Research on Torsional Effect of Friction Pendulum Isolation Structure Based on Nonlinear Time History Analysis

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Abstract. A multi-layer irregular reinforced concrete frame structure in the 8-degree area is taken as the research object, and the working principle and hysteretic model of the friction pendulum bearing (FPB) are explained in detail. With the help of SAP2000 finite element software, a friction pendulum isolation model and its corresponding non-isolation model were established. Plastic hinge constitutive models were defined at both ends of the beams and columns of the RC frame structure, and 100 sets of two-way elastoplastic time history analysis of ground motion are carried out by using dynamic time history method. The results show that: under rare earthquakes, the seismic response of interlayer displacement, interlayer shear, interlayer torque and interlayer torsion angle of the structure after friction pendulum isolation is significantly reduced. Among them, the maximum torsional angle of the base-isolated structure is reduced by nearly 60% compared to the maximum inter-layer torsional angle of the non-isolated structure, and the torque of the first-layer base-isolated structure is reduced by nearly 74.1% compared to the torque of the non-isolated structure, which can prevent serious torsional damage under rare earthquakes and ensure the safety of the structure.

1. Introduction
The anti-seismic needs of buildings in the new era not only ensure the safety of people’s lives, but also minimize the loss of people’s property, so seismic isolation devices are widely used in modern structural anti-seismic projects. Base isolation[1]by connecting the isolation device to the top of the building foundation and the bottom of the pillars of the superstructure to form an energy dissipation layer, the building originally fixed on the foundation is separated from the foundation, and then the building is divided into three parts: foundation, isolation layer and superstructure. When an earthquake occurs, most of the energy is consumed by the deformation of the isolation device, and a large amount of seismic energy is prevented from being transferred to the superstructure, thereby reducing the earthquake action and greatly improving the safety of the building. At present, rubber isolation bearings are widely used in China, but the friction pendulum isolation bearings are rarely used in construction.

The friction pendulum bearing (FPS/FPB) was developed by Zayas et al.[2]in the United States at the University of California, Berkeley. The friction pendulum bearing has strong resetting and self-limiting capabilities, has low sensitivity and high stability to the seismic excitation frequency range, and has excellent energy dissipation mechanism and comprehensive performance such as seismic isolation [3]. In addition, the period of the friction pendulum system is only affected by the radius of the friction pendulum and the acceleration of gravity, and has nothing to do with the quality of the building itself, which brings great convenience to the period control. In recent years, the friction pendulum has attracted the attention of a large number of scholars and engineers because of its outstanding isolation performance and strong operability. The data shows that in foreign countries, friction pendulum isolation
bearings have been widely used in practical cases [4-5], and have a bright future. With the rapid development of economy, irregular structures are appearing more and more due to the requirements of building appearance and construction site. When an earthquake comes, irregular structures are likely to undergo large torsion due to the eccentricity of their structure, causing serious torsional damage to the structure. Research by scholars at home and abroad shows that the use of isolation devices can reduce the torsional effect of irregular eccentric structures, but there are relatively few studies on irregular buildings using friction pendulum bearings. Therefore, the study of irregular frame friction pendulum structures under earthquake action, the reversal reaction is of great significance and engineering value.

2. Working principle and hysteresis model of friction pendulum bearing

2.1. Friction pendulum structure and its working principle

The friction pendulum bearing is composed of an upper support plate, a lower support plate, an articulated slider, a sliding spherical surface, and a low-friction material. As shown in figure 1, the upper support plate has a sliding cavity. When the slider slides, the block can be kept level along the slide. The chute has the same radius of curvature as the surface of the chute, and the surface of the chute is coated with a low-friction material, such as polytetrafluoroethylene. When the earthquake action exceeds the static friction force, the slider moves the superstructure back and forth to dissipate energy. The friction and stiffness in the sliding phase are proportional to the vertical load. The horizontal force of the support is the combined force of the friction force of the sliding surface and the restoring force generated by the rising of the superstructure along the spherical surface of the slideway.

![Figure 1. Section diagram of FPB.](Image)

![Figure 2. Biaxial model of FPB](Image)

2.2. Hysteretic model of friction pendulum

Friction pendulum system [6] in large-scale finite element software SAP2000, nonlinear connection element can be used to simulate friction pendulum for bidirectional seismic dynamic time history analysis. The model is coupled with friction plasticity in shear deformation and has fracture line in axial direction, as shown in figure 2. In the two horizontal directions, i.e. x and y, the horizontal shear of the bearing is the sum of friction force and swing force, namely:

\[
F = \begin{cases}
    F_x = \frac{P}{R} u_x + \mu P Z_x \\
    F_y = \frac{P}{R} u_y + \mu P Z_y
\end{cases}
\]  

(2.1)

The relationship between friction and deformation follows the Park-Wen [7] hysteresis model:

\[
F_x = \frac{P}{R} u_x + \mu P Z_x 
\]  

(2.2)

\[
F_y = \frac{P}{R} u_y + \mu P Z_y 
\]  

(2.3)

In the above formula, \( P \) is the axial load, \( u_x \) and \( u_y \) are the displacement when sliding, \( \frac{P}{R} u_x \) and \( \frac{P}{R} u_y \)
are the swing forces in x and y directions, $\mu_\xi$ and $\mu_\eta$ are the sliding coefficients of the friction pendulum materials in x and y directions respectively, and they change according to the following formula:

$$\mu_\xi = f_\xi - (f_\xi - s_\xi) e^{-\nu \tau}$$
$$\mu_\eta = f_\eta - (f_\eta - s_\eta) e^{-\nu \tau}$$

(2.4)

(2.5)

Where $s_\xi$ and $s_\eta$ are static friction coefficients; $f_\xi$ and $f_\eta$ are dynamic friction coefficients; $r_\xi$ and $r_\eta$ are reverse characteristic slip speed. $z_\xi$ and $z_\eta$ are internal variables of the hysteresis model[8], respectively, and change as follows:

$$\begin{bmatrix}
\dot{Z}_\xi \\
\dot{Z}_\eta
\end{bmatrix} = \begin{bmatrix}
A u_\xi \\
A u_\eta
\end{bmatrix} - \begin{bmatrix}
Z_\xi (\gamma \text{sgn}(u_\xi, Z_\xi) + \beta) & Z_\xi (\gamma \text{sgn}(u_\xi, Z_\xi) + \beta)
\end{bmatrix} \begin{bmatrix}
\dot{u}_\xi \\
\dot{u}_\eta
\end{bmatrix}$$

(2.6)

Where $A$, $\beta$, and $\gamma$ are the dimensionless quantities that control the shape of the hysteresis curve, and take $A = 1$ and $\beta = \gamma = 0.5$, the following formula can be further derived:

$$\begin{bmatrix}
\dot{Z}_\xi \\
\dot{Z}_\eta
\end{bmatrix} = \begin{bmatrix}
1 - a_\xi Z_\eta & -a_\xi Z_\xi Z_\eta \\
-a_\xi Z_\xi & 1 - a_\xi Z_\eta
\end{bmatrix} \begin{bmatrix}
k_\xi \ddot{u}_\eta \\
k_\eta \ddot{u}_\xi
\end{bmatrix}$$

(2.7)

For the interface like PTFE-steel, the friction coefficient generally increases with the slip speed. The internal hysteresis variables $(Z_\xi^2 + Z_\eta^2)^{1/2} \leq 1$, $(Z_\xi^2 + Z_\eta^2)^{1/2} = 1$ represent yield, where $k_\xi$ and $k_\eta$ are the elastic shear stiffness of the slider without sliding.

$$a_\xi = \begin{cases}
1 & u_\xi > 0 \\
0 & u_\xi \leq 0
\end{cases}$$

$$a_\eta = \begin{cases}
1 & u_\eta > 0 \\
0 & u_\eta \leq 0
\end{cases}$$

3. Project overview and calculation model

3.1. Project overview

This project is a 6-story RC frame structure, the plane is "L" type, and the height of the structural layer is 3.6m. According to Article 3.4.3 of Code for seismic design of buildings[9], the concave size of the structure plane is larger than the total size of the corresponding projection direction 30% belongs to irregular buildings. The column section is 700mm × 700 mm, the main beam section is 700mm × 300mm, the secondary beam section is 600mm × 300mm, the floor thickness is 120mm. The strength grade of concrete is C30, the longitudinal stress reinforcement is HRB400, Stirrups are HRB335. The dead weight of the structure and the constant load of one to five floors are 3KN/m², and the infill wall on the frame beam is converted to a constant load of 7KN/m. The live load of one to five floors is 2KN/m². The roof load is 4KN/m², and the live load is 0.5KN/m². The seismic fortification intensity is 8 degrees, the proposed site category is Category II, and the earthquake is grouped into the first group. The design basic acceleration is 0.2g, and the maximum acceleration time history is 400cm/s².

3.2. Calculation model

SAP2000 finite element software was used to establish fixed structure and friction pendulum isolated structure. In the finite element software, the frame element uses the three-dimensional beam-column theory to calculate the biaxial bending, torsion, axial tension and compression and biaxial shear effects, which can better simulate the beam and column. Most of the non-isolated structures will become nonlinear under rare earthquakes. If linear simulation is used, it will not meet the actual situation.
order to simulate the nonlinearity of the material, by defining the frame element plastic hinges, that is, the beam column plastic hinges, the frame beams both ends of the main axis are designated with M3 bending hinges on the main axis, and P-M2-M3 hinges with interaction of axial forces and bending moments are designated on both ends of the frame columns. Both types of hinges use the default hinges recommended by the software. A 1.6m high isolation layer is set up in the friction pendulum isolation structure, and the isolation bearing is simulated by the friction isolator nonlinear connection element. The non-isolated structure is fixed on the foundation directly. As shown in figure 3. The stiffness of FPB is related to the vertical force it bears[10]. According to the vertical force it bears and the bearings parameters[11], the initial stiffness and equivalent stiffness can be calculated, as shown in table 1. Install the designed friction pendulum bearings between the bottom of the bottom columns and the top of the foundation, a total of 36, as shown in figure 4.

![Figure 3. 3D model of structure](image)

![Figure 4. Arrangement of FPB.](image)

|                | FPB1  | FPB2  |
|----------------|-------|-------|
| Vertical stiffness (KN/mm) | 3500  | 3500  |
| Initial stiffness (KN/m)    | 14764 | 21654 |
| Effective stiffness (KN/m)  | 1125  | 1650  |
| Friction coefficient, slow  | 0.02  | 0.02  |
| Friction coefficient, fast  | 0.03  | 0.03  |
| Ratio parameter (s/m)       | 20    | 20    |
| Radius of curvature (m)     | 1.5   | 1.5   |

4. Modal analysis
Before the dynamic time history analysis, a modal analysis is first performed, which is mainly used to calculate the vibration mode and period (frequency) of the structure. With the help of modal analysis,
the inherent dynamic characteristics of the structure can be understood. For the dynamic characteristics of the non-isolated structure, SAP2000 finite element software was used for modal analysis to extract the first three modes of the structure, as shown in Table 2. After isolation using friction pendulum bearings, the basic period of the structure has increased from 0.733s to 2.338s, which is nearly 3.2 times longer than the period of the non-isolated structure. It can be far away from the predominant period of the building, avoid resonance and reduce the seismic response of the structure. It can also be seen from the table that the mass participation coefficient of fixed base structure in the two directions of \( UY \) and \( RZ \) in the second and third modes is relatively large, while the mass participation coefficient of isolated structure in the second and third modes is relatively large in only one direction, which indicates that the occurrence of translation torsion coupling is effectively limited after the isolation is adopted.

| Type           | Vibration model | Period | Mode mass participation coefficient (%) |
|----------------|-----------------|--------|-----------------------------------------|
|                |                 |        | UX       | UY       | RZ       |
| Fixed structure| 1               | 0.733  | 80.4     | 0        | 0.2      |
|                | 2               | 0.646  | 0        | 63.6     | 17.6     |
|                | 3               | 0.618  | 0.2      | 17.9     | 63.4     |
| Isolated       | 1               | 2.338  | 98.8     | 0        | 1.0      |
| structure      | 2               | 2.308  | 0        | 99.8     | 0        |
|                | 3               | 2.218  | 0.01     | 0        | 98.9     |

5. Dynamic time history analysis

5.1. Seismic wave input

According to the code for seismic design of buildings in China[9], this model is an irregular structure, and the two-way seismic wave input should be carried out to consider the torsional effect of the structure. How to select and select several ground motions as input in the analysis has not been agreed by scholars at home and abroad. The choice of input ground motion ignores the differences in construction sites and often uses several typical seismic waves (such as EL-Centro waves, Taft waves, etc.), resulting in very different calculation results for different inputs of the same structure at the same intensity. Therefore, reasonable selection of seismic waves is extremely important for studying the seismic performance of structures. This article uses the Chinese standard seismic design response spectrum as the target spectrum[12] and downloads 100 sets of ground motions with a good degree of fit from the Pacific Earthquake Engineering Research Center (PEER) ground motion database. Each group of ground motions consists of three seismic waves. Two seismic waves in the horizontal direction are selected as input waves, and the response spectrum curve and the standard spectrum curve of the seismic wave are shown in figure 5. Due to the limited space, this article only studies the response of structures under rare earthquakes. Adjust the peak acceleration to the rare earthquake acceleration 400cm/s², and input them in two directions in X direction and Y direction respectively. The peak acceleration value is 1 (X main direction):0.85 (Y direction) input. Because there are many seismic waves, the following calculation results are the average of 100 seismic wave responses.
5.2. Structural response under rare earthquake

5.2.1. Displacement response. The maximum interlayer displacement of the structure reflects the size of the structural deformation and is one of the important parameters to judge the degree of structural damage. The maximum inter-layer displacement of non-isolated and isolated structure is shown in table 3 under the action of two-way earthquakes. Floor number 0 represents the isolation layer. It can be seen from table 3 that the non-isolated structure undergoes shear deformation under earthquake action, while the deformation of the friction pendulum isolation structure is mainly concentrated in the isolation layer, and the superstructure is approximately rigid body translation. In addition, due to the large deformation of the isolation layer, a lot of seismic energy is consumed, and the upper structure keeps linear elasticity approximately. From the data analysis in the table, it can be seen that the maximum interlayer displacement in X direction is reduced by nearly 76.5% and the maximum interlayer displacement in Y direction is reduced by nearly 78.6%. Therefore, the interlayer displacement of the structure after the friction pendulum isolation is well controlled in the seismic response.

Table 3. The interlayer displacement of fixed structure and isolated structure.

| Floor number | Maximum interlayer displacement of each layer under rare earthquake (m) | Fixed structure | Isolated structure |
|--------------|-----------------------------------------------------------------------|----------------|-------------------|
|              | X direction | Y direction | X direction | Y direction |
| 0            | 0.094       | 0.088       | 0.094       | 0.088       |
| 1            | 0.010       | 0.008       | 0.004       | 0.003       |
| 2            | 0.016       | 0.013       | 0.005       | 0.004       |
| 3            | 0.018       | 0.014       | 0.005       | 0.003       |
| 4            | 0.034       | 0.013       | 0.008       | 0.003       |
| 5            | 0.014       | 0.010       | 0.003       | 0.002       |
| 6            | 0.011       | 0.006       | 0.002       | 0.001       |

5.2.2. Interlaminar shear contrast. In this paper, the maximum interlayer shear of each floor in two horizontal directions of non-isolated and isolation is extracted, as shown in table 4. For comparison, the custom reduction rate is equal to \((a - b) / a \times 100\%\), \(a\) represents the shear of fixed structure, and \(b\) represents the shear of isolation. It can be seen from the table that in the elastic-plastic time history analysis, the maximum reduction rate in X direction is 51.5%, and the maximum reduction rate in Y direction is 53.5%. The isolation effect is quite obvious.
Table 4. Interlayer shear of fixed base structure and isolated structure.

| Floor number | Maximum shear of each layer in X direction (KN) | Reduction rate | Maximum shear of each layer in Y direction (KN) | Reduction rate |
|--------------|-----------------------------------------------|----------------|-----------------------------------------------|----------------|
|              | Fixed structure                               | Isolated structure | Fixed structure                               | Isolated structure |
| 1            | 8125.86                                       | 4609.68         | 43.3%                                         | 7808.01         | 4307.11 | 44.8% |
| 2            | 6546.50                                       | 4315.43         | 34.1%                                         | 6462.81         | 3940.33 | 39.0% |
| 3            | 5619.36                                       | 3880.11         | 30.1%                                         | 5517.03         | 3510.11 | 36.4% |
| 4            | 5106.96                                       | 3389.05         | 33.6%                                         | 4941.79         | 3077.54 | 37.7% |
| 5            | 4410.40                                       | 2691.23         | 39.0%                                         | 4141.84         | 2418.76 | 41.6% |
| 6            | 3031.66                                       | 1468.96         | 51.5%                                         | 2669.64         | 1241.57 | 53.5% |

5.2.3. Interlayer torque. In this paper, the maximum inter story torque of fixed base structure and friction pendulum isolation is extracted, as shown in figure 6. It can be seen that the maximum inter story torque of non-isolated structure is at the bottom layer, which decreases with the layer height, because the seismic force on the bottom layer is relatively large, and decreases with the increase of the floor. However, the inter-layer torque of the seismic isolation structure increases slowly with the height of the layer, reaches the peak at the fourth layer, and then slowly decreases layer by layer. This is because the isolation layer dissipates most of the energy. After isolation, the data in the figure shows that the torque between the isolation layers is significantly lower than that of the non-isolated layer. Especially for the first floor, the torque of the isolated structure is reduced by nearly 74.1% compared to the torque of the non-isolated structure, which avoids the brittle torsional failure of the first floor columns under rare earthquakes.

![Figure 6. Interlayer torque of fixed structure and interlayer torque of isolation structure.](image)

5.2.4. Interlaminar torsional angle. In this paper, the interlaminar torsional angle is used to measure the torsional effect of the structure. The calculation result is shown in figure 7. Floor number 0 represents the isolation layer. As can be seen from the figure, the curve between the torsion angle and the height of the floor after isolation is "L" type, the torsion is concentrated in the isolation layer, and the torsion angle of the superstructure is significantly reduced, and the size is very close. The torsion angle and the floor height curve of the non-isolated structure is in the shape of "->", and the torsion is concentrated on the second and third floors. It can be seen that under the action of the earthquake, the floating range of the torsion angle of the non-isolated structure is relatively large, and the torsion of the middle floor is

![Figure 7. The interlaminar torsional angle of fixed structure and the interlaminar torsional angle of isolated structure.](image)
relatively severe. However, when the friction pendulum bearing is used, the torsional angle fluctuation of the superstructure is relatively stable and the numerical value is relatively small, and the maximum value is only 40.8% of the maximum torsion angle of the non-isolated structure.

6. Conclusions
In this paper, 100 sets of two-way elasto-plastic time-history analysis of the non-isolated frame structure and the friction pendulum isolation structure are carried out, and the main conclusions are as follows:

(1) Using the friction pendulum isolation bearings can effectively increase the natural vibration period of the structure. The first three periods are about 3.2 times that of the fixed base structure, and the main mode mass participation coefficient has only one direction, so it can effectively restrain the occurrence of translation torsion coupling after isolation.

(2) Under rare earthquakes, the maximum interlayer displacement of the friction pendulum isolation structure in the X direction is reduced by nearly 76.5%, and the maximum interlayer displacement in the Y direction is reduced by nearly 78.6%, which can ensure that the deformation of the upper structure remains within the elastic range under rare earthquakes. Because the nonlinear of the structure is considered based on the elastic-plastic time history analysis, it can provide some reference value for the practical engineering.

(3) Under the action of two-way earthquake, the inter story torque of isolation is significantly lower than that of the fixed base structure. Especially for the first floor, the torque of the isolated structure is reduced by nearly 74.1% compared to the torque of the non-isolated structure, which can prevent the torsional damage of the first floor columns under rare earthquakes.

(4) The torsion of the non-isolated structure is concentrated in the 2nd and 3rd layers, while the torsion of the isolated structure is concentrated in the isolation layer, the torsion angle of the upper structure is significantly reduced, and the size is very close. The maximum value is only 40.8% of the maximum torsion angle of the non-isolated structure, which prevents serious torsional damage and ensures the safety of the structure.

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