Data-driven structural assessment of variable-inclination diagrid systems under lateral loading

Geetha L[1], *Ambika* Valmiki K S[1], *Shivanand* C G[2*], *Nayana* B S[2], *Kavya* S Kallimani[2], *Rakesh* Kumar[3]

[1]Department of Civil Engineering, Dayananda Sagar College of Engineering, Bengaluru, 560111 Karnataka, India.
[2]Department of Civil Engineering, The Oxford College of Engineering, Bengaluru, 560068 Karnataka, India.
[3]Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand.

Abstract. Technological advancements, changes in people's lifestyles, and the needs of the current population have all contributed to the construction of tall structures. Current trends indicate that the geometrical configuration of the diagrid structural system to be used for high-rise buildings provides aesthetic potential and structural efficiency. Buildings in seismically active places must be constructed with consideration for their lateral stability during severe earthquakes. Many lateral load resisting systems are classified as interior and exterior structures, such as diagrid, hexa-grid or mega frame systems, which are provided at the outer periphery of buildings they come under exterior structures. Normal bracing systems will be uneconomical if the number of storeys is more than 25; hence, a new grid system has been developed, i.e. the diagrid system. Compared to other methods, diagrids are aesthetically more pleasant and provide better rigidity to structures. Here, analysis of a normal framing system without any load resisting system, diagrids with different diagonal angles and a conventional system will be conducted by using analysis and design software, Extended Three-Dimensional analysis of building systems (ETABS V22.5.0). A typical square floor layout of 36mx36m is considered, and all structural parts are developed according to IS 456-2000. Wind and earthquake parameters are considered from IS875-2015 (part III) and IS1893-2016, respectively. The analytical results are contrasted in terms of base shear, storey drift, time history, and storey displacement.

1 Introduction

The scarcity of free land, rising costs, and urbanization have led engineers to design vertical cities. To achieve vertical development, buildings must be constructed as high as feasible. It

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[*] Corresponding Author: shivanand.ghule@gmail.com

is the responsibility of a structural designer to ensure that the desired building stands and remains stable during its life. The construction of tall buildings is increasing day by day, so safe analysis and construction are required.

Construction of tall buildings is not as easy as that of normal conventional buildings due to the lateral loads, lateral displacement will induce bending, and shear lag effects will be more, so that in order to resist lateral loads, new systems were invented, known as lateral load resisting systems [1]. The most common issue governing the design of a tall structure is the building's drift, rather than its fully stressed rate. The load-resisting systems become more important than the structural system withstanding gravitational stresses as the building's height increases [5]. Diagrid is gaining popularity among artistic and structural developers of tall structures due to its reliability and aesthetic appearance. Diagrid buildings from traditional exterior braced frame construction as they eliminate moist vertical columns [6]. They don't require high shear stiffness cores, as shear can be carried by diagrids situated on the perimeter. A diagrid structure is formed as a vertical cantilever beam on the ground that has been divided into modules along its height based on the diagrid pattern. One module is defined as a single floor of diagrids that spans many storeys. Application of soft computing machine learning techniques for the result validation is a reliable practice [11].

1.1 Diagrid Component

These are made up of joined nodes, which contribute to structural stability [8]. They are:

- Nodes: These are the joints that connect all members. Members can be joined to a gusset plate through bolting or welding at their ends. It can be hinged or fixed.
- Diagonal members: Aid in transferring both lateral and gravitational stress through axial action. They can be constructed of steel, concrete, wood or composite materials. The steel diagonal is the most widely utilised.
- Ring beams: Exterior floor beams connect the nodes at floor levels. Ring beams contribute to the nonlinear behaviour of the structure and plastic hinge creation.
- Tie beams: Transport loads from the RC core to the diagrid structure. They can also balance varying forces.
- Core: Primary duty is to support gravity loads and reduce the span of floor beams.

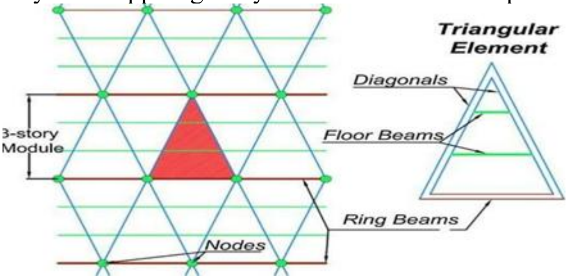

Fig 1. Representation of a 3-storey diagrid module and a triangular element

2 Literature Review

Md. Touseef et al. (2023) [1] studied seismic force behavior on bare frames, braced frames and 4 diagrid frames with varied angles on a 24x24 m symmetric plan. He carried out the design of a G+15- storey structure and constructed 6 models, similar to a bare frame, another that's a braced frame and the other 4 that are varied diagrid angles, using ETABS software. The analysis was done using time period, base shear, time history, and storey displacement as pointers of test results. He concluded that the diagrid angles of 64.88˚ and 57.99 ˚ are displacement and storey drift ratio cases, and the time period is most effective for the diagrid structural system. R. M. Ashwini et al. (2022) [2] investigated diagrid structures on leaning terrain, which were compared to the conventional structures, and they calculated the optimal diagrid angle for different terrain slopes. When comparing diagrid to conventional structures on sloping terrain, a 12-storey structure is utilised, and the best angle for diagrid on sloping land is determined using ETABS software, and a 48-storey structure is used for analysis and modelling. The optimal diagrid angle is 60 to 75 degrees, their exploitation employing the response spectrum method demonstrates that the diagrid structures outperform traditional construction on sloping terrain. The models were tested by altering the diagrid angles. When erected on sloped terrain, a diagrid structure exhibits less lateral displacement and storey drift than conventional structures. A diagrid has a higher base shear and storey stiffness than conventional buildings. Diagrid construction has significantly lower seismic weights than ordinary buildings. Results showed that when the ground has a 15˚ inclination, adopting a diagrid angle of 60.94 degrees helps to reduce both lateral displacement and storey drift. When the slope is increased to 25 degrees, the diagrid angle of 69.67˚ performs better in reducing the same response parameter. The best diagrid angles for sloped terrain are 60.94˚ for a 15˚slope and 69.67˚ for a 25˚slope. S. Babhulkar et al. (2021) [3] compared the design of a 15- storey building (24m x24 m) with the traditional building. They considered three types of models, such as diagrids with two, four and six modules. The results were presented in terms of displacement, shear, and drift. The reaction within limitations such as storey float and storey shear resulted in inclined portions at the exterior of buildings. The composite grid is more efficient at opposing lateral loads on both the inside and outside. Because of the vertical section at the external outskirt of the structure, there is a huge decrease in cement in the diagrid construction, making it more effective. N. B. Panchal et al. (2014) [4] examined the performance of a G+36 diagrid structure during seismic events at different angles. They utilised nonlinear time history and pushover analysis techniques. The impact of the diagrid core on structural behaviour; internal gravity frames are substituted with diagrid frames. Pushover analysis showed that diagrid cores can improve the hardening behaviour of buildings when the angles of perimeter panels are lower or equivalent to those of the core, as opposed to standard diagrid. Using E-tabs software, time history analyses are used to evaluate the storey drift ratio, energy dissipation, and hinge distribution of structures [7]. They concluded that models function well under rare ground distribution, with well-spaced hinges and diagrid structures that can withstand large deformation during seismic activity. Y. Meng et al. (2025) [9] developed a fuzzy control algorithm to evaluate and control the response of high-rise buildings under earthquake loads. The fuzzy model predicted structural responses such as displacement and drift and improved vibration control performance. A. Mangir (2023) [10] developed a Fuzzy Inference System (FIS) to estimate seismic design parameters used in response spectrum analysis. The model evaluates earthquake response parameters that directly influence seismic forces and structural behaviour of buildings.

By providing inclined portions at the external periphery of buildings, the composite diagrid structure is more effective at opposing lateral loads on both the inside and outside. Because of the vertical section at the external outskirt of the structure, there is a huge decrease in cement in the diagrid construction, making it more effective. Hybrid diagrid systems (combining diagrid with tubular core or bracing) further improve drift control and stiffness in tall buildings. The optimal diagrid angle for best performance commonly lies between 60° and 75°, with angles around 63° to 70° being most effective. The triangular configuration of diagrids provides greater lateral stiffness and effectively resists seismic and wind loads. Diagrid buildings generally show lower storey drift, reduced lateral displacement, and higher rigidity compared to conventional frames. Material usage and structural weight are significantly reduced. Recent studies have demonstrated the applicability of fuzzy logic in predicting seismic responses of tall buildings subjected to lateral loads. Attempts will be made to predict the diagrid configuration for tall buildings.

3 Methodology

The methodology used in this research study involves a well-defined, structured process. First, a full literature survey was undertaken to identify research gaps in existing studies as well as suitable approaches that could be used. Following that, a design for the building was selected based on the results of the literature survey. This selection was followed by the development of detailed structural models of the selected building. After completion of the detailed structural models, these were subjected to finite element analysis using the ETABS software package. Results from these analyses were extracted and organised so they could be compared across all parameters of interest. Lastly, the results of the structural performance comparisons were verified using a fuzzy inference system in order to ensure that the results would be reliable and robust.

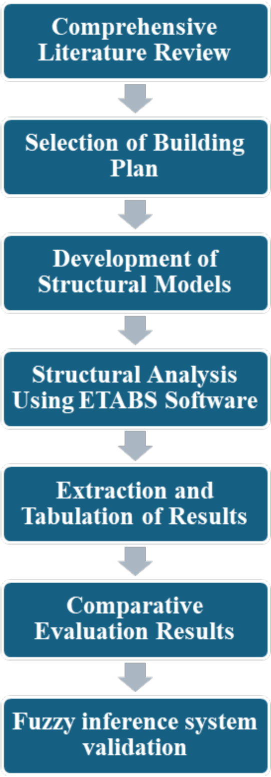

Fig 2. Methodology of the study

4 Model Specification

Analysis of 30-storey RC buildings with and without diagrid systems is carried out using ETABS software. Diagonal members are assumed as a beam with fixed conditions at both ends. Columns and beams are arranged in two-node elements with 6 degrees of freedom at each node. Indian standard codes (IS456-2000, IS 875-2015 and IS-1893-2016) are used for the analysis. Parameters such as storey shear, base shear, maximum storey displacement and maximum inter-storey drift are tabulated for each model for all cases studied.

The details of models were, Plan dimensions = 36 m x 36 m, Number of storeys =30, Floor to floor height = 3 m, Depth of slab =120 mm, Number of bays in X-direction = 9, Number of bays in Y-direction = 9, Beam dimensions: B1 – 250mm x 450mm, B2 – 300mm x 600mm, Column dimensions: C1 - 1000mmx1000mm (Exterior columns), C2 – 900mm x 900mm (Interior columns), Live load = 3.5 kN/m^2, Floor finish = 1.5 kN/m^2, Live load on roof =1.75 kN/m^2, Floor finish on roof = 2.5 kN/m^2, Seismic parameters: Location: Amritsar, Zone IV, Importance factor: 1.0, Response reduction factor: 5, Wind parameters: Wind speed, Vb: 47 m/s, Terrain category: 3, Class B. M40 Concrete, Fe-415 grade reinforcing steel was used for the model.

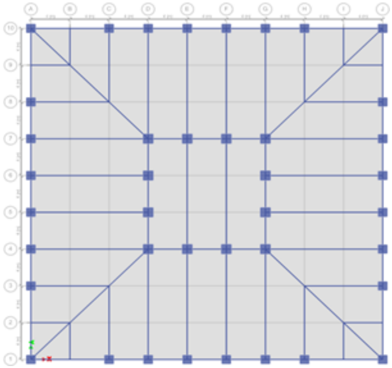

Fig 3. Plan View of linear system

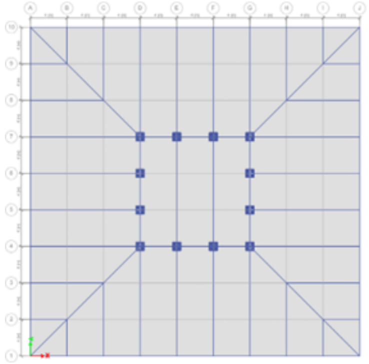

Fig 4. Plan view for all diagrid systems

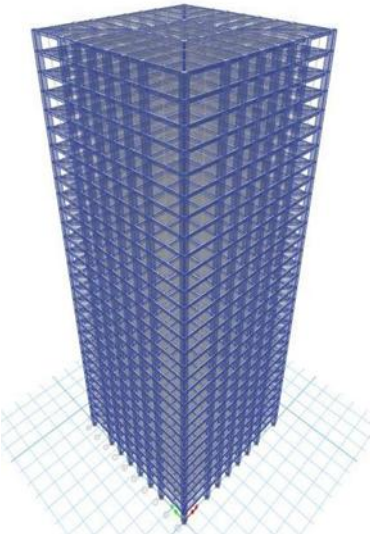

Fig 5. 3D View of linear system

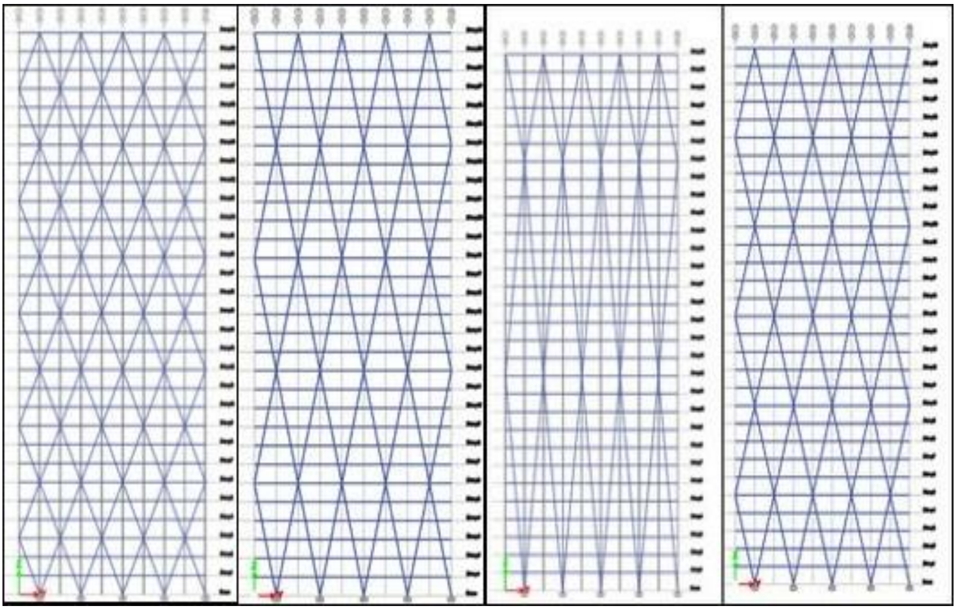

Fig 6. Elevation of the diagrid structural system showing varying diagonal angles: 66.06° (M1), 77.47° (M2), 83.65° (M3), and 75.06° (M4).

5 Results of Analysis

Table 1. Maximum and minimum displacement and drift values due to earthquake, wind and response spectrum cases

Model		**Displacement (mm)**		**Drift**	
		Maximum	Minimum	Maximum	Minimum
Regular Structure	Earthquake Load	300.079	2.777	0.004506	0.000926
	Wind Load	172.838	2.15	0.0031	0.00048
	Response Spectrum	234.217	2.664	0.03857	0.000888
M1	Earthquake Load	75.174	0.97	0.00101	0.000323
	Wind Load	53.597	0.983	0.000729	0.000328
	Response Spectrum	51.863	0.912	0.000717	0.000304
M2	Earthquake Load	116.145	1.833	0.001727	0.000518
	Wind Load	85.047	1.939	0.001509	0.000313
	Response Spectrum	86.024	1.03	0.001520	0.000373
M3	Earthquake Load	187.985	3.385	0.00336	0.00046
	Wind Load	139.941	3.532	0.002479	0.000276
	Response Spectrum	146.769	3.456	0.002776	0.000347
M4	Earthquake Load	100.693	1.521	0.001432	0.000507
	Wind Load	73.349	1.60	0.001113	0.000335
	Response Spectrum	73.65	1.562	0.001137	0.000397

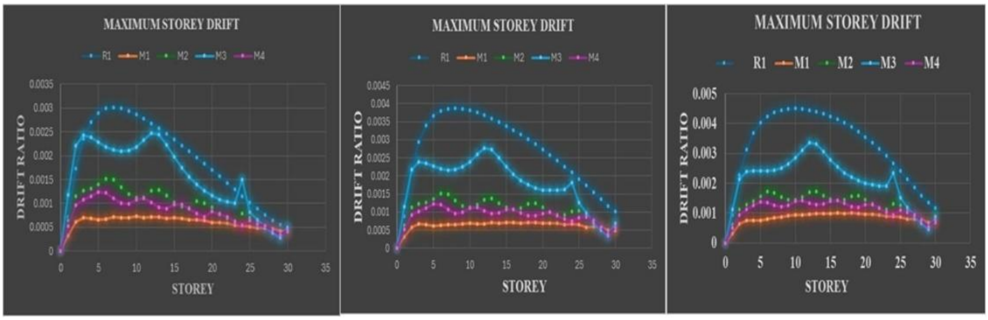

Fig 7. Inter-storey drift ratio of different diagrid systems under response spectrum, earthquake load, and wind load cases.

The inter-storey drift responses for different structural configurations under response spectrum, earthquake, and wind load cases are illustrated in Table 1 and Figure 7. It is observed that the conventional structural system without a dedicated lateral load-resisting mechanism exhibits the highest storey drift values. Among the diagrid configurations considered, the model with a 66° diagonal angle (M1) demonstrates comparatively higher drift values than the other diagrid models. In contrast, the diagrid systems with 66.03° (M1) and 75.06° (M4) diagonal angles exhibit lower drift responses, indicating improved lateral stiffness and enhanced structural performance. Furthermore, the configuration with a 63.65° diagonal angle (M2) shows the highest drift values among the diagrid models, particularly under the response spectrum load case, whereas models M1 (66.03°) and M4 (75.06°) demonstrate comparatively better performance.

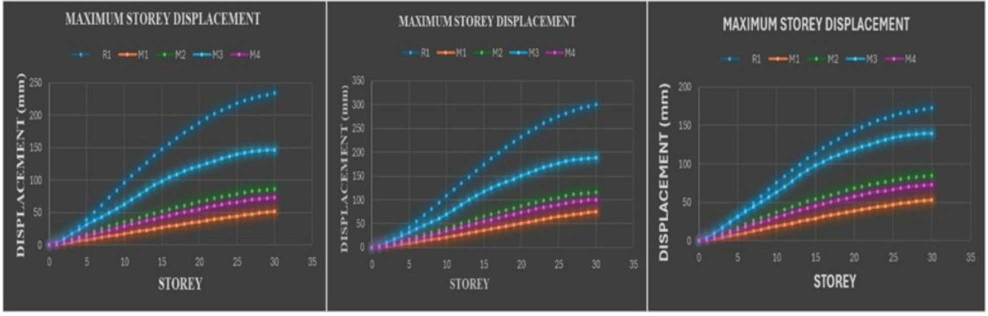

Fig 8. Storey displacement of different grid systems under response spectrum, earthquake load, and wind load cases.

The difference in maximum storey displacement for each structural type during response spectrum, earthquake, and wind load conditions is illustrated in Table 1 and Figure 8. Clearly, the conventional framed structure with no dedicated lateral load resisting system has the largest maximum displacement for all loading conditions.

Diagrid configurations illustrate that the model with an angle of 66.06° (M1) produces the least amount of storey displacement; thus, providing superior lateral stiffness and improved structural performance. Diagrid Models with an angle of 75.06° (M4) and 77.47° (M2) produce relatively low top-storey displacements, as compared to the conventional structure. Conversely, the diagrid Model with an angle of 83.65° (M3) shows greater than average displacement for all diagrid models examined, yet less than that for the conventional framed structure. The results clearly demonstrate that diagrid structures exhibit significant reductions in storey displacement relative to traditional buildings. As expected, the configuration with an angle of 66.06° (M1) demonstrated the best overall performance, exhibiting a maximum displacement reduction of approximately 78% with the smallest maximum top-storey displacement of 51.863 mm.

Table 2. Comparative Drift Ratio and Displacement of Structural Models under Response Spectrum Analysis

Modals	Drift ratio	Displacement in mm	Percentage reduction in displacement
Regular Structure	0.001015	234.217	-
M1	0.000491	51.863	78%
M2	0.00067	86.024	63.27%
M3	0.000969	146.769	37.33%

M4	0.000576	91.92	60.75%

Table 2 illustrates how the displacement values and drift ratios compare across the different load cases using response spectra. Of all the frame types used in this study, the conventional frame type has the largest displacement value of 234.217 mm and the largest drift ratio value of 0.001015. When comparing the four diagrid configurations used in this study (M1 - 66.06° diagonal; M2 - 30° diagonal; M3 - 45° diagonal; M4 - 90° diagonal), Model M1 has the least amount of displacement (51.863 mm) and is also the model with the least drift ratio (0.000491). Model M1 has a displacement reduction of approximately 78% when compared to the regular frame type. Models M2 and M4 have both significant improvements when compared to the regular frame type, with displacement reductions of approximately 63.27% and 60.75%, respectively. However, Model M3 has a larger displacement than the other three diagrid configurations. Overall, the data indicate that the diagrid structural system provides greater lateral stiffness and less structural displacement when compared to the other structural systems. In addition, the results indicate that the 66.06° diagonal configuration of the diagrid structural system provides the best performance.

6 Fuzzy Logic-Based Validation of ETABS Results

To verify the structural response resulting from the ETABS analysis, a fuzzy inference framework was used. Fuzzy logic can effectively model nonlinear and uncertain relationships between structural parameters, which do not need an explicit formulation by means of mathematical equations. In the above research, fuzzy models have been developed with respect to different membership functions (MFs) such as triangular, trapezoidal and Gaussian. The fuzzy model has to produce the same structural response as that produced by ETABS, and therefore, to verify the consistency of the results. The structural response considered as the input variables are the diagrid angle values, whereas the maximum displacements and the storey drifts represent the output variables.

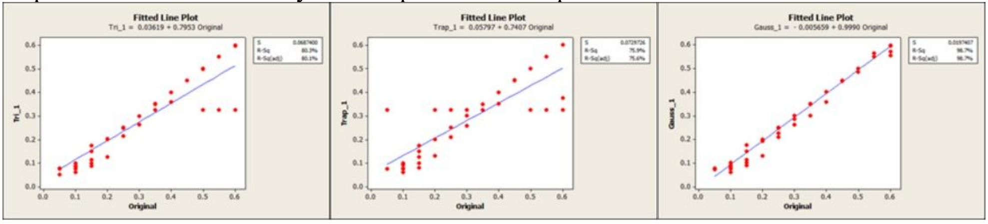

Fig 9. Regression plots for Original and Fuzzy Triangular, Trapezoidal and Gaussian Model Displacement

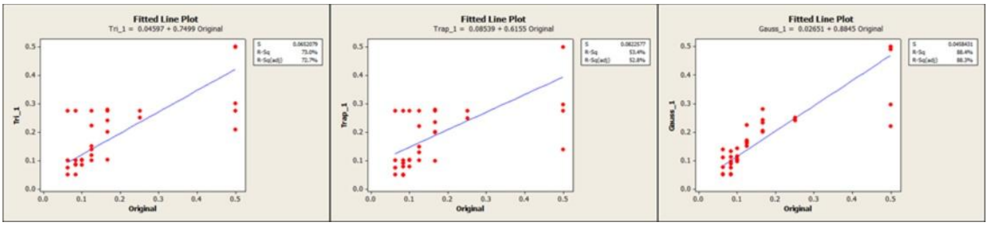

Fig 10. Regression plots for Original and Fuzzy Triangular, Trapezoidal and Gaussian Model Storey drift

The prediction quality of the Fuzzy Inference System (FIS), proposed in this study, was assessed through performing linear regression analyses with respect to the benchmark results from the ETABS FEA. As illustrated in Figures 9 and 10, the Correlation between Displacement and storey drift was determined using three different membership functions (MF). The statistical measures of S2 and R2 are presented in each plot as evidence that the FIS accurately maps the relationships between the input variables and structural demand. Additionally, the high R2 values associated with all models indicate that the fuzzy approach could be used as an accurate, computationally inexpensive alternative to time-consuming FEA during preliminary design phases.

7 Conclusion

Diagrid configurations at angles of 66.06° (M1), 77.47° (M2), 75.06° (M4), and 83.65° (M3) were evaluated for structural performance in comparison to a traditional structural system. A key finding was that M1, the 66.06° diagrid configuration, had the lowest values of storey drift and displacement and therefore exhibited the highest level of structural performance. The findings from this research indicated that diagrid angles in the range of 66°-75° provided the most effective way to minimise both displacement and storey drift. The findings also show that M3, the 83.65° diagrid configuration, has the greatest amount of displacement when compared to the other two diagrid configurations. Additionally, it was found that the structural system without the use of diagrids resulted in greater amounts of both storey displacement and drift than all the structural systems using diagrids. A reduction of 78% (M1), 63.27% (M2), 68.55% (M4), and 37.33% (M3) in displacement under response spectrum analysis, as compared to the traditional structural system, was observed. As a result of the transfer of load via diagonal elements of the structure, the primary function of the interior columns in diagrid systems is to resist gravity forces, which allows for improved structural efficiency. Fuzzy inference models demonstrated a high degree of correlation to the ETABS results. Therefore, it was shown that fuzzy logic can be used to predict the structural response (displacement and storey drift) of diagrid systems.

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