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Review on Experimental and Analytical Investigation of Advanced Retrofitting Techniques for Fire-Damaged RCC Structures Incorporating Self-Healing Polymers and Fire-Resistant Coating Systems

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Abstract: Fire-induced deterioration significantly reduces the strength, durability, and serviceability of reinforced cement concrete (RCC) structures due to irreversible damage to concrete and reinforcing steel. Conventional repair methods often provide only partial restoration and require frequent maintenance. This study presents a comprehensive investigation of advanced retrofitting techniques incorporating self-healing polymers and fire-resistant coating systems for rehabilitating fire-damaged RCC structures. The review covers recent developments in fiber-reinforced polymers (FRP), ultra-high-performance fiber-reinforced concrete (UHPFRC), strain-hardening cementitious composites (SHCC), basalt fiber engineered geopolymer composites (BFEGC), cementitious repair mortars, and intelligent self-healing materials. Experimental evaluation includes compressive strength, flexural behavior, bond performance, crack-healing efficiency, ultrasonic pulse velocity, and residual durability after exposure to 400–900°C. Analytical investigations employ finite element modeling and thermo-mechanical simulations to predict structural performance. The findings demonstrate that advanced retrofitting systems substantially improve post-fire strength, crack resistance, durability, and long-term resilience, offering sustainable solutions for repairing fire-damaged RCC infrastructure.

Keywords: Fire-damaged RCC structures; Structural retrofitting; Self-healing polymers; Fire-resistant coatings; Fiber reinforced polymer.

I. INTRODUCTION

Reinforced cement concrete (RCC) structures constitute the backbone of modern infrastructure, supporting residential buildings, bridges, industrial facilities, tunnels, and transportation networks. Despite concrete being inherently non-combustible, exposure to elevated temperatures during fire substantially reduces its mechanical properties. Concrete experiences dehydration, thermal cracking, explosive spalling, and reduction in compressive strength, while reinforcing steel loses yield strength and stiffness as temperatures exceed 500°C. Consequently, many fire-damaged structures require rehabilitation rather than demolition to reduce economic losses and environmental impacts.

Traditional repair methods such as concrete jacketing, steel plate bonding, epoxy injection, and shotcrete have been widely implemented for restoring structural performance. Although these techniques improve load-carrying capacity, they often suffer from durability concerns, incompatibility with existing concrete, susceptibility to corrosion, and limited effectiveness under repeated thermal loading. Recent advances in construction materials have therefore focused on developing intelligent repair systems capable of autonomously repairing cracks while simultaneously resisting future fire exposure.

Self-healing polymers have emerged as a revolutionary technology in concrete rehabilitation. These materials contain encapsulated healing agents or bacteria that activate upon crack formation, sealing microcracks and restoring structural continuity. Simultaneously, fire-resistant coating systems—including intumescent coatings, ceramic-based coatings, and geopolymer protective layers—act as thermal barriers that delay heat transfer into structural components. The combination of autonomous crack repair with thermal protection offers a multi-functional solution capable of improving both residual strength and long-term durability.

In parallel, computational techniques such as finite element analysis (FEA), computational fluid dynamics (CFD), and machine learning have significantly enhanced the ability to predict structural behavior under fire conditions. Numerical models enable engineers to estimate temperature distribution, crack propagation, stress redistribution, and failure mechanisms before implementing rehabilitation strategies. Such analytical approaches complement experimental investigations and reduce the cost associated with full-scale fire testing.

Therefore, this study proposes an integrated experimental and analytical framework for evaluating advanced retrofitting techniques incorporating self-healing polymers and fire-resistant coating systems. By synthesizing recent developments in repair materials, structural assessment, and numerical simulation, the research aims to establish effective rehabilitation strategies capable of restoring structural integrity, enhancing durability, and extending the service life of fire-damaged RCC structures.

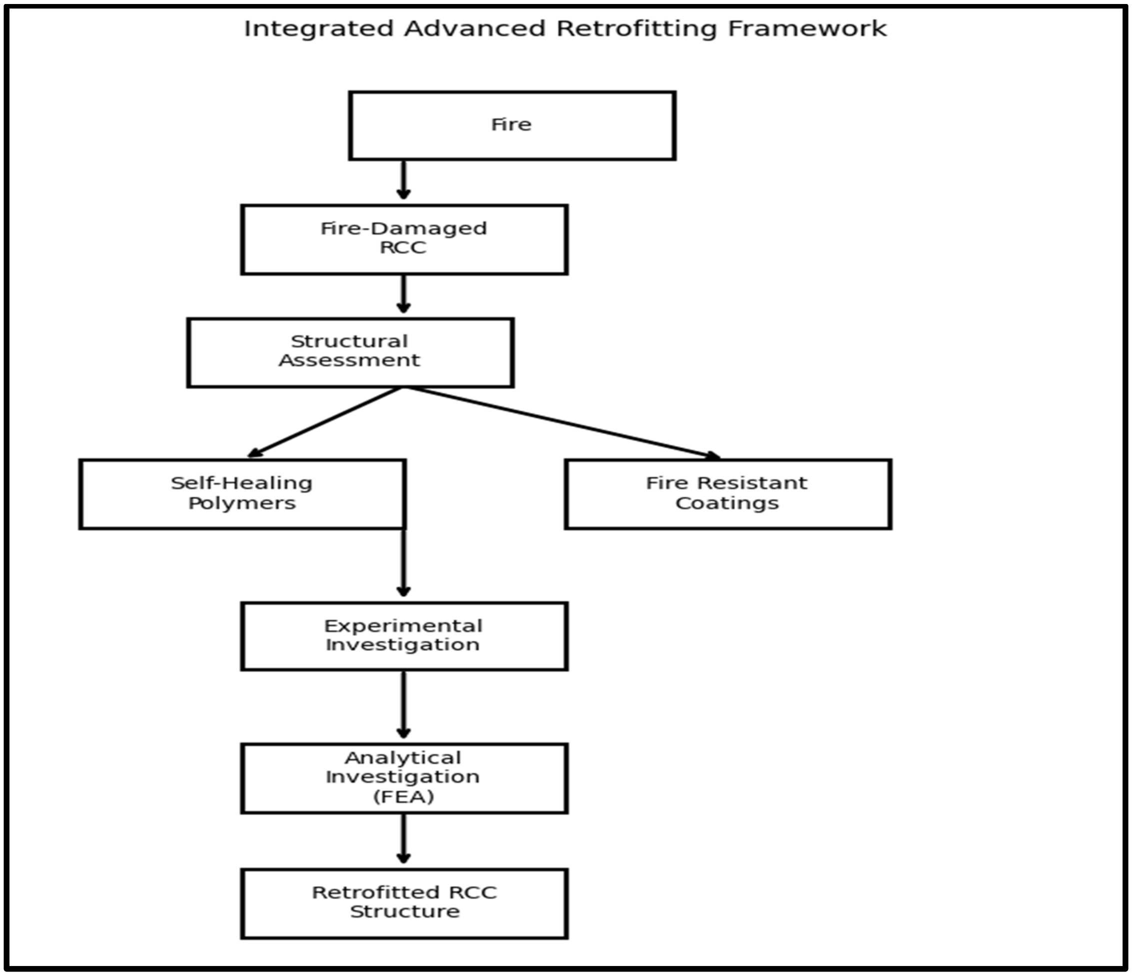

Figure 1. Integrated Framework for Experimental and Analytical Investigation of Fire-Damaged RCC Structures

II. LITERATURE REVIEW

Vedrtnam et al. (2025) experimentally and numerically investigated post-fire self-healing concrete to improve the durability of fire-damaged structures. The study demonstrated that self-healing mechanisms effectively reduced crack propagation, restored mechanical performance, and enhanced long-term durability after elevated temperature exposure. Numerical simulations closely matched experimental observations, confirming the potential of self-healing concrete for sustainable post-fire rehabilitation.

Bhadauria et al. (2025) presented a comprehensive review of innovative fire-resistant building materials, focusing on advanced cementitious composites, fiber-reinforced materials, geopolymers, and protective coatings. The review highlighted that integrating fire-resistant materials with sustainable construction practices significantly improves thermal stability, structural integrity, and service life while reducing maintenance requirements.

Das (2025) investigated the bond behavior between reinforcing steel and concrete after fire exposure using experimental testing and numerical modeling. The study reported substantial bond degradation with increasing temperature due to microcracking and deterioration of the concrete-steel interface. The developed numerical model accurately predicted post-fire bond performance and can assist in structural assessment and rehabilitation planning.

Akeed et al. (2025) reviewed the structural performance and rehabilitation of reinforced concrete elements exposed to elevated temperatures. The study emphasized the effectiveness of advanced repair materials, fiber-reinforced composites, and strengthening techniques in restoring strength, ductility, and durability of fire-damaged concrete structures, thereby improving their post-fire serviceability.

P. Ms (2025) evaluated reinforced concrete columns strengthened using a basalt fiber-reinforced polymer (BFRP)-based basalt fiber engineered geopolymer composite (BFEGC) system under fire and cooling conditions. The results showed significant improvements in load-carrying capacity, crack resistance, and residual structural performance, demonstrating the suitability of the BFRP-BFEGC system for fire-damaged structural rehabilitation.

Nair and Akbar (2025) reviewed the fire resistance of structures subjected to post-earthquake fire scenarios. The study discussed the combined effects of seismic damage and subsequent fire exposure on structural safety and highlighted the importance of resilient materials, performance-based design, and advanced retrofitting techniques for enhancing structural resilience against multi-hazard events.

Ezziane et al. (2025) investigated the behavior of concrete subjected to elevated temperatures and evaluated suitable rehabilitation strategies for restoring structural performance. The study reported that advanced repair materials and optimized strengthening techniques effectively improved residual mechanical properties, crack resistance, and durability following fire exposure.

Martin et al. (2022) examined the susceptibility of heat-cured concrete to delayed ettringite formation (DEF) by analyzing the influence of alkali content, sulfate concentration, and curing temperature. The findings showed that excessive heat curing increased the risk of DEF, potentially affecting long-term durability and dimensional stability of concrete exposed to high temperatures.

Tapas et al. (2022) investigated the influence of carbonation on the compressive strength development of high-slag mortars. The study found that carbonation significantly affected hydration reactions and strength development, providing valuable insights into the long-term durability and performance of sustainable cementitious materials under aggressive environmental conditions.

Boyd-Weetman et al. (2022) studied the effects of alkali immersion on alkali-silica reaction (ASR) progression in Australian aggregate concrete. The research demonstrated that alkali exposure accelerated ASR-induced expansion and microcracking, highlighting the importance of controlling chemical deterioration to ensure the long-term durability and structural reliability of concrete infrastructure.

Rakhsh Mahpour (2024) investigated the suitability of a lime-based nonwoven layered flax fiber composite for strengthening historic masonry structures. The study evaluated its microstructural characteristics, mechanical performance, durability, and sustainability, concluding that the composite provides effective reinforcement while maintaining compatibility with heritage materials and improving long-term structural performance.

Awoyera et al. (2024a) reviewed sustainable structural retrofitting materials for fire-damaged reinforced concrete buildings. The study highlighted the effectiveness of green repair materials, including fiber-reinforced composites, geopolymers, and eco-friendly cementitious systems, in restoring structural strength, enhancing fire resistance, and reducing the environmental impact of rehabilitation practices.

Yang et al. (2019) experimentally investigated the shear behavior of fire-damaged reinforced concrete T-beams strengthened with prestressed steel straps. The results showed significant improvements in shear capacity, stiffness, crack control, and load-carrying performance, demonstrating that prestressed steel straps are an efficient retrofitting solution for fire-damaged beams.

Awoyera et al. (2024b) evaluated the structural performance of fire-damaged concrete beams retrofitted with bamboo fiber laminates. The findings indicated considerable recovery in flexural strength, stiffness, and energy absorption capacity, highlighting bamboo fiber laminates as a sustainable and cost-effective alternative to conventional strengthening materials.

Zhou and Wang (2019) reviewed repair techniques for fire-damaged reinforced concrete members subjected to axial loading. The study summarized various rehabilitation methods, including concrete jacketing, fiber-reinforced polymer systems, and steel plate strengthening, emphasizing their effectiveness in restoring load-bearing capacity and structural reliability.

Noman et al. (2022) investigated the effectiveness of low-cost repair techniques for restoring the mechanical properties of fire-damaged concrete. Experimental results showed that economical repair methods, such as cementitious overlays and repair mortars, significantly improved compressive strength, stiffness, and durability, making them suitable for practical rehabilitation applications.

Ma et al. (2019) reviewed repair methods for fire-damaged reinforced concrete flexural members. The authors discussed conventional and advanced strengthening techniques, including FRP composites, steel plate bonding, and concrete overlays, concluding that appropriate repair strategies can effectively restore flexural strength, ductility, and serviceability.

Khalaf et al. (2026) investigated the rehabilitation of fire-damaged reinforced concrete columns using advanced composite materials. The study reported that composite strengthening systems significantly enhanced axial load capacity, confinement efficiency, ductility, and residual structural performance, demonstrating their effectiveness for post-fire rehabilitation.

Anasco Bastin et al. (2017) compared different restoration techniques for fire-damaged reinforced concrete flexural members. The study evaluated methods such as epoxy injection, ferrocement jacketing, reinforced concrete jacketing, and fiber-reinforced polymer strengthening, concluding that advanced composite systems provided superior structural recovery and durability.

Qiu et al. (2021) reviewed post-fire repair strategies for concrete structural members by examining fire exposure conditions and recovered structural performance. The study emphasized the importance of proper damage assessment, material selection, and strengthening techniques to achieve reliable restoration of strength, durability, and long-term serviceability in fire-damaged concrete structures.

Abdullah et al. (2015) reviewed the application of ultra-high-performance fiber-reinforced concrete (UHPFRC) as a repair material for fire-damaged reinforced concrete structures. The study highlighted the superior mechanical properties, excellent bond strength, low permeability, and high durability of UHPFRC, making it an effective material for restoring the structural integrity of fire-affected concrete members.

Table 1: Comparative Summary of Previous Studies on Fire-Damaged RCC Repair and Rehabilitation

Author(s) & Year	Material/Technique	Key Findings
Vedrtnam et al. (2025)	Self-healing concrete	Improved crack healing, durability, and residual strength after fire exposure.
Bhadauria et al. (2025)	Fire-resistant materials	Advanced composites and coatings enhanced fire resistance and structural performance.
Das (2025)	Steel–concrete bond analysis	Fire significantly reduced bond strength; numerical model predicted post-fire behavior.
P. Ms (2025)	BFRP–BFEGC strengthening	Increased load capacity, crack resistance, and residual performance of RC columns.
Awoyera et al. (2024)	Green retrofitting materials	Sustainable repair materials restored structural performance while reducing environmental impact.
Yang et al. (2019)	Prestressed steel straps	Enhanced shear strength and stiffness of fire-damaged RC T-beams.
Li et al. (2022)	SHCC repair	Improved flexural strength, ductility, and crack control of repaired beams.
Abdullah et al. (2015)	UHPFRC repair	Excellent bond strength, durability, and mechanical performance for fire-damaged concrete.
Qin et al. (2022)	Fire damage assessment	Highlighted integrated destructive and non-destructive evaluation methods for rehabilitation.
Khalaf et al. (2026)	Advanced composite rehabilitation	Significantly improved axial capacity, ductility, and structural resilience of RC columns.

Li et al. (2022) experimentally investigated the flexural behavior of fire-damaged concrete beams repaired with strain-hardening cementitious composites (SHCC). The results demonstrated significant improvements in flexural strength, ductility, crack control, and energy dissipation, confirming SHCC as a promising repair material for post-fire structural rehabilitation.

Abdalla and Karim (2022) critically reviewed repair materials for different fire-damaged reinforced concrete structural members. The authors compared conventional cementitious materials, epoxy systems, fiber-reinforced polymers, and advanced composites, concluding that material selection should be based on the extent of fire damage, structural requirements, and long-term durability.

Baharuddin et al. (2020) investigated the bond strength performance of ultra-high-performance fiber-reinforced concrete (UHPFRC) used for repairing fire-damaged concrete. The study reported excellent bonding characteristics between the repair layer and damaged substrate, leading to enhanced structural performance and improved service life after rehabilitation.

Biradar et al. (2024) presented a comprehensive review of fire-induced damage mechanisms in reinforced concrete structures. The study discussed the thermal degradation of concrete and reinforcing steel, cracking, spalling, and residual strength reduction while emphasizing the need for accurate damage assessment and effective rehabilitation strategies.

Hua et al. (2023) explored the use of advanced numerical modeling techniques for assessing fire damage in reinforced concrete tunnel linings. The study demonstrated that thermo-mechanical simulation models can accurately predict temperature distribution, material degradation, and structural response, supporting reliable post-fire evaluation and repair planning.

Qin et al. (2022) provided a comprehensive review of fire damage assessment methods for reinforced concrete structures. The authors summarized destructive and non-destructive evaluation techniques, residual strength prediction models, and structural assessment procedures, highlighting the importance of integrated evaluation methods for effective rehabilitation.

Ghatak et al. (2021) assessed the structural condition of a fire-damaged reinforced concrete building using visual inspection, material testing, and structural analysis. The investigation identified the extent of thermal damage and proposed appropriate strengthening measures, demonstrating the importance of systematic post-fire assessment before rehabilitation.

Mpalaskas et al. (2024) investigated the application of non-destructive evaluation (NDE) techniques for assessing fire-damaged steel-fiber-reinforced concrete. The study showed that ultrasonic and sensor-based evaluation methods effectively identified internal defects, material degradation, and residual structural capacity, thereby supporting optimized rehabilitation decisions.

Kog (2021) presented a practical guide for the assessment and repair of fire-damaged concrete building structures. The study outlined systematic procedures for fire damage inspection, material evaluation, structural analysis, repair selection, and quality control, providing engineers with practical recommendations for restoring fire-damaged reinforced concrete buildings.

III. CONCLUSION

Fire exposure significantly deteriorates the mechanical properties, durability, and serviceability of reinforced cement concrete (RCC) structures through concrete degradation, reinforcement damage, cracking, spalling, and loss of bond strength. The reviewed literature demonstrates that conventional repair methods often provide limited restoration, whereas advanced rehabilitation materials and techniques offer substantial improvements in post-fire structural performance. Fiber-reinforced polymers (FRP), ultra-high-performance fiber-reinforced concrete (UHPFRC), strain-hardening cementitious composites (SHCC), basalt fiber engineered geopolymer composites (BFEGC), bamboo fiber laminates, and self-healing cementitious systems have shown excellent potential for restoring strength, stiffness, ductility, and durability of fire-damaged members.

Recent studies also emphasize the importance of comprehensive post-fire damage assessment using both destructive and non-destructive evaluation techniques, supported by numerical modeling and thermo-mechanical simulations. These approaches enable accurate prediction of residual structural capacity and facilitate the selection of appropriate rehabilitation strategies. Furthermore, the integration of intelligent self-healing materials with fire-resistant coatings has emerged as a promising solution for extending service life, reducing maintenance requirements, and enhancing structural resilience.

Sustainable repair materials, including geopolymers, natural fiber composites, and eco-friendly cementitious systems, have demonstrated considerable environmental and economic advantages while maintaining satisfactory structural performance. The adoption of advanced retrofitting systems not only improves the safety and reliability of existing infrastructure but also supports sustainable construction practices by minimizing demolition waste and reducing the demand for new construction materials.

Overall, the literature indicates that future research should focus on the long-term durability of repaired structures under combined environmental and mechanical loading, optimization of self-healing technologies, development of standardized post-fire assessment procedures, and incorporation of artificial intelligence and digital monitoring techniques for real-time structural health evaluation. These advancements will contribute to the development of resilient, durable, and sustainable rehabilitation strategies for fire-damaged RCC structures and support the formulation of future design guidelines and engineering standards.

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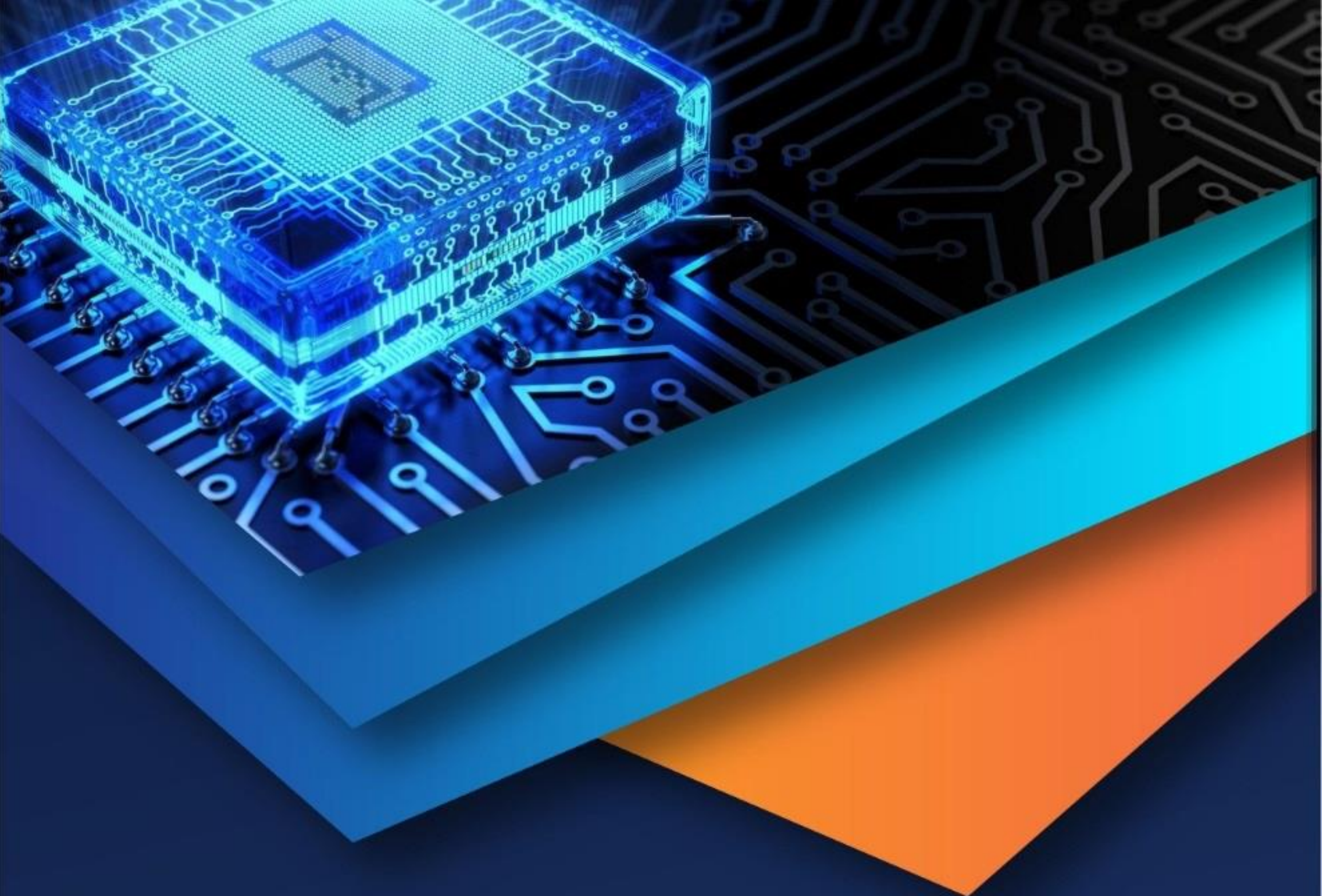

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