# Influence Analysis of Connecting Style on Vertical Earthquake Response of High Rise Buildings with Connecting Structure

**Zheng Nina[1], Yang Zhihong[1], Yang Qiong[2], Dai Xun[3], Ji Shuyan[4]**

[1] *PhD candidate, College of Civil Engineering, Chongqing University, Chongqing, China*
[2] *Engineer, Dept. of Structural Engineering, Sichuan Institute of Building Research, China*
[3] *Postgradute, College of Civil Engineering, Chongqing University, Chongqing, China*
[4] *Associate Professor, College of Civil Engineering, Chongqing University, Chongqing, China*
*Email: zhengnina@cqu.edu.cn*

**ABSTRACT :**

The vertical earthquake actions of high rise buildings with connecting structure are necessary to consider for there are abundant vertical vibration modes of the connecting body with big span usually. In this paper, high-rise building examples with connecting structure are designed with 4 kinds of joining style popularly in practice. Then, the vertical earthquake actions of examples are analyzed. Based on the analysis results, the influence of connecting style on the vertical earthquake action of connecting structure and main structure are investigated. Based on the analysis, the following conclusions are achieved: ①The overall dynamic characteristics of the connected structure with symmetric towers are very limited changed with connecting way of the 4 types, as well as the vertical vibration mode; ②Under vertical earthquakes, the shear force of the bar at end span of corridor due to the vertical earthquakes is the biggest in the model R-R, while the smallest in the model H-H, So for the connected structure design, the connecting style H-H would be better, ③The vertical displacement of the connected structure is too small to influence the its design. ④The ratio of the axial force caused by the vertical earthquake action and the dead load in column 1 which supports the connected structure is too big to ignore. The conclusions above could be considered during the actual design.

**KEYWORDS:** High-rise Building with Connecting Structure, Connecting Stiffness, Connecting Location, Connecting Style, Vertical Earthquake Actions

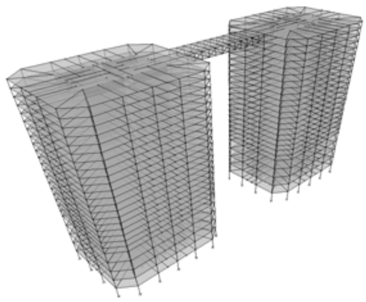
The twin or multi-towers in high-rise buildings are often connected by a joining (or connective corridor) on a definite height and such structure are named connecting structure. The vertical earthquake actions of such structure are necessary to consider for there are abundant vertical vibration modes of the connecting body with big span usually. The connecting structure and the near main structure were damaged severely by vertical earthquake action in mounts of historical earthquake damages, so that the high-rise building with connecting structure is necessary to analyzed and designed under vertical earthquake action. There are some research achievements of influence of factors on horizontal earthquake actions of high-rise building with connecting structure, but the correspondingly studies on vertical earthquake actions is rare by now. On the same time, there have not sufficient operational clauses about this problem in the code of seismic design of structure of China.

In this paper, high-rise building examples with connecting structure are designed with 4 kinds of joining style popularly in practice. Then, the vertical earthquake actions of examples are analyzed. Based on the analysis results, the influence of connecting style on the vertical earthquake action of connecting structure and main structure are investigated.

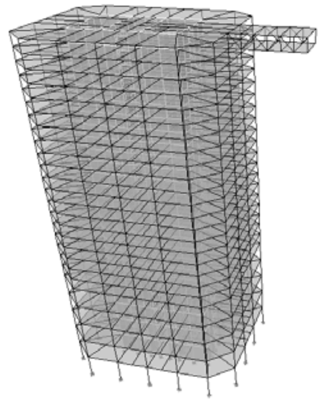
## 1. EXAMPLE INTRODUCTION

The example connecting structure is designed by connecting double same tower with a top connective corridor (fig.1). The total stories of the tower are 25 with the height 96.0m. The tower is frame-core wall structure (fig.2), and the basic design information is shown in table 1.1. The depth of slabs is 120mm, the concrete used in slab and beam is C30. The uniform dead load on the floor is $2kN/m^2$, and the live load is $3kN/m^2$ which changed to $0.5kN/m^2$ at the top floor (including the connective corridor).

The connective corridor is between the height of 92.7m and 96m with the span of 36m. It is composed of steel truss, in which the size of beam is 300X300X15, the column is 200X200X10, the slant rod is 150X150X10, and the depth of slab is 6mm, all the material is Q345. In this paper, 4 types of connection are studied, that are rigid connection in both sides (referred to as MODEL R-R), articulated connection in both sides (referred to as MODEL H-H), one rigid and one articulated (referred to as MODEL R-H), and cantilever. The cantilever is 18m in length to get the same span with the connected part.



(1) Model R-R,H-H,R-H



(2)Model Cantilever

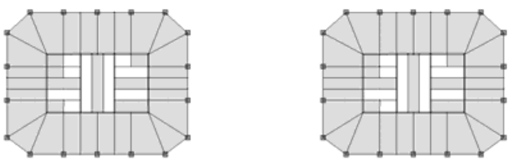
Fig.1 3-D views of examples

In the example, the structural importance factor is 1.0, the seismic intensity is 8 (group 1), the design basic acceleration of ground motion is 0.2g, site type is II, and the characteristic ground period is 0.4s. Under the vertical earthquake effect, the connected part would react so obviously that the vertical earthquake response analysis is necessary, according to Code for Seismic Design of Buildings (GB50011-2001) and Technical Specification for Concrete Structures of Tall Building (JGJ3-2002). Mode-superposition response spectrum method is adopted to calculate vertical earthquake response, and the vertical response spectrum is similar with horizontal one whose Max influence factor is 0.65 times to the horizontal one.

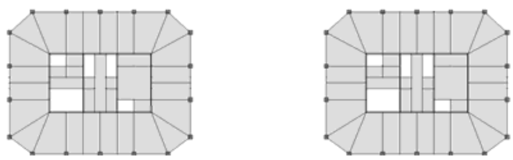
The software ETABS (v9.1.6) is adopted to calculate, in which the beam, column, shear wall and slab are simulated by 3-D beam element, shell element, and elastic slab element respectively (the location of the holes is from the experience). During the calculation, the vertical vibration performance is closely related to the horizontal distribution of the mass (especially the connected part), so the definition of the mass must be serious due to the practice. According to GB50011-2001, the gravity representative is the sum of deadweight standard value of the structure and half of the floor uniform live load. Therefore, when the mass is defined in the ETABS, “from loads” should be selected, and the mass multiplier for dead load and live load is 1.0 and 0.5 respectively.

Table 1.1 Basic information of the structure (mm)

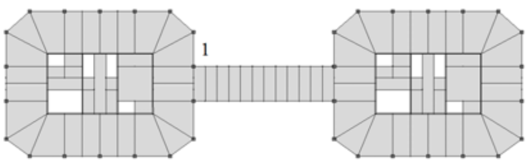
| Floor | Storey height | Concrete strength grade | Depth of the shear wall in x direction | Depth of the shear wall in y direction | Column size (b*h) |
|---|---|---|---|---|---|
| 1~5 | 6000 | C50 | 300 | 200 | 1200*1200 |
| 6~18 | 3300 | C40 | 250 | 200 | 1000*1000 |
| 19~25 | 3300 | C30 | 200 | 200 | 800*800 |

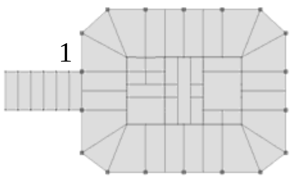


(1) Floor 1~5 of model R-R,H-H,and R-H



(2) Floor 6~23 of model R-R,H-H,and R-H



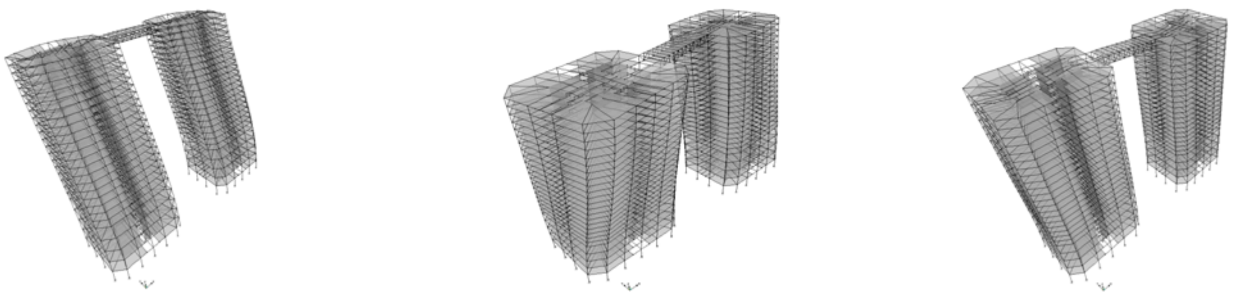
（3）Floor 24~25 of model R-R,H-H,and R-H （4）Floor 24~25 of model cantilever

Figure 2 Layouts of models

## 2. VERTICAL VIBRATION MODEL ANALYSIS

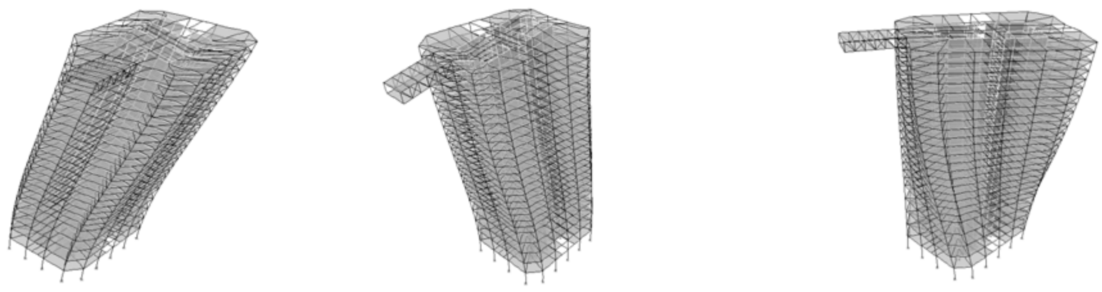
There are 6 components could be achieved by ETABS through the 3-D dynamic program, while the vertical vibration modal could be determined through the mass participation coefficient. Generally speaking, in one mode, the direction corresponding to the maximum of the mass participation coefficients in 6 different directions is the principle vibration mode. In this example, the former 50 modes have been studied, and all of the participation masses have meet the requirements of Technical Specification for Concrete Structures of Tall Building (JGJ3-2002), that to the multi-tower structures, the participation mass related to the number of the calculated modes should not be less than 90% of the total mass.

The first 3 modes of the examples above are similar to each other; the first fundamental period is about 1.5s, the first 3 modes are y translation, x translation and rotation respectively, the 1st, 2nd, 3rd mode of the MODEL R-R is shown in Fig.3, and the ones belong to the cantilever are shown in Fig.4.



（1）The first mode （2）The second mode （3）The third mode

Figure 3 The first 3 modes for model R-R



（1）The first mode （2）The second mode （3）The third mode

Figure 4 The first 3 modes for the model Cantilever

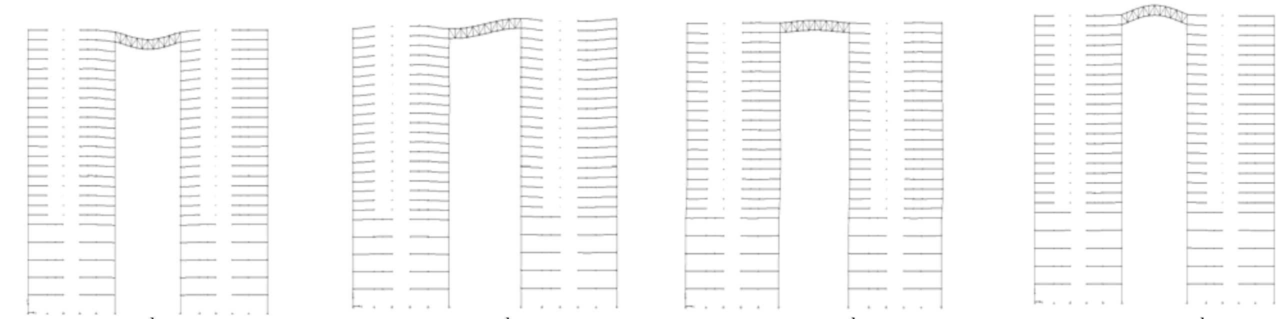
The distribution of structures' vertical vibration modes is shown in table 2.1, and the elevation views of the first 2 vertical vibration modes are seen in Fig.5. From the table 2.1, there are rich vertical vibrations in the 50 modes in which the mass participation of the horizontal vibration components takes more than 92% of the total mass, and the vertical vibrations' takes 82%. It is verified that, to the large span or the long cantilever structure, the consideration for vertical earthquake action is necessary in the high seismic fortification intensity zone. Taking the model R-R for example, there are 18 vertical vibrations in the 50 modes. The periods of these modes belong to 0.22213s~0.17171s, which are in the plateau of the response spectrum. The vertical mode of the model cantilever appears first in the 10th mode, earlier than the other connection ways.

According to the comparison of the 4 examples, the connection way has little influence to the periods and the modes distribution of the whole structure, for the periods are almost same and the first 3 modes is similar. Thus from this angle, the connection way shows little relationship to the dynamic performance of the overall structure.

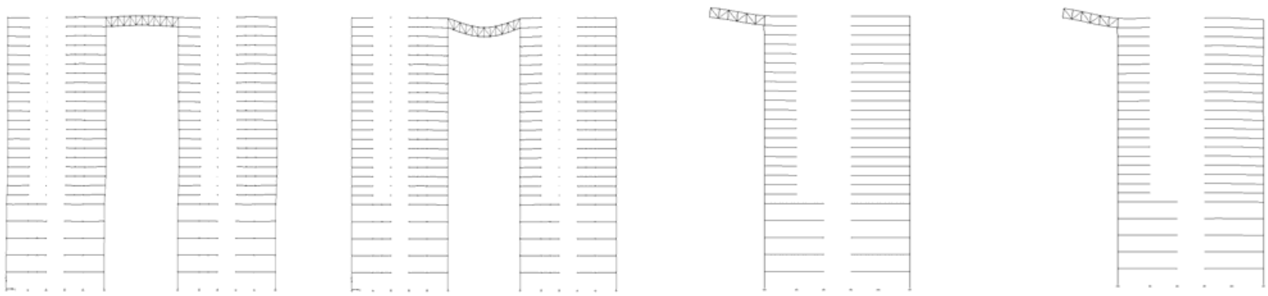
Also, there is little difference among the periods corresponding to the low vertical modes which determines the vertical earthquake action of the connections so that dynamic characteristic of the connections with different connective ways are similar, and all the periods are in the plateau.

Table 2.1 Information for the vertical vibrations

| Model | The 1st vertical vibration/period | The other vertical vibrations(among the periods) | The ratio |
|---|---|---|---|
| R-R | 23/0.22213 | 24，25，35~50（0.21529~0.17171） | 0.22213/1.53738=0.14449 |
| H-H | 19/0.25981 | 20，21，25，26，29，30，36~46，48~50（0.25775~0.17282） | 0.25981/1.53640=0.16910 |
| R-H | 19/0.25981 | 20，21，25，26，29，30，36~46，48~50（0.25655~0.17282） | 0.25981/1.53640=0.16910 |
| Cantilever | 10/0. 26662 | 14，20~24，26，28（0. 21473~0. 16714） | 0.26662/1. 53761=0. 17340 |



（1）the 23rd for R-R （2）the 24th for R-R （3）the 19th for H-H （4）the 20th for H-H



（5）the 19th for R-H （6）the 20th for R-H （7）the 10th for cantilever （8）the 14th for cantilever

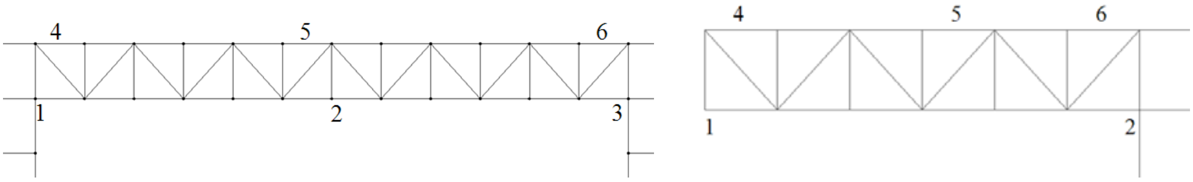
Figure 5 The first 2 vertical modes for every structures

## 3. THE INFLUENCE DUE TO CONNECTED STYLE

The effect of different connection way on the vertical earthquake response could be studied from the shear force in connected part, displacement, and axial force in column 1 that connected to the joint gallery.

### *3.1 The influence to the vertical earthquake response*

The shear forces of the bars in different places of the connected structure are shown in table 3.1, and the bars' number is seen in Fig.6. The shear forces are signed $V_D$ under the dead load, and $V_{EZ}$ under the vertical earthquake action, using $V_{EZ}/V_D$（%）to compare the affection to the vertical earthquake response under the 4 connecting styles.




（1）Model R-R,H-H and R-H （2）Model cantilever

Figure 6 The studied bars and points

Table 3.1 Shear force in the connected structure due to vertical earthquake (N)

| Example | Internal force | 4 | 5 | 6 |
|---|---|---|---|---|
| R-R | $V_D$ | -175421.86 | 3859.03 | 180397.09 |
| | $V_{EZ}$ | 94819.95 | 1568.36 | 98966.39 |
| | $V_{EZ}/V_D$（%） | 54.05% | 40.64% | 54.86% |
| H-H | $V_D$ | -7390.15 | 4314.69 | 8671.68 |
| | $V_{EZ}$ | 2197.02 | 1777.22 | 2722.88 |
| | $V_{EZ}/V_D$（%） | 29.73% | 41.19% | 31.4% |
| R-H | $V_D$ | -33434.08 | 4282.61 | 8654.44 |
| | $V_{EZ}$ | 14904.79 | 1768.20 | 2770.54 |
| | $V_{EZ}/V_D$（%） | 44.58% | 41.29% | 32.01% |
| Cantilever | $V_D$ | -2696.74 | 8944.87 | 111435.96 |
| | $V_{EZ}$ | 615.15 | 4666.88 | 29071.92 |
| | $V_{EZ}/V_D$（%） | 22.81% | 52.17% | 26.09% |

From the table 3.1, some rules can be concluded:

①For the R-R structure, the $V_{EZ}/V_D$(54.05%)at the ends(bar 4 and 6) is bigger than that (40.64%) at the mid span(bar 5);

②For the H-H structure, the $V_{EZ}/V_D$ (29.73%)at the ends (bar 4 and 6) is smaller than that(41.19%) at the mid span(bar 5);

③For the R-H structure, the $V_{EZ}/V_D$ is decreasing smaller， from 44.58% of bar 4 at the rigid end to 41.19% of the bar 5 at the mid span, then comes to 32.01% of the bar 6 at the hinged end.

④For the cantilever structure, the $V_{EZ}/V_G$ shows a small-big-small trend, that is 22.81% of bar 4 at the free end, 52.17% of bar 5 at the mid span, and 26.09% of the bar 6 at the cantilever end. This means that, to the bars at the middle, the shear force due to the vertical earthquake action is too big to ignore.

Comprehensively, to the bars at the ends, the $V_{EZ}/V_G$（%）achieves the biggest(54.86%) at rigid connected, and get the smallest(29.73%) at hinged connected, 25.13% difference between the two. However, to the bars at the middle, there is little difference about the ratio. So to the connected structure design, the connecting style H-H would be better, for the shear force caused by the vertical earthquake is the smallest.

### *3.2 The influence to the displacement of corridor*

Here, the effect of the connection way on the displacement of corridor would be investigated. The joints studied are shown in Fig.6. For the model R-R, H-H, and R-H, the relative displacement $U_{2\text{-}1}$ means $U_2$ -$U_1$, and for the model cantilever, $U_{1\text{-}2}$ means $U_1$ –$U_2$.

Table 3.2 The displacements and relative displacements of the connected structure

| Joint | R-R | | H-H | | R-H | | The cantilever | |
|---|---|---|---|---|---|---|---|---|
| | Uz | $U_{2-1}$ | Uz | $U_{2-1}$ | Uz | $U_{2-1}$ | Uz | $U_{1-2}$ |
| 1 | 2.59 | — | 1.5269 | — | 1.5324 | — | 11.9111 | 10.2596 |
| 2 | 9.7042 | 7.1142 | 10.2040 | 8.6771 | 10.2704 | 8.738 | 1.6515 | — |

From table 3.2, under the vertical earthquake, the joints' displacement is not big, and according to Design Code for the Steel Structures (GB50012-2003), the allowable deflection value is 144mm for the connected structure, and 72mm for the cantilever.

Among the 4 connecting styles structures, the relative displacement (7.11mm) of the model R-R is the smallest, 10.26mm of the cantilever is the biggest, there is 3.15mm difference and 44% increasing between them. The relative displacements of model H-H and R-H are between the two mentioned above, and little difference.

For reducing the vertical displacement of the connected structure due to vertical earthquake, R-R connection would be the best, while the cantilever is the worst. Nevertheless, the displacement and the deflection are still too small to influence the overall structure.

### *3.3 The analysis on the axial force of column*

This section investigates the influence of connection styles on the axial force under vertical earthquake impact of column in the tower. The column 1 Investigated is shown in Figure 2. ND indicates the axial force under dead load and NEZ indicates the axial force under vertical earthquake action, NEZ / ND (%) indicates the ratio of the two. For the model R-H, the column 1 is on the rigid connection, the column on the hinged side of the structure is not listed for the rules are similar.

The axial force and the ration mentioned above of column 1 are listed in table 3.3. The axial forces and the ratios $N_{EZ}$ / $N_D$ from the bottom to the top of column 1 are showed in figure 7.

Table 3.3 $N_D$, $N_{EZ,}$ and ratio of $N_{EZ}$ / $N_D$（%）

| | The bottom floor | | | The 25th floor | | |
|---|---|---|---|---|---|---|
| Model | $N_D$ | $N_{EZ}$ | $N_{EZ}$ / $N_D$ (%) | $N_D$ | $N_{EZ}$ | $N_{EZ}$ / $N_D$ (%) |
| R-R | 10759.555 | 1360.837 | 12.65 | 754.516 | 296.155 | 39.51 |
| H-H | 10699.754 | 873.583 | 8.16 | 841.992 | 245.128 | 29.1129 |
| R-H | 10697.932 | 872.509 | 8.16 | 750.120 | 215.387 | 28.7138 |
| Cantilever | 10745.086 | 932.863 | 8.68 | 641.197 | 120.207 | 18.75 |

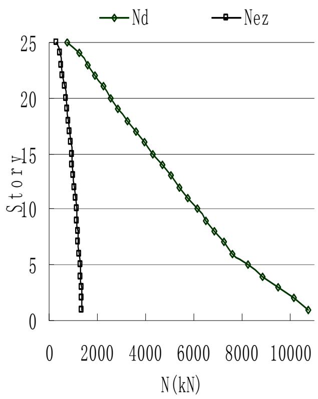
Based on table 3.3 and figure 7, there are some laws can be deduced.

①The axial force under dead load of column 1 linear increases from the top to the bottom and the increasing trend is evident. While the axial force under the vertical earthquake linear increases with flat slope ratio.

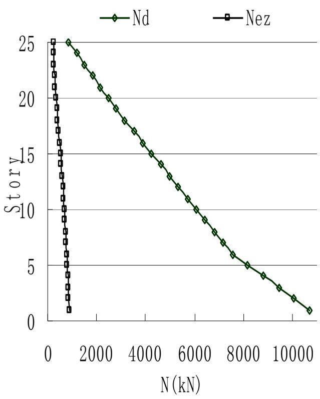
② In all structures, the maximum ratio of $N_{EZ}$ / $N_D$ (39.51 percent) occurred in the 25-storey of model R-R, the minimum (8.16 percent) occurred in the bottom story of model H-H, all this showed that the vertical earthquake has larger impact on the axial forces of the column joining with the connections. For high-rise buildings in high seismic intensity areas, the axial forces of the column caused by the vertical earthquake are so significant that can not be ignored in structural design.

③ The largest margin of Four kinds of ratio of column 1 is 4.49 percent (12.65-8.16) in the bottom story and 20.76 percent in the 25th story(39.51-18.75).It showed that the stronger the connections, the bigger the axial forces caused by vertical earthquake and the higher the floor, the bigger the ratio of $N_{EZ}/N_D$. So connection ways have great influence to the axial forces of the column connected corridor.

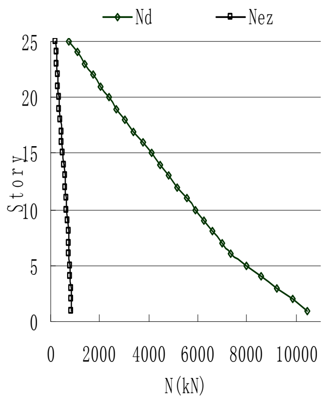
④ With the floors increasing, the ratio of $N_{EZ}/N_D$ is increasing gently in bottom and medium stories and rapidly in top stories. In all model examples, the increasing trend of model R-R is the biggest. The ratio of $N_{EZ}/N_D$ of model R-R is much larger than other models. There is little difference in the $N_{EZ}/N_D$ ratios of model R-H and model H-H and two curves are almost coincidence. It showed that the vertical earthquake actions of column of model R-R is largest in all models.



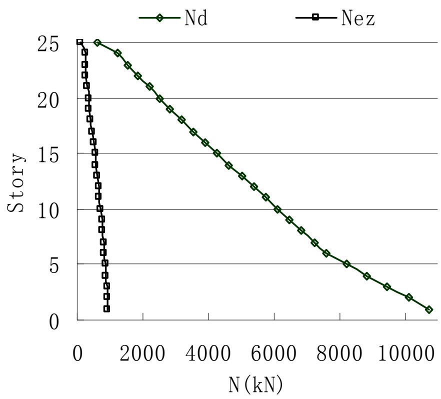

（1）Model R-R



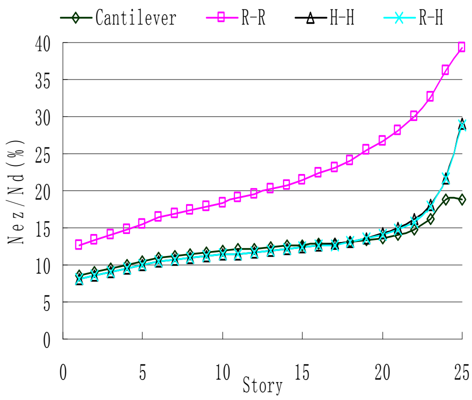

（2）Model H-H




（3）Model R-H




（4）Model cantilever




(5) $N_{EZ}/N_D$

Fig.7 Variation of $N_{EZ}$ and $N_D$ and $N_{EZ}/N_D$ for column 1

⑤the $N_{EZ}/N_D$ ratio of column 1 of model cantilever is smallest in all models, thus the affect of vertical earthquake on axial force of model cantilever is smallest.

## 4 CONCLUSIONS

Based on investigations in this paper, some conclusions can be generalized as:

①when the towers are symmetric, the overall dynamic characteristics of the connected structure are very limited changed with connecting way of the 4 types. Though there is some different about the order of the vertical modes, still the vertical vibration periods are all in the plateau of the spectrum, and there is little relationship between the connecting style and the vertical vibration mode.

②Under the vertical earthquakes, the vertical shear force in the bars at the ends span are effected hardly by the connecting style, while the vertical shear force in the bars at the middle span are effected lightly. The vertical shear force in the side span of model R-R is biggest, and the ones of model H-H is smallest, so it is better to choose H-H connection for the connected structure designing economically.

③Under the vertical earthquakes, the vertical displacement of the connected structure in model R-R is the smallest, and ones of model cantilever is the biggest. The vertical displacement is too small to influence the design of connected structure.

④The ratio of the axial force caused by the vertical earthquake action and the dead load in column 1 which supports the connected structure is too big to ignore. Among the 4 types of connecting styles, the axial force due to the vertical earthquake of column 1 in model R-R is the biggest, while that in model cantilever is the smallest.

The conclusions above could be considered during the actual design.

## REFERENCES

Technical Specification for Concrete Structures of Tall Building. JGJ3-2002.
Code for seismic design of buildings. GB50011-2001.
Shi Wenlong, Sun Feifei, Li Guoqiang.(2007).analysis on vertical seismic response of a connected multi-tower building. Architechetual structural. 37:8,65-69.
Code for design of steel structures. GB50012-2003.