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Effect of Fiber Orientation Angle on Stress Intensity Factor of Composite Laminated Crack Plate

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Abstract: This paper presents the effect of fiber orientation angle on fracture toughness of single edge notched composite laminate crack plate due to the tensile load. Determining the mode I stress intensity factor for specimen with seven different fiber orientation angles were computed individually by using analytical and finite element method solutions are presented using macro mechanics approach composite analysis of laminate by using ABAQUS 6.13 finite element package are obtained. It is observed that the stress intensity factors of fiber orientation angle are influenced the fracture toughness variations. The results obtained from finite element approaches and analytical showed good comparison.
Keywords: Composite laminate, Crack, Fracture toughness, Stress intensity factor

I. INTRODUCTION

Composite laminate materials have many applications ranging from Airplanes, Space crafts, Solar panels, Racing car bodies, Bicycle frames, Fishing rods, Storage tanks, Ships, boats, automotive to most of the industrial application and numerous advantages due to its high specific strength and high specific modulus, lighter weight and longer life. [1] Now a day the need and uses of composite material increased across the global.

A lamina is a flat (or sometimes curved) arrangement of unidirectional (or woven) fibers suspended in a matrix material. A lamina is generally assumed to be orthotropic, and its thickness depends on the material from which it is made. Laminate is a stack of lamina. Layers of different materials are joined together. The mechanical response of a laminate is different from that of the individual lamina that forms it.

In the fracture mechanics approach, it is recognized that no matter how careful the manufacturing process is defects will always be present. Whether these defects grow into catastrophic cracks or not depends of the size of the defects, the state of stress to which they are subjected, and the toughness of the material. [2] These cracks initiate at structural discontinuities such as holes, material defects, or other abrupt changes in configuration and may propagate to failure under operating stress levels. Replacing components of engineering structures is often too expensive and may be unnecessary.

Mechanical systems can then be designed by using the fracture mechanics parameters. The fracture toughness of the material, a widely accepted fracture parameter, can be used in determination of the material strength against crack growth under external loads and can be easily calculated in terms of stress intensity factors. Value of the stress intensity factor (SIF) at the critical failure load is defined as the fracture toughness.

In Composite laminates, fracture crack propagation takes place through any of the three modes or through a combination of the three modes. Mode I fracture (opening mode) represents the crack propagation under normal in plane loading where the crack is positioned perpendicular to the applied load. Mode II fracture (sliding mode) represents crack propagation due to shear type failure where the load applied is transverse to crack length. Mode III fracture (Tearing mode) represents crack propagation due to tear type failure where the load applied is parallel to the crack length. Mode I usually plays a dominate role in engineering application and considered to be the most dangerous.

The computational problems for cracked systems, however, are clearly related to the numerical technique adopted for the analyses. Fracture mechanics, in this sense, has been extensively studied with the Finite Element Method (FEM), especially after the 1960s, due to the progressive increase of the computational power available for computational research. It is famous that the finite element method gives with a high accuracy the SIFs at the crack tip [10]. To determine the strength of composite laminate plate (with longitudinal surface or through cracks) is related to the Common Test Specimen Geometries, the crack length, the material yield strength, and fracture toughness according to different lamina angle. Develop 3D modeling of different composite laminate crack plate Determine analyzing with Abaqus 6.13 software. Compare stress intensity factor found from Abaqus 6.13 and the numerical result.

II. RELATED WORK

As indicated above, researchers are operational with the problems of inter ply cracking. T. Prabeena, D. Srikanth Rao, N. Gopikrishna [3] Evaluate the fracture toughness of glass fiber/epoxy composites of fracture toughness of the specimen was employed to conduct mode-I fracture test using special loading fixtures as per ASTM standards of DCB5528 specimen. Fracture toughness is more for specimen, which indicates that the above oriented specimen is preferable among all the other oriented specimens. The crack propagation is decreases with the increase of fracture toughness. In the fracture test the sample tolerates maximum stress up to some limit and then it starts decreasing before it gets failed. P.V. Lakshmi, M. Lakshmi, P. Seema [4] author shown that 90° is an optimum helix angle in built-up of composite tubes prepared of glass fiber and epoxy resin. The deformation of 90° is less compared of other helix angles and very close to Mild Steel tube. The results when compared composite material results shows much closer to conventional materials like mild steel in terms of stress and deformation. Laffan, Pinho, Robinson, Iannucci, McMillan [13] Through a discussion of microscopy of failed specimens and a micromechanical FE model it was concluded that the 45^0 crack was most likely the result of pure compression failure of the fibers, rather than through a micro buckling type process. Nicholas, Rossana and Tornabene [5] The Stress Intensity Factor obtained from the Generalized Differential Quadrature method are based on a linear interpolation of the stresses near the crack tip within a certain distance of interpolation, and agree very well with those computed predictions available in the literature. This proves the accuracy and efficiency of the proposed method for fracturing problems, also with the adoption of a limited number of grid distributions in space near the crack tip. Al-Ansari, Hashim N. Al-Mahmud,Saddam [13] This paper analyzed that FEM is more accurate than the MFree method because of its ability to describe the interaction between the fiber and matrix properties and the calculation technique of SIF used in each method.

III. METHODOLOGY

A. Geometry and Theoretical Approach

The geometry of single edge notched composite laminate crack plate is defined by Depth / plate thickness (B), Width (W), Crack length (a), Length (L) , as shown in Figure 1.

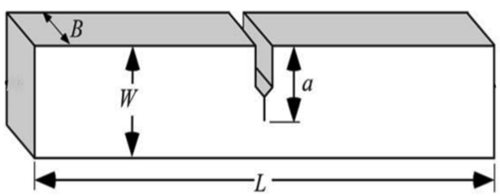

Fig 1.A Single edge crack plate

Analytical method for determination of mode I stress intensity factor for specimen of Single edge crack plate[1,11]
The properties of carbon fiber composite laminate IM7/8552 carbon/epoxy laminate are as shown in table 1.

Table-1
Mechanical properties of Laminate

Properties	Value
Longitudinal modulus (E11)	171.4 MPa
Transverse modulus (E22)	9.08 MPa
shear modulus (G12)	5.29 MPa
Poission's ratio (V12)	0.32
Poission's ratio (V23)	0.4

The properties of the composite lamina parallel and perpendicular to the loading direction (parallel and perpendicular to the plate geometrical axes) for different fiber orientations are obtained using the following transformation relations.

$$\frac{1}{E_x} = \frac{\cos^2\theta}{E_1}(\cos^2\theta - \sin^2\theta\ \nu_{12}) + \frac{\sin^2\theta}{E_2}(\sin^2\theta - \cos^2\theta\ V_{21}) + \frac{\cos^2\theta \sin^2\theta}{G_{12}}$$

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$$\frac{1}{Ey} = \frac{sin^2\theta}{E_1}(\sin^2\theta - \cos^2\theta\ V_{12}) + \frac{\cos^2\theta}{E_2}(\cos^2\theta - \sin^2\theta\, V_{21}) + \cos^2\theta \sin^2\theta$$

$$\frac{V_x}{E_x} = \frac{Vy}{Ey} = \frac{\cos^2\theta}{E_1}(\cos^2\theta v_{12} - \sin^2\theta\ ) + \frac{\sin^2\theta}{E_2}(\sin^2\theta\, v_{21} - \cos^2\theta\ ) + \frac{\cos^2\theta \sin^2\theta}{G_{12}}$$

$$\frac{1}{Gxy} = \frac{1}{G_{12}}$$

The stress-intensity solutions for all of these configurations are given of the *KI* solutions in have the following form

$$K_I = \frac{P}{B\sqrt{W}}\ f\left(\frac{a}{W}\right) Y(□□$$

Where

P = Applied load (N)

$f\left(\frac{a}{W}\right)$ = Dimensionless geometry function.

B = Depth / plate thickness (mm)

W = Width (mm)

a = Crack length (mm)

L = Length (mm)

Y(□□□□□□□□□Material orthotropy correction parameter

□ = Measures parameters of plane material orthotropy

Sij = Compliances

□□□□$\frac{2S_{12}+S_{66}}{2\sqrt{S_{11}S_{22}}}$

$S_{11} = \frac{1}{E_x}$ $S_{22} = \frac{1}{Ey}$ $S_{12} = \frac{V_x}{E_x} = \frac{Vy}{Ey}$ $S_{66} = \frac{1}{Gxy}$

$$f = \frac{\sqrt{2 tan\frac{\pi a}{2W}}}{cos\frac{\pi a}{2W}}[0.752 + 2.02\left(\frac{a}{W}\right) + 0.37\left(1 - \sin\frac{\pi a}{2W}\right)^3]$$

Y(□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□²□□□□□□□□□□□□□□□³□□□□□□□□□□□]$^{1/4}$

B. Modeling and Analysis

Finite Element approach: The following section leads you through the ABAQUS/CAE modeling process by visiting each of the modules and showing you the basic steps to create and analyze a single edge crack. Abaqus 6.13 analysis uses following steps: Creating a part, Creating a material, Defining and assigning section properties, Assembling the model, Defining your analysis steps, Creating the crack and the seam, Applying a boundary condition and a load to the model and Meshing the model. The plate geometry considered has the dimensions Length=30, Width=15 and thickness=3. It is modeled as a 24 layered composite laminate having transversely placed crack (Perpendicular to plate length) with a crack length of 5 mm with the same plate changing orientation angle ±15°, ±25°, ±35°, ±45°, ±55°, ±65° and ±75°. For material takes from mechanical properties of carbon fiber composite laminate from table 1.

Figure 2 shows the three dimensional model of Single edge crack plate the arrangement of upper plate for applying the load and the lower plate are analytical rigid or fix. Types of structural analysis are used in model Static Analysis. The beginning of the crack length and the crack tip Singularity and type 0.25 as mid side node parameter and select Collapsed element side, duplicate nodes. The deformed mesh around the crack tip, you must use Wedge Element Shape. ABAQUS know that you are working with quadrangular elements and will analyze it as degenerated quadrangular elements. Also, with 3D geometry, it is difficult to get the mesh to sweep around the singularity and then sweep from one face to another. To force this you need to make sure that there is just one element along the length of the line within the circular region. As it is a swept mesh you only need to assign an element number along this line on one side as the seeding scheme will propagate to the other side. Assigning an element type selected Quadratic as Geometric Order Reduced integration C3D20: A 20-node quadratic tetrahedron elements brick is used and mesh size. In meshing chosen Hex element shape, sweep technique and medial axis algorithm. For mainly problems, the most efficient mesh design for the crack tip region belongs to the “spider web” configuration. This configuration consists of concentric rings of four sided elements that are focused toward the crack tip. The close ring is formed by quadrangular elements degenerated to triangles. Total numbers nodes are 85096 and number of elements are 19269.

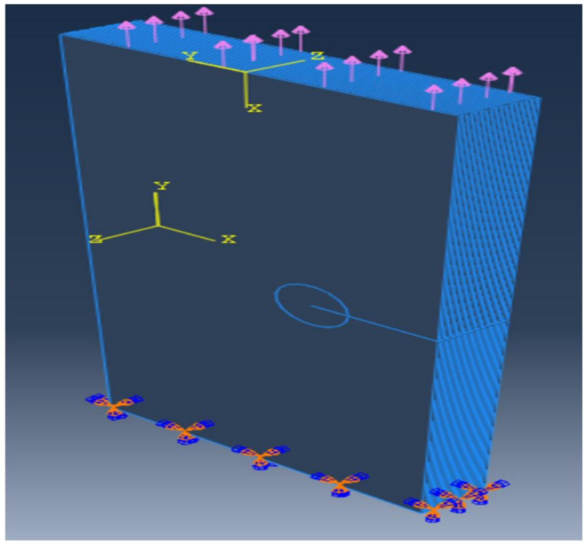


Fig 2.Model of Single edge crack plate

IV. RESULT

Result of Von Mises stress and displacement for SIF of a plate with single edge crack length are getting as shown figure 4 respectively from abaqus 6.13 Maximum value of von Mises stress and displacement are increase and decrease due to fibre orientation angle. The maximum stress intensity factor around the crack tip for different fiber orientations obtained from theory and finite element analysis are tabulated in table 2.The stress intensity factor distribution around the crack tip for Fifteen degree fiber orientation is shown in figure 4 and variation of stress intensity factor around the crack vicinity with fiber angle is shown in figure 3.

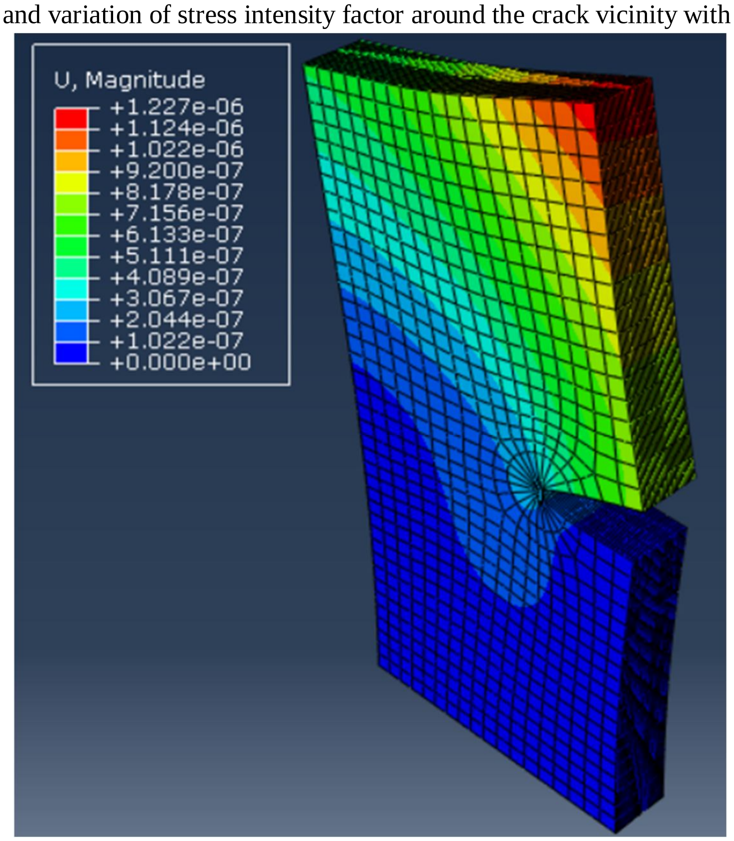


Fig. 3 Displacement Side Edge crack Plate ±15°

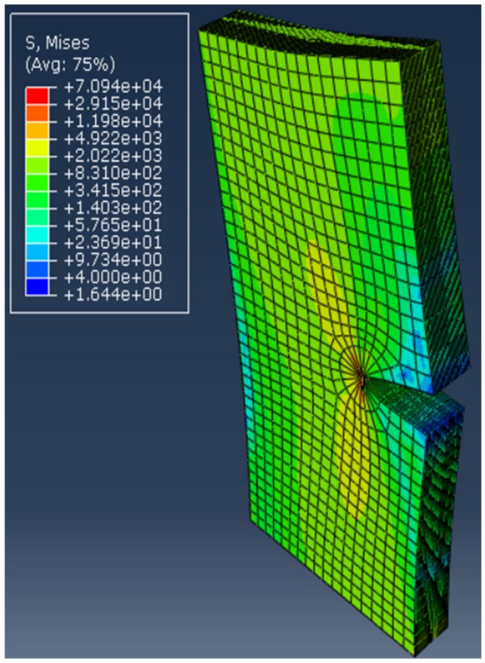
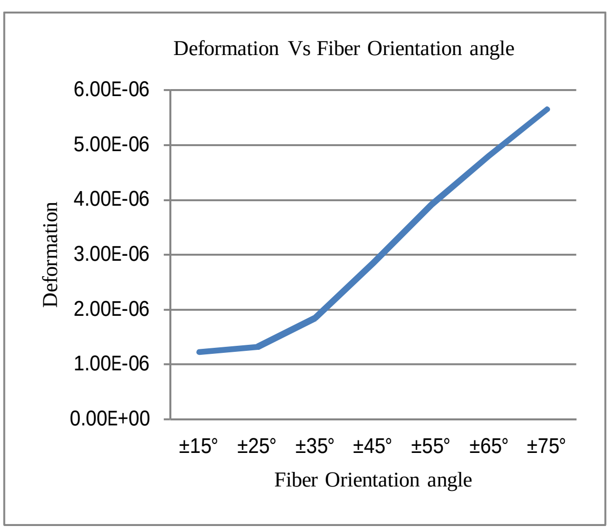


Fig. 4 Von Mises Stress Side Edge crack Plate ±15°

Table 2 Maximum Stresses, Deformations and FEM Result of SIF K1 for Single edge crack with Different Orientations angle

Orientations	Deformations	Mises stress	Abaqus	Analytical
±15°	1.227e-06	7.094e+04	178.1	179.8
±25°	1.321e-06	7.166e+04	179.9	180.6
±35°	1.843e-06	7.626e+04	198.7	199.9
±45°	2.847e-06	9.133e+04	241.4	242.8
±55°	3.916e-06	1.038e+05	267.5	268.7
±65°	4.800e-06	1.131e+05	292.2	294.2
±75°	5.654e-06	1.134e+05	327.7	329.3



Graph 1 Deformation variations with Fiber Orientation angle

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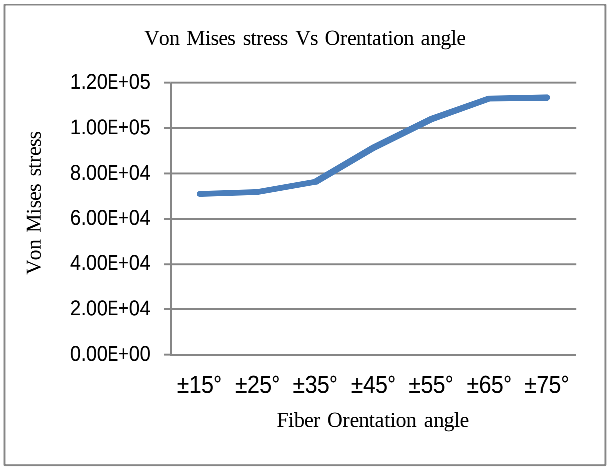
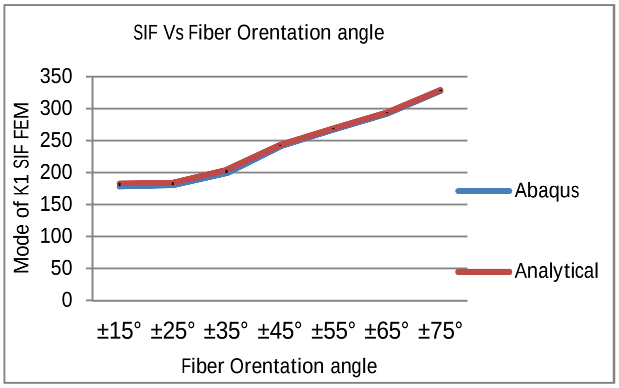


Graph 2 Von Mises stress variations with Fiber Orientation angle



Graph 3 SIF variations with Fiber Orientation angle

Graph 1 shows the variation of Deformation on the crack plate for different fiber orientations. It is observed that the Deformation is maximum 75 degrees. From 15 degrees, the fibers are more or less approximately parallel to the crack front and have minimum values of deformation. The number of displacement fibers at the crack front is very less and the major portion of the load is taken up by the matrix phase. This results in low deformation distribution around the crack tip and the plate. From 75 degrees, there is high probability of slippage of fibers due to induced shear stresses apart from the normal tensile stresses at fiber matrix interface with have high displacement. This results in high deformation around the crack tip. From 75 degrees and above the number of continuous fibers sharing the far field uniformly applied deformation also increases resulting in reduction of deformation around the crack tip.

Graph 2 shows the variation of stress around the crack tip for different fiber orientations. It is observed that the stress is maximum 75 degrees. From 15 degrees, the fibers are more or less approximately parallel to the crack front. The number of discontinuous fibers at the crack front is very less and the major portion of the load is taken up by the matrix phase. This results in low stress distribution around the crack tip. From 75 degrees, there is high probability of slippage of fibers due to induced shear stresses apart from the normal tensile stresses at fiber matrix interface. This results in high stress around the crack tip. From 75 degrees and above the number of continuous fibers sharing the far field uniformly applied stress also increases resulting in reduction of stress around the crack tip.

Graph 3 shows the variation of stress intensity factor around the crack tip for different fiber orientations. It is observed that the stress intensity is maximum 75 degrees. From 15 degrees, the fibers are more or less approximately parallel to the crack front. The number of discontinuous fibers at the crack front is very less and the major portion of the load is taken up by the matrix phase. This results in low stress intensity factor distribution around the crack tip. From 75 degrees, there is high probability of slippage of fibers due to induced shear stresses apart from the normal tensile stresses at fiber matrix interface. This results in high stress intensity factor around the crack tip. From 75 degrees and above the number of continuous fibers sharing the far field uniformly applied pressure intensity also increases resulting in reduction of stress intensity factor around the crack tip.

V. CONCLUSION

In the present work is influence of fiber orientation angle on fracture toughness of single edge notched composite laminate crack plate of carbon / epoxy orthotropic laminate. The validity of modeling and analysis techniques using finite element approaches was proved by comparing the results with theoretically result. The following are the observation of this study. The effect of the variation of fiber reinforcement angle on fracture toughness is decreases with increasing fiber orientation angle θ. When numerical results are compared with finite method approaches, it is seen that the results of numerical methods are very close.

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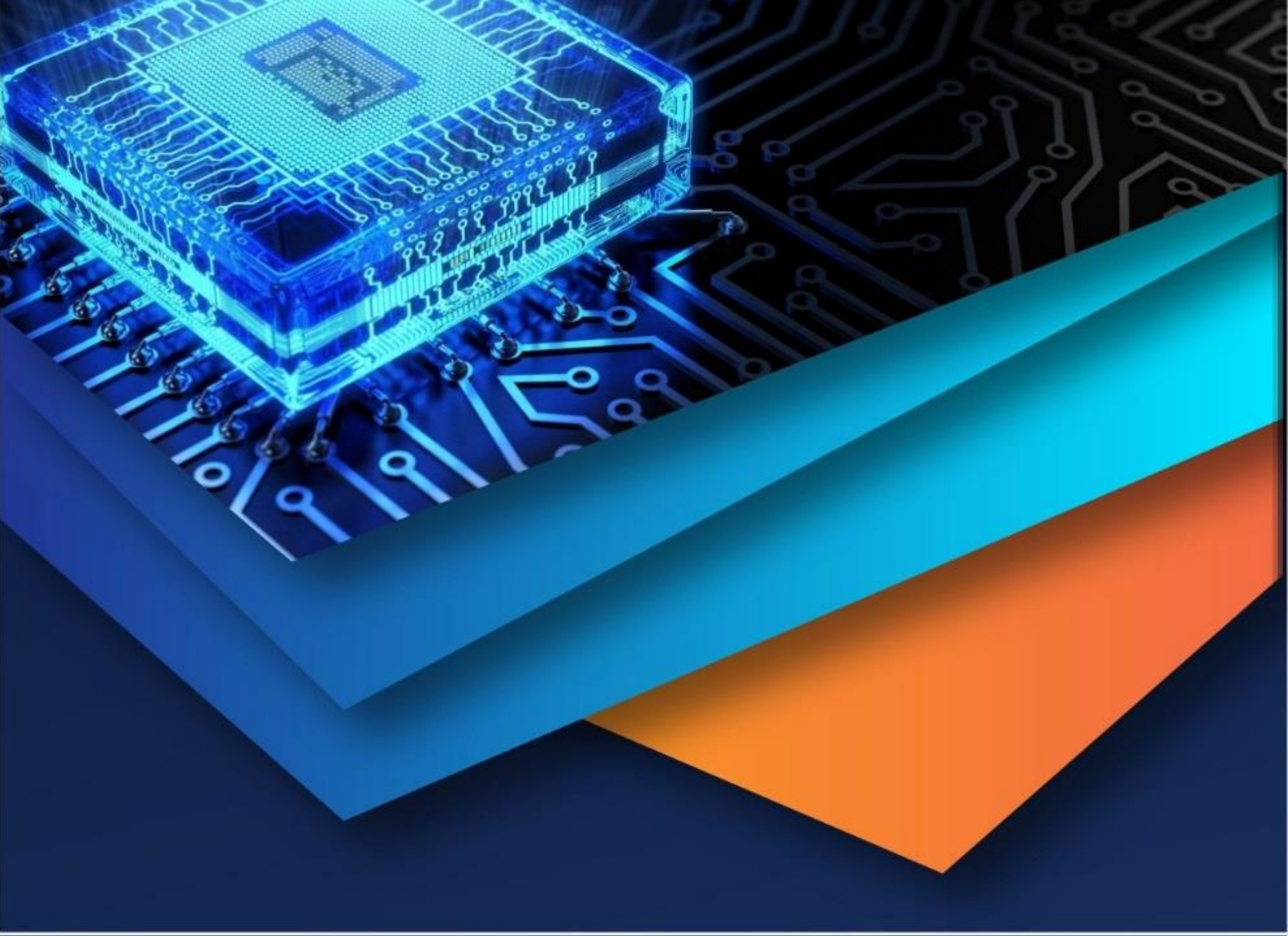

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