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Analysis of the Feasibility of a Diagrid Bracing System in Tall Buildings

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Abstract: The primary goal of this study is to provide a superior lateral load-resisting system. In this study, the diagrid structural system is considered, with the shear wall core present at the center part of the building and the diagrid bracings provided at the outer periphery of the structure, which is formed of steel material. The diagrid, which is made up of inclined diagonal steel sections, allows the diagonal member to function axially to resist lateral loads. Due to its structural effectiveness and versatility in architectural planning, the diagrid structural system has recently been used in tall buildings. A 14-story Diagrid composite building is selected, and its analysis and design results are presented. The Diagrid bracing system is connected to the full bays, the diagrid bracing system is connected to the mid-end bays, and the diagrid bracing system is connected to the end bays these are the three different types of models that have been studied. The diagrid bracing system has been modeled by using structural steel material, and the remaining structure has been modeled by using concrete material. A standard 60 m x 60 m floor plan has been considered. FEM-based software called ETABS has been used to model and analyze structures. A PT slab and a PT band beam have been used in the model frame for the span of 10 m. By considering all possible load combinations, all structural members made of steel and concrete are analyzed by IS: 800:2007 and IS: 456:2000, respectively.

I. INTRODUCTION

Bracing systems are often employed in the creation of skyscrapers. It is followed by mega frame structures, diagrid structures, and three-dimensional (3D) space structures. In multistory buildings, bracing systems are often employed as a lateral stability mechanism. The Diagrid bracing system is an important structural system for providing stiffness and strength to withstand lateral loads. It is a quite an effective and affordable technique for lateral force resistance. The word ‘diagrid’ is the combination of the word ‘diagonal’ and ‘grid’. A component of the bracing system, which evolved from the traditional bracing system, is a diagrid system. It includes enormous diagonal bracings on the building's exterior, which is typically visible to the public; as a result, it also serves as an aesthetic element for architects. Thus, the field of structural engineering produces a lot of innovative ideas, such as the bare frame, beam-column moment frame, etc. This structural system is appropriate and easy to build. However, it has drawbacks, such as their poor lateral load resistance at higher heights. These lateral loads are mostly caused by wind and seismic forces. As we raise the height of the structure, wind forces begin to govern over seismic forces.

Different structural systems are developed to resist lateral forces, which include:

1) Moment Frame with the Structural Wall System,
2) Structural Wall System,
3) Structural Wall System with Flat Slab Floor System,
4) Core and Outrigger Structural System,
5) Structural Wall + Frame Tube System,
6) Tube-in-Tube Structural System,
7) Multiple Tube System, etc.

The recent and most popular structural system that is in existence is the “diagrid structural system”. This type of structure is very reliable from the structural point of view, and it has been in use for a decade.

II. OBJECTIVES

1) To compute lateral load shared by the core element, periphery columns, and internal columns.
2) To analyze diagrid structures, study the diagrid systems with their changing positions to resist the lateral load with different configurations.
3) To create and analyze the structural models and to review and report the following parameters:
   a) To propose different configurations of cross diagonal bracing system connected to full bays, mid-end bays, and end bays and present results.
   b) To observe the effect of diagrid on the minimization of lateral deflection of the structure.
   c) To examine the structure's behavior in terms of structural parameters such as modal participation mass ratio, max story drift, max story displacement, etc.

III. LITERATURE REVIEW

K. S. Moon., (2011) in his paper entitled, analyzed the structural performance and efficiency of the diagrid system in large structures with intricate shapes. The rate of twisting and the angle of tilting were studied using parametric structural models. The diagrid structure is modeled as a cantilever beam one end fixed on the ground and the other hanging. According to the repeating diagrid design, it was divided longitudinally into modules. Each module had a single level of diagrids that covered several stories. It is concluded that the core structures resist gravity loads while the perimeter diagrids resist the impending lateral load.

K. Jani & P. V. Patel., (2013) analyzed and designed a diagrid structural system for high-rise steel buildings. In his study, the buildings with different story heights are considered, such as thirty-six, fifty, sixty, seventy, and eighty-story diagrid steel structures are analyzed and designed. Based on finite elements for modeling, ETABS software is used. The entire structure was designed using IS 800-2007. A building's structural design of the building is dominated by lateral loads because of seismic and wind effects. The internal core of the structure resists the lateral load acting on it. The internal structural system typically comprises of a braced frame with a shear wall core that resists lateral loads from the center. The external structural system consists of a framed tube and a braced frame, with internal columns and peripheral diagonal columns each resisting one of the two types of loads: gravity and lateral. Therefore, the internal columns should be designed for gravity loads only. Diagrid buildings typically do not need a core since diagrids on the building's exterior can support lateral shear.

R. D. Deshpande et al., (2015) contrasted structural systems with diagrids and conventional structures. The modeling and analysis of structural members were done using ETABS software. For the structure's analysis and design, dynamic wind loads across and along the wind direction were considered. The study's primary goal was to assess the efficacy of conventional and diagrid structural constructions. The diagrid structural system outperforms all performance evaluation criteria, including efficiency and sustainability. Comparing the construction to a traditional building with the same size and features, it exhibits comparatively less deflection. Greater weight reduction makes the structure lighter and increases its resistance to lateral stresses. When compared to the typical orthogonal building, which required 15255 tonnes of steel, Diagrid used 11247 tonnes, which is approximately 28% less. The diagrid structure featured a greater accessible area, reduced deflection, and used 28% less steel than a conventional structure.

K. Kamath et al., (2016) analyzed a diagrid structure's performance using non-linear static pushover analysis. The models under study had a circular floor layout and an aspect ratio H/B value that ranged from 2.67 to 4.26. The external bracing used in the study had angles of 59, 71, and 78 degrees. The base's breadth was fixed at 12 meters while the structure's height was adjusted in accordance. Using plastic hinges and the moment-curvature connection, the element's non-linear behavior was modeled in accordance with FEMA 356 specifications. The structure was subjected to a lateral load that increased gradually throughout the analysis until the desired displacement was achieved. The top story of the structure was gradually changed during the pushover study using the displacement control approach such that the necessary horizontal forces were going to push the structure laterally. The parameters assessed for the evaluation of the structure's seismic response include base shear and roof displacement. Studies revealed that the performance of the structure is significantly impacted by the brace angle and aspect ratio.

IV. METHODOLOGY

A. Modeling and Analysis

In this study, the 14-story structure with 60 m x 60 m footprint plan dimensions has been considered. The story height is 4.2 m. Pairs of bracing are placed on the building's exterior in diagrid constructions. Cross bracing connected to end, mid & end, end bays that three different models are considered about its location, and the no of bays in which it is provided. The span length between each

column is 10 m. A continuous wide beam with dimensions of 1500 mm by 750 mm is provided for the structure. These beams are only spanning in one direction.
slabs with a thickness of 250 mm are provided to span over 10 m which will be considered in the design for the PT slab.
Exterior columns are 1500mm x 1500mm in dimension.
Interior columns are 1000 mm x 1000 mm in dimension.
To model Diagrid-Bracing, ISMB 500 steel section was used.

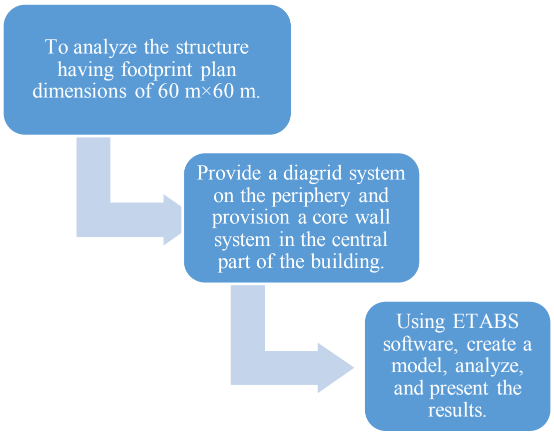

Fig.1: Flow chart of methodology

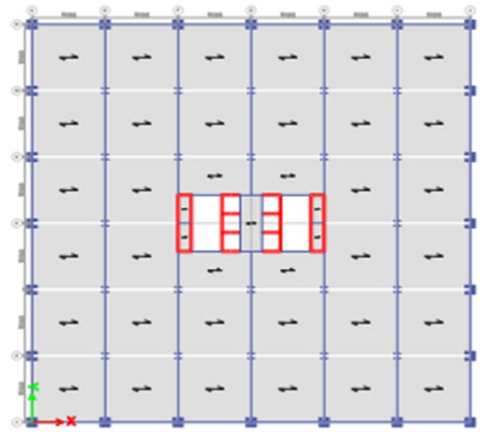

Fig.2: Plan view of the model

B. *Seismic Load*

According to the guidelines in IS: 1893-2016 Part I, the loading caused by the earthquake is estimated. The following parameters are included:

1) Seismic Zone = III
2) Zone Factor (Z) = 0.16
3) Importance Factor (I) = 1.2
4) Response Reduction Factor (SMRF) R = 5
5) Damping (value) Ratio = 5%
6) Type of Soil = II
7) Fundamental Translation Natural Period (T_a) = $0.09 \times \frac{H}{\sqrt{D}}$

C. *Wind Load*

Based on the provision provided in IS: 875 - 2015 Part III, the wind pressure is considered when designing. The following are the parameters: -

1) Basic Wind Speed (V_b) = 44 m/sec
2) Terrain Category = IV
3) Risk Coefficient (k_1) = 1.0
4) Terrain Factor (k_2) = 0.8
5) Topography Factor (k_3) = 1.0
6) Importance Factor for the Cyclonic Region (k_4) = 1.0

V. RESULTS

A. *Base Shear & Deflection of wind & Earthquake Forces*

The building is primarily subject to two forms of loads. such as lateral loads and gravitational loads. The lateral loads comes into the picture because of earthquakes and wind forces. The table below shows the average value of all model's Base shear and deflection for wind and earthquake force thus, it can be concluded that the earthquake forces are more dominant than the wind forces.

Forces	Base shear	Deflection (mm)

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Earthquake forces	33347.95	100
Wind forces	3771.98	10

1) *Story Displacement:* The maximum story displacement graphs based on linear dynamic analysis is presented below for all the models.

Maximum allowable story displacement = $\frac{H}{500}$

H is the total height of the building.

=58800/500 =117.67mm

Maximum allowable story displacement = 117.67mm

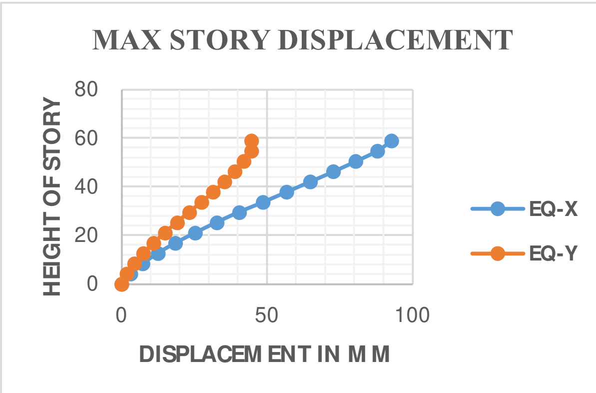


Fig.1: Cross bracing connected to each floor with full Bays

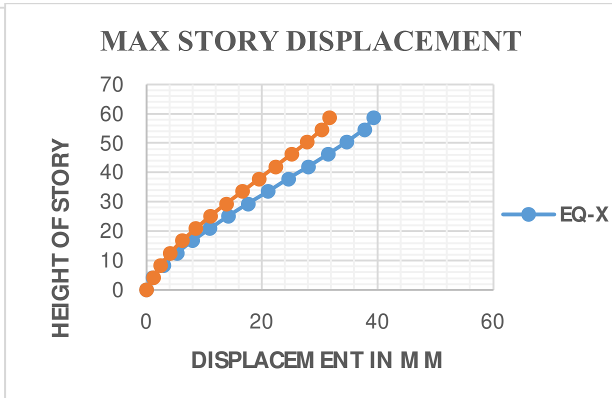


Fig.2: cross bracing connected to each floor with mid & end bays.

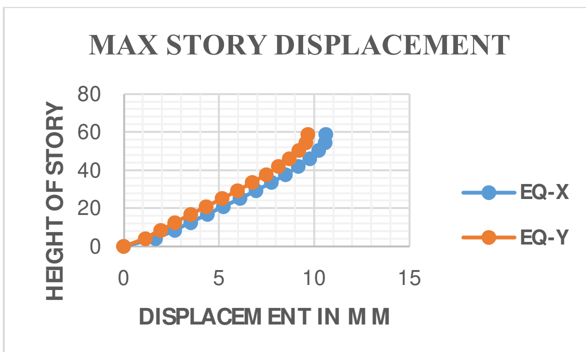


Fig.3: Cross bracing connected to each floor with end bays.

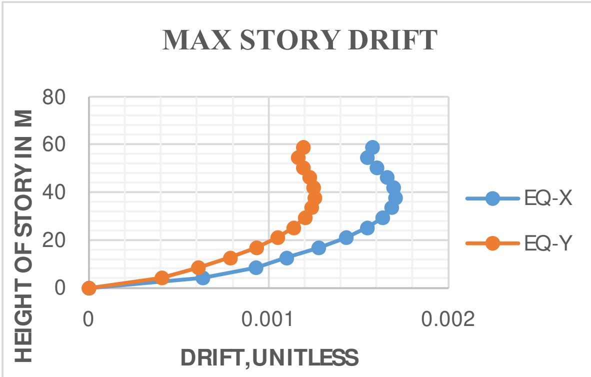
2) *Story Drift:* The maximum story drift graphs based on linear dynamic analysis is presented below for all the models.

Story drift cannot be more than 0.004 times the story height in any one story. (As per IS 1893-2016)

For EQ-X direction,

Maximum allowable story drift = 0.004X4.2

=0.0168



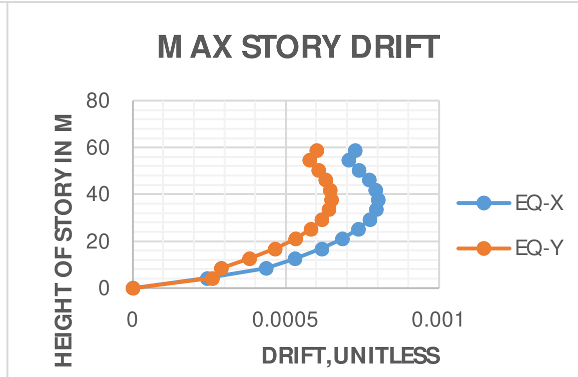


Fig.4: Cross bracing connected to each floor with full Bays Fig.5: cross bracing connected to each floor with mid & end bays.

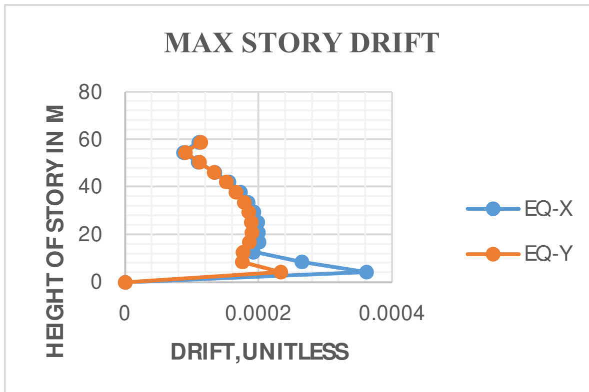


Fig.6: Cross bracing connected to each floor with end bays.

B. Modal Participating Mass Ratios

The level of a given mode's contribution to the structure's reaction to a force or displacement excitation in a particular direction is known as its modal participation.

The lateral stiffness of a building in each main plan direction is decided by the stiffness of the beams, columns, braces, and structural walls. If the first three modes contribute less than 65% of the mass participation factor in each primary plan direction, the structure is said to show lateral story irregularity in that direction. In the two main plan directions, the building's essential lateral natural periods are 10% of the greater value closer to one another.

Table.1: Cross bracing connected to each floor with full bays.

TABLE: Modal Participating Mass Ratios								
Case	Mode	Period	UX	UY	SumUX	SumUY	RZ	SumRZ
		sec						
Modal	1	1.829	0.713	0	0.7135	0	0	0
Modal	2	1.553	0	0.7037	0.7135	0.7037	0.000031	0.000031
Modal	3	1.047	0	0.00003	0.7135	0.7037	0.7681	0.7681

Time period difference $= \frac{1.829-1.553}{1.829} \times 100$

= 15.09%

In all three modes, the modal participation mass ratio exceeds 65%. Thus, OK.

Table.2: Cross bracing connected to each floor with mid-end bays

TABLE: Modal Participating Mass Ratios								
Case	Mode	Period	UX	UY	SumUX	SumUY	RZ	SumRZ
		sec						
Modal	1	1.24	0.6988	0.0001	0.6988	0.0001	0.00001302	0.00001302
Modal	2	1.1	0.0001	0.6906	0.6989	0.6907	0.0001	0.0002
Modal	3	0.745	0.00001367	0.000003134	0.6989	0.6907	0.7339	0.7341

Time period difference $= \frac{1.24-1.1}{1.24} \times 100$

$= \mathbf{11.29\%}$

In all three modes, the modal participation mass ratio exceeds 65%. Thus, OK.

Table.3: Cross bracing connected to each floor with end bays

TABLE: Modal Participating Mass Ratios								
Case	Mode	Period	UX	UY	SumUX	SumUY	RZ	SumRZ
		sec						
Modal	1	0.74	0.8651	0	0.8651	0	0.000001903	0.000001903
Modal	2	0.60	0	0.8301	0.8651	0.8301	0	0.000001904
Modal	3	0.522	0.000002111	0	0.8651	0.8301	0.9444	0.9444

Time period difference $= \frac{0.74-0.60}{0.74} \times 100$

$= \mathbf{18.91\%}$

In all three modes, the modal participation mass ratio exceeds 65%. Thus, OK

VI. CONCLUSIVE REMARKS

1) After analysing the different models, it has been found that the shear wall core and outer peripheral columns attract 90% of the lateral load and all internal columns attract only 10% of the lateral load, as a result, internal columns might only be designed for gravity loads.

2) The table below lists the lateral loads experienced by the inner columns, shear wall core, and exterior columns for each of the three models.

Model no	Model name	Load on External column (%)	Load on Shear wall (%)	Load on Internal column (%)
1	Cross bracing connected to each floor with end bays	51%	39%	10%
2	Cross bracing connected to each floor with mid & end bays	67.23%	29.78%	2.99%
3	Cross bracing connected to each floor with full bays	50%	39.67%	10.48%

3) The cross bracing connected to each floor model is workable to carry the lateral load efficiently. In this case, the external column takes fifty or more than fifty percent of the load, and the internal column takes ten or less than 10% of the load.

4) The cross bracing connected to each floor with a mid-end bays model is more workable to carry the lateral load efficiently. In this case, the external column takes 67.23% of the load, the shear wall core takes 29.78%, and the internal column takes 2.99% of the load so the internal column may be designed for gravity load only.

VII. ACKNOWLEDGMENT

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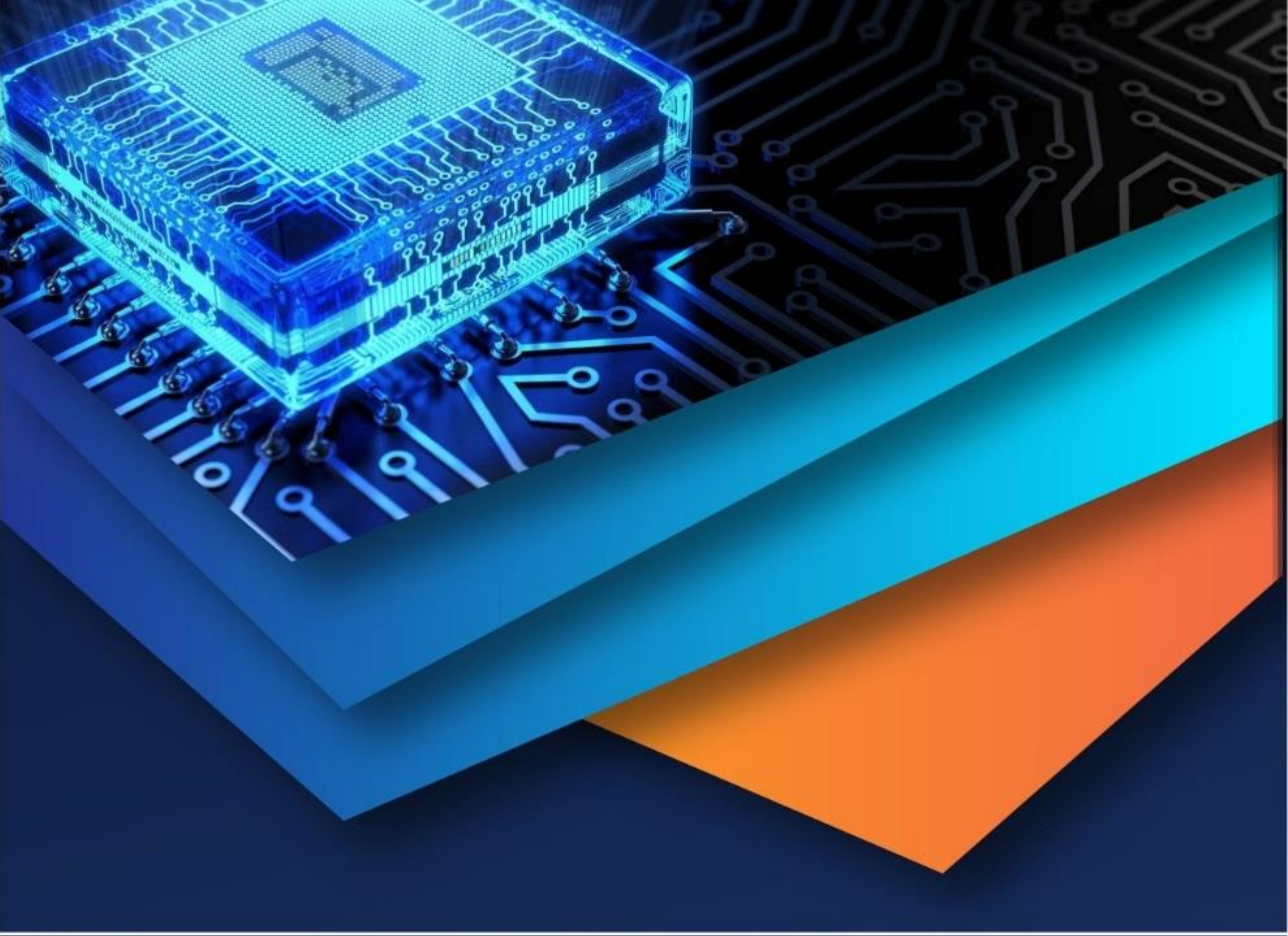

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