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Seismic Performance of Bridge Bearings Using Shape Memory Alloy- A Review

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Abstract: Shape Memory Alloys (SMAs) are unique materials with a paramount potential for various applications in bridges. The property of this material lies in its ability to undergo large deformations and return to its unreformed shape through stress removal (superelasticity) or heating (shape memory effect). This paper critically examines the fundamental characteristics of SMA and Mathematical modeling of hysteretic and superelastic properties of SMA also existing SMA models are discussed.
Keywords: Base Isolation, Seismic Performance of Bridge, Shape Memory Alloy, SMA Modeling.

I. INTRODUCTION

Large proportions of the population in the world lives in seismic hazard regions are at risk from earthquakes of varying severity and frequency of occurrence. Every year earthquakes cause significant loss of life and damage to property. Progress in design and assessment methods of civil structures traditionally followed major earthquakes, whenever the need of improving the safety level of engineering structures became evident. When it was realized in the 1950s and 1960s that structures can survive levels of response accelerations apparently exceeding the ultimate strength level, concept of ductility was formalized and began to be adopted, attributing to the structures the capacity of deforming in elastically without significant strength loss, thus surviving high level earthquakes. It was also understood that a general improvement of the structural response could be obtained by modifying the structural dynamic characteristics and dissipating the seismic energy during the earthquakes.

Bridges play an important role in the transportation network on which goods and people are transported, and their failure will not only result in an interruption of this basic need but also impede the relief and rescue efforts. In the most recent 2008 Winchuan earthquake, many highway bridges were either severely damaged or completely collapsed in China, leading to not only significant economic losses but also large loss of lives due to the transportation supply disruption and the lack of access to medical care[1]. Seismic isolation has been considered as a reliable and cost-effective technology to alleviate the risks of seismic damages to highway bridges (D. Cardone)[2]

Laminated rubber bearings are one of widely used devices in seismic isolation of bridges and buildings. They are revealed the ability to carry vertical loads in compression and to accommodate shear deformations. The rubber layers, reinforced with steel shims, reduce the freedom to bulge by increasing the vertical stiffness of the bearing. Three types of laminated rubber bearings are widely used as seismic isolation devices: natural rubber bearing (RB), lead rubber bearing (LRB), and high damping rubber bearing (HDRB). RB occupies flexibility property and small damping and hence it has been used to accommodate the thermal movement, the effects of pre-stressing, creep, and shrinkage of superstructure of elevated highway or it has been used in seismic isolation by combining with other energy dissipation devices, such as lead, steel and viscous damper, etc. (Khan et al., 2015)[3]. Other two types of bearings possess high damping which are developed and widely used in various civil infrastructures including bridges in many countries, especially in Japan and USA (Khan, 2016). [4]HDRB possess a variety of mechanical properties, which are influenced by their compounding effect, nonlinear elasto-plastic behavior and temperature and strain-rate dependent viscosity property [5].

Researchers work in smart structure technology focuses on the application of smart materials in structures. A particularly interesting class of smart materials is known as shape memory alloys (SMAs).SMAs have the ability to regain their original shape after deformation well beyond 6-8% strain (Hurlebaus et al.)[6]. This shape recovery is happen due to phase transformations that can be induced by either a stress or a temperature change. Due to its hysteretic behavior and excellent re-centring capability, SMA can be used in a various civil applications. The other key features of SMAs include high strength, good fatigue and corrosion resistance, large damping capacity, ability to undergo large deformations, and availability in many possible shapes and configurations. Over the past few years, SMAs have been widely investigated for their possible application in civil engineering structures. Dolce et al.[7] evaluated the effectiveness of SMA braces in reinforced concrete structures, results from shaking table test demonstrated that SMA bars can provide favourable self-centring capability

II. SHAPE MEMORY ALLOY (SMA)

A shape-memory alloy (SMA, smart metal, memory metal, memory alloy, muscle wire, smart alloy) is an alloy that remembers its original shape and that when deformed returns to its pre-deformed shape when heated or stressed. The two main types of shape-memory alloys are (1) one way shape memory alloy, and (2) Two way shape memory alloy, Shape memory alloys (SMAs) are one kind of smart and functional materials that can restore to their pre-determined and original shape after deformation via unloading or applying thermal load. They have two solid phases; martensite or unstable phase in which material is at low temperature and austenite, parent, or high-temperature phase.[8] In this regard, four characteristic temperatures are defined to determine the temperature ranges for starting and finishing the phase transformation between martensite and austenite. Figure 2.1 illustrates the martensite fraction in an SMA material as a function of temperature in the absence of applied stress. There are four characteristic temperatures at which phase transformations occur:

Austenite start temperature (A_s), where the material starts to transform from twinned martensite to austenite.

Austenite finish temperature (A_f), where the material is completely transformed to austenite,

Martensite start temperature (M_s), where austenite begins to transform into twinned martensite,

Martensite finish temperature (M_f), where the transformation to martensite is completed.

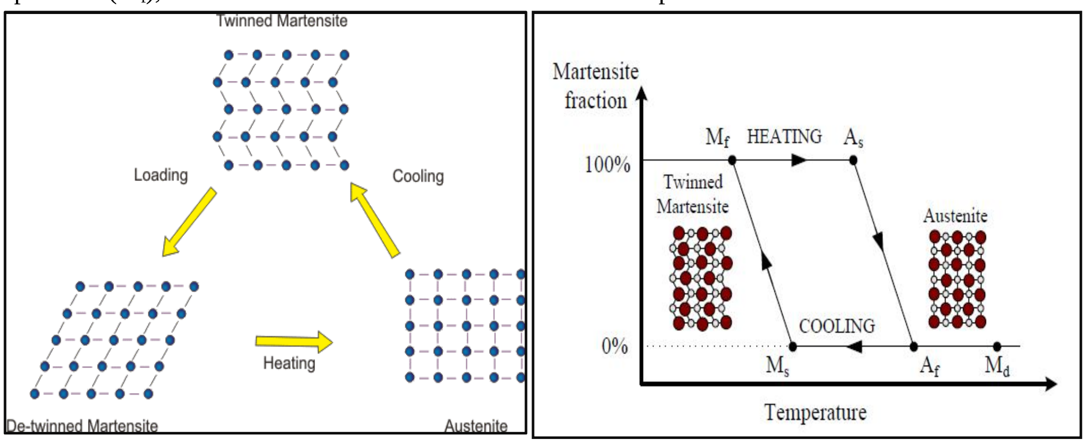


Figure 1 Schematic Working of SMA

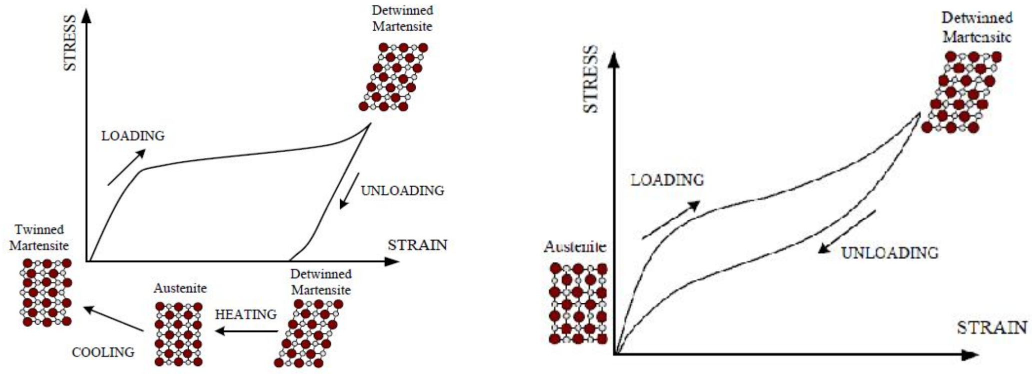
Following are two properties of Shape Memory Alloy

A. Shape Memory Effect

The shape memory effect is the ability of SMA material to recover its original shape after being deformed through a thermal cycling. If the temperature is below M_f, the SMA is in its twinned martensite phase. When a stress above a critical level is applied, the material transforms to detwinned martensite phase and retains this phase upon the removal of the load. It can regain its initial shape when the SMA material is heated to a temperature above A_f. Heating the material above A_f results in the formation of the austenite phase and a complete shape recovery. By a subsequent cooling, the SMA transforms to initial twinned martensite phase without residual deformation. Figure 2.2 illustrates the shape memory effect on a stress-strain curve and a temperature diagram.

B. Superelastic Effect

The superelastic effect is described as the recovery of large strain as a result of the stress-induced martensite phase transformations under constant temperature.SMA is in its austenite phase at relatively high temperatures (temperatures above A_f). When a sufficiently high stress is applied to the material in the austenite phase, the SMA transforms into the detwinned martensite. When the load is released, a reverse transformation to the austenite state takes place, which results incomplete shape recovery and a substantial hysteretic loop. A stress-strain curve and a temperature diagram demonstrating the superelastic effect of SMAs are shown in Figure 1.5. Note that if the temperature is below A_f but above As, there will be only a partial shape recovery. Also, if the temperature is above a critical temperature termed M_d, the material is stabilized in the austenite phase and the martensite transformations cannot be induced by an applied load.



(a) (b)

Figure2 Properties of SMA; (a) Shape Memory Effect, (b) Superelastic Effect

III. MODELING

This modeling aims to studying the behavior of shape memory alloys materials. To understanding the behavior of SMA many researchers developed mathematical models by considering different property of SMA. Most basic mathematical model is suggested by Grasser and Cozzarelli.

A. Graesser and Cozzarelli SMA Model

Graesser and Cozzarelli[9] proposed a one dimensional model representing the stress strain characteristics of SMAs which is a modification of the rate independent Ozdemir's model for the hysteresis behavior. The proposed model is given as

$$\dot{\sigma} = E.\left[\dot{\varepsilon} - |\dot{\varepsilon}|.\left(\frac{\sigma-\beta}{Y}\right)^{n}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1)$$

Where;

σ is the one dimensional stress,

E is the elastic modulus,

ε denotes strain,

Y is the yield stress,

*n*is a constant that controls the sharpness of the transition from the elastic state to the plastic transformation phase,

$\dot{\sigma}$ and$\dot{\varepsilon}$ denote the ordinary time derivative of the stress and strain respectively, and

β is the one-dimensional back stress, given by,

$$\beta = E.\alpha\{\varepsilon^{in} + f_t.|\dot{\varepsilon}|^{c}.\mathrm{erf}(a.\varepsilon).[u(-\dot{\varepsilon}.\varepsilon)]\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.2)$$

Where f_t, a and c material constants that determines the shape and size of the hysteresis, the amount of strain recovered during unloading, and the elastic modulus of the unloading stress plateau, respectively. The term α controls the slope of the stress-strain curve in the inelastic range. ε^{in} represent inelastic strain, given by $\varepsilon^{in} = \varepsilon - \sigma/E$. u(x) is the unit step function and erf(x) is the error function defined as,

$$u(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases}$$

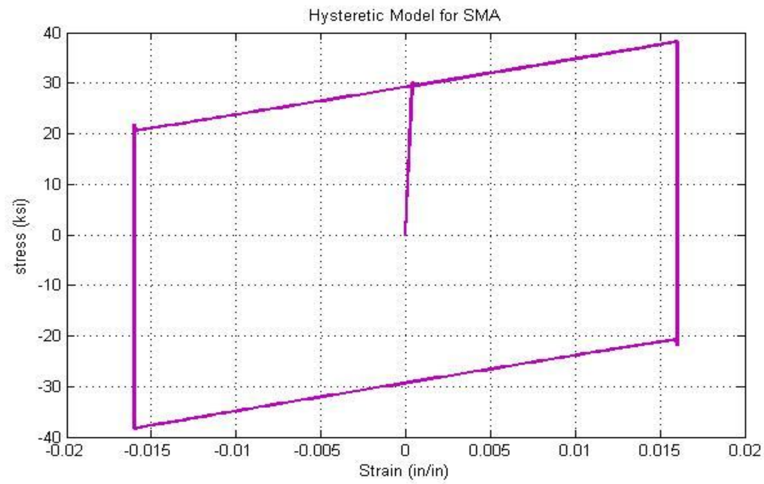
$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}.dt$$

By proper choice of the elastic modulus, yield stress, inelastic modulus and the constants ft, α, c etc. it is possible to arrive at the hysteresis property and the superelastic type of behavior of shape memory alloys. For example choosing ft = 0 will represent the hysteresis loop of the material in pure martensite form while ft > 0 will give us the superelastic behavior.

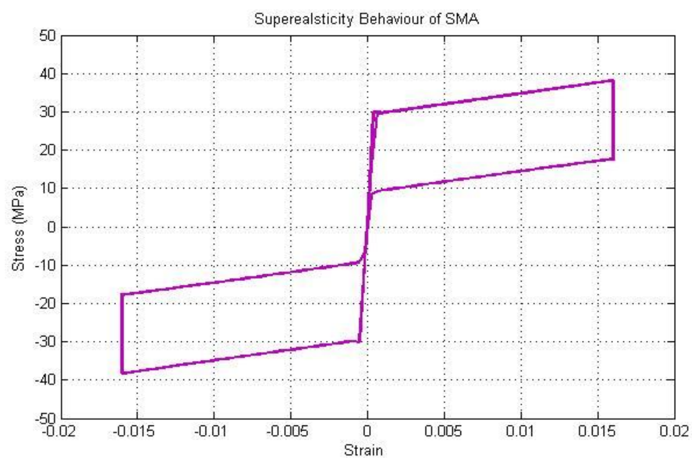
For the purposes of model demonstration, the material constants E, Y and α are selected as E=28500 ksi, Y= 30 ksi and α=0.0197 (E_y= αE/(1+α)= 550 ksi).

The overstress power is selected as *n* = 3 initially the constant $f_t$is chosen as zero. This will eliminate the participation of the term $f_t.|\dot{\varepsilon}|^{c}.\mathrm{erf}(a.\varepsilon).[u(-\dot{\varepsilon}.\varepsilon)]\}$ from the backstress. A sinusoidal cyclic loading condition is taken to be a strain-controlled test ranging from ε = -0.016 to ε= 0.016. The frequency of strain loading is taken as w = 1 radian/sec and the time step h = 0.025 sec is used in conjunction with 300 numerical integration time steps.

The hysteretic and superelastic behavior calculated using Equations. (3.1) and (3.2) for this set of conditions is shown in Figure 3.1.



(a) Hysteretic Effect



(bSuperelasticity) Effect

Figure3 G-C SMA model : (a) Hysteretic Effect, (b) Superelasticity Effect

B. Extended Superelastic Model of SMA or Wilde Model

This model is proposed by Wilde *et al.*[10](1997). In order to fully exploit the potential ofSMAs the martensite hardening effects need to be considered. Here the existing Graesser Cozzarelli model is extended to represent hardening of SMA after transition to martensite is completed. This model allows the use of SMAs in a wider range of strains and depicts properties that add to their benefits as base isolators. The modified model is of the form

$$\dot{\sigma} = E.\left[\dot{\varepsilon} - |\dot{\varepsilon}|.\left(\frac{\sigma-\beta}{Y}\right)^{n}\right].u_1(\varepsilon) + E_m.\dot{\varepsilon}.u_2(\varepsilon) + (3a_1.\dot{\varepsilon}\varepsilon^2 + 2a_2.sign(\varepsilon).\dot{\varepsilon}\varepsilon + a_3.\dot{\varepsilon})u_3(\varepsilon) \ldots\ldots\ldots.. (3.3)$$

Where backstress β is given by

$$\beta = E.\alpha\{\varepsilon^{in} + f_t.|\dot{\varepsilon}|^c.\mathrm{erf}(a.\varepsilon).[u(-\dot{\varepsilon}.\varepsilon)]\}$$

$u_1(\varepsilon)$, $u_2(\varepsilon)$ and $u_3(\varepsilon)$ are

$$u_1 = (1 - u_2(\varepsilon) - u_3(\varepsilon))$$

$u_2(\varepsilon)=1$, for $|\varepsilon| \geq \varepsilon_m$
0, otherwise

$u_3(\varepsilon) = 1$ $\varepsilon\dot{\varepsilon}>0$ and $\varepsilon_1<|\varepsilon|<\varepsilon_m$
0 otherwise

The signum function is given by

$$Sig(x) = \begin{cases} -1 & x < 0 \\ 0 & x = 0 \\ 1 & x > 0 \end{cases}$$

As depicted in Figure 3.2 the parameter E_m represent elastic modulus in pure martensite state. The elastic Martensite behavior is included by incorporating the term $E_m \cdot \dot{\varepsilon} \cdot u_2(\varepsilon)$. This term is activated when the strain is higher than ε_m. ε_m is the strain where the complete martensite transformation is completed. The last term in the constitutive equation is added to obtain a smooth transition from the curve of slope E_y to the curve of slope E_m and is evaluated only during loading and for the strain $\varepsilon_1<|\varepsilon|<\varepsilon_m$. The limits are determined based on experiments conducted on that particular alloy. This transition phase is controlled by the constants a_1, a_2 and a_3 included in the last term which are selected so that the slope of the function defined at the boundaries (i.e. at ε_1 and ε_m) are consistent with the slopes of SMA plastic behavior and martensite elastic response.

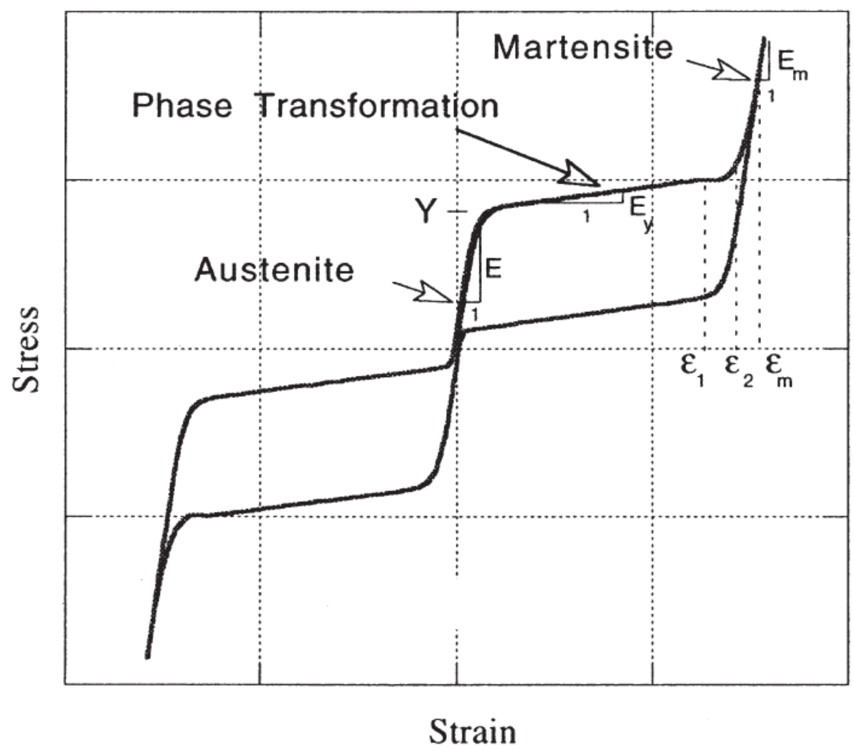


Figure 4 Schematic Stress–Strain Relations of the Extended Hysteretic Model of Shape Memory Alloy.

After rearranging the equation we get stress;

$$\sigma = \left[\left\{\dot{\varepsilon} - \frac{(\dot{\sigma} - (E_m.\dot{\varepsilon}.u_2(\varepsilon)) - (3a_1.\dot{\varepsilon}\varepsilon^2 + 2a_2.sign(\varepsilon).\dot{\varepsilon}\varepsilon + a_3.\dot{\varepsilon})u_3(\varepsilon))}{E.u_1(\varepsilon)}\right\}.\frac{1}{|\dot{\varepsilon}|}\right]^{1/n} Y + \beta \ldots\ldots\ldots\ldots (3.4)$$

Data consider for demonstration

t	E	Em	Y	α	n	a	c	f_t
0-300	98300 MPa	98300 MPa	144.9 MPa	0.0197	1	900	0.001	0.08

Considering superelastic range ε_m =0.05

The peak strain is vary between ε = - 0.06 sin(ωt) to 0.06 sin(ωt)…………………………..…..…….. (3.5)

Where ω = 1 rad/sec

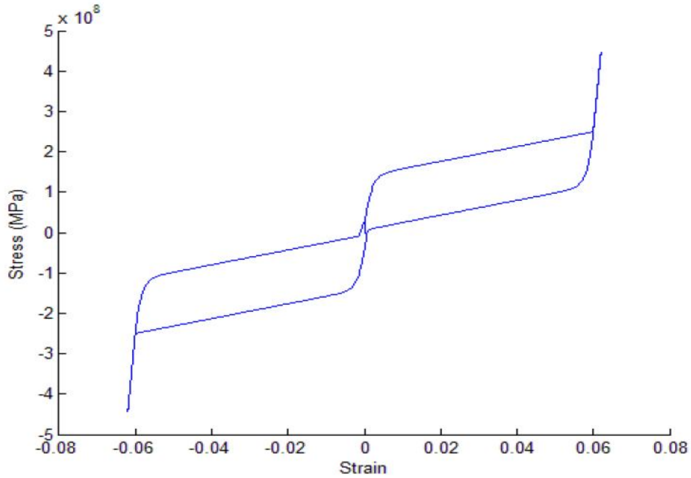


Figure 5SuperelasticityBehaviour of SMA Wilde Model

IV. APPLICATION OF SMA

Sharad Ghodkeet, al. [11] studied response of the base-isolated benchmark building with Shape Memory Alloys (SMA) supplemented Elastomeric Rubber Bearing(ERB) isolation systems are carried out by time history analysis. An equivalent elastic-viscous model of SMA is proposed to simulate the nonlinear behavior of SMA. Authors proposed equivalent linear model is established by using system identification method; that model is valid for any type of isolated structures (i.e. Bridges, Buildings, Water tanks etc.). The proposed equivalent linear model of SMA is a modified form of AASHTO guidelines specifications, and therefore practicing engineers can freely use it in the design.

Eunsoo Choi, et. al,[12]illustrated the behavior of shape memory alloy in tension and discussed the variation of stiffness and stress on the hyteresis curves. A three-span continuous steel bridge was used for seismic analyzed to compare the performance of lead–rubber bearings (LRB) with the proposed bearings. Authors showed that large residual deformation of LRB occurred even with a weak ground motion of peak ground acceleration (PGA) of 0.2g. The proposed bearings effectively limited the relative displacement of the deck when tested for the strong ground motions and almost recovered the original.

NitinChavan, et, al.[13] Studied the effect of seismic isolation on the seismic response of bridge components. In this study, first existing bridge with Elastomeric bridge bearing is modeled and analyzed to get the seismic response of bridge components and then that results are compared with Elastomeric isolator in place of elastomeric bearing. Modeling and analysis of Highway Bridge is done with help of Structural Analysis and Program 2000 Software. Time history analysis of bridge is conducted for 1940 Imperial Valley earthquake ground motion record. It is found from analysis results that significant reduction in seismic response of bridge components can be achieved by replacing elastomeric bearing with elastomeric isolator.

A. M. Billah. et. al. [14] presented a paper for smart isolation system for highway bridges, consisting of superelastic Shape Memory Alloy (SE-SMA) had been explored and its performance had been compared to that of other two types of isolation devices, which are high damping rubber bearing (HDRB) and lead rubber bearing (LRB). Result shown the SMA isolator satisfactorily restrained the deck displacement and the relative displacement between deck and pier for strong ground motions. Also the SMA isolation system has inherent centring ability due to the superelastic response of the alloy.

V. CONCLUSION

This paper presents a review of the basic properties of shape memory alloys (SMA) and applications of shape memory alloys in civil structures.Shape memory alloy is a unique material and has found increasing application in many research areas. A shape memory alloy has an ability to undergo large deformation also studied the fundamental characteristic of shape memory alloy, some of the application of shape memory alloy in civil structures, and the constitutive modeling of shape memory alloys are discussed.

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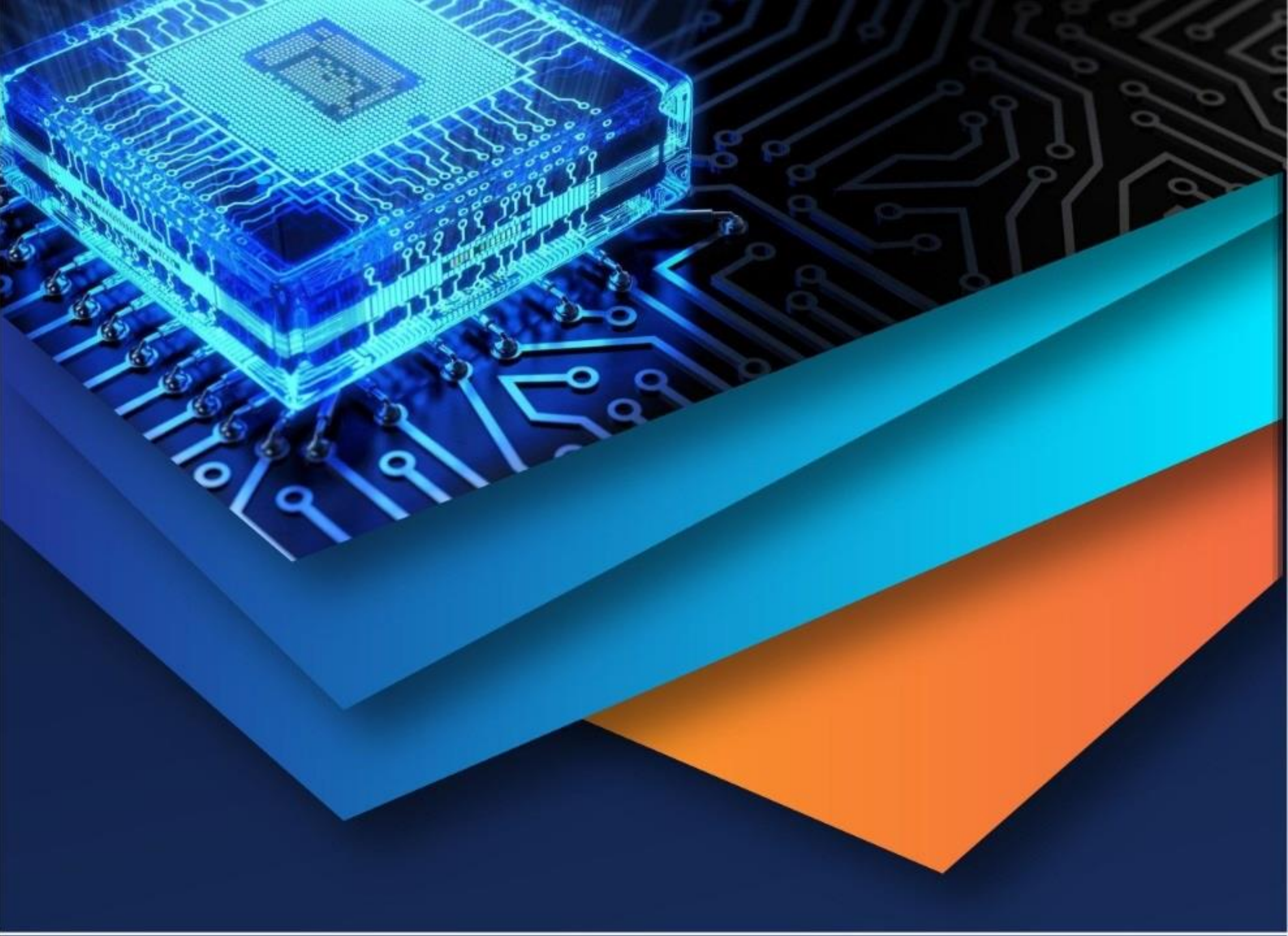

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