Seismic isolation analysis and design of a plane irregular building structure in high earthquake intensity area

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Abstract. Taking the large commercial complex building of Changzhou Golden Eagle Plaza as the research object, this paper analyzes various parameters of typical special-shaped space structure under different isolation schemes under the conditions of earthquake protection, rare earthquake and extremely rare earthquake, compares three isolation layer design combinations of rubber isolation bearing, lead isolation bearing, rubber isolation bearing + lead isolation bearing, and studies the influence of different isolation layer arrangement schemes on the steel core and mass center of the building structure. The results show that the reasonable isolation design can obtain the reasonable arrangement pattern and rule of the plane irregular building structure in a high seismic intensity area by comparing and analyzing the arrangement schemes of different types and forms of isolation bearings in the isolation structure model.

Keywords: special-shaped spatial steel structure; time-history analysis; Keywords direct analysis design; isolation arrangement; Elastoplastic analysis.

1. Introduction

As an earthquake-prone country, earthquake disasters frequently occur in China, bringing serious life hazards and property losses. To reduce the damage to building structures caused by earthquake disasters, isolation technology is widely used in structural engineering. An isolation structure can reduce the load of the superstructure by reducing the input seismic action of the superstructure and can solve the contradiction between seismic capacity and building function. At the same time, with the development of the economy and technology in our country, there are more and more high-rise buildings. It is an inevitable trend to popularize the application of isolation technology in high-rise structures.

At present, the isolation design method can be divided into two kinds, one is the damping coefficient method based on the Code for Seismic Design of Buildings [7], and the other is the direct design method based on the Standard for Seismic Isolation Design of Buildings [6]. The principle of damping coefficient method is to divide the isolated structure into superstructure, isolation layer and substructure, and design each part step by step based on the damping objective. This method has been widely used in seismic isolation engineering design, such as the seismic isolation technology adopted in the air bridge of Chongqing Raffles Project, and the largest high-rise seismic isolation residential complex in the world designed by Li Aiqun and Zeng Demin in 2017 (Hebei Yanjiao Tianyang Innovation City, about 1.14 million m2), isolation design of Beijing Daxing Airport, etc. After the application of isolation technology in such high-rise structures, the seismic performance of the building is enhanced, and the foundation cost in general design can be significantly reduced. All bearings and dampers can be installed on site, thus greatly shortening the construction period and bringing good economic benefits.

The direct design method is based on the idea of performance-based design and the basic requirement of seismic elastic design. The calculation and analysis model including superstructure, isolation layer and substructure is used for analysis and design. Compared with the damping coefficient method, this method has a shorter application time and is more in line with the real stress state of the isolated structure. The Standard for Design of Seismic Isolation of Buildings [6] defines the performance criteria for isolated structures with reference to existing seismic performance criteria. Its essence is to improve the small earthquake, moderate earthquake and large earthquake in the seismic performance to the moderate earthquake, large earthquake and extreme earthquake in the isolation performance. Compared with the traditional seismic structure design, the upper and lower piers and isolation layer should also be considered. Therefore, before adopting the design method of the Standard for Seismic Isolation Design of Buildings [6], the performance objectives of the isolated structure should be defined in detail according to the importance of different parts of the isolated structure.

In view of the above situation, this paper through a commercial complex project, using finite element analysis software to establish a model and design a variety of programs of isolation layer, through the steel center eccentricity and center of gravity eccentricity and other indicators to compare and select, get a reasonable layout, and through MIDAS GEN dynamic time-history analysis, through the engineering example summarized the universal law of isolation bearing layout.

2. Project Overview

The project is located in a certain area of Changzhou City. See Figure 1 for the architectural effect. The planned land area is 56,000 square meters, and the total construction area is 342,300 square meters. The bottom of the commercial building in the north is about 182.5m long and 50.6m wide, with three floors underground and six floors above ground. The height of the main roof is 32.63m, and the frame-shear wall structure is adopted, as shown in Figure 2.

Figure 3 D architectural renderings

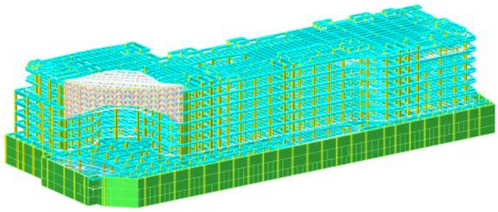


Fig. 2 Schematic diagram of overall structure

The entrance of the commercial building in the north is located at the corner of the structure, which is composed of special-shaped roof and curved curtain wall, as shown in Figure 3. The commercial complex mainly undertakes the functions of commerce, catering, entertainment, etc. The daily flow of people is large, and the seismic fortification category is the key fortification category. The basic wind pressure of the project site is 0.40kN/m2, and the ground roughness is Class B. The basic snow pressure is 0.35kN/m2, and the roof snow distribution coefficient is 1.0 [6]. The construction site is classified as Class II, the eigenvalue period is 0.45s, the seismic fortification intensity is 8 degree, the design basic seismic acceleration is 0.20g, and the design seismic group is Group II [7].

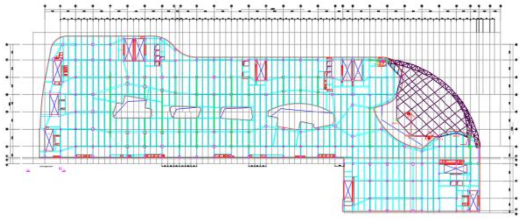
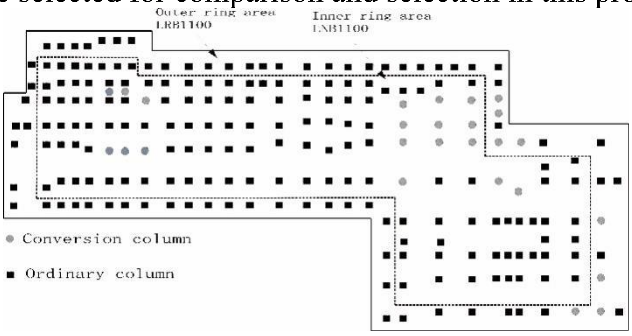


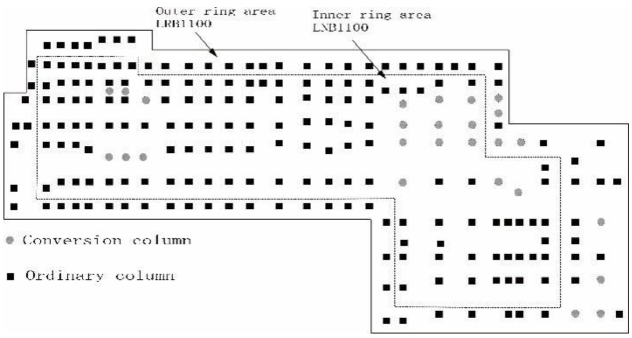
Figure 3 Layout Plan

3. Comparison and selection of isolation bearing schemes

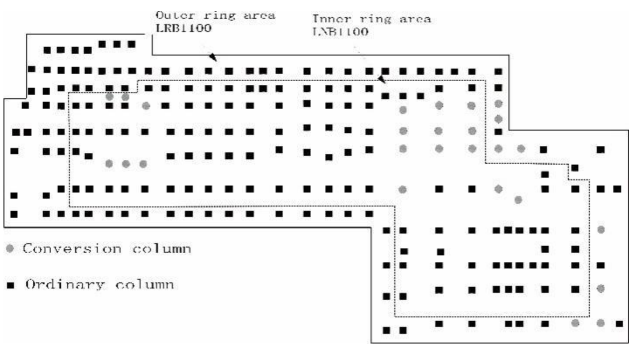
The upper model is established and the seismic fortification intensity is reduced by 1 degree for preliminary calculation. The superstructure is designed by preliminary calculation, and the column bottom reaction force is extracted to arrange the isolation bearings. In order to improve the torsional and shear bearing capacity of the whole building and achieve better seismic isolation effect, the LRB1100 lead rubber bearing is used in the outer ring area, the L NR 1100 common rubber bearing is used in the inner ring area, and the L NR 1600 common rubber bearing and LRB1600 lead rubber bearing are used in the bearing close to the centroid and rigid center of the structure. The following four isolation schemes are selected for comparison and selection in this project.



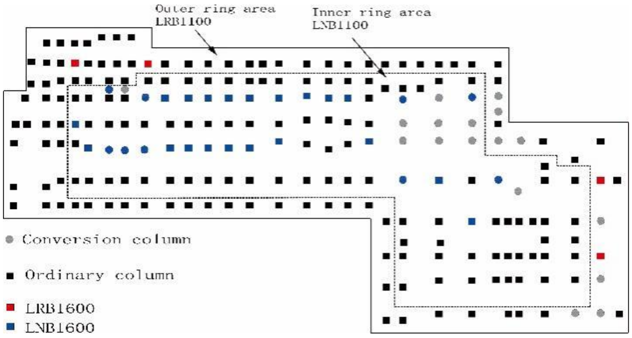
(a) Scheme 1



(b) Scheme 2



(c) Scheme 3



(d) Scheme 4

The main mechanical characteristic parameters of L NR 1100, L NR1600 ordinary rubber bearings and LRB1100, LRB1600 lead rubber bearings and the main calculation results of four schemes are shown in Tables 1 and 2.

Table 1 Mechanical performance parameters of seismic isolation support

Support Models	Vertical compressive height(KN/mm)	Equivalent horizontal stiffness(KN/mm)	Equivalent damping ratio（%）	Pre-yielding strength(KN/mm)	Yield force (KN)	Post-yielding strength(KN/mm)
LRB1100	6929	4.539	21.6	29.24	290.8	29.24
LNR1100	5143	1.806	0.0	-	-	-
LRB1600	6929	4.539	21.6	29.24	290.8	29.24
LNR1600	7712	2.674	0.0	-	-	-

Table 2 The main calculation results of the four design schemes

plan	Self-vibration cycle/s	Base shear value(X direction)				Horizontal shock absorption coefficient	Seismic isolation eccentricity/%	
		Proximate fault seismic		Ordinary seismic		Pulse seismic	X direction	Y direction
		Seismic isolation model	Non-seismic isolation model	Seismic isolation model	Non-seismic isolation model			
1	4.198	114874	216842	99921	188559	0.52	8.9256	2.8798
2	4.213	115176	216849	100263	188565	0.51	11.4570	3.6048
3	4.018	116665	216854	101448	188568	0.50	1.0844	1.0322
4	3.987	116829	216858	101734	188560	0.51	0.1779	0.5020

During equivalent elastic analysis, the equivalent stiffness corresponding to the horizontal shear strain of 100% shall be selected for isolation bearing according to the definition of earthquake intensity of fortification earthquake, and the equivalent damping ratio of the isolation layer shall be calculated according to the method specified in Article 12.2.4 of Resistance Code, and then distributed to each lead rubber bearing according to stiffness proportion. The horizontal damping coefficient is calculated by 2 natural waves and 1 artificial wave (obtained by automatic screening of P KPM software) and the average value of the results is obtained. See Table 2 for the calculation results of the natural vibration period and horizontal damping coefficient of the isolated structure in each scheme.

It can be seen from Table 2 that the base shear force of the non-isolated model is significantly reduced after the isolation bearing is used. The first three periods of the non-isolated structure in Scheme 4 are 2.07s, 1.89s and 1.74s, and 3.99s, 3.91s and 3.61s after isolation. The addition of the isolation bearing significantly improves the basic period of the structure, and the isolation effect is obvious. The base shear force of the isolated structure calculated by near-fault earthquake motion is significantly greater than that of the ordinary earthquake motion. In Scheme 1, the lead core 1100 bearing is arranged in the outer circle, and the rubber 1100 bearing is arranged in the rest of the bearings. However, the steel core deviates from the center of gravity to a large extent, which is mainly reflected in the large deviation in X direction, and a large number of gravity loads exceed the limit.

During the adjustment, it was found that more steel bearings on the left side of the building drawing or more rubber bearings on the right side would move the rigid center to the left along the X direction and thus close to the center of gravity. In the same way, the deviation in the Y direction can also be caused by arranging more steel core bearings on the upper side or increasing the arrangement of rubber bearings on the lower side, so that the steel core moves upward along the Y direction and is close to the center of gravity, and the arrangement scheme is gradually optimized according to the law, so that the eccentricity of the isolation layer is finally controlled within a reasonable range, and meanwhile, the bearings closer to the center of gravity and the rigid center of the structure bear greater compressive stress than the edge bearings, so that sufficient safety reserves can be fully reserved for the bearings.LNR 1600 common rubber bearing and LRB1600 lead rubber bearing with better isolation performance are selected.

4. Analysis of isolated structure

4.1 Elastic analysis of earthquake fortification

According to the preliminary scheme design and comparison, scheme 4 is adopted as the final scheme for analysis. Except for the parameters analyzed, the maximum value of the inter-story shear ratio of the structure under different earthquake input directions before and after the isolation of the superstructure is 0.51, and the isolation effect reaches the goal of reducing one degree. The maximum story drift angle of the superstructure is 1/571, which is less than the code limit of 1/400 [6]. The maximum compressive stress of isolation bearing under the action of gravity load representative value is 14.68MPa, which is less than the specification limit of 15MPa [6]. Through the above analysis, it can be seen that the structure meets the isolation performance target of earthquake protection.

4.2 Elastic analysis of rare earthquake

The equivalent elastic analysis and elastic time-history analysis of isolated structure under rare earthquake action are carried out in PKPM. According to the specification [6], 2 natural waves and 1 day artificial wave are selected for elastic time-history analysis. The base shear force obtained from elastic time-history analysis for each wave is compared with the calculation results of response spectrum. See Table 3 for the results.

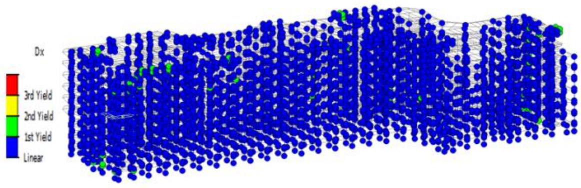
Table 3: Substrate shear force comparison

Seismic wave	Time history analysis of basement shear force/reaction spectrum method	
	X direction	Y direction
Natural wave 1	**0.99**	**1.00**
Natural wave 2	**0.98**	**1.00**
Artificial wave	**0.99**	**1.00**

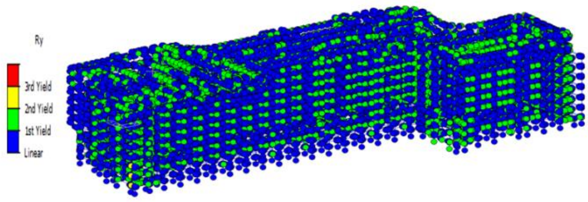
The wave selection results shall meet the requirements that the structural bottom shear force calculated by single seismic wave shall not be less than 65% of the calculated value by CQC method and shall not be greater than 135% of the calculated value by CQC method, and the average value of structural bottom shear force calculated by multiple time history curves shall not be less than 80% of the calculated value by CQC method and shall not be greater than 120% of the calculated value by CQC method [7]. The envelope values of equivalent elastic analysis and elastic time-history analysis are taken as the calculation results of the model, and the design of the isolation layer and the substructure is guided according to the calculation results: 1) The maximum story drift angle of superstructure in X and Y directions is 1/111 and 1/231 respectively, which is less than the specification limit of 1/100 [6]. 2) Under the simultaneous action of horizontal and vertical rare earthquakes, only the steel core bearing at the edge part has tensile stress overrun, and there is no tensile stress in the core area and the steel core area close to the center of mass, which meets the requirements of the specification [6] that the tensile stress shall not be greater than 1.0MPa, and the whole structure meets the requirements of repairable under severe earthquakes. 3) The maximum horizontal displacement of the isolation bearing under the action of rare earthquake is 371mm, which is not greater than the smaller value of 0.55 times of the diameter of the bearing and 3.0 times of the sum of the rubber thickness of each layer. [8] It can be seen from the above analysis that the structure meets the isolation performance target under rare earthquake.

4.3 Elastoplastic analysis of extremely rare earthquake

According to the analysis and design under the fortification earthquake intensity and rare earthquake intensity, the MIDAS GEN analysis model including reinforcement information is established, and the same seismic wave selected under the fortification earthquake intensity is used to carry out the extremely rare earthquake dynamic elastoplastic time history analysis. The yield state of the structure was obtained from the analysis, as shown in Figure 4.



(a) Vertical member yield condition



(b) Horizontal member yield condition

Figure 4 Elastoplastic analysis results of extremely rare earthquakes

Under the action of extremely rare earthquake, the vertical and horizontal members of the isolation layer and the substructure are in the elastic stage, only a few vertical members of the superstructure enter the yield state, and only some horizontal members are damaged.

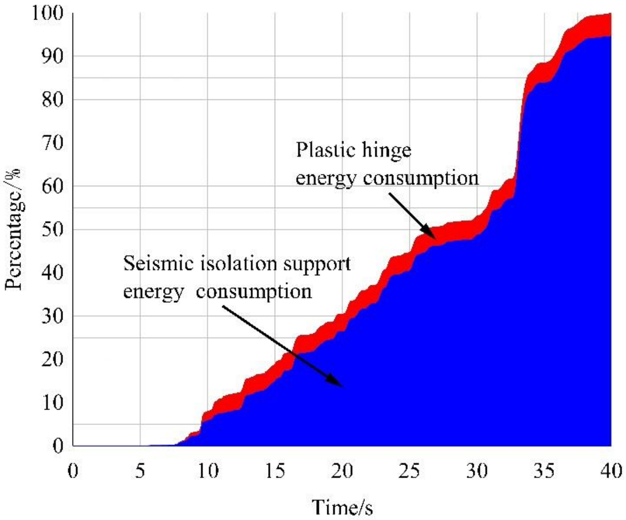


Figure 5 Energy consumption

It can be seen from the above analysis that the structure can meet the goal of "no collapse under large earthquake" when encountering extremely rare earthquake, and there is no need to carry out progressive collapse analysis because there is no damage to key components.

5. Conclusions

The structure is a typical complex special-shaped space steel structure, located at the corner of the commercial complex, with complex stress and irregular plane and elevation characteristics, which puts forward higher requirements for structural analysis and design:

For a complex special-shaped space structure model, it is necessary to establish multiple analysis models based on different analysis software to verify the model's accuracy. Two analytical models are established by MIDAS GEN and PKPM, and the accuracy of the models is verified by comparing the calculation results of the two models.

(2) Combined with the existing structural analysis methods (equivalent elastic analysis, dynamic elastic-plastic analysis), the general rules of isolation layer arrangement are summarized, which provides experience for the design of the isolation layer.

(3) The direct analysis method based on the performance objective is applied to the large commercial complex of Changzhou Golden Eagle Plaza. The main performance objectives, such as the eccentricity, the maximum deflection angle, and the natural vibration period of the structure are controlled in a reasonable range by reasonably arranging the isolation bearings and applying the high-performance isolation bearings. The results show that the improved isolation scheme can be.

(4) The direct analysis method based on the performance objective is applied to the large commercial complex of Changzhou Golden Eagle Plaza. The main performance objectives such as the eccentricity, the maximum deflection angle and the natural vibration period of the structure are controlled in a reasonable range by reasonably arranging the isolation bearings and applying the high performance isolation bearings. The results show that the improved isolation scheme can be used in the analysis and design of the isolation structure of the special-shaped structure.

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