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Comprehensive Review on the Studies on Castellated Beam

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Abstract: The numerous studies on castellated beams, a kind of steel beam that is frequently employed in structural engineering due to its exceptional strength-to-weight ratio and aesthetic appeal, are examined in this thorough literature review. Standard I-beams are split and reassembled to form web apertures in castellated beams, which preserve structural strength while using less material. Important subjects covered in the paper include the structural performance of castellated beams under bending, shearing, and axial loads, among other loading situations. Important design considerations are also covered, such as how hole size, shape, and placement affect beam efficiency. Research on castellated beams' buckling properties, fatigue durability, and failure modes is reviewed, as are methods for improving their design to strike a compromise between cost and performance. Furthermore, the paper highlights advancements in computational methods, particularly the use of software for finite element analysis (FEA), such as Abaqus, which has emerged as a crucial tool for simulating the complex behaviours of castellated beams. The significance of experimental studies in confirming analytical models and expanding our understanding of castellated beam behavior in real-world scenarios is also included in the review. In order to keep up with the latest developments in castellated beam design and technology, engineers and researchers can benefit greatly from consulting this survey of the literature.
Keywords: Literature review, Castellated beams, Finite element analysis, FEM, Web openings

I. INTRODUCTION

In civil engineering, steel beams are essential because of their strength, resilience, and versatility in a range of structural applications. For load support and preserving structural stability in large-scale construction projects like skyscrapers, bridges, and industrial structures, steel beams are essential. Because of their exceptional tensile strength, which allows them to withstand significant stress, they are ideal for transporting big objects over long distances without bending too much. Steel's durability and safety are increased by its resistance to fire, corrosion, and extreme weather. More complex architectural designs are also made possible by steel's elasticity, which enables engineers to build roomy spaces with fewer support columns. Finally, the use of steel beams makes modern infrastructure more sustainable, safe, and effective, making them an essential component of civil engineering projects.

Castellated beams, a structural steel beam variation, have drawn a lot of interest in structural and civil engineering because of its efficiency, aesthetic appeal, and ability to use less material without compromising structural integrity. A typical I-beam is cut along its web to make these beams, and the parts are then put back together to form a series of apertures called "web openings." For applications where structural strength and cost effectiveness are crucial, including in floor systems, roof frameworks, and large-span constructions, the result is a sturdy yet lightweight beam. Considerable work has been done over the years to understand how castellated beams behave under various loading conditions. Studies have looked at how various web opening geometries affect the beam's strength, stiffness, and overall performance. The impact of hole sizes, shapes, and locations, as well as the potential for stress concentrations and localized failures around the borders of the apertures, are prominent research topics. Furthermore, given their significance for the durability and safety of these buildings, research on the buckling properties, fatigue resistance, and causes of failure of castellated beams has been crucial.

The advancement of castellated beam technology has been greatly aided by developments in computational tools, particularly finite element analysis (FEA) software like Abaqus. Engineers may improve beam designs before conducting actual experiments thanks to these tools, which enable comprehensive simulations of complicated structural phenomena, including nonlinear deformations and dynamic reactions. Despite these developments, experimental studies remain essential in the field of study because they validate theoretical models and offer useful information on the behavior of castellated beams. This review of the literature aims to provide a comprehensive overview of the design, analysis, and use of castellated beams in modern structural engineering by aggregating the results of several works on the subject.

II. DEVELOPMENT OF CASTELLATED BEAMS

Castellated beams have become a highly effective structural component, commonly utilized in contemporary construction because of their exceptional strength-to-weight ratio and efficient use of materials. The origin of castellated beams dates back to the mid-20th century when engineers started investigating ways to enhance the utilization of steel in structural uses. These beams are formed by slicing a standard I-beam through its web and rearranging the two portions in an offset or interlocked configuration. This alteration notably boosts the beam's strength without a proportional increase in weight, rendering them suitable for situations that require both structural reliability and material efficiency. The concept of castellating beams arose as an answer to the growing necessity for lightweight, high-strength structural elements. Before the advent of castellated beams, conventional I-beams were predominantly utilized in construction; however, these beams had limitations regarding material efficiency and usage. The technique of slicing and reshaping the I-beam web permits a greater web depth, thereby enhancing the beam's bending strength and overall load-bearing capacity. Furthermore, the perforated or "castle-like" design of these beams, resulting from the web cutouts, is the origin of their name and serves as a significant design characteristic that distinguishes them from other structural components.

Notable advancements in castellated beam technology occurred during the 1950s and 1960s. Engineers discovered that through careful planning of the cut patterns and reassembling the I-beam sections, it was feasible to create a beam that retained the load-bearing capability of a solid I-beam while significantly minimizing material usage. This innovation proved particularly beneficial in extensive construction projects, where the ongoing challenge was to lower material costs without sacrificing structural strength. With the growing utilization of steel and the demand for more efficient construction materials, the design and production of castellated beams continued to progress throughout the latter half of the 20th century. Initially, castellated beams were commonly produced by cutting the I-beam webs with basic hand tools or machinery, but as technology advanced, more advanced techniques, such as laser cutting and automated welding, emerged. These innovations permitted increased accuracy and the capacity to fabricate beams in various shapes and sizes, thus broadening their application spectrum.

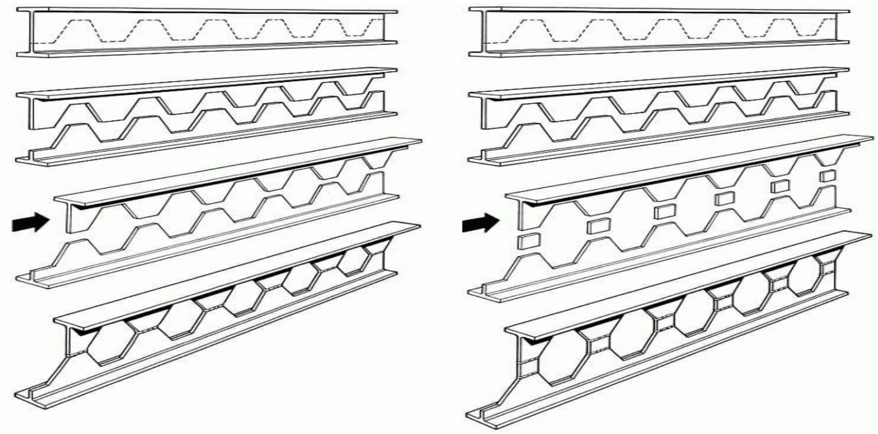

Fig 1 Development of Castellated beams

Recently, the advancement of castellated beams has been further improved through the use of computational design tools and the Finite Element Method (FEM) for structural analysis. Engineers can now accurately model and evaluate the performance of castellated beams under different load conditions, refining their designs for specific applications. This modern methodology has increased the versatility of castellated beams, allowing their application in diverse structures, ranging from industrial buildings to bridges and even skyscraper projects. Nowadays, castellated beams are recognized as a fundamental component in the design of steel structures, especially in scenarios that require both strength and cost-effectiveness. Their ongoing development, influenced by technological progress and the necessity for sustainable construction practices, guarantees their significance in contemporary engineering.

III. LITERATURE REVIEW

The examination of castellated beams has attracted considerable interest in the field of structural engineering because of their economical nature, efficient use of materials, and improved strength-to-weight ratios. Castellated beams, formed by slicing and reconfiguring conventional I-beams, provide a response to the increasing need for optimized and sustainable structural elements. Numerous studies have investigated different approaches to evaluate these beams, mainly concentrating on their performance under various loading scenarios, design enhancements, and structural characteristics.

A. Early Studies on Castellated Beams

Early research on castellated beams primarily focused on their geometric design and fundamental load-carrying ability. Castellated beams, a more affordable option for long-span buildings, were created in the 1930s as a response to rising steel costs [1]. By using cutting and welding, this technique improves load-bearing capacity by allowing for increased beam depth without the need for additional weight [2]. Pioneering researchers like Woods and Procter (1953) were among the first to investigate the benefits of castellated beams, showing that they could provide similar strength to solid beams while being lighter. These initial studies concentrated on empirical techniques for determining the bending and shear capacities of the beam, relying on simplified assumptions regarding stress distribution [3].

B. Structural Behavior of Castellated Beams

Castellated beams, due to their unique geometric configuration that includes openings in the web, exhibit distinct structural properties compared to solid beams. The presence of these openings significantly influences the load-carrying capacity, bending strength, shear strength, and deflection characteristics of the beam. Research by Zhou et al. (2002) demonstrated that castellated beams provide a better strength-to-weight ratio than solid beams, mainly because the web openings lead to a reduction in weight [4]. However, the strength and stability of these beams are heavily affected by the dimensions, shapes, and arrangement of the openings. The study conducted by Lee et al. (2016) provided further understanding of how castellated beams perform when subjected to lateral-torsional buckling, highlighting that altering the web opening patterns could enhance the stability of these beams [5]. Their strength-to-weight ratio is greatly enhanced by the design, which makes them appropriate for a range of uses. Hexagonal, circular, and rectangular web opening geometries are common and have varying effects on the beam's performance [6] .

C. Shear and Bending Strength of Castellated Beams

The shear strength of castellated beams is a crucial factor that must be carefully assessed. Mahmoud et al. (2004) investigated the shear properties of castellated beams under various loading conditions and found that the shape of the beam's web openings significantly influences shear distribution [7]. Their research highlighted that castellated beams generally exhibit lower shear strength than solid beams, and certain enhancements (like web stiffeners) can improve their shear capacity. On the other hand, castellated beams tend to have greater bending strength because of their reduced weight, allowing for longer spans to be achieved with the same amount of material. Hutchinson and Moffatt (2009) noted that as the aspect ratio (the ratio of the beam's depth to its thickness) increases, the bending strength of castellated beams typically rises [8].

D. Finite Element Analysis (FEA) of Castellated Beams

Finite Element Analysis (FEA) has emerged as an essential method for assessing the behavior of castellated beams. Ali et al. (2015) used FEA to simulate the response of castellated beams under different loading conditions and geometric modifications. Their study provided a comprehensive understanding of stress distribution, deformation patterns, and failure mechanisms. The results confirmed that the openings in the web can act as stress concentrators, leading to localized plastic deformation. However, they also pointed out that the overall effectiveness of the beam could be improved by altering the shapes and sizes of the web openings [9].

E. Optimization Techniques for Castellated Beams

The optimization of castellated beam design has been thoroughly examined in recent research efforts to improve their performance and lower expenses. Gupta and Ahuja (2012) proposed a framework for optimization that employs genetic algorithms to determine the optimal shape of web openings for maximizing the strength-to-weight ratio. Their findings revealed that the effectiveness of a specific configuration is significantly affected by the unique loading and boundary conditions of the given application [10]. Gültekin and Öztürk (2017) developed a design optimization method for castellated beams that focuses on balancing strength and stability, with the goal of reducing material usage while ensuring compliance with essential safety regulations [11].

F. Applications of Castellated Beams

Castellated beams are becoming more and more common in civil constructions due to their cost-effectiveness, enhanced load-bearing capacity, and lightweight design. Their unique design, which includes gaps in the web, allows for innovative applications in a range of building types, including parking garages, towering structures, and medical facilities. The main applications and benefits of castellated beams in civil engineering are covered in depth in the following sections.

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Castellated beams are frequently used in construction, particularly in the design of structures that span long distances, like bridges and roofs. Cavalcante et al. (2018) performed a comprehensive review of castellated beams in both residential and industrial applications, noting their ability to reduce material costs while preserving performance. The openings present in castellated beams allow for the straightforward routing of mechanical services, such as ductwork and piping, making them particularly advantageous for buildings with complex service needs [12]. Castellated beams are frequently used in modern construction because of their adaptability in terms of design and capacity to support both electrical and mechanical systems [13]. The goal of ongoing studies is to improve their design by looking at things like stiffener placement and opening shape in order to enhance performance under various loading scenarios [14]. Studies show that castellated beams have better resistance to collapse, especially when featuring square openings, as these facilitate the formation of catenary mechanisms in extreme loading conditions. Properly designing web openings can greatly enhance structural performance during significant deformations [15].

G. Experimental and Analytical Studies

Experimental studies have played a crucial role in supporting the analytical and numerical models developed for castellated beams. Yeh and Yang (2008) conducted tests on the flexural capacity of castellated beams and found that traditional beam theory could effectively estimate the ultimate load-carrying capacity of these beams by making appropriate adjustments for the web openings [16]. The work by Sowder et al. (2015) also confirmed that the predicted responses of castellated beams under bending were in close agreement with the observed results; however, discrepancies were noted in shear predictions, highlighting the need for more advanced models to account for the impact of web openings on shear transfer [17]. Greater flexural and shear strengths are exhibited by beams having hexagonal holes at reduced angles, increasing their usefulness in modern structural applications [18]. When compared to conventional designs, the strength of these beams may be increased by up to 44% by adding reinforcement around web apertures [19]. It is typical design practice to reinforce the end-plate area in order to provide plastic hinges inside a steel frame construction that uses steel beam-to-column end-plate connection connections. The mechanical properties and failure mechanisms of connections across several parameter ranges are explored, and the impact of end-plate thickness on the connection's operating mechanism is investigated. By taking into consideration the contributions of the beam components to the connection's rotation, this study proposes a method for determining the connection's initial rotational stiffness that guarantees high accuracy[20].

In order to evaluate and anticipate the performance of composite castellated steel beams (CCSB) under both static loads and fire situations, Behnam's study concentrated on creating a nonlinear analytical and prediction model. According to the results of the parametric analysis, the CCSB's load-carrying capacity is negatively impacted by lengthening; on the other hand, the CCSB's load-carrying capacity is improved by increasing the size of the castellated beam [21].

Caisong created a computational model using the nonlinear finite element method and used drop weight impact experiments to investigate the effects of irregular dynamic loads on castellated steel beams (CSBs) [22]. According to Abdelaziz, the overall structural behavior of reinforced concrete perforated (castellated) beams with two equal spans that are exposed to external pre-stressing has been studied experimentally and numerically. As indicated by the numerical results, the percentage of moment redistribution in both sagging and hogging moments seems to be reduced more effectively by increasing the amount of primary tensile steel, the eccentricity of the strands in the hogging moment region, and the effective pre-stressing force [23].

Furthermore, several techniques suggested in the standards and recommendations for designing castellated beams under flexure may overestimate or underestimate the moment of failure when taking into consideration the interplay between plasticization and the global buckling mode [24]. The castellated beams with thick flanges, narrow web, and intermediate overall slenderness are more likely to exhibit the lateral-distortional buckling (LDB) mode [25]. For tapered castellated beam-column portal frames, the linear stiffness ratio between the beam and column must be more than 2.735. Accordingly, the seismic performance of the structure is not significantly affected by a web opening ratio of the castellated column between 50% and 70% [26]. Beam-column components have received little attention in previous research, which has mostly focused on castellated beams. Twelve castellated beams, both short and long, as well as columns and beam-column components, were the subjects of an experimental investigation. The usefulness of finite element analysis (FEA) as a numerical approach was confirmed by comparing the experimental results with FEA. The experimental findings and FEA showed good agreement [27]. Hot-rolled Square Tubular Beams (STBs) and Castellated Tubular Beams (CTBs) with simply supported end conditions were tested for the effects of castellation on their bending strength and stiffness. The castellation process significantly increased the hollow tube sections' flexural capacity and stiffness, according to the findings of the bending tests. The detected geometric defects and material and geometric nonlinearity were included into finite element (FE) models for STBs and CTBs. When it came to ultimate bending strength, moment versus mid-span deflection behavior, and mechanisms of failure, the existing FE models showed a significant correlation with the experimental data [28].

Previous studies have shown that the primary cause of castellated steel beams' apparent failure is lateral distortional buckling (LDB). According to the study, LDB happens when web partitions and eccentric loading are used together. The ultimate load capacity was reduced by 5% as a result of eccentric loading. The final load-carry capacity increased by 7% with the addition of web partitions. A greater load capacity was shown by specimens with vertical stiffeners, which helps to lessen lateral distortional buckling in castellated steel beams [29]. The application of external pre-stressing might make up for the loss in ultimate capacity caused by supplying castellated aperture [30].

Shear-induced web-post buckling is a frequent failure mechanism in beams with successive web openings, and it is particularly common in fire scenarios. The steel's modulus of elasticity decreases more quickly than its strength as the temperature rises, making the beam more susceptible to failure due to instability [31]. Due to lateral-torsional buckling, the points on high-web steel beams exhibit irregular deviations, making it challenging to measure displacements perpendicular to the load precisely since fixed measuring equipment are unable to offer correct readings. It is possible to accurately identify both in-plane and out-of-plane deformations in castellated steel beams caused by bending moments and lateral torsional buckling by applying image processing techniques [32].

The restricted thermal elongation in a Castellated steel beam during a fire results in a lesser compression force than in a solid web beam since the axial stiffness of a Castellated steel beam is less than that of the original solid web steel beam [33]. In order to get an understanding of the critical stresses and buckling modes associated with typical flange-to-web width and thickness ratios, eigenvalue calculations are performed for Litzka-type beams using the Finite Element Method (FEM). The Generalized Beam Theory (GBT) is used to analyse the typical compression "tee" in order to assess how member length and stress gradients affect critical stress. The effects of web transverse bending and flange torsional stiffness on the "tee's" behavior are examined, and the prediction equations are derived using an energy technique [34]. Bending-torsion failure or bending failure of the beam flange were the failure modes of the castellated beam, whereas the bending failure of the beam flange after concrete slab collapse was the failure mode of the castellated composite beam. The stiffener can successfully stop web-post buckling, and the concrete slab can effectively control the torsion of the beam flange, lower the height of the compression web, and limit the buckling development of the web [35]. Buckling of the compression flange causes the castellated composite beams to collapse when the negative moment acts alone. When shear force and negative moment work together, the web post buckles, causing the castellated composite beams to collapse. The yield load of the specimen may be calculated using the development curve of the stress surrounding the orifice as a guide. The buckling of the composite beam's web post may be efficiently reduced by the transverse stiffener. As the opening rate increases from 0.47 to 0.6, the bearing capacities of the castellated composite beams under the two working conditions decrease by 8.7% and 10.5%, respectively [36]. In comparison to the deflections of the control beam and the beam with mild steel stiffeners, the deflection of the CFRP-stiffening beam is determined to be 12.04% and 16% lower, respectively. Since CFRP stiffeners increase load-carrying capacity while reducing weight and making application easier, they can thus be chosen over mild steel stiffeners [37]. In contrast to castellations in plain web beams, a 30° corrugated-castellated beam with a casing assembly demonstrated over 60% of the load-carrying capability. Furthermore, the identical beam's mass-to-capacity ratio was larger [38]. Significant residual shear strength and excellent deformation ability were shown by inverted castellated T-steel reinforced UHPC (ICTSRU) beams following the peak load. The carrying capacity and failure mechanisms of the ITSRU beams were greatly impacted by the shear span-to-depth ratio. Shear resistance dropped by 19% and 48%, respectively, when the span-to-depth ratio rose from 1.1 to 1.6 and 2.1, changing the failure mode from shear to flexural failure. The shear strength and ductility of ICTSRU beams may be increased by increasing the stirrup ratio and the steel fiber volume percentage, which will lessen the onset and spread of diagonal fractures [39]. The behavior and failure modes of composite beams are significantly influenced by the strength of steel beams, which may alter the composite beams' failure mode in a fire. The design values derived from Eurocode 4 for composite beams at increased temperatures were compared with the fire resistances of the castellated and non-castellated composite beams as determined by the finite element analyses. With the exception of a few composite beams heated using the conventional fire curve at load ratios of 0.4 and 0.5, it is demonstrated that the Eurocode 4 is conservative for the majority of unprotected composite castellated and non-castellated steel beams [40]. The study of castellated beams has attracted a lot of interest because of its benefits, which include lower weight and material consumption. Even if they improve structural efficiency, it is still difficult to predict how they would behave, especially when it comes to shear strength and stability under dynamic loading circumstances. Optimization strategies are still being investigated in ongoing research, with an emphasis on enhancing analytical models and integrating experimental validation. It is anticipated that future advancements would further improve design procedures, increasing the effectiveness and adaptability of castellated beams as a structural engineering choice. The goal of the current work is to offer an exhaustive review of the research done on the behavior of castellated beams with various forms as web apertures.

IV. CONCLUSION

The analysis of studies on castellated beams can be summarized as follows:

1) Creative Structural Solution: Because of its unique shape and ability to combine durability with reduced material consumption, castellated beams have proven to be a successful and affordable structural choice, widely used in construction. Their web opening design makes it possible to manufacture lighter beams without sacrificing their capacity to support loads, which is very useful in modern construction projects where sustainability and material efficiency are crucial.
2) Enhanced Load-Bearing Capability: Numerous studies highlight the remarkable strength-to-weight ratio of castellated beams, which permits wide spans and reduced material costs. Because of this feature, they are ideal for commercial and industrial projects where it is essential to have lengthy, unhindered spans without intermediary supports.
3) Broad Range of Uses: The versatility of castellated beams is demonstrated by their application in a variety of industries, including the construction of multi-story buildings, warehouses, and bridges. Their incorporation into various domains attests to their continued relevance and widespread use as a modern engineering solution.
4) Design Factors and Issues: The review also emphasizes the need of understanding the design requirements, such as the impact of web apertures on the fatigue performance and buckling behavior of the beam. Despite the many advantages of castellated beams, engineers must carefully consider factors like stability, shear capacity, and local buckling while designing them.
5) Developments in Design and Manufacturing Software: The optimization of castellated beams has been greatly impacted by the development of advanced production processes and computational design tools. More precise designs and efficient mass manufacture of these beams are made possible by this advancement.
6) Future Research: More studies are needed to address the issues related to castellated beams' long-term performance, particularly with regard to fatigue, fire resistance, and dynamic loading. Furthermore, innovative production techniques and hybrid materials have the potential to further enhance their functions.

Castellated beams continue to be an essential part of structural engineering, offering significant benefits in terms of strength, adaptability, and material efficiency. Future building projects are expected to benefit from their expanded uses and improved performance due to ongoing research and technology advancements.

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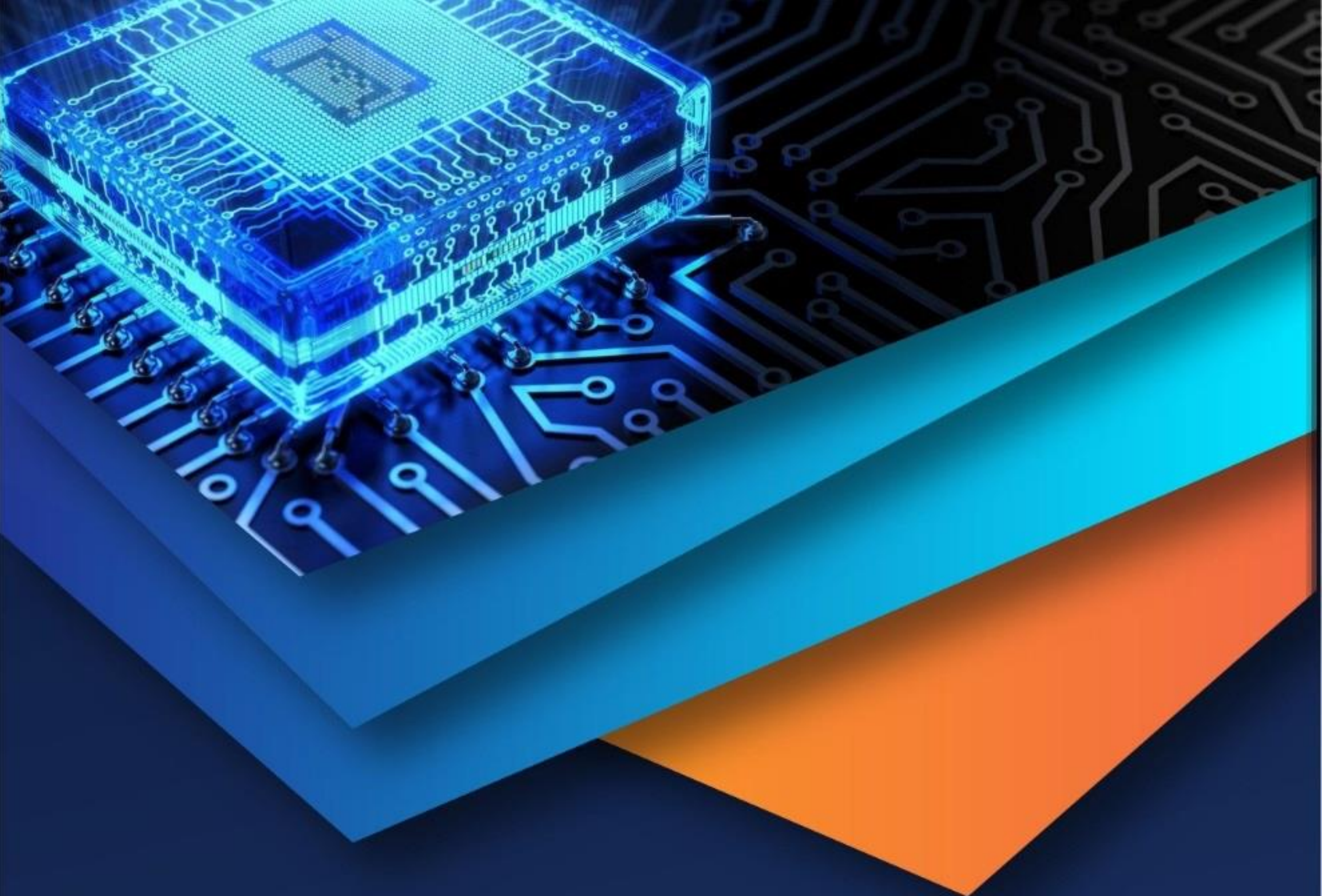

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