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Seismic Analysis of Structure by Introducing Weak Story on Top as Tuned Mass Damper

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Abstract: The current trend toward structures of increasing heights and the use of lightweight, high strength materials and advanced construction techniques has led to more flexible and low damped structures. Understandably, these structures are very sensitive to natural excitations such as wind and earthquakes, leading to vibrations inducing possible structural failure, along with occupant discomfort due to vibrations. Hence, it is necessary to search for an effective system to control vibrations. Control of seismic responses based on various passive, active, hybrid and semi-active control approaches offers excellent opportunities to mitigate damage and loss of serviceability caused by natural hazards. There are various methods of seismic responses control. The tuned mass damper (TMD) as an added energy-absorbing system is one of the available systems of structural control. Tuned Mass Damper (TMD) is a passive control system which absorbs energy and reduces response of vibration. TMD is found to be a simple effective inexpensive and reliable means for decreasing undesirable vibration of structure caused by seismic or wind excitation. This research explores additional top storey as tuned mass damper in building system for reducing the seismic response of tall structure and mitigating damage. The proposed structural configuration separates the upper storey of structure to act as the 'tuned' mass. This additional storey is also of RCC buildings and its beam and column sizes are smaller than that of building. The effect of TMD on the seismic response of structure is studied. It is seen that TMD in the form of weak storey at the **top of building reduces the displacement, column bending moment, and column shear force and storey shear.**

KeyWords: Seismic response, Optimum parameters, Tuned mass damper (TMD), Natural frequency, mass ratio, Displacement, Column Bending Moment, Column Shear force, Storey shear.

I. INTRODUCTION

In structural engineering the major goal has been the, maintaining the structural stability against effect of various forces acting on the structure. Earthquake and wind are the two important external forces that need to be taken in account while designing a structure, as they can greatly affect stability of structure. Efforts have led to development of techniques like base isolation, active control and passive control devices. Base isolation technique is shown to be quite effective and it requires insertion of isolation device at the foundation level, which may require constant maintenance. Active control techniques turn out to be quite costly for buildings, as they need continuous power supply. In developing countries like India, such control devices can become popular only if they are easy to construct.

With the aim of developing such a simple control device, some studies have been undertaken in last decades. In these studies a simple type of Tuned Mass Damper (TMD) has been proposed for controlling seismic responses of structure. TMD is the simplest form of vibration absorbers which is relatively easy to be implemented. By adding a small additional mass where the stiffness and damping are designed in proper way, the vibration of the building can be reduced. In order to perform TMD properly, the properties of TMD have to be designed so that the response of building can be reduced.

Fahim Sadek et. al. (1997) [1] carried out the research on methods of estimating the parameters of Tuned Mass Damper for seismic applications. The overall objective of the paper was to determine the optimum parameters of TMD that results in considerable reduction in the response to earthquake loading. SDOF and MDOF system were considered for analysis and optimum parameters of TMD were obtained. The results indicated that the proposed TMD parameter reduces the displacement and acceleration response significantly (upto 50%).

Miyama et. al. (1992) [2] proposed elastic element at the top story which supports the total mass and the elasto- plastic element which absorb most of input energy. In this paper, the energy dissipation ratio and the deformation of top storey is investigated under parameters like yield force, stiffness of elastic range, stiffness of plastic range, and mass of top storey. By analyzing this system for three different earthquake motions, they presented that a top story with 5% mass ratio can reduce the seismic response significantly, by tuning the strength and the inelastic stiffness of the top storey. But considering the deformation of the top storey 10% of the total mass is preferable as top mass. Then it is possible to realize the structural system which absorbs most of the input energy at the top storey leaving the other storey's undamaged.

In present study a simple form of TMD in the form of an additional storey at the top of building is considered. This additional storey is designed in such a way that the mass of the additional storey should be about 3 to 5% of total mass of building for this condition to satisfy, the beam and column of this additional storey will be smaller in size than that of the building. The storey height, member sizes of weak storey will be devised based on the principle of TMD i.e. the natural frequency of TMD (weak storey) should have same natural frequency as that of main building.

II. THEORETICAL FORMULATION

A. *Theoretical Background of Tuned Mass Dampers*

The concept of tuned mass dampers dates back to 1909 {Frahn 1909}. The vibration absorber consists of a small mass and a spring attached to the main mass and spring. Under harmonic loading it can be shown that the main mass can be kept completely stationary when the frequency of the small mass is tuned (equal) to the excitation frequency. Typically a TMD consists of an inertial mass attached to the building location with maximum motion, generally near the top, through a spring and damping mechanism, TMDs transmit inertial force to the building's frame to reduce its motion, with their effectiveness determined by their dynamic characteristics, stroke and the amount of added mass they employ. A typical model of SDOF structure and TMD is shown below. Where m is the main mass, m_d is the damper mass, k is the main spring stiffness, k_d is the absorber spring stiffness, c_d is the absorber damping, f (t) is the force acting on the main mass and g (t) is the force acting on the damper mass.

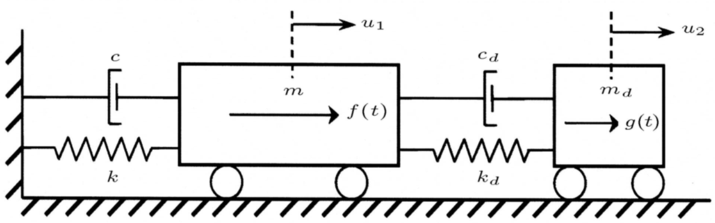

Figure No 1 Model of SDOF structure and TMD

B. *Parameters of TMD for Further Seismic Analysis*

Fahim Sadek et. al. formulated optimum parameters of TMD for SDOF and MDOF system, which are given below.

For un-damped structure the tuning ratio 'f' is found to be equal to 1/ (1+μ) and the damping ratio 'ξ' is equal to $\sqrt{\mu / (1+\mu)}$. Also for damped structure the following equations were obtained,

$$f = \frac{1}{1+\mu}\left[1-\beta\sqrt{\frac{\mu}{1+\mu}}\right] \quad \xi = \frac{\beta}{1+\mu} + \sqrt{\frac{\mu}{1+\mu}} \qquad (1)$$

Where μ is mass ratio, β is damping ratio. Also it was found that the tuning ratio 'f' for a MDOF system is nearly equal to tuning ratio of SODF system for mass ratio of μϕ. Were ϕ is amplitude of first mode of vibration for a unit modal participation factor. Also damping ratio of MDOF is equal to SDOF system multiplied by ϕ.

$$f = \frac{1}{1+\mu\phi}\left[1-\beta\sqrt{\frac{\mu\phi}{1+\mu\phi}}\right] \quad \xi = \phi\left[\frac{\beta}{1+\mu} + \sqrt{\frac{\mu}{1+\mu}}\right] \qquad (2)$$

By using the above formulas and optimum parameters of TMD can be obtained, which results considerable reduction in response to earthquake loading

III. PROBLEM FORMULATION

The present study aims at study of the effect of provision of storey at the top of the structure as tuned mass damper. The research is carried to study the effect of tuned mass damper on structures with square shape with increase in storey height also with varying mass ratios. The analysis is carried out on ETABS 2015 software. The research consist of 18 models, with G + 4, G + 6, G + 8 storey's and mass ratio 3, 3.5, 4, 4.5, 5. The building plan is shown in Figure No 1. The plan for Model 1 to 18 is similar except

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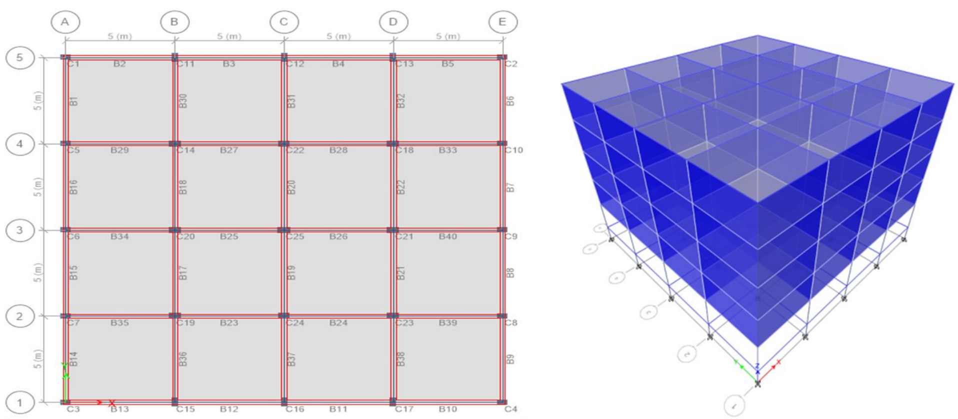
height. And the height of all storeys is taken as 3m with plinth level as 1.5m.Youngs modulus of elasticity for concrete is taken as 29580.4MPa and that for masonry is taken as 3500MPa.

A. Dimensions of Structural Members and Loading Details

Floor Height is considered as 3m, Bay length considered 5m, Number Stories considered are for study are 4, 6, 8 and Mass Ratios considered are 3, 3.5, 4, 4.5, 5. Weight is assigned which covers the dead load of beams, column, slab and walls. Floor finish is assigned as 1kN/m^2, Live load is considered as 3kN/m^2 and seismic load parameters considered as per IS 1893-2002.



(A) (B)

Figure No 2. A) Plan of Building B) 3D view of 4 X 4 bay 4 storey's

The details of column and beam sizes for various model is tabulated in Table No 1.

Table No 1 Column and Beam size details

Label used in software	Group Label	Dimension of Column in mm
C1, C2, C3, C4	C1	300 x 450
C5, C6, C7, C8, C9, C10, C11, C12,	C2	300 x 500
C14, C18, C19, C20, C21, C22, C23,	C3	350 x 550
C25	C4	350 x 600
B1 to B16	B1	300 x 400
B17 to B40	B2	300 x 500

After finalizing the column and beam sizes the analysis of models is carried out and following building characteristics of fundamental frequency and modal mass are obtained and tabulated in Table No 2.

Table No 2 Basic Building characteristics

System	Fundamental Frequency (Cyc / sec)	Modal mass (kg)
G + 4	1.796	2300200.2
G + 6	1.465	3241358.672
G + 8	1.422	4103637.57

In order to obtain the optimum parameters of TMD the basic building characteristics of structure without TMD are to be known. Further by using formulas obtained by Fahim Sadek et. al. mentioned as above 2.2 are used for calculation of optimum parameters of TMD. And based on the obtained mass of TMD the sizes of TMD are finalized by trial and error. The frequency of TMD

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obtained is kept same as that of frequency of structure by varying the height of top storey. The details of formulas and the parameters obtained are listed in theoretical formulation. The details of models considered for analysis are described in table below.

Table No.3 Models formulated for study with 4 bays in X and 4 bays in Y direction

S.R. No	No of Storey	Designation	Model No	Mass Ratio
1	G + 4 storey	W/O TMD	Model 1	Without TMD
2		MR 3	Model 2	3
3		MR 3.5	Model 3	3.5
4		MR 4	Model 4	4
5		MR 4.5	Model 5	4.5
6		MR 5	Model 6	5
7	G + 6 Storey	W/O TMD	Model 7	Without TMD
8		MR 3	Model 8	3
9		MR 3.5	Model 9	3.5
10		MR 4	Model 10	4
11		MR 4.5	Model 11	4.5
12		MR 5	Model 12	5
13	G + 8 Storey	W/O TMD	Model 13	Without TMD
14		MR 3	Model 14	3
15		MR 3.5	Model 15	3.5
16		MR 4	Model 16	4
17		MR 4.5	Model 17	4.5
18		MR 5	Model 18	5

Table No 4 Optimum parameters of TMD

Model No	No of Storey	Mass Ratio	Mass of TMD (Kg)	Natural frequency of TMD for mode 1 (Cyc / sec)
Model 2	G + 4	3	68976.17	1.592
Model 3		3.5	84171.83	1.533
Model 4		4	94044.23	1.472
Model 5		4.5	101431.8	1.474
Model 6		5	109587.12	1.415
Model 8	G + 6	3	104681.2	1.225
Model 9		3.5	113537.36	1.214
Model 10		4	128669.31	1.28
Model 11		4.5	135263.65	1.291
Model 12		5	162545.75	1.195
Model 14	G + 8	3	130077.36	1.169
Model 15		3.5	140271.52	1.132
Model 16		4	162609.45	1.074
Model 17		4.5	182404.96	1.155
Model 18		5	202793.26	1.106

Once the optimum parameters are obtained, the column, beam sizes, slab thickness of TMD is arrived by various trial and errors in order to match the mass obtained by using the mass ratio formula as mentioned in above equation no (1) and (2). The analysis is carried out and details of results obtained are presented further.

Table No 5 Details of TMD

Model No	No of Storey	Column Size (mm)	Beam Size (mm)	Slab Thickness (mm)	Height of top storey (m)
Model 2	G +4	150 x 200	150 x 200	50	3.3
Model 3		150 x 200	150 x 200	65	3.4
Model 4		150 x 300	150 x 300	65	4.1
Model 5		200 x 300	200 x 300	65	4.8
Model 6		200 x 300	175 x 300	70	5.1
Model 8	G +6	150 x 250	150 x 250	80	4
Model 9		200 x 250	200 x 250	80	4.7
Model 10		200 x 250	200 x 250	95	4.8
Model 11		200 x 300	200 x 300	95	4.9
Model 12		200 x 350	200 x 350	115	5.2
Model 14	G +8	200 x 400	200 x 400	75	6
Model 15		200 x 400	200 x 400	85	6
Model 16		200 x 450	200 x 450	100	6.2
Model 17		230 x 450	230 x 450	110	6.4
Model 18		230 x 450	230 x 450	130	6.4

B. Seismic Analysis

After arriving at TMD, its seismic analysis is carried out. Natural frequency of TMD is extracted from analysis.

Table No 6. Free vibration characteristics of TMD are analyzed and tabulated

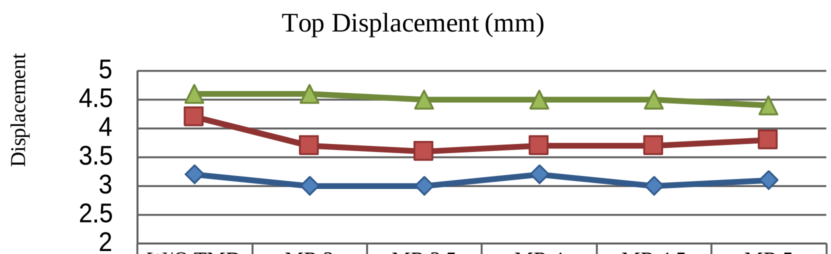
Mass Ratio	Model No	Frequency	Model No	Frequency	Model No	Frequency
MR 3	Model 2	1.592	Model 8	1.225	Model 14	1.169
MR 3.5	Model 3	1.533	Model 9	1.214	Model 15	1.132
MR 4	Model 4	1.472	Model 10	1.28	Model 16	1.074
MR 4.5	Model 5	1.415	Model 11	1.291	Model 17	1.155
MR 5	Model 6	1.474	Model 12	1.195	Model 18	1.106

IV. RESULT AND DISCUSSION

After obtaining the final sizes of TMD the TMD is introduced on the structure and analysis of models with weak storey and without weak storey at top is carried out. A comparative result of structure without TMD and TMD with mass ratio 3, 3.5, 4, 4.5, 5, is presented. Graphical presentation of maximum displacement, column bending moment, column shear force is presented below.

A. Variation in Displacement at Top for Structures with TMD & without TMD

The variation for displacement at the top of structure with TMD and without TMD for G + 4, G + 6, G + 8 structures is presented in Graph no 1.



	W/O TMD	MR 3	MR 3.5	MR 4	MR 4.5	MR 5
G + 4	3.2	3	3	3.2	3	3.1
G + 6	4.2	3.7	3.6	3.7	3.7	3.8
G + 8	4.6	4.6	4.5	4.5	4.5	4.4

Graph No 1 Variation in Displacement at Top for structures with TMD

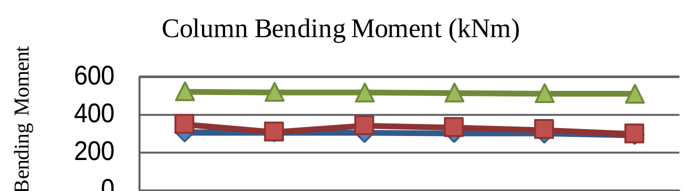
In G + 4 categories model without TMD has maximum displacement, which further decreases for MR 3 and 3.5. There afterwards MR 4 produces higher displacement which further decreases marginally for MR 4.5 and again increases marginally for MR 5.

In case of G + 6 building, model without TMD is having maximum displacement. The displacement is reducing for MR 3, 3.5 again displacements are increasing for MR 4, 4.5 and 5. The percentage change for subsequent MR is insignificant.

For G + 8 models nearly linear variation is observed for all MR values and minimum displacement is observed for MR 5 and overall reduction in displacement is observed about 4.54%. Minor reduction in displacement is observed due to addition of top storey as TMD for all building categories. For G + 4 building models maximum reduction in displacement observed is 6.67% and for G + 6 models is about 16.67%. However marginal reduction in displacement is observed for G + 8 models (4.54%).

B. Variation in Column Bending Moment for Structures with TMD & without TMD

The graph below shows the variation in column bending moment for G +4, G+6 & G+ 8 structures at first storey of each model with varying mass ratios. As maximum column bending moment is observed at Ist storey of the structure.



	W/O TMD	MR 3	MR 3.5	MR 4	MR 4.5	MR 5
G + 4	305.18	304.207	302.89	301.37	299.53	290.745
G + 6	347.73	307.34	341	329.778	318.5	295.69
G + 8	521.41	518.73	516.23	514.874	511.234	509.47

Graph No 2 Variation in Column Bending Moment along Storey 1 for structures with TMD

In above graph, it is observed that variation graph of column bending moment for G + 4 and G + 6 is almost same. Maximum column bending moment is observed for model without TMD. Further column bending moment decreases linearly as MR increases.

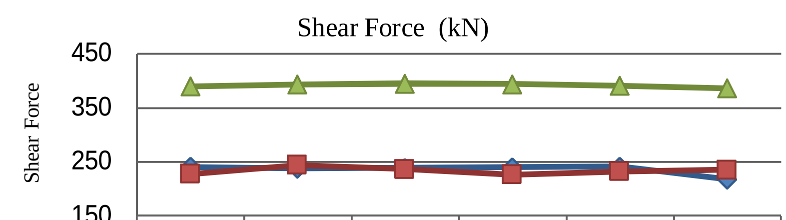
Similarly in G + 6 categories sudden drop is observed for MR 3. It has increased again and further linear reduction is observed. The Column bending moment decreases by 6% for MR 5 as compared to model with TMD.

In G + 8 categories, a linear reduction in column bending moment is observed. Maximum Column bending moment is observed for model without TMD. Column Bending Moment is reduced by the introduction of TMD. Overall the variation in column bending moent is insignificant.

For all the storey combinations, lowest bending moment is observed for MR 5. The highest reduction in bending moment due to introduction of TMD is 4.96% for MR 5 for G + 4 structures, for G + 6 Models reduction observed is around 17.6%. The reduction in column bending moment due to introduction of TMD is marginal for G + 8 structures (2.23%).

C. Variation in Column Shear Force for Structures with TMD & without TMD

The variation in Column Shear Force for structures with TMD & without TMD is presented in graph no 3. It is observed that column shear forces at Ist storey is maximum.



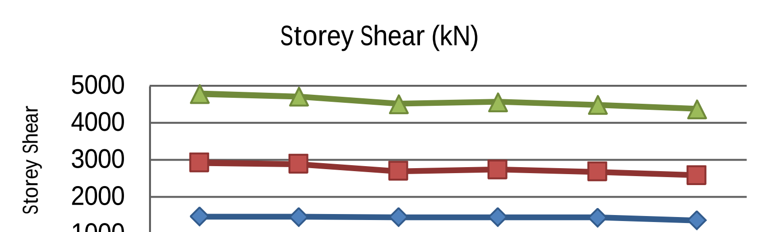
	WO	MR 3	MR 3.5	MR 4	MR 4.5	MR 5
G + 4	240.488	237.5	238.97	240.2	241.31	217.57
G + 6	227.774	244.256	236.6	226.176	232.28	235.149
G + 8	390.126	393.69	395.16	394.21	391.24	386.19

Graph No 3 Variation in Column Shear Force along Storey 1 for structures with TMD

Insignificant variation in column shear force, due to change in MR is observed from above graph. In G + 4 and G + 6 categories model without TMD has maximum column shear force. The line representing G + 4 and G + 6 categories models are closer to each other. In case of G + 8 categories maximum column shear force are observed for model without TMD. Slight increment is observed for MR 3 and 3.5 and marginal reduction is observed for MR 4, 4.5 and 5. Among all mass ratios minimum shear force is observed for mass ratio 5 for G + 4 structure and same trend is observed for G + 6 and G + 8 structures. The reduction in shear force after introduction of TMD is 10.53% for G + 4 structures. However marginal reduction in shear force is observed in G + 6 and G + 8 category structures.

D. Variation in Storey Shear for Structures with TMD & without TMD

The variation in Storey Shear Force for structures with TMD & without TMD is presented in graph no 4.



	W/O TMD	MR 3	MR 3.5	MR 4	MR 4.5	MR 5
G + 8	1862.6	1827.89	1818.53	1825.76	1816.09	1799.62
G + 6	1453.74	1418.66	1237.24	1288.35	1234.09	1215.65
G + 4	1472.54	1468.07	1461.43	1454	1445.11	1371.04

Graph No 4 Variation in Storey Shear along Storey 1 for structures with TMD

From Graph 4, it is observed that due to introduction of TMD the reduction in magnitude of storey shear occurs with increase in mass ratio. For G + 4 categories marginal reduction in storey shear is observed. The graph obtained is almost a linear one. Maximum storey shear observed for model without TMD. Further the line goes on decreasing as mass ratio increases. In G +6 model without TMD has maximum storey shear further marginal reduction is observed for MR 3 but further @ --% reduction is observed for MR 3.5 and the pattern of mild reduction is observed for further models. Similarly for G + 8 steeper reductions in magnitude of storey shear is observed upto MR 3.5. There afterwards it decreases linearly at a milder rateThe reduction in storey shear observed is 7.4%, 16.81% and 7.4% for G + 4, G + 6 and G + 8 category structure respectively.

V. CONCLUSION

In this research, the seismic performance of the Tuned mass damper is studied and compared with that of structures without Tuned mass damper. The properties of the added mass (Column, beam, slab thickness) are varied widely to obtain the optimum values which minimize the seismic effect. The parameters like displacement, top displacement, and column bending moment, column shear force, and storey shear are considered for study. The square type model 1 to 18 of category G + 4, G + 6 and G + 8 structures have been studied

A. The structures with TMD of mass ratio 5 are giving better seismic performance.

B. The implemented analysis shows that the performance of structure with TMD is better than that of structure without TMD, resulting in substantial reduction of top storey displacement in G + 4 G + 6 category and marginal in G + 8 category structures.

C. If top storey is provided with TMD for a square shape building with varying height, the major impact is on column bending moment which has reduced significantly for G + 4 and G + 6 structures and marginally for G + 8 structures.

D. Introduction of TMD in structure marginally reduces the frequency which in turn increase time period of structure. The increase in time period results in reduction in storey shear. As mass ratio is increased the frequency of structure is reduced.

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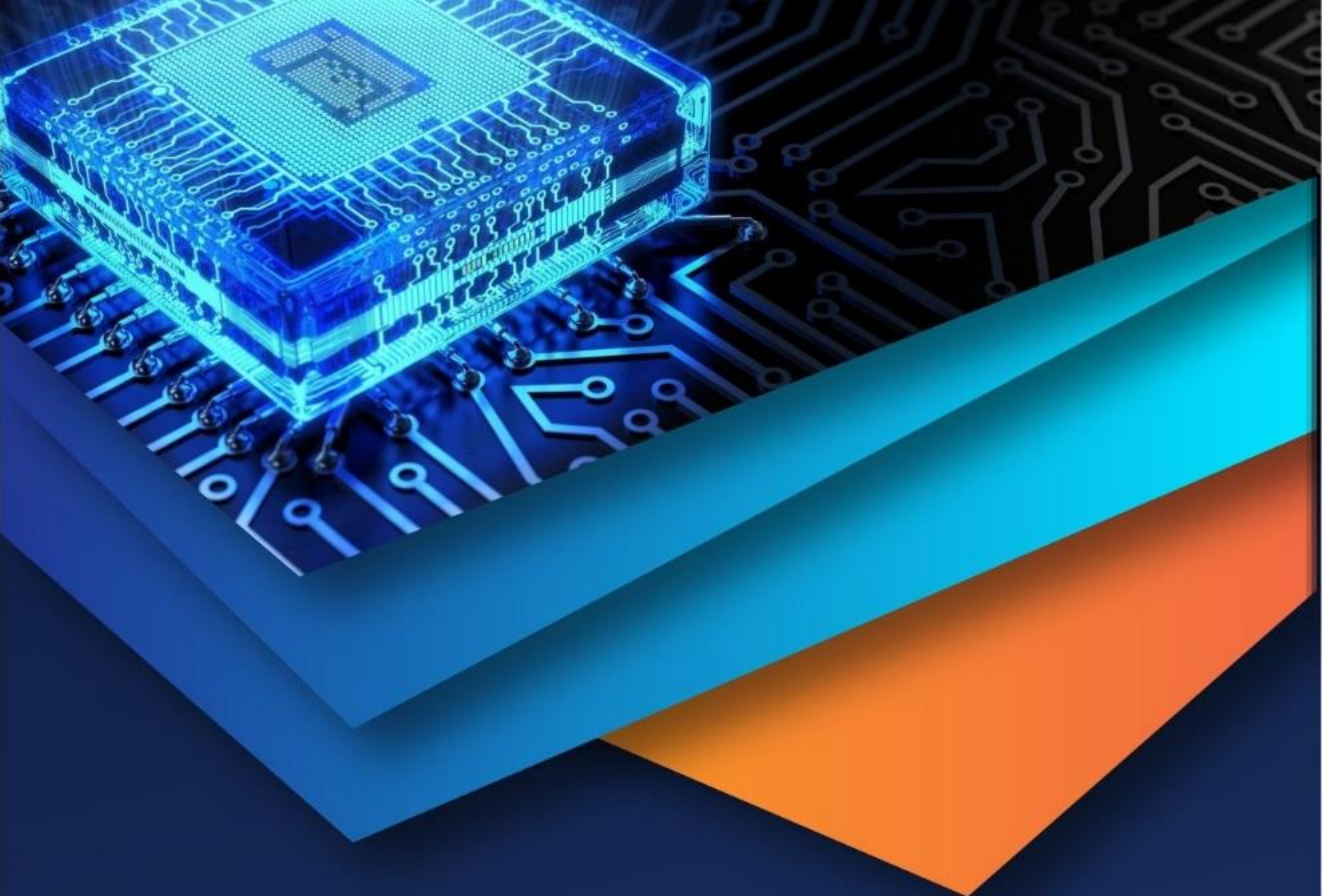

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