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RESPONSE OF BUCKLING RESTRAINED BRACED-DIAGRID STRUCTURE

Soham S. Patil, PG Student, Department of Civil Engineering, AISSMS College of Engineering, Pune, India.
Manisha V. Waghmare, Assistant Professor, Department of Civil Engineering, AISSMS College of Engineering, Pune, India.

Abstract
This study investigates the seismic performance of Steel-Diagrid and BRB-Diagrid structures. In high seismic zones, strong lateral framing systems are crucial to withstand seismic forces. The lateral load resistance can be provided by either interior or exterior structural systems. While the Diagrid resists the lateral load by axial action of diagonal member provided on the periphery of the structure and the BRB structural system resists lateral load due to their significant ductility and energy dissipation capacity. Despite their individual merits, there's a lack of research on combining BRB and diagrid structures. The main objective of the present study is to investigate the seismic performance of Steel-Diagrid and BRB-Diagrid structures. For this work, comparative time history analysis has been carried out for five different earthquake ground motions between framed, steel-diagrid, and BRB-diagrid structural systems, each consisting of 20 storeys (total 18 models). The design of BRB has been carried out using AISC 341-05. Modelling and analysis have been carried out using commercial software ETABS 2016. The comparative analyses of the results are presented. The structural stability of diagrid structures increases significantly when diagonal columns are replaced by BRB members.

Keywords: Diagrid structural system, Buckling Restrained Braces (BRB), Time History Analysis, AISC 341-05.

I. Introduction
Diagrid structures are a type of structural framework composed of beams that intersect in a diagonal pattern, forming a grid-like pattern of diagonals. They are used in the design of high-rise buildings and roofs due to their structural effectiveness and architectural aesthetics. The diagonal members in diagrid structures act both as inclined columns and as bracing elements, carrying gravity loads as well as lateral forces, and minimizing shear racking effects. The BRB structural system, or buckling restrained braced frames, is a seismic load resisting system composed of beams, columns, and buckling restrained braces (BRBs). Unlike conventional braces, BRBs can yield under both tension and compression without buckling, leading to symmetrical hysteresis behaviour.
Over the past two decades, diagrid and BRBFs have grown in popularity as a primary seismic force-resisting system (SFRS) and are now used extensively in new construction and retrofit applications due to their economy, design simplicity and that provides significant stiffness and ductility. There have been many studies done to confirm the behavior and performance of the diagrid and BRB structural system.

II. Literature
Liu et al. (2023) [3] conducted a study on diagrid core-tube structures, examining how variations in stiffness ratio and diagonal angle impact seismic performance. Their findings showed significant changes in floor shear force redistribution, decreased storey shear coefficient with increased earthquake intensity and stiffness ratio. They identified 77° diagonal angle and 0.64 stiffness ratio as optimal for structural ductility, noting an increase in overstrength factor with stiffness ratio. **Heshmati et al. (2022)** [4] proposed the use of Hybrid Buckling Restrained Braces (HBRBs) in diagrid structures to improve seismic resilience. Through numerical simulations, they demonstrated that integrating HBRBs enhanced ductility, over-strength, collapse safety, and self-centering capacity, providing valuable insights for selecting optimal HBRB configurations.

Ashtari et al. (2021) introduced a fuzzy-genetic algorithm approach to optimize geometrical patterns and structural weight of tall buildings with diagrid systems. They achieved up to 33% reduction in structural weight while improving seismic response, offering insights for enhancing diagrid structure design and seismic performance.

Sadeghi et al. (2020) [6] investigated the seismic performance of diagrid structures enhanced with buckling restrained braces (BRBs). They found improved seismic performance due to plastic damage accumulation in BRBs, with higher response modification factors and ductility ratios compared to original diagrid models.

Nayak et al. (2020) [8] compared diagrid and braced tube systems for tall buildings, emphasizing the unique advantages of diagrid structures. Their earthquake and wind analyses highlighted the superior structural efficiency and architectural benefits of diagrids.

Rujhan et al. (2020) [7] analyzed and designed a diagrid structural system for a 48-story building, focusing on parameters like lateral stiffness, displacement, and load distribution. They utilized manual calculations and software tools to ensure static and dynamic control.

Tirkey et al. (2019) [9] conducted a case study on diagrid structures, demonstrating their superiority over conventional buildings in seismic and wind analyses. They showcased the innovation of diagrids in tall building construction, offering increased stiffness and lighter weight.

Mele et al. (2014) [16] provided an overview of diagrid structures, highlighting their aesthetic quality and structural efficiency. They discussed resisting mechanisms under gravity and wind loads, recent research on geometry's impact, and recommended concrete-filled steel tube columns for improved seismic performance.

Jani et al. (2013) [18] also discussed the aesthetic and structural merits of diagrid structures, along with recommendations for seismic performance enhancement using concrete-filled steel tube columns and buckling restrained braces.

Moon et al. (2011) [21] examined the growing use of diagrid systems for tall buildings and proposed a stiffness-based preliminary design methodology. They provided design guidelines based on storey heights and diagonal configurations to optimize diagrid structures within specific height ranges.

It is found from the literature survey that diagrid and BRB structural system are proven to be more effective in increasing the seismic performance of the structure than the conventional braced system under effect of lateral load. Numbers of studies are available on different geometrical configurations (angle variation) of diagrid structural system. There is no record of studies focusing on combination of BRB and diagrid structure so far. Hence, use of BRBs as diagonal columns in Diagrid structural system with angle variation will be studied in the present research.

III. Objectives of the Study

The primary objective of this research is to investigate the seismic performance of the BRB-Diagrid and Steel-Diagrid structures.

IV. Building Parameters

The present study is to evaluate the comparative analysis of conventional, diagrid and BRB-diagrid structural system. All building parameters are presented in Table 1 and shown in Fig.1. Building parameters are taken from Biradar et al. (2019) [10] except floor to floor height, size of diagrid structure and diagonal angle. The dead load and live load on floor slab are 4 kN/m^2 and 2.5 kN/m^2. Modeling and analysis is carried out using commercial software ETABS 2016.

Table 1: Parameters of Building

Sr. No.	Description	Values
i.	Type of Structure	Composite
ii.	Grade of Steel	A992Fy50
iii.	Grade of Concrete	4000 psi

iv.	Plan Dimension	36 m x 36 m
v.	Floor to Floor Height	3.3 m
vi.	No. of Storeys	10, 20, 30
vii.	Beam Size	W 600
viii.	Column Size	W 475
ix.	Size of Diagrid Member	400 mm x 400 mm x 25 mm
x.	Size of BRB Member	StarBRB 52.0
xi.	Slab Thickness	150 mm
xii.	Diagonal Angle	Upper Storey: 65.56° Lower Storey: 73.14°

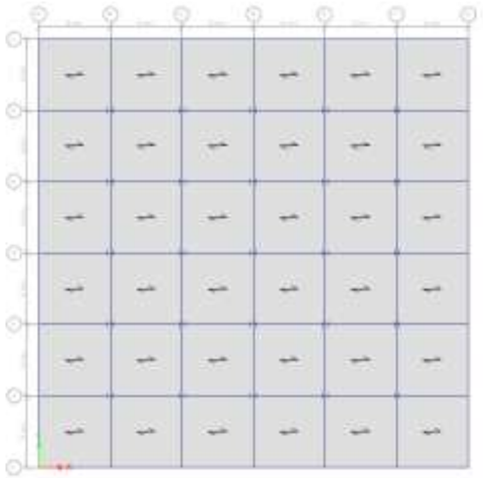

Fig.1. Plan of G+20 story building

Table 2 and Table 3 shows stiffness and fundamental time period of frame, steel-diagrid and BRB-structures. Stiffness of BRB-diagrid is more compared to frame and steel-diagrid structure because of characteristics of BRB element and its connectivity to periphery of the structure. Time period of BRB-Diagrid is less than that of Steel-Diagrid and framed structure. Diagonal members of BRB-diagrid and steel-diagrid structures sustain more lateral forces as compared to framed structure. Generally time period depends on the mass and stiffness of structure, but in this case mass of all structures is almost same, the difference is in time period due to the difference in stiffness of structure. Stiffness of structure is inversely proportional to time period of structure. So, as stiffness increases, time period decreases.

Table 2: Stiffness

	Stiffness (kN/m)
Frame	204094.42
Steel-Diagrid	392723.73
BRB-Diagrid	447804.02

Table 3: Fundamental Time Period

	Fundamental Time Period (s)
Frame	4.34
Steel-Diagrid	1.29
BRB-Diagrid	1.21

V. Slope Variation of Diagrid Structure

Based on the results of the previous study on diagrid structure with uniform and gradually varying angles, an optimal angle range was found. Diagrid structures are designed using the uniform optimal angle for each height approximately as the median angle of changing angles. Lateral stiffness of the diagrid structure is increased and consequently its maximum displacement is reduced. Considering the fact that bending moments increase drastically towards the base and govern the design of the lower portion, while shear forces increase almost linearly and generally govern the upper portion of diagrid structure, it is presumed that the diagonal angles of diagrid should become steeper towards the base. In this study, set of two angles has been considered for analysis. For lower storey angle of 73.14° and for upper storey angle of 65.56° is considered. Fig. 2 shows elevation and 3D view of diagrid structure with angle variation for G+20 buildings.

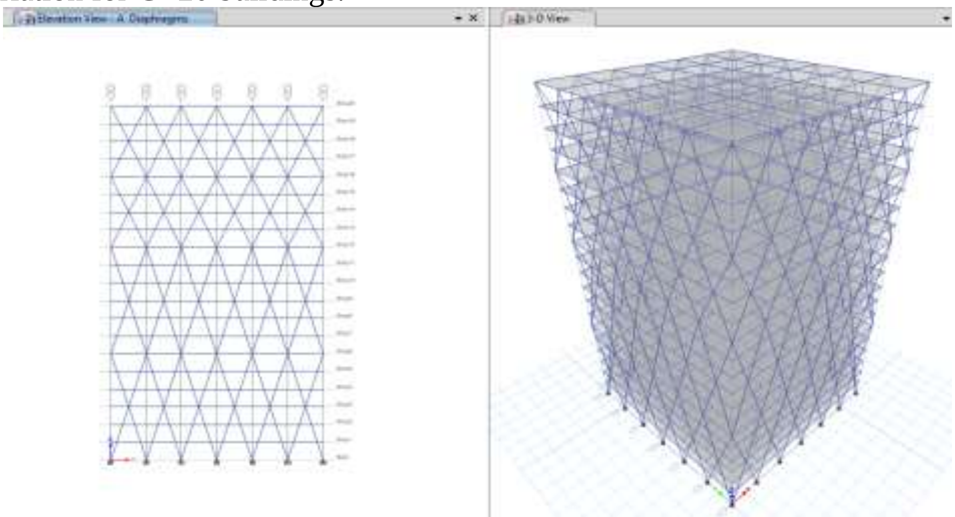

Fig. 2: Elevation and 3D view of G+20 building

VI. Seismic Response of Structure

Linear Time History Analysis was performed on G+20 frame, steel-diagrid and BRB-diagrid structures. Ground motion data for time history analysis is obtained from Earthquake Engineering Research Institute (EERI), California and presented in Table 4.

Table 4: Ground motion Characteristics

Sr. No.	Earthquake	Station	Magnitude	PGA (m/s²)
i.	North-East India (1986)	Ummoalong	4.5	0.62
ii.	India-Bangladesh Border (1988)	Dauki	5.8	0.37
iii.	India-Burma Border (1988)	Lisong	7.2	2.20
iv.	Uttarkashi (1991)	Batwari	7.0	2.42
v.	Chamoli (1999)	Gopeshwari	6.6	1.95

In this section, seismic response of BRB-Diagrid and Steel-Diagrid structures is presented in terms of acceleration-time graph, storey displacement and storey drift.

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a. Acceleration-Time Graph

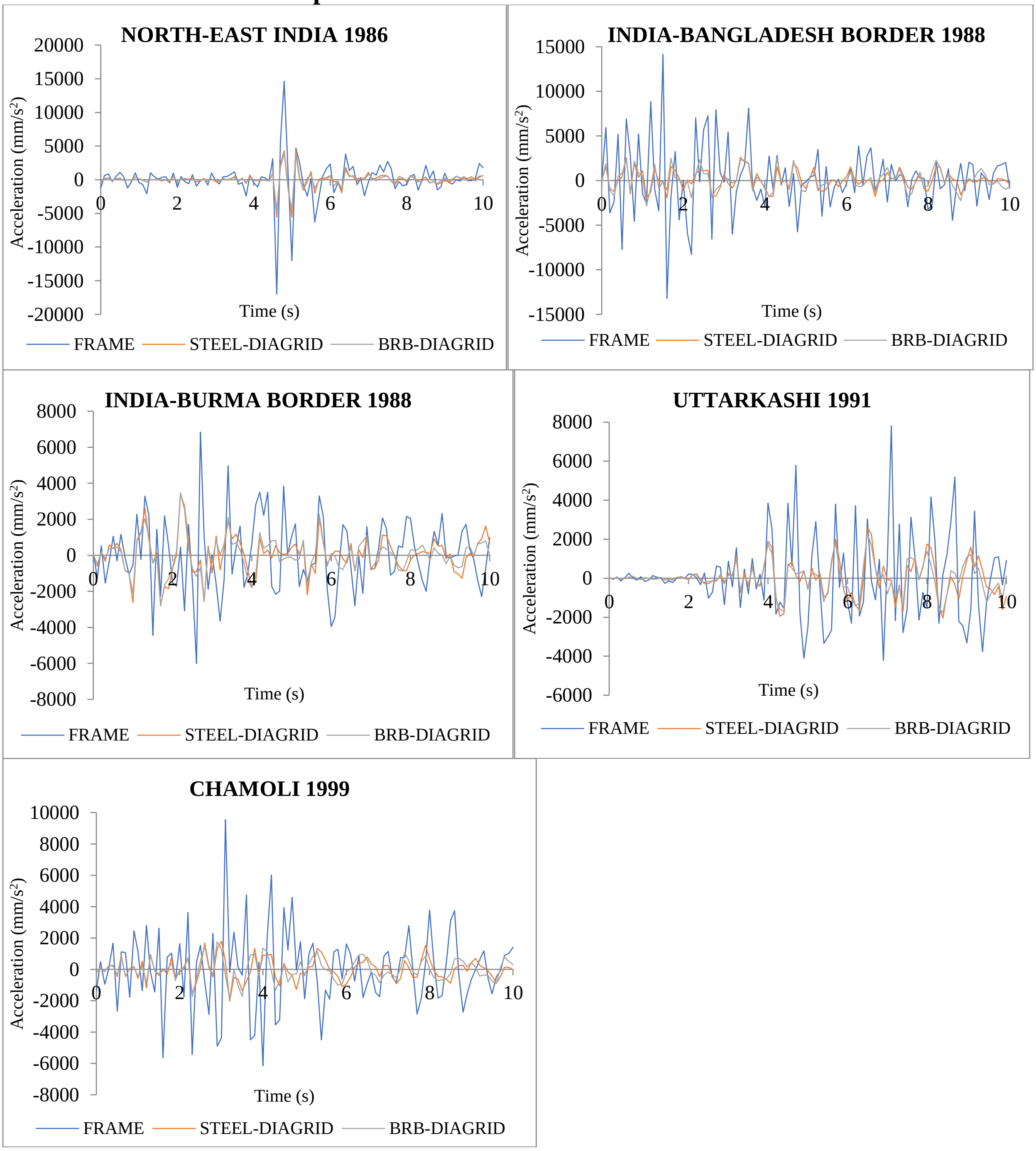

Fig. 3: Acceleration-Time Graph

As shown in Fig. 3, acceleration of frame structure is more than that of steel-diagrid and BRB-diagrid structures. BRB-diagrid structure experiences less acceleration because of the presence of diagonal bracing which provides enhanced lateral stiffness and resistance to lateral loads.

b. Storey Displacement

Table 5: Storey Displacement (mm)

	Frame	Steel-Diagrid	% Diff.	BRB-Diagrid	% Diff.
North-East India (1986)	202.72	39.895	80	37.911	81

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India-Bangladesh Border (1988)	122.819	20.759	83	17.639	86
India-Burma Border (1988)	316.538	53.782	83	48.669	85
Uttarkashi (1991)	327.203	56.324	83	49.899	85
Chamoli (1999)	254.119	49.968	80	47.444	81

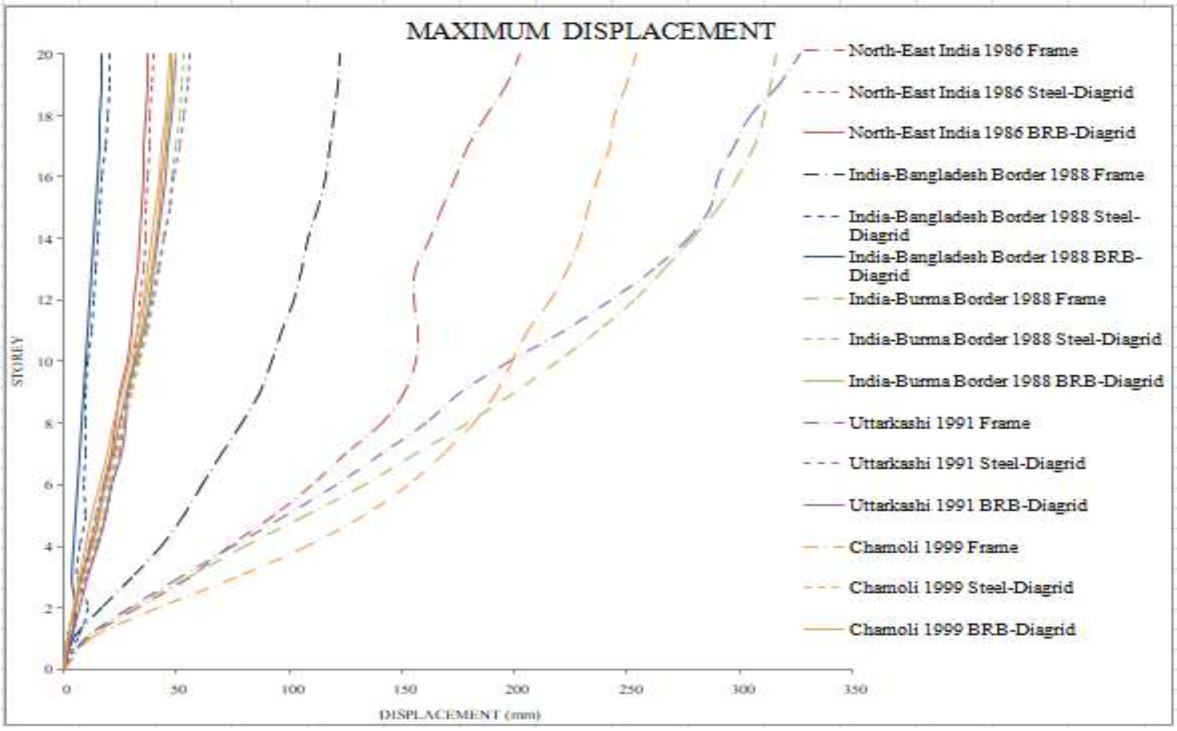

Fig. 4: Storey Displacement

As shown in Table 5 and Fig. 4, displacement of BRB-Diagrid structure is less than that of Steel-Diagrid and framed structure. Displacement of BRB-diagrid structure reduces up to 84% and for steel-diagrid structure up to 81% when compared with frame structure. Response of BRB-diagrid structure is best as compared with frame and steel-diagrid structure because of triangulation provided by diagonal columns and property of BRB to dissipate energy which helps resist lateral forces in turn increasing stiffness. This increased stiffness reduces displacement of the structure.

c. Storey Drift

Table 6: Storey Drift

	FRAME	STEEL-DIAGRID	% DIFF.	BRB-DIAGRID	% DIFF.
North-East India (1986)	0.00729	0.001553	79	0.001312	82
India-Bangladesh Border (1988)	0.00422	0.001276	70	0.001224	71
India-Burma Border (1988)	0.00885	0.001674	82	0.001658	81
Uttarkashi (1991)	0.01084	0.00205	81	0.001735	84
Chamoli (1999)	0.00822	0.001674	80	0.001308	84

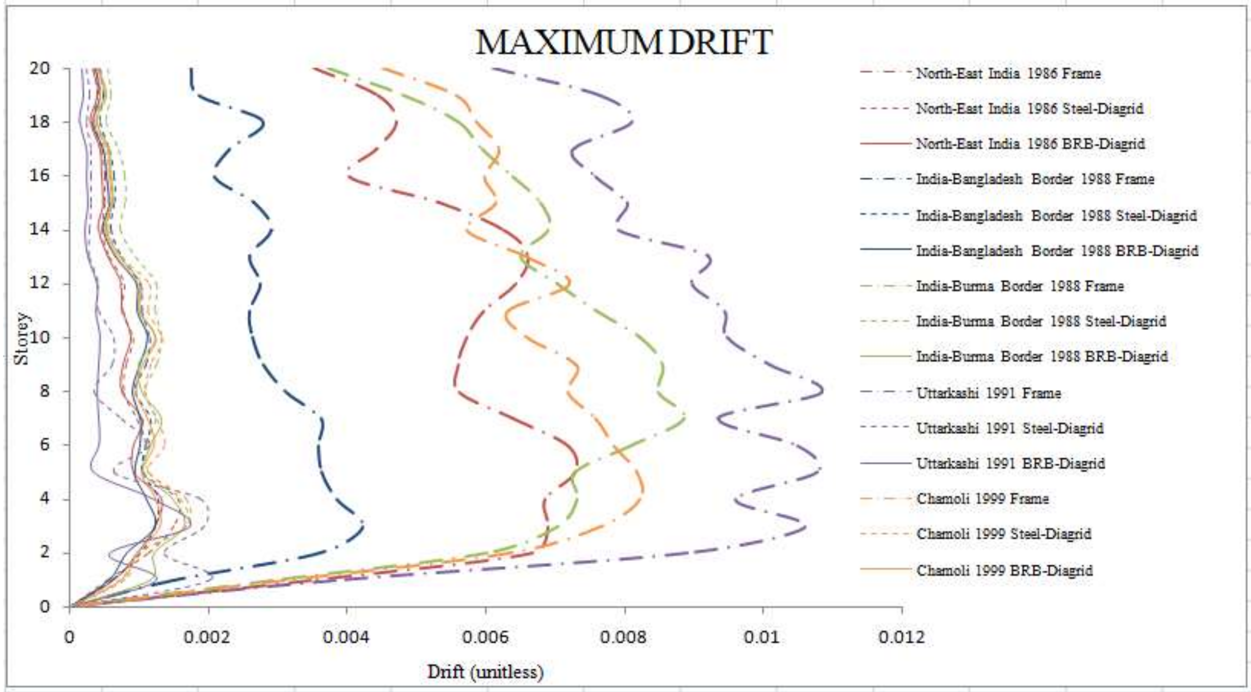

Fig. 5: Storey Drift

As shown in Table 6 and Fig. 5, storey drift of BRB-Diagrid structure is less than that of Steel-Diagrid and framed structure. Drift of BRB-diagrid structure reduces up to 80% and for steel-diagrid structure up to 78% when compared with frame structure. Response of BRB-diagrid structure is best as compared with frame and steel-diagrid structure because of triangulation provided by diagonal columns and property of BRB to dissipate energy which helps resist lateral forces in turn increasing stiffness. This increased stiffness reduces drift of the structure.

VIII. Conclusion

This study aims to investigate seismic response of Buckling Restrained Braced-Diagrid Structure. Through time-history analyses, it evaluates key structural responses like acceleration, displacement and drift for frame, steel-diagrid and BRB-diagrid structures. Additionally, the study investigates the effect of diagonal columns on the seismic performance of Steel-Diagrid and BRB-Diagrid structures. The conclusions drawn from the findings outlined in this research are as follows:

1. The analysis reveals that BRB-diagrid structures exhibit lower displacement, storey drift, and higher base shear compared to frame and steel-diagrid structures due to enhanced lateral stiffness from diagonal bracing and energy dissipation properties of BRB.
2. Storey Displacement of BRB-diagrid structure reduces by 84% and that of steel-diagrid structure reduces by 81% compared to frame structure. Storey Drift of BRB-diagrid structure reduces by 80% and that of steel-diagrid reduces by 78% compared to frame structure.

In summary, the research emphasizes the significance of Buckling-Restrained Braces (BRB) in reducing seismic effects on diagrid structures.

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