Effects of Vertical Stiffness of Rubber Bearings on the Vertical Seismic Response of Isolated High-rise Building

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Abstract: A hybrid model is used to simulate the characteristics of the rubber bearing, which can accurately reflect the vertical stiffness properties. In this paper, the analysis method nonlinear seismic response of isolated high-rise building (IHRB) was described by a case study in high seismic intensity region. In addition, accurate simulation of horizontal mechanical characteristics of rubber bearing and influence analysis of different ratio of the tensile to compressive stiffness (RTCS) of rubber bearing were conducted. The results show that the RTCS have slight effect on the compressive stress of the rubber bearing, the axial force of the piers, and the acceleration at the top of the building, but has significant influence on the tensile stress of the rubber bearing and axial force of the frame column and cannot be neglected. Moreover, with the increase in the RTCS, the axial force of the frame column at each floor decreases. The larger RTCS will underestimates the axial force on the frame column under the rare earthquake. As the RTCS is reduced, the rubber bearing is less prone to tension, but the large RTCS will overestimates the tensile stress of the bearing under the rare earthquake. When the RTCS is smaller than 1:6, it has a slight effect on the vertical seismic response of the IHRB.

1. Introduction

As an effective technological approach to prevent disasters and reduce damages on the architectural structures, the seismic isolation technique has been widely used in buildings at the earthquake-prone regions and has been tested under practical earthquake condition which can effectively alleviate the seismic effect on architectural structures and provide safety assurance for the buildings at the high-prone earthquake regions [1-5]. Recently, the requirements for using the seismic isolation technique in high-rise buildings at earthquake-prone regions are constantly increasing. With relatively large height-width ratio, the bending moment at the base of the high rise building is relatively large. Therefore, under the effect of the earthquake, the isolation bearing is prone to be under tensile conditions [6-7]. Interior damages in the rubber after being exposed to tension loads, which decrease the elastic properties of the bearing, and tension stresses appear in the isolation bearing. This implies a risk of overturning the superstructure.

Currently, available computer software used for seismic isolation design analysis, provides isolation bearing with mechanical characteristics that generally have the same tensile and compressive stiffness, therefore the non-linear mechanical characteristics of the isolation bearing with different
tensile and compressive stiffness are not taken into consideration. However, these isolation bearing cannot reflect realistic mechanical characteristics of the isolation bearing under inelastic conditions\cite{8,9}. To simplify the design, the seismic design specifications for high rise seismic isolated buildings are the same as the seismic design specifications for the low-rise seismic-isolated buildings, without considering the vertical effects of the earthquake or ways adopting equivalent vertical earthquake loads\cite{10}. Furthermore, for the IHRBs, the gravity load of the superstructure is very large, which obviously influences the nonlinear characteristics of the isolation layer\cite{11}. Therefore, it is difficult to accurately reflect and estimate vertical effects of the rare earthquake\cite{12,13}. In previous studies shown that the significant effect of the vertical component of earthquake on the response of structure such as axial force, overturning moment, and relative movement between core walls and external columns for high-rise buildings or isolated structures subjected to vertical earthquakes\cite{14,15}. Horizontal earthquakes are the primary source that produce tension in the isolation bearings for base-isolated tall building, and vertical earthquakes make the situation more promoted\cite{16,17}. Based on this, it is necessary to consider the non-linear mechanical characteristics of the isolation bearing with different tensile and compressive stiffness, and study the tensile conditions and vertical seismic response of the IHRB under three-dimensional earthquake.

In this study, a three-dimensional seismic time history was applied to an IHRB under different RTCS, and the effect of the seismic isolation design with the consideration of the different tensile and compressive stiffness on the vertical seismic response was discussed. The range of reasonable values of the RTCS of the seismic isolated bearing was studied as well.

2. Dynamic Analysis Model and Ground Motions

2.1 Mechanical Properties Simulation of Rubber Bearing

The mechanical properties of the laminated rubber bearing are mainly reflected in the horizontal hysteretic behavior, axial compression and axial tension properties. Studies have indicated that when the laminated rubber bearing enters an inelastic state, the compressive stiffness of the bearing is about 0.1 to 0.2 times the tensile stiffness\cite{18}. To assure the normal working performances of the laminated rubber bearing, the Code for Seismic Design of Buildings (GB50011-2010)\cite{10}, stipulates that the tensile stress of the isolation bearing under rare earthquakes should not be higher than 1 MPa. For the high-rise seismic isolated buildings, the isolation bearing under rare earthquake may be subjected to tensile stress, when the bearing comes to the inelastic state, the stiffness of the bearing decreases dramatically. Therefore, it is needed to analyze by using the mechanical model with different compressive and tensile stiffness for obtaining accurate results, as shown in Fig.1(a).

The computer software SAP2000 is used in this paper for earthquake time-history analyses of the seismic isolated structure. However, the vertical properties of the Rubber Isolator connecting elements in SAP2000 is the equal stiffness model (tensile stiffness equal to compressive stiffness), and which in the horizontal direction is the Bouc-Wen model, as shown in Fig. 1(b). Therefore, this paper uses Rubber Isolator element and the Gap element in parallel to simulated the Rubber bearing element\cite{9}. The mechanical properties of the Gap elements are described in Eq. (1) as follows:

\[
f = \begin{cases} 
  k(d + \text{open}) & d + \text{open} < 0 \\
  0 & d + \text{open} \geq 0 
\end{cases}
\]

where \(k\) is the spring constant, \(d\) is the interior deformation of the spring, \(\text{open}\) is the initial distance of the gap, \(\text{open}\) value must be positive or zero.

Fig.2 shows the axial deformation behavior of the Gap element. Using the Gap element, the gap can be set as zero to simulate the objects that are only under compression. When the isolation bearing under compression, the vertical stiffness of the isolation bearing is taken by the Rubber Isolator and the Gap together, while the horizontal stiffness is taken by the Rubber Isolator only; when is under tension, the vertical stiffness of the isolation bearing is taken by the Rubber Isolator only, the horizontal stiffness is still taken by the Rubber Isolator. This implies that the mechanical
characteristics of the isolation bearing with different compression and tension stiffness can be effectively simulated, while the horizontal stiffness of the bearing is not changed.

![Figure 1 Mechanical model for rubber bearings](image1)

![Figure 2 Mechanical model for Gap element](image2)

2.2 Analysis Model of a High-rise Isolated Structure

We employ a fourteen story tall isolated frame-core tube structure for an analytical study. The height of the seismic isolated layer is 1.6 m and the total height of the structure is 62.3 m. The stiffness model of the superstructure is assumed to linear elastic and have a rigid diaphragm, the beams and columns are modeled with frame elements, shell element are used for the shear walls, membrane elements are used for the floor slab, and the isolation bearing is simulated by using the Rubber Isolator and Gap elements in parallel. The finite element model of this structure is shown in Fig. 3. The main design considerations for the analysis of this structure are\(^\text{10}\): the seismic fortification intensity is 8 degrees, the site classification is II, the design earthquake classification corresponds to the first group, and the design working life of the structure is 50 years.

Three kinds of the rubber bearings are chosen for designing the seismic isolated layer; the lead rubber bearings with diameter of 1100 mm are arranged under the frame columns outside the structure, the natural rubber bearings with diameter of 1300 mm are arranged at the four corners of the core tube, and natural rubber bearings with diameter of 1100 mm are arranged at other positions of the core tube. There is a total of 45 isolation bearings arranged. The mechanical parameters and numbers of each groups of the isolation bearing are listed in Table 1. The isolation bearing arrangements is shown in Fig. 4. The ratios of the tensile to compressive stiffness are 1:1, 1:2, 1:5, 1:6, 1:7, 1:8, 1:9, 1:10, 1:11, and 1:12, and are separated in sets of 10 models for study. The values of vertical strength for the Rubber Isolator and Gap elements are listed in Table 2, for which equal tension and compression strength is only simulated with the Rubber Isolator element.

![Figure 3 Analysis model of isolated high-rise structure](image3)

![Figure 4 Arrangements of isolators](image4)

| Type of the bearing | Thickness of the bearing (mm) | Vertical stiffness | Equivalent horizontal stiffness | Yield stiffness | Yield force (kN) | Number |
|--------------------|--------------------------------|--------------------|-------------------------------|----------------|-----------------|--------|
| L11                | 1100                           |                    |                               |                |                 | 1.00   |
| L12                | 1300                           |                    |                               |                |                 | 1.00   |
| L13                | 1100                           |                    |                               |                |                 | 1.00   |
| L14                | 1300                           |                    |                               |                |                 | 1.00   |
| L15                | 1100                           |                    |                               |                |                 | 1.00   |
| L16                | 1300                           |                    |                               |                |                 | 1.00   |

\(^{10}\) \text{Seismic fortification intensity, site classification, earthquake classification, and design working life.}
2.3 Ground Motions

This paper adopts 7 groups of three-dimensional seismic records from the database of the U.S. Pacific Earthquake Engineering Research Center (PEER) that include; El Centro Array #3, Parachute Test Site, Gebze, TCU046, TCU122, Lab. Gran Gassoand and Canterbury Aero Club, as seen in Table 3. When the seismic fortification intensity is 8 degree, according to the seismic code [10], the maximum ground acceleration value is 510 gal. When the X direction is input as the main direction, the ratio of the peak acceleration values for the three components of the earthquake shaking are X:Y:Z=1:0.85:0.65; When the Y direction is input as the main direction, the ratio of the peak acceleration values for the three components are X:Y:Z=0.85:1.0:0.65. The comparison between the response spectra for the 7 groups of the three-component acceleration seismic records and the Chinese GB 50011-2010 design spectra [10], is shown in Fig.5.

| Events          | Station          | Date  | Mw  | R_{np} (km) | V_{s30} (m/s) |
|-----------------|------------------|-------|-----|-------------|---------------|
| Imperial Valley | El Centro Array  #3 | 1979  | 6.53 | 12.85       | 162.94        |
| Imperial Valley | Parachute Test Site | 1979  | 6.53 | 12.69       | 348.69        |
| Kocaeli         | Gebze            | 1999  | 7.51 | 10.92       | 792.00        |
| Chi-Chi         | TCU046           | 1999  | 7.62 | 16.74       | 465.55        |
| Chi-Chi         | TCU122           | 1999  | 6.20 | 19.30       | 475.46        |
| L’Aquila        | Lab. Gran Gassoand | 2009  | 6.30 | 11.15       | 547.00        |
| Darfield        | Canterbury Aero Club | 2010  | 7.00 | 14.48       | 280.26        |
3. Vertical Seismic Response of the Isolated Layer

A certain number of records on macroseismic damage from strong motions indicate that the effects of the vertical component of an earthquake on the buildings at high seismicity regions are significant [19, 20]. It is possible that tensile stresses occurs in the IHRB under certain earthquake conditions. In the present paper, the multi-dimensional characteristics of the seismic input motions are considered. The tensile and compressive stresses in the seismic isolated bearing were verified and analyzed by choosing different ratios of the tensile to compressive stiffness. The load combination used to verify the tensile stress on the seismic isolated bearing are \[1.0 \times \text{Dead Load} + 0.5 \times \text{Live Load} + 1.3 \times \text{The Minimum Axial Force Under Rare Earthquake};\] The load combination used to verify the compressive stress on the seismic isolated bearing are: \[1.2 \times \text{Dead Load} + 0.6 \times \text{Live Load} + 1.3 \times \text{The Maximum Axial Force Under Rare Earthquake},\] where the average value for the 7 groups of seismic motions is chosen as the seismic response.

3.1 Tensile Stress Response of the Rubber Bearing

The results of the effects in the bearing under different ratios of the tensile to compressive stiffness calculated from this study are shown in Fig.6. The stress is positive when the bearing is under tension, while the stress is negative when the bearing is under compression. When the RTCS is equivalent, the maximum tensile stress is notoriously larger than when the RTCS is not equivalent. Therefore, it can be concluded that the RTCS has a significant effect on the tensile stress. It can be observed from the general trend of the tensile stress on the bearing that when the RTCS decreases, the tensile stress is less likely to occur. When the RTCS of the bearing is 1:1 and 1:2, there are more bearings under tension. This mainly focuses on the seismic isolated bearings at the edge of the core tube of the shear wall (L19 to L42), among which the 4 bearings at the corner of the core tube have the most unfavorable tensile bearing stresses, with the tensile stress over 1 MPa, exceeding the limit value specified in the code [10]. When the RTCS decreases from 1:6 to 1:12, its effect on the tensile stress is not noticeable. It can be observed that the tensile curves of the bearings are very close, with insignificant differences of the tensile stress values, and the bearings are not under tension. It can be also observed that the decrease in the RTCS can reduce the number of bearings under tension, while the equivalent RTCS overestimates the tensile stress of the bearing under the rare earthquake.
3.2 Compressive Stress Response of the Rubber Bearing

Fig. 7 shows the maximum compressive stress of the bearings under the rare earthquake. It can be observed that the effects of the RTCS of the bearing on the maximum compressive stress is not noticeable, except for a little difference at the bearing of the core tube (L19 to L45), when the RTCS of the bearing decreases from 1:6 to 1:12, the maximum compressive stress curves are almost overlapping each other indicating no significant effects.

4. Vertical Seismic Responses of the Superstructure

In order to investigate the effects of the RTCS on the vertical seismic response of the superstructure, typical vertical components are chosen and analyzed, including frame columns at the 1st floor A, B, C, D and pier of the shear wall E, F. The maximum axial force is used as the index to measure the effects of the RTCS on the dynamic response of the vertical structure, and two nodes 293 and 302 are chosen at the top of the structure to analyze the effects of the RTCS on the vertical acceleration of the top of the structure.

4.1 Axial Force Response of Columns and Piers

Table 4 and Table 5 list the maximum axial force of the typical frame columns at the 1st floor with different ratios of the tensile to compressive stiffness. It can be observed that the general trend of the maximum axial force in the typical frame column is that it increases with the decrease of the RTCS, among which the maximum difference is 18.42%, which occurs at the frame column A under the earthquake condition where Y is considered the main direction of the motion. When the RTCS decreases from 1:6 to 1:12, the difference of the axial force in the frame column become smaller and the effects are not noticeable. When the RTCS is within this range, the maximum amplification of the A column is only 4.38% under the earthquake with X-direction as the main direction.
It can be observed from Fig. 8 that with the decrease of RTCS, the axial force of the frame column A along each floor increases. Similarly, when the RTCS decreases from 1:6 to 1:12, the curves of the axial force in the frame column along each floor are almost the same. Therefore, when the RTCS is equivalent, the axial force of the frame column is underestimated, which causes potential safety hazard for the design of the superstructure.

Table 4 Maximum axial force in the first floor columns subjected to horizontal earthquake conditions when X is considered the main direction of the motion (kN)

| Stiffness ratio | Column components |
|-----------------|-------------------|
|                 | A     | B     | C     | D     |
| 1:1             | 7885  | 7931  | 7352  | 8238  |
| 1:2             | 8717  | 8309  | 7494  | 8533  |
| 1:5             | 9347  | 9134  | 7373  | 8699  |
| 1:6             | 9789  | 9177  | 7532  | 8767  |
| 1:7             | 9888  | 9302  | 7505  | 8768  |
| 1:8             | 9961  | 9396  | 7481  | 8768  |
| 1:9             | 10038 | 9512  | 7487  | 8795  |
| 1:10            | 10076 | 9515  | 7429  | 8746  |
| 1:11            | 10150 | 9555  | 7403  | 8735  |
| 1:12            | 10218 | 9589  | 7378  | 8726  |
| Mean            | 9607  | 9142  | 7443  | 8678  |
| MaxDiff         | 17.92%| 13.25%| 1.23% | 5.06% |

Note: MaxDiff = \[|\text{Maximum(or Minimum)} - \text{Mean}|/\text{Mean}\]

Table 5 Maximum axial force in the first floor columns subjected to horizontal earthquake conditions when Y is considered the main direction of the motion (kN)

| Stiffness ratio | Column components |
|-----------------|-------------------|
|                 | A     | B     | C     | D     |
| 1:1             | 7692  | 8159  | 7461  | 7995  |
| 1:2             | 8501  | 8619  | 7581  | 8219  |
| 1:5             | 9184  | 9163  | 7445  | 8712  |
| 1:6             | 9560  | 9358  | 7607  | 8615  |
| 1:7             | 9666  | 9450  | 7573  | 8652  |
| 1:8             | 9775  | 9517  | 7541  | 8676  |
| 1:9             | 9895  | 9608  | 7539  | 8731  |
| 1:10            | 9947  | 9605  | 7477  | 8690  |
| 1:11            | 10008 | 9637  | 7450  | 8689  |
| 1:12            | 10055 | 9660  | 7428  | 8686  |
| Mean            | 9428  | 9278  | 7510  | 8567  |
| MaxDiff         | 18.42%| 12.06%| 1.29% | 6.67% |
Figure 8 Influence of the axial force in the frame column

Table 6 shows axial force of the piers in the first floor under different values of the RTCS. It can be observed that the effect of RTCS on the axial force of the piers is not significant, with a maximum difference of 5.93%, which occurs at the pier F under the earthquake condition where Y-direction is considered the main direction of the motion. The axial forces on the pier F along each floor under different ratios of the tensile to compressive stiffness are shown in Fig.9. It can be observed that the ratios of the tensile to compressive stiffness have little effect on the piers for floors 1 to 3, which can be neglected. The curves of the axial force of piers at floor 3 to 14 overlap each other which indicates are not affected by the RTCS.

Table 6 Maximum axial force at piers (kN)

| Stiffness ratio | X-direction | Y-direction |
|----------------|-------------|-------------|
|                | Pier components |             |             |
|                | E           | F           | E           | F           |
| 1:1            | 16362       | 14843       | 16433       | 15552       |
| 1:2            | 16668       | 15425       | 16849       | 16277       |
| 1:5            | 16827       | 15798       | 17524       | 16730       |
| 1:6            | 16902       | 15795       | 17351       | 16649       |
| 1:7            | 16873       | 15800       | 17375       | 16658       |
| 1:8            | 16839       | 15796       | 17378       | 16652       |
| 1:9            | 16987       | 15936       | 17590       | 16810       |
| 1:10           | 16784       | 15790       | 17404       | 16665       |
| 1:11           | 16754       | 15783       | 17408       | 16665       |
| 1:12           | 16727       | 15775       | 17407       | 16665       |
| Mean           | 16772       | 15674       | 17272       | 16532       |
| MaxDiff        | 2.45%       | 5.30%       | 4.86%       | 5.93%       |
4.2 Vertical Acceleration Response of Top Floor

Table 7 presents peak values of the vertical acceleration of two nodes at the top of the structure. It can be observed that the maximum values of vertical acceleration under different ratios of the tensile to compressive stiffness are almost the same, with a maximum difference of 6.03%, which occurs at the node 302 under the earthquake condition where Y is considered the main direction of the motion. Therefore, the RTCS of the bearings has no significant effects on the maximum values of vertical acceleration at the superstructure.

Table 7 Maximum vertical acceleration values at the top floor of the structure (m/s²)

| Stiffness ratio | X-direction | Y-direction |
|-----------------|-------------|-------------|
|                 | Nodes       |             |
|                 | 293         | 302         |
|                 | 293         | 302         |
| 1:1             | 5.14        | 4.45        |
| 1:2             | 5.26        | 4.62        |
| 1:5             | 5.34        | 4.52        |
| 1:6             | 5.30        | 4.60        |
| 1:7             | 5.31        | 4.58        |
| 1:8             | 5.33        | 4.58        |
| 1:9             | 5.34        | 4.58        |
| 1:10            | 5.35        | 4.58        |
| 1:11            | 5.36        | 4.58        |
| 1:12            | 5.37        | 4.57        |

Mean 5.31 5.28

MaxDiff 3.20% 2.71% 2.54% 6.03%

5. Conclusions

In this study, an modified method for the rubber isolation bearing was applied to simulate the mechanical characteristics of different tensile and compression stiffness. And the three-dimensional seismic time histories of a IHRBs was analyzed. The effects of the RTCS on the vertical seismic response of the structure were discussed. The main conclusions from this study are the following:
1) Under the effects of the three-dimensional seismic ground motions, the RTCS has relatively significant effects on the tensile stress of the high-rise rubber seismic isolated bearing, especially when the RTCS is equivalent, the tensile stress of the bearing is overestimated, which is not consistent with the practical load-carrying capability. When the RTCS decreases from 1:6 to 1:12, the tensile stress curves of the bearings are very close to each other, and the difference of the tensile stress is not significant. The consideration of different ratios of the tensile to compressive stiffness has no significant effects on the validation of the compressive stresses of the bearing.

2) The axial force in the frame columns of the superstructure increases with the decrease of the RTCS, and this behavior is observed to be consistent at each floor. When the RTCS of the bearing decreases from 1:6 to 1:12, the difference of the axial force in the frame columns is small; the effect of RTCS on the axial force of the piers is not significant and only has little effect on the piers of the bottom floor, which can be neglected; similarly, no significant effects were observed on the peak acceleration at the top of the structure.

3) When analyzing high-rise seismic-isolated structure, it is suggested to consider the variation on the mechanical properties with different ratios of the tensile to compressive stiffness of the rubber bearing. The RTCS need be chosen to have a relatively small effect on the seismic response of the structure. For the isolated high-rise structures studied in the present work, when RTCS of the rubber bearing is smaller than 1:6, it had very small effect on the seismic response of the structure.

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