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Performance Comparison Of Diagrid Systems With Eccentric Connections And Concrete-Filled Steel Columns

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Abstract: Diagrid buildings incorporate diagonal members connected at specific angles along the building's perimeter, replacing conventional vertical columns for load transfer. These angled connections facilitate axial load transfer, enhancing lateral stiffness and overall structural efficiency. The performance of such structures is influenced by the orientation of the diagonals and the types of structural members used. This study focuses on analyzing the performance of a diagrid building featuring eccentric connections and replacing traditional built-up columns with Concrete Filled Steel Tubes (CFST). A G+30 diagrid structure with a 20m x 20m floor plan is considered. Dynamic wind and seismic analyses are performed to assess the impact of various parameters. Additionally, a nonlinear static analysis is conducted to evaluate the hinge formation pattern in the eccentrically connected diagrid structure.

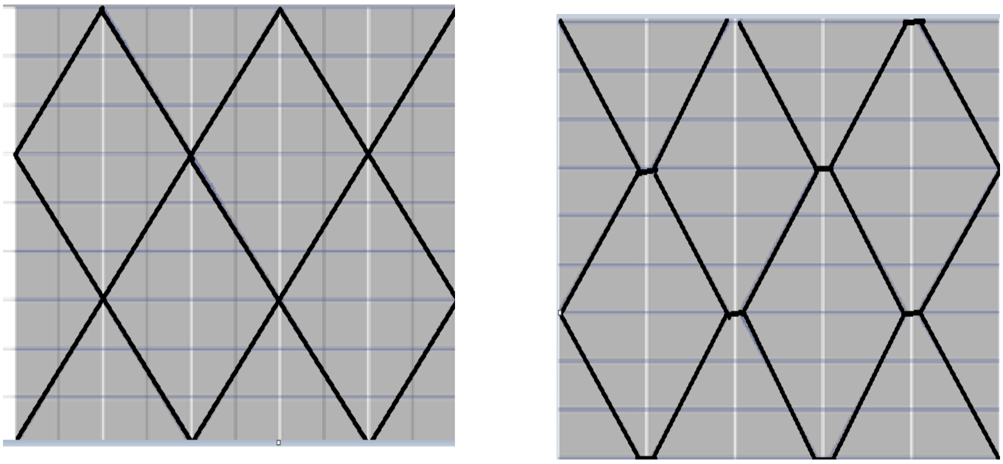
***Index Terms* -** Diagrid building, Eccentric connection, Concrete Filled Steel Tube columns.

1.INTRODUCTION

Diagrid buildings represent an architectural innovation, utilizing inclined structural elements along the building's perimeter for support. Instead of traditional vertical columns, diagonally connected members are employed, enabling both vertical and lateral loads to be transferred through axial forces. This mechanism enhances lateral stiffness by reducing shear deformation, thereby improving the overall structural efficiency. Additionally, the absence of exterior columns in diagrid systems offers greater flexibility in floor space planning and contributes to a distinctive and aesthetically appealing exterior design

In addition to structural efficiency, diagrid buildings offer sustainability benefits by minimizing the use of construction materials and reducing overall resource consumption. The absence of exterior columns enhances natural lighting within the building, contributing to improved energy efficiency. Furthermore, the structural system grants architects greater design flexibility, enabling the creation of distinctive and innovative architectural forms.

The orientation of exterior diagonal structural elements plays a critical role in determining the structural performance of diagrid buildings. This study investigates the behavior of a diagrid structure featuring eccentrically connected diagrid modules along with the replacement of conventional built-up columns by Concrete Filled Steel Tube (CFST) columns. To understand the influence of these modifications, multiple configurations—incorporating or excluding eccentric connections and CFST columns—are analyzed both individually and in combination. The performance evaluation is carried out using dynamic wind and seismic analyses, while a pushover analysis is employed to study the hinge formation patterns specifically in eccentrically connected diagrid systems.



(a) (b)

Fig. 1 (a) Concentric connection of Diagrids, (b) Eccentric connection of Diagrids

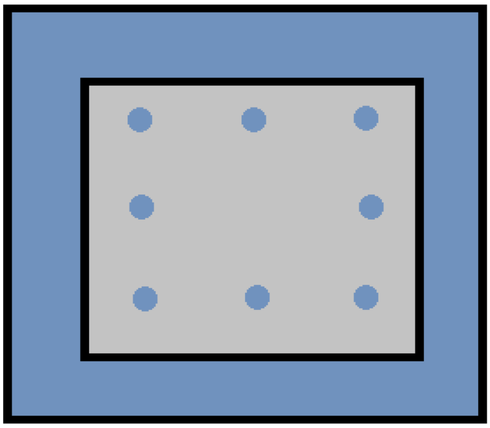


Fig. 2 Concrete Filled Steel Tube

2. LITERATURE WORK

The orientation and placement of diagonal members significantly influence the structural performance of diagrid buildings. To better understand the design methodology and determine the optimal diagonal orientation, studies conducted by Kyoung-Sun Moon were reviewed [10][11][12]. In study [10], the effect of various diagonal configurations on the behavior of diagrid structures was examined. It was found that for diagrids with uniform diagonal angles, the optimal angle increases with building height. This is because taller buildings, with higher height-to-width ratios, exhibit behavior similar to bending beams. In such cases, steeper diagonal angles are more effective in resisting bending moments through axial action. For high-rise diagrid structures with aspect ratios ranging from approximately 4 to 9, the optimal diagonal angle lies between 60° and 70°.

The optimal inclination angle for diagonal members is determined based on the building's total height to ensure adequate shear and bending rigidity [11]. Diagonals are distributed across multiple stories depending on this inclination angle and the inter-story height, with their connections forming triangulated or diamond-shaped closed loops known as modules. Typically, these modules intersect at a common point, resulting in a concentric connection that provides higher stiffness but lower ductility [4]. To enhance ductility and improve energy dissipation, Minu Ann Peter [15] recommends introducing a link beam between modules. This modification leads to an eccentric connection, where modules are connected at the ends of the link beam, replacing the traditional concentric configuration.

The link beam connecting each diagrid module functions as the structural weak point, intended to form the first plastic hinge. This controlled yielding allows the rest of the structural elements to remain stable and predominantly elastic for a longer duration [15]. In the study conducted by [15], various link beam lengths ranging from 400 mm to 1000 mm, in 100 mm increments, were analyzed. The results indicated that as the length of the link beam increased, both story displacements and inter-story drifts also increased. At a link length of 600 mm, these parameters exceeded the permissible limits specified by design codes. Consequently, for the present study, a link beam length of 500 mm was selected to ensure compliance with code requirements and maintain structural performance.

A secondary effect of using eccentrically connected diagrid modules is the increase in story displacements and inter-story drifts. To mitigate these effects, an additional performance enhancement strategy involves replacing interior built-up columns with composite columns. In the present study, Concrete Filled Steel Tube (CFST) columns are utilized as the composite alternative. CFST columns are recommended for improving structural performance while allowing for smaller cross-sectional dimensions. Their use enhances both ductility and load-carrying capacity, as the steel casing provides confinement to the concrete core, resulting in better composite action [13].

3. METHODOLOGY

The primary objective of this study is to evaluate the performance of a diagrid building incorporating eccentrically connected modules and the replacement of conventional built-up columns with Concrete Filled Steel Tube (CFST) columns.

To achieve this, a G+30 storied diagrid structure with a floor plan of 20m × 20m, as illustrated in Fig. 4, was analysed. The building features an inter-story height of 3.6 meters. The structural system includes IS WB 550 sections as primary beams, IS MB 500 sections as secondary beams, and a slab thickness of 150 mm. Each diagrid module spans six stories. The CFST columns used are circular tubes with a diameter of 450 mm and a wall thickness of 25 mm. To isolate and understand the impact of each design parameter, four different structural models were developed, each incorporating one or both of the proposed modifications.

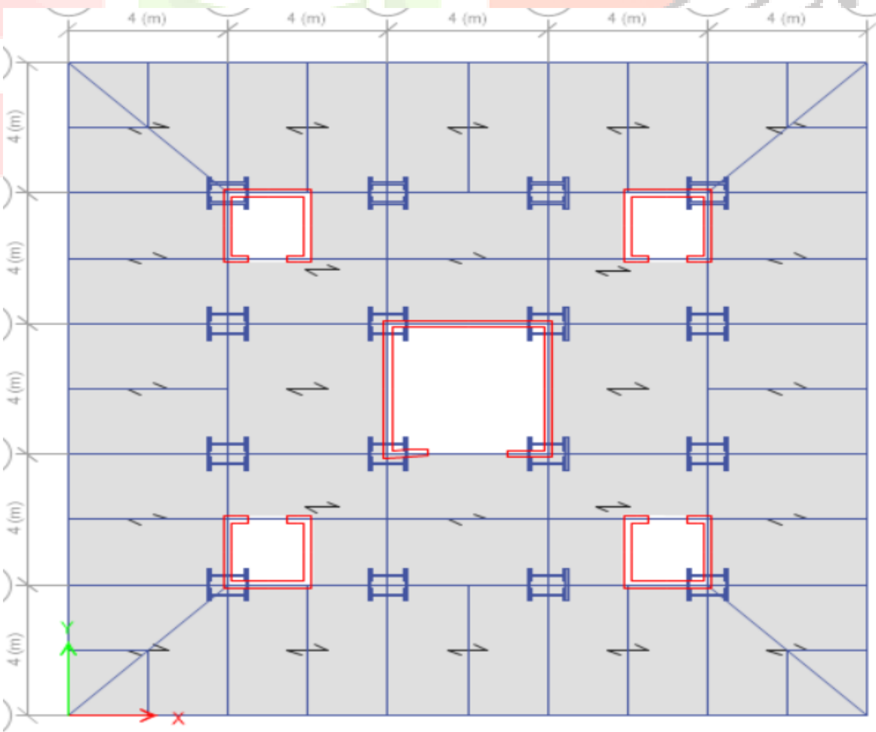


Fig. 3. Building plan

Details of Model 1:

Model 1 serves as the baseline for comparison. It represents a diagrid building without eccentric connections, featuring conventional built-up interior columns. Details of the built-up columns are provided in Figure 5.

Details of Model 2:

Model 2 represents a diagrid building with a 500 mm eccentric connection between modules, while retaining the conventional built-up interior columns.

Details of Model 3:

Model 3 represents a diagrid building with Concrete Filled Steel Tube (CFST) columns. The dimensions of the CFST columns were determined by satisfying the requirements of both the AISC code and IS 11384 (2022). Based on these standards, the CFST columns were designed with a tube thickness of 85 mm and filled with M30 grade concrete.

Details of Model 4:

Model 4 represents a diagrid building incorporating both the 500 mm eccentric connections between modules and CFST interior columns.

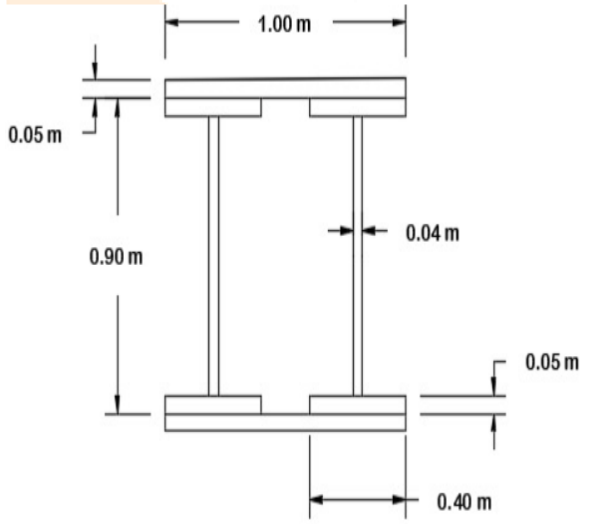


Fig. 4. Built-up Column dimensions

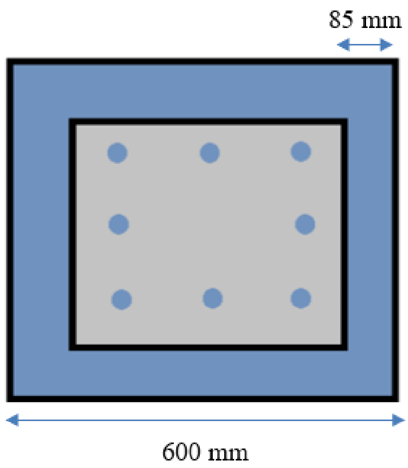


Fig. 5. Concrete Filled Tube Column

The preliminary plan area, structural element dimensions, and loads were adopted from reference [15]. The loads considered on the structure include Dead Load (DL), Live Load (LL), Wind Load (WL), and Earthquake Load (EQ), with the following values:

- Dead Load (DL): 3.75 kN/m²
- Live Load (LL): 2.5 kN/m²
- Earthquake Load (EQ) (Zone II): 0.1
- Wind Speed: 44 m/s
- Soil Type: II (Medium Soil)
- Damping Ratio: 5%

Load combinations were formulated according to the Limit State of Serviceability, following Table 4 of IS 800 (2015)

In this study, seismic dynamic analysis was performed using Response Spectrum Analysis in accordance with IS 1893 (Part 1): 2016. Additionally, dynamic wind analysis was conducted using the Gust Factor Method following IS 875 (Part 3): 2015. The performance of the four models was compared based on the results of both analyses, focusing on story displacements and story drifts.

4. EXPERIMENTAL RESULTS

4.1 Response spectrum Analysis

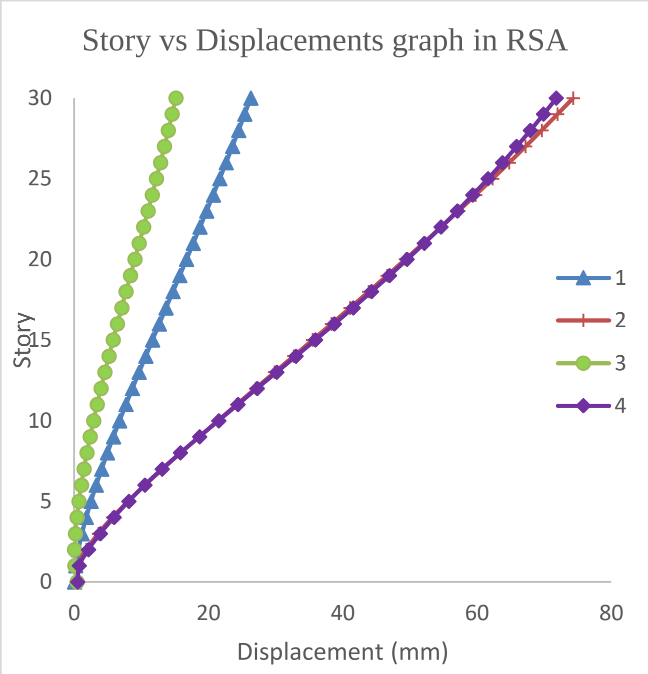
Seismic dynamic analysis was performed using Response Spectrum Analysis in accordance with IS 1893 (Part 1): 2016, with all necessary data input into CSI ETABS software. Following IS 16700 guidelines for tall buildings, the total building drift is limited to H/500, which corresponds to 216 mm for this study. The maximum allowable inter-story drift for design earthquake forces is restricted to h_i/250, equal to 14.4 mm (calculated as 3600 mm/250). The load combination of Dead Load plus Earthquake Load (DL + EL) was selected for comparison.

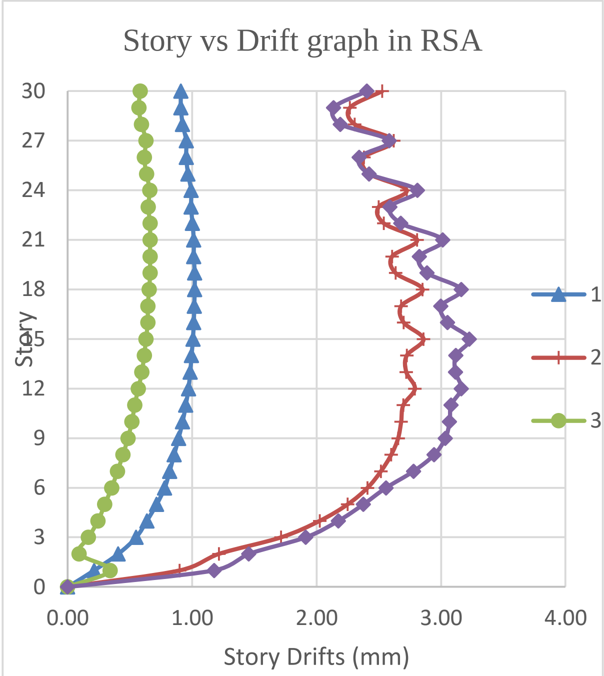
Story Displacements:

The story displacements for each model are presented in Graph 1. All models exhibit displacements below the permissible H/500 limit. Model 2, featuring built-up columns with eccentric connections, showed the maximum displacement. Conversely, Model 3, which uses CFST columns without eccentric connections, demonstrated the least displacement despite the reduced column cross-section. Model 4, combining eccentric connections with CFST columns, exhibited slightly lower displacements than Model 2.

Story Drifts:

Story drifts for each model are illustrated in Graph 2. All values are within the allowable h_i/250 limit. Model 4, incorporating both CFST columns and eccentric connections, showed the highest story drift, while Model 3, with CFST columns and no eccentricity, exhibited the lowest drift despite the smaller column size. Model 4 showed slightly greater drift compared to Model 2.





(1) (2)

Graph 1. *Story vs Displacements graph in RSA* Graph 2. *Story vs Displacements graph in RSA*

4.2 Dynamic Wind Analysis

Dynamic Wind Analysis (DWA) was conducted using the Gust Factor Method in accordance with IS 875 (Part 3): 2015, with all required input data processed through CSI ETABS software. Following IS 16700 guidelines for tall buildings, the total building drift is limited to H/500, which corresponds to 216 mm for this study. The maximum allowable inter-story drift is restricted to h_i/400, equal to 9 mm (calculated as 3600 mm/400). The load combination of Dead Load plus Wind Load (DL + WL) was used for performance comparison.

Story Displacements:

Graph 3 presents the story displacements from the DWA for all models. In every case, displacements remain below the H/500 limit. Model 2, with built-up columns and eccentric connections, recorded the highest displacements. Models 1 (built-up columns without eccentricity) and 3 (CFST columns without eccentricity) exhibited similar displacement levels despite Model 3 having smaller column cross sections. Model 4, combining eccentric connections and CFST columns, showed lower displacements compared to Model 2.

Story Drifts:

Story drifts for all models under DWA are shown in Graph 4. All drifts are within the permissible h_i/400 limit. Model 2 again experienced the maximum inter-story drift. Model 1 showed slightly less drift than Model 3, while Model 4 demonstrated reduced drift compared to Model 2.

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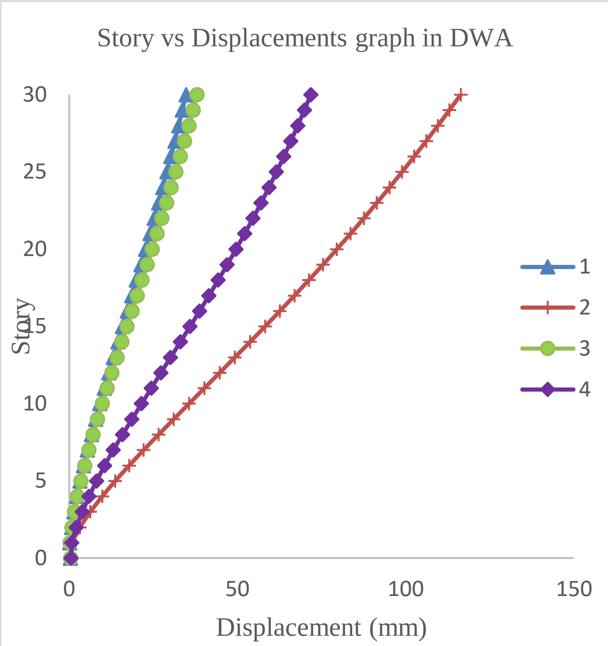
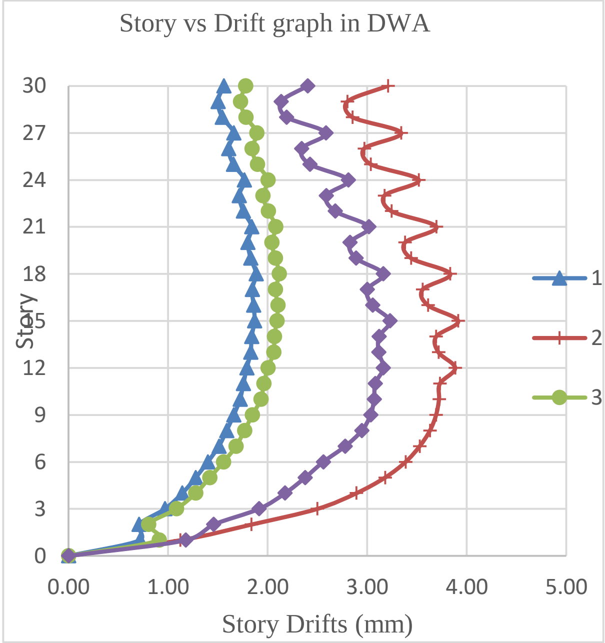


(1)

Graph 3. Story vs Displacements graph in DWA

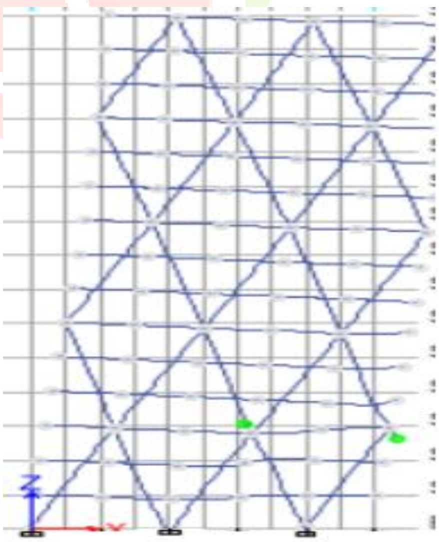


(2)

Graph 4. Story vs Displacements graph in DWA

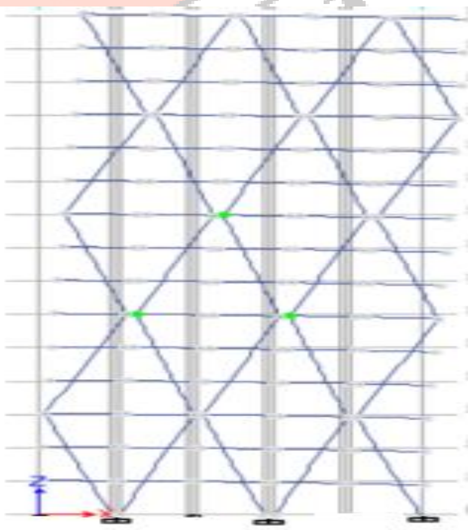
4.3 Push over analysis

To predict the actual behavior of the buildings and simulate hinge formation, nonlinear static analysis was performed following the methodology outlined in study [15]. A target displacement of 1000 mm was applied to the building models to monitor their response. The nonlinear behavior of structural members was modeled by incorporating plastic hinges in accordance with FEMA 356 guidelines.



(a)

Fig. 4. Hinge formation in Model_1in Diagrids



(b)

Fig. 5. Hinge formation in Model 2 in link beam

In Model 1, hinge formation initiates within the diagrid members themselves, which compromises the overall stability of the building. In contrast, Model 2 exhibits hinge formation primarily in the eccentric link beams, resulting in a comparatively more stable structural response. The observed hinge locations in this study align closely with the findings reported in [15].

The analysis and results indicate that the arrangement of diagrid modules significantly influences the performance of diagrid buildings. Overall story displacements and drifts tend to increase with the introduction of eccentric connections between modules. While both concentric and eccentric connections exhibit similar patterns of displacement growth with increasing story height, the story drifts reveal a distinct behavior: stories containing the eccentric link beams experience greater drifts than adjacent stories, with this pattern becoming noticeable from approximately one-third of the building's height.

Hinge formation initiates within the diagrid members for buildings with concentric connections, whereas in buildings with eccentric connections, hinges form primarily in the link beams.

Replacing built-up columns with CFST columns allows for a smaller cross-sectional area while simultaneously reducing displacements and drifts compared to the larger cross sections required for built-up columns.

Moreover, combining CFST columns with eccentric module connections in diagrid buildings results in slightly reduced displacements and drifts compared to models with only eccentric connections.

5. Conclusions

Based on the above observations, the following conclusions can be drawn:

- Eccentric connections between diagrid modules lead to increased story displacements and drifts.
- Hinge formation occurs primarily in the eccentric link beams, contributing to improved building stability.
- CFST columns require a smaller cross-sectional area compared to built-up columns.
- Replacing built-up columns with CFST columns reduces both displacements and drifts.
- The combined use of eccentrically connected modules and CFST columns is recommended for enhanced structural performance.

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