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The Evolution and Advancements in the field of Wind Engineering: A State of Art Review

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Abstract: This paper deals with the circumstances of evolution of Wind Engineering as a new nomenclature. The origin of it could be traced long back to 1960s where wind was considered to be a simple static drag force. With the advent of a new field of Wind Engineering, the concept of wind has been revolutionized from a relatively simple term to a more complex term involving computational aspects. The journey of Wind Engineering right from its inception to the present stage is examined thoroughly through a state of art review. The effect on wind as a major lateral load on structures which has broaden the outlook for further studies in this specific field along with the major wind damaged structures that acted as an eye opener for the researchers are also stated briefly.
Keywords: Wind analysis, turbulence, geometry, CFD, wind engineering.

I. INTRODUCTION

The past half century has witnessed remarkably noticeable advancements in the concept of wind loading in structural design, thus marked as an appropriate period for retrospection. During earlier part of 1900s wind forces were not of major concern, rather was considered to be a simple terminology contributing to static drag forces. As the effect of wind on structures kept on causing destruction, there arose a need for detailed research in this area. Later on, as the researches progressed at a rapid pace, the concept was redefined from simple and static to complex and dynamic force, demanding more attention in structural analysis and design [1]. Within few decades, the field of Wind Engineering grew up as an agglomeration of different disciplines namely Structural Mechanics, Aerodynamics, Structural Dynamics, Computational Mechanics etc. To define Wind Engineering in a simple manner, it is a subset of different engineering disciplines like mechanical engineering, structural engineering along with applied physics and meteorology introduced with a motive to analyse the effect of wind in both natural and artificial environment and to quantify the aid and harm caused by wind while interfering with any obstruction in its path. Wind Engineering has thus become one of the young, yet established branch of science, which deals with the behaviour of structures when exposed to wind.

This paper is divided into four sections. The first section deals in detail on the historic perspective of wind before the inception of an independent branch of Wind Engineering. The second section throws light on Wind Damaged Structures, which acted as eye opener for the need to study the behaviour of wind. The third section is on the effect of wind on structures and the final section describes the various wind analysis techniques in Indian context.

II. HISTORICAL PERSPECTIVE ON WIND

From the dawning of civilization to the Renaissance, wind forces were categorized by a mythological view [2]. The structures were heavy and massive, with heavy dead loads contributing to stiffer structures than predicted, on which effect of wind forces were not visible, hence resulting in a difficulty to estimate the forces acting on them and the impact of such forces.

In most part of the world, structures were evolved out of experience and tradition, and not with a theoretical backup. Most of the structures built were not so tall, except some religious structures [3]. The structures were of pyramidal shape, polygonal shape or conical shape while glancing from bottom to top, which ultimately causes only less turbulence than sharp edged shapes [1]. The destruction caused by wind those days where categorized as act of God. During the latter part of 16th century, the structures subjected to wind force were becoming more vulnerable, hence demanding more attention. Due to ignorance of conceptual knowledge, much of effort to resist wind forces were in vain. With the advent of an era of Renaissance, at the latter part of 16th century, intellectual outlook overruled traditional believes. Followed by the birth of modern science, in 17th and 18th century along with the contributions from Newton, Euler and Bernoulli did much to the field of Wind Engineering. This period led to the development of Classical Hydrodynamics build on the contributions from Newton, Euler and Bernoulli and also the formulation of fundamental equations of fluid flow by Navier in 1845. Meanwhile Hardley and Smeaton conducted first model experiment in the year 1759 and Reynolds revealed the differences in laminar and turbulent flow, thus pointing out the deficiencies of Classical

Hydrodynamics. The deficiencies were overcome by the introduction of Boundary Layer Aerodynamics by Prandtl and von Karman and also with the development of statistical theory of turbulence by Taylor in 1935 [3].

Few years later, an independent field of Wind Engineering came into existence to tackle the issues of wind load on structures and to correspondingly monitor the behaviour of structure to wind forces.

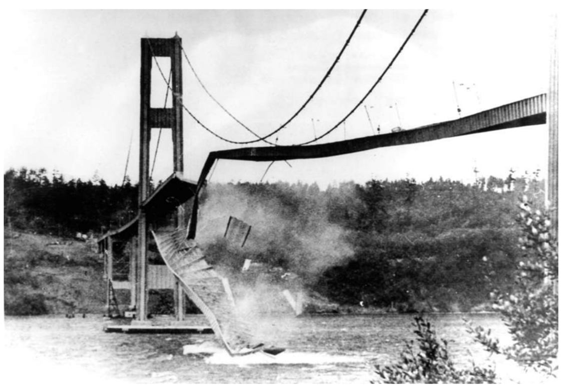
III. WIND DAMAGED STRUCTURES

Till the beginning of 19th century, massive structures were not so common, but latter with the introduction of steel and reinforced concrete as materials for construction more refinement has been observed in the field of structural design. With the onset of computer methods during twentieth century, the process of design became handier resulting in huge and tall structures worldwide. It was during the last two centuries, major failures to structures occurred periodically [4] due to action of wind forces on them thus demanding the interest of more research in this discipline.

Long span bridges often produced the most remarkable and notable failures of all time, namely the Brighton Chain Pier of England (1836), Tay Bridge of Scotland (1879) Tacoma Narrow Bridge of USA (1940). Other structures that were a victim to the wind forces includes the collapse of Ferrybridge Cooling Tower of UK (1965) and permanent deformation of Great Plains Life Building of Texas (1970) [4]. All these weren't just left as victimized, rather proved as a spark for further research and development across respective nation and even worldwide.

Some major windstorms have also resulted in large scale destruction and damage of residential buildings. The impact caused by Hurricane Andrew in Florida (1992) has been the costliest natural disaster in the state till date [5]. Strong winds from hurricane affected four south-eastern countries causing about billion in damage and several deaths. Various tropical cyclones such as Yorkshire storm in UK (1962), Tracy in Australia (1974), Hugo (1989), Georges (1998) in US and Winter Gales in Europe (1987, 1990 and 1999) also resulted in severe destruction of structure.

Wind Damaged structures namely Tacoma Bridge, Ferrybridge Cooling Tower and the aerial view of a part of Florida after being hit by Hurricane Andrew is shown in figure 1.



(a)

(b)

(c)

Fig. 1 Wind Damaged Structures: (a) Tacoma Narrow Bridge collapse [6] (b) Ferrybridge Cooling Tower collapse [7] (c) Florida after Hurricane Andrew [8].

The title of first tall building in Japan would belong to the traditional wooden pagodas in Japanese cities. These pagodas are highly susceptible to strong typhoons. 48 m high Shiten'noji Pagoda collapsed as a result of typhoon Muroto in 1934. From then onward, the history of development, design and construction of tall structures was a record of fight with strong wind forces [5]. The development of new construction techniques in the 19th century has resulted in structures that are slender, low in damping and relatively light in weight, hence exposing the structure to the effect of wind acting upon it more severely than before, as the effect of wind kept on increasing with increase in altitude. It has made things more complex to be handled in a more conceptual and computational way.

IV. EFFECT OF WIND ON STRUCTURES

Wind is basically defined as a large group of eddies of varying sizes that are bound to possess rotational characteristics. They are carried along general stream of air moving relative to the earth's surface. The interference of wind with the surface features results in gustiness of wind. The effect of wind on structures can be categorized into three: static, dynamic and aerodynamic in nature. The response of structure to wind forces is primarily dependent on the type of structure. In such cases when the structure experiences a deflection on account of wind load, it becomes mandatory to consider the dynamic and aerodynamic effects in addition to the static effect [9]. In depth knowledge of Structural Mechanics and Fluid Mechanics makes it easier to properly figure out the fluid-structure interaction (wind flow and civil engineering structure or building). The response of the structure to the repeated loads of successive gusts has been listed out as the primary factor in tall building design. Repeated loading of structure subjected to wind forces results in fatigue failure, excessive deflection in top storeys, cracking of building elements and may even result in discomfort to inhabitants impairing the concept of reliability.

A building can be considered to have failed if it becomes unserviceable due to action of single load of high impact or repeated loads [10]. From there onward, it was made crystal clear that the impact of fluctuating loads caused by wind forces are an inevitable component to be accounted for while analyzing and designing tall structures, especially with those structures of large aspect ratio.

The primary concern of structural engineers in dealing with wind loads, is on the mean velocity profile of wind. The state of turbulence of natural wind approaching the structure as well as the local turbulence caused by structure as a result of wind hitting it are the two major aspects of turbulent flow that are under consideration. [11] brought into focus the concept of bluff body aerodynamics aspect of wind-structure interaction. This has given a spark for further research in detail on development of body pressures around structure as a result of fluid flow.

The sensitivity of building to wind forces was found to depend on meteorological properties of wind, exposure type and also on the aerodynamic characteristics of building/structures. Studies by [12] put forth a detailed description of those factors, along with their relative influence on the overall response of structure.

Flexible or slender structures are subjected to wind induced along and across direction of wind loads. Along-wind is due to buffeting effects caused by turbulence and across-wind is primarily due to alternate-side vortex shedding. Three forms of wind induced motion are most prominent. They are galloping, fluttering and ovalling [13]. Galloping is most prominent in non-circular cross sections and is characterized by progressively increasing amplitude of transverse vibration with the increase in wind speed, resulting in transverse oscillation of the structure. Fluttering is the oscillatory motion due to combined bending and torsion. It occurs as a result of coupling between aerodynamic force and elastic deformation of the structure. Fluttering is common in long span suspension bridge decks or similar structures with large d/t (depth to thickness) value. Ovalling is the phenomenon visible in thin walled structures whose diameter to thickness is of the order of 100. Such oscillations result in radial deformation of the hollow structure.

V. WIND ANALYSIS TECHNIQUES IN INDIAN CONTEXT

With the discovery of improved construction materials and faster construction techniques, the field of Civil Engineering has amplified itself at a faster pace and so Wind Engineering too flourished rapidly in last century. Better materials, resulted in lighter structures from massive ones, tall and slender structures than bulky structures. A rapid sprout in the population demanded taller buildings to accommodate people, hence putting in idea of vertical construction. Invention of lift for vertical transport along with discovery of steel and concrete made it easier than expected. Meanwhile, the importance of impact of wind load on tall structures increased proportionally with the altitude. Since the tall buildings become inevitable, researchers were compelled to put in more effort to refine Wind Engineering and to frame certain regulations to ensure serviceability and reliability of structures. New standards came up in different nations, separately for wind analysis. Experimental set ups were established and finally at present computers have taken up the analysis using Computational Mechanics.

Though initially certain standards were established namely the American Standards, British Standards etc., it wasn't sufficient to meet the design demands in India. With a motive to build wind resistant structures in India, code of practice IS 875 (Part 3)-1987 was formulated by a team of experts. IS 875 (Part 3)-1987 throws light on Indian scenario categorizing them into different terrain category. Wind load analysis is to be done using pressure coefficient or force coefficient method or even using the most commonly adopted Gust Factor method/Gust Effectiveness method [14]. The calculations are based on basic wind speed, which is given in the wind map of India, determined on the basis of gust velocity averaged over a short time interval of 3 seconds as applicable at a height of 10 m above mean ground level, worked out for a return period of 50 years [13]. The code addresses solution for most general building shapes and roofs, but as time passes by incorporation of different complex geometry has become inevitable and hence certain improvements are to be incorporated in code to facilitate the purpose.

Since the effect of wind load hitting a newly built structure is dependent on meteorological and topographical features of adjacent structures, no two cases are similar. The terrain category and the adjacent building geometry is location dependent, the whole process of computing the wind load on the building involves numerous steps in calculation. In such situations, the experimental testing method using wind tunnel becomes more effective.

Wind tunnel is a huge tube usually used in aerodynamic researches to study the effect of air moving past solid objects mounted in the middle for testing. The model of solid object is scaled down usually to ratio of 1:400 to 1:600 and correspondingly the velocity of air is also scaled for study using wind tunnel [14].

Initially used in the field of Aerospace Engineering, wind tunnel now finds its application in an extended field of research and thereby in Civil Engineering in determining the flow past buildings and structures. Although wind tunnel is conventionally used for the past years, for complex structures, the refinement of geometry and scaling model is tedious, hence involving a huge quantum of work and consuming more time. Further the modelling of a building requires the modelling of adjacent buildings to properly quantify the impact of wind on the newly planned building. The pressure on the building is tapped by using sensors or manometer tubes and is tabulated further. The figure 2 represents a wind tunnel along with the principal building and adjacent buildings.

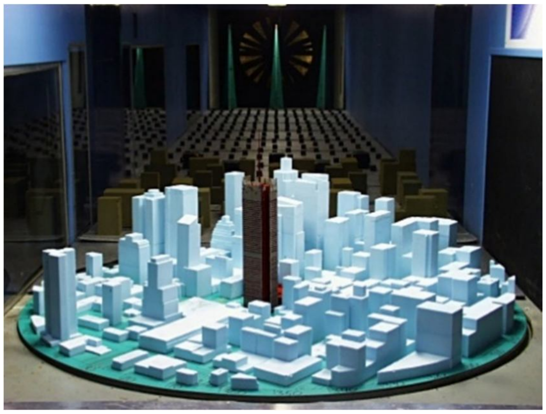


Fig. 2 Wind Tunnel Testing [15]

The most common test section dimensions of wind tunnel are: width 9 to 12 feet, height 8 to 10 feet and length 75 to 100 feet. Wind speed generated ranges from 25 to 100 miles per hour. Typically, there are two types of test model being used: High Frequency Base Balance Model (HFBBM) and Aeroelastic Model (AM) [14]. HFBBM measures the overall fluctuating load for computing the dynamic responses and AM is used for direct measurement of loads, deflection and acceleration in such cases when the lateral loading due to wind are more prominent.

Wind simulation criteria was proposed for wind test by [16]. The general criteria for Atmospheric Boundary Layer (ABL) simulation for testing building and structures are vertical distribution of mean wind speed and longitudinal turbulence intensity generated in wind tunnel should be similar to natural site conditions. Atmospheric Boundary Layer (ABL) for high-rise, Atmospheric Surface Layer (ASL) for low-rise and length scale of turbulence are to be scaled geometrically.

Comparative study of the major international codes and standards for determining along-wind on tall buildings was done [17]. Although major codes rely on Gust Loading Factor approach, each employ unique definition of wind characteristics such as wind velocity profile, turbulence intensity profile, turbulence length scale etc.

The father of Wind Engineering -Jack E. Cermak owes a tribute for his pioneering contributions to Wind Engineering [18]. The discussion in his paper encompasses the modelling of wind field, structural aerodynamics, computational methods, dynamics of structures, codes and design tools, damping devices etc. The improved performance of tall building has been determined using Wind Tunnel test [19]. It has been rightly pointed out that many building codes address only the along-wind or drag forces and often fail to look into across forces, which is dominant in the behaviour of tall structures and torsional forces developed as a result of spatial non-uniformity of wind force. It was concluded that the response is primarily due to vibration in the fundamental mode.

A detailed study on response of tall buildings to wind loads was done by [20]. Studies on across wind aerodynamic damping, interference effect of wind forces etc. were done to propose a new concept of 'mode coupling factor' and a modified SRSS method to accommodate the multimode contribution and coupling effects. The concept of aerodynamic stability of structure against wind forces gained more momentum with the work of [21]. It was found out that for static structures, the effect of wind force depends only on external shape of structure, whereas for dynamic structures there exist an additional interaction with the motion of the structure. in such cases when the wind energy absorbed by structures exceeds the energy released by structural damping, amplitude of oscillation increases resulting in an aerodynamically unstable structure.

It was brought into light the new improvements and advancements in wind analysis, capable of supporting more advanced dynamic analysis rather than considering the quasi-static behaviour [22]. They stated that analysis methods, basic wind speed etc. differ because of the difference in strategies set by different nations and requirements of country.

Further researches have been done in optimizing the external shape out of which a study by [23] proved to be a crucial outcome. The performance was improved by introducing curved edges instead of sharp corners. Buildings having circular or elliptical plan perform better to resist wind forces as the surface area perpendicular to wind direction is less than prismatic buildings.

Researches are still in progress in establishing proper criteria. A year back, the advanced technical issues related to wind loading in tall structures was investigated on a Performance Based Design (PBD) approach [24]. It deals with identifying key elements to save economy for a serviceable, safe and strong design.

According to recent statistics published by the Council on Tall Buildings and Urban Habitat (CTBUH), there is a huge hike in number of tall buildings every year. It demands the development of faster and more reliable techniques for analysis and design to resist wind load acting on them. With the advent of modern high-speed computing, in collaboration with the Computational Fluid Dynamics discipline, much of a progress has been witnessed in the branch of Wind Engineering as well as in Civil Engineering.

A study on numerical evaluation of wind load on tall building using CFD was done [26]. Various techniques such as Large Eddy Simulation (LES), Reynolds Averaged Navier Stokes equation (RANS) etc. were discussed in detail and he also point out the difficulties due to large Reynolds number, impinging at front etc. Since FLUENT code is based on Finite Volume method, it offers high flexibility in mesh generation of both structured as well as unstructured meshes. A sample of CFD analysis denoting the direction and intensity of flow around a square building is depicted in the figure 3, done using a Computational Software.

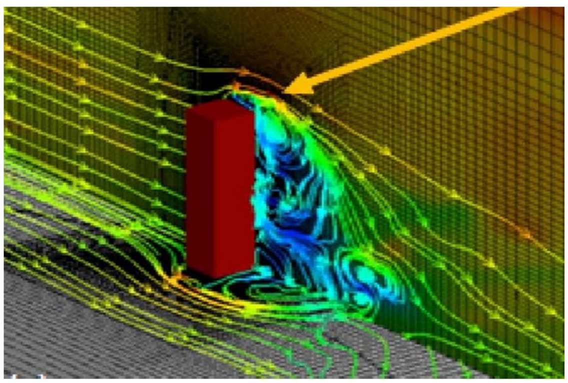


Fig. 3 Simulation using CFD [25]

The building innovations from CFD in urban wind environment and natural ventilation conditions was done, comparing CFD results with wind tunnel study [27]. The simulation using CFD proves to be more time and cost saving approach, especially in early planning stage.

It was concluded that the effect of wind force is more dominating than earthquake load in high-rise structures, provided the height is determined prior [28]. The simulation using CFD give flexibility in modelling than in wind tunnel test. The application of CFD in wind load analysis of tall buildings has been covered in detail [29]. Six different turbulent models available in Ansys FLUENT is also incorporated. It has been suggested that Large Eddy Simulation (LES) and k-ε model is most commonly adopted for wind analysis of tall buildings.

An analytical and numerical comparison of wind load on tall structures was studied [30]. In doing so, it was evident that the numerical simulation using CFD was capable to produce credible results and is easily used even in case of unorthodox shapes than analytical method according to IS 875-Part 3:1987. CFD proves to be a powerful alternative capable of analyzing the flow separation and visualization accurately.

A case study to check the feasibility of using CFD model in high-rise building wind analysis was carried out [31]. The researcher stated that strict adherence of CFD for wind around buildings can definitely serve as an alternative to time consuming wind tunnel test. The wind pressure obtained via CFD analysis is usually lower than the value predicted by IS 875-Part 3:1987, resulting in economy of structural framing.

VI. CONCLUSIONS

From a mythological aspect, the terminology wind and the field Wind Engineering has developed a new dimension of more complex and scientific approach. Wind damaged structures proved to be a spark for more and in-depth research in the field of Wind Engineering, which ultimately came up as a collective idea involving Structural Mechanics, Computational Methods and Structural Dynamics. In order to tackle the population hike, mankind found solution for constructing aerodynamically stable high-rise buildings by implementing codes/standards. Then eventually experimental method of Wind Tunnel testing took the space to rectify the gaps of codes, especially for unorthodox or irregular shapes. When high speed computing techniques came into existence, a new approach of Computational Fluid Dynamics using Ansys FLUENT started yielding accurate results within less time and cost. Thus, within a very short span of nearly 50 years, Wind Engineering emerged as a stable branch of study with researches progressing in all directions very swiftly, adding up new advancements every now and then. CFD has thus occupied a vital place in a wide engineering application (within the scope of wind engineering) as of today, opening further areas and scope of development in a very rapid pace.

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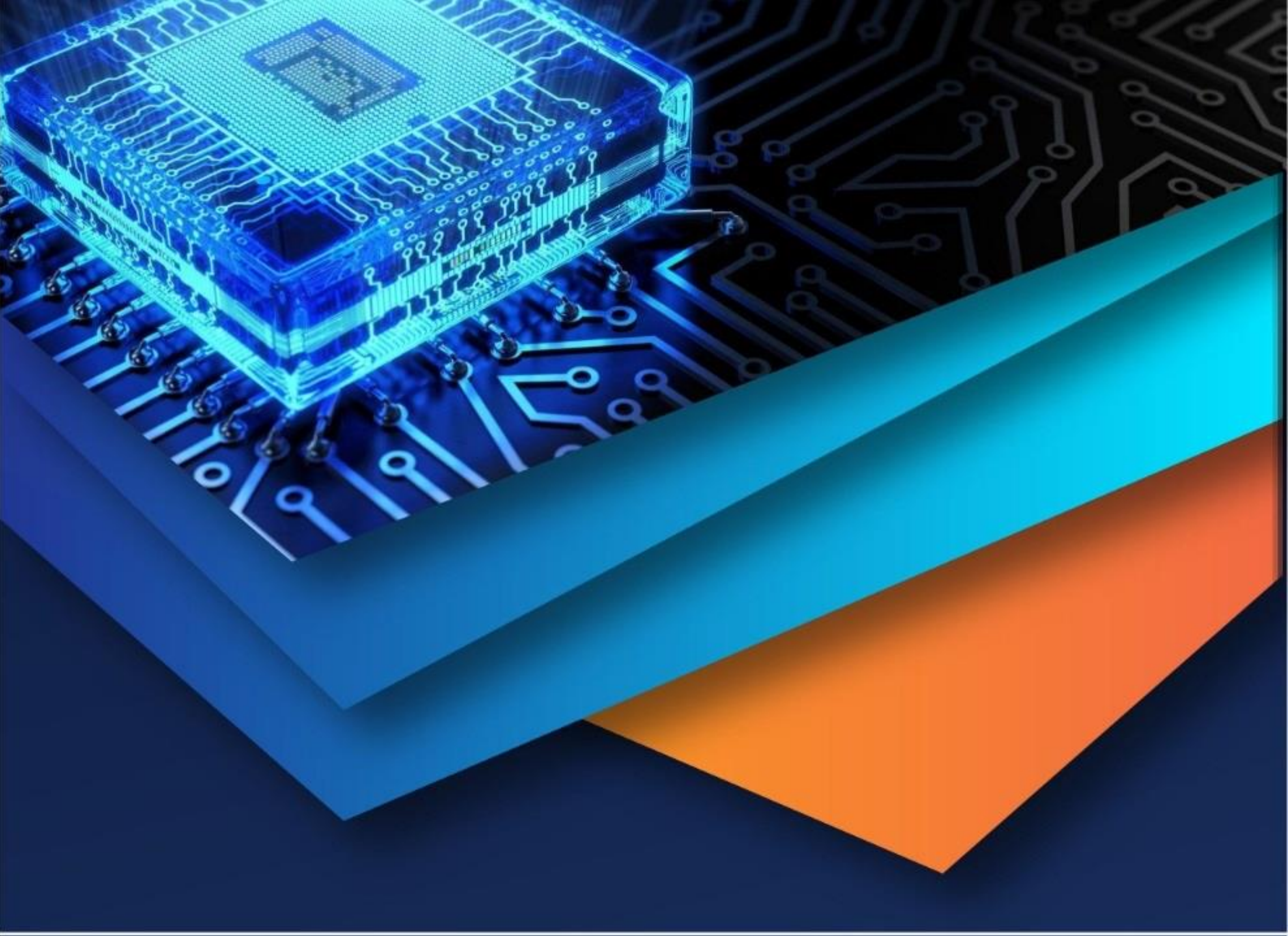

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