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Buckling Analysis of Cellular Steel Beams with and without Stiffeners

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Abstract— Cellular beams became popular day by day as an efficient structural form in steel construction since their introduction. Their design and making process provides greater flexibility in beam proportioning for strength, depth, size and location of circular holes. The advantages of manufacturing these beams is to increase overall beam depth, the moment of inertia and section modulus, which results in greater strength and rigidity. Cellular beams are used as primary or secondary floor beams in order to achieve long spans and service integration. They are also used as roof beams, and are the best solution for curved roof applications, combining weight savings with a low-cost manufacturing process. Even though it had many advantages, some failure modes are associated with this type due to the presence of openings which is not presented on solid beams. Stiffeners are the best solutions to overcome the failures and resist buckling of beams. The first part of the research program focuses on the finite element modelling of cellular steel beams with and without stiffeners in ANSYS software. In the second part of the research, finite element analysis program is used to perform elastic buckling analysis and predict critical loads of all steel cellular beams with and without stiffeners.
Keywords— Cellular beam without stiffeners (CWOS); Cellular beam with ring stiffeners (CWRS); Cellular beam with transverse stiffeners (CWTS); Web-post buckling; Veirendeel bending failure

I. INTRODUCTION

Construction industry has been one of the leading fields among many others in the world. Structural engineering has a major role in the construction field which every day becoming more widespread and sophisticated. One of the main materials used by structural engineers is structural steel. The history of structural steel industry is over one hundred years old. As the technology of steel structures progress, more types of steel sections were produced to improve the structural steel's mechanical properties and also to obtain sections that allow usage for more aesthetic applications by satisfying the architectural needs. Perforated sections, such as, castellated, cellular and sinusoidal beams are good example to such newly developed sections. Castellated beam section with hexagonal opening was the first that developed in the past. The smooth rounded edges of the openings in cellular beams resolved one of the main problems in castellated beams which is the sharp edges of the hexagonal opening. In most cases, these sharp edges caused some failure modes in the beam web due to accumulation of high shear stresses around the perforations. The main aim in producing such sections was to increase their resistance against bending due to the increased height. This approach would also cause an increase in the moment of inertia leading to sections that better meet the serviceability and aesthetic requirement. Researchers and designers keep trying to develop these kinds of members with the aim of achieving steel sections with better mechanical properties, more economical and lower risks for failure. There are mainly five types of failures associated with cellular beams which are not presented in solid beams. To use the cellular beams in to its best advantages the failures need to be avoided. To overcome the buckling failures in cellular beams under heavy loading we have to provide stiffeners in opening area or web post area with proper dimensions.

A. *Failure modes of cellular beam*

The failure of cellular beams are different from solid beams due to its geometric non linearity. The main failure modes associated with cellular beams are

1) *Formation of Flexure Mechanism:* This mode of failure can occur when a section is subject to pure bending. The span subjected to pure bending moment, the tee-sections above and below the holes yielded in a manner similar to that of a plain webbed beam, although the spread of yield towards the central axis was stopped by the presence of the holes by which time the two throat sections had become completely plastic in compression and in tension.

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2) *Web-Post Buckling:* This failure type is caused by two reasons. The web post under action of the horizontal shear force becomes distorted and the form of distortion is like a propeller. The one inclined edge of the web post is under compression and the opposite one under tension. Such stress distribution causes the web post buckles under the shear force. The second reason is the failure can be caused by applying concentrate the force or the reaction above the web post. Web post buckles without any twisting unlike in the case with web post buckling due to shear force.

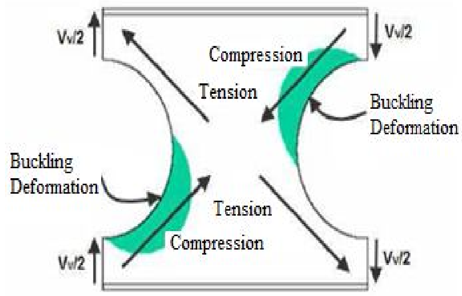

Fig 1. Typical web-post behavior

3) *Lateral Torsional Buckling:* Lateral torsional buckling is usually associated with longer span beams with inadequate lateral support to the compression flange. The reduced torsional stiffness of the web-expanded beam, which is a result of relatively deeper and slender section properties, contributes to lateral buckling mode. The web openings only had a negligible effect on the overall lateral torsional buckling behavior of the web expanded beams.

Fig 2. Lateral torsional buckling mode of cellular beams

4) *Formation of a Vierendeel Bending Mechanism:* The vierendeel failure is defined as the continuous formation of plastic hinges at the ends of four T-sections above and below the opening. The shear force acts the beam, T sections above and below the openings have to carry the shear force and primary and secondary bending moments. The primary bending moment is usual bending moment which acts the beam. The secondary bending moment, also called vierendeel moment, arise from a shear forces in T-sections.

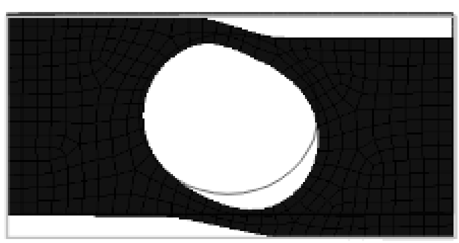

Fig 3.Vierendeel failure

5) *Rupture of the Welded Joint in a Web Post:* Rupture of a welded joint in a web-post can result when the width of the web-post or length of welded joint is small. This mode of failure is caused by the action of the horizontal shearing force in the web-post, which is needed to balance the shear forces applied at the points of contra flexure at the end of the upper I section.

II. FINITE ELEMENT METHOD

The finite element method (FEM) is a numerical technique for finding approximate solutions of partial differential equations as well as integral equations. The basic concept behind FEM is that a body or structure is divided into smaller elements of finite dimensions called finite elements. The original structure is then considered as an assemblage of these elements at a finite number of joints called

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nodes. ANSYS is a general purpose Finite Element Analysis program that solves a vast area of solid and structural mechanics problems in geometrically complicated regions.

A. Modelling

The cellular steel beams are modelled and analyzed in ANSYS software by finite element analysis. For steel structures SOLID185 is the most appropriate element which specify the properties of steel. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The SOLID 185 element used for the modelling of the cellular beams and stiffeners also. The material properties of the steel given are modulus of elasticity and poisson's ratio for the linear buckling analysis. The dimensions of the cellular steel beams considered for the study are given below. The beams are studied under three aspect ratio (Length/Depth), i.e. 5, 10 and 15.

Total depth, D = 450 mm
Width of flange, B = 140 mm
Thickness of flange, t_f = 13.1 mm
Thickness of web, t_w = 7.7 mm
Centre to centre spacing of openings, S =450 mm
Depth of openings =450 mm

Table 1
Material properties

Modulus of elasticity (Es)	200000 MPa
Poison's ratio(υ)	.3

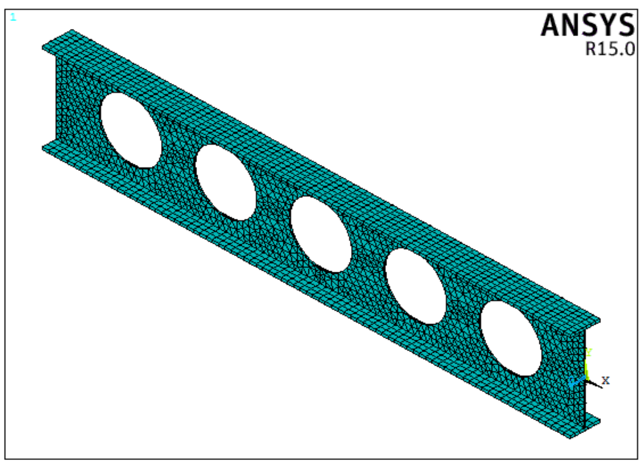

Fig 4. Cellular beam without stiffeners

B. Stiffeners

It is common practice to use stiffeners to strengthen the moment and shear resistance of steel plates and connections along the longitudinal or transverse direction when designing lightweight structures. It is observed that there is no regulated knowledge of how a beam with circular web openings would behave if a transverse stiffener or ring stiffeners was placed in the beams. Primary issues that have arisen with the use of perforated beams relate to the shape of the openings should have, how large the openings should be, the proximity of the openings to each other, web slenderness, type of loading, and provision of lateral supports. Significant experimental and theoretical research has been made in the last decade with the aim to maximize the web opening area and minimize the self-weight of the beam.

To overcome the buckling failures in cellular beams under heavy loading we have to provide stiffeners in opening area or web post area with proper dimensions. The strength enhancement is important in case where large load concentration is observed in the beam. The behavior and failure modes are necessary to be checked using stiffeners in the appropriate place so that the efficiency of the beam is increased in worst condition of stress concentration and web buckling.

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Table 2

Parameters of stiffeners

Stiffeners	Thickness (mm)	Volume (mm^3)
Transverse	5	140171
Ring	5	146084

Here the buckling analysis is conducted for cellular beam without stiffeners (CWOS), cellular beam with ring stiffeners (CWRS) and cellular beam with transverse stiffeners (CWTS) to get the critical buckling load and failure pattern. This models are created with different aspect ratios. That is the aspect ratio 5, 10 and 15 respectively. The thickness of the stiffener is provide 5 mm as per IS code. Stiffeners are provided double sided.

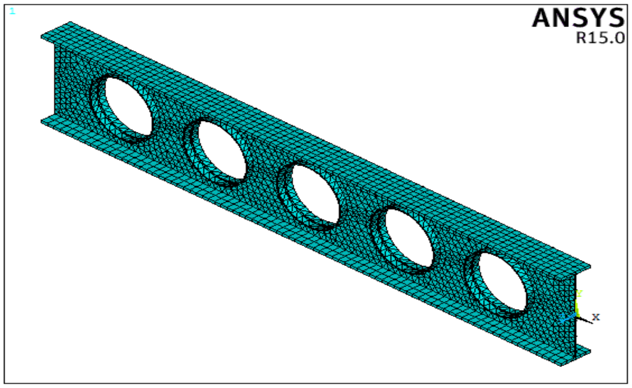

Fig 5. Cellular beam with ring stiffeners

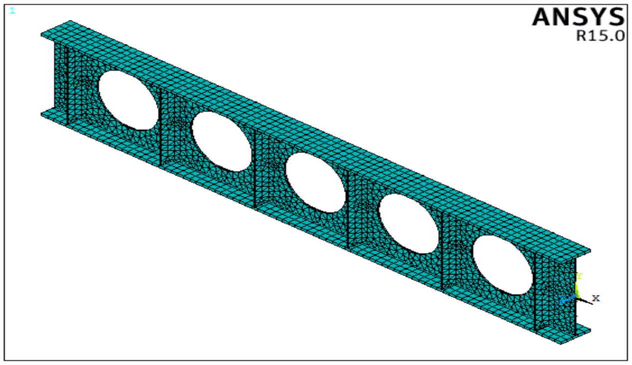

Fig 6. Cellular beam with transverse stiffeners

C. Buckling analysis

The structures subjected to compression loads that have not achieved the material strength limits can show a failure mode called buckling. Buckling is characterized by a sudden failure of a structural member subjected to high compressive stress, where the actual compressive stress at a point of failure is less than the ultimate compressive stress that the material is capable of withstanding. In other words once a critical load is reached, the slender component draws aside instead of taking up additional load. The failure can be analyzed using a technique well known as linear buckling analysis. The goal of this analysis to determine the critical buckling load. Eigenvalue buckling analysis predicts the theoretical buckling strength of an ideal elastic structure. It computes the structural eigenvalues for the given system loading and constraints.

To calculate the effect stiffeners in cellular beams, the critical loads were evaluated by an eigenvalue buckling analysis. The boundary condition provided as two end fixed and the laterally support is provided by restraining the lateral motion. Loading condition is applied as unit load along the mid span of the upper flange. The Eigen value solver uses a unit force to determine the necessary buckling load. Applying a load other than 1 will scale the answer by a factor of the load.

III. RESULTS AND DISCUSSIONS

The effect of stiffeners on the buckling resistance of cellular beam is analyzed and the results are expressed as graphs. The beams

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with 5, 10 and 15 aspect ratio is studied without stiffeners, with transverse stiffeners and with ring stiffeners. The x axis of the graph represents the aspect ratio of beams and y axis presents the buckling load of each beam. Cellular beam without stiffeners (CWOS), cellular beam with ring stiffeners (CWRS) and cellular beam with transverse stiffeners. (CWTS) are plotted separately.

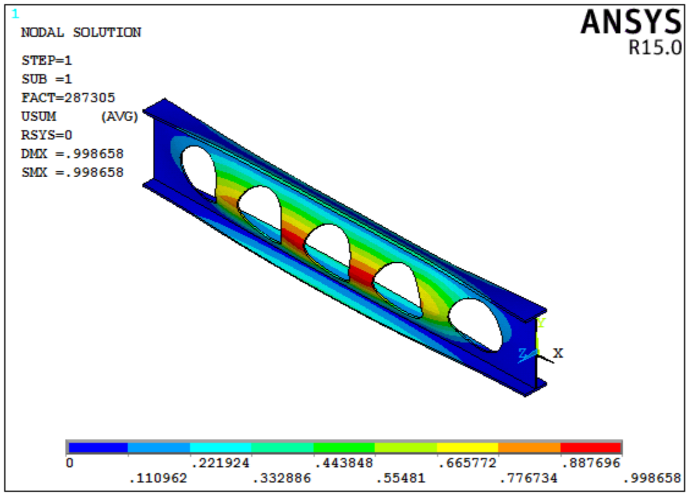

Fig 7. Buckled cellular beam without stiffeners

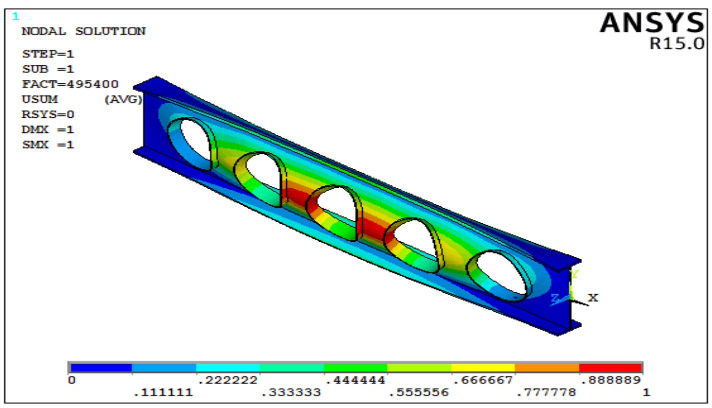

Fig 8. Buckled cellular beam with ring stiffeners

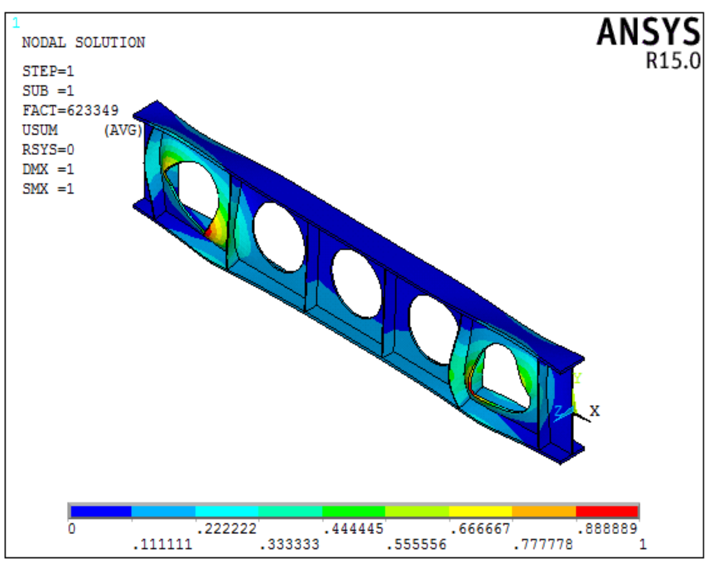

Fig 9. Buckled cellular beam with transverse stiffeners

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Table 3
Critical buckling load of cellular beams with and without stiffeners

Cellular Beams	Buckling Load(kN)		
	L/D =5	L/D=10	L/D=15
CWOS	287	205	176
CWRS	495	361	282
CWTS	623	442	348

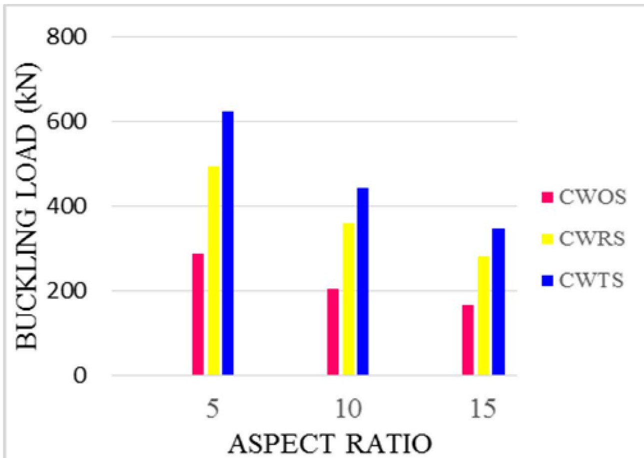

Fig 10. Comparison of buckling load –aspect ratio

From the results obtained from the buckling analysis, it is clear that the presence of stiffeners increase the critical load. The vertical stiffeners have more buckling resistance than the ring stiffeners because web buckling is the major buckling failures in cellular beam. The presence of ring stiffeners reduce the stress concentration this will ultimately reduce vierendeel bending failure. That is the local plastic deformation on the transverse diameter of isolated openings close to concentrated loads or at points of maximum stress can be avoided by ring stiffeners. The presence of transverse stiffeners reduce the web buckling. The transverse stiffener, each acts as a single short column which will be a proper link for the load transfer to the bottom flange. The ring stiffeners can be used when an additional load is coming above the opening so that the stress is reduced and strength increased. The transverse stiffeners are preferable when an additional load is coming over the web post so that the early buckling can resist.

IV. CONCLUSIONS

In this study the buckling analysis of cellular steel beams with and without stiffeners has been investigated. The following conclusions are obtained from the investigations.

A. The stiffeners can increase the buckling capacity of cellular beams and avoid the failures.
B. Transverse stiffeners are better in resisting the buckling of cellular beam than ring stiffeners.The manufacture of transverse stiffeners would become easier and more economic.
C. The ring stiffeners around the openings reduce the stress concentration and resist from the failure due to vierendeel mechanism
D. The transverse stiffeners on the web-post reduced the web post buckling failure. The transverse stiffener, each acts as a single short column which will be a proper link for the load transfer to the bottom flange.
E. Buckling load reduces with increase of aspect ratio of cellular beams.

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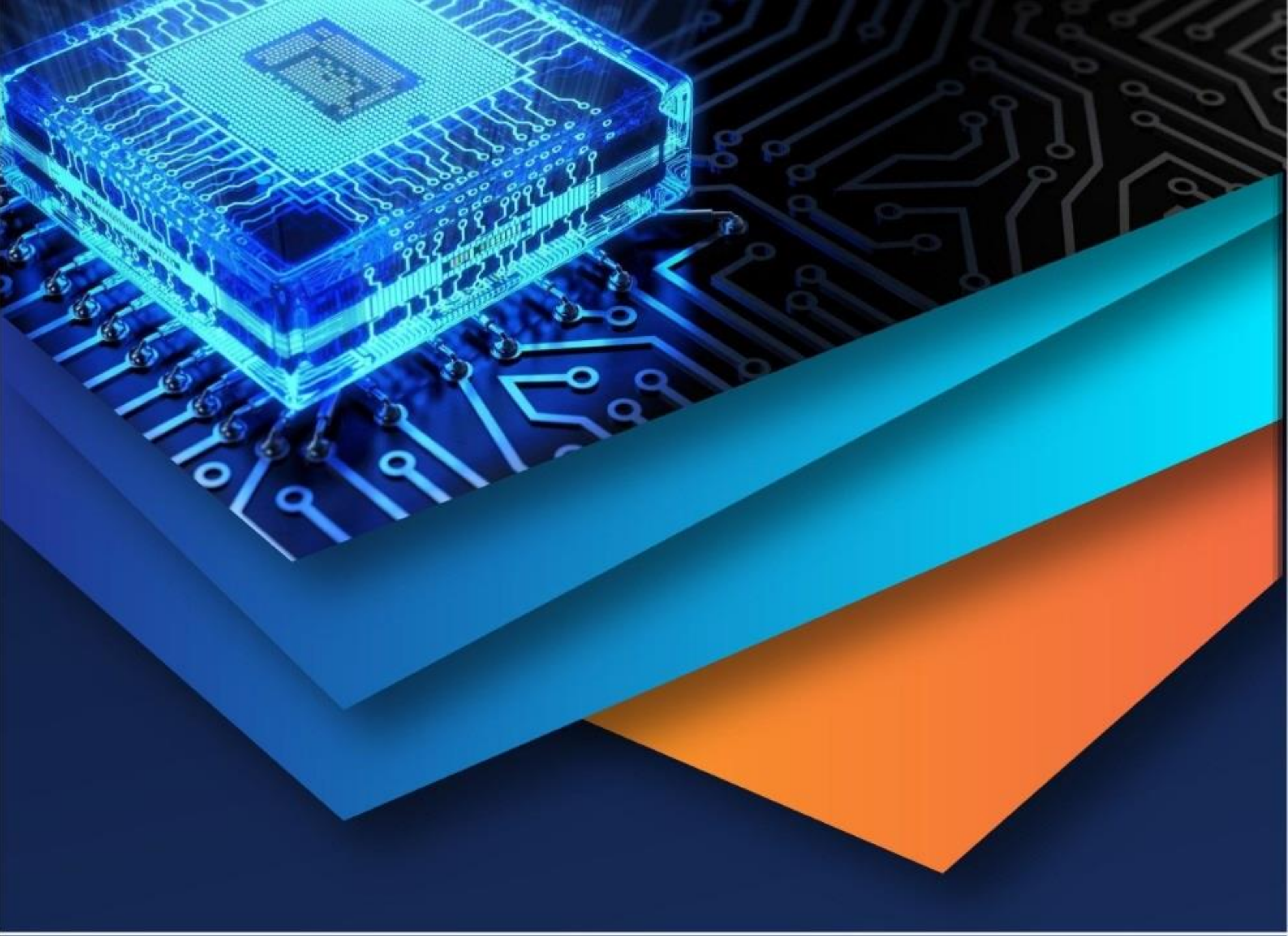

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