Displacement-based Behavior Design Method for High-rise Seismic Isolation

XiaoHuan Wang¹,*

¹ school of Jiangsu University of Science and Technology, Zhenjiang, China

*Corresponding author e-mail: 845241926@qq.com

Abstract. Based on the displacement-based behavior design method, this paper studies the high-rise isolation structure. Compared with ordinary low-rise buildings, high-rise buildings have more floors and longer periods. The elastic displacement angle and the elastic-plastic displacement angle are classified, the difference of the influence of bearing diameter and shape coefficient on the structural period is discussed, and the selection of isolation bearings is optimized considering the difficulties in the design of high-rise isolation structures.

1. Introduction

In recent years, domestic and foreign scholars have made more and more extensive and mature researches on sex design methods. Lin [1] and other works are relatively mature in the field of passive control. The design flow based on displacement method proposed by them is suitable for damping structures with different energy dissipation elements. Before determining the displacement response spectrum of the structure, the damping ratio of the energy dissipation and damping structure needs to be estimated first and then checked. Li Tao [2] and other high-rise buildings put forward standards for structural layout selection and materials. Through structural analysis of buildings under "small earthquake", "medium earthquake" and "large earthquake", all of them are within the performance target range, but most of them are designed under the condition of meeting the fortification standards, and no method for high-rise performance design can be obtained.

2. Design Contents of High-rise Isolation Structure

2.1. Transformation of Equivalent Degrees of Freedom

DDBD of high-rise isolated structure can simplify the calculation when using equivalent single-degree-of-freedom model, while equivalent mass, equivalent stiffness and equivalent damping ratio need to be transformed from the original multi-degree-of-freedom model of isolated structure. The mass of the high-rise isolated structure is higher than that of the low-rise isolated structure, the natural vibration period is higher, and the stiffness requirement is higher. After equivalent linearization, the additional damping ratio of the isolated layer changes correspondingly under the condition that the tensile stress of the rubber isolated bearing meets, which affects the selection of the equivalent period. Therefore, equivalent linearization of high-rise isolated structures is very important for the design method.

The essence of equivalent linearization is the transformation of degrees of freedom. The transformed single-degree-of-freedom system and the original multi-degree-of-freedom system should have the same equivalent mass and equivalent damping ratio. The behavior design of high-rise isolated
structures is suitable for the preliminary design stage in which only horizontal vibration is considered. According to the obtained experience, the equivalent mass can be calculated according to the following formula after the equivalent degree of freedom is converted:

\[ M_{eq} = \frac{\sum_{i} m_i A_i}{\Delta_i} \]  

(1)

Among them, according to the Technical Specification for Concrete Structures of High-rise Buildings (JGJ 3-2002)\(^{(3)}\), reinforced concrete structures with 10 floors or more or with a height of more than 28 meters are called high-rise building structures. The formula (1) \( n \) should be at least 10 layers. More than 100 meters are super high-rise buildings, which will not be discussed in this paper.

The superstructure was subjected to horizontal earthquake, resulting in target displacements of \( \Delta_1, \Delta_2, \ldots, \Delta_i, \ldots, \Delta_n \). \( \Delta_i \) is the horizontal displacement of the \( i \)th layer of the superstructure. Including the elastic displacement of the superstructure and the elastic-plastic displacement under large earthquakes. When the structural displacement index is selected as "immediate occupancy", the target displacement of the superstructure only includes elastic displacement, and the expression of \( \Delta_i \) is as follows:

\[ \Delta_i = \Delta_{ei} \]  

(2)

When the structural displacement index is selected as "collapse prevention", the target displacement of the superstructure is the sum of elastic displacement and elastic-plastic displacement, and the expression of \( \Delta_i \) is as follows:

\[ \Delta_i = \Delta_{ei} + \Delta_{pi} \]  

(3)

The elastic displacement \( \Delta_{ei} \) of the upper structure is determined by the displacement index of "immediate occupancy" of various structures, and the interlayer displacement angle \( \Delta_{ei} \) is taken for calculation. The elastic-plastic displacement of the superstructure is determined by the displacement index \( \Delta_{pi} \) of "collapse prevention" of various structures, and the interlayer displacement angle is taken for \( \Delta_{pi} \) calculation. Therefore, the target displacement of each layer of the superstructure is:

\[ \Delta_i = \Delta_{i-1} + \theta \Delta_i \]  

(4)

According to different behavior levels, the corresponding displacement index is selected, and the tensile stress is always less than 1MPa. Therefore, the target displacement of each floor under the action of horizontal force can be obtained, and the equivalent displacement target after equivalent linearization is calculated by the following formula:

\[ \Delta_{eq} = \frac{\sum_{i} m_i \Delta_i^2}{\sum_{i} m_i \Delta_i} \]  

(5)

2.2. Determination of Equivalent Damping Ratio

Damping plays a role in damping free vibration. Damping ratio is the ratio of damping coefficient to critical damping coefficient. Based on the damping ratios defined by various countries, the general values of damping ratios are given, i.e. for reinforced concrete structures, the values \( \xi_{eh} \) are between 0.03 and 0.08, for steel structures, the values \( \xi_{eh} \) are between 0.01 and 0.02, and for steel-concrete structures, the values are generally between 0.025 and 0.035. When the structure enters the yield state, the damping ratio \( \xi_{ep} \) is larger than the original damping ratio \( \xi_{eh} \) when the original structure is
damped. The damping ratio \( \xi_p \) expression in plastic state is:

\[
\xi_p = 0.444(\mu - 1) \mu \pi
\]

(6)

Iwan W D\(^{[4]}\) proposed an equivalent linearization calculation method. The inelastic response spectrum is estimated from the elastic response spectrum. The damping ratio \( \xi_p \) expression in plastic state is obtained as follows:

\[
\xi_p = 0.2(1 - \frac{1}{\mu})
\]

(7)

It can be seen from the above two formulas that when \( \mu = 1 \), the damping ratio in plastic state is zero.

The double-line model of the isolation layer can effectively represent the stiffness and yield force of the structure before and after yielding under earthquake. It is more appropriate to simulate the isolation layer with the double-line model, which is shown in the following figure:

![Fig.1 The bilinear force deformation relationship of isolators](image)

\( \Delta_y \) is the target displacement of isolation layer, \( K_0 \) is equivalent stiffness of isolation layer, \( K_1 \) is the pre-yield stiffness, \( K_2 \) is Post-yield stiffness, \( \alpha \) is Second stiffness coefficient. \( K_2 = K_1 \alpha \).

Bilinear restoring force of isolation layer provides damping force for the structure to return to its original position when viscous damper and rubber isolation bearing jointly provide damping force. Generally, an equivalent damping ratio of isolation layer \( \xi_{is} \) is estimated by a hysteretic history:

\[
\xi_{is} = \frac{E_D}{4 \pi E_S}
\]

(8)

2.3 Design Problems and Selection Methods of Bearings for High-rise Isolation Structures

Isolation bearings can be roughly divided into laminated rubber bearings, sliding plate bearings and rolling bearings. Due to better control of the performance characteristics of laminated rubber bearings, laminated rubber bearings are widely used at present. Natural rubber bearings and lead rubber bearings belong to laminated rubber bearings. Grasping the relationship between tensile deformation and horizontal deformation of isolation bearings is especially important in the design of rubber bearings for high-rise structures. When the rubber bearing is pulled, the interior will be damaged, because the interior is under negative pressure, thus creating a void. Tensile design of isolation bearings for high-rise structures is extremely difficult and is usually determined based on experimental data and experience. The ultimate tensile stress is related to the thickness of rubber bearing, while the horizontal stress is related to the diameter of rubber bearing. The shape factor of the laminated rubber support S is specified as follows:
\[ S = \frac{D}{t} \]  

(9)

D is the diameter of the rubber bearing, \( t \) is the thickness of the rubber bearing.

Laminated rubber bearings have great influence on the structural period. Increasing the thickness of rubber \( t \) and decreasing the elastic modulus of rubber \( G \) can increase the structural period. The relation diagram between the structural period and the diameter of the rubber bearing is given as follows.

**Fig.2** Relationship between isolation period and diameter

Diameter and shape coefficient have great influence on the structural period. With the increase of diameter, the period increases slightly, while the ratio of stress \( \sigma \) the shape coefficient \( S \) increases, the structural period increases obviously. By understanding the relationship between the internal physical properties of the isolation bearing and the structural period, the appropriate rubber isolation bearing can be selected according to the period.

3. Conclusion

After discussion and research in this paper, the equivalent linearization method suitable for high-rise isolated structures is determined, and the equivalent damping ratio is determined in plastic state. Bilinear model can be used in high-rise isolated buildings.

References
[1] Lin YY, Tsai MH, Hwang JS, Chang KC. Direct displacement-based design for building with passive energy dissipation systems, J. Engineering Structures 2003; 25: 25–37.
[2] Tao Li, Performance-based Seismic Research and Analysis of a High-rise Building Exceeding Code, D 2019.
[3] The Technical Specification for Concrete Structures of High-rise Buildings (JGJ 3-2002).
[4] Iwan W D. Estimating inelastic response spectra from elastic spectra, J. Earthquake Engineering & Structural Dynamics, 1980, 8(4): 375-388.