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Numerical Investigations of Multilayered Sandwich Structures under Free Vibrations

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***Abstract:** Important structural properties of composite materials, such as high strength-to-weight and high stiffness-to-weight ratios, have resulted in a great need for these materials in various engineering industries, such as Mechanical, Civil, Automobile and Aerospace Engineering. This paper presents results from numerical investigations using software based on Finite Element Method (FEM) and its comparison with other theories from the literature under free vibrations of 5 and 7 layered sandwich plates. This study utilizes the finite element method to perform modal analysis of a sandwich composite plate with a honeycomb core. In this paper, the modal responses of a flat rectangular sandwich plate with a honeycomb core using FEM software are presented. To confirm the accuracy and reliability of the current model, validation with present literature is studied. In this study, aluminum honeycomb is used as the core materials, while glass fiber reinforced composite is used for the top and bottom of the plate to examine modal responses. Free vibration responses are investigated for the various boundary situations. The modal analysis of composite sandwich constructions was investigated, and the results were verified using available literature. The sandwich structure was solved using a finite element approach, which was modeled in ABAQUS software. The results indicated that frequencies by FEM software are in good agreement with other literature results.*
***Keywords:** ABAQUS, Finite Element Method, Free Vibrations, Modal Analysis, Sandwich Plates .*

I. INTRODUCTION

Sandwich structures are widely used in aerospace, automotive, and construction industries due to their lightweight and high stiffness properties. Free vibration analysis of sandwich structures is important for understanding their dynamic behavior, which is essential for design and optimization purposes. Free vibrations of sandwich structures can be analyzed using various methods, including analytical, numerical, and experimental techniques. Analytical methods, such as classical lamination theory and higher-order sandwich panel theories, provide closed-form solutions for simple sandwich structures. Numerical methods, such as finite element analysis, can handle more complex geometries and material properties, but require significant computational resources. Experimental methods, such as modal analysis, provide direct measurement of the natural frequencies and modes of vibration of the sandwich structures. The vibrational behavior of sandwich structures is affected by various factors, such as the geometry, material properties, boundary conditions, and loading conditions. The presence of core materials, such as foam or honeycomb, can significantly affect the vibration modes and frequencies of the sandwich structures. Delamination, which is a common failure mode in sandwich structures, can also affect the vibrational behavior by altering the stiffness and damping properties of the structure. Free vibration analysis of sandwich structures is essential for the design and optimization of structures that require high dynamic performance. By understanding the natural frequencies and modes of vibration of the sandwich structures, engineers can design structures that avoid resonance and reduce the risk of failure due to dynamic loads. Ahmed [1] used finite element displacement method to investigate the free vibration characteristics of curved sandwich beams under clamped-clamped boundary conditions. Goyal [2] studied the free vibrations of sandwich beams having a central mass. Shu [3] solved the free vibrations of sandwich beams with single and double delamination analytically. Frostig and Baruch [4] presented a free vibration analysis of sandwich beams under simply supported boundary conditions based on a higher-order beam theory for the skins and a two-dimensional elasticity solution for the core. By applying the discrete Green function, a free vibration analysis of a three-layer sandwich beam with an elastic or viscoelastic core and arbitrary boundary conditions was presented by Sakiyama et al. [5]. Furthermore, a related work about free vibration of stiffened rectangular plates using Green's functions was presented in [6]. Kameswara Rao et al. [7] used a fully third-order model of laminated composite and sandwich beams based on a higher-order mixed theory. Kapuria et al. [8] presented a third-order zig-zag theory for the static, free and forced vibration analysis of sandwich beams. Bhangale and Ganesan [9] studied the buckling and vibration behavior of a functionally graded material sandwich beam having constrained viscoelastic layer in thermal environment by using the finite element method. An assessment of higher-order and zig-zag displacement-based theories for the stability and free vibration of sandwich beams was proposed by Wu and Chen [10].

Kulkarni and Kapuria [11] focuses on the development of an improved numerical method for analyzing the free vibration behavior of composite and sandwich plates. The authors introduce a discrete Kirchhoff quadrilateral element that incorporates the third-order zigzag theory. This approach allows for a more accurate representation of the displacement field and captures the shear deformation effects that are present in composite and sandwich plates. The element is formulated based on the variational principle and includes the effect of transverse shear stresses using the third-order zigzag theory. Wang et al. [12] addresses the analysis of the free vibration behavior of skew sandwich plates with laminated facings. Skew plates are structural elements with non-orthogonal angles between their principal axes and the plate boundaries. The authors present a comprehensive study on the free vibration characteristics of skew sandwich plates by employing a numerical approach. They developed a finite element model based on the Mindlin plate theory, which considers the effects of transverse shear deformation and rotary inertia. The laminated facings are modeled using the layer-wise theory, accounting for the individual stiffness and orientation of each layer. Chakrabarti and Sheikh [13] introduce a new refined element for analyzing the vibration of laminate-faced sandwich plates. Their study aims to enhance the accuracy of numerical simulations by considering higher-order effects and accurately capturing the behavior of these complex structures. Belarbi et al. [14] present a layerwise finite element formulation for the free vibration analysis of laminated composite and sandwich plates. Their work focuses on developing an accurate numerical model that accounts for the layer-wise variations in material properties, providing a reliable tool for predicting the dynamic behavior of these plates. Burlayenko et al. [15] evaluate displacement-based finite element models used for the free vibration analysis of homogeneous and composite plates. Their study compares different models and assesses their accuracy in predicting natural frequencies and mode shapes, highlighting the strengths and limitations of each approach. Rahmani et al. [16] investigate the free vibration response of a composite sandwich cylindrical shell with a flexible core. Their study focuses on the dynamic behavior of this specific configuration and explores the effects of core flexibility on the natural frequencies and mode shapes of the shell structure. Malekzadeh and Sayyidmousavi [17] analyze the free vibration of sandwich plates with a uniformly distributed attached mass, flexible core, and different boundary conditions. Their research explores the influence of various parameters on the vibration behavior and provides insights into the design and optimization of sandwich plate structures. Jam et al. [18] propose an improved high-order theory for the analysis of the free vibration of sandwich panels. Their study aims to overcome the limitations of existing theories and provide a more accurate prediction of natural frequencies and mode shapes for these structures. Meunier and Shenoi [19] investigate the free vibration analysis of composite sandwich plates. Their work focuses on analyzing the dynamic behavior of these plates and provides valuable insights into the effects of material properties, geometric parameters, and boundary conditions on the natural frequencies and mode shapes. Nayak et al. [20] study the free vibration analysis of composite sandwich plates based on Reddy's higher-order theory. Their research aims to improve the accuracy of numerical models by considering higher-order effects and providing more reliable predictions of the dynamic behavior of these plates. In summary, the reviewed papers contribute to the understanding of free vibration analysis in composite and sandwich plates. They introduce refined element formulations, layerwise finite element models, and improved theories to accurately predict natural frequencies and mode shapes. These studies provide valuable insights for the design, analysis, and optimization of composite and sandwich plate structures in various applications. In this paper free vibration analysis is presented using ABAQUS [21] FE tool.

II. FREE VIBRATION ANALYSIS OF SANDWICH PLATE

A. Example 1: Free Vibrations of five layered symmetric sandwich plate

In this example, a five-layer ($0^0/90^0$/CORE/$90^0/0^0$) symmetric sandwich plate is considered with each ply in the face sheets being of thickness 0.05h, and core of thickness 0.8h.The elastic material properties are taken from Table 1. Table 2 shows the comparison of first mode frequency of 5 layered symmetric cross ply sandwich plate with all sides simply supported. The comparison is made with analytical and numerical Finite Element Methods.

Table 1. Material Properties of 5 layered composite sandwich plate

Quantity	Unit	Face Sheet	Core
E_1	GPa	276	0.5776
E_2	GPa	6.9	0.5776
E_3	GPa	6.9	0.5776
G_{12}	GPa	6.9	0.1079
G_{23}	GPa	6.9	0.22215
G_{31}	GPa	6.9	0.1079
ν_{12}	0.28	0.0025	0.3
ν_{13}	0.28	0.0025	0.3
ν_{23}	0.33	0.0025	0.3
ρ	Kg/m^3	681.8	1,000

Table 2. Comparison of first mode frequency of 5 layered symmetric cross ply sandwich plate (SSSS)

S	ABAQUS Present	Belarbi et al. [14]	Kulkarni and Kapuria [11]	Kulkarni and Kapuria [11]	Wang et al. [12]	Chakrabarti and Shaikh [13]	% error wrt [11]
6.67	10.44378	10.564	10.524	13.315	11.414	10.56	-0.76
10	9.775746	9.871	9.828	12.088	10.555	10.051	-0.53
20	7.640946	7.742	7.6880	8.721	8.029	7.927	-0.61

The comparison of present ABAQUS with other theories of first mode natural frequency of five layered cross ply sandwich plate (SSSS) is presented in Table 2, Numerical results are in good agreement with 3D elasticity and FEM results. ABAQUS gives marginal 0.76 % error. Following Figs. 1-4 show frequencies for various plate boundary conditions, like SCSC and CCCC and for aspect ratios 5 and 10, ABAQUS shows satisfactory agreement with other theories reported in the literature.

B. Example 2: Free Vibrations of seven layered symmetric cross ply and angle ply laminated sandwich plate

In this example, a 7 layered symmetric cross and angle ply laminated composite sandwich plate is analyzed under free vibrations. ABAQUS modelling is carried out considering S4R: A 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains element. The material properties are given in Table 3. Tables 4 and 5 present comparison of first 4 mode frequencies for cross ply and angle play laminated sandwich plates.

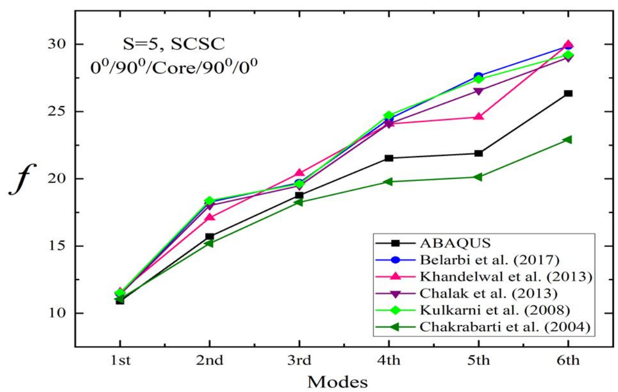

Fig. 1. Natural frequencies of 5 layered symmetric cross ply sandwich plate for S = 5, SCSC boundary condition.

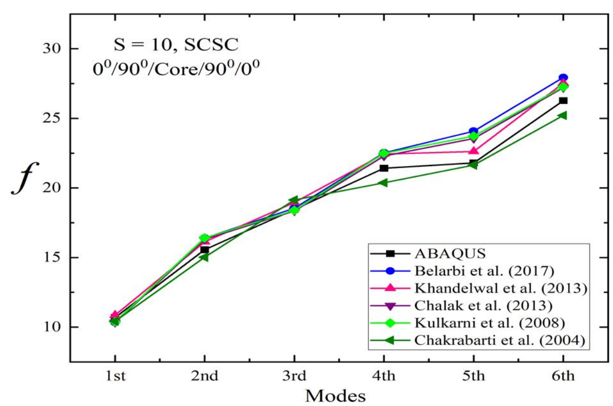

Fig. 2. Natural frequencies of 5 layered symmetric cross ply sandwich plate for S = 10, SCSC boundary condition.

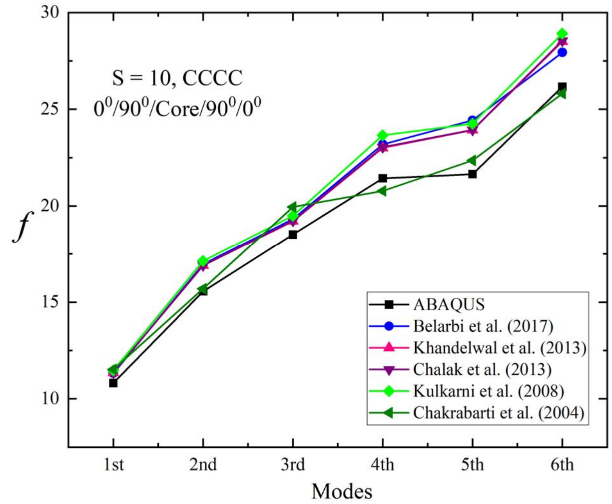

Fig. 3. Natural frequencies of 5 layered symmetric cross ply sandwich plate for S = 10, CCCC boundary condition.

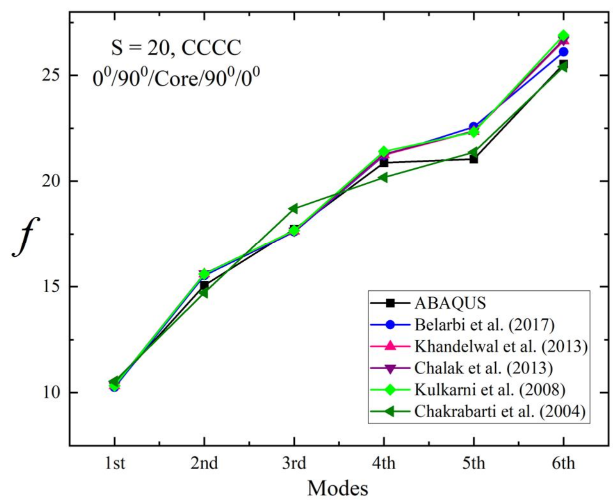

Fig. 4. Natural frequencies of 5 layered symmetric cross ply sandwich plate for S = 20, CCCC boundary condition.

Table 3. Material properties of 7 layered sandwich plate

Material	E1 (GPa)	E2 (GPa)	E3 (GPa)	G12 (GPa)	G13 (GPa)	G23 (GPa)	ν	ρ kg/m^3
FRP Face Sheets	24.51	7.77	7.77	3.34	3.34	1.34	0.25	1800
PVC Core C70.130	0.1036	0.1036	0.1036	0.05	0.05	0.05	0.32	130

Table 4. Comparison of present ABAQUS FEM results of first natural frequency of 7 layered symmetrical cross ply laminated sandwich plate

$0^0/90^0/0^0$/CORE/$0^0/90^0/0^0$ Plate	Theory	Mode 1	Mode 2	Mode 3	Mode 4
Present ABAQUS	4 Noded Shell Element	13.78835	26.18084	26.78262	34.90808
Belarbi et al. [14]	QSFT52 (16x16)	14.44	26.826	27.456	35.706
Burlayenko et al. [15]	FEM-3D-LW	14.62	26.8	27.4	35.55
Rahmani et al. [16]	Analytical LW	14.27	26.31	27.04	34.95
Malekzadeh, K et al. [17]	FEM-3D-LW	14.74	26.83	27.53	35.6
Jam et al. [18]	Analytical-LW	15.04	26.733	27.329	35.316
Meunier and Shenoi [19]	Analytical-HSDT	15.28	28.69	30.01	38.86
Nayak et al. [20]	FEM-Q9-HSDT	15.04	28.1	29.2	37.76
Nayak et al. [20]	FEM-Q4-HSDT	15.34	30.18	31.96	40.94

The example investigates the convergence of a ABAQUS FE modelling by examining a simply supported square sandwich plate consisting of seven layers. Two sandwich plates with different lay ups on the face sheets, namely [$0^0/90^0/0^0$/CORE/$0^0/90^0/0^0$] and [$45^0/-45^0/45^0$/CORE/$-45^0/45^0/-45^0$], are considered. The core material is HEREX-C70.130 PVC foam, while the face sheets are composed of glass polyester resin. The plate has the following geometric properties: a/h = 10, a/b = 1, and h_c/h = 0.88, where h represents the total plate thickness. The comparison involves analytical solutions based on the Layerwise (LW) approach by Jam et al. [18] and Rahmani et al. [16]. Three-dimensional (3D) finite element (FE) models also based on the LW approach (FEM-3D-LW) by Aalekzadeh and Sayyidmousavi [17] and Burlayenko et al. [15]. FEM-Q9 and Q4 solutions based on the Higher-Order Shear Deformation Theory (HSDT) by Nayak et al. [20], and another analytical solution based on HSDT by Meunier and Shenoi [19]. The comparison results demonstrate the performance and convergence of the current FE modelling.
Table 4 presents the initial four dimensionless natural frequencies of $0^0/90^0/0^0$/CORE/$0^0/90^0/0^0$ symmetric sandwich plate, which were calculated in this paper and compared by the work of other authors. The finite element (FE) and analytical models are compared by analyzing a thick sandwich plate with a soft foam core. The present ABAQUS uses 4 node shell element and gives the frequency slightly higher than other FE models for mode 1. In mode 2, the frequency predicted by ABAQUS is slightly less than other models. In mode 3 and 4, higher than other FE and analytical models as shown in Table 4. Table 5 demonstrates Comparison of present ABAQUS FEM results of first 4 natural frequencies of 7 layered symmetrical angle ply ($45^0/-45^0/45^0$/CORE/$45^0/-45^0/45^0$) laminated sandwich plates. Here ABAQUS underpredicts the frequencies as compared to other analytical and FE solutions.

Table 5. Comparison of present ABAQUS FEM results of first natural frequency of 7 layered symmetrical angle ply laminated sandwich plate

$45^0/-45^0/45^0$/CORE/ $45^0/-45^0/45^0$ Plate	Theory	Mode 1	Mode 2	Mode 3	Mode 4
Present ABAQUS	4 Noded Shell Element	13.94671	26.24666	26.53882	35.13882
Belarbi et al. [14]	QSFT52	15.419	28.756	27.456	35.706
Burlayenko et al. [15]	FEM-3D-LW	15.405	26.8	27.4	35.55
Rahmani et al. [16]	Analytical LW	15.42	26.31	27.04	34.95
Malekzadeh, K et al. [17]	FEM-3D-LW	14.74	26.83	27.53	35.6
Jam et al. [18]	Analytical-LW	15.81	26.733	27.329	35.316
Meunier and Shenoi [19]	Analytical-HSDT	16.38	28.69	30.01	38.86
Nayak et al. [20]	FEM-Q9-HSDT	16.09	28.1	29.2	37.76
Nayak et al. [20]	FEM-Q4-HSDT	16.43	30.18	31.96	40.94

Following Fig. 5 shows the first 8 frequencies from present ABAQUS.

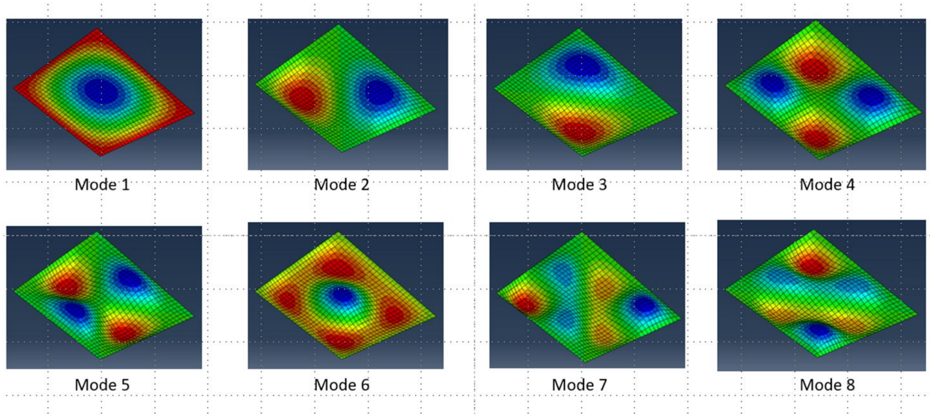

Fig. 5. First 8 frequencies modes from present ABAQUS

III. CONCLUSION

This paper presents an investigation into the modal responses of a flat rectangular sandwich plate with a honeycomb core using finite element method (FEM) software. The accuracy and reliability of the proposed model are validated through comparisons with existing literature. The study focuses on using aluminum honeycomb as the core material and glass fiber reinforced composite for the top and bottom layers of the plate to analyze the modal responses. Various boundary conditions are considered to examine the free vibration behavior. Modal analysis of composite sandwich structures is conducted, and the obtained results are compared with those available in the literature. The sandwich structure is solved using the ABAQUS software through a finite element approach. The findings reveal that the frequencies obtained from the FEM software align well with the results reported in other literature, affirming the accuracy of the current model.

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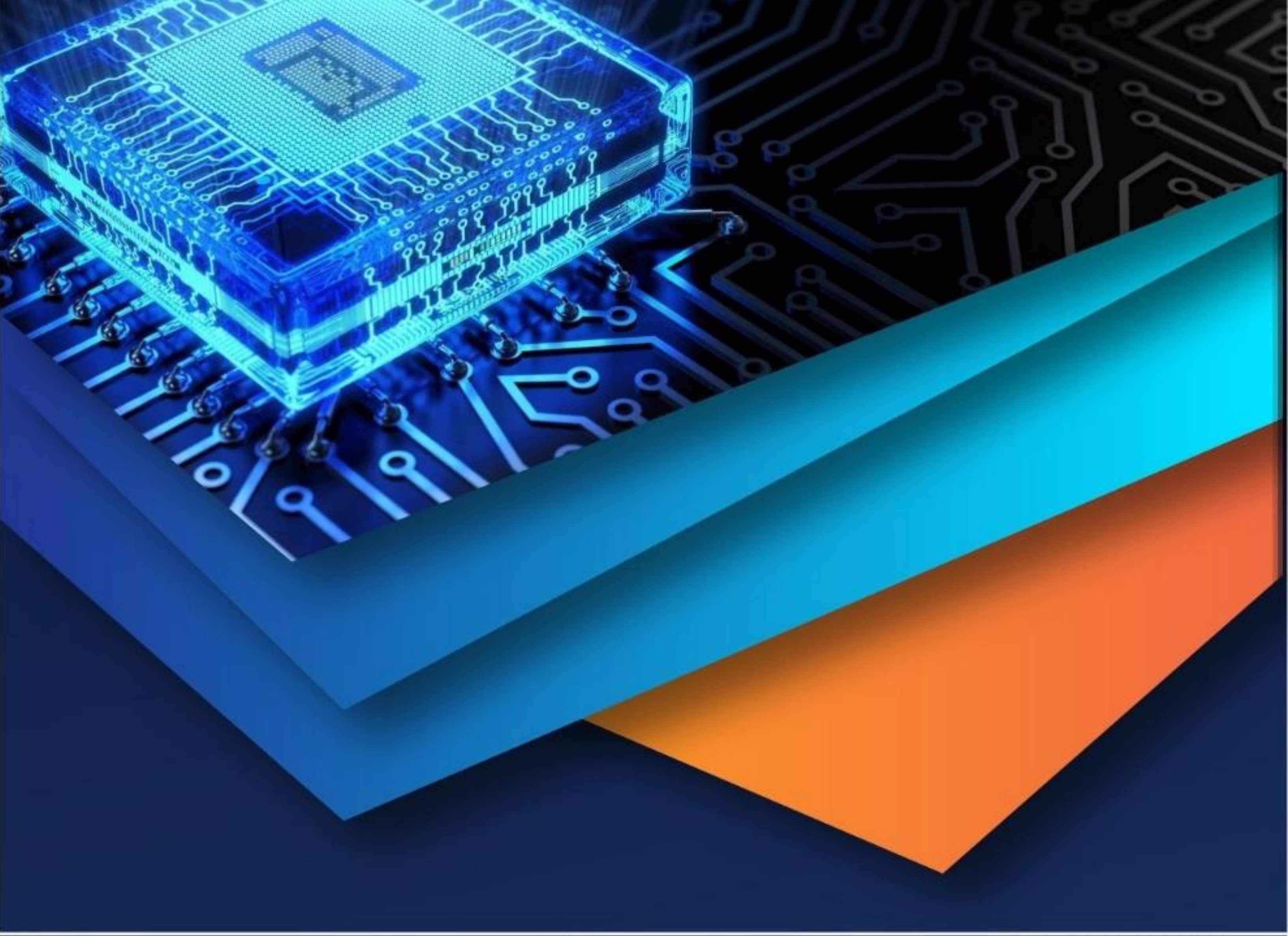

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