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Seismic Response of a G+40 Storey RC Building with Different Slenderness Ratios Using Response Spectrum Analysis in ETABS

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Abstract: ***In a tall building the proportions of the plan matter as much as the height. The slenderness ratio, which is the height divided by the least plan dimension, decides how much the building sways and how strongly the overturning effect acts on the outer columns. A narrow tower has a smaller floor area and therefore attracts a smaller seismic force, but it is also more flexible, and these two effects work against each other.***
This paper studies a G+40 storey reinforced concrete frame building, 123 m high, with a plan length of 24 m and four different widths of 25 m, 20 m, 15 m and 10 m. The slenderness ratios (H/B) are 4.92, 6.15, 8.2 and 12.3. The four models are analysed by response spectrum analysis in ETABS for Seismic Zone V, and the storey drift, storey shear, bending moment, torsion, time period and modal stiffness are compared.
When the width is reduced from 25 m to 10 m, the shear, bending moment and torsion at storey 6 reduce by 55% to 64%, because the seismic weight reduces. The drift in the Y direction, however, increases by 66% and crosses the limit of 0.004 at nine of the twenty storeys reported, and the first mode time period increases by 12%. A building with H/B of 12.3 therefore needs an additional lateral load resisting system.
Keywords: Slenderness ratio, tall building, response spectrum analysis, storey drift, storey shear, torsion, time period, ETABS.

I. INTRODUCTION

A building shakes during an earthquake and inertia forces are generated in every floor. These forces travel through the slabs, beams and columns and finally reach the soil through the foundation. How well the building behaves depends on its strength and stiffness, but also on its shape. The plan form, the ratio of length to width and the ratio of height to width are the geometric properties which affect the seismic response most.

For a tall building, the height alone does not tell much about its seismic behaviour. A tower with a wide plan and a tower with a narrow plan of the same height behave quite differently. The narrow tower acts like a tall cantilever. The overturning moment due to the lateral load is resisted by a short lever arm, so the axial forces in the outer columns become large and the sway at the top becomes large. On the other side, the narrow tower has less floor area, less weight and therefore smaller seismic forces. It is not clear without analysis which of the two effects governs, and this is the question studied in this paper.

A. Slenderness Ratio

The slenderness ratio of a building is taken as the height of the building divided by its least lateral dimension in plan, H/B. The plan aspect ratio is the ratio of the length to the width, L/B. In this study the height and the length are kept constant and only the width is changed, so that the effect of the slenderness ratio can be seen separately from the other parameters.

B. Objectives of the study

1) To model a G+40 reinforced concrete building in ETABS with four plan widths, which give slenderness ratios of 4.92, 6.15, 8.2 and 12.3.
2) To analyse the four models by response spectrum analysis for Seismic Zone V.
3) To compare the storey drift, storey shear, bending moment, torsion, time period and modal stiffness of the models.
4) To find out how the slenderness ratio changes the seismic demand and the serviceability of the building.

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II. LITERATURE REVIEW

Arnold and Reitherman (1982) discussed the problems that arise from the configuration of a building in seismic design, and explained why architectural requirements often lead to such problems. Their book is one of the main references on the effect of building form on earthquake performance.

Murty (2005) explained in the IITK-BMTPC Earthquake Tips that the behaviour of a building during an earthquake depends on its overall shape, size and geometry, and also on the path by which the earthquake forces are carried to the ground.

Sanyal (2008) stressed that the seismic performance of a building improves when the architect and the structural engineer work together at the planning stage, and that a poorly configured building will not perform well in a damaging earthquake.

Awida et al. (2011) studied the influence of the slenderness ratio on residential concrete towers using ETABS. A case study of two thirty storey towers with slenderness ratios of 8.60 and 4.77 was considered for the wind and seismic conditions of Kuwait. The slender tower showed a wind drift about 6.3 times that of the stockier tower when wind tunnel results were used, and the authors concluded that the slenderness ratio is one of the main factors affecting the behaviour of tall buildings.

Sadh and Pendharkar (2016) analysed sixteen regular reinforced concrete buildings with different plan aspect ratios and different vertical aspect ratios, with 4, 16, 24 and 32 storeys. The models were analysed by response spectrum analysis in ETABS for seismic zone III as per IS 1893 (Part 1):2002. Base shear, overturning moment, drift, displacement and time period were found to increase with the number of bays and the number of storeys, and buildings with a plan aspect ratio above 4 were found to perform poorly.

III. METHODOLOGY OF THE PROJECT

A. Response Spectrum Analysis

Response spectrum analysis is a linear dynamic method. The building is treated as a set of vibration modes. For each mode the maximum response is read from the design response spectrum, which depends on the seismic zone, the soil type and the damping, and the modal responses are combined to get the total response of the building. Since the higher modes are included, the method gives a better picture for tall buildings than the equivalent static method.

In the present study, the design spectrum of IS 1893 (Part 1):2002 for medium soil (Type II) and 5% damping is used in ETABS. The spectral acceleration coefficient is given as a function of the time period. Twelve modes are extracted for each model.

B. Model specifications

A G+40 storey building in Seismic Zone V is analysed in ETABS. The basic parameters considered are given below.

1.	Grade of concrete	M40
2.	Grade of steel	HYSD Fe600
3.	Plan length	24 m
4.	Plan width	25, 20, 15 and 10 m
5.	Total height	123 m
6.	Number of storeys	G+40
7.	Storey height	3 m
8.	Beam size	500x230 to 350x230 mm
9.	Column size	500x500 to 350x350 mm
10.	Slab thickness	150 mm and 120 mm
11.	Live load	5 kN/m²
12.	Dead load	2 kN/m²
13.	Density of concrete	25 kN/m³
14.	Seismic zone	V
15.	Site type	II (medium soil)
16.	Importance factor	1.5
17.	Response reduction factor	5
18.	Damping ratio	5%
19.	Basic wind speed	44 m/s
20.	Factors k1, k2, k3	1.08, 1.14, 1.36
21.	Wind design code	IS 875 (Part 3):1987
22.	RCC design code	IS 456:2000

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23. Steel design code	IS 800:2007
24. Earthquake code	IS 1893 (Part 1):2002

The beam and column sizes are reduced in steps of ten floors, from 500 mm at the lower floors to 350 mm at the top floors. The slab is 150 mm thick up to the 20th floor and 120 mm above it.

C. Modelling procedure

The models are prepared in ETABS in the usual sequence. The units are set to kN and m, the grid lines and the storey data are defined, and the material properties and the frame and slab sections are entered. The beams and columns are drawn as line objects and the slabs as area objects, and a rigid diaphragm is assigned at every floor. Dead load, live load, earthquake load and wind load patterns are defined, the floor loads are assigned, and the mass source is defined from the self weight and the applied loads. All the columns are fixed at the base. After this the analysis is run for all the load cases.

D. Loads and seismic parameters

The self weight of the members is calculated by ETABS from the density of concrete. A dead load of 2 kN/m² and a live load of 5 kN/m² are applied on the floors as uniform surface loads. The earthquake loading is defined by the zone factor of Zone V, the importance factor of 1.5, the response reduction factor of 5 and the medium soil type, and the wind loading is defined by the basic wind speed of 44 m/s with the factors k1, k2 and k3 given in the list above. The response spectrum is applied separately in the X and Y directions, and in this way the response of each model is obtained in both the directions.

E. Building models in ETABS

The four models have the same height, the same length of 24 m, the same member sizes and the same loads. Only the width of the plan is changed, by removing bays in the Y direction, as shown in Fig. 1 and Table 1. Model 1 has the widest plan and the lowest slenderness ratio, and Model 4 has the narrowest plan and the highest slenderness ratio.

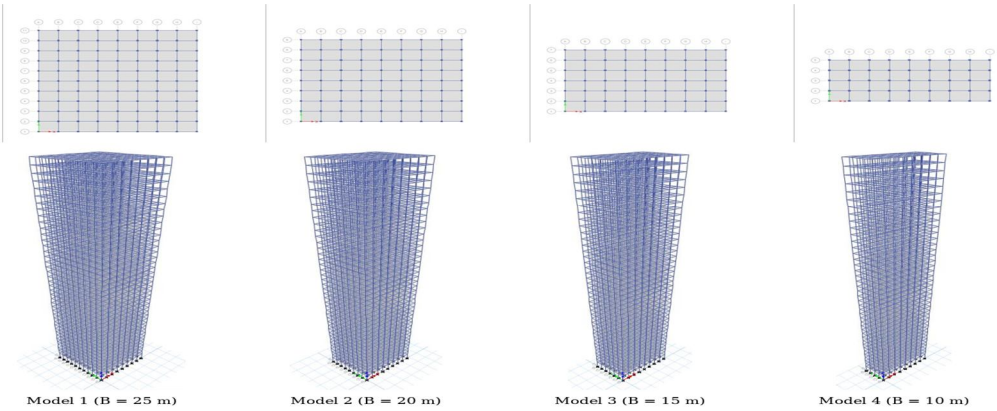


Fig. 1: Plan and 3D view of the four ETABS models

Table 1: Models considered

Model	Plan L x B (m)	Height H (m)	H/B	Plan area (m²)
Model 1	24 x 25	123	4.92	600
Model 2	24 x 20	123	6.15	480
Model 3	24 x 15	123	8.2	360
Model 4	24 x 10	123	12.3	240

IV. RESULTS AND ANALYSIS

The results of the four models are compared in this section. The values are reported for twenty selected storeys, namely storeys 40 to 36, 30 to 26, 20 to 16 and 10 to 6, which are counted from the base. The changes are calculated with respect to Model 1 (H/B = 4.92).

A. Comparison of Storey Drift

Fig. 2 gives the storey drift in the X and Y directions. In the X direction, in which the length is constant, the drift reduces as the width reduces. The maximum drift is 0.00292 for Model 1 and 0.00229 for Model 4, a reduction of 21.6%. The Y direction is the direction of the reduced width, and the trend is opposite. The maximum drift increases from 0.00279 for Model 1 to 0.00321, 0.00375 and 0.00464 for Models 2, 3 and 4, which is an increase of 15.1%, 34.4% and 66.3% (Table 2).

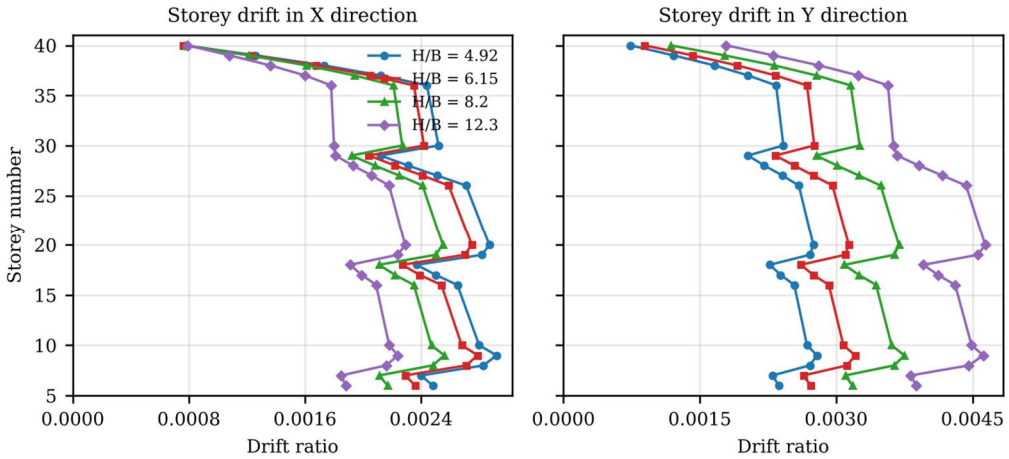


Fig. 2: Comparison of storey drift in the X and Y directions

Table 2: Maximum storey drift ratio

Model	H/B	Drift X	Drift Y	Change in Y (%)
Model 1	4.92	0.00292	0.00279	-
Model 2	6.15	0.00279	0.00321	+15.1
Model 3	8.2	0.00256	0.00375	+34.4
Model 4	12.3	0.00229	0.00464	+66.3

The drift limit of IS 1893 (Part 1):2002 is 0.004 times the storey height, so the drift ratio should not exceed 0.004. Models 1 and 2 are well within this limit in both directions. Model 3 has a maximum of 0.00375 in the Y direction, which is close to the limit. In Model 4 the drift in the Y direction is more than 0.004 at nine of the twenty reported storeys (storeys 27, 26, 20, 19, 17, 16, 10, 9 and 8), and the model does not satisfy the serviceability requirement as it stands.

B. Comparison of Storey Shear

The storey shear (Fig. 3) is the highest for Model 1 and decreases steadily as the width decreases. At storey 6 the shear in the X direction is 1974.4 kN for Model 1 and 878.5 kN for Model 4, which is 55.5% less, and in the Y direction the values are 2077.0 kN and 797.0 kN, which is 61.6% less (Table 3). The plan area reduces by 20%, 40% and 60% in Models 2, 3 and 4, and the shear in the Y direction reduces by 20.8%, 41.7% and 61.6%. This shows that the shear follows the seismic weight of the building, which is proportional to the floor area.

Table 3: Storey shear, bending moment and torsion at storey 6

Model	Vx (kN)	Vy (kN)	Mx (kN-m)	My (kN-m)	T (kN-m)
Model 1	1974.4	2077.0	69691	66404	127412
Model 2	1606.0	1645.6	54803	53987	99328
Model 3	1237.2	1211.7	39754	41558	73096
Model 4	878.5	797.0	25438	29720	48944

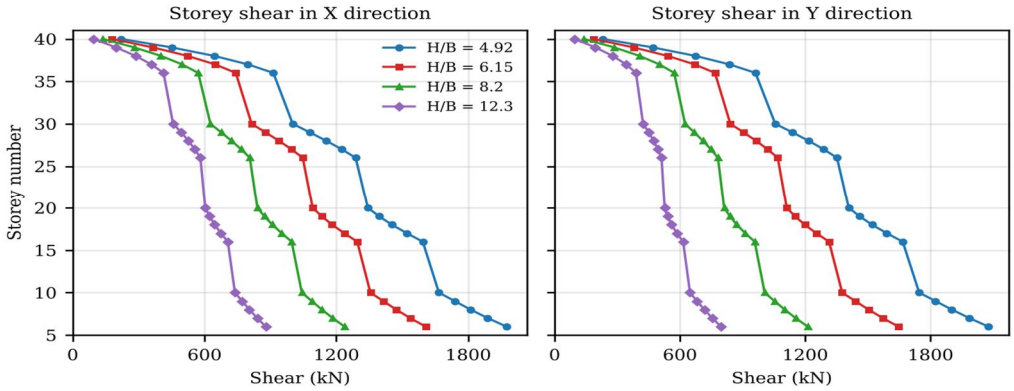


Fig. 3: Comparison of storey shear in the X and Y directions

C. Comparison of Bending Moment and Torsion

The storey bending moments in both directions (Fig. 4) increase from the top to the bottom and reduce as the width reduces. At storey 6, the moment about the X axis reduces by 21.4%, 43.0% and 63.5% for Models 2, 3 and 4, and the moment about the Y axis reduces by 18.7%, 37.4% and 55.2%. The storey torsion (Fig. 5) behaves in the same way, with reductions of 22.0%, 42.6% and 61.6% at storey 6. These quantities are lower in the narrow buildings only because the narrow buildings are lighter. They should not be taken as a sign of a better performance, since the drift of the same buildings is larger.

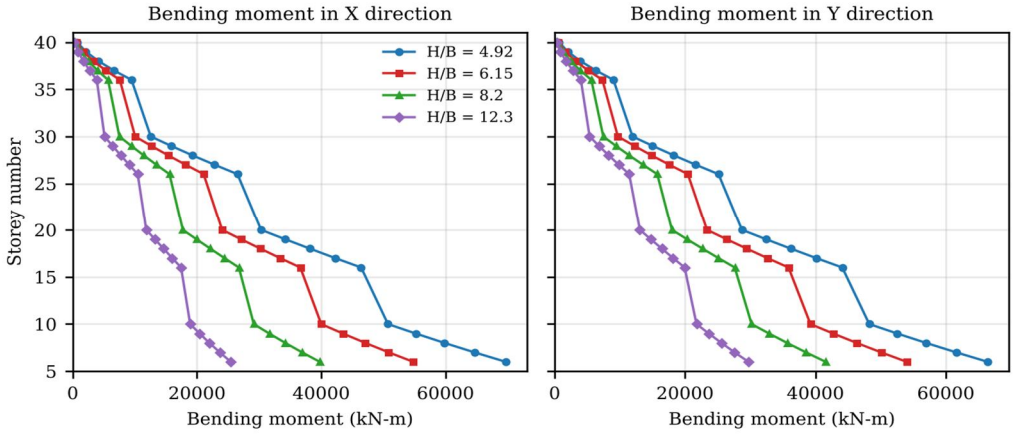


Fig. 4: Comparison of bending moment in the X and Y directions

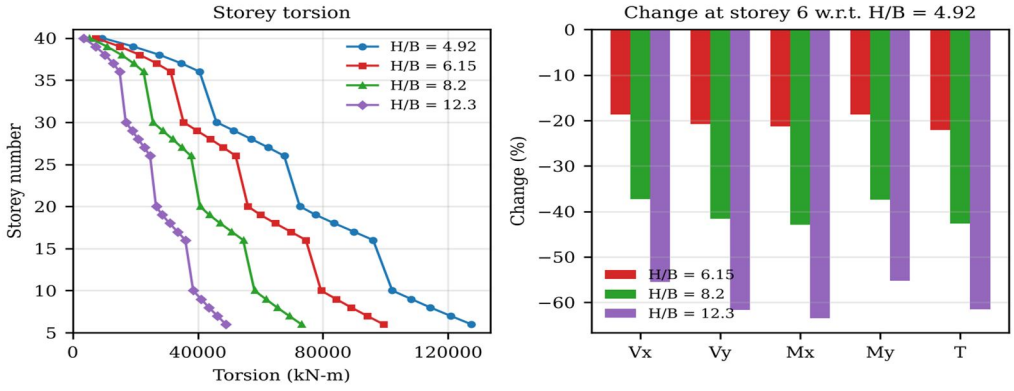


Fig. 5: Storey torsion and change of the responses at storey 6

D. Comparison of time period and modal stiffness

The first mode time period is 1.930 s for Model 1, 1.917 s for Model 2, 1.959 s for Model 3 and 2.164 s for Model 4 (Table 4 and Fig. 6). The time period of the narrowest building is 12.1% more than that of the widest building, so the narrow building is more flexible. The second and third modes are less affected. The modes four to twelve differ by not more than about 5% among the models. The modal stiffness in Fig. 6 is the eigenvalue of each mode, which is equal to the square of the circular frequency. It is 10.60, 10.75, 10.29 and 8.43 rad²/s² for the first mode of the four models, and it increases with the mode number in all the models, as expected.

Table 4: Time period and frequency of the first three modes

Model	T1 (s)	f1 (Hz)	T2 (s)	f2 (Hz)	T3 (s)	f3 (Hz)
Model 1	1.930	0.518	1.838	0.544	1.686	0.593
Model 2	1.917	0.522	1.881	0.532	1.672	0.598
Model 3	1.959	0.511	1.896	0.527	1.681	0.595
Model 4	2.164	0.462	1.884	0.531	1.785	0.560

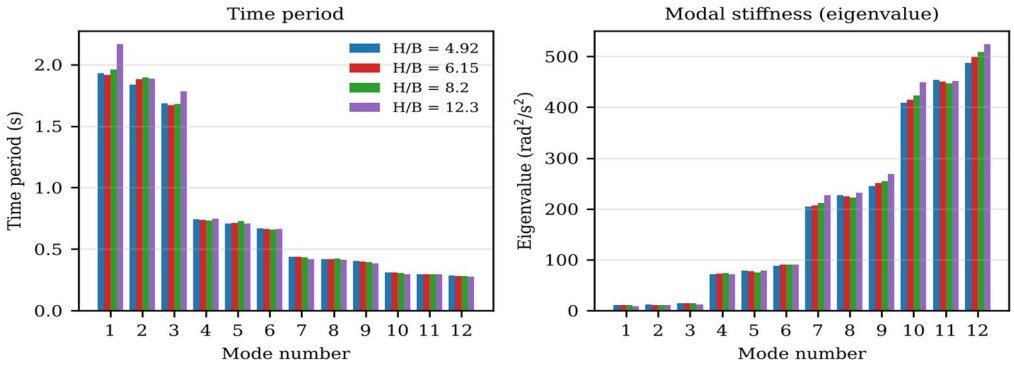


Fig. 6: Time period and modal stiffness for the first twelve modes

E. Overall Change with the Slenderness Ratio

The changes of all the quantities with respect to Model 1 are collected in Table 5. The quantities which depend on the seismic force, namely the storey shear, the bending moment and the torsion, reduce nearly in proportion to the plan area. The quantities which describe the flexibility of the building, namely the drift in the Y direction and the first mode time period, change in the opposite direction. The drift in the Y direction is the most sensitive of all the response quantities, since it increases by 66.3% for Model 4 while the time period increases by 12.1%.

Table 5: Change with respect to Model 1 (H/B = 4.92)

Quantity	Model 2 (%)	Model 3 (%)	Model 4 (%)
Plan area	-20.0	-40.0	-60.0
Maximum drift in X	-4.5	-12.3	-21.6
Maximum drift in Y	+15.1	+34.4	+66.3
Shear Vx at storey 6	-18.7	-37.3	-55.5
Shear Vy at storey 6	-20.8	-41.7	-61.6
Moment Mx at storey 6	-21.4	-43.0	-63.5
Moment My at storey 6	-18.7	-37.4	-55.2
Torsion T at storey 6	-22.0	-42.6	-61.6
First mode time period	-0.7	+1.5	+12.1

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Taking all the results together, a narrow plan reduces the force demand but increases the sway of the building, and the sway in the narrow direction is the quantity that finally limits the slenderness. For this frame, with the member sizes used, a slenderness ratio of about 8 is near the limit of what the frame can carry. Above this, the drift in the narrow direction is more than the code limit.

V. CONCLUSIONS

From this analysis the following conclusions were made

1) A G+40 reinforced concrete building was analysed by response spectrum analysis for four plan widths, which give slenderness ratios of 4.92, 6.15, 8.2 and 12.3.

2) The storey shear, bending moment and torsion reduce as the width reduces. At storey 6 the reductions for the narrowest building are 55.5% and 61.6% in shear, 63.5% and 55.2% in bending and 61.6% in torsion. The reduction follows the reduction in the floor area, because the seismic weight becomes less.

3) The storey drift in the X direction reduces by 21.6% as the width reduces, but the drift in the Y direction increases by 15.1%, 34.4% and 66.3% for Models 2, 3 and 4.

4) The drift in the Y direction of the building with H/B = 12.3 is more than the limit of 0.004 at nine of the twenty storeys reported. The building with H/B = 8.2 is close to the limit, and the buildings with H/B of 4.92 and 6.15 satisfy it.

5) The first mode time period is 12.1% more for the building with H/B = 12.3 than for the building with H/B = 4.92. The higher modes are nearly the same for all the models.

6) The lower forces in the slender buildings are because of their smaller weight and not because of better behaviour. The slenderness ratio should be checked against the drift limit, and not only against the forces.

7) For the frame studied here, the slenderness ratio of about 8 is the practical limit. A building with a higher ratio needs a wider plan, larger members or an additional lateral load resisting system such as shear walls or bracing.

8) The study is for a bare frame without any lateral load resisting system other than the frame itself.

A. Scope for Future Work

1) Shear walls, bracing, outriggers and dampers can be added to the slender models to reduce the drift in the narrow direction.

2) Irregular buildings, such as the setback type, can be studied for different slenderness ratios.

3) Time history analysis and wind analysis can be carried out to check the response under these loads.

4) Buildings with more storeys and different plan aspect ratios can be considered.

VI. ACKNOWLEDGEMENT

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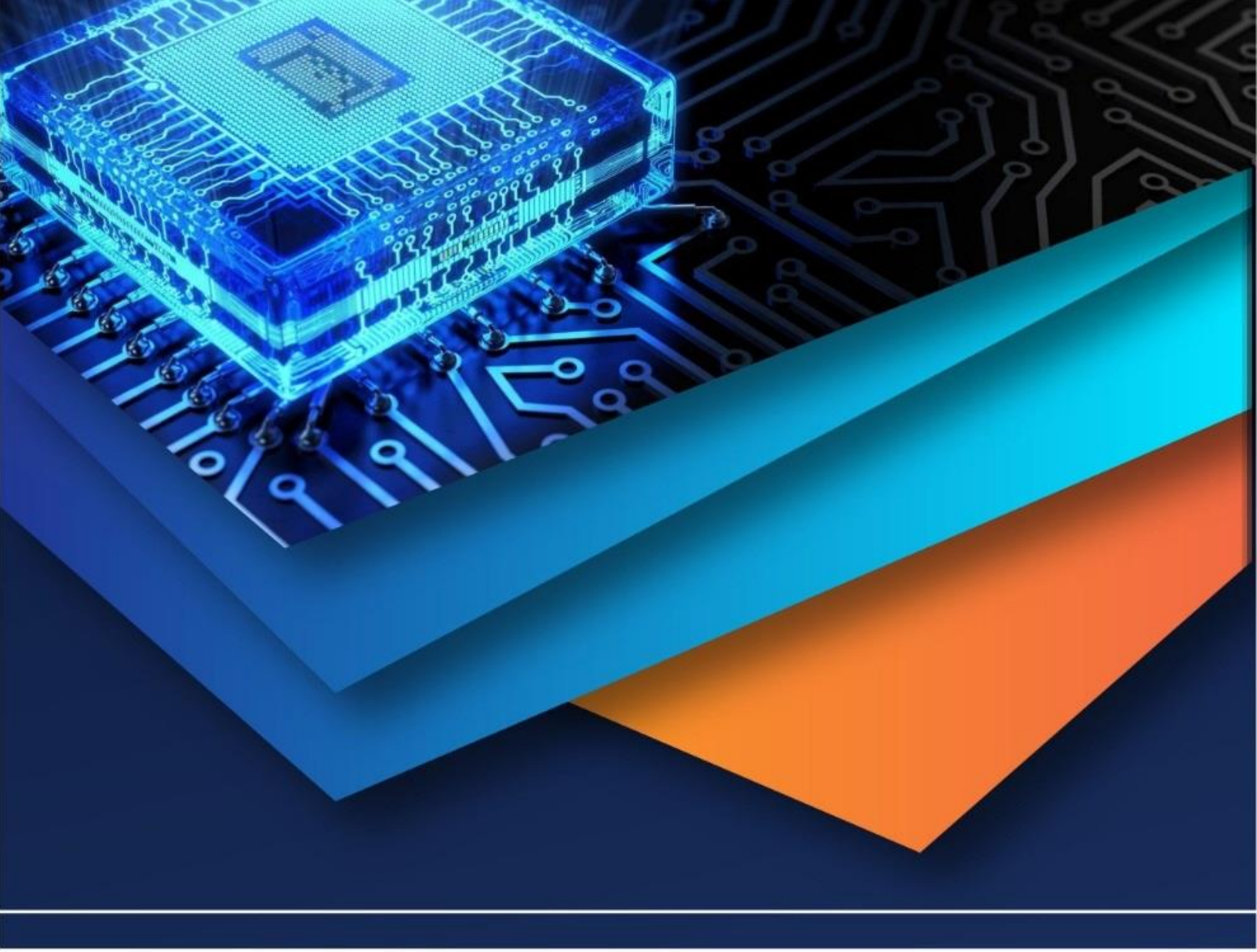
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