**Discussion for Key Issues of Isolation Technology Applied in Long-Span Complex Buildings**

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**ABSTRACT**

High seismic precautionary intensity areas are widely distributed in China. Along with the rapid development on urbanization process, the requirements for quality and safety of buildings are constantly increasing. Long-span buildings are generally public-type buildings and characterized by dense crowds, high importance, and complex shapes. Thus these buildings have strict requirements for seismic performance and large demand for reduction of earthquake actions. At present, the development of isolation technology is relatively advanced and its application in long-span buildings can effectively reduce earthquake actions and improve seismic performance of structures, so that long-span buildings can effectively play the function of post-earthquake disaster relief. In this paper, the key issues in the application of isolation technology in long-span complex structures are discussed, including torsional control, temperature effects, wind-resistant design, boundary constraints, vertical seismic action, and the layout of the playing field on isolation layer of stadium structure, which can provide reference for related programs.

*Keywords: torsional control; temperature effects; wind-resistant design; boundary constraints; vertical seismic action*

**1. Introduction**

China is located in the Eurasian plate with frequent earthquakes and wide distribution of high-intensity areas. As is shown below in seismic ground motion parameters zonation map of China[1] (Figure 1), the high-intensity areas in China are mainly located in the central and western regions such as Shanxi, Shaanxi, Gansu, Yunnan, Sichuan, Tibet and Xinjiang. With the further development of West China Development and ‘the Belt and Road’, the pace of urbanization in the western region and the central region of China has accelerated. Meanwhile, the demand for public-type buildings including stadiums, airport terminals, railway stations, exhibition buildings, etc. has increased. As the main architectural form of public-type buildings, long-span buildings are characterized by dense crowds, high importance, and complex shapes, thus have more difficulty on seismic design. In addition, long-span buildings generally serve as temporary shelters for post-earthquake disaster relief. Therefore, effective measures must be taken to ensure buildings have normal functions after earthquakes.



Figure 1. Seismic ground motion parameters zonation map of China

In recent years, seismic isolation technology is developing rapidly. According to the statistical results of national seismic isolation building construction projects by the Ministry of Housing and Urban-Rural Development, by the end of 2014, 2015 and 2016, the total numbers of isolation building which have been built in China are 2662, 3181 and 3659. Respectively, the numbers of building equipped with damping members which have been built in China was 174, 270 and 432. These numbers illustrate that the application of seismic isolation technology is becoming more and more widespread. Regarding to the height of buildings, most of the seismic isolation buildings are between 24 and 60 meters, which is related to the applicability of isolation technology. The isolation technology extends the natural vibration period of structures and increases the structural damping to achieve the purpose of seismic dissipation. The shorter period of non-isolated structure has, the more obvious effect appears on the extension of period and on isolation. In addition, the current isolation bearing is mainly laminated rubber isolation bearings. According to the poor performance of rubber isolation bearings under tensile forces, it is necessary to limit tension on bearing under horizontal loads. When the upper structure is mainly under bending deformation, the vertical member under horizontal loads is subjected to a larger tensile force. Therefore, for seismic isolation buildings, the deformation of the upper structure should be mainly shear deformation. Generally speaking, the smaller height to width ratio the structure has, the greater proportion of shear deformation appears when the structure is subjected to horizontal loads. Therefore, isolation is the most suitable technology for low-rise buildings.

The long-span buildings are generally not high, mainly under 40 meters, which is naturally suitable for isolation. At the same time, due to the characteristics of dense population, high importance and complex body shapes, huge requirements for high seismic performance and shock absorption are needed. The application of isolation technology in long-span buildings can effectively meet the requirements for shock absorption and improve seismic performance.

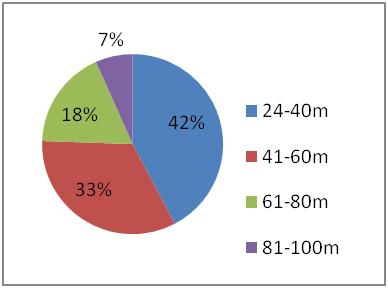


Figure 2. Height distribution of completed isolation buildings

**2. Application Form of Seismic Isolation Technology in Long-Span Buildings**

There are two main methods to apply seismic isolation technology in long-span buildings: roof support isolation and base isolation.

***2.1 Roof Support Isolation***

For the roof support isolation, the bearing is arranged between the roof and the lower support. It has the following characteristics:

(1) Compared with the multi-layer structure, the long-span roof has lighter weight. And as the support has limited allowable deformation, by using common isolation bearing, the extension of period is relatively short and the horizontal seismic decreasing is limited.

(2) A long-span roof is generally a space structure system with high degree of freedom, complex dynamic characteristics, dense frequency and mode distribution. And its structural vibration is featured with three-dimensional characteristics[2]. Meanwhile, common isolation bearings are only effective in horizontal direction, so the structure may have a huge response under vertical earthquake, which means the seismic decreasing effect of common isolation bearings is limited.

(3) Long-span roofs have large spans. Internal forces of structure members are generally controlled by gravity loads and temperature stress, not earthquake.

Therefore, when long-span roofs are equipped with isolation technology, they should be fully demonstrated in terms of their effectiveness and necessity. In fact, the roof support vibration isolation is not only effective on the energy dissipation for the roof. On the one hand, since the horizontal restraint stiffness of isolation bearing is small, by setting isolation bearings at the support of roof, the temperature stress of roof lid can be released during the change of temperature. Therefore, the internal force of roof lid and the reaction force to the lower support structure can be reduced effectively. For example, the gymnasium in University of Science and Technology Beijing[3] installed plate-type rubber bearings between the steel mesh frame roof and supporting steel tube columns. The main exhibition hall in Ningbo International Convention and Exhibition Center[4] applied a sliding seismic spherical bearing support under a steel roof cover. Both of cases above reduced the temperature effect in long-span roof and the horizontal force of supporting member. On the other hand, applying roof isolation will reduce the overall structural stiffness, which means the seismic action to the lower support structure may reduce. The Shanghai International Circuit[5] settled a seismic isolation support at the bottom of the news center (mega-long span fusiform steel truss structure) across the top of the tower, which effectively reduce the temperature stress of the roof structure and the seismic action to the lower supporting structure, such as the grandstand and the control tower.

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| http://img3.fengniao.com/active/20080725aoyun/1/7/6593.jpg |  |
| a) Building real map | b) Detail of rubber bearing |

Figure 3. University of Science and Technology Beijing stadium

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| Figure 4. Main exhibition hall of Ningbo International Convention and Exhibition Center | Figure 5. Shanghai International Circuit |

***2.2 Base Isolation***

Base isolation ranges bearings between the building and foundation. The main structure (including the roof and lower functional structure) is completely isolated from the foundation through the isolation layer. Seismic energy is generally absorbed by the isolation layer from being transferred into the building. The seismic force to the main structure is greatly reduced. Base isolation in long-span buildings has following characteristics:

(1) Base isolation can reduce horizontal seismic effect on both long-span roof and lower functional structure. Using base isolation, the main structure has good performance under earthquake action, thus ensuring the normal function of the building after earthquake and playing the better role of earthquake relief shelter.

(2) The lower support structure under long-span roof is generally low in height and large in stiffness. It also has natural shock absorption demand and isolation advantages.

(3) Applying base isolation reduces the seismic effect to the upper main structure. The freedom of architectural design also increases to meet the requirements of long-span complex structures.

(4) Since the horizontal stiffness of isolation bearing is small, base isolation has specific benefits for releasing overall temperature stress of the structure.

At present, long-span buildings built in China with basic isolation include Suqian City Gymnasium[6] (with 122 rubber isolation bearings and 12 viscous dampers), Beijing New Airport Terminal[7] (with total 1152 rubber isolation bearings and elastic skateboard supports and 160 viscous dampers), Kunming Changshui Airport Terminal[8] (with 1720 rubber isolation bearings and 104 viscous dampers) and Guangdong Science Center[9] (with 120 rubber isolation bearings)[10] In other nations, New M.H. de Young Museum in Los Angeles (with 152 rubber isolation bearings and 24 viscous dampers), SFO Airlines Station in San Francisco (with 267 pillar-type friction-type vibration isolation bearings), Kusanagi Sports Complex in Shizuoka, Japan and Oita Prefectural Art Museum used base isolation technology as well.

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| http://www.suqian.gov.cn/cnsq/qtjd/201310/245a8bb993514930a2d231a6b7922d2f/images/3f9537d355024493965223e85715b65b.jpg |  |
| a) Building real map | b) Isolation layer layout |

Figure 6. Suqian City Gymnasium

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| a) Architectural rendering | b) Isolation layer layout |

Figure 7. Beijing New Airport Terminal



Figure 8. Guangdong Science Cente

**3. Key Issues of Isolation Technology Applied in Long-Span Complex Buildings**

***3.1 Torsion Control***

The structures of long-span buildings are diversified, and the problem of torsion in irregular structures is particularly prominent. Domestic and international standards generally use the torsional displacement ratio and period ratio to evaluate the torsional effect of structure. Period ratio refers to the ratio of the first mode period dominated by torsion and the first mode period dominated by translational mode. This ratio measures the relative values between torsional stiffness and lateral stiffness. Research shows when period ratio approaches 1, the torsional component of ground motion will significantly increase the torsional effect of the structure. Even if the structure is uniformly symmetrical, the ground torsional motion will stimulate huge torsion[11]. By limiting the period ratio, serious lateral-torsional coupling can be avoided which is caused by excessive closeness between torsion period and translational period, resulting in multiplication of dynamic torque. However, the torsional period ratio does not directly reflect the magnitude of the structural torsional effect. It is only one of the factors that affect torsional effect. In fact, it is the torsional displacement ratio more generally reflects the magnitude of the structural torsional effect. The purpose of controlling the torsional period ratio is still to control the torsional displacement ratio and other torsional effects [12].

For the structure with isolation technology, the stiffness of isolation layer is quite small compared to the upper structure. Therefore, the vibration shape of overall structure is mainly directed by the isolation layer. When the eccentricity of isolation layer is small, the structural vibration mode can be changed from a complex torsional vibration mode with a wide frequency domain to a low-order translational vibration mode, thus the torsional coupling effect is reduced. However, since the horizontal stiffness and torsional stiffness of the isolation layer are small, the translational period of the structure is very close to the torsion period so that the torsional period ratio is hard to meet the requirements from codes [13]. Research shows that for isolated structures, the structural torsion may be small when the structure has a large torsional period[14]. Therefore, it is not appropriate to control the torsional effect of isolated structure by controlling the torsional period ratio.

Dang Yu et al. [14] recommended torsional displacement ratio to be used as a factor for judging the irregularity of torsion in isolation structure. For the calculation of torsional displacement ratio, the Chinese code[15] refers to the larger value of the ratio of the maximum horizontal displacement and the interlayer displacement of the vertical member to the average horizontal displacement and the interlayer displacement, under a specific horizontal force. The specific horizontal force uses the story shears under earthquake, named as specific shears in the following paper. And the torques caused by the specific shears considering 5% of the accidental eccentricity, named as specific torques in the following paper. There are two methods to calculate the torsional displacement ratio of isolating structures:

(1) According to the Chinese Code for Seismic Design of Buildings [15], the upper non-isolation structure is taken for calculation, and the specific force uses the seismic shears considering the isolating influence, by overall multiplied a reduction factor. It can be simply expressed as:

 (1)

Where:

*△*max, *△*ave - the maximum and average story drift

*F*、*T* - the specific shear and the specific torque before considering isolation

*F*I、*T*I - the specific shear and the specific torque after considering isolation

*K*T、*K*F - the specific shear and the specific torque after considering isolation

*L* – the maximum plan diameter of floor

*β* - seismic reduction factor considering isolation

It can be seen that when this method is used to calculate the torsional displacement ratio of isolation structure, the shear force and torque are reduced by a same ratio, thus the displacement ration is exactly the same as the non-isolation structure. The benefit of the isolation technology on decreasing the structural torsion is not reflected.

(2) The structure is modeled as a whole, including the upper non-isolation structure and the isolation layer. The horizontal stiffness of the isolation bearing is considered according to the equivalent secant stiffness under medium earthquake. By making elastic response spectrum analysis or time history analysis of the whole structure, the seismic shear of each story is obtained, according to which the specified shear and torque are calculated, so as the torsional displacement ratio. This method can consider the effect of the isolation layer on changing the value and distribution of the seismic action at each floor, and more realistically reflects the torsional effect of the isolation structure.

Therefore, for the torsion calculation of the isolation structure, it is recommended not to use the torsional period ratio as the control index, but to use the torsional displacement ratio. When calculating displacement ratio, using method (2) mentioned above to correctly reflect the torsional effect of isolation structure.

***3.2 Temperature Effect***

The span of long-span structure is generally huge and the temperature stress is big as well. Especially in the structure of Long-span steel roof, the force caused by temperature generally leads the design force of the structure member. It is effective to release the temperature stress by reducing the constraint to the structural expansion or shrink under temperature load case. For example, reducing the constraint stiffness of the structural support. For the isolation structure, since the horizontal stiffness of isolation bearing is small, it has a natural advantage in reducing the temperature stress. The temperature effect of isolation structure has the following characteristics:

(1) Since the horizontal stiffness of the isolation bearings is small while the vertical stiffness is large, for the long-span structures, the horizontal force under temperature load case can mostly be released, while the vertical force decreases relatively small, as shown in the following table (Table 1). In general, the temperature stress of upper structure can be greatly reduced after using the isolation technology.

Table 1. Comparison of internal forces of a high-rise steel structure under 30°C heating conditions

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| --- | --- | --- | --- | --- |
| **Items** | | **Isolation structure** | **Non-isolation structure** | **Iso/Non-iso** |
| Bottom reaction | Horizontal  Reaction  V0（kN） | 220 | 1847 | 12% |
| Vertical reaction P0 （kN） | 1232 | 2105 | 59% |

(2) In order to ensure the safety of isolation structure, the maximum horizontal force on isolation bearing caused by temperature effect should be less than its yielding force.

(3) Since the isolation layer helps release the temperature stress of the upper structure, the deformation joint of upper structure can be reduced in number or even eliminated in design. When the structure is too long, the shrinkage and creep of concrete may lead large lateral displacement to the seismic isolation bearing during the construction phase[16]. In addition, cracking on the concrete beam in isolation layer may occur[17], which has an impact on the performance during the subsequent application period. Therefore, non-load deformation during the construction stage should be controlled by specific measures to ensure the safe construction of the isolation structure, such as making calculation and prediction of construction deformation on the isolation structure, post-casting division and on-site monitoring, etc. With reference to the Chinese code Rubber Isolation Bearings for Buildings [18], the creep deformation of the linear rubber bearing and the lead rubber bearing should be controlled to be less than 5% of the total thickness of the rubber layer.

As mentioned above, on the one hand, the application of isolation technology can fully utilize the mechanical properties of isolation bearings to control the temperature effect, reduce temperature seams and simplify the design of long-span floor and roof. On the other hand, the force subjected to the isolation support and the non-load deformation are required to be controlled during the construction period.

***3.3 Wind-Resistant Design***

The seismic dissipation mechanism of isolation is that bearings yield under the earthquake action and the stiffness of isolation layer reduces. The seismic energy can be dissipated through the hysteretic deformation of isolation bearings. Therefore, the seismic energy transferred to the upper structure greatly reduces. However, it is unexpected that the isolation bearing becomes yield and has obvious deformation under the wind load. Therefore, the design should ensure that the yield strength of the isolation layer is larger than the design wind load.

Long-span building is generally low in height, however, its windward surface is large. When the length to width ratio is relatively big, the wind load of the long side is large. However, the yield strength of isolation layer is almost equal along all angles. Therefore, the situation easily happens that the resistant bearing capacity does not meet the design requirements for long-term wind load. In addition, due to the extension of natural vibration period in isolation structure, the structural reaction under wind load is more significant than non-isolated structure. For these reasons, there are usually two types of wind-resistant design methods for isolation structures:

(1) Increasing the number of lead rubber bearings can increase the total yield shear capacity of isolation layer. This method works directly. However, as the lead bearings increases, the horizontal stiffness of isolation layer increases, which weakens the isolation effect. Research shows that for buildings under massive wind loads, it seems difficult for the isolation layer to hold up a 50-year wind without yielding, while keeping a certain capability of seismic dissipation[19]. Therefore, using the method of increasing number of lead rubber bearings in the area with a large wind load also requires the consideration of the balance between the wind resistance design and seismic dissipation effect.

(2) Separately attaching wind-resistant devices is another method to carry the wind load. The wind-resistant device works under normal condition to provide horizontal resistance, makes sure the isolation layer will not yield under wind load. When the structure suffers medium and large earthquakes, the wind-resistant device will yield or be destroyed and no longer work, so it will not influence the seismic dissipation effect of isolation layer. At present, the existing wind-resistant devices mainly contain steel plate wind-resistant bearings[20], wind-resistant cables[21], wind-resistant bolts, etc. The seismic dissipation effect under earthquake action should not be reduced by attached devices, which may additionally increase the stiffness of isolation layer. This problem above should be fully demonstrated when deciding to use wind-resistant devices.

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| Figure 9. Steel plate wind-resistant support | Figure 10. Wind-resistant cable | Figure 11. Wind-resistant plug |

***3.4 Influence of Bearing Boundary Constraints***

Code for Seismic Design of buildings (CHINA)[15] suggests a separate design method for seismic isolation design. By using horizontal seismic decrease coefficient, the upper structure adopts the traditional response spectrum calculation method and is designed according to the earthquake influence coefficient corrected by isolation effect. In general, the model of upper structure design uses the model of ‘supporting pier above isolation bearing + isolation layer + structure above isolation layer’. Considering the torsional stiffness and bending stiffness of rubber bearings are very small compared with the concrete column, the supporting pier is hinged at the lower end. The design model is shown as below.

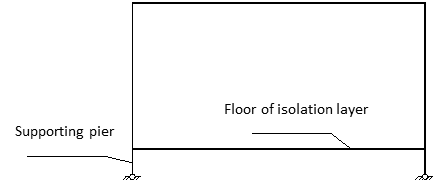


Figure 12. Upper structure design modal sketch

Due to the large cross-section and short length of supporting pier, the line stiffness of pier is large. When using the calculation model above, the bending moment at the ends of pier is large under gravity load, while the beam and column connected to it carries small bending moments. (Figure 13) However, in practice, due to the small horizontal stiffness of isolation bearings, the bending moment at the bottom end of pier is very small. Under gravity load, the bending moments at ends of supporting pier is small while the beam and column connected to it have a large bending moment. (Figure 14) Therefore, the calculation model mentioned above will underestimate the internal torque of the beams and columns in isolation layer under the gravity load. It may be an unsafe design when beams and columns have characteristic of large span and their design forces are controlled by the gravity load. Therefore, it is recommended that in the design of upper structure with long-span, the calculations should be checked by the model considering the actual horizontal stiffness of support.

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| Figure 13. Moment diagram of bottom hinge model | Figure 14. Moment diagram of model consider actual isolator stiffness |

***3.5 Vertical Seismic Action***

The seismic isolation bearings currently used in building structures are mainly laminated rubber bearings and sliding bearings, which can only isolate horizontal earthquake actions, but do not have significant isolation effect for vertical actions[22]. The long-span structure has a high degree of freedom, complex dynamic characteristics and dense frequency and mode distribution[2]. The structural reactions caused by seismic actions from different directions are often with the same magnitude, thus the consideration of vertical seismic action should be more careful than ordinary structures.

According to Code for Seismic Design of Buildings (CHINA)[21], the comparison of vertical seismic action calculation between isolation structure and traditional structure is shown in the table below. (Table 2) This table illustrates that compared with traditional seismic structure, the calculation of vertical seismic action for isolation structure requires a wider range of calculations (all types of structures need to be calculated) and the standard value for vertical seismic action is larger.

Table. 2 Comparison of vertical seismic action calculation between isolated structure and traditional structure

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| **Items** | **Conditions require vertical seismic action calculation** | **Standard value for vertical seismic action** |
| Traditional seismic structure | seismic grade 9 degree high-rise buildings | Fevk=αmaxGeq |
| Long-span、roof、Long cantilever structure | 8 degree: 0.1G ~ 0.13 G  9 degree: 0.2 G ~ 0.25 G |
| Isolation structure | Seismic grade 9 degree and 8 degree when horizontal damping coefficient ≤ 0.3 | Fevk=αmaxGeq,  8 degree (0.2g) ≥ 0.2G,  8 degree (0.3g) ≥ 0.3G,  9 degree ≥ 0.4G |

The internal forces generated by gravity loads and vertical earthquake actions in long-span buildings tend to be large, and the application of isolation technology increases the calculation requirements for vertical seismic actions. Therefore, the internal forces of structure members may increase. This case above should be fully considered when comparing different isolation schemes of long-span building.

***3.6 The Layout of the Playing Field on Isolation Layer***

Stadium-type buildings are one of the main types of buildings in long-span buildings. Compared with other long-span buildings, stadium-type buildings have relatively special characteristics in terms of architectural function layout. Generally speaking, stadium-type building is composed of surrounding functional areas (including grandstand, foyer, walkway, toilet, etc.) and a central playing field. The roof is supported by surrounding vertical members and there is no vertical member in the playing field. Therefore, when the stadium building uses base isolation, the layout of isolation layer can be designed by the following two methods:

(1) All structures above the base are isolated. The advantage of this method is that the overall structure of isolation layer is complete and simple. However, for the slab in playing field increases one floor weight, the seismic action to the upper structure increases. Moreover, the amount of bearings under playing field also increases, which makes the cost relatively high.

(2) Considering that there are no vertical members in the playing field, so it is not necessary to apply isolation in this area. The isolation layer is hollow under playing field. Therefore, this area is directly connected to the foundation, while the isolation bearings are set between surrounding functional area and foundation. In order to ensure the free movement of isolation layer in horizontal direction under earthquake action, the isolation joint should be set between the playing field and the surrounding functional area. The advantage of this method is that the area of isolation floor and the numbers of isolation bearings under playing field are reduced. It is good for finance. In addition, the weight of upper structure is reduced so that the earthquake action to the upper structure decreases as well. However, the surrounding functional area is separated from the playing field by isolation joint, which should also be considered in construction practice. In order to increase the integrity of the isolation layer, the floor slab of isolation layer needs to be thickened.

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| a) All isolation above the base | b) Non-isolation under the playing field |

Figure 15. Isolation layer layout

In actual design process, according to the use of the building, engineers can comprehensively weigh the advantages and disadvantages of different methods to choose the appropriate isolation layer layout.

**4. Conclusion**

(1) High seismic precautionary intensity areas are widely distributed in China. Along with the rapid development on urbanization process, the requirements for long-span buildings are constantly increasing. Effective seismic measures need to be taken to improve the seismic performance and quality of buildings.

(2) At present, the development of isolation technology is relatively advanced and its application in long-span buildings can effectively reduce earthquake actions and improve seismic performance of structures, so that long-span buildings can effectively play the function of post-earthquake disaster relief.

(3) There are two main methods to apply seismic isolation technology in long-span buildings: roof support isolation and base isolation. Roof support isolation has a significant effect on reducing temperature stress to the roof members and horizontal force to the supporting members. Base isolation can effectively reduce horizontal seismic action to the overall structure meanwhile releasing part of the temperature stress.

(4) It is not reasonable to control the torsional effect of isolation structure by torsional period ratio and the torsional displacement ratio in code. It is recommended to directly use the spatial model to analyze the seismic reaction considering accidental eccentricity and moderately broaden the torsional displacement ratio limit according to the story drift between structural layers.

(5) The isolation technology is beneficial to release the temperature stress in long-span buildings and reduce the number of temperature joints, which facilitates the design of long-span floor and roof. However, it is supposed to control the non-load deformation of isolation layer during construction to ensure the safety of the construction and the safety of the structure in subsequent use period.

(6) The design of isolation layer should ensure that it would not yield under the design wind load. The problem of insufficient wind resistance can be solved by increasing the number of lead rubber bearings or setting up wind-resistant devices.

(7) The design upper structure model adopting hinge constraint with supports will underestimate the bending moment of beams and columns in isolation layer under the gravity loads so that the design of beams and columns is partial to be unsafe. In the design of upper structure with long span, it is recommended to use the model considering the elastic support for the check and verification.

(8) Long-span buildings are greatly affected by vertical earthquake actions, while the standard calculations for the vertical seismic action of isolation structures are stricter than ordinary structures. The application of isolation technology increases the calculation requirements for vertical seismic actions. Therefore, the internal forces of structure members may increase. This case above should be fully considered when comparing different isolation schemes of Long-span buildings.

(9) According to the features of the functional layout of stadium buildings, the isolation floor can be hollow under the playing field to reduce the setting of the isolation floor slab and the number of isolation bearings under the playing field. Economic advantages can be obtained while the seismic action to the upper structure can be reduced.

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