Research on Mechanical Behaviour of High-rise Diagonal Grid Tube Structure and Case study

Qian Fu 1, Xuerong Wang 1, Tao Dai 2
1 School of Information Engineering, Nanjing Audit University, Nanjing 211815, China
2 China Shanghai Architectural Design & Research Institute Co., Ltd., Shanghai 200063, China

wangxuerong4079@126.com

Abstract. In order to obtain the mechanical characteristics of high-rise diagonal grid tube structure under horizontal and/or vertical loads, three types of structure model, which were diagonal grid tube structure, diagonal grid–frame tube and framed tube structure, were established by the finite element software Etabs. The laws of internal force distribution, interstory displacement, base shear and shear hysteresis effect, were analysed deeply. The results from three-model showed that compared with the framed tube structure, the diagonal grid tube structure had the larger stiffness and the shorter period. Under the horizontal seismic load, the total shear force of the diagonal grid tube structure improved 20% by that of the conventional framed tube structure, with the interlayer shear force and the interlayer displacement angle distribution keeping basically the same. The inclining column to the diagonal grid structure could enhance the lateral stiffness in its plane effectively, but hardly improve the lateral stiffness out of its plane. Then, the performance under the vertical load was also discussed. Under the action of the vertical load, the shear hysteresis effect appeared, especially for the flange inclined column. Subsequently, the feasibility of the diagonal grid tube in the engineering projects was evaluated. The finite element software ABAQUS was used to analyse the dynamic elastoplastic time history performance of a one-way oblique grid system high-rise building under rare earthquakes. The results showed that the maximum interlayer displacement of the structure was less than the limit of Chinese codes and standards, and the structure could achieve the goal of anti-seismic fortification without collapse under strong earthquakes. There was a conclusion that the diagonal grid tube could be applied as a part of the overall structure for high-rise or super-tall buildings in the zones with seismic design intensity of 7 degree.

1. Introduction
As the outer tube of high-rise buildings, the oblique grid composed of two-way continuous crossed diagonal bars could provide greater lateral stiffness and bear horizontal and vertical loads at the same time [1-3]. In the 1960s, the U.S. IBM Building first adopted an oblique grid structure system, and then the Swiss Re Building, Hearst Building, CCTV Building, Canton Tower and other buildings were built one after another, indicating that it had been increasingly applied to high-rise building structures as a new structural system.
U.S. scholar Moon K-S (2005) [4-5] first proposed the concept of oblique grid and discussed the optimization of oblique column angle. Johan Leonard [6] analyzed the influence of oblique column angle and column spacing on the lateral displacement and shear-lag effect of oblique grid structure. In China, Zhang Chonghou first proposed the concept of high-rise oblique grid structure, proposed the basic structure of high-rise oblique grid structure system, and analyzed the relevant influencing factors of its lateral resistance [7-8]. Fang Xiaodan et al. [9] conducted an experimental study on the plane and space intersecting joint model of concrete-filled steel tubular (CFST) columns outside the oblique grid of Canton West Tower. They proposed two joint structures, and analyzed the joint structures, their failure modes and ultimate bearing capacity under different inclined angles and different loading modes. Han Xiaolei [10] used PERFORM-3D software to carry out nonlinear analysis of super-high-rise concrete filled steel tube mega-oblique grid tube-in-tube structures under strong earthquakes. The responses of the structures under earthquakes of 7, 8 and 9 degrees were compared. The results showed that the structural system is suitable for high seismic fortification zones and provides a basis for the application of the structural system. G.Milana and P.Olmati et al. [11] studied the lateral resistance and ductility of 40-floor oblique grid structures with 42°, 60° and 75° and frame core-tube structures with outrigger trusses. The calculation results showed that the skew grid structure with 60° has the best structural performance. J.Leonard [12] made a comparative study on the shear-lag effect of 60-floor oblique grid tube structure and traditional frame tube structure. Shi Qingxuan and Ren Hao et al. [13-14] studied the generation mechanism of shear-lag effect of high-rise oblique grid structure, and compared it with frame-tube structure, and analyzed the influence of oblique angle, span-to-height ratio of main ring beam, height-to-width ratio of structure and arrangement of corner columns on shear-lag effect of high-rise oblique grid-tube structure.

This paper is organized as the following. In Section I, the research and development of oblique grid structure system is summarized and commented. In Section II, three types of structure model, which are diagonal grid tube structure, diagonal grid–frame tube and framed tube structure, are established respectively. The influence of oblique grid on the mechanical properties such as lateral stiffness and shear lag of buildings is emphatically investigated. In Section III, the feasibility of the diagonal grid system in practical application is verified through the dynamic elastoplastic time-history response analysis of a one-way skew grid over.run high-rise building under rare earthquakes. Finally, the conclusions of this paper are summarized.

2. Analysis on mechanical behaviour of diagonal grid tube structure

2.1 Model establishment

Three types of structure model were established by the finite element software Etabs, which were model A, model B, and C, shown in Figure 1. Model A was a structure composed of diagonal grid tube (steel) and shear wall-corewall (reinforced concrete). Model B was a structure composed of diagonal grid tube-frame tube (steel) and shear wall-corewall (reinforced concrete). And Model C was a structure composed of frame tube (steel) and shear wall-corewall (reinforced concrete). Four corner columns were placed at the four corners of the models respectively. Meanwhile, the steel consumption of the rest frame column was the same with the corner columns’. The shear wall-corewall had the same size and thickness of the three models. The main parameters of the model could be described as follows. The models consisted of 30 layers, with a total height of 108 m and 5.4 m storey height. The size of outer frame was 30m×30m, while the inner core tube 15m×15m. C50 concrete was used for the first to tenth floors, C40 for the eleventh to twentieth floors and C30 for the twenty-first to thirty floors. The thickness of corewall outer walls was 300mm, while with 200mm of the inner walls. The distance between the inner and outer walls was 7.5m. Based on the assumption of rigid slab, the thickness of slab was 120mm. Other parameters of the models were shown in Table 1.
2.2 Loading Arrangement

The values of storey dead load (D) and live load (L) were 5kN/m² and 3 kN/m² respectively, according to Chinese architectural structure load standards (GB50009-2001). Fundamental wind pressure was the basic data, and $v_0 = 0.9$ kN/m² of 100 year frequency, in structural wind resistance design. The wind load coefficient of the structure was taken as $s = 1.4$, and the ground roughness was B.

Considering the torsion effect under bi-directional earthquake action on the structure and no vertical earthquake action, the Responses under Horizontal Earthquake of the models was calculated by using the mode-superposition response spectrum method given in Chinese seismic design code (GB50011-2010). The seismic intensity was 7 degree ($0.15g$), with the classification of design earthquake NO.1, the characteristic period of the site $T_g$ of 0.45s and the period shortening factor given of 0.9, for the ground case III. The maximum influence coefficient of horizontal earthquakes under frequent earthquakes was 0.12. The structural damping ratio was 0.04, and the quality source was calculated according to the formula $1.0D + 0.5L$.

2.3 Results Analysis

Modal analysis and elastic stage analysis under gravity load representative value, wind load and earthquake load are respectively carried out on the above three models. Table 2 shows the parameter comparison of model analysis.

From the modal analysis results in the above table, it can be seen that the three models all show the conventional structural characteristics of first-order second-order translational third-order torsion, in which the period of Model A is the smallest, Model C is the second, Model B is the largest, the structural dimensions of beam-slab walls of the three models are the same, the total mass of structures is approximately equal, only the arrangement of columns is different, which indicates that the overall spatial stiffness of oblique grid tubes is larger than that of frame tubes, and in Model B, the natural
vibration period along the plane direction of vertical frame columns is the largest. The natural vibration period along the plane direction of the oblique grid is included in Model A and Model C, which shows that the oblique column in the oblique grid structure can provide greater lateral stiffness in plane, but its contribution to lateral stiffness out of plane is weak.

Table 2. Parameter comparison of model analysis

| Structure form | Total mass (103kg) | T1(s)  | T2(s)  | T3(s)  | T4(s)  | T5(s)  | T6(s)  |
|---------------|-------------------|--------|--------|--------|--------|--------|--------|
| Model A       | 42920             | 1.58   | 1.58   | 0.62   | 0.37   | 0.37   | 0.21   |
| Model B       | 42080             | 2.23   | (Along the direction of frame column) | 1.63   | (Along oblique grid direction) | 0.78   | 0.45   | 0.37   | 0.26   |
| Model C       | 41720             | 2.04   | 2.04   | 0.86   | 0.44   | 0.44   | 0.29   |

The distribution of earthquake shear force among inner and outer tubes and the displacement of structures in three models were given in Table 3. under bi-directional earthquake action. It can be seen from Table. 3. that, the total shear force of the Model C is the smallest among the three, while that of model A is between B and C. The proportion of Model C, Model A and Model B is 1:1.23: 1.34. There are also obvious differences in the distribution of seismic shear forces between the inner and outer tube of the three structural models. The shear force that diagonal grid tube bears accounts for 36.4% of total shear force in Model A. In Model B, most of the shear force can be beared by the shear wall-corewall, while that outer frame tube bearing only occupied 4.7%, under the X direction (in the direction of the vertical frame column plane) horizontal earthquake action. The shear force beared by the outer frame tube equivalents to that of Model A, under the Y direction (in the plane direction of diagonal grid) horizontal earthquake action. However, the shear force that outer frame tube bears accounts for 7.3% of total shear force. The top displacement of Model B is the largest in the X direction and the smallest in the Y direction, among the three models. The position of the maximum drift angle is located at the upper middle of the structure.

Table 3. Shear and displacement

| Structure form | X-horizontal earthquake (kN) | Y-horizontal earthquake (kN) | X/Y top displacement (mm) |
|---------------|-------------------------------|-------------------------------|--------------------------|
|               | Qx(kN)                        | Qy(kN)                        | X/Y maximum drift angle   |
| Model A       | 5612                          | 9824                          | 40/40                    |
| Model B       | 792                           | 16000                         | 60.9/38.3                |
| Model C       | 921                           | 11647                         | 55.3/55.3                |

Q\text{x} represents the shear beared by the outer frame, and Q\text{y} represents the shear beared by the shear wall-corewall.

Distribution maps of interlayer shear and drift angle under horizontal earthquake are shown in Figure 2 and Figure 3, respectively. It can be seen that the shear beared by diagonal grid tube is slightly larger than that beared by vertical frame column, however, interlayer drift angle is slightly smaller among the three models.
Distribution maps of bending moment and axial force of single outer frame under horizontal earthquake are shown in Figure 4. It can be seen that the bending moment mutation at the intersection of the main floor beam and the corner column is not obvious in the diagonal grid tube structure. The vertical displacements of three models are 16.1 mm for model A, 14.3 mm for model B and 13.2 mm for model C under vertical loads, with no obvious difference.

2.4. Shear-Lag Effect of Skew Net Cylinder
Based on the Model A with a 65° in the previous section, only seismic load is applied in its X direction. Figure 5 shows the vertical axial force distribution at the four intersections of the web frame part and the corresponding compression flange frame part of the layer where the oblique column and the corner column intersect. As can be seen from Figure 5:

1) When the oblique grid is used as the peripheral cylinder of the frame-tube structure, there is also a shear-lag effect under lateral load, of which the flange frame is obvious and the web frame is not obvious.

2) Compared with the general dense column deep beam frame-tube structure, under the action of lateral load, the axial force distribution of the oblique grid tube flange frame is small in the middle and large on both sides, but in the area above the middle of the structure, its axial force shows the trend of large in the middle and small on both sides, and in the top area of the structure, the axial force is in tension at the intersection of two corner columns and inclined columns in the plane of the compressed
flange, which is different from the dense column deep beam frame-tube; In the plane of web plate, the shear lag curve from the bottom to the top of the structure is equivalent, unlike the curve of dense column deep beam frame tube which tends to be flat with the increase of height.

The shear-lag effect of skew grid structure makes the stress of skew members uneven, which should be considered as an important factor in actual engineering design. Generally speaking, selecting a reasonable oblique angle of the inclined column has a certain influence on the shear lag of the structure, and the smaller the oblique angle is, the better it is to avoid the occurrence of shear lag. Another important factor affecting the shear-lag effect is the plane shape and side length of the mesh tube. The longer the flange frame, the greater the shear lag, and the smaller the axial force of the column in the middle of the flange frame. Therefore, squares, circles and regular polygons are ideal plane shapes for frame tube structures, and too large a plane length dimension of the net tube or rectangular planes are unfavorable.

![Graphs showing shear-lag effect](image)

3. Engineering Application
The tower structure has a total height of 313.8m and adopts concrete-filled steel tube columns, profiled steel beams and reinforced concrete core tube structures, and steel skew grid trusses are adopted on the east and west sides. The aspect ratio of the structure is 8.2 and that of the core tube is 18.9. Only two columns are set up on the east and west sides respectively, with 500mm high H-section steel skew grid truss in between, and the column spacing is 33.6 meters (west) and 38.1 meters (east), respectively. The steel skew grid truss is shown in Figure 6(a).

In order to improve the ductility of the outer frame and reduce the section size of the frame column, the frame column adopts concrete filled steel tube columns, the ratio of the column diameter to the wall thickness of the steel tube is controlled between 40 and 50, the section size of the frame column at the bottom layer is Φ1800mm, and the section size is gradually reduced upward to Φ 1000 mm; The east and west sides are combined with the building facade effect, only two square concrete-filled steel tube columns with a size of 2000x2500mm are respectively arranged, and the section size is gradually
reduced upwards to 600x2500mm: The frame beam is a profiled steel beam with a height of 600 mm. The schematic diagram of the outer frame is shown in Figure 6(b). The size of the bottom core tube is 16.5x29.0m, the shear wall thickness is 1100mm, and the section size is gradually reduced upward to 550 mm. The schematic diagram of shear wall is shown in Figure 6(c). Four outrigger trusses are arranged along the Y direction in the 24-and 56-storey equipment refuge floors to increase the rigidity of the structure along the Y direction, and waist trusses are arranged to be connected at the periphery, so that the vertical members of the outer frame are stressed uniformly, and the two lateral force resistant structural systems jointly bear the overturning moment and shear force of the structure caused by wind load and earthquake action through the outrigger trusses arranged on the two floors. The schematic diagram of the outrigger truss is shown in Figure 6(d). The bearing capacity of the reinforced part at the bottom of the barrel is designed according to the non-yielding design under moderate earthquake, and section steel is arranged in the shear wall of the core barrel. Steel columns embedded in shear walls are shown in Figure 6(e).

![Figure 6. Model schematic diagram](image)

### 3.1 Establishment of Finite Element Model

When establishing ABAQUS dynamic elasto-plastic analysis model, the ETABS model should be designed in depth, the membrane element floor in the model should be changed into shell element, and the shell element of the floor should be automatically divided at the intersection of node and beam element. After that, the ETABS model is exported to SAP2000, and all shell elements and beam elements are subdivided in SAP2000. In the process of subdivision, beam elements and shell elements share nodes as much as possible. The subdivision size of the unit is controlled at about 2m. After subdividing the cells, the nodes are merged according to a tolerance of 0.05m to remove redundant nodes. At the same time, the beam element with length less than 0.5m and the shell element with too small circumference or area are eliminated to ensure the rationality of calculating the time step in the display time history analysis of the ABAQUS model finally generated.

Members such as steel beams, concrete-filled steel tubes, embedded steel columns in shear walls and steel oblique grid trusses are all simulated by B31 element provided by ABAQUS. Shear wall and floor are simulated by quadrilateral reduced integral shell element, in which floor is considered as elastic element. The steel Model Adopts bilinear dynamic hardening Model and considers Bauschinger effect. In the cycle process, there is no stiffness degradation. Set the strength-to-buckling ratio of steel to 1.2 and the ultimate strain to 0.025. The shell element adopts the elastoplastic damage constitutive model of concrete in ABAQUS program.

Rayleigh damping system is used in ABAQUS explicit analysis beita stiffness damping in this system seriously affects the time step of stability calculation. After trial calculation, Rayleigh damping system considering only alpha mass damping is adopted in the analysis. The free vibration method is
used to calculate the corresponding alpha value according to the natural vibration frequency and damping ratio corresponding to the first vibration mode of the structure. Damping ratio of steel-concrete hybrid structure is 0.05 in large earthquake elastoplastic analysis.

3.2 Elastoplastic Result Analysis

3.2.1 ABAQUS Model Modal Analysis Results
Modal analysis is carried out on the structural model, which is shown in Table 4. The results show that the first period and the second period of the structure are close to each other, which indicates that the oblique grid truss is adopted on the east and west sides to effectively improve the rigidity of the structure in the north and south directions.

| Table 4. Modal analysis |
|-------------------------|
| T₁/s | T₂/s | T₃/s | T₄/s | T₅/s | T₆/s |
| ABAQUS | 7.23 | 6.73 | 4.08 | 2.08 | 1.66 | 1.33 |

3.2.2 Overall Deformation of Structure
Under rare earthquake, the structure can complete 35s dynamic elasto-plastic time history analysis, and the maximum displacement of the vertex of the structure is 1/147 of the total height of the structure. Considering the second-order effect and large deformation, the structure can finally remain upright, meeting the seismic fortification requirement of "no collapse under large earthquake".

3.2.3 Elasto-plastic Maximum Interlayer Displacement under Rare Earthquakes
Take the position shown in Figure 6 and take the four nodes around the shear wall core barrel as the input points and analysis points of structural displacement. Figure 7 shows the variation curve of the maximum elastic-plastic interlayer displacement angle of each layer along the height under six working conditions. According to the code for seismic design of buildings, the limit value of the elastic-plastic displacement angle of the hybrid frame-reinforced concrete core tube structure is 1/100, and it can be seen from Figure 7 that the interlayer displacement angle of the structure does not exceed the limit value of the code.

| Figure 7. Elasto-plastic interlaminar displacement angle under various working conditions |

3.2.4 Maximum Floor Shear Force of Structure under Rare Earthquakes
Since the results of six time-history conditions of seismic wave are basically the same, the representative L256-257 wave (X:Y=1:0.85) condition is selected for analysis.

1) L256-257 wave (X:Y=1:0.85)
Figure 8 shows the interlayer shear time history of the first floor of the structure in x and y directions respectively. From the time-history curves shown above, it can be concluded that the maximum base shear forces in the X and Y directions are 141MN and 148MN under this working condition, and the corresponding maximum shear weights are as follows.

| Table 5. Maximum base shear-weight ratio |
|----------------------------------------|
| X direction   | Y direction   |
| Maximum base shear (MN)   | 141         | 148         |
| shear-weight ratio         | 7.1%        | 7.5%        |

2) L781-L782 wave (X:Y=1:0.85)

Figure 9 shows the interlayer shear time history of the first floor of the structure in X and Y directions respectively. From the time history curves shown above, it can be concluded that the maximum base shear forces in the X and Y directions are 134MN and 181MN under this working condition, and the corresponding maximum shear weights are shown in Table 6 below.

| Table 6. Maximum base shear-weight ratio |
|----------------------------------------|
| X direction   | Y direction   |
| Maximum base shear (MN)   | 134         | 181         |
| shear-weight ratio         | 6.8%        | 9.4%        |

3) L750-4-L750-5 wave (X:Y=0.85:1)
Figure 10. Time history curves of base shear in X and Y directions

Table 7. Maximum base shear-weight ratio

|         | X direction | Y direction |
|---------|-------------|-------------|
| Maximum base shear (MN) | 112 | 193 |
| shear-weight ratio | 5.6% | 9.8% |

As can be seen from Table 7, the requirements are met in both directions. From the above, it can be seen that the overall seismic performance of the structure (inter-floor displacement angle, shear force between the first stories, etc.) meets the specification requirements, and the oblique grid truss effectively improves the Y-direction stiffness of the structure.

The whole structure and all kinds of components still have large elastic-plastic deformation capacity reserve, and the earthquake damage is relatively light, thus meeting the requirements of seismic performance design objectives. Under the action of rare earthquake, the whole structure is safe and there is no danger of collapse. The seismic performance meets the seismic performance goal of "no collapse under large earthquake".

From the above, it can be seen that the overall seismic performance of the structure (inter-floor displacement angle, shear force between the first stories, etc.) meets the specification requirements, and the oblique grid truss effectively improves the Y-direction stiffness of the structure.

The whole structure and all kinds of components still have large elastic-plastic deformation capacity reserve, and the earthquake damage is relatively light, thus meeting the requirements of seismic performance design objectives. Under the action of rare earthquake, the whole structure is safe and there is no danger of collapse. The seismic performance meets the seismic performance goal of "no collapse under large earthquake".

4. Conclusions

The main conclusions of the study may be presented as follows:

1) The diagonal grid tube has the characteristics of greater rigidity and shorter period. The total seismic shear force under horizontal earthquake is 20% more than that of the former, but the distribution of interlayer shear force and interlayer displacement angle is basically the same. Under the action of lateral load, there is also a shear-lag effect in the oblique net cylinder, in which the inclined column at the flange is more obvious. In the bottom region of the structure, the axial force distribution is smaller in the middle and larger on both sides, but in the region above the middle of the structure, the axial force is larger in the middle and smaller on both sides;

2) Taking a super high-rise building project as the background, combined with the application of diagonal grid tube and frame combination as the peripheral frame of the overall structure in this project, the
A dynamic elasto-plastic time history analysis under rare earthquake is carried out by using finite element software. The results show that the maximum inter-floor displacement of the structure is less than the standard limit, and the structure can meet the fortification requirement of "no collapse under large earthquake". Diagonal grid tube can be used as a part of the whole structure in high-rise or super-high-rise building structures in earthquake areas.

Acknowledgment

This work is supported by the State Natural Science Fund project of China (71471082).

References

[1] J. P. Moehle, “Displacement based design of RC structures,” Proc. 10th world conf. earthquake eng., Madrid. Its Appl., pp. 4297–4302, 1992.
[2] Fajfar, P.and Fischinger, M, “Non-linear seismic analysis of RC Buildings: Implications of a case study,” European Earthquake Engineering s., vol.1, 31–43.
[3] Chopra AK, “Dynamics of Structures: Theory and Applications to Earthquake Engineering,” Prentice-Hall: Englewood Cliffs s., Its Appl., 1995.
[4] Moon K-S, Connor J, and Fernandez J, “Diagrid structural systems for tall buildings : Characteristics and methodology for preliminary design,” The Structural Design of Tall and Special Buildings., vol.2, 205–230, 2007.
[5] Moon K-S, “Optimal grid geometry of diagrid structures for tall buildings,” Architectural Science Review., vol.3, 239–251, 2008.
[6] Leonard J. Investigation of shear Lag Effect in High-rise Buildings with Diagrid system., Cambri-dge: Massachusetts Institute of Technology., Its Appl., 2007.
[7] Zhang Qinghou and Zhao Feng, “Basic concepts of high-rise reticulated tube structure system,” Journal of Tsinghua University (Natural Science Edition)., vol.9, 1399–1403, 2008.
[8] Zhang Qinghou and Zhao Feng, “Analysis of Related Influencing Factors on Lateral Resistance of High-rise Oblique Lattice Tube Structural System,” Civil Engineering Journal., vol.11, 42–46, 2009.
[9] Fang Xiaodan, “Experimental research on large intersected joints of guangzhou tower with oblique grid,” Journal of Architectural Structure., vol.1, 56–62, 2010.
[10] Han Xiaolei and Chen Xuewei, “Nonlinear Analysis of Concrete Filled Steel Tubular Mega-Oblique Mesh Cylinder Structure,” Journal of Seismic Engineering and Engineering Vibration., vol.4, 77–84, 2009.
[11] Milana G., Olmati P and Gkoumas K, “Ultimate capacity of diagrid systems for tall buildings in normal configuration and damaged state,” Periodica polytechnica civil engineering., vol.59, 381–391,2015.
[12] Leonard J., “Investigation of shear lag effect in high-rise buildings with diagrid system, Massachusetts institute of technology,” 2007.
[13] Shi Qingxuan and Ren Hao, “Study on Lateral Displacement Angle of Oblique Mesh Tube Structure in High-rise Buildings,” Journal of Xi'an University of Architectural Science and Technology (Natural Science Edition)., vol.6, 771–775, 2015.
[14] Shi Qingxuan and Ren Hao, “Study on shear lag effect of skew grid tube structure in high-rise buildings,” Journal of Architectural Structure., vol.4, 1–7, 2016.