iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 6 **Issue:** VI **Month of publication:** June 2018

DOI: http://doi.org/10.22214/ijraset.2018.6202

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 6 Issue VI, June 2018- Available at www.ijraset.com

Prediction of Tensile Properties of Novel Natural Fiber Based Fiber Metal Laminates (FMLs) using FEM

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***Abstract**: The present investigation deals with the prediction of tensile properties of a novel jute fiber based Fiber Metal Laminate (FML). Periodic Micromechanics is used to determine the orthotropic elastic properties of the fiber reinforced epoxy lamina, and the effect of fiber volume fraction on the tensile behavior of the FML is studied using FEM. The elastic and plastic Young's moduli and tensile yield strength of FMLs are determined by the curve fitting technique. The tensile strength obtained through this method is compared to that obtained by the analytical model available in the literature and a very good agreement is observed between the two. It is found that both the Young's moduli improve with an increase in the fiber volume fraction with a simultaneous increase in the tensile yield strength. Correlations for predicting the elastic and plastic Young's moduli as well as the tensile yield strength of the FMLs are also presented. Based on the observations of the present investigation, the FEM can be established to be an imperative tool for the study of the mechanical behavior of the FMLs.*
***Keywords**: Fiber Metal Laminates, Periodic micromechanics, FEM, ANSYS*

I. INTRODUCTION

Fiber reinforced composites have replaced metals and alloys in most of the structural applications in the recent years. A more relevant and masterful materials that have recently evolved in the development of advanced composites are the Fiber Metal Laminates (FMLs). An FML tends to take advantage of ductility of engineering metals viz. aluminum, magnesium and their alloys and the high specific properties of fiber reinforced plastics resulting in the evolution of a material having properties superior to its constituents. The FMLs are known to possess excellent impact properties, good blunt notch and residual strengths, flame retardency and good manufacturability. The first commercial use of ARALL (Aramid Reinforced Aluminum Laminates) started in the year 1982 for aircraft wings applications. In the year 1987, another generation of these laminates with the trade name GLARE (Glass fiber Reinforced Aluminum Laminates) was put forth consisting of aluminum alloy sheets and unidirectional or bidirectional reinforced glass fiber/epoxy prepegs. GLARE and ARALL have been the most heavily researched FML till date. The structural performance of FMLs depends upon the stacking sequence, individual lamina properties, orientation of fibres in the lamina [1]. The need of shorter lead time in the manufacturing of composites and incorporating frequent changes in the geometrical properties viz. fiber orientation, stacking sequence and the lamina thicknesses of the laminates has pushed the designers to thrive for novel analytical as well as numerical methods for the same. Use of finite element analysis for the analysis of fiber-metallic laminates (FMLs) has gained tremendous relevance in recent years. Elasto-plastic behavior of an ARALL laminate in combination with the mechanical properties of aluminum and Kevlar was modeled through CLT by [2]. The tensile strength of many FMLs was observed to be superior to the different aerospace grade aluminum alloys with an added advantage of weight reduction by [3]. Analytical modeling and numerical simulation of the tensile properties of hybrid FMLs was modeled by [4]. An analytical procedure for the calculation of uniaxial stress-strain behavior of GLARE was presented by [5]. The tensile properties of novel FMLs were studied experimentally, analytically and through finite element method by [6]. They used the modified Classical Laminate Theory (CLT) to obtain the stress-strain behavior of developed FMLs analytically. A more recent effort to in this direction has been made by [7] who tried to assess the stress-strain behavior of the available grades of GLARE through Cohesive Zone Modeling (CZM) approach in ANSYS.

In the present investigation, the effect of fiber volume fraction on the tensile properties of a novel aluminum (AA 5086) FML based on epoxy and jute fiber has been studied using Finite Element Method. A mathematical model available in the literature has been used to validate the approach used here. It is observed that there is a good agreement between the two approaches. An important consideration in the finite element modeling of FML is the incorporation of the elasto-plastic behavior of the metal layer which has been taken care of in the present analysis through specialized material model as discussed in a subsequent section.

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II. MATERIALS AND METHODS

A. Reinforcement and Matrix

Jute is an eco-friendly natural fiber owing to its biodegradability and renewability. It is mainly grown in the South-Asian region including, Indian, Bangladesh, Thailand and China with Bangladesh producing around 90% of the world's total jute. It is known to possess good strength and is cheaper in cost than the other natural fibres [8]. The chemical composition of jute fiber is as given below:

Table I Chemical Composition Of Jute Fiber [8]

Component	Cellulose	Hemicellulose	Lignin	Ash	Pectin	Wax	Moisture
Percentage	61-71%	13.6-20.6%	12-13%	0.5-2%	~ 0.2%	~ 0.5%	~ 12.6%

Table II Mechanical Properties Of Jute Fiber [9]

Property	Tensile strength	Modulus of Elasticity	Elongation at break	Density
Value	410-780 MPa	26.5 GPa	1.9 %	1.48 g/cc

The high cellulose content of the jute fiber makes it an attractive reinforcement option in a wide variety of polymer matrices. Table 2 shows the mechanical properties of Jute fibres. Epoxy matrix with material properties as given in the table 3 has been used as the matrix material in the present investigation. Epoxy is a known thermosetting plastic with excellent mechanical properties such as stiffness and strength. Epoxy is used as a matrix material in a wide variety of polymer matrix composites (PMCs). Matrix has a dual role to play in the composites – they transfer and distribute the load applied to the fibres (reinforcement) and also protect them against harsh environmental as well as operating conditions.

B. Aluminum Alloy (AA 5086)

Aluminum alloy AA 5086 is used as the metal layers in this research. The mechanical properties of aluminum alloy AA 5086 are given in the tablel below:

Table IIIIVV Mechanical Properties Of Aa 5086 **[5]** Alloy And Epoxy Matrix

Elastic Young's modulus	Tangent modulus	Yield Strength
46.5 GPa	770 MPa	275 MPa
3.4 GPa	-	-

AA 5086 shows a bilinear isotropic stress strain behavior under tensile loading. This very fact introduces nonlinearity in the stress-strain behavior of FMLs thus requiring specialized techniques such as the FEM.

C. Finite Element Modeling

Three general pathways of modeling FMLs have been outlined by [7]. These are micro scale: fibres and matrix are studied individually; meso scale: individual lamina is modeled and analyzed and macro scale: entire laminate is considered to be a homogenized laminate. Due to obvious reasons, the meso scale modeling was used in this research. The physical relevance of straight sided specimens for tensile testing of FMLs has been displayed by [6]. In the light of that, in the present analysis also a straight sided finite element model of size 175 mm x 25 mm x 1 mm was employed to obtain the tensile behavior of the FMLs. Each layer is considered to be equal to 0.2 mm in thickness with 5 layers in total. The FMLs were modeled in a commercially available finite element solver ANSYS using the SHELL 91 elements. The SHELL 91 is a layered element with nonlinear capabilities. It is defined by eight nodes (having six degrees of freedom at each node), thickness of each layer, material direction in each layer and orthotropic material properties. The load was applied at each free vertical end of the model in 20 sub steps to capture the non-linear material behavior accurately. Before that, all the nodes present in the vertical ends of the model were coupled with each other to avoid localized deformation due to the application of concentrated tensile load on a node. The bilinear behavior of the aluminum AA5086 sheet was incorporated in the material properties using the Mises plasticity model. Figure below shows the laminates as modeled in ANSYS.

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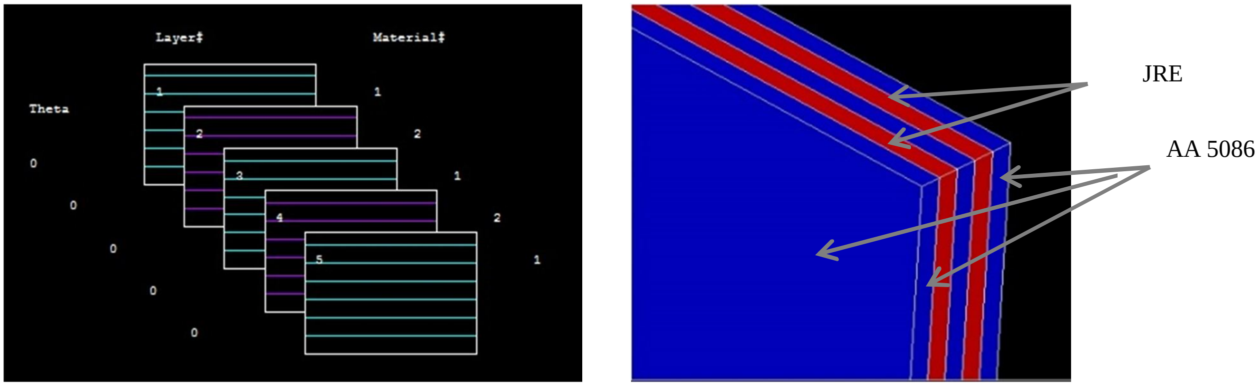


(a) (b)

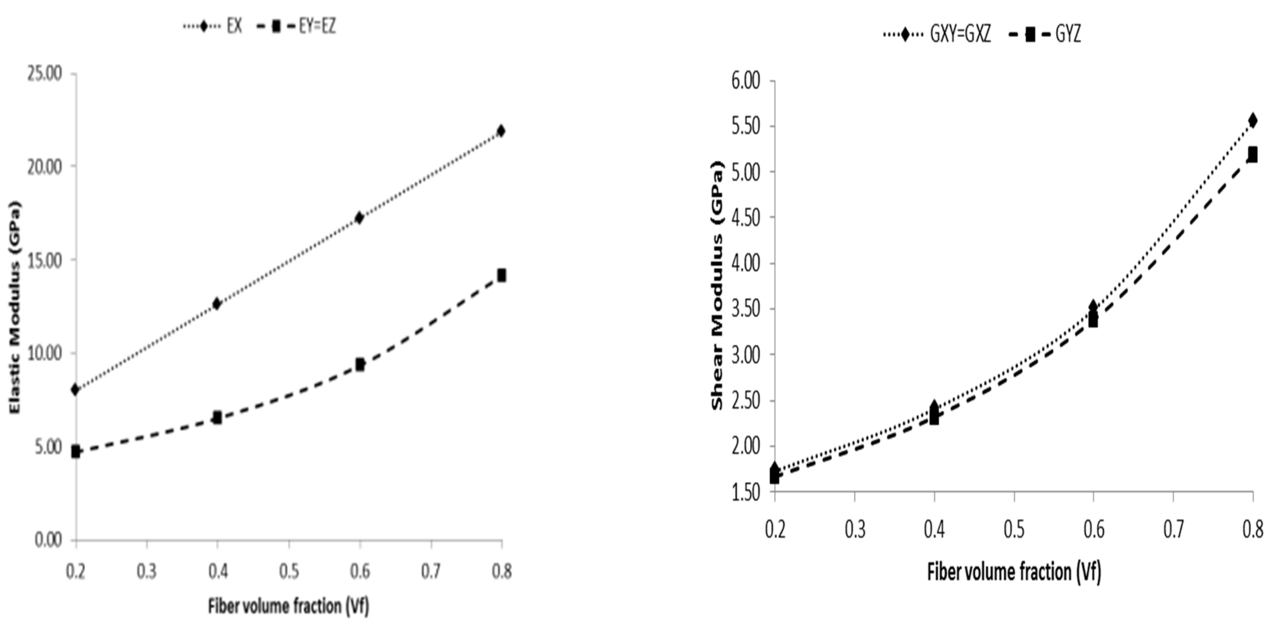
Fig.1. (a) Layup as defined in ANSYS and (b) Alternate layers of AA 5086 and Jute fiber reinforced epoxy (JRE) in 3/2 configuration.

D. Mathematical Modeling

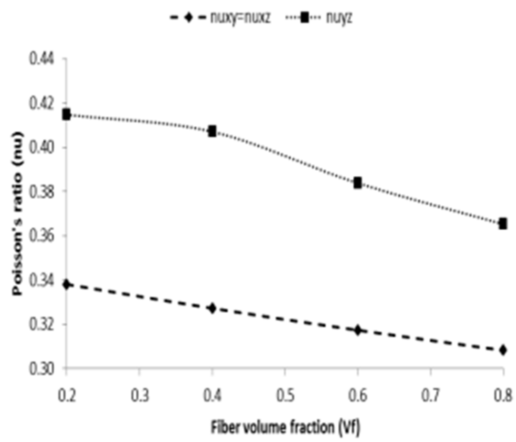
An analytical model based on the modified CLT for predicting the tensile behavior of the tensile properties of a balanced symmetric laminate has been proposed by [6]. The model is applicable to balanced symmetric laminates having no out of plane deformations. In this model the CLT has been modified to incorporate the elasto-plastic behavior of the metallic layer.

E. Micromechanics

The orthotropic material properties of the individual lamina can be determined using the micromechanics of the composite materials. Unlike the isotropic materials, the engineering properties of the orthotropic materials can be obtained by studying the behavior of its individual components viz. matrix and reinforcement. Many empirical, semi-empirical, experimental, finite element and finite difference based methods have been proposed by different researchers [1]. The objective of the micromechanics is to obtain the relation between the elastic properties of the lamina such as stiffness based on the individual properties of the constituents and their volume fraction. Most of the proposed micromechanics methods require one or two constants to be determined by experiments and therefore not closed form in nature. An analytical closed form solution of the above problem based on the Fourier series technique has been proposed by [10]. They also compared the obtained results with experimental ones and observed a high degree of agreement between the two. In the present investigation, the elastic properties of the Epoxy-Jute fiber lamina have been determined using the relations provided by implementing them through short subroutines in MATLAB. Figure 2 shows the variation of different elastic properties with the fiber volume fraction V_f.



(a) (b)



(c)

Fig. 2. Variation of the elastic properties with fiber volume fraction

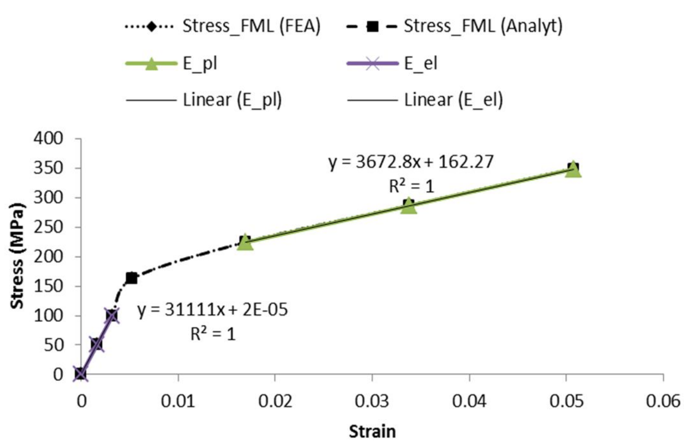
The FMLs considered in this study are designated as follows

Table Iii Designation Of Laminates

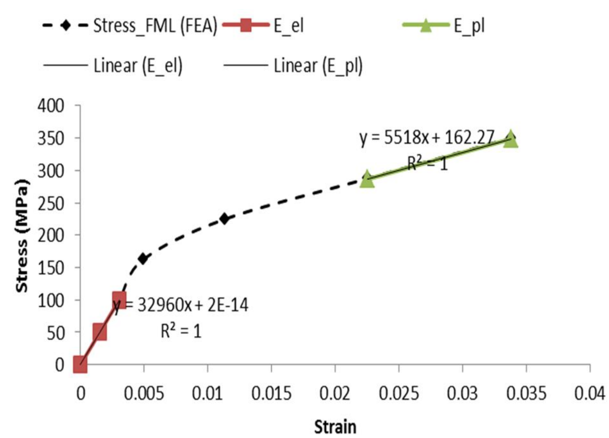
Fiber volume fraction	Matrix volume fraction	Designation
0.2	0.8	Al/JRE (0.2)/Al/JRE (0.2)/Al
0.4	0.6	Al/JRE (0.4)/Al/JRE (0.4)/Al
0.6	0.4	Al/JRE (0.6)/Al/JRE (0.6)/Al
0.8	0.2	Al/JRE (0.8)/Al/JRE (0.8)/Al

III. RESULTS AND DISCUSSION

This section focuses on the study of the effect of the fiber volume fraction on the tensile properties of the FMLs. Analytical method proposed by [6] has been used to validate the approach for fibre volume fraction of 0.2 in the Epoxy-Jute fiber lamina. Figure 3 above shows the stress-strain behavior of the FMLs under tensile loading, to perfectly capture the non-linearity introduced due to the aluminum layers, the tensile load is divided into 20 substeps and the load is applied in ramped mode. In the case of Al/JRE (0.2)/Al/JRE (0.2)/Al laminate (fig.3 (a)) the elastic Young's modulus is 31111 MPa, whereas the plastic Young's modulus is equal to 3672.8 MPa. As the fiber volume fraction is increased to 0.4, the resulting FML Al/JRE (0.4)/Al/JRE (0.4)/Al has an elastic Young's modulus of 32960 MPa (an increase of about 6% over the previous one), and a plastic Young's modulus equal to 5518 MPa which is about 50% more than the earlier case. Similarly, the elastic and plastic Young's moduli for Al/JRE (0.6)/Al/JRE (0.6)/Al and Al/JRE (0.8)/Al/JRE (0.8)/Al are found to improve fig. 3 (c)-(d) with the addition of fiber to the Epoxy-Jute fiber lamina.



(a)



(b)

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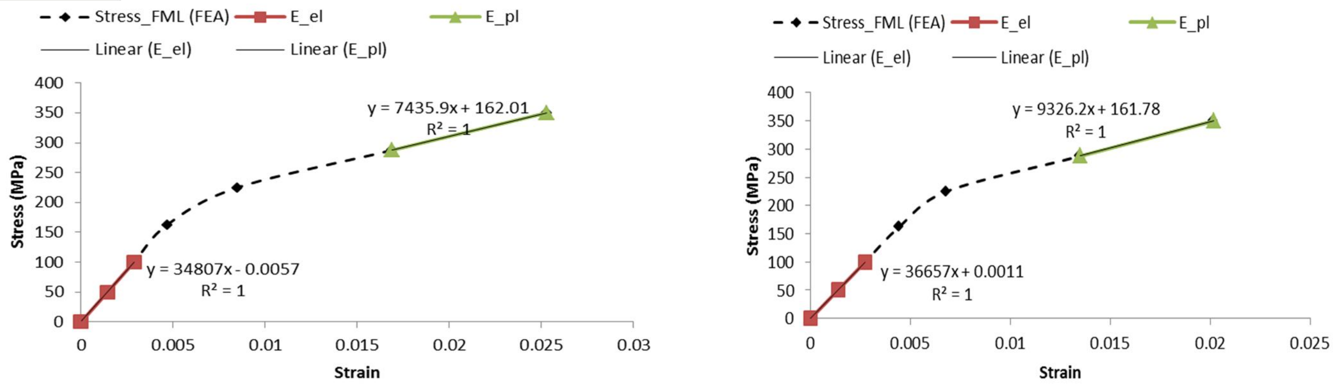
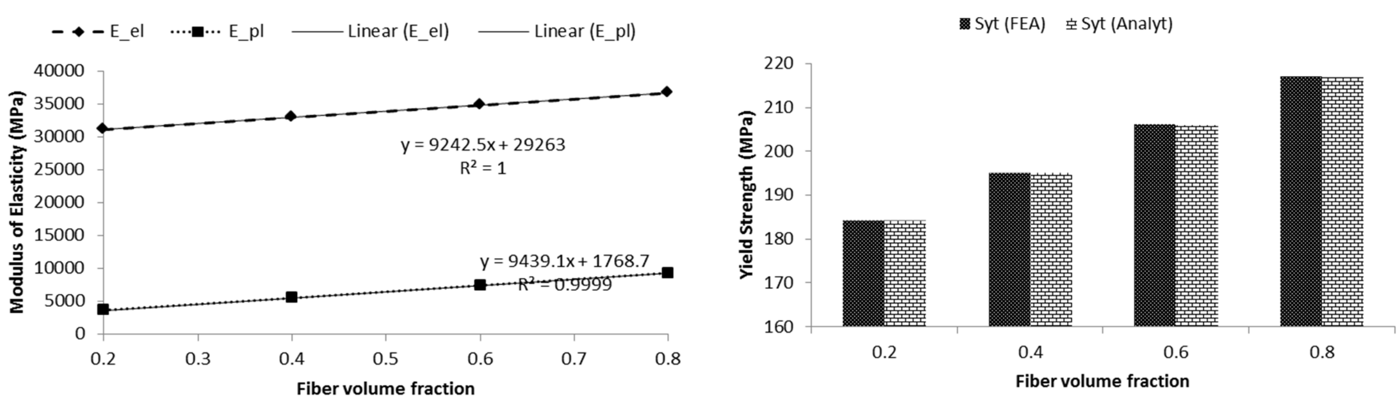


(c) (d)

Fig. 3. Stress-strain behavior of (a) Al/JRE (0.2)/Al/JRE (0.2)/Al, (b) Al/JRE (0.4)/Al/JRE (0.4)/Al, (c) Al/JRE (0.6)/Al/JRE (0.6)/Al and (c) Al/JRE (0.8)/Al/JRE (0.8)/Al



(a) (b)

Fig. 4. (a) Variation of Young's moduli of FMLs with fiber volume fraction and (b) Variation of yield strength of FMLs with fiber volume fraction

Table iv comparison of the tensile yield strength S_{yt} predicted by fea and analytical model

V_f	S_{yt}(FEA) (MPa)	S_{yt}(Analyt)(MPa)
0.2	183.99	184.04
0.4	194.90	194.91
0.6	206.03	205.84
0.8	216.98	216.77

Figure 4 (a) shows the variation of elastic and plastic Young's moduli with the fiber volume fraction. The yield strength of the FMLs is found to improve with increase in fiber volume fraction. This is signified by figure 4 (b) above. Figure 4 (b) shows the variation of tensile yield strength of the FMLs with fiber volume fraction as expected, maximum yield strength is obtained for the FML in which V_f =0.8. Table 4 above indicates this increase in the tensile yield strength.

IV. SUMMARY AND CONCLUSION

In the present investigation, tensile properties of novel jute fiber and epoxy base aluminum FMLs having different fiber volume fraction have been studied using FEM. The elastic properties of the jute reinforced epoxy lamina are calculated using the formulas for the stiffness of composites having periodic microstructure from the published literature. The results of the FEM (yield strength, elastic and plastic Young's moduli) are compared with an analytical model available in literature and a good agreement between the two is observed. It can be concluded that FEA is an effective tool for the study of mechanical behavior of FMLs with an added advantage of tolerance for quick and easy design changes before the actual fabrication of composites. This leads ultimately to shorter lead times in the fabrication of composites. Based on the statistical analysis two correlations with R^2 value equal to 1 for the prediction of the elastic and plastic Young's moduli using fiber volume fraction have been deduced and are given by:

$$E_{el} = 9242.5V_f + 29263 \qquad \text{For elastic Young's modulus}$$

$$E_{pl} = 9439.1V_f + 1768.7 \qquad \text{For plastic Young's modulus}$$

Another relation for predicting yield strength from the fiber volume fraction V_f is obtained as:

$$S_{yt} = 55.04V_f + 172.95$$

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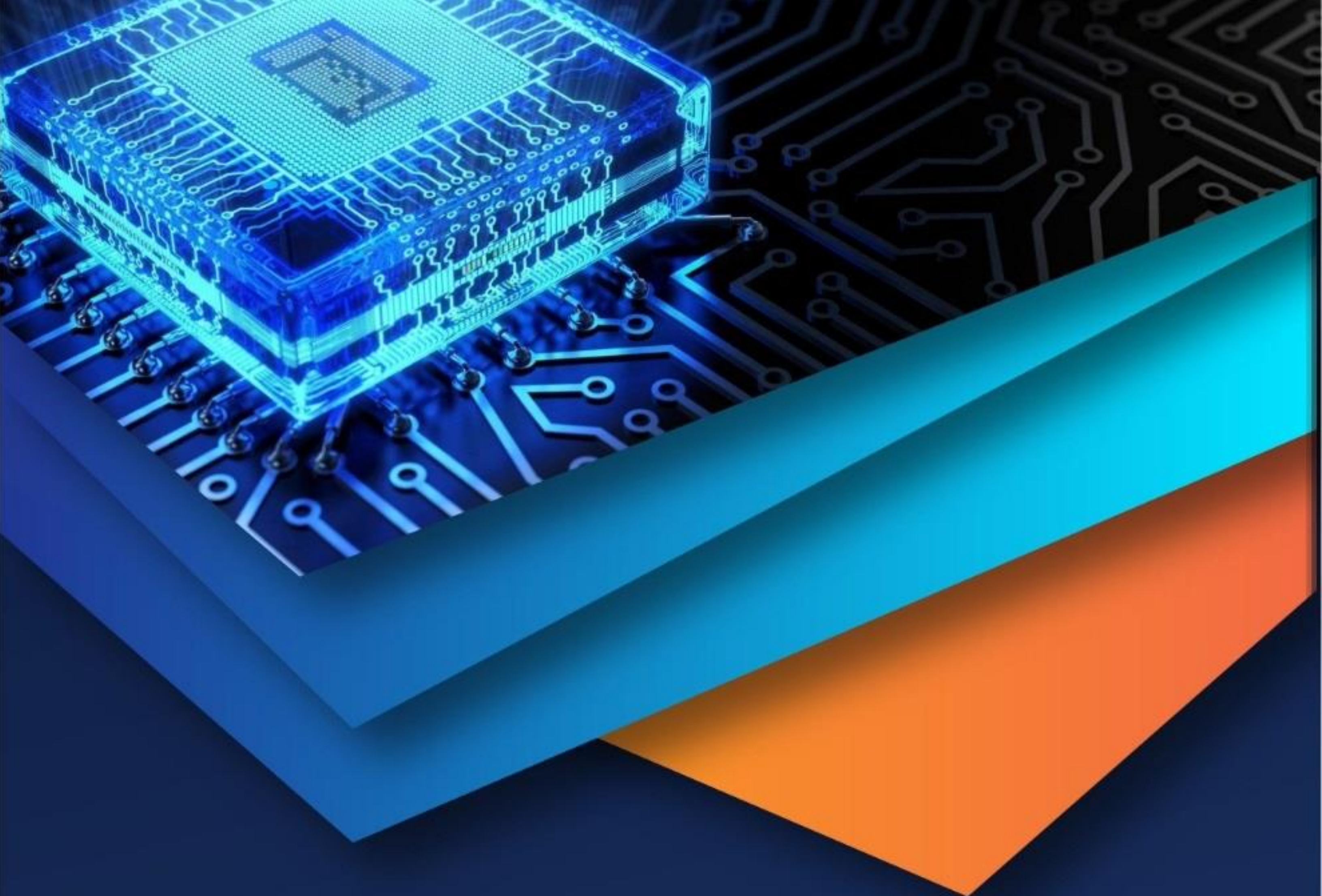

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