Evaluation of Lateral Stability of the Diagrid Tall Structure Under Different Earthquake Forces

Swaral R. Naik and S. N. Desai

Abstract Diagrid structural mechanism, being aesthetically appealing, structurally efficient and material saving, has gained a lot of attention and acceptance among the architects and structural designers engaged in modern era infrastructures in densely packed urban areas. Conventional way of providing seismic stability to the structure is either by bracing systems or shear wall system. Diagrid system combines the responsibilities of the vertical columns and the bracings as one single structural member—a diagonal member only. This has not only shown increase in the lateral stability of the structure, but it is also proven for reduction in material usage up to 20%. Diagrid is more acceptable nowadays mainly due to the column-free spaces and freedom in interior planning that it can offer to the inhabitants. This study focuses on behaviour of a Diagrid structure subjected to different seismic forces. An existing Diagrid tall structure (Hearst tower, NY, USA) and a similar dimensioned regular conventional structure are compared under various existing earthquake shakings. The time history dynamic analysis is done using FE software SAP2000. The Diagrid structure showed higher lateral seismic stability than the conventional system.

Keywords Diagrid · Tall structure · Seismic analysis · SAP2000

1 Introduction

In urban areas, tall structures have become the only option for providing houses as well as the corporate offices using lesser land. Many structural systems have evolved since about five decades to make the tall structures more stable and efficient

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S. R. Naik (✉) · S. N. Desai
Applied Mechanics Department, SVNIT, Surat, India
e-mail: naikswaral@gmail.com

S. N. Desai
e-mail: snd@amd.svnit.ac.in

S. R. Naik
Applied Mechanics Department, GEC, Bharuch, India

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[1]. Framed shear truss, Bracing systems, framed tube system, truss tube system, bundled tube systems, outrigger system, shear wall system, etc. [2] have been in the choices of the structural designers and architects with respect to their ability to resist large lateral forces (mainly seismic and wind) [3, 4].

There is number of tall structures which are constructed with the above mechanisms and they are still standing, satisfying their purpose and serving the habitants. Diagrid system, a newcomer to the above list, has started showing its capabilities and strength. A conventional structural system will have a framed beam-column structure, mainly resisting gravity loads, assisted by an auxiliary lateral load resisting system [5]. But a Diagrid will have a single system which will be resisting all the gravity loads as well as the lateral loads (Fig. 1). The diagonal columns will contribute to take the gravity load and the lateral load, by simply transforming them into axial forces. Unlikely to beam-column framing, a Diagrid has a triangulated framing. This triangulation is called a Diagrid module. A single module may consist of more than one storey, depending on the Diagrid angle, θ. Many researchers have worked to evaluate an optimum angle of Diagrid (between 60 and 70°), mainly considering wind force [6]. Diagrid node is the main junction which distributes both the gravity as well as the lateral loads to the diagonal members (see Fig. 2). In conventional moment frame system, external forces are transferred through beam-column junction, creating bending moments in vertical columns, whereas in Diagrid system all the forces are transferred through a node, generating axial forces in the diagonal columns [7]. Thus, the diagonal columns (either of RCC or Steel) being very strong in resisting axial forces, they are more efficiently utilized—a major reason behind the ancient structures lasting since centuries (least bending moments in main structural members, pure axial forces only). Till now, around 20 buildings are already constructed using Diagrid systems. Most of these structures are in the regions of heavy wind gust and are optimized with respect to resist wind forces [8]. However, the response of a tall structure under earthquake forces is a critical parameter for design, as a quake does not offer much time for the panicked occupants to escape. Thus, evaluation of response of the tall Diagrid structure under earthquake forces is an essential study. Unfortunately, there is still a large research gap in this area of seismic evaluation of Diagrid structures.

This research mainly includes dynamic time history analysis of Diagrid tall structure under various earthquake motions using FE software SAP2000. The building under the study should not be imaginary or non-practical (as many researchers have mistaken before) here we have taken as reference, Hearst Magazine Tower situated at NY, USA. Actual data of this tall structure is procured and modelled accordingly in the software. Later, a same dimensioned simple moment frame tall structure is also modelled with the same geometry, loads and member sizes data. These two models are analyzed for different known earthquake time histories and the responses are compared.

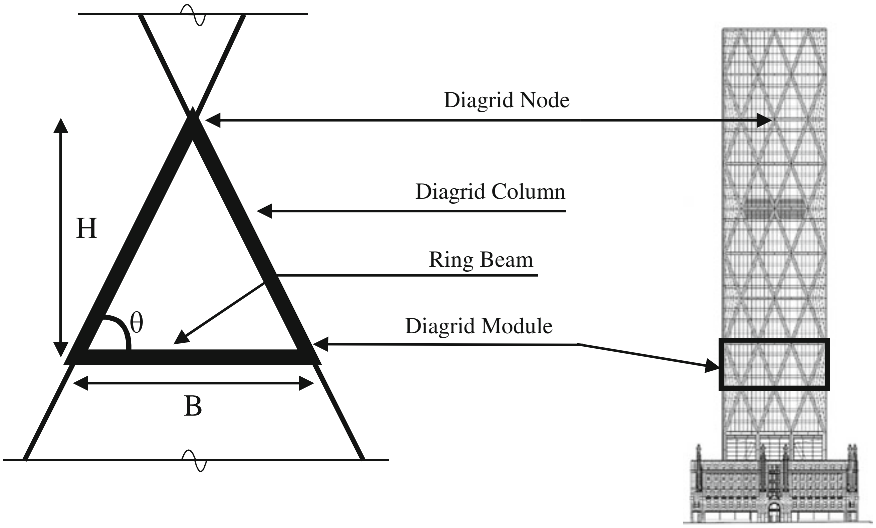


Fig. 1 A typical diagrid building elevation and its components [9]

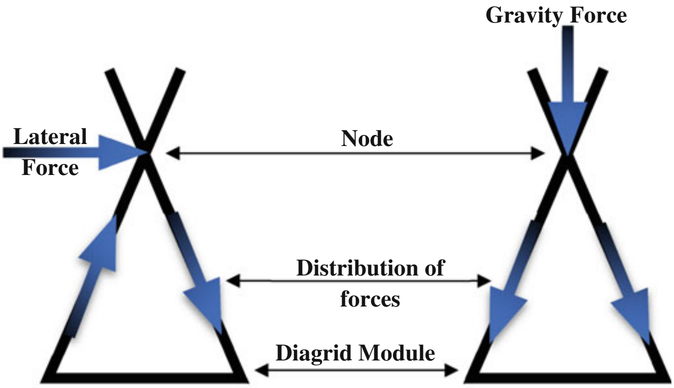


Fig. 2 Distribution of external forces in a typical diagrid module

2 Details of Hearst Tower, NY, USA

A symmetric rectangular plan shape and comparatively low height are the main reasons behind finalizing Hearst Tower as the reference Diagrid building for the analysis. All the geometrical and structural data are procured [10]. Neglecting the interior architectural features and ancillary minor details, a main structural framing is modelled in the software (Fig. 3).

The building consists of the first floor of about 80 ft. height, which is kept as an open space for architectural requirement. This floor is constructed using mega

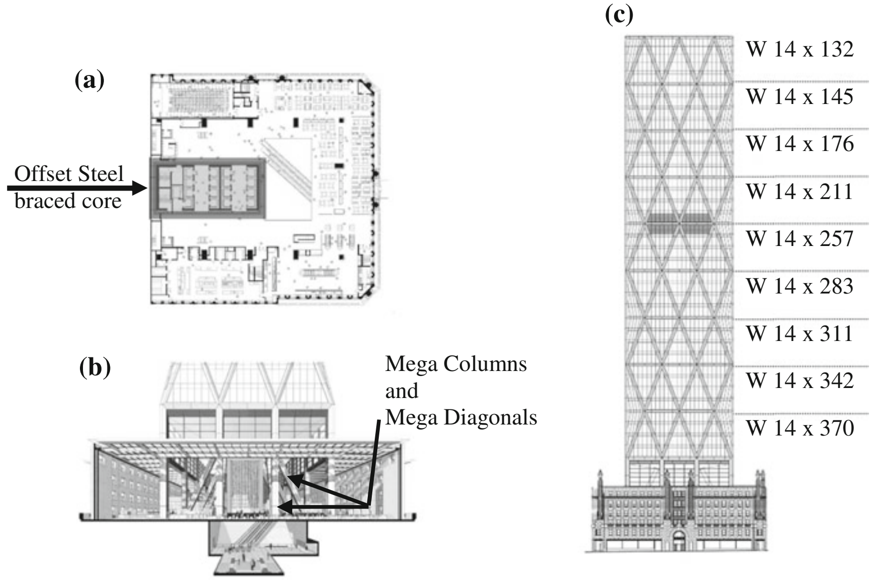


Fig. 3 **a** Typical plan with offset steel braced core. **b** First floor with columns and mega diagonals, omitted for modelling. **c** Diagrid member section details [9]

vertical columns and mega diagonals (as named by the developer of the building Norman and Fosters) [11]. This first 80 ft height of the building is neglected in the analysis. Thus, the building modelled in SAP2000 has only 36 floors, having only Diagrid through the height. The building is designed by Norman & Fosters company, considering mainly gravity loads and wind loads as per ASCE codes for Manhattan, NY, USA.

3 Details of the Seismic Evaluation

The finite element model constructed in SAP2000 software has all the major features of the actual Hearst tower. Also, for comparative study, a same dimensioned simple moment frame building is also constructed in SAP2000.

3.1 Earthquake Data Inputs and Details

The earthquake time histories here considered are, as per Table 1. Behaviour of a structure under various earthquakes is analyzed and compared. The earthquake time history is the actual acceleration versus time data that are captured at the earthquake

Table 1 Details of Hearst Tower, NY, USA [12]

Parameter	Actual hearst building
Story nos.	36 (Diagrid) + 10 = 46
Plan dimension	48 m × 37 m
Total height	148.86 m (Diagrid) + 34.14 m (80 ft)
Diagrid module	Triangle with (b × h) = 12.12 m × 16.54 m, α = 70°
Load per floor area	Average (LL) 5 KN/m^2
Diagrid member sizes	Varying from top to bottom, W 14 × 132 to W 14 × 370, AISC sections
Peripheral ring beam size	W 30 × 90
Floor beam size	W 21 × 55 and W 21 × 48
Slab/Deck details	*Vulcraft* 3VLI Deck (6″ + additional 2″ for fire), 12′ span, Max^m load 110 PSF (5.86 KN/m^2)
Material used	Structural steel A992 Grade ASTM
Central core	Offset steel braced core

station. This data has thousands of values at a regular time interval (say 0.02 or 0.005 or 0.01 s etc) which results into a trace as shown in Fig. 4. Peak Ground Acceleration (PGA) and its occurrence time, are the value that matters the most in seismic analysis. The structure will also show a similar kind of graph, of displacement versus time for the respective time history. In the graph, the peak deflection of the structure may or may not be occurring at the same time of the PGA occurrence. Though the structure is going to experience shaking, the main concern is the maximum deflection while shaking. Structure designers consider this value of deflection for the seismic design.

Moreover, whether a structure is stiffer or flexible depends on its value of natural frequency (first modal frequency). Structure with lower natural frequency is flexible than the structure with a higher natural frequency. This parameter is also taken into consideration for comparing the structures.

3.2 Details of SAP2000 Models

The SAP2000 Diagrid model is made with the same exact data available of the original Hearst Tower, NY, USA. This model is analyzed using above-mentioned earthquake time histories. The Diagrid model is also compared with the conventional moment frame building. The SAP2000 models are as shown in Fig. 5.

The Diagrid model consists of only the Diagrid part of the actual Hearst tower. The Diagrid model also consists of an offset braced steel core (see Fig. 3b). All the diagonal members, ring beams, floor beams and slab details are as per the actual Hearst tower data (see Table 2).

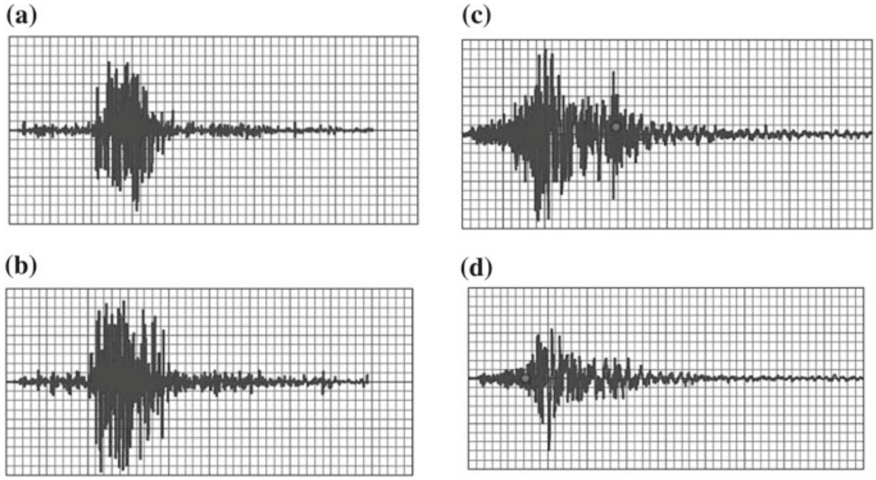


Fig. 4 Earthquake time history samples, acceleration versus time data. **a** Bhuj earthquake, Component 0, **b** Bhuj Earthquake, Component 90, **c** Yermo earthquake, Component 0, **d** Yermo earthquake, Component 90

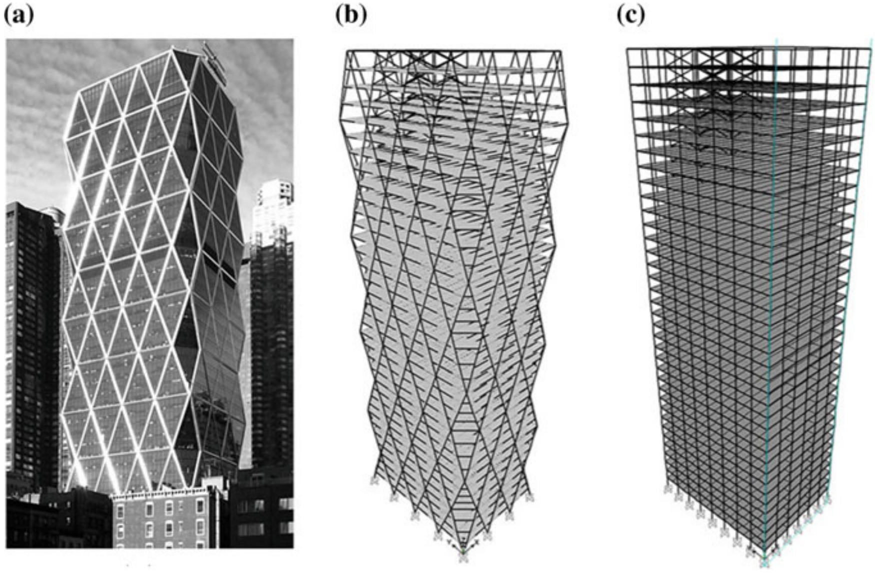


Fig. 5 3D view of the **a** Hearst tower, **b** diagrid model, **c** simple conventional model

The Simple model is made as same as the Diagrid structure. All the details are kept same except the orientation of the peripheral diagonals. The simple model consists of vertical peripheral columns.

Table 2 Details of earthquake time histories considered

Earthquake	Duration (s)	PGA (cm/s/s)	Time (s)	Component (°)
Petrolia, CA, USA	60	649.442	3.28	90
Newhall, CA, USA	60	578.19	4.32	0
Altadena, CA, USA	40	438.9	2.84	0
El Centro, CA, USA	39.1	428.09	5.94	90
Chamoli, UK, India	24.34	352.83	4.6	90
Yermo, CA, USA	80	240.016	16.32	90
Bhuj, GJ, India	133.5	103.82	46.94	0

The dead weight and the weight due to live loads on both the models come out to be almost the same. This is a major criterion for comparing lateral stiffness of a structure. Here, weight (mass) being equal, the only difference in two models is their lateral stiffness. Thus, this study mainly focuses on achieving higher lateral strength keeping the same material usage. The preliminary design check of these models is done using CSI ETABS software.

4 Results and Discussion of the Dynamic Time History Analysis

The first major comparing parameter is the natural frequency of the structures. After the complete modal analysis, the first mode for both the structure is in the X direction, i.e. the direction having lesser plan dimension. This satisfies the conceptual knowledge regarding the shaking modes and modal frequencies. The first modal frequency (natural frequency) of the Diagrid model is 0.214 Hz, whereas the same modal frequency for the simple building is 0.1 Hz (Fig. 6).

Further, both the models are analyzed using different time histories. It is to be understood that the maximum top displacement of the structure may or may not be occurring at the same time instant of the PGA. The top displacement also depends on the duration of the earthquake, intensity and occurrence of PGA. But the graph of top displacement versus time will be of a similar shape of the respected time history. The following figures (Fig. 7) shows some of the top displacement versus time results for both the models.

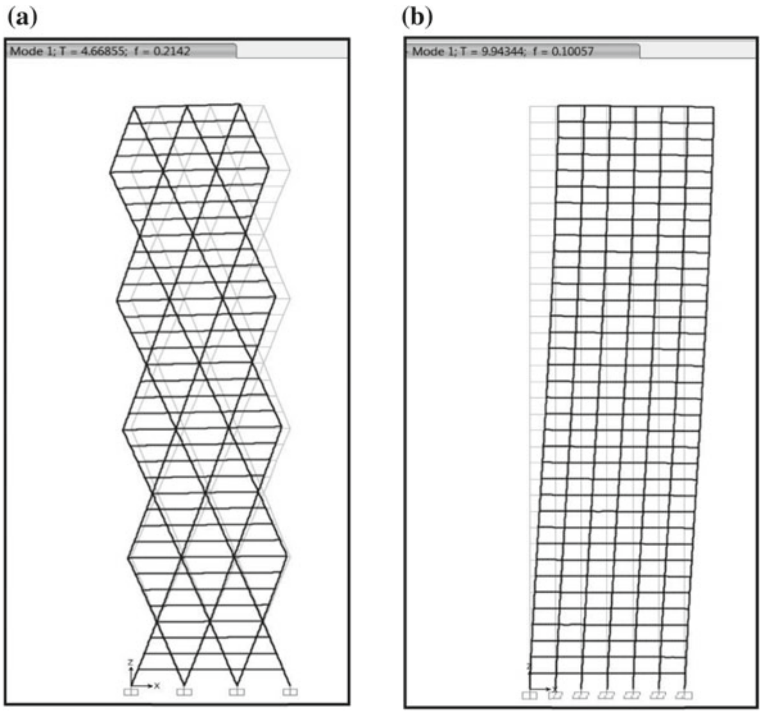
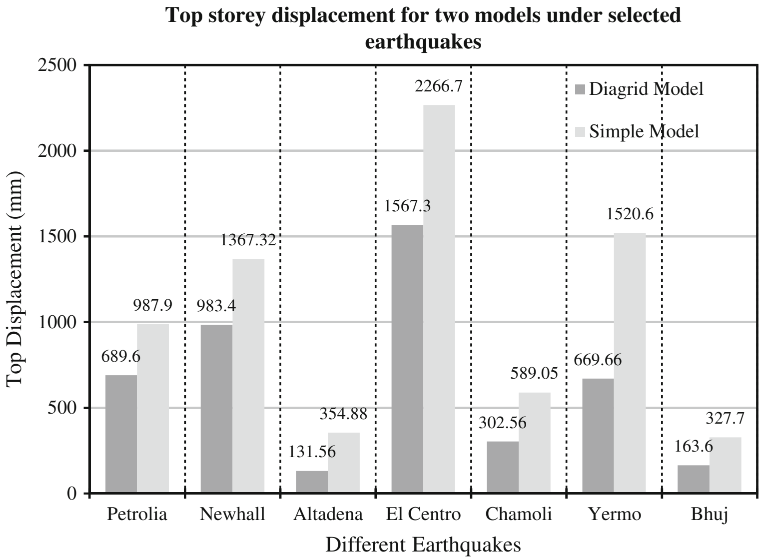


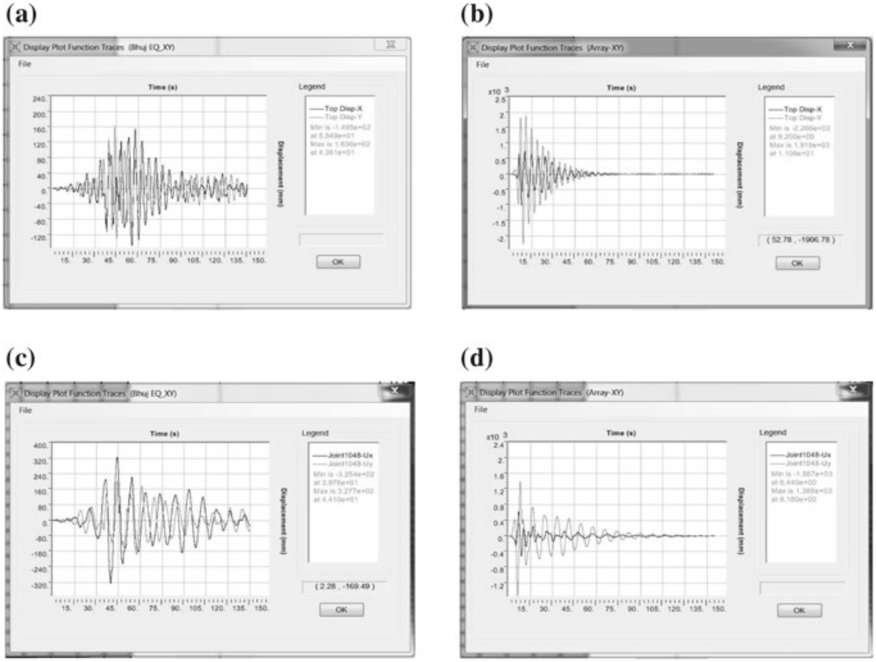
Fig. 6 First modal deflection of **a** diagrid model, **b** simple model

4.1 Top Displacement Results

Top displacement values for Diagrid model for all the earthquakes are much lesser than the values for a simple moment frame model. This is because of the orientation of the load carrying member being inclined in Diagrid model. The diagonal orientation of columns is converting all the gravity as well as lateral forces into axial forces. The same earthquake (say Bhuj EQ) is deflecting both the models very differently.

In Diagrid, the model shows higher lateral stiffness which also reveals from its more of a shear mode deflection pattern, whereas a simple model having lower lateral stiffness exhibits a bending mode deflection pattern (see Fig. 8).





(a) Top Disp-X, Top Disp-Y
Min is -1.495e+02
at 5.549e+01
Max is 1.636e+02
at 4.361e+01

(b) Top Disp-X, Top Disp-Y
Min is -2.266e+03
at 9.200e+00
Max is 1.919e+03
at 1.106e+01
(52.78 , -1906.78)

(c) Joint1048-Ux, Joint1048-Uy
Min is -3.254e+02
at 3.976e+01
Max is 3.277e+02
at 4.410e+01
(2.28 , -169.49)

(d) Joint1048-Ux, Joint1048-Uy
Min is -1.567e+03
at 6.440e+00
Max is 1.386e+03
at 8.180e+00

Fig. 7 Some of the top displacement versus time results of **a** Diagrid model Bhuj EQ, **b** Diagrid model El Centro EQ, **c** simple model Bhuj EQ, **d** simple model El Centro EQ

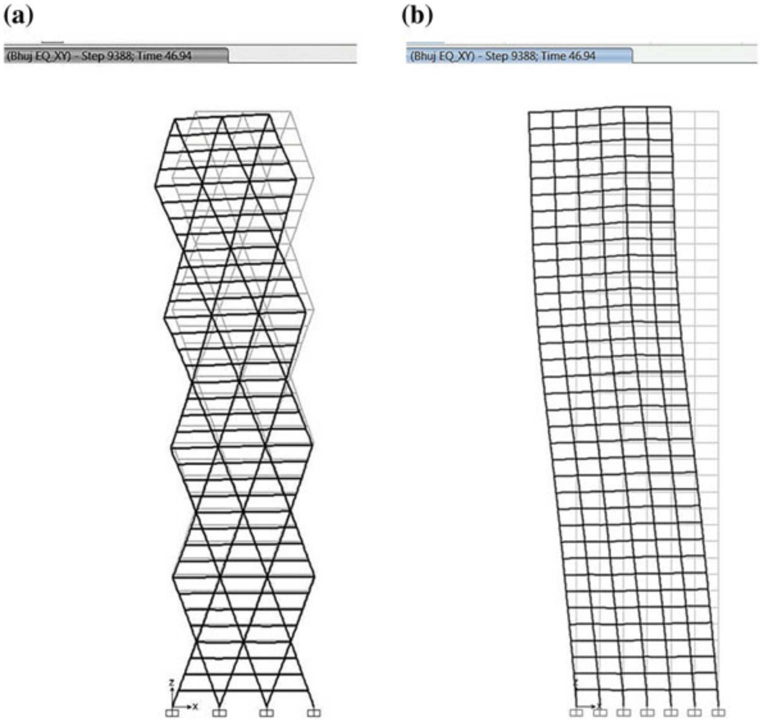


Fig. 8 Deflected shape of the models due to Bhuj EQ at PGA for **a** diagrid model, **b** simple model

5 Conclusion

Diagrid structural mechanism being aesthetically appealing as well effective in providing higher strength, should be adopted for high rise infrastructures. The peripheral diagonal column, because of their unique orientation, transfers all the imposed loads into axial forces, which makes it more optimized as the load transferring mechanism. Conventional vertical columns which transfer load as axial as well as large bending moments, requires higher cross sections, hence larger area and inertia to resist the forces, whereas Diagrid experiences mainly axial forces only, which helps in using smaller sections than the conventional requirement. Results have shown that Diagrid shows a great difference compared to the simple model as far as seismic forces are concerned. The Diagrid model is experiencing much lesser lateral top displacement than the simple conventional model. The deflection values show almost 30–35% deviations, which is a great difference as far as the seismic behaviour of the structure is a concern. Comparatively, lower PGA earthquakes with longer duration can lead to larger top displacements than the higher PGA with short duration. Looking to the top displacement versus time graph (see Fig. 6), it is evident that after the occurrence of PGA, the Diagrid model comes to rest position faster than the simple model, which makes Diagrid much damped than the simple building. This result can lead to optimize the Diagrid mechanism to be used for even much higher tall infrastructures.

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