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Review on Vibration Analysis of Cracked Cantilever Beam

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Abstract: A unique feature of fiber-reinforced composite materials is that it allows structural tailoring for favorable dynamic performance, due to the directional nature of composite materials. Because of the directed character, material coupling occurs, resulting in coupled vibration modes and complicating dynamic analysis. A transverse triangular force impulse modulated by a harmonic motion excites the beam. For the substance of the beam, the Kelvin–Voigt model is employed. The fractured beam is represented by two sub-beams linked by a massless elastic rotating spring. The beams are designed to function in wet environments, which cause rusting. Corrosion causes cracks to form in beams, altering their inherent frequency and mode shape. The present paper examines the different investigations that have been done to investigate the impact of fracture on the dynamic properties of beams. The researchers provided a comprehensive evaluation of the impact of crack design factors (crack depth, crack location) on cantilever beam transverse and torsional frequencies. It is also given the analytical approach, numerical method, and experimental methods for studying the impact of fracture on vibration characteristics.
Keywords: Cantilever Beam, Crack dimensions, Damage, Kelvin–Voigt model.

I. INTRODUCTION

Beams are widely used as structural element in civil, mechanical, naval, and aeronautical engineering. Damage is one of the important aspects in structural analysis and engineering. Damage analysis is done to promise the safety as well as economic growth of the industries. During operation, all structures are subjected to degenerative effects that may cause initiation of structural defects such as cracks which, as time progresses, lead to the catastrophic failure or breakdown of the structure.

Dynamic response of the structure affected by the following aspects of the crack

1) Position of crack
2) Depth of crack
3) Number of cracks

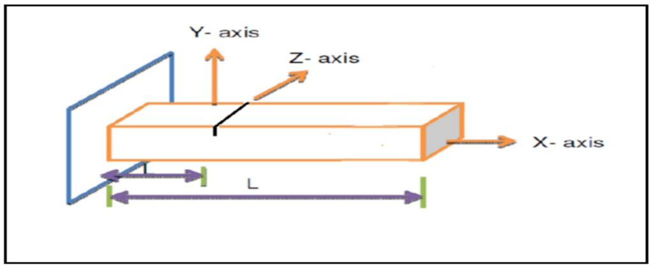

Figure 1: Rectangular beam

The free bending vibration of a Euler-Bernoulli beam of a constant rectangular cross-section is given by the following differential equation 1 as given.

$$EI\frac{d^4y}{dx^4} - mw_i^2 y = 0 \qquad (1)$$

Where m is the mass of the beam per unit length (kg/m) w_i is the natural frequency of the ith mode (rad/sec), E is the modulus of elasticity (N/m²) and I is the moment of inertia (m4). By defining equation (1) is rearranged as a fourth-order differential equation as follows: $\frac{d^4y}{dx^4} - \lambda^4 y = 0$

$$\lambda^4 = \frac{w_i^2 m}{EI} \qquad (2)$$

The general solution to equation (2) is

$$\gamma = Acos\lambda_i x + Bsin\lambda_i x + Ccosh\lambda_i x + Dsinh\lambda_i x \qquad (3)$$

A, B, C, and D are constants and is a frequency parameter. Because bending vibration is being investigated, the edge fracture is represented as a rotating spring with a lumped stiffness. The fracture is presumed to be open. The beam is split into two parts based on this modeling: the first and second segments are on the left and right sides of the fracture, respectively.

II. LITERATURE REVIEW

Ngoc-DuongNguyen [1] performed research that offers a Ritz-type solution for free vibration and buckling analysis of thin-walled composite and functionally graded sandwich I-beams. Material variation over thickness of functionally graded beams follows a power-law distribution. The displacement field is based on first-order shear deformation theory, which may be reduced to a non-shear deformable displacement field. Lagrange's equations are used to develop the governing equations of motion. The Ritz technique is used to calculate the natural frequencies and critical buckling loads of thin-walled beams in non-shear deformable and shear deformable theories. The numerical findings are compared to earlier studies, and the effects of fibre angle, material distribution, span-to-height ratio, and shear deformation on the critical buckling loads and natural frequencies of thin-walled I-beams under different boundary conditions are investigated.

Gunda et al. [2] used the Rayleigh-Ritz technique to perform an analytical study of laminated composite beams. The amplitude of vibrations in composite beams with asymmetric layup orientations was significant. The geometric nonlinearity caused by the membrane stretching of a laminated composite beam resulted in significant deformation. In general, the nonlinear harmonic radian frequency findings produced from the R–R method's closed-form solutions correspond well with the results obtained from basic iterative finite element formulation. Furthermore, the closed-form equations are adjusted for the harmonic motion assumption based on the presence of quadratic and cubic nonlinearity in the literature. It is worth noting that composite beams can produce asymmetric frequency vs. amplitude curves depending on the nature of the displacement direction, as opposed to isotropic beams, which exhibit cubic nonlinearity only and produce symmetric frequency vs. amplitude curves regardless of the sign of the amplitude.

Using experimental methods, Orhan Sadettin [3] studied the impact of single and double edged fractures on cantilever beams. The natural frequencies of a cantilever beam are significantly affected by variations in fracture depth and crack position. In order to detect the fracture in a cantilever beam, free and forced vibration analysis of a cracked beam were conducted in this research. Single-edge and two-edge cracks were studied. According to the findings of the research, free vibration analysis gives enough information for detecting single and two cracks, while forced vibration can only identify a single fracture condition. The dynamic response of the forced vibration, on the other hand, better reflects changes in fracture depth and position than the free vibration, where the difference between natural frequencies corresponding to a change in crack depth and location is only a small impact.

Chasalevris and Papadopoulos [4] investigated a fractured beam with fractures of variable depth, relative angle of crack, and location of crack. The rotating transverse fracture is represented by a local compliance matrix with two degrees of freedom. The fracture is modeled in two planes, and the stress intensity factor, as well as other expressions for strain energy release rate, is determined. This decrease is investigated here for six distinct factors, namely the crack's depth, position, and rotational angle. The first three flexural Eigen modes may be calculated and displayed by holding these six parameters constant. The theory of wavelets is employed here to detect the positions of the fractures due to its sensitivity to changes in slope or displacement, decreasing the number of independent factors. As is widely known, the presence of a crack on a beam under bending causes a slope discontinuity in the elastic line of the beam that is analogous to the crack depth and, in this case, to the angular position. Under certain conditions, the wavelet transformation of a vibration mode or the vibration response of the structure may be utilised to detect fractures. If the locations are known, then the depths and angles may be calculated. The diagrams of the first three eigen values against fracture depth and rotational angle are utilised in this case to determine the remaining unknown parameters for both cracks.

Mei [5] investigated composite beams experimentally using the wave vibration method. The bending and torsional deformations that occurred on a composite beam were studied. According to the findings, low frequency material coupling impacts torsional modes, while material coupling throughout the whole frequency range influences flexural modes. For the substance of the beam, the Kelvin-Voigt model is employed. The studied issue is explored within the framework of the Euler-Bernoulli beam theory utilising an energy-based finite element technique. Lagrange's equations are used to develop the system of equations of motion. The resulting system of linear differential equations is reduced to a system of linear algebraic equations and solved in the time and frequency domains using the Newmark average acceleration technique.

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To determine the correctness of the current formulation and findings, a comparison study is carried out with previously published results from the literature. There is a lot of agreement. The effects of material dispersion and temperature rise on the wave propagation of the FGM beam are thoroughly studied in the research.

Mei [6] also “studied the local wave transmission and reflection properties on composite beams at different discontinuities”. The material connection between the bending and torsional modes of deformation that is often present in laminated composite beams owing to ply orientation is also investigated. Vibrations propagate, reflect, and transmit in a structure from a wave perspective. On an axially loaded materially linked composite Timoshenko beam, the transmission and reflection matrices for different discontinuities are calculated. General point supports, borders, and changes in section are examples of such discontinuities. The matrix relationships between the injected waves and the externally applied forces and moments are also determined. These matrices may be integrated to offer a succinct and systematic method to vibration analysis of axially loaded materially linked composite Timoshenko beams or complicated structures made up of such beam components. The systematic method is shown with numerical examples for which comparison findings may be found in the literature.

Mei [7] has investigated material coupling in composite cantilever beams. Torionsal deformation was coupled with bending deformation, and the impact on torsional modes was assessed using the "Timoshenko beam vibration viewpoint." Because of the directed character of composite materials, fiber-reinforced composite materials have a unique property that enables structural tailoring for beneficial dynamic performance. Because of the directed character, material coupling occurs, resulting in coupled vibrational modes and complicating dynamic analysis. The majority of recent dynamic research on composite structures concentrates on free vibration analysis. First, the local wave transmission and reflection properties at different discontinuities are investigated in this study. General point supports, borders, and changes in sections are examples of such discontinuities. The matrix relationships between the injected waves and the externally applied forces and moments are also determined. The free and forced vibration responses of physically linked composite Euler–Bernoulli beams are produced by constructing these matrices. The method to wave-based vibration analysis is shown to be succinct and systematic. There are numerical examples provided.

Nahvi and Jabbari [8] studied the impact of cracks on beam vibration characteristics. The cantilever beam was first stimulated using a hammer. An accelerometer connected to the cantilever beam captures the vibration response of external stimulation. The contour plots of normalised frequency were plotted versus fracture depth under the premise of an open crack. To prevent non-linearity, the fracture is considered to be constantly open. Contours of the normalised frequency in terms of the normalised crack depth and position are shown to locate the crack. The intersection of contours with constant modal natural frequency planes is used to determine the location and depth of a fracture. The cracked element inside the cantilever beam is identified using a minimization technique. The suggested technique is based on observed beam frequencies and mode shapes.

Patil and Maiti [9, 16] developed a technique for predicting the location and magnitude of numerous fractures based on natural frequency measurements (three normal cracks). The analysis's findings were verified using experimental data. The rotational spring was modelled using the energy technique, and the theoretical prediction is based on numerous cantilever beam segments. The amount of strain energy retained in a rotating spring is specified by the segments (or damage index). The crack size is calculated using a conventional stiffness-to-crack-size relationship. A number of measured frequencies equal to twice the number of cracks is sufficient for predicting the location and size of all cracks. The accuracy of crack detail prediction is promising. The greatest inaccuracy in forecasting crack site falls as the number of cracks increases. It is less than 10% and 20% for two and three cracks, respectively. In both instances, the greatest error in estimating the fracture size is less than 12% and 30%, respectively. A method for overcoming prediction failure in situations when one of the fractures is situated near an anti-node has been proposed.

Dharmaraju et al. [10] studied a cantilever beam with a transverse open fracture using finite element analysis. The fracture was modelled using a local compliance matrix with four degrees of freedom. The beam received dynamic stimulation in the form of a specified harmonic force. The output of amplitude was tested for various fracture depth sizes. A four-degree-of-freedom local compliance matrix was used to simulate the fracture. There are diagonal and off-diagonal terms in this compliance matrix. To dynamically excite the beam, a specified amplitude and frequency harmonic force is employed. Numerical examples have been used to demonstrate the current identification methods.

The identification algorithms have been tested against measurement noise and found to be fairly resistant against it. The method requires knowledge of the force. As a consequence, in a genuine system, the precision of the outcome is determined by the acquired force.

Kim et al. [11] investigated the natural frequency of a composite shaft experimentally. The casing width varies, and the core material utilised in the study was steel. According to the results, increasing the breadth of the casing increases the natural frequency of the shaft.

From the standpoint of natural frequencies, it has recently been shown that certain carbon fiber-reinforced composite shafts with a metal core or casing outperform all carbon fibre reinforced plastics (CFRP) or metal shafts. However, it has not been documented if the advantage of metal/CFRP hybrid shafts exists in general situations of different fibre angles, length-to-diameter ratios, material characteristics, and metal layer thicknesses. The effects of a steel core or casing on the bending natural frequencies of CFRP shafts are studied analytically in this research. The equations of motion for metal/CFRP hybrid shafts are developed in order to determine the frequencies. Several beam theories are examined, and variations in frequency prediction between these theories are also given. It has been discovered that in certain instances, an optimal steel thickness exists in order to optimise the frequencies of the steel/CFRP shafts. Parametric studies are also performed over a broad variety of design variables, and design recommendations for hybrid shafts are eventually distilled.

Karama et al. [13] investigated the mechanical behaviour of a multi-layered laminated composite analytically. The shear stress function with an exponential function is used. The model has been verified for several instances of buckling and bending on cross-ply laminate. This paper introduces a novel multi-layer laminated composite structure model for predicting the mechanical behaviour of multi-layered laminated composite structures. As an example, the mechanical behaviour of a laminated composite beam (90°/0°/0°/90°) is investigated from both a static and dynamic standpoint. The findings are compared to Abou Harb's model "Sinus" and finite element technique. The findings indicate that this new model is more exact than previous ones when compared to finite element technique results (Abaqus). The kinematics described by Ossadzow were utilised to introduce continuity on the interfaces of each layer. The concept of virtual power is used to construct the equilibrium equations and natural boundary conditions. Different instances in bending, buckling, and free vibration were examined to verify the novel suggested model.

Lee et al. [14] used differential equations to construct analytical equations for horizontally curved beams. The derived equations are based on free vibration in a Cartesian coordinate system. Torsional inertia is also taken into account. The differential equations that control the free vibrations of elastic, horizontally curved beams with unsymmetric axes were constructed using Cartesian coordinates rather than polar coordinates, and the impact of torsional inertia was taken into account. Frequencies and mode forms for parabolic curved beams with both clamped and hinged ends were calculated numerically. Natural frequency comparisons between this research and SAP 2000 were performed to verify the ideas and numerical techniques presented herein. The newly developed differential equations in Cartesian coordinates greatly increased convergence efficiency. The lowest four natural frequency parameters were given as functions of three non-dimensional system characteristics: the horizontal rise to chord length ratio, the span length to chord length ratio, and the slenderness ratio, with and without torsional inertia. Typical vertical displacement mode forms were also shown. The differential equations that control the free vibrations of elastic parabolic arches with unsymmetric axes are calculated in Cartesian coordinates rather than polar coordinates. The effects of axial extension, shear deformation, and rotatory inertia are all included in the formulation. Frequencies and mode forms for arches with clamped-clamped and hinged-hinged ends are calculated numerically. The newly developed governing equations in Cartesian coordinates greatly enhance convergence efficiency. The four lowest natural frequency parameters are given as functions of four non-dimensional system characteristics: rise to chord length ratio, span length to chord length ratio, slenderness ratio, and shear parameter. The typical mode forms of vibrating arches are also shown. The inherent frequency and mode forms of clamped (both ends) are calculated. Another study was also carried out to calculate horizontally curved beams, with the impact of shear deformation and inertial included [12].

Moon-Young et al. [15] proposed a stiffness matrix for beam formulation (thin walled). They discovered the “total potential energy in general form by introducing the displacement field based on semi tangential rotations and deriving transformation equations between displacement and force parameters specified at the arbitrary axis and the centroid-shear centre axis, respectively.” The total potential energy of non-symmetric thin-walled beam-columns in general form is presented by introducing a displacement field based on semitangential rotations and deriving transformation equations between displacement and force parameters defined at the arbitrary axis and the centroid-shear centre axis, respectively. The total potential energy is then used to develop governing equations and force–deformation relations for a shear-deformable, uniform beam element, and a system of linear eigenproblems with non-symmetric matrices is built using 14 displacement parameters.

Then, utilising force–deformation relationships, explicit formulas for displacement parameters are constructed, and precise dynamic stiffness matrices are established. Furthermore, for spatial stability analysis, a modified numerical technique for eliminating numerous zero eigenvalues and evaluating the precise static stiffness matrix is proposed. Finally, the spatially linked natural frequencies and buckling loads are assessed and compared with analytical solutions or findings examined using thin-walled beam elements and ABAQUS's shell elements to show the validity and correctness of this research.

Yang et al. [17] investigated a beam with an open fracture experimentally. To investigate the impact of fractures on vibration characteristics, a numerical model based on energy was employed. The strain energy was calculated, as well as the equivalent bending stiffness across the full length of the beam. An energy-based computational model is constructed to study the effect of fractures on structural dynamic properties during vibration of a beam with an open crack (s). The equivalent bending stiffness across the beam length is calculated once the strain energy in the fractured beam is determined. The cracked beam is then treated as a continuous system with changing moment of intertia, and equations of transverse vibration for a rectangular beam with one or two cracks are derived. To find the frequencies and vibration modes, Galerkin's technique is used. The frequency contours with respect to crack depth and position are determined and displayed to detect the crack. The intersection of contours from various modes may be utilised to determine the position and depth of a fracture.

Ruotolo et al.[18] used forced response analysis to examine the impact of fracture depth and position on a cantilever beam. The harmonic sine kind of forced stimulation was used on the beam, and the vibration amplitude was calculated. The results indicate that changing the position of the fracture and the depth of the crack affects the vibration amplitude. The study has been expanded to include the first and higher order harmonics of the response to a harmonic forcing in order to describe the fractured beam's nonlinear behaviour. Correlating the higher order harmonics of the response with the forcing term, the so-called higher order frequency response function (FRFs), defined from the Volterra series representation of the dynamics of nonlinear systems, can be determined by simulating the time domain response of the cracked beam with a finite element model. The ultimate goal will be to use such a sequence of FRFs, an estimate of which may be measured in a stepwise sine test on the beam to show both the position and depth of the crack, providing the foundation of an experimental structural damage detection method.

Abramovich [19] modified previous Timoshenko beam equations by adding a component that represents combined inertial and shear deformation. The given equation was used to investigate the vibration characteristics of composite beams. Timoshenko type equations are used to investigate the free vibration of symmetrically laminated composite beams. The study includes shear deformation and rotational inertia, however the term reflecting the combined action of both factors is removed in the Timoshenko equations. A detailed analytical study of the natural frequencies of laminated beams with various boundary conditions at their ends is conducted, with numerical examples computed for a hinged-hinged beam.

Suresh et al. [20] carried out a numerical study on beams to evaluate the impact of torsion and warping on the vibrational properties of beams. The analytical findings are compared to those found in the literature. Based on the comparison, the effect of the warping function in determining the coupling terms in the modulus method, as well as the natural frequencies of the beam, has been determined. The study reveals that, in certain instances, the discrepancy between the outcomes of the two methods is significant. These discrepancies may be ascribed to the limitations placed on the deformation and flexibility of the beam by the warping behaviour description chosen. Finally, the effect of material qualities on the structural dynamic features of the beam is investigated for various composites and orthotropy angles.

III. CONCLUSION

A. The effect of crack, beam thickness and plate thickness has significant effect on buckling, bending and vibration characteristics of cantilever beam.
B. The effect of steel casing/core is significant in bending natural frequency of composite material beams.
C. Various higher order beam theories are presented which are refined which predicted much better and accurate results.
D. The FEM can be used a tool in damage detection of cracks in cantilever beam by studying mode shapes and variation in natural frequency.

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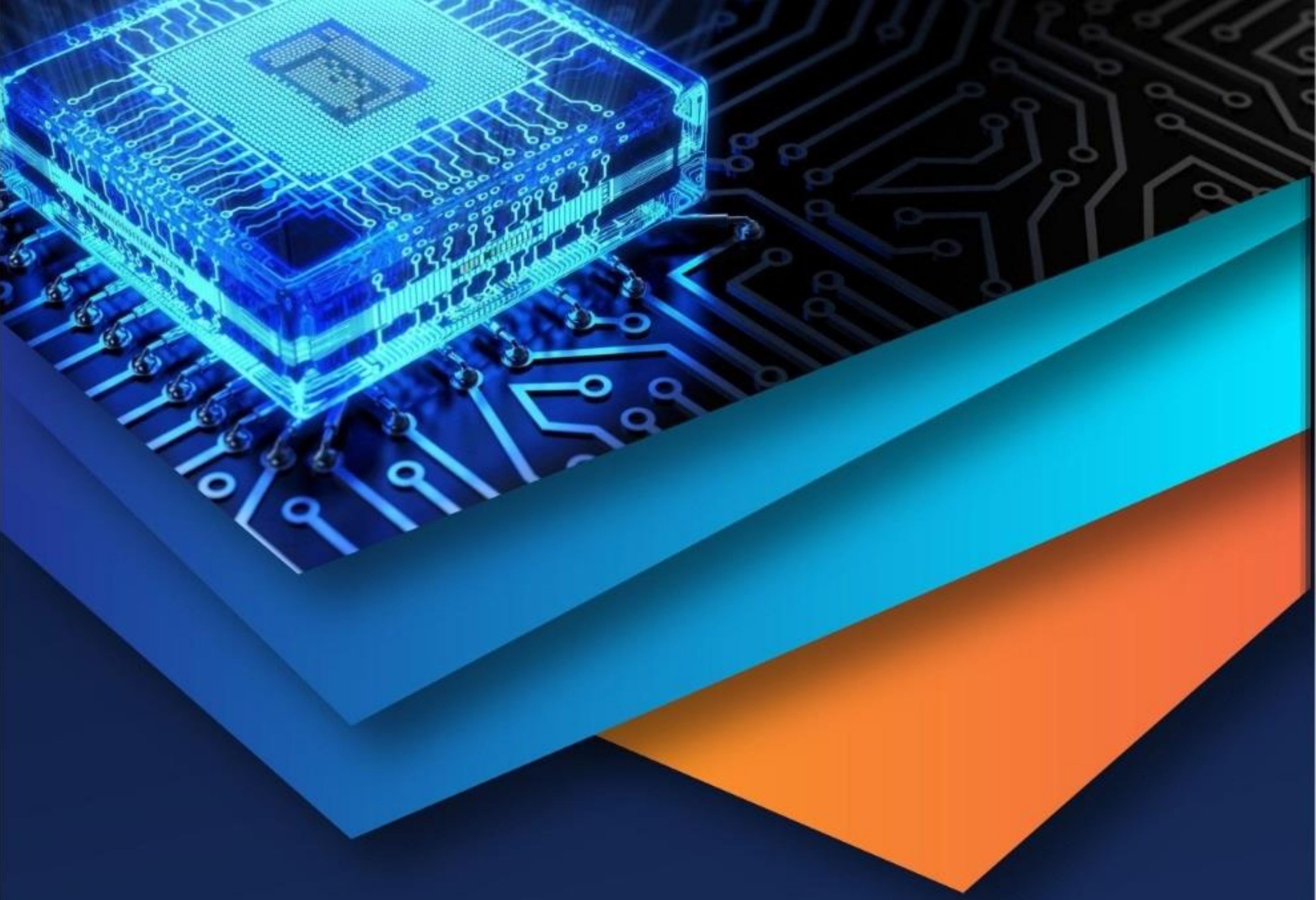

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