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Increasing the seismic resistance of diagrid structures using buckling restrained braces as secondary bracings in different arrangements as per IS 1893:2016

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Abstract— *Diagrid structural system is a recently developed system for high-rise buildings. In this system, inclined columns take up both axial and lateral loads, eliminating the perimeter columns and reducing the consumption of structural steel and providing efficient structural performance with excellent architectural flexibility and sustainability. However, recent studies on this system reported insufficient energy dissipation capacity and inadequate ductility. This limited ductility and energy dissipation capacity become critical under solid ground motion. As the primary diagonal members carry gravity and lateral loads besides higher stiffness, these diagonal members lose elasticity at certain deformations and start yielding resulting in inadequate strength, leading to global collapse. In this study, buckling restrained secondary braces are used to increase the seismic performance of the Diagrid structure. In the Buckling restrained braced system, the BRBs brace is restrained, and strength in compression and tension will remain unaffected. The core material in BRB is made of low yield steel-consuming high seismic energy while undergoing large plastic deformations simplifying the hysteretic property and ultimately increasing the energy dissipation capacity. 50 story high regular, C and L-shaped Diagrid buildings located in seismic zone 5 with different arrangements of BRBS as secondary braces were analysed using the response Spectrum Method in ETABS software as per IS 1893:2016. The results showed that secondary bracings of BRBs in X-arrangement significantly improved the seismic performance of the Diagrid structure, reducing the time period by 10%, displacement by 25% and maximum story drift by 20%.*

Keywords—*Buckling restrained brace, Diagrid, Dynamic analysis, ETABS, Sustainability.*

I. INTRODUCTION

The fast improvement of urban communities adds to an expansion in the metropolitan populace, and with the restricted land accessible, there is a need to develop tall structures. The prominent force that influences the design of tall buildings is the lateral load, primarily due to earthquakes and wind. Advances in primary designing, development techniques, accessibility of superior materials, and computational programming make designing complex-shaped tall structures conceivable. The design code provisions emphasise increasing the structure ductility. Thus, ductility and higher energy dissipation for earthquake-prone zones are necessary for tall buildings. Bracings in tall buildings are accepted worldwide because of their excellent aesthetics and lateral load-distributing capabilities. Many skyscrapers and their structural system install concentric, x- shaped, k-shaped and eccentric bracings. Recently advantages of bracings have been utilised, and diagonals are provided on the perimeter. In a Diagrid structure, the load is distributed by the members by the triangular configurations created by diagonal members combined with beams throughout the height. The load transfer mechanism of the Diagrid structure is axial conduct. The diagonals transfer gravity and horizontal load, increasing shear carrying capacity, flexural rigidity, and making the building more redundant.

Along with the better load transfer mechanism Diagrid, the structural system gives excellent architectural flexibility such as perfect commodity, firmness, and delight. The Diagrid structure also utilises less structural steel than framed structures. According to the repetitive diagrid pattern, the Diagrid structure is modelled as a cantilever beam on the base and segmented heightwise into modules. The number of stories defines this module size.

A. Diagrid structure as Sustainable structural system

Abbaspoor and Behjo [1] studied that the particulate matter (PM) and CO concentrations near the tall buildings and found significant pollution besides the building due to winds and eddy currents. There is a need to have more green vertical spaces and construct sustainable tall buildings. The sky gardens efficiently reduce pollution and energy. The temperature is maintained, i.e. colder in summer and warmer in winters, by absorbing the heat. The sustainability of a structural system for buildings can be assessed using life cycle assessments tools (LCA). The Diagrid structural system is a sustainable structural system having higher lateral stiffness. In this system, inclined columns take up both axial and lateral loads, eliminating the perimeter columns reducing the consumption of structural steel by 20% and energy by 25%, and significantly reducing overall carbon emissions compared to the conventional system [2]–[4]. This system also makes the accessibility of more open space inside the building. The sky gardens can be efficiently allocated in the Diagrid structures, reducing energy and improving sustainability. For encouraging green buildings and sustainable designs, the US council has established Leadership in Energy and environmental design (LEED). The LEED grants rating to the buildings on sustainability. The Hearst tower located in Newyork has been constructed using a diagrid structural system. This tower has obtained a gold rating from LEED for its sustainable design.

II. LITERATURE REVIEW

The preliminary sizes for diagonal members are calculated based on the stiffness approach by adopting the maximum displacement criterion, i.e. $u < H/500$ [5]. The extensive research conducted to find the optimum angle found that the optimum angle for Diagrid structures is between 60°-75°[5]–[10] . Studies on varying angle Diagrid showed that varying angles give efficient and more economical designs[11], [12]. Studies on Diagrid structure using Indian standards found that the Diagrid structure can carry horizontal and vertical load effectively. The interior vertical structural elements only need to be designed for gravity loads[1], [9], [13], [14]. The major problem is excessive story drifts and multi-story buckling modes. This problem was solved when secondary bracings were provided at the core of the building [13], [15]. The Diagrid structure also has a better resistance against progressive collapse, and the nonlinear analysis procedure for advanced failure gives more accurate results [16]. The irregular Diagrid buildings and different types of braced steel structures were analysed using response spectrum method according to Indian standards [17]–[19].

The problems associated with the Diagrid structural system are its inadequate ductility and energy dissipation capacity. During earthquakes, this limited ductility and energy dissipation capacity become critical under solid ground motion. As the primary diagonal members carry gravity and lateral loads besides higher stiffness, these diagonal members lose elasticity at certain deformations and start yielding resulting in inadequate strength, leading to global collapse. These limitations are very much eliminated when Diagrids are arranged as eccentric braces separated by link beams which act as fuse elements. Using time history analysis, Nasim & Zhang [20] analysed a 21 story Diagrid buildings with replaceable shear links as fuse elements. The results showed a significant increase in seismic performance. Dabbaghchian et al. [21] compared eccentric Diagrid and regular Diagrid structures using static and dynamic analysis. The results displayed that shear links are the first to yield, followed by secondary beams. The primary diagonal members remain within the elastic region, the mean roof displacement is reduced, and safety margins are increased. The Diagrid structural system is not a completely ductile system which affects its performance under highly seismic zones, and there is limited research on Diagrid structural system having structural irregularities. Also, the Diagrid structural system display problems, i.e. the multi-storied buckling modes and extreme inter-story drift under seismic loads. The Diagrid structural system needs to be optimised for better energy dissipation. It requires a detailed analytical study for the optimal installation strategy of buckling restrained braces (BRBs) as secondary braces to attenuate the earthquake-induced energy Diagrid systems. In regular structures bracings effectively minimise the displacements and story drifts [22].

A. Buckling restrained braces

Earthquake and wind forces are the most prominent forces in the design of tall steel buildings. These lateral forces result in huge lateral deformations. However, the brace effectively minimises the lateral deformations but is relatively ineffective under large compressive forces, displaying buckling distortion. Ultimately showing an uneven hysteretic performance in tension and compression and characteristically showing a considerable loss in strength when monotonically loaded in compression or at regular intervals. In BRBs, the brace is restrained, and strength is conformed in compression and tension. BRBs simplify the hysteretic property and ultimately increase the energy dissipation capacity. Xie [23] illustrated the behaviour of a conventional brace and buckling restrained brace. In place of regular braces, buckling restrained braces (BRBs) are extensively used for seismic protection because of their increased energy dissipation capacity and resistance against lateral deformations. Sadeghi & Rofooei [24] utilised the advantages of BRBs and analysed a Diagrid structure having BRBs using time history analysis. The result showed a significant increase in seismic performance. Partial replacement of primary members with BRBs sections performed the best in diagrid structure under seismic loads. Lin et al. [25] compared the seismic performance with an outrigger system equipped with buckling restrained braces Fahaminia and Zahrai [26] combines the benefits of buckling restrained braces and shape memory alloys, modelled BRBs core with shape memory alloy. This configuration significantly reduced the residual deformations of the frames.

B. Brb configuration

BRB has four parts shown in fig.1:

- Brace unit which takes axial force
- Hardened transition part connecting brace with the connection
- Encasing part having a buckling-restraining Part which avoids the brace from buckling
- A debonding material or a gap is placed between the brace and BRB. This gap will help in proper sliding of brace inside buckling restraining part. Transverse expansion takes place when the brace gets yield under compression.

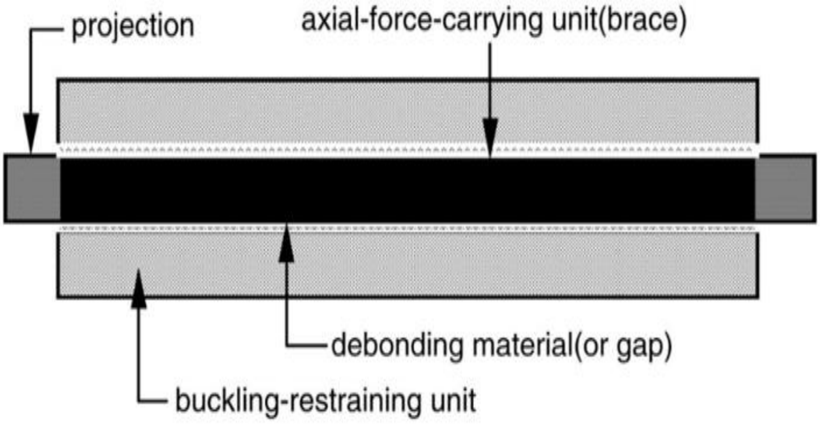

Fig. 1 Components of buckling restrained braces[23]

III. DETAILS OF BUILDINGS UNDERSTUDY

To increase the Diagrid structure's seismic performance, the benefits of buckling restrained braces are utilised in this study. Both regular and irregular buildings (I and C shaped) are modelled and analysed by conducting dynamic analysis in ETABS according to IS 1893:2016. The symmetric building is the square configuration with 48 m × 48 m having a core of 12m x 12m and an asymmetric structure with a C and L shaped plan. The decrease in plan area will result in plan irregularity, the L- shaped and C-shaped building models have plan irregularities. In the regular Diagrid building model the diaphragm is modelled as rigid and semi-rigid for plan irregular building. The codes used for the analysis are IS 1893:2016 and IS 800:2007. All the buildings are 50 stories tall with story height of 3.5 m. The building models are175 m high. The live design load and dead loads are 5 kN/m² and 5 kN/m². The mass source of the building is 100 per cent for dead load and 50% for the live load. The structure is analysed for lateral load due to earthquake considering a seismic factor of 0.36 (zone V), soil type of medium, zone factor of 0.36, response reduction factor of 5, and structure importance of 1.5 factor as per IS 1893:2016. The steel and concrete grades are Fe 345 and M30, respectively. The damping ratio is 5%.

A. Modelling details

For all regular, C-shaped and L-shaped Diagrid structure models, the steel material used for beams, columns and diagonals members is Fe 345 (Fy=350N/mm2). The sections used for the diagonal members are 700mm x 700mm x 18mm steel pipe sections. The interior columns are of steel tube section of 600mm x 600mm x 16mm. The frame beams sections used are ISMB 550. The diagonal beams are of build-up sections of ISWB 600 having cover plates of 250mm x 50mm on both sides. The slab material is concrete of grade M30 and thickness is 125 mm, and steel material used for buckling restrained braces is Fe 250 and star seismic BRBs from ETABS predefined sections a section of Star seismic 31.5 is used. The columns are of steel tube section of 600mm x 600mm x 16mm.

The models considered in this study are shown below:

1. Regular diagrid structure- (RDS)
2. Diagrid structure with diagonal buckling restrained bracings as secondary braces (RDS-D-BRB)
3. Diagrid structure with v buckling restrained bracings (RDS- V-BRB)
4. Diagrid structure with x buckling restrained bracings (RDS-V-BRB)
5. Diagrid structure with eccentric buckling restrained bracings (RDS-E-BRB)
6. Diagrid structure with inverted v buckling restrained bracings (RDS-IV-BRB)
7. L-shaped diagrid structure (LDS)
8. L-shaped diagrid with diagonal buckling restrained bracings (LDS-D-BRB)
9. L-shaped diagrid with v-buckling restrained bracings (LDS-V-BRB)
10. L-shaped diagrid with x-buckling restrained bracings (LDS-X-BRB)
11. L-shaped diagrid structure with eccentric buckling restrained bracings (LDS-E-BRB)
12. L-shaped diagrid structure with v - buckling restrained bracings (LDS-IV-BRB)
13. C-shaped diagrid structure (CDS)
14. C-shaped diagrid structure with diagonal buckling restrained bracings (CDS-D-BRB)

15. C-shaped diagrid structure with v - buckling restrained bracings (CDC-V-BRB)
16. C-shaped diagrid structure with x - buckling restrained bracings (CDS-X-BRB)
17. C-shaped diagrid structure with eccentric - buckling restrained bracings (CDS-E-BRB)
18. C-shaped diagrid structure with inverted - buckling restrained bracings (CDS-IV-BRB)

B. 3d model, Plan and elevations of models

The views of regular Diagrid structure are shown in fig 2.

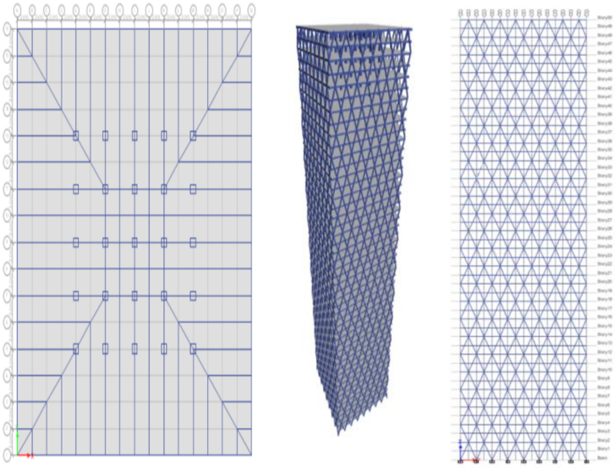

Fig. 2 (a) Plan, 3d model and Elevation of the regular Diagrid structure

The placement of the secondary bracing system for regular diagrid structure- (RDS) is shown in fig. 3

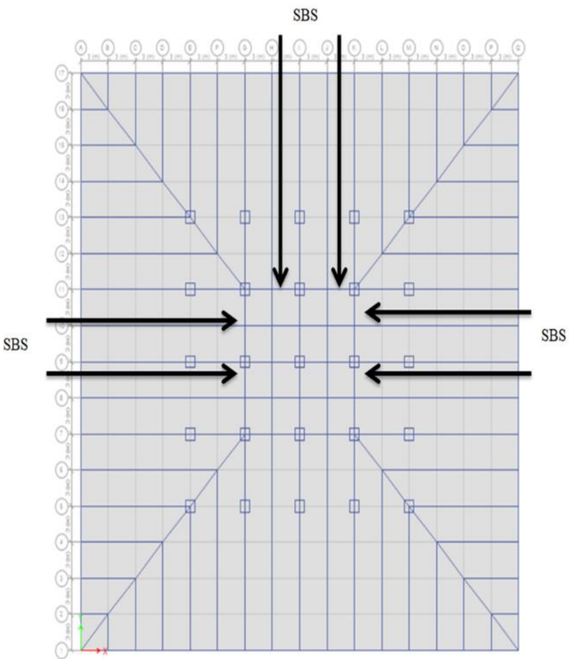

Fig. 3 Plan to show the location of secondary bracing system in regular Diagrid structure (RDS)

The arrangement of different types buckling restrained braces for regular Diagrid structure is shown in fig. 4

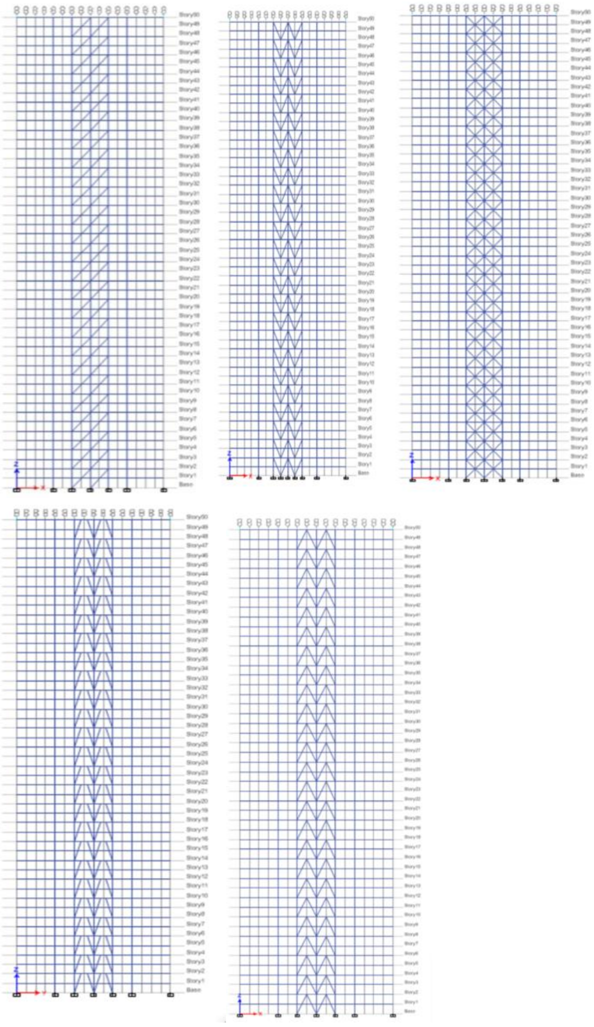

Fig. 4 Elevations showing the different arrangements of the secondary bracing system

The Plan and 3d model of L shaped and C shaped Diagrid structure is shown in fig. 5 and fig. 6. The location of the secondary bracing system for the L and C shaped diagrid system is shown in fig. 7.

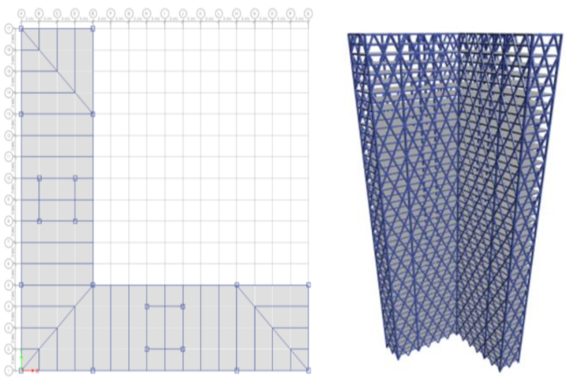

Fig. 5 Plan and 3d model of L shaped diagrid structure

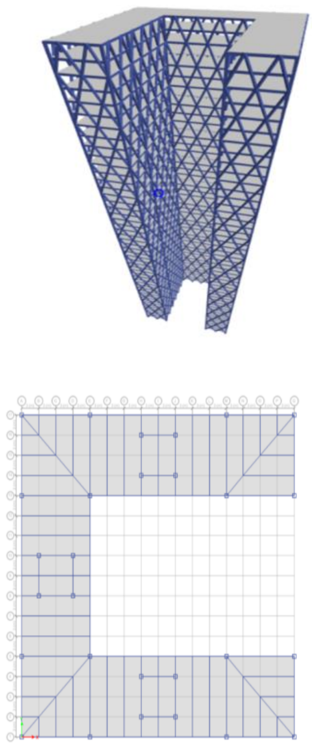

Fig. 6 Plan and 3d model of C shaped diagrid structure

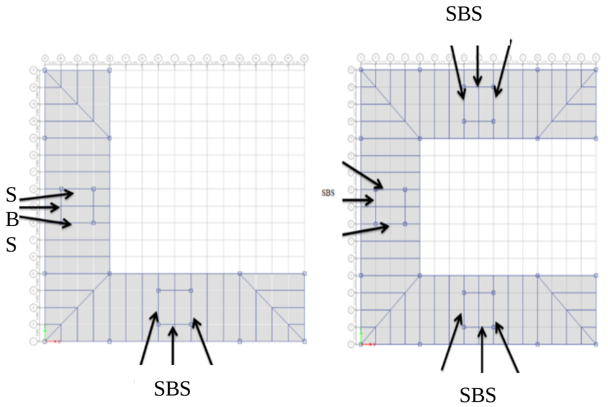

Fig. 7 Plan showing the location of the secondary bracing system for L shaped and C shaped diagrid structure

IV. SEISMIC ANALYSIS OF THE BUILDINGS UNDERSTUDY

The response spectrum analysis method is used to calculate and estimate the response of the structures under dynamic loadings. These dynamic loadings result from earthquakes and other violent shakings that last for a short duration and are primarily non-deterministic and transient dynamic events. The response spectrum method is founded on a particular form of superposition mode. The main indication is to provide a response that offers a limiting value for exactly how much an Eigen mode has a specific natural frequency, and damping can be agitated by a dynamic event.

In this study, response spectrum analysis as per IS 1893:2016 for seismic zone V is used for the dynamic analysis. The research is performed using ETABS, and results of time period, story drift, base shear and story displacement are calculated and interpreted.

A. Time period

The sideways action causing the building to move front and backwards is the fundamental mode and will determine the structural response. The time taken to complete first mode shape is the time period. This usually depends on the mass and stiffness of the structure.The graph in Fig. 8 shows the time period value for RDS. Fig. 9 for L shaped and fig. 10 for C shaped diagrid models. The results show a significant decrease in the time period with buckling restrained braces as secondary braces. The time period is maximum for regular-shaped diagrid and minimum for C shaped. All the arrangements of the secondary bracing system reduce the time period. The X arrangements performs the best and reduce the time period by 10% for regular Diagrid structure, 8.4% for L shaped, and 4% for C shaped Diagrid system.

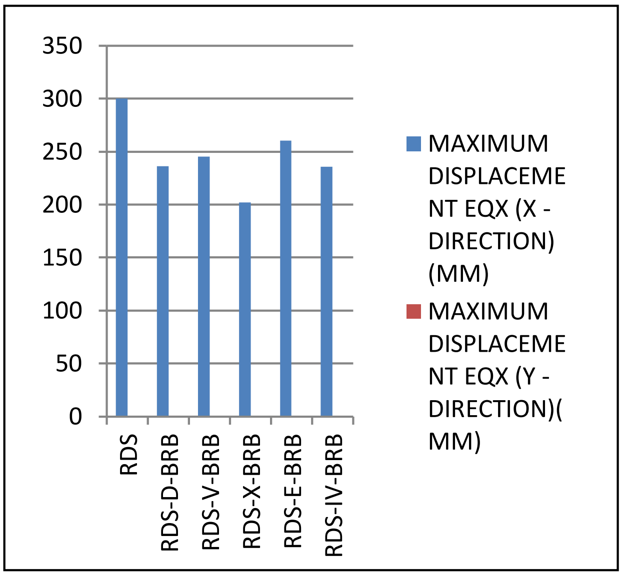

Fig. 8 Time -period for regular-shaped Diagrid having different configurations of BRBs as SBS

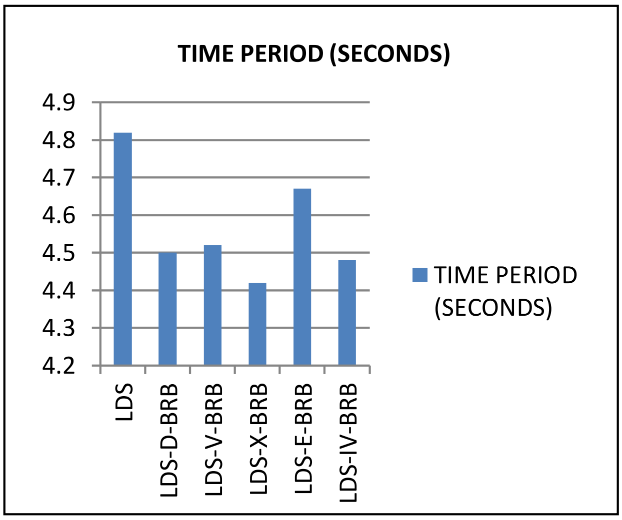

Fig. 9 Time -period for L-shaped Diagrid havin different configurations of BRBs as SBS

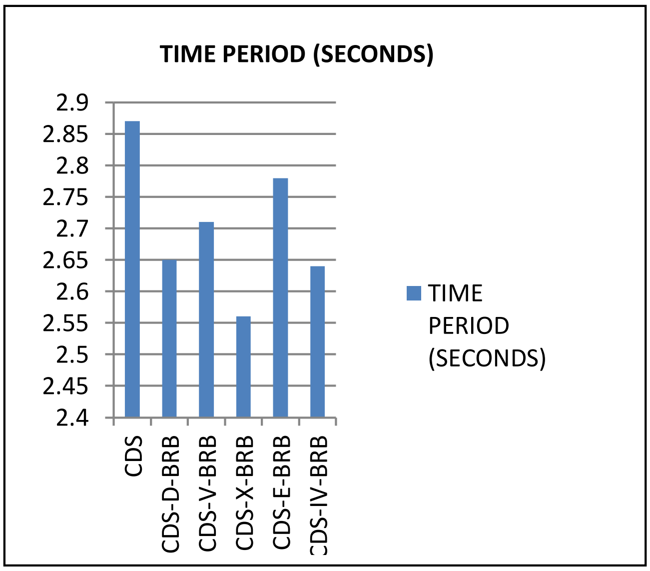

Fig. 9 Time -period for C-shaped Diagrid having different configurations of BRBs as SBS

B. Base shear

The graphs shown in Fig. 10, 11 and 12 shows the base shear value for regular diagrid, L shaped and C shaped diagrid respectively. The value of the base shear is maximum for regular Diagrid structure and minimum for C shaped Diagrid. It is observed that with the introduction of BRBs as the secondary bracing system the base shear value decreases, and the X bracing system is more efficient, reducing the base shear for all the models.

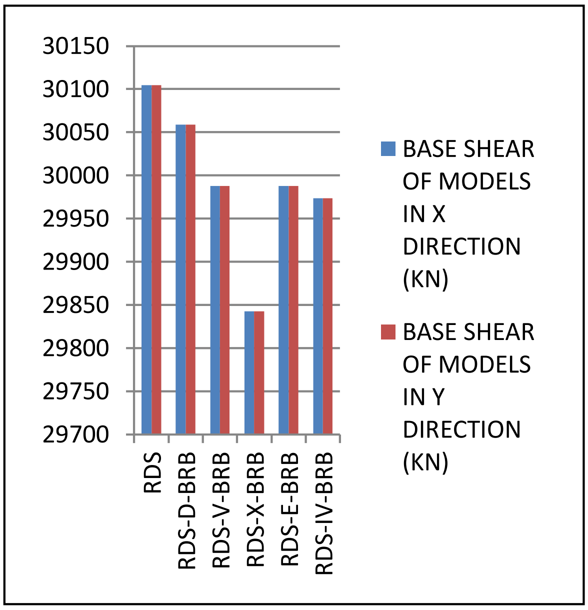

Fig. 10 Base shear for regular Diagrid having different configurations of BRBs as SBS

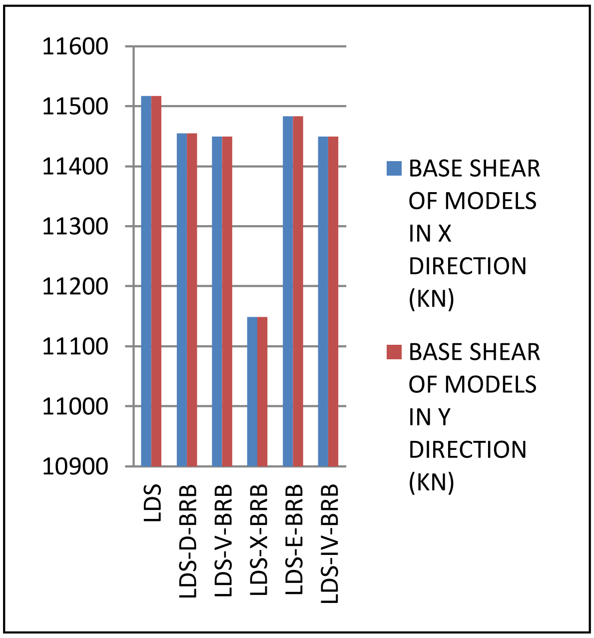

Fig. 11 Base shear for L- Diagrid having different configurations of BRBs as SBS

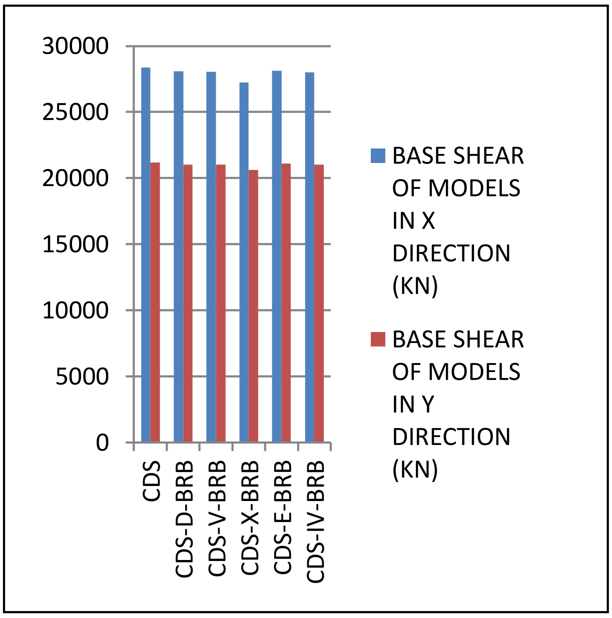

Fig. 12 Base shear for C- Diagrid having different configurations of BRBs as SBS

C. Maximum displacements

Maximum displacement is the total horizontal displacement of the structure in relation to the base of the building. The graphs shown in Fig. 13, 14 and 15 shows the base shear value for regular diagrid, L shaped and C shaped diagrid respectively.From the analysis, the maximum displacement is maximum for C shaped Diagrid and over the limit of H/500 as prescribed by IS 800:2007. The L shape has minor displacement. It is observed that with the introduction of BRBs as the secondary bracing system, the value of the displacement decreases, and the X bracing system is more efficient, reducing the displacement by 25% for regular Diagrid structure, 15% for L shaped, and 12% for C shaped Diagrid system.

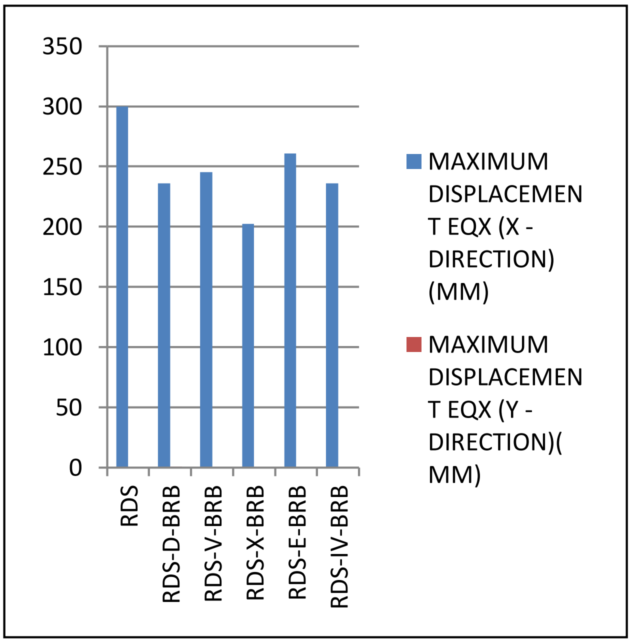

Fig. 13 Base shear for regular Diagrid having different configurations of BRBs as SBS

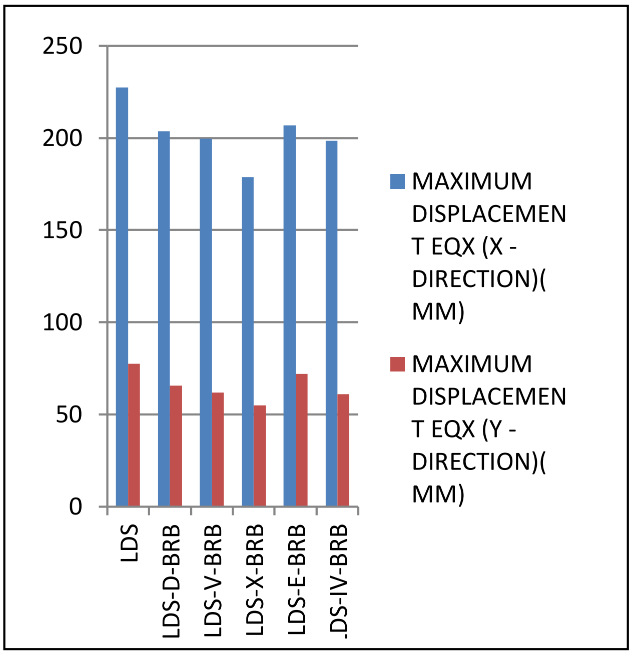

Fig. 14 Base shear for L- shaped Diagrid having different configurations of BRBs as SBS

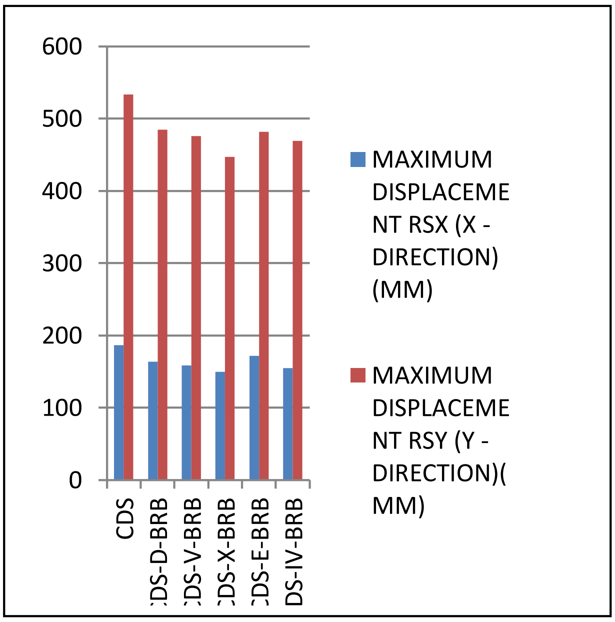

Fig. 15 Base shear for C-shaped Diagrid having different configurations of BRBs as SBS

D. Maximum inter-story drift

The graphs shown in Fig. 16, 17 and 18 shows the base shear value for regular diagrid, L shaped and C shaped diagrid respectively.the regular Diagrid structure has maximum story drift as compared to L and C shaped. The value of story drift is higher for C shaped and lower for L-shaped Diagrid. With brbs in X arrangement as secondary bracing reduces the maximum drift by 20% for regular Diagrid structure, 8% for L-shaped Diagrid, and 14.5% for C-shaped Diagrid structure. This arrangement is the most efficient as compared to other arrangements.

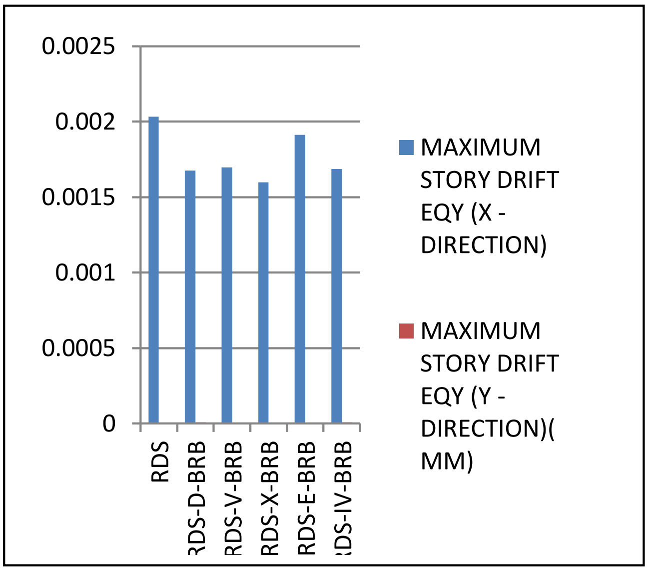

Fig. 16 Story drift for Regular Diagrid structure having different configurations of BRBs as SBS

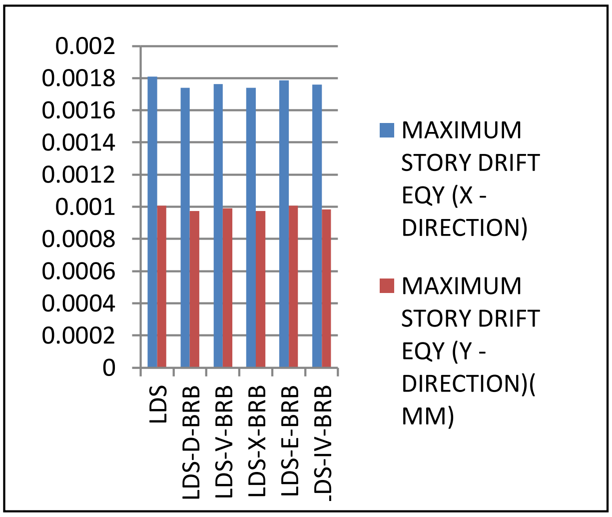

Fig. 17 Story drift for L-shaped Diagrid structure having different configurations of BRBs as SBS

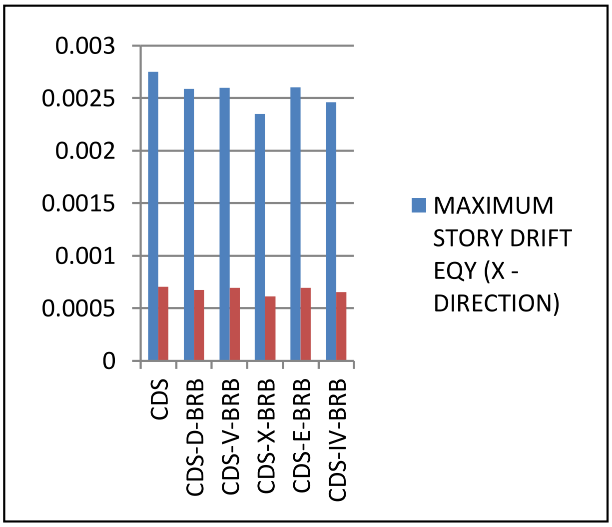

Fig. 18 Story drift for C-shaped Diagrid structure having different configurations of BRBs as SBS

V. CONCLUSIONS

This study presents the perspective of buckling restrained braces to increase the seismic performance of the 50 story regular and irregular Diagrid structures by providing buckling restrained braces and finding the most effective arrangement of BRBs to resist the seismic loads. The following are conclusions of this study:

1. The diagrid structural system is a sustainable system for tall buildings. With the introduction of BRBs as secondary bracings, the seismic performance of regular and irregular diagrid structures is increased significantly.
2. The performance of C shaped Diagrid structure is the poorest, having higher displacements and story drifts.
3. The time period is reduced with the introduction of BRBs. The X arrangement performs the best reducing the time period by 10% for regular Diagrid structure, 8.4% for L shaped, and 4% for C shaped Diagrid system.
4. The value of base shear should be minimum as the structure with increased base shear will attract more horizontal forces and be subjected to more damage during a seismic event. The base shear is maximum for regular Diagrid structure and minimum for C shaped Diagrid.
5. The L shape has minor displacement and with the X bracing system of BRBs the displacement is reduced by 25% for regular Diagrid structure, 15% for L shaped, and 12% for C shaped Diagrid system.
6. Inter-story drift is the story displacement in the lateral direction between the successive stories divided by the story height. The story drift is found to be maximum for C shaped and minimum for L-shaped Diagrid. With BRBs in X arrangement as secondary bracing the maximum drift is reduced by 20% for regular Diagrid structure, 8% for L-shaped Diagrid, and 14.5% for C-shaped Diagrid structure.
7. The performance of BRBs in the diagonal, V , inverted V and eccentric arrangement are significantly lower than the X arrangement, the eccentric arrangement is most inefficient, slightly reducing the displacements and drifts by 6%.

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