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Evaluation of Dissipated Energy in Rock Mass under In-Situ Plate Load Test

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Abstract: Deformability characteristic of rock mass is assessed on the basis of classical elasto-plastic theory. But, the analysis is based only on the concepts of stress and strain, and may not be sufficient enough to assess the actual deformational behaviour, as the evaluation procedure established by the standards considers only the deformation at the peak stress levels and not the complete stress-deformation behaviour of rock mass. Also, the stress-deformation behaviour of rock mass, describing its specific mechanical state, is only one aspect. The deformation of rock mass is partially irreversible process involving energy dissipation. The application of external forces changes the stress and deformation distribution within the rock mass, while at the same time some of the dissipated energy creates damages/ plastic deformation in the rock mass. This paper establishes a framework to facilitate the study of energy conversion that occurs during the deformation of rock mass in in-situ plate load test. The data of four in-situ plate load tests conducted in a drift of Himalayan rock mass composed of metamorphosed Granite Gneiss is used for analysis. Further, assessment of total strain energy transmitted to the rock mass by the external force, recovered elastic strain energy (which was bidirectional and reversible, and was related to intrinsic property of rock, mainly Elastic Modulus and Poisson's Ratio) and lost/ dissipated strain energy (which was unidirectional and irreversible and had results in internal damage and plastic deformation in the rock mass) is done. From the presented cases, it is found that 70 to 80% of strain energy transmitted to the system had been lost/ dissipated and the rest 20 to 30% of strain energy was recovered as elastic strain energy.
Keywords: Dissipated Energy, Rock Mass, Plate Load Test,

I. INTRODUCTION

Deformability characteristic of rock mass is one of the fundamental elements to evaluate the stability of engineering structures founded over or within the rock mass. The strength criteria based on classical elasto-plastic theory are used to judge the deformability characteristics [1] – [4]. However, the analysis is based only on the concepts of stress and strain, and may not be sufficient enough to assess the actual deformational behaviour. It is because of the fact that the response of the rock mass to the imposed loads is complex due to it's extremely inhomogeneous and anisotropic setup at micro levels, which in turn results in non-linear and scale dependent outcomes. The stress-deformation behaviour of rock mass, describing it specific mechanical state, is only one aspect. The deformation of rock mass is partially irreversible process involving energy dissipation. The application of external forces change the stress and strain distribution within the rock mass, while at the same time some of the dissipated energy creates damages/ plastic deformation in the rock [5], [6].

Law of conservation of energy states that the total energy of an isolated system remains constant which means that the energy can neither be created nor destroyed; rather it can only be transformed or transferred from one form to the another. The energy conversion is an essential characteristic of materials physical processes and rock failure is an instability phenomenon driven by strain energy. The strain energy evolution runs through the entire process of rock deformation and failure [7]. The deformation of a rock mass under an external load can be considered as a closed system assuming that the total strain energy produced is only due to the work done by the external load and there is no heat conversion from mechanical work.

The strain energy of a material can be defined as the increase in the energy associated with the deformation of material, which is equal to the work due by the slowly increasing load applied to the material. The work done by the load (P) results in the increase of strain energy associated with the deformation of the material, which is equal to the area under the load deformation diagram (Fig. 1) between x=0 and $x=x_1$.

$$Total\ Strain\ Energy = Uo = \int_0^{x1} Pdx$$

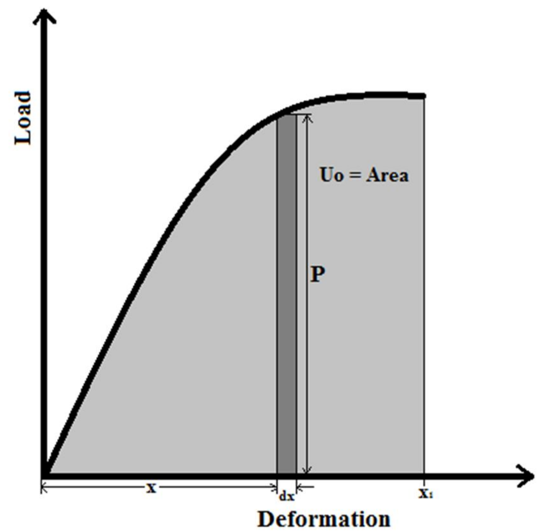

Fig. 1 Strain Energy Evaluation Curve

Fig. 2 illustrates a typical Load versus Deformation curve of rock subjected to uniaxial loading and unloading, in which hatched area under the curve represents the dissipated energy U_d, and the darker filled-in area represents the releasable elastic strain energy stored in the rock U_e. Energy dissipation is unidirectional and irreversible, which results in internal damage and plastic deformation in the rock. However, elastic strain energy is bidirectional and reversible, and is related to intrinsic property of rock, mainly Elastic Modulus and Poisson's Ratio [8].

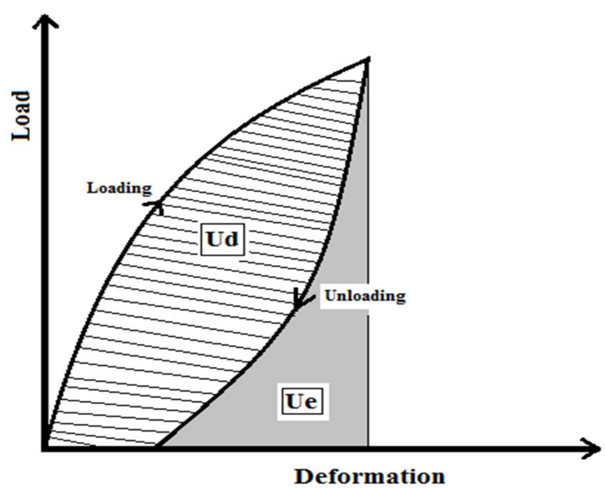

Fig. 2 Typical Load V/s Deformation Curve to evaluate Elastic and Dissipated Strain Energy

According to first law of thermodynamics, total strain energy (U_o) can be calculated by the as:

$$U_o = U_e + U_d$$

Where,

U_o is the total strain energy transmitted to the rock mass by the external force applied

U_e is the recovered elastic strain energy

U_d is the strain energy dissipated

This paper establishes a framework to facilitate the study of energy conversion that occurs during the deformation of rock mass in in-situ plate load test. The data of four in-situ plate load tests (PLT) conducted in a drift of Himalayan rock mass composed of metamorphosed Granite Gneiss were used to calculate the strain energy. Furthermore, the U_o, U_e and U_d are also assessed.

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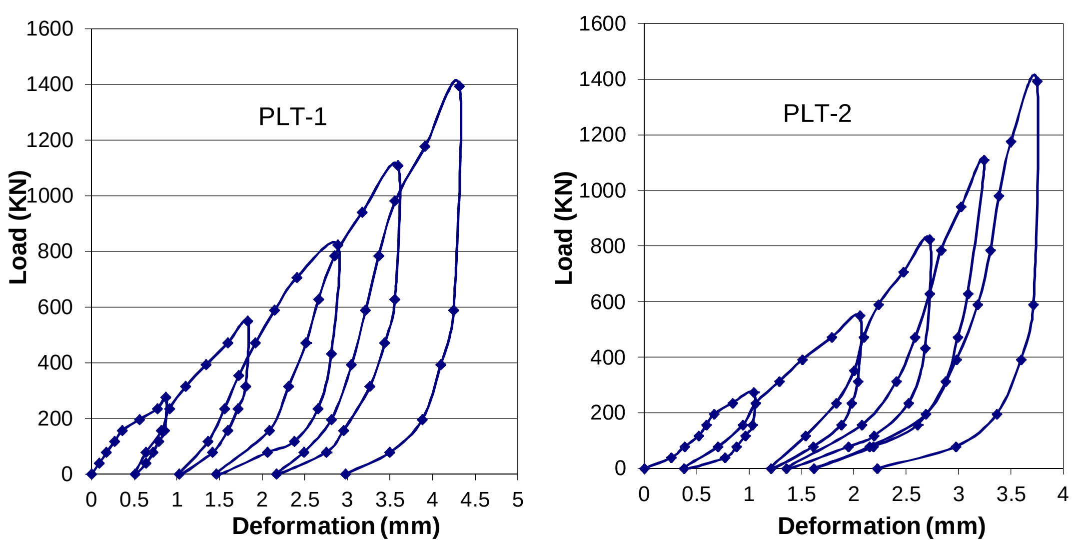
II. IN-SITU PLATE LOAD TEST

Set up of typical in-situ plate load test assembly and deformation measuring arrangement is shown in Fig. 3. Detailed testing procedure and site preparation methods can be referred from [9]–[11]. All data presented in this paper are collected by standard operating procedures mentioned in the said standards. The load was applied by means of jack and pump and the tests were completed in five cycles of loading and unloading at different peak loads, Deformation were recorded by four dial gauges with accuracy of 0.01mm installed diagonally on bottom of plate. The deformations reported are average of the four dial gauges.

Fig. 3 In-situ Plate Load Test Setup

Load deformation curves are shown in Fig. 4(a) to 4(d) for plate load tests PLT-1 to PLT- 4 respectively were obtained for four plate load tests conducted at the project site at different locations.



(a) (b)

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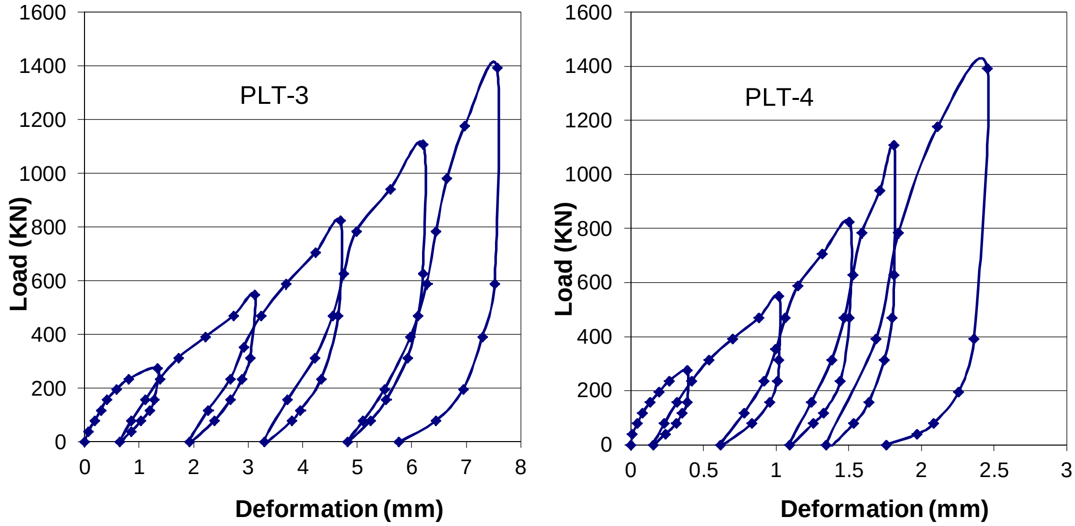

(c) (d)

Fig. 4 Load-Deformation Curves

III. ENERGY CALCULATION METHOD

In this paper, three energies – total strain energy transmitted to the rock mass when the external force is applied, recovered elastic strain energy and strain energy dissipated in each cycle – are calculated ignoring other negligible energies like thermal, chemical or other possible energies. In other words, the system in consideration here is a closed loop system.

A typically separated load deformation curve of first cycle of PLT -1 is shown in Fig. 5. As the plotted graph shows Load (kN) verses Deformation (mm) curve, hence, area under the curve of graph gives quantum of energy in Joule (1 Newton-Meter = 1 Joule). Area under loading curve gives U_o – total energy absorbed by the rock mass under influence of work done on rock mass. While area under unloading curve gives U_e – elastic energy released by rock mass due to the effect of elastic rebound during unloading. Difference of above two energy gives U_d – energy dissipated in rock mass.

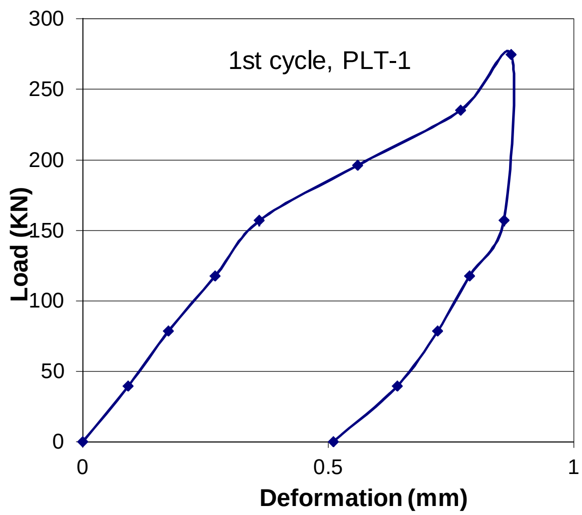

Fig. 5 Load - Deformation curve of first cycle of PLT 1

Area under curve is calculated by trapezoidal method in which a curve in divided into several small trapezoids and area of each trapezoid is calculated by geometrical method. Sum of area of each trapezoid gives total area under the curve as shown in Fig. 6(a) and 6(b).

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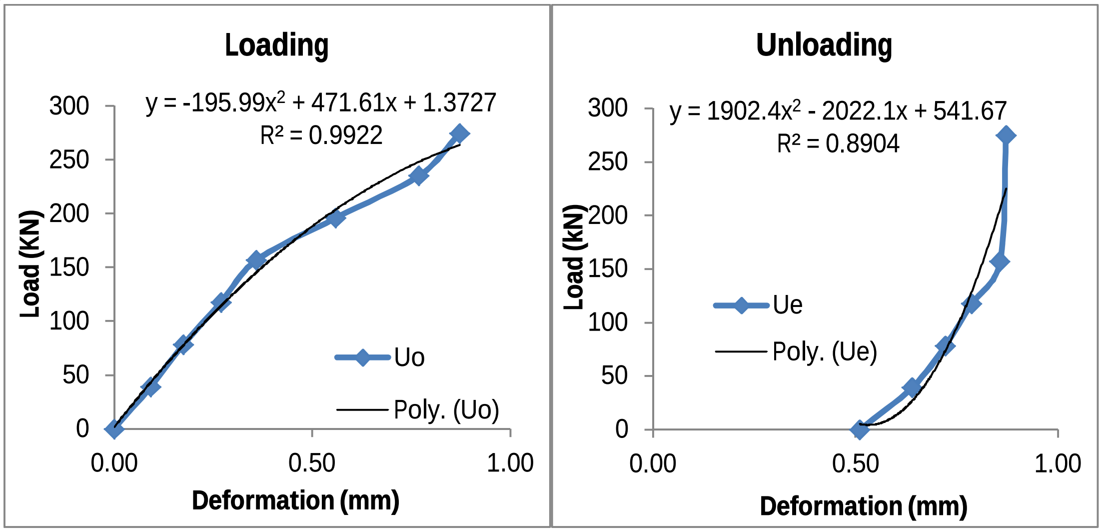

(a) (b)

Fig. 6 Area calculation during loading and unloading from Load-Deformation Curves

Area under curve obtained by trapezoid method is confirmed by integration method also. In this method, polynomial equations of loading and unloading curve are integrated separately by substituting its lower and upper limits, which gives area under the curve respectively. Areas of the curves obtained by both methods are found to be approximately same.

IV. DISCUSSION

The data of four in-situ plate load tests conducted in a drift of Himalayan rock mass composed of metamorphosed Granite Gneiss were utilized to calculate the strain energy. During the testing, load was applied in five cycles of 275, 550, 825, 1110 and 1400 kN corresponding to stress of 1.0, 2.0, 3.0, 4.0 and 5.0MPa respectively. The energy values of PLT-1 to PLT-4 have been calculated and presented in the Table 1. The total strain energy transmitted to the rock mass when the external force is applied (U_o in Joules) and recovered elastic energy (U_e in Joules) were calculated by calculating area under Load-Deformation curve shown in Fig. 4(a) to 4(d) respectively for each cycle of loading and unloading as mentioned above. Dissipated energy (U_d in Joules) is difference of U_o and U_e.

TABLE 1

Energy Values of Plate Load Tests 1 To 4

PLT 1					PLT 2				
Stress	Energy (Joule)			Lost %	Stress	Energy (Joule)			Lost %
(MPa)	U_o	U_e	U_d	(U_d/U_o)	(MPa)	U_o	U_e	U_d	(U_d/U_o)
1	135.14	26.64	108.5	80	1	138.09	33.7	104.39	76
2	410.65	94.96	315.69	77	2	461.96	91.63	370.33	80
3	839.5	203.67	635.83	76	3	580.81	186.54	394.27	68
4	1104.89	284.27	820.62	74	4	748.99	370.12	378.87	51
5	1380.74	278.97	1101.77	80	5	876.14	242.09	634.05	72
PLT 3					PLT 4				
Stress	Energy (Joule)			Lost %	Stress	Energy (Joule)			Lost %
(MPa)	U_o	U_e	U_d	(U_d/U_o)	(MPa)	U_o	U_e	U_d	(U_d/U_o)
1	248.09	54.49	193.6	78	1	69.9	14.67	55.23	79
2	780.19	172.46	607.73	78	2	271.54	36.1	235.44	87
3	1236.65	239.76	996.89	81	3	381.71	56.07	325.64	85
4	1712.47	275.12	1437.35	84	4	362.67	73.28	289.39	80
5	1759.13	353.61	1405.52	80	5	859.26	146.07	713.19	83

Average energy values of all four plate load tests at each loading cycle are presented in Table 2 and Energy distribution graph of U_o, U_e and U_d against each stress level is shown in Fig. 7.

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Table 2
Average Energy Values

Average				
Stress	Energy (Joule)			Lost %
(MPa)	U_o	U_e	U_d	(U_d/U_o)
1	148	32	115	78
2	481	99	382	79
3	760	172	588	77
4	982	251	732	74
5	1219	255	964	79

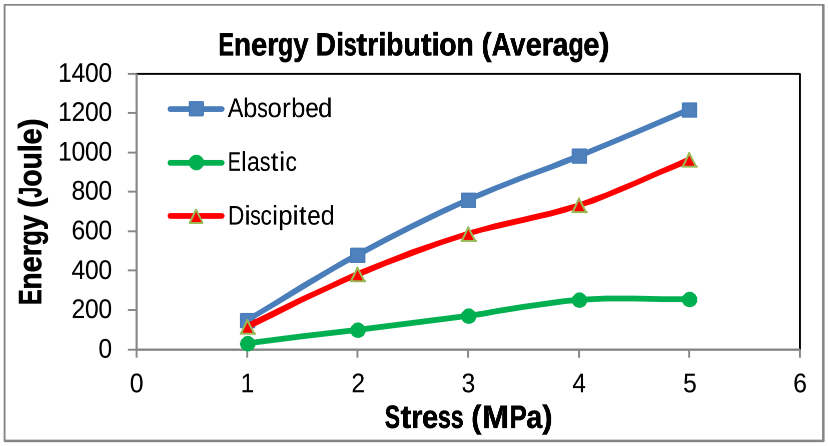

Fig. 7 Energy Distribution curve

Strain energy is a type of potential energy that is stored in a structural member as a result of elastic/ plastic deformation under the application of external load. And, strain energy is a function of load and deformation, so with the increase in load the strain energies are increasing. The amount of strain energy stored/ transmitted to the system at a constant load in the four different PLTs are the function of deformation at different locations. Table 1, Table 2 and Fig. 7 infers that 70 to 80% of strain energy transmitted to the system had been lost/ dissipated which is unidirectional and irreversible and had results in internal damage and plastic deformation in the rock mass. And, 20 to 30% of strain energy transmitted to the system was elastic strain energy which is bidirectional and reversible, and was related to intrinsic property of rock, mainly Elastic Modulus and Poisson's Ratio. Fig. 7 infers that the elastic rebound energy is becoming constant after fourth cycle, i.e., at 4 and 5MPa cycles. However, not conclusive, there may be remote chances that the elastic deformation beyond the same may turn out to be same/ similar.

V. CONCLUSIONS

From the presented cases, it is found that 70 to 80% of strain energy transmitted to the system is lost/ dissipated which was unidirectional and irreversible and resulted in internal damage and plastic deformation in the rock mass. 20 to 30% of strain energy transmitted to the system was elastic strain energy which was bidirectional and reversible, and was related to intrinsic property of rock, mainly Elastic Modulus and Poisson's Ratio. However, the percentages stated here are rock variant and location specific. Further, energy analysis methods can be employed for the assessment of deformability characteristics of rock mass. The evaluation of dissipated energy method takes complete stress-deformation behaviour of rock mass into consideration. Hence, the energy analysis method can be considered more realistic than that of the evaluation procedure established by the standards.

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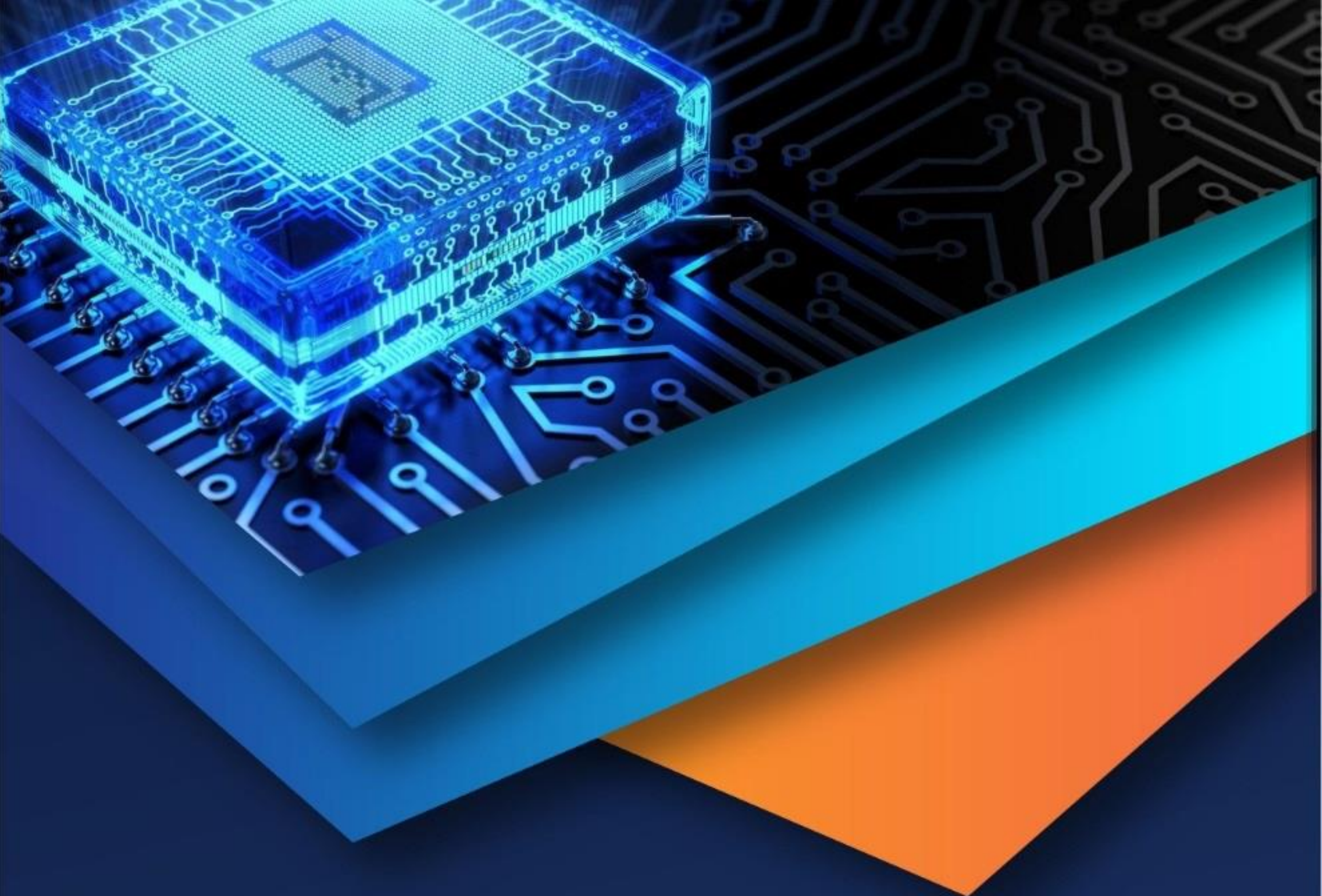

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