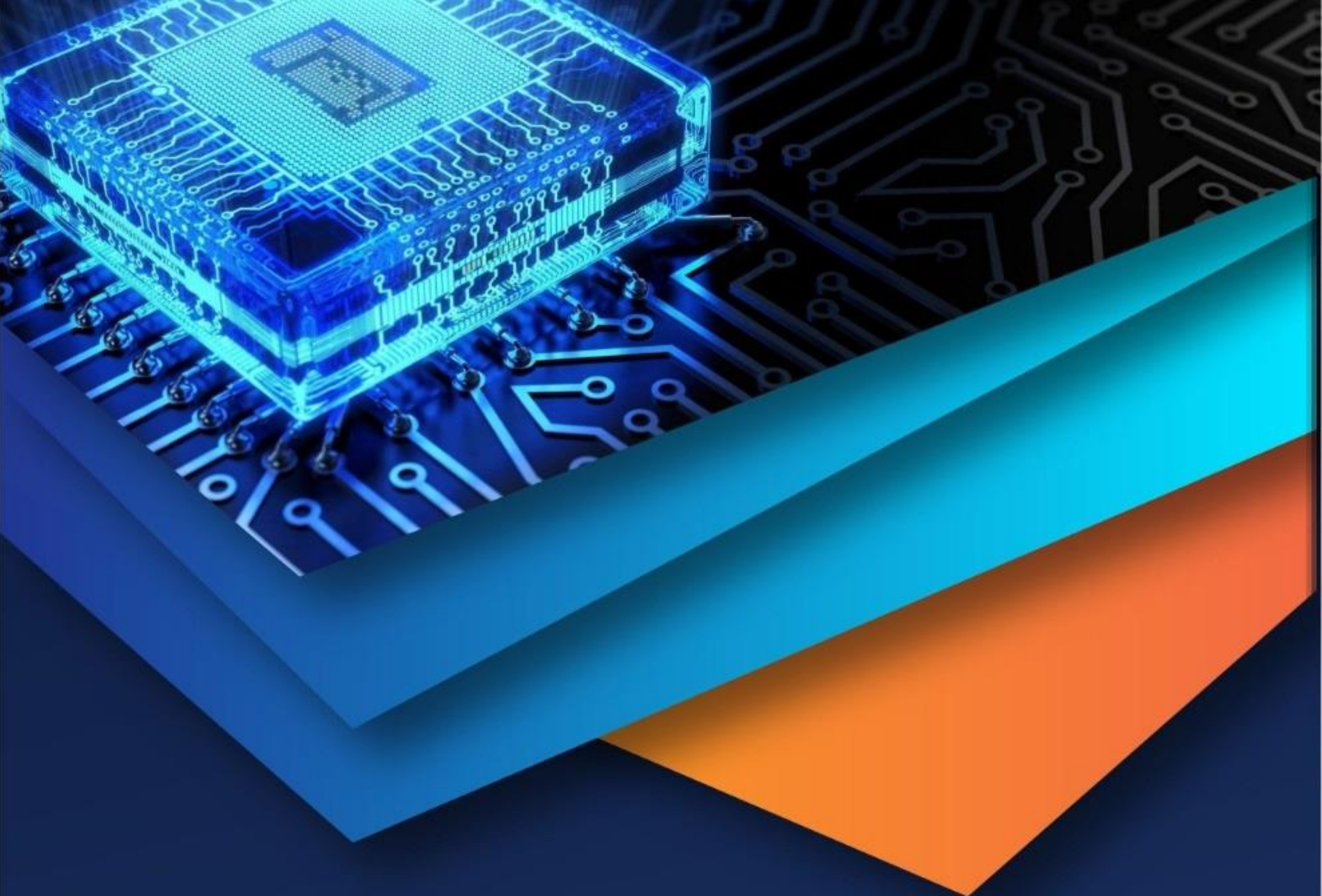

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