Preliminary Design of Diagrid Tall Building

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Abstract

A triangulated exoskeleton, or diagird, structural system has emerging as a structurally efficient and architecturally valid solution for tall buildings. The diagrid creates a highly efficient and redundant tube structure by providing a structural network allowing multiple load paths. The diagrid system has higher inherent torsional rigidity than most other structural systems. The structural design of a tall building involves several stages, including the conceptual design, approximate analysis, preliminary design and optimization, followed by detailed and final design.

The objective of this paper is to present the preliminary design methodology for diagrid structural system for tall building. Three buildings with different height (82-, 64-, and 38-story with height of 287m, 224m, and 133m, respectively) and footprint (with plan dimension of 48m x 48m, 52m x 35.5m, and 33m x 33m, respectively) are selected for this study. The preliminary design and optimization follows an iterative approach by satisfying drift and acceleration limits while reducing section sizes and changing the structural system geometry. The methodology of Moon et al [1], with some modifications, is used herein to obtain the preliminary member sizes of the buildings. This preliminary member sizes are checked for suitability under earthquake and wind loads at the preliminary design stage. After a few iterations, preliminary structures are obtained.

1. Introduction

The structural design of a tall building involves several stages, including the conceptual design, approximate analysis, preliminary design and optimization, followed by detailed and final design. The main design criteria are strength, serviceability and human comfort. The aim of the structural engineer is to arrive at suitable structural schemes to satisfy these criteria and assess their relative economy. At the conceptual design stage, for a very tall building design, several structural systems are examined using approximate or simplified analyses to come up with a preliminary structural system for the building. The objective of this paper is to present the preliminary design methodology for diagrid structural system for tall building.

Section 2 to 4 presents the theoretical development and preliminary design studies of 64-, 82-, and 38-story building are presented in Section 5, 6, and 7, respectively. And, Section 8 presents the summary of the study.

2. Optimal Angle of Diagonal Members

With some approximate calculations, Moon et al [1] found that (a) the optimal angle of the diagonals to achieve maximum shear rigidity for a diagrid system is about 35^0, and (b) the optimal angle of the diagonals to achieve maximum bending rigidity is 90^0. Here angle refers to the inclination of the diagonal member with respect to the horizontal plane (Figure 1). As a real structure needs to resist both shear force and bending moment, it is expected that the optimal angle of the diagonal members of a diagrid structure will fall between these two angles. Short buildings with low aspect ratio (height/width) behave like shear beams, and tall buildings with high aspect ratio tend to behave like bending beams. Thus, it is expected that as the building height to base width increases, the optimal angle also increases. Studies of 60 story structures shown in Figure 1 with different diagonal angles (34^0, 53^0, 63^0, 69^0, 76^0, 82^0, 90^0), reveales the building with diagonal angle of 69^0 produce minimum horizontal displacement at the top story [1]. Figure 1 used a constant inclination of braces along the entire height of the structure. Contrarily, studies on the rest of this paper show that better performance for a diagrid structure with high aspect ratio can be achieved through a change in diagonal angles along the height of the structure.

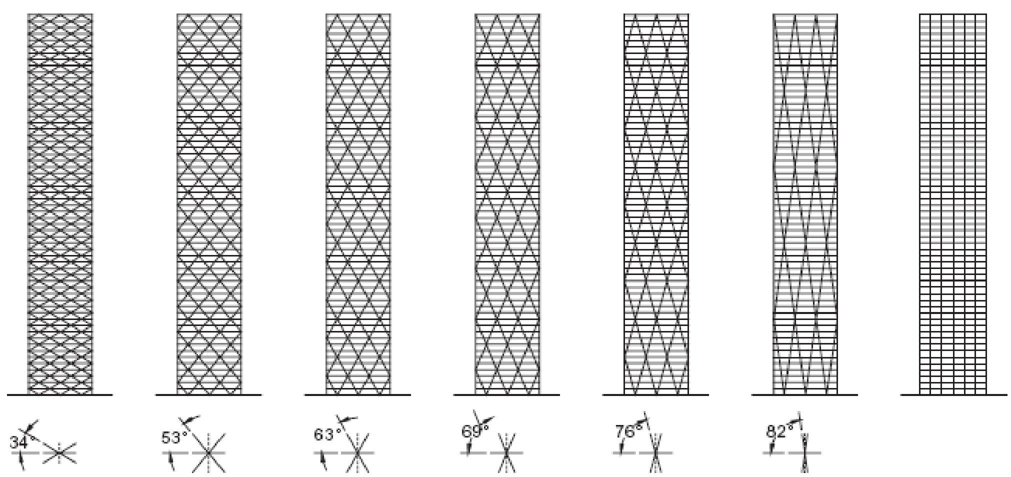

Figure 1: 60-story structures with various diagonal angles to find out optimal angle [1]

3. Shear Stiffness and Bending Stiffness of a Diagrid Structure Module

The working principle of a diagrid system is to convert global building moment, shear and torsion into "axial action" in the diagonal brace elements. This may be visualized as in Figure 2, where an eight-story diagrid structure module is shown. Note in this figure the definition of

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flange and web planes as related to the direction of loading. A stiffness-based approach [2] is followed in this section to study the shear and bending stiffness of a diagrid module.

The building is modelled as a column, and subdivided longitudinally into modules according to the repetitive diagrid pattern selected. Each module is defined by a single set of diagrids that extend over n stories. Figure 2 illustrates the case of an eight-story module. For this approach, diagonal braces are predominantly undergoing axial action; the contributions of bending and torsional forces to deformations are not very significant. Therefore, it is assumed here that axial deformation of braces will be the primary contributor to the total building deformation and, consequently, bending, shear and torsional deformation of braces are neglected in this preliminary analysis.

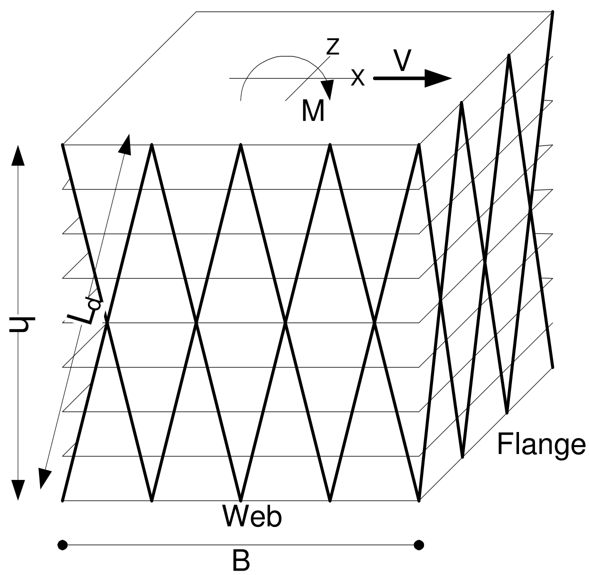


Figure 2: Eight-story diagrid structure module

3.1 Shear Stiffness

Referring to Figure 3(a), which shows only two diagonal braces from the module shown in Figure 2, a shearing force of v_2 contributes to a horizontal displacement of Δu. It can be easily shown that:

$$v_2 = 2\left(\frac{A_d E_d}{L_d}\cos^2\theta\right).\Delta u \tag{1}$$

where, θ is the inclination of the diagonal, A_d is the cross-sectional area of diagonals, E_d is the Young's Modulus of the diagonal material, and L_d is length of the diagonal. If V is the total module shear and Nw is the number of diagonals in one web plane of a module (Figure 2), then

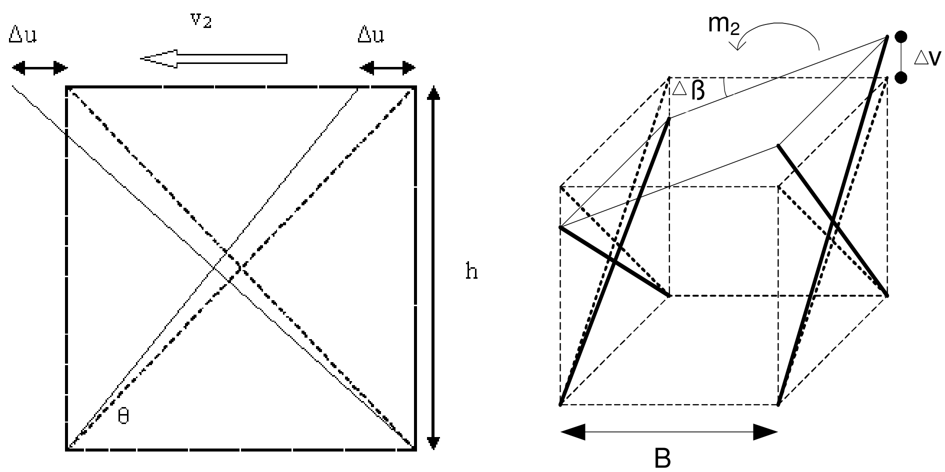
$$V = 2.N_w\left(\frac{A_{d,w} E_d}{L_d}\cos^2\theta\right).\Delta u \tag{2}$$

$$V = K_T.\Delta u \tag{3}$$

where K_T is the equivalent shear stiffness: $K_T = 2.N_w\left(\frac{A_{d,w}E_d}{L_d}\cos^2\theta\right)$ (4)

The relationship between K_T and the equivalent average module transverse shearing strain (γ) is:

$$\gamma = \frac{\Delta u}{h} = \frac{V}{K_T h} \tag{5}$$



(a) (b)

Figure 3: (a) Shear deformation of the module shown in Figure 2 – a portion of the web plane is shown; (b) Bending deformation of the module shown in Figure 2 – a portion of the flange plane is shown

3.2 Bending Stiffness

Referring to Figure 3(b), which shows only two diagonal braces from each flange plane of the module shown in Figure 2, a bending moment of m_2 contributes to a rotation of $\Delta\beta$ to the overall deformation of the module. It can be easily shown from Figure 3(b) that:

$$m_2 = 2\left[\frac{B^2.A_d.E_d}{2.L_d}.\sin^2\theta\right].\Delta\beta \tag{6}$$

If M is the total moment of the module and N_f is the number of diagonals in one flange plane of the module (Figure 2), then

$$M = N_f.\left[\frac{B^2.A_{d,f}.E_d}{2.L_d}.\sin^2\theta\right].\Delta\beta \tag{7}$$

$$M = K_B.\ \Delta\beta \tag{8}$$

Where bending stiffness is: $K_B = N_f.\left[\frac{B^2.A_{d,f}.E_d}{2.L_d}.\sin^2\theta\right]$ (9)

The contribution of bending strain to the overall deformation is:

$\chi = \frac{\Delta\beta}{h}$, if bending strain is constant over the height of the module.

4. Specifying the Shear and Bending Deformation

Moon et al [1] stated that optimal design from a motion perspective corresponds to a state of uniform shear and bending strain (deformation) along the height of the structure under the design loading. Such a distribution is possible as the bending and shear stiffness of the module correspond to those of a truss, where such a distribution is made possible by artful distribution of member sizes. Moon et al [1] applied the principle of uniform shear and bending deformation along the height of the structure, as shown in Figure 4a, for all the preliminary studies. At the beginning, this study utilized the strain distribution in Figure 4a for preliminary sizing of the lateral load resisting system. However, studies discussed on the later parts of this paper reveal that a preliminary design based on a triangular bending and uniform shear strain distribution (Figure 4b), combined with a variation of diagonal angles along the height of the structure, yields much better performance.

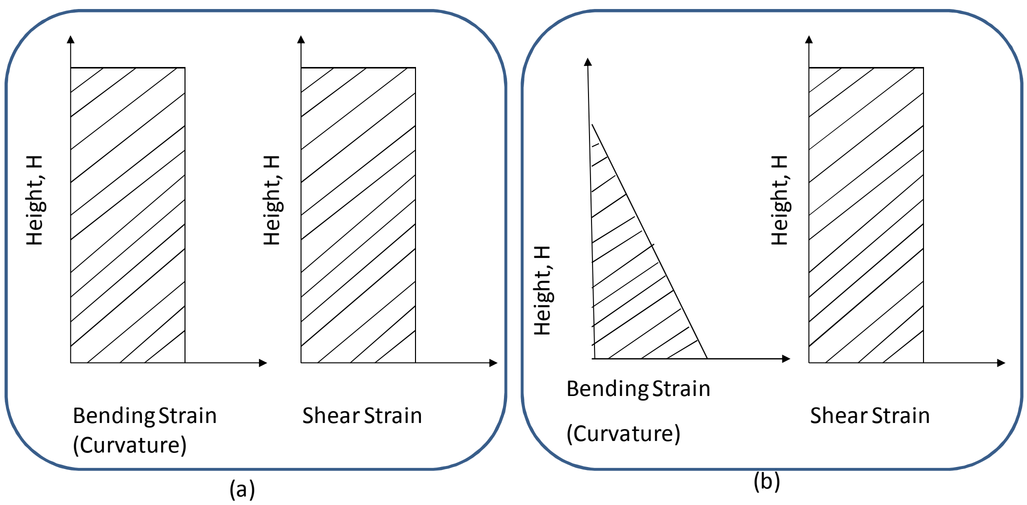


Figure 4: Shear and bending strain distribution along the height of the structure: (a) uniform curvature & shear strain distribution; (b) triangular curvature distribution & uniform shear strain distribution

4.1 Uniform Bending and Shear Strain Distribution

If the members of the lateral load resisting system are proportioned to achieve a uniform bending and shear strain distribution along the height of the building (Figure 4a) and assuming the diagrid structure is modelled as a cantilever beam, the deflection at the roof level of the structure is given by:

$$u(H) = \gamma H + \frac{\chi H^2}{2} \qquad (10)$$

where, γH is the contribution from shear deformation and $\frac{\chi H^2}{2}$ is the contribution from bending. γ is the uniform shear strain and χ is the uniform bending strain (curvature) along the height of the structure.

In order to specify the relative contribution of shear versus bending deformation, a dimensionless factor s is introduced, which is equal to the ratio of the displacement at the top of the structure due to bending and the displacement due to shear:

$$s = \frac{\chi H^2}{2} \Big/ \gamma H = \frac{H\chi}{2\gamma} \tag{11}$$

The maximum allowable displacement is usually expressed as a fraction of the total building height: u(H)=H/α, where typical values ranges from H/500 to H/400. With this allowable displacement and combining equation (10) and (11):

$$u(H) = (1+s)\gamma H = H/\alpha \tag{12}$$

$$\gamma = \frac{1}{(1+s)\alpha} \tag{13}$$

$$\chi = \frac{2s}{H(1+s)\alpha} \tag{14}$$

From these, a parametric study can be carried out to find the optimum value of s . Then Equations (13) and (14) will yield the design values for γ and the rotation (Δβ) at the top of each module (Figure 3b) can be obtained by summing the curvature along the height of the module. If χ is the uniform curvature then, $\Delta\beta = \chi.h$ is the rotation at top of the module.

Inputting the value of γ into Equations (4) and (5) and the $\Delta\beta$ value into equation (7), the member sizes (cross-sectional area) of the module can be computed from the following equations:

$$A_{d,w} = \frac{VL_d}{2N_w E h \gamma \cos^2\theta} \tag{15}$$

$$A_{d,f} = \frac{2ML_d}{N_f B^2 E h \chi \sin^2\theta} \tag{16}$$

where, $A_{d,w}$ is the required cross-sectional area of diagonal members of the web plane (Figure 2) to resist the module shear force of V, and $A_{d,f}$ is the required cross-section area of the diagonal members in the flange plane (Figure 2) to resist the module bending moment of M.

4.2 Triangular Bending and Uniform Shear Strain Distribution

If the members of the lateral load resisting system are proportioned to achieve a triangular bending and uniform shear strain distribution along the height of the building as shown in Figure 4b, and assuming the diagrid structure is modelled as a cantilever beam, the deflection at the roof level of the structure can be given by:

$$u(H) = \gamma H + \frac{1}{3}\phi H^2 \tag{17}$$

where, γH is the contribution from shear deformation and $\frac{1}{3}\phi H^2$ is the contribution from bending and γ is the uniform shear strain and ϕ is the bending strain (curvature) at the base of the structure whereas curvature at the top of the structure is zero as shown in Figure 4b.

In order to specify the relative contribution of shear versus bending deformation, a dimensionless factor s' is introduced, which is equal to the ratio of the displacement at the top of the structure due to bending and the displacement due to shear:

$$s' = \frac{1}{3}\phi H^2 \Big/ \gamma H = \frac{\phi H}{3\gamma} \tag{18}$$

Assuming an allowable displacement and combining Equation (17) and (18):

$$u(H) = (1+s')\gamma H = H/\alpha \tag{19}$$

$$\gamma = \frac{1}{(1+s')\alpha} \tag{20}$$

$$\chi = \frac{3s'}{H(1+s')\alpha} \tag{21}$$

Again, a parametric study is carried out to find an optimum value of s', and then Equations (20) and (21) will yield γ and χ.

Inputting the value of γ into Equations (4) and (5) and the value of $\Delta\beta$ into Equation (7), the member sizes (cross-sectional area) for this strain distribution can be computed using the following equations:

$$A_{d,w} = \frac{VL_d}{2N_w Eh\gamma\cos^2\theta} \tag{22}$$

$$A_{d,f} = \frac{2ML_d}{N_f B^2 E.\Delta\beta.\sin^2\theta} \tag{23}$$

5. Preliminary Design Studies for the 64-story Building

The methodology presented in Section 2 to 4 is applied to the 64-story diagrid structure. Several iterations are carried out to determine the optimal preliminary member sizes and configuration of the diagrid structure so that it can resist both earthquake and wind action efficiently. Although several iterations are carried out, only two iteration steps are presented in this section.

5.1 Iteration 1

The design assumptions used for this iteration are: (i) Uniform bending and shear strain distribution along the height of the structure (Figure 4a); (ii) Constant inclination of braces along the entire height of the structure (Figure 1); (iii) Member sizes are proportioned in such a way that a wind drift of H/500 is achieved.

The first step is to divide the structure into appropriate structural modules. As Section 2 shows, an inclination of about 69^0 is suitable the selected eight-story module (Figure 2). The inclination of the diagonals in the long face (LF) of the module is 64.9^0 and that for the short face (SF) is 67.4^0, which are well within the optimal limits. Eight 8-story modules produce the 64-story structure.

The shear forces and bending moments for each module are calculated based on equivalent static wind loads [3]. Following the calculation steps presented in Section 3 to 4, the member sizes of all the stories are calculated to satisfy both shear and bending requirements [3]. Table 1 presents the preliminary choice of pipe sections for all the diagonals of the building.

Table 1: Preliminary member sizes for the 64-story diagrid structure (Iteration 1)

Story	Pipe section for Long face members	Pipe section for Short face members
1st – 8th	900mm dia, 100mm thickness	750mm dia, 60mm thickness
9th – 16th	830mm dia, 90mm thickness	750mm dia, 57.5mm thickness
17th – 24th	750mm dia, 75mm thickness	750mm dia, 55mm thickness
25th – 32nd	750mm dia, 55mm thickness	750mm dia, 50mm thickness
33rd – 40th	650mm dia, 45mm thickness	700mm dia, 50mm thickness
41st – 48th	550mm dia, 35mm thickness	650mm dia, 42.5mm thickness
49th – 56nd	500mm dia, 25mm thickness	600mm dia, 35mm thickness
57th – 64th	500mm dia, 15mm thickness	550mm dia, 25mm thickness

The structure having the preliminary design of Table 1 is analyzed with SAP2000 for modal properties. Figure 5a shows the mode shapes in the two translational directions. It is evident from the figure that the mode shape lines are not smooth enough, especially in the upper part of the structure. The fundamental periods in the two translational directions are T_{1Z}=4.76 sec and T_{1X}=3.61 sec and in torsional direction T_{1Y}=1.42 sec. The inter-story drift plot (Figure 6a) due to wind shows that the lower part of the structure is extremely stiff and the upper part of the structure is very soft and overall the response of the structure is not satisfactory.

For a quick and very crude estimate of the structure's response to earthquake loads, a non-linear model of this preliminary structure is developed in SAP2000 using an axial link element. The axial link element used can have non-linear hysteretic deformation in the axial direction of the diagonal braces. A bi-linear force-deformation relationship is used for all the braces. The Kobe earthquake motion at Takarazu station is used to perform a 3D nonlinear time history analysis. Figure 7a shows the inter-story drift of the structure and it is evident that overall response of the structure is not satisfactory, as the top part of the structure is again very flexible when compared to the bottom part of the structure.

5.2 Iteration 2

The design assumptions used for this iteration are: (i) a triangular bending and uniform shear strain distribution along the height of the structure (Figure 4b); (ii) a variation of angle of inclination of the braces along the height of the structure (Figure 8a); (c) the member sizes are proportioned in such a way that a wind drift of H/450 is achieved.

Five 8-story modules (Figure 2), two 6-story modules and three 4-story modules are used to construct the 64-story structure as shown in Figure 8a. Thus, the inclination of the diagonals is decreased along the height of the structure. Table 2 presents the preliminary choice of pipe sections for all the diagonals of the building.

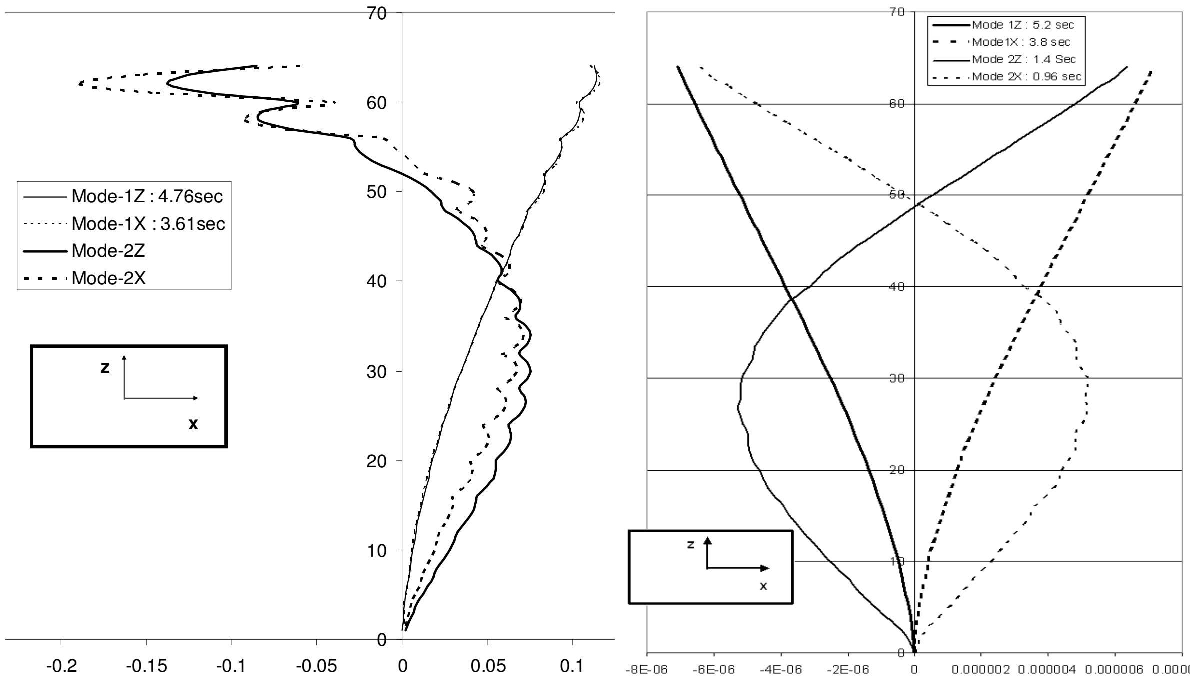
Figure 5b shows the mode shape in the two translational directions. The mode shapes indicate better behaviour of the building. The fundamental periods in the two translational directions are T_{1Z}=5.2 sec and T_{1X}=3.8 sec and in torsional direction T_{1Y}=1.41 sec. A plot of inter-story drifts due to wind is shown in Figure 6b. Inspection of the figure shows the response of the structure appears satisfactory. The maximum acceleration at the roof level is found to be 22.7 mili-g and the RMS acceleration is 6.1 mili-g; both are below the acceptable limits.

Similar to Iteration 1, The Kobe earthquake motion at Takarazu station is used to perform a 3D nonlinear time history analysis. Figure 7b shows the inter-story drift of the structure and it is evident that overall response of the structure is much better compare to the building of Iteration1.

6. Preliminary Design Studies for the 82-story Building

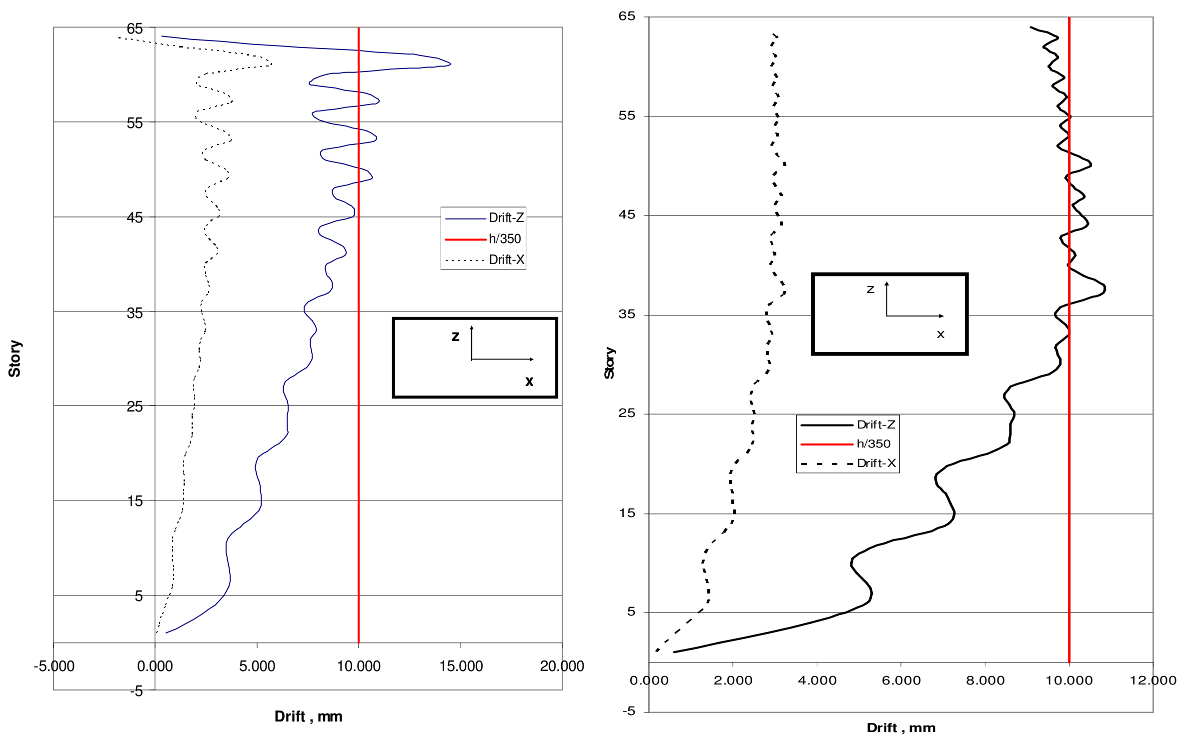
Similar to the 64-story structure, the methodology presented in Section 2 to 4 was applied to the 82-story diagrid structure (Figure 8b). As design assumption in Section 5.2 yielded better performance for the 64-story structure, the same are used for this 82-story structure.

The first step is to divide the structure into appropriate structural modules. Six 8-story modules (Figure 2), three 6-story modules and four 4-story modules are used to construct the 82-story structure as shown in Figure 8b. Thus, the inclination of the diagonals is decreased along the height of the structure. Table 3 presents the preliminary choice of pipe sections for all the diagonals of the building.



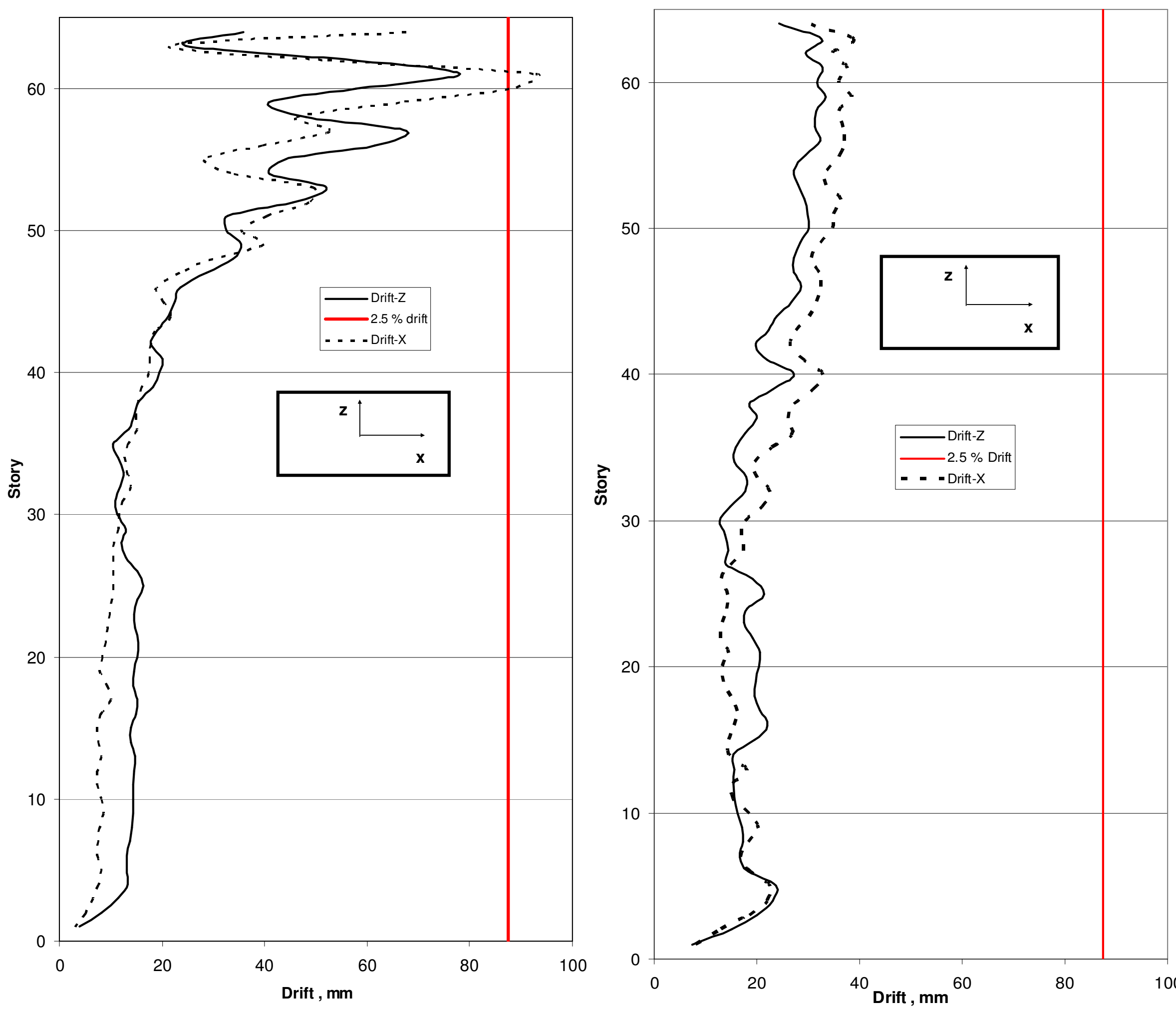
(a) (b)

Figure 5: Mode shape of the 64-story preliminary structure of (a) Iteration-1; (b) Iteration-2



(a) (b)

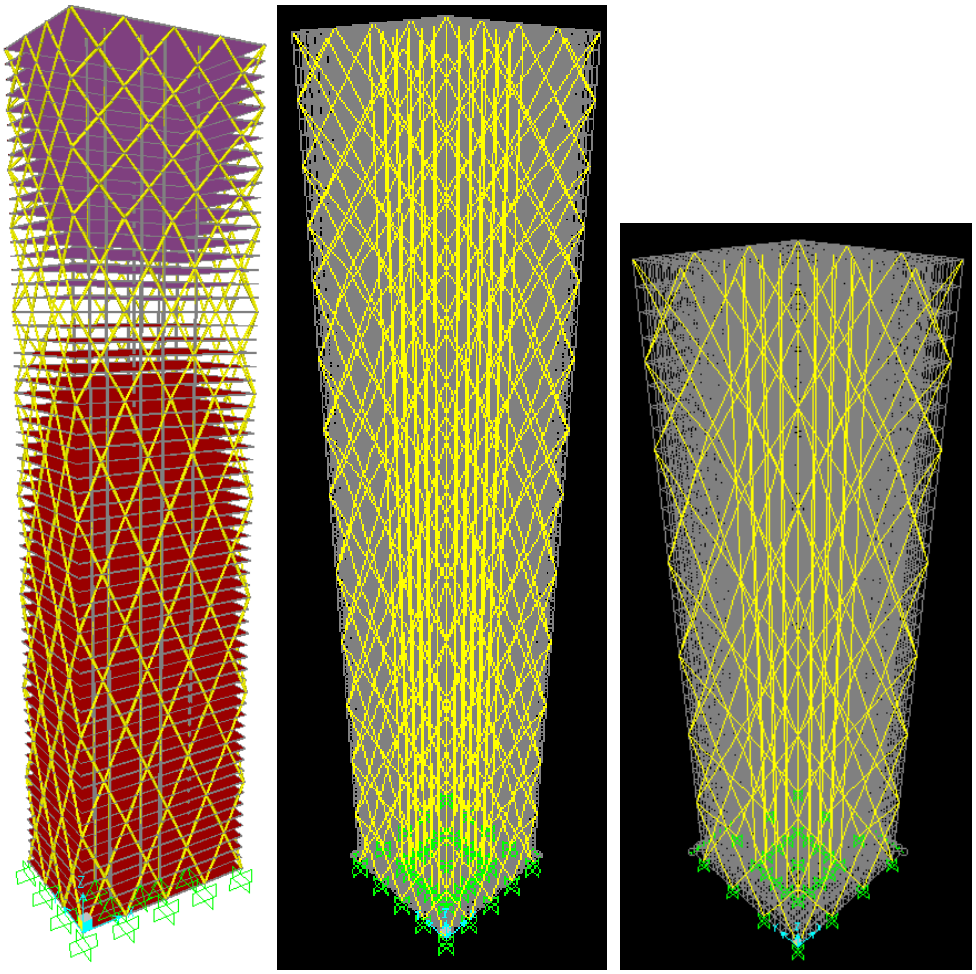
Figure 6: Inter-story drift of the 64-story structure due to wind from (a) Iteration-1; (b) Iteration-2



(a) (b)

Figure 7: Inter-story drift of the 64-story structure due to Kobe earthquake from (a) Iteration-1; (b) Iteration-2

Figure 9a shows the mode shape in the translational direction. The mode shapes indicate that the behaviour of the building is acceptable. The fundamental periods in the two translational directions are T_{1Z}=5.567 sec and T_{1X}=5.567 sec and in torsional direction T_{1Y}=1.558 sec. A plot of deflection of the structure due to wind is shown in Figure 9b. The roof displacement is found to be 0.534 m in cross-wind direction and 0.471 m in along wind direction, which is a little less than H/450. The maximum acceleration at the roof level is found to be 31.9 mili-g and 21.9 mili-g in cross-wind and along-wind direction, respectively; and the RMS acceleration is 8.6 mili-g and 6 mili-g in cross-wind and along-wind direction, respectively. It is important to note here that cross-wind displacement and acceleration dominate the design, as is the case with typical tall building. The limit for maximum acceleration is 25 mili-g and that for RMS acceleration is 9 mili-g. As can be seen, controlling the acceleration and displacement for wind was the main concern during the preliminary design stage of this structure.



(a) (b) (c)

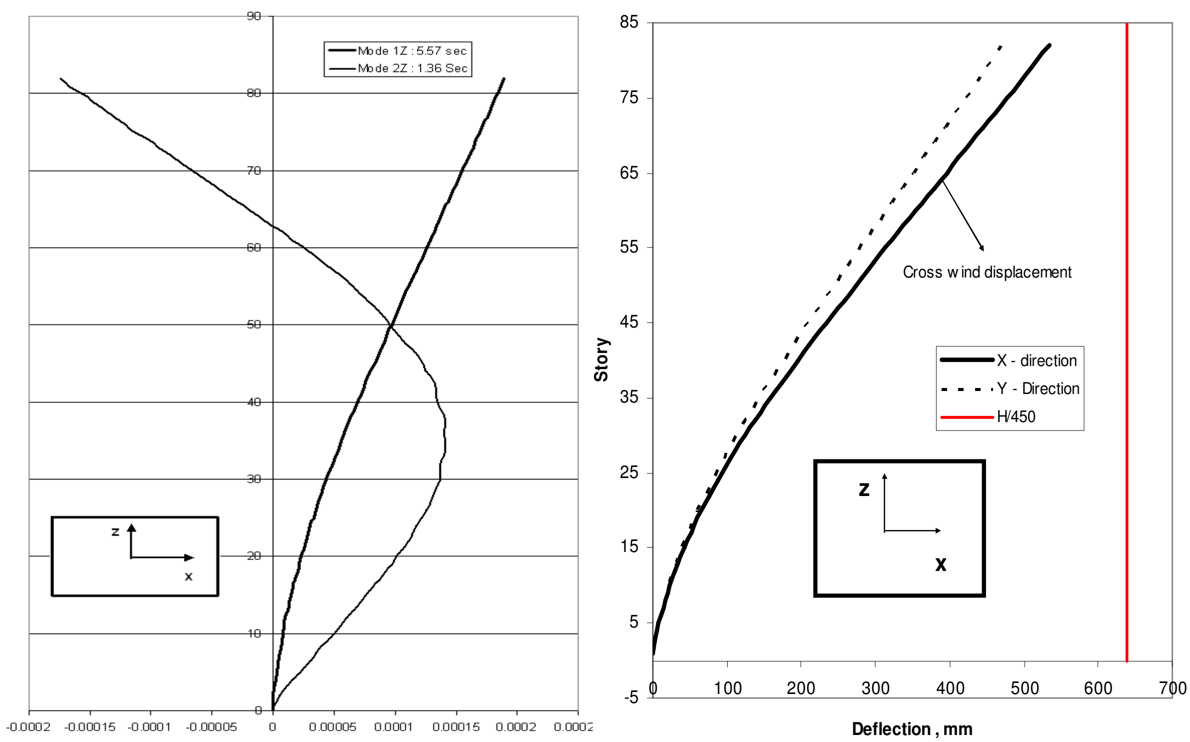
Figure 8: 3-D view of Diagrid structure (a) 64-story; (b) 82-story; (c) 38-story

Table 2: Preliminary member sizes for the 64-story diagrid structure (Iteration 2)

Story	Pipe section for Long face members	Pipe section for Short face members
1st – 8th	750mm dia, 70mm thickness	750mm dia, 50mm thickness
9th – 16th	750mm dia, 70mm thickness	750mm dia, 50mm thickness
17th – 24th	750mm dia, 65mm thickness	750mm dia, 50mm thickness
25th – 32nd	750mm dia, 57.5mm thickness	700mm dia, 47.5mm thickness
33rd – 40th	750mm dia, 50mm thickness	700mm dia, 40mm thickness
41st – 46th	700mm dia, 45mm thickness	650mm dia, 35mm thickness
47th – 52nd	700mm dia, 45mm thickness	650mm dia, 35mm thickness
53rd – 56th	650mm dia, 40mm thickness	600mm dia, 30mm thickness
57th – 60th	650mm dia, 40mm thickness	600mm dia, 30mm thickness
61st – 64th	650mm dia, 40mm thickness	600mm dia, 30mm thickness

Table 3: Preliminary member sizes for the 82-story diagrid structure

Story	Pipe section
1st – 8th	800mm dia, 80mm thickness
9th – 16th	800mm dia, 80mm thickness
17th – 24th	800mm dia, 75mm thickness
25th – 32nd	750mm dia, 75mm thickness
33rd – 40th	750mm dia, 70mm thickness
41st – 48th	750mm dia, 65mm thickness
49th – 54th	750mm dia, 65mm thickness
55th – 60th	700mm dia, 60mm thickness
61st – 66th	700mm dia, 55mm thickness
67th – 70th	700mm dia, 55mm thickness
71st – 74th	650mm dia, 55mm thickness
75th – 78th	650mm dia, 50mm thickness
79th – 82nd	600mm dia, 50mm thickness



(a) (b)

Figure 9:(a) 1st and 2nd translational mode; (b) deflection due to wind of the 82-story structure

7. Preliminary Design Studies for the 38-story Building

Similar to the other two structure, the methodology presented in Section 2 to 4 was applied to the 38-story diagrid structure (Figure 8c). Design assumptions in Section 5.2 are used for this 38-story structure.

Five 6-story modules and two 4-story modules are used to construct the 38-story structure as shown in Figure 8c. Thus, the inclination of the diagonals is decreased along the height of the structure. Preliminary member sizes are shown in Table 4.

Figure 10 shows the mode shape in the translational direction. The mode shapes indicate that the behaviour of the building is acceptable. The roof displacement is found to be 0.144 m, which is a less than H/450 and maximum acceleration at roof level is 15.5 mili-g due to wind. Behaviour of the structure due to seismic action was given much consideration while selecting the preliminary member sizes.

Table 4: Preliminary member sizes for the 38-story diagrid structure

Story	**Pipe section**
1^{st} – 6^{th}	450mm dia, 30mm thickness
7^{th} – 12^{th}	450mm dia, 30mm thickness
13^{th} – 18^{th}	500mm dia, 30mm thickness
19^{th} – 24^{nd}	475mm dia, 30mm thickness
25^{rd} – 30^{th}	450mm dia, 30mm thickness
31^{st} – 34^{th}	425mm dia, 25mm thickness
35^{th} – 38^{th}	425mm dia, 25mm thickness

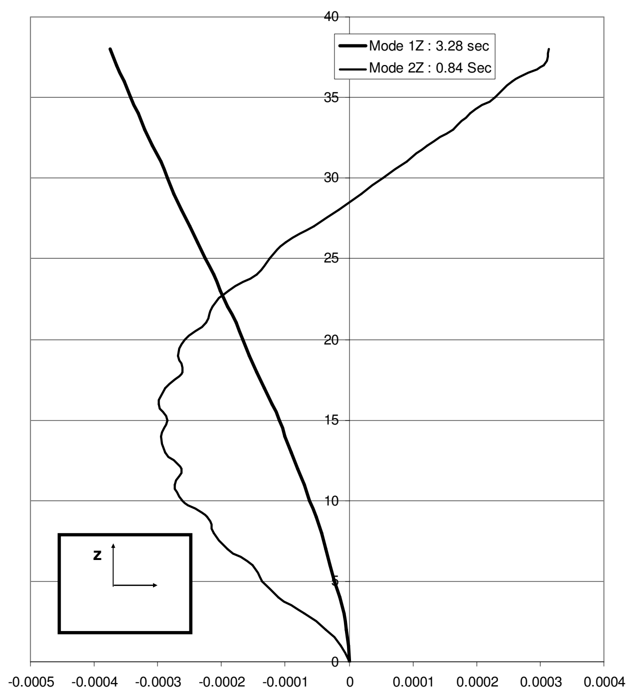


Figure 10: 1^{st} and 2^{nd} translational mode of the 38-story building

8. Conclusion

Preliminary design and optimization for diagrid structural system is presented in this paper. Case studies of three buildings with different height (82-, 64-, and 38-story) and footprint are presented. Following the methodology presented here, the preliminary structure of all the buildings satisfy the requirements: (a) H/450 limit on top floor displacement; (b) h/350 inter-story drift limit for wind; (c) 9 mili-g RMS acceleration limit, etc. The study shows that better dynamic behaviour of a tall diagrid structure can be obtained by changing the diagonals' angle of inclination along the building height and by assuming a philosophy of *constant shear strain* distribution combined with a *triangular flexural strain* distribution along building height. This more effectively forces most of the nonlinearity to occur in the lower portion of the structure during an earthquake and resulted in a better inter-story drift distribution along the height of the building for a wind event.

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