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CALCULATION AND ANALYSIS OF THE PHYSICAL STOREY DRIFT FOR HIGH-RISE FRAME-DIAGRID STRUCTURES

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ABSTRACT

The high-rise frame-diagrid structure is a new type of dual system structure. The inner frame part can create a large space, and the external diagrid part can provide a larger lateral stiffness. In this paper, the lateral deformation formula for the high-rise frame-diagrid structures is derived. The bending deformation of the structure is divided into the bending rotational deformation and the floor rigid rotational deformation. The physical storey drift is proposed. The physical storey drift is directly related to the structural damage. When the structure is in the plastic state, the structure maximum storey drift and maximum physical storey drift are in different positions. It is recommended to use both storey drift and physical storey drift as structural deformation limitation criteria. Finally, the proposed method is used to structural parameters analysis for the high-rise frame-diagrid structure. It provides reference for the structural design.

KEYWORDS

Dual system; Lateral deformation; Bending deformation; Physical storey drift; Parameters analysis

INTRODUCTION

The traditional frame structure has better mechanical behaviour when it is subjected to gravity loads. But the lateral stiffness of the frame structure is caused by the bending and shearing stiffness of the beam and column, and the lateral stiffness is smaller than other structural systems [1]. With the increase of building height, structural deformation cannot be ignored by horizontal loads such as wind and seismic load. For this reason, a diagrid structure with large lateral stiffness is to be used in practice [2, 3]. The diagrid structure is a triangular space grid structure system composed of diagonal columns and ring beams [3]. The diagonal column in the diagrid structure system is mainly subjected to axial force, which can effectively utilize the material mechanical properties to provide greater lateral stiffness [4, 5]. At present, the diagrid structure has been successfully applied to practical projects such as the West Tower of Guangzhou in China, the Hearst Building in New York, and the CCTV headquarters in China [6]. And the super high-rise building approximately under 200 meters high can accommodate the diagrid tube outer cylinder and the interior include frame structures. This typical practice to it is the New York Hearst Building. This structural system can be called a high-rise frame diagrid structure.

High-rise buildings deformation limitation criteria is especially important in structural design [7, 8]. The storey drift is also an important limitation criteria, and frame-diagrid structure is no

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exception. The main purpose of limiting the storey drift of high-rise buildings is threefold: (a) to ensure the stability of the structure; (b) to prevent cracking or obvious damage of non-structural components such as infill walls and decoration; (c) to satisfy human comfort under horizontal loads. The seismic hazard showed that there is a clear relationship between the storey drift and the building damage. The storey drift limitation required in the most building design codes [9-12]. However, these specifications do not distinguish different lateral deformation features. For example, the structure dominated by bending deformation will have a large error, which should be deducted the influence of the rotational deformation of the rigid body on the floor in the design. UBC1997 specified the storey drift under wind and seismic loads. IBC2000 storey drift limitation is similar to UBC1997, but it is mainly specified building seismic state. The Chinese seismic code also specified the storey drift limitation of different structural systems [11, 12]. However, in all the literature, there is little research storey drift features for the frame-diagrid structure systems.

In order to study the storey drift of building structures, it is necessary to carefully study the structural deformation caused by horizontal loads. Under the horizontal loads, the structure bending deformation causes the floor rigid rotation. The deformation caused by rigid rotation has no direct relevance to the structural mechanical behaviour, which can be called harmless deformation. Directly causing the stress of structure component is the building shear deformation and rotational deformation, which can be called harmful deformation, also can be called physical deformation [13]. Generally, the harmless deformation for the low-rise and mid-rise structure is negligible. The shear deformation of frame structure is dominant, and the bending deformation accounts for a small proportion. The bending deformation of the high-rise shear wall structure is dominant, and the shear deformation accounts for a small proportion. So the physical deformation of the high-rise shear wall structure cannot be ignored [14-16]. The frame-diagrid structure is a dual system, which has both bending and shear deformation. Therefore, under the horizontal loads, the structural deformation of the frame-diagrid structure needs further study.

In this paper, the bending and shear deformation of frame-diagrid structure is analysed. The storey drift composition of the structural system is analysed. The calculation method for the physical storey drift is given.

FRAME-DIAGRID STRUCTURE DEFORMATION THEORETICAL DERIVATION

The horizontal loads of the frame-diagrid structure mainly include wind loads and seismic loads. The simplified analysis model of the frame-diagrid structure is shown in Figure 1. All the diagrid components are merged into a total diagrid, and all the frame components are merged into a total frame. The total diagrid and total frame deformation are uniform at any floors. The structure is subjected to arbitrary horizontal load q(x). The continuous interaction force between the total diagrid and the total frame is p(x). The total frame stiffness is the sum of the shear stiffness of all beam and column components. Introducing C_F is the shear stiffness of the total frame, it can be calculated from the literature [16]. The diagrid stiffness can be calculated by literature [17]. K_{D} and C_{D} are the equivalent bending stiffness and shear stiffness of the total diagrid, respectively.

The diagrid structure is regarded as a cantilever beam considering both bending and shear deformation. The relationship among bending moment, shear force and load relationship are as follows [18]:

$$M_{\mathrm{D}} = K_{\mathrm{D}} \frac{dw_{\mathrm{M}}{}^{2}(x)}{dx^{2}} \quad (1)$$

$$V_{\mathrm{D}} = C_{\mathrm{D}} \frac{dw_{\mathrm{V}}(x)}{dx} = -K_{\mathrm{D}} \frac{dw_{\mathrm{M}}{}^{3}(x)}{dx^{3}} \quad (2)$$

$$p_D(x) = p(x) - q(x) = K_D \frac{dw_M{}^4(x)}{dx^4} \qquad (3)$$

where $w_M(x)$ is the deformation caused by the bending deformation, and $w_V(x)$ is the deformation caused by shear deformation. The total deformation $w(x)$ is as follows:

$$w(x) = w_M(x) + w_V(x) \qquad (4)$$

According to the definition of the shear force, differentiating with respect to x, we get $dV_F / dx = -q(x)$ .Combined with Equation (3), we get:

$$\begin{aligned} p(x) &= K_D \frac{dw_M{}^4(x)}{dx^4} - \frac{dV_F}{dx} = K_D \frac{dw_M{}^4(x)}{dx^4} - C_F\left(\frac{d^2 w_M}{dx^2} + \frac{d^2 w_V}{dx^2}\right) \\ &= \left(K_D + \frac{K_D C_F}{C_D}\right) \frac{dw_M{}^4(x)}{dx^4} - C_F \frac{d^2 w_M}{dx^2} \end{aligned} \qquad (5)$$

Introducing $\lambda = \sqrt{\frac{H^2 C_D \cdot C_F}{K_D (C_D + C_F)}}$ and $\xi = x / H$. Equation (5) can be written as follows:

$$\frac{d^4 w_M(\xi)}{d\xi^4} - \lambda^2 \frac{d^2 w_M(\xi)}{d\xi^2} = \frac{H^4 C_D}{K_D (C_D + C_F)} p(\xi) \qquad (6)$$

This equation is a bending deformation differential equation for structures. $w_V(\xi)$ and $w_M(\xi)$ can be obtained by Equation (2).

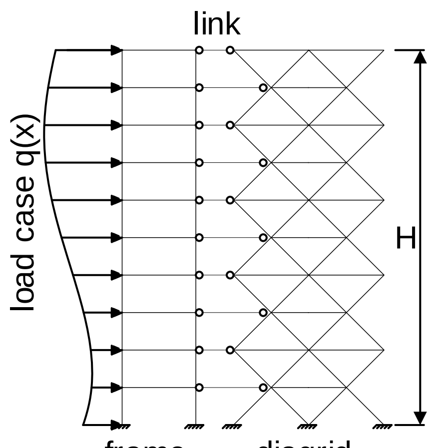

Fig.1 - Simplified analysis model for the frame-diagrid structure

PROPOSED PHYSICAL STOREY DRIFT

The deformation of the structure usually consists of the shear deformation and the bending deformation. The bending deformation consists of the bending rotational deformation and the floor rigid rotational deformation. The floor rigid rotational deformation is caused by the bending deformation of the lower floor. For the frame structure the shear deformation is dominant [1]. However, for the structure with bending deformation, the structural damage is directly related to the maximum bending rotational deformation, which can be called physical deformation [13]. The lateral deformation of the high-rise frame-diagrid structure is shown in Figure 2.

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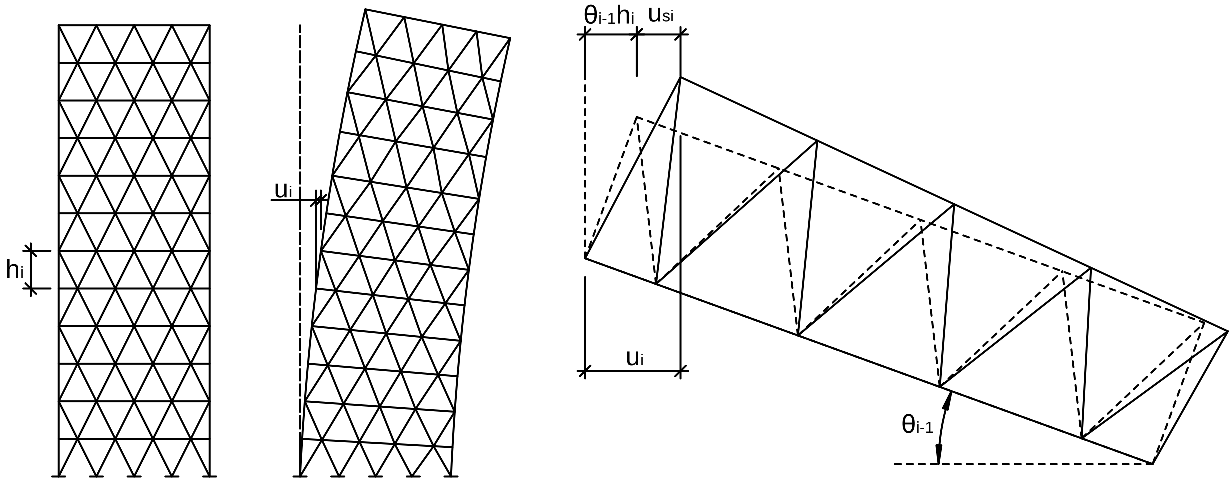
The lateral bending deformation value of the frame-diagrid structure can be obtained by the above Equation (6), and the structural ith storey deformation u_{i} can be written as follow:

$$u_{\mathrm{i}} = w_{\mathrm{i}} - w_{\mathrm{i-1}} \qquad (7)$$

where w_{i} is the i[th] storey bending deformation; $w_{\mathrm{i-1}}$ is the i-1[th] storey bending deformation.



(a) undeformed state *(b)deformation state* *(c) local amplification of deformation*

Fig.2 - High-rise frame-diagrid structure lateral deformation

Under the horizontal load, the frame-diagrid structure lateral storey deformation is caused by the shear storey deformation and the bending storey deformation. u_{i} can be derived as follows:

$$u_{\mathrm{i}} = u_{\mathrm{Vi}} + u_{\mathrm{Mi}} = u_{\mathrm{Vi}} + (u'_{\mathrm{Mi}} + \tilde{u}_{\mathrm{M}i}) \qquad (8)$$

$$u_{\mathrm{Si}} = u_{\mathrm{i}} - \tilde{u}_{\mathrm{Mi}} \qquad (9)$$

$$\tilde{u}_{\mathrm{Mi}} = \theta_{\mathrm{i-1}} h_{\mathrm{i}} \qquad (10)$$

where u_{Vi}、 u_{Mi}、 $u'_{\mathrm{M}i}$、 $\tilde{u}_{\mathrm{Mi}}$ is the i[th] storey deformation caused by the shear deformation, the i[th] storey deformation caused by the bending deformation, the i[th] storey deformation caused by the bending rotational deformation, and the i[th] storey deformation caused by the floor rigid rotational deformation. u_{Si} is the storey deformation deducting the floor rigid rotational drift.

$\theta_{\mathrm{i-1}} = dw_{\mathrm{Mi-1}}(x) / dx$ is floor rigid rotational angle. h_{i} is the i[th] storey height of the structure.

In the high-rise buildings $\tilde{u}_{\mathrm{Mi}}$ is caused by the floor rigid rotational deformation. The floor rigid rotational deformation does not cause damage of the structure. $\tilde{u}_{\mathrm{Mi}}$ can be called harmless storey deformation.

u_{Si} is caused by the shear deformation and bending rotational deformation, which is the directly causing damage of the structural components. u_{Si} can be called harmful storey deformation, also can be called physical storey deformation.

The storey drift is defined as storey deformation divided by storey height. The frame-diagrid structure has both bending deformation and shear deformation. By studying the frame-diagrid structure physical storey drift, the damage location along the height of the structure can be determined quickly.

VERIFICATION EXAMPLE AND DISCUSSION

A 40-storey frame-diagrid structure with rectangular floor plan was designed for a verification example, as shown in Figure 3. The width of the structure is 43.2m; the storey height is 4.5m; the angle of diagonal column θ is 68.2 degree; the total height H is 180m. All the structural material is steel material. The elastic modulus of the material is 200Gpa. The cross section of the components is given in Table 1. The horizontal loads are three commonly used loads Case1-3 in the design of high-rise structure [16]. In Case 1, the top point lateral load is 90 kN ; in Case 2, the uniform distributed lateral load 1 kN/m , in Case 3, the reverse triangle distribution lateral load 1.636 kN/m .The lateral deformation of the structure is calculated by using the method proposed in the Section 1 of this paper and the finite element method(FEM). The calculated results are compared, as shown in Figure 4. The lateral deformation Case 1 error is 3.4%, the Case 2 error is 4.1%, and the Case 3 error is 3.7%. The shear deformation and bending deformation can be further calculated by proposed method. The ratio of structural shear deformation to bending deformation is different under different cases. The storey drift of the structure under three cases conditions can be calculated by above Equation (7). The results are shown in Figure 5. It can be seen that the storey drift of the frame-diagrid structure is related to the load types. Under the horizontal uniform load, the storey drift increases with the increase of the height of the structure. However, under reverse triangle distribution lateral load or the top point lateral load, the storey drift first increases and then decreases with the increase of the height of the structure.

In order to verify whether the maximum storey drift and physical storey drift are in the same height of the structure, the elastic-plastic model is used for further discussion. The structural arrangement, material and the component section area are the same as the example above Figure 3. This model is named 4FFD6. The dead load is 6.5 kN/m^2 , including the weight of the floor slab. The live load is 3.5 kN/m^2 . The Perform-3D software program [19] was used to simulate the linear and nonlinear behaviour of the diagrid structure. The strain-hardening bilinear model is adopted for steel material, and the strain-hardening coefficient is 0.01. The nonlinear structural element used herein fiber element, and takes into account the interaction between the axial force and bending moment of the diagonal column [20]. According to Chinese Code for Seismic Resistance of Buildings [11], GB50011-2010, assuming the building is located in Class II site, the design seismic group is Group 2, and the design basic ground acceleration is 0.20g. Using ATC-40 Pushover capability spectrum method [21], the seismic performance spectrum and the capability spectrum are used to determine the performance points of the structure to evaluate the seismic performance of the structure. The demand spectrum parameters are determined by the horizontal seismic influence coefficient specified by GB50011-2010. The horizontal seismic coefficient is 0.16 for frequently earthquakes, 0.45 for local fortification earthquakes and 0.9 for rarely earthquakes. In this paper, Pushover analysis is performed along the height distribution according to the structure first mode in the horizontal direction.

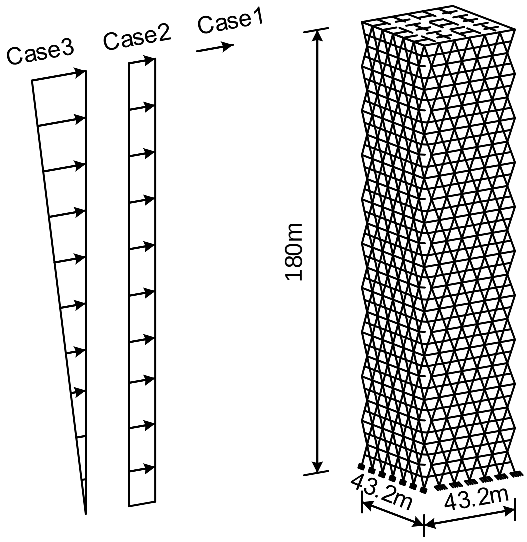


Fig.3 - Example model

Tab. 1 - Model 4FFD6 component cross sections

Storey	Diagonal column section /mm	Frame column section /mm	Ring beam and frame beam section /mm
1-8	Tube1000×30	Tube 1000×30	Tube 300×800×20
9-16	Tube 750×25	Tube 750×25	
17-24	Tube 650×20	Tube 650×20	
25-40	Tube 550×18	Tube 550×18	

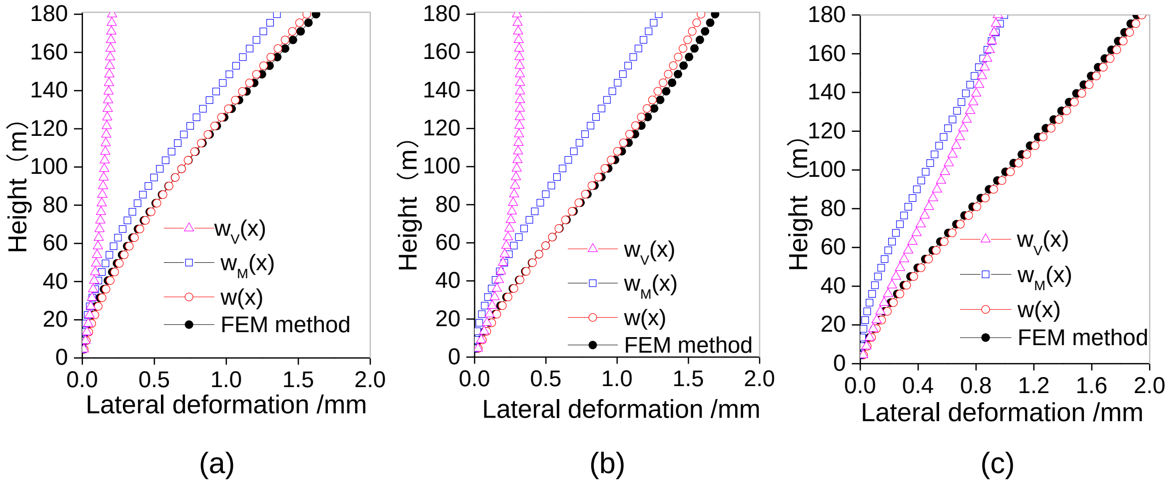


Fig. 4 - Result of lateral deformation. (a) Case 1: Top point lateral load (b) Case 2: Uniform distributed lateral load and (c) Case 3: Reverse triangle distribution lateral load

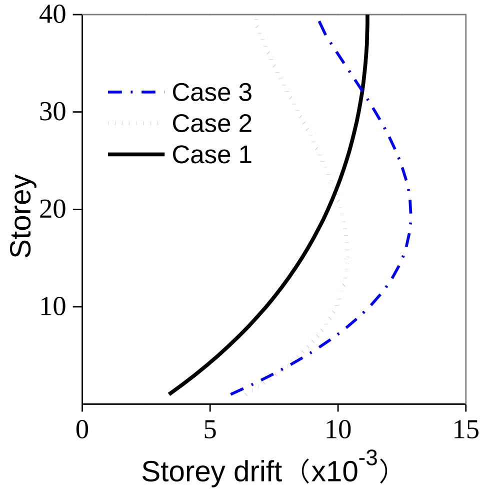


Fig.5 - The storey drift under 3 cases

The curve of the storey drift of the model 4FFD6 during frequently earthquakes and rarely earthquakes are shown in Figure 6, respectively. During frequently earthquakes, the structure maximum storey drift is 1/352, which is on the 25th floor; in this floor the physical storey drift is 1/4471, which accounts for 7.9% of the storey drift. During rarely earthquakes, the structure maximum storey drift is 1/144, which is on the 25th floor; in this floor the physical storey drift is 1/1582, which accounts for 9.1% of the storey drift. The maximum storey physical drift is 1/544 on the 17th floor, which accounts for 34.3% of the storey drift. It can be seen that the structure maximum storey drift and maximum physical storey drift are in different positions under different seismic loads. It is recommended to use both storey drift and physical storey drift as structural deformation limitation criteria.

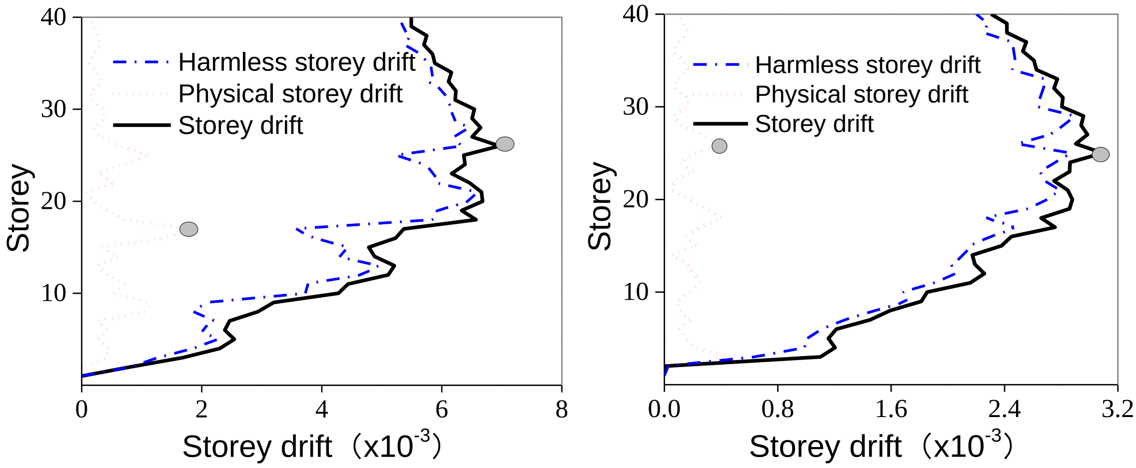
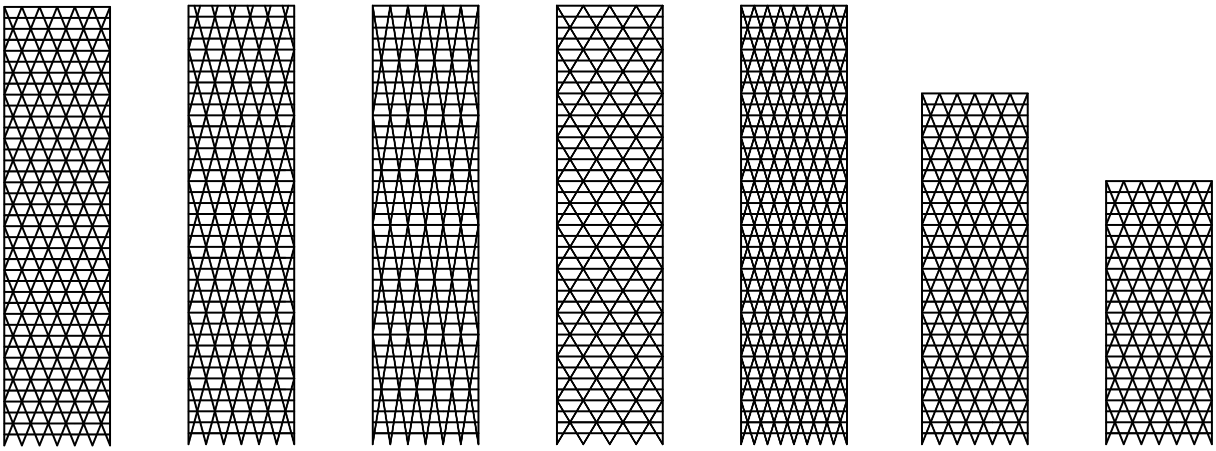


Fig. 6 - Storey drift of model 4FFD6 (a) during frequently earthquakes (b) during rarely earthquakes

STRUCTURAL PARAMETERS ANALYSIS USING STOREY DRIFT



(a) 4FFD6 (b) 6FFD6 (c) 10FFD6 (d) 4FFD4 (e) 4FFD8 (f) 4FFD6(32) (g) 4FFD6(24)

Fig. 7 - Vertical view of structural model

As mentioned above, the physical storey drift is directly related to the structural damage. It is suggested using both storey drift and physical storey drift as structural deformation limitation criteria. The parameters of high-rise frame-diagrid system are analysed by the method proposed in this paper during rarely earthquakes.

On the basis of the model 4FFD6, as shown in Figure 7, by adjusting the parameters such as the diagonal column section, the diagonal column angle, the main ring beam span and structure aspect ratio, nine comparative calculation models are designed, which are: 4FFD6, 4F15FD6, 4F20FD6, 6FFD6, 10FFD6, 4FFD8, 4FFD4, 4FFD6 (32), 4FFD6 (24). For example, model 4FFD6 is 4 stories and 6 spans with each diagrid module. Model 4F15FD6 indicates that the diagonal column section area is 1.5 times that of model 4FFD6. Model 4FFD6 (32) indicates that the model is 32 stories.

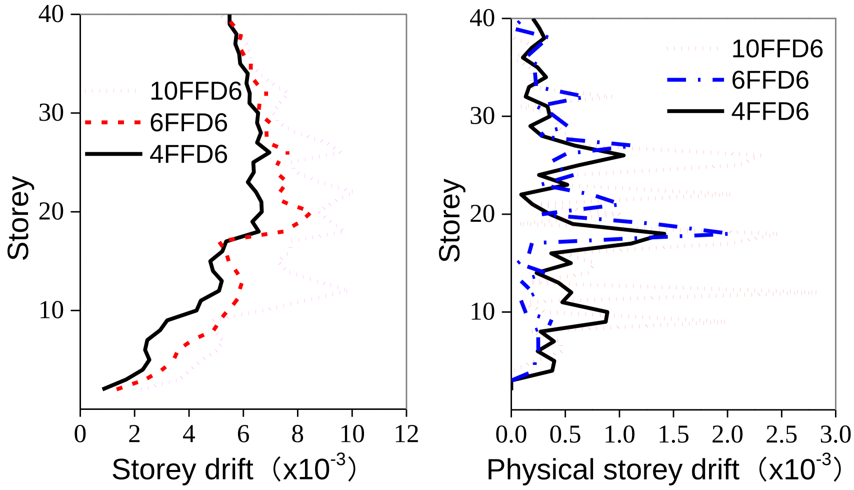


Fig.8 - Storey drift and physical storey drift under different diagonal column angles (The angles of the diagonal columns of 4FFD6, 6FFD6 and 10FFD6 is 68°, 75° and 81°, respectively)

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Diagonal column angle

The angles of the diagonal columns of model 4FFD6, 6FFD6 and 10FFD6 are 68°, 75° and 81°, respectively. The storey drift and the physical storey drift are shown in Figure 8. It can be seen that the storey drift of the structure first increases and then decreases along the height direction of the floor, and the angle between the structural diagonal column and the horizontal angle is larger, the storey drift is larger. The physical storey drift increases first and then decreases along the height of the floor, and the larger the angle between the structural diagonal column and the horizontal, the larger the physical storey drift and the larger the variation. Therefore, in the structural design, the structural stress and deformation can be made more reasonable by reasonable adjustment of the angle of the diagonal column, which is beneficial to improve the seismic performance of the structure.

Diagonal column section

The diagonal columns section area of the model 4FFD6, 4F15FD6 and 4F20FD6 are 1x, 1.5x and 2x, respectively, of the model 4FFD6. The storey drift and the physical storey drift curve of each structure are shown in Figure 9. It can be seen that the storey drift of the structure and the physical storey drift first increase and then decrease along the height direction of the floor. The larger the diameter and wall thickness of the inclined column steel tube, the smaller the storey drift and the physical storey drift, the position of the physical storey drift the maximum value rises along the floor. Therefore, in the structural design, the structural stress and deformation can be made more reasonable by reasonable adjustment of the diagonal column section, which is beneficial to improve the seismic performance of the structure.

Main ring beam span

The structural main ring beam spans of the model 4FFD4, 4FFD6 and 4FFD8 are 4 spans, 6 spans and 8 spans. The storey drift and the physical storey drift curve of each structure are shown in Figure 10. The storey drift and the physical storey drift increase first and then decrease along the height direction of the floor. The larger the span number of the main ring beam is, the smaller the storey drift between the layers is, the lower the position of the most value is. But the physical storey drift is not changed greatly. There is a significant difference between the storey drift and the physical storey drift. In the structural design, the structural force and deformation can be more reasonable by reasonable adjustment of the main ring beam span, which is beneficial to improve the seismic performance of the structure.

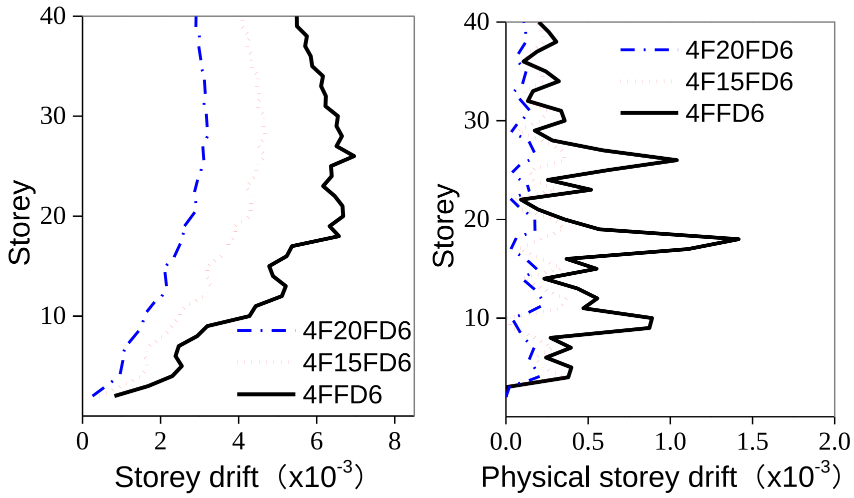

Fig.9 - Storey drift and physical storey drift under different diagonal column section (The diameters and wall thicknesses of the diagonal columns of the models 4FFD6, 4F15FD6 and 4F20FD6 are 1x, 1.5x and 2x, respectively, of the model 4FFD6)

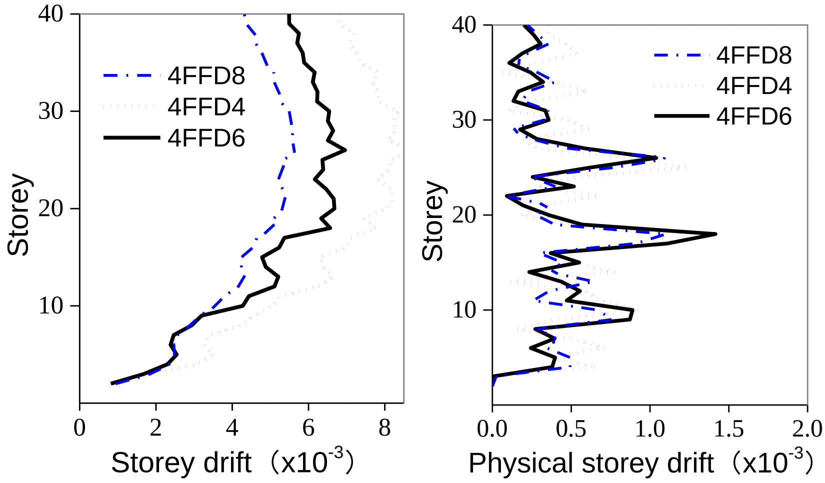

Fig.10 - Storey drift and physical storey drift under different main ring beam span (The structural main ring beam spans of the models 4FFD4, 4FFD6 and 4FFD8 are 4 spans, 6 spans and 8 spans)

Structure aspect ratio

The structural aspect ratios of the model, 4FFD6(24), 4FFD6(32) and 4FFD6 are 2.67, 3.56 span and 4.44, respectively. The storey drift and the physical storey drift of the structure are shown in Figure 11. The storey drift of the structure and the physical storey drift increase first and then decrease along the height direction of the floor. The larger the aspect ratio of the structure, the larger the storey drift and the physical storey drift. In the structural design, the structural strength and deformation can be rationalized by reasonable adjustment of the aspect ratio of the structure, which is beneficial to improve the seismic performance of the structure.

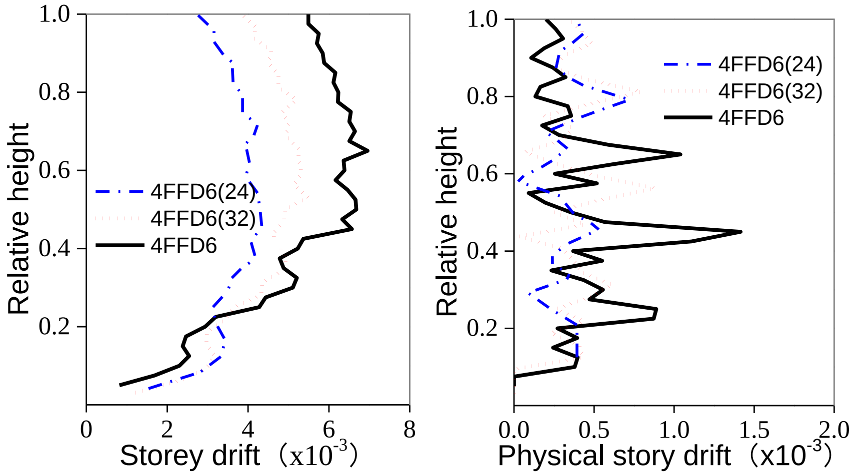

Fig.11 - Storey drift and physical storey drift under different structure aspect ratio (The structural aspect ratios of the model, 4FFD6(24), 4FFD6(32) and 4FFD6 are 2.67, 3.56 span and 4.44, respectively)

CONCLUSION

The frame-diagrid structure has obvious advantages in the structure selection. The storey drift of the structure is analyzed in detail, and we obtained the following main conclusions.

The lateral deformation formula for the high-rise frame-diagrid structures is derived. The bending deformation of the structure is divided into the bending rotational deformation and the floor rigid rotational deformation. The calculation method of the physical storey drift of the frame-diagrid structure system is obtained. The physical storey drift is directly related to the structural damage. When the structure is in the plastic state, the structure maximum storey drift and maximum physical storey drift are in different positions. It is recommended to use both storey drift and physical storey drift as structural deformation limitation criteria. The proposed method is used to structural parameters analysis for the high-rise frame-diagrid structure. The angle of the diagonal column, the cross section area of the diagonal column, the span of the main ring beam and the aspect ratio of the structure in the frame-diagrid structure have a influence on the storey drift of the structure; however, for the physical storey drift, the diagonal column angle and the diagonal column section have a great influence on it, and the main ring beam space and the structural aspect ratios have a little influence on it.

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