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NUMERICAL SIMULATION ANALYSIS ON EARTHQUAKE DAMAGE OF UNDERGROUND STRUCTURE BASED ON FIBER MODEL

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ABSTRACT :

In this paper, the soil-structure finite element model of DAKAI subway station damaged in 1995 KOBE earthquake was built by two dimensional plane strain element, in full accordance with the actual structure size and ground information of DAKAI subway station. The non-linearity of material and non-linearity of member for RC station structure was considered with fiber element model. The soil dynamical non-linearity was considered by equivalent damp and equivalent shear modulus of soil in earthquake. The input wave was vertical acceleration earthquake wave and south-north horizontal earthquake wave which were recorded at 83m underground in Port Island in KOBE earthquake. The software of MIDAS was used to simulate the earthquake response and destruction process of DAKAI subway station. The earthquake damage mechanism of the DAKAI subway station was studied. The damage type of column, wall and roof was analyzed. And the conclusions were obtained as following:（1）The middle column was first damaged in earthquake, which is the weakest part in the entire underground structure;（2）The horizontal earthquake was the main factor of underground structure destruction and the vertical earthquake accelerates the reinforced concrete column destroyed;（3）The column damage resulted in structure internal force redistribution and final collapse of the entire structure （4） The shear damage and bending damage coexist in the column and the failure type of the lining is mainly the bending damage.

KEYWORDS: underground structure, fiber model, middle column, equivalent linearization, destroy mechanism

1. INTRODUCTION

With the development of society and the growing urban population, large underground structures are being unprecedented development such as subway and underground shopping malls. In recent years, many earthquake damages show: the underground structures would be seriously damaged or even collapse under strong earthquakes, of which the damage of DAKAI subway station happened in the Kobe earthquake in Japan was one of the most serious ones. The anti-seismic study of underground structure has aroused extensive attention, however, the earthquake damage process and the failure mechanism of the underground structure are still not full explained. In this paper, the DAKAI subway station is taken as the study object, the preliminary analysis of earthquake damage process of underground structure is obtained by using fiber model unit.

2. CALCULATION OBJECTS AND SOIL CONDITIONS

In this paper, the typical cross section of Dakai subway station (Figure 1) is used as the study object, where the damage is the most serious. The soil conditions of the DAKAI subway station is shown in table 2.1[1].

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DAKAI subway station is built by the cut-and-cover method,7.17 m high and 17.0 m wide, with a soil cover of 4.8 m above the top of the structure. The central columns had rectangular cross section of 0.4 m by 1.0 m with axial spacing of 3.5 m in the longitudinal direction. Bars with diameters ranging from 16 mm to 25 mm are used in the walls and slabs and bars with diameter 32 mm are used in the central columns, the average reinforcement ratios of the central column, top and bottom slabs and lateral walls were 6.0%,1.0% and 0.8% respective, bars with diameter of 9mm were used as transverse hoop in the columns at a spacing of 350mm[2-3]. In this paper, the structure utilized c30 concrete and the concrete parameters see table 2.2, the yield stress of the steel bars was 300MPa and the elastic modulus was 2.0×10^5MPa.

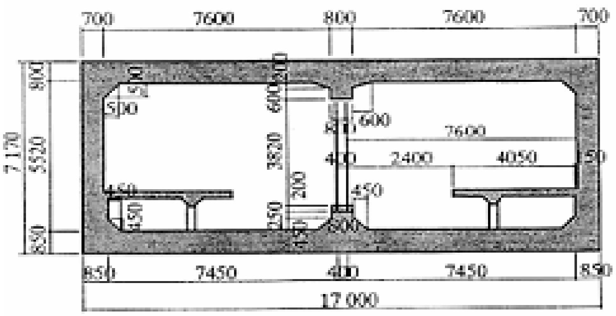

Figure 1 Cross sections of DAKAI station

Table 2.1 Physical parameters of ground soils of Dakai Subway Station

Soil type	Depth (m)	Unit weight (t/m^3)	Shear wave velocity (m/s)	Poisson ratio
Artificial filling	0～1.0	1.9	140	0.33
Holocene sand	1.0～5.1	1.9	140	0.32
Holocene sand	5.1～8.3	1.9	170	0.32
Pleistocene clay	8.3～11.4	1.9	190	0.40
Pleistocene clay	11.4～17.2	1.9	240	0.30
Pleistocene sand	17.2～22.2	2.0	330	0.26

Table 2.2 Parameters values of concrete

Elastic modulus (MPa)	Poisson ratio	Density (Kg/m^3)	Compressive strength (MPa)	Tensile strength (MPa)	Damping ratio
3.0×10^4	0.18	2450	20.1	2.01	5%

3. FINITE ELEMENT MODEL AND CALCULATION METHOD

3.1. Finite Element Model

Figure 2 shows part of the FEM mesh. In the finite element model, the part of reinforced concrete station is modeled by beam element and surrounding soil is modeled by plane strain element. The longitudinal size of the beam element simulating middle column of subway station is reduced according to width of column and axial spacing of column. Two lateral boundaries and top boundary of finite element model adopt free boundary, bottom boundary is fixed boundary, the length and height of the model respectively are 202.4m and 21.8m.

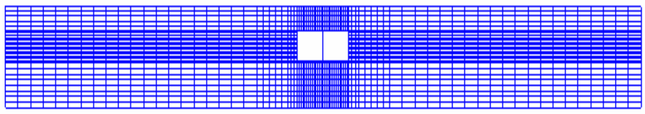

Figure 2 Part of the DAKAI station FEM mesh

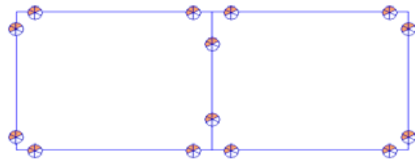

Figure 3 The location of fiber element

In order to understand the destruction process of underground structure, the fiber model element was used in the weakest part of underground structure. The so-called fiber model, is that the cross section of bar is divided into many fibers. Each fiber only has uniaxial stress and axial deformation. The stress characteristic of fiber materials is described by the material uniaxial stress-strain relationship. The relation of moment-curvature of component cross-section is accurate expressed based on the plane section assumption[4]. Figure 3 shows the location of fiber element.

In this paper, the constitutive models of concrete adopt the modified Kent-Park model (see figure 4), which do not take account of the concrete tensile performance but take the increase of concrete strength subject to stirrup confinement into account. The constitutive model of reinforcing steel bars adopt modified Menegotto-Pinto model [5] (see figure 5). When the section is divided into fibers, the different material part will be divided into different fiber element. Figure 6 is the fiber composition schematic diagram of reinforced concrete.

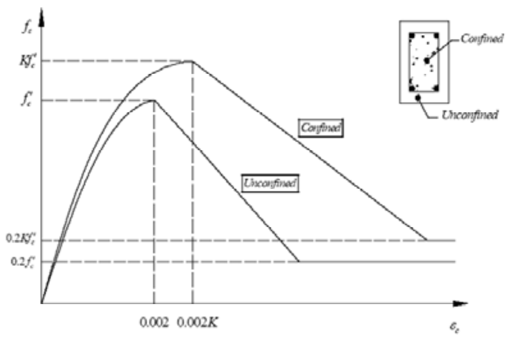

Figure 4 Constitutive model of concrete

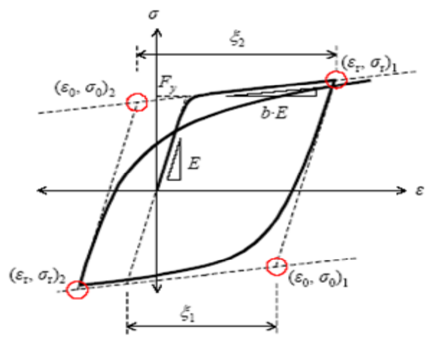

Figure 5 Constitutive model of steel bar

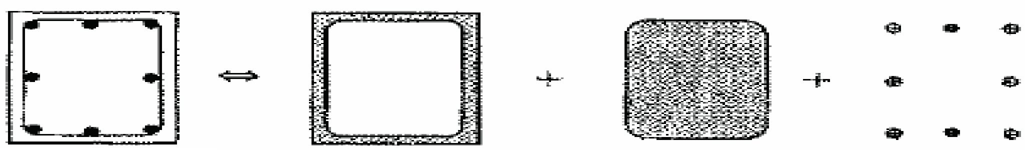

Figure 6 The fiber composition schematic diagram of reinforced concrete

3.2. The Input Ground Motion

In this paper, the input wave was vertical acceleration earthquake wave and south-north horizontal earthquake wave which were recorded at 83m underground in Port Island in KOBE earthquake. The distance between the site of earthquake wave recording and the eastern part of DAKAI subway station is only 4 km, and the soil conditions of two places are similar. Figure 7 is the acceleration waves of input ground motion.

3.3. The Dynamic Nonlinearity of Soils

In this paper, the dynamic nonlinearity of soils is considered by utilizing the equivalent linearity method. Firstly, one dimension earthquake response of DAKAI subway station soil layer is analyzed and computed by the one dimension equivalent linearization procedure SHAKE91. Secondly, the effective shear modulus and the equivalent damping ratio which are obtained in the one dimension earthquake response analysis are used as the input parameters in the two dimension finite element model [6]. Figure 8 is the shear model-versus-shear strain and damping ratio-versus-shear strain relation curves of soil which are obtained by Seed. The table 3.1 shows the effective shear modulus and effective damping ration that are calculated in the one dimension earthquake response analysis.

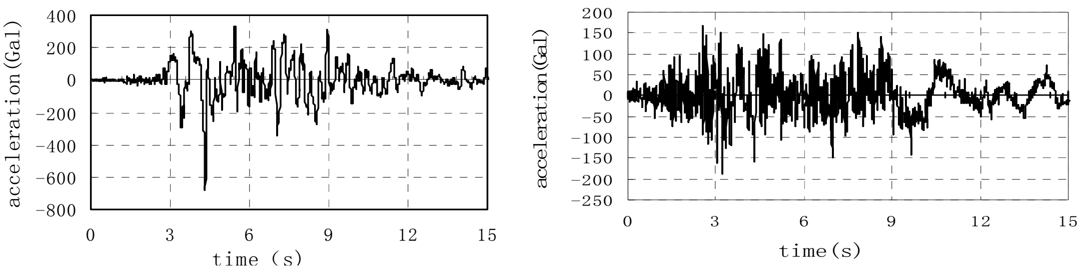

Figure 7 The input ground motion

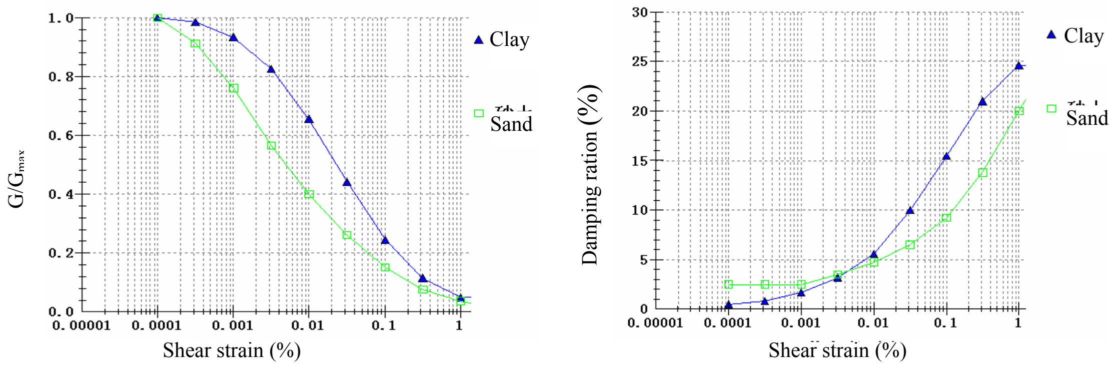

Figure 8 The dynamic nonlinearity curves of soil

Table 3.1 the effective shear modulus and effective damping ration

Soil numbering	depth (m)	damping ration	shear modulus (KN/m^2)	Soil numbering	depth (m)	damping ration	shear modulus (KN/m^2)
1	0.5	0.059	11601.4	11	10.6	0.235	4716.2
2	1.55	0.111	4539.1	12	11.6	0.189	18194.5
3	2.6	0.158	2365.3	13	12.7	0.199	15570.7
4	3.6	0.198	1431.6	14	13.9	0.209	12932.5
5	4.6	0.229	943.2	15	15.1	0.212	12271.7
6	5.6	0.184	2580.7	16	16.3	0.214	11845.6
7	6.6	0.213	1752.4	17	17.5	0.115	24845.1
8	7.6	0.234	1292.8	18	18.7	0.118	23796.3
9	8.6	0.220	6684.0	19	19.9	0.122	22292.8
10	9.6	0.227	5702.5	20	21.1	0.128	20210.1

4. ANALYSIS OF THE CALCULATION RESULTS

Based on the above two-dimensional finite element model, the internal force contour map and stress contour map of DAKAI subway station under KOBE earthquake action are obtained (see figure 9). It can be obtained from the figure 9 that although the internal force on middle column is not maximum, the stress on middle column is much larger than the stress on other positions due to the relative smaller section size of the middle column. In addition, unlike the lateral wall, there is no the constraint of the surrounding soil, so the middle column should be the weakest link in the whole underground structure.

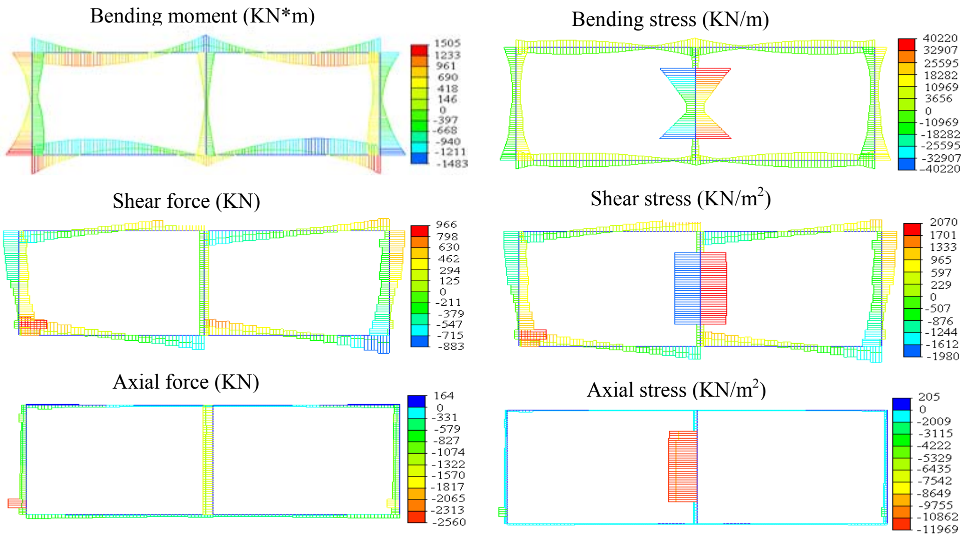

Figure 9 The contour map of subway station

Figure 10 shows the stress time-history curves of concrete fibers and bending moment on the middle column cross-section. We can know from figure 10 that the horizontal ground motion becomes intense after three seconds and the concrete fibers on the middle column section experience many times procedures of pulling and pressing with large amplitude, all concrete fibers appear compression failure in 4.2 second and the stress of the fibers become 0, namely the concrete on the whole section exit the working state. Figure 11 is the hysteretic curve of the steel bars on the middle column, it shows the steel bars on middle column appear alternately tensile stress and compressive stress, but the strain state always is compression yield situation. The biggest compression strain is about 10%.

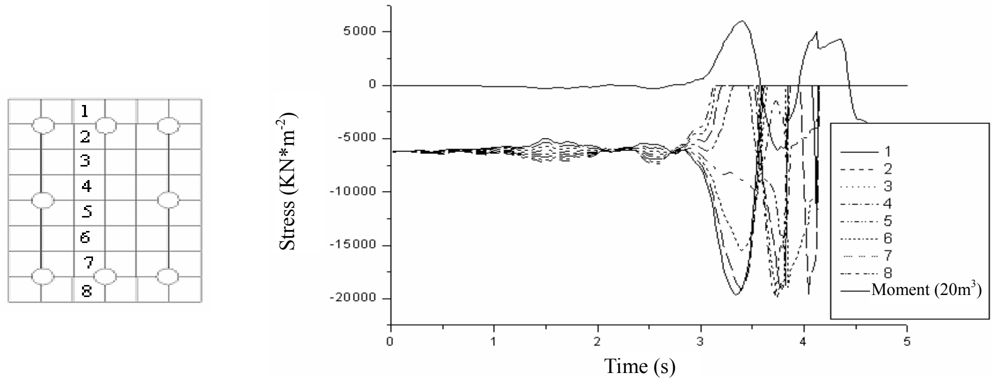

Figure 10 The fibers numbering and time-history of stress

The failure of fiber element is divided into crushing of concrete fiber element and tensile yield of steel fiber element. Because the structure failure caused by crushing of concrete is more serious than the one that is caused by tensile yield of steel, this paper uses crushing of concrete as the basis of structure failure. Figure

12 shows the positions of the horizontal ground motion and vertical ground motion corresponding to the time when the middle column initial appearance crushing of concrete fiber element. It is found that initial crushing of concrete is present to the first large peak of horizontal ground motion but not to the first large peak of vertical ground motion.

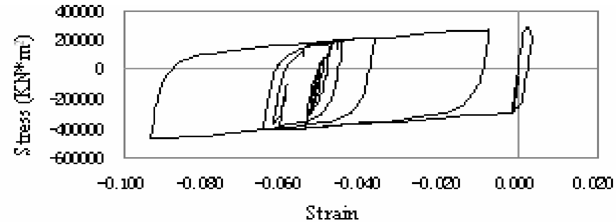

Figure 11 The hysteretic curve of the steel bars

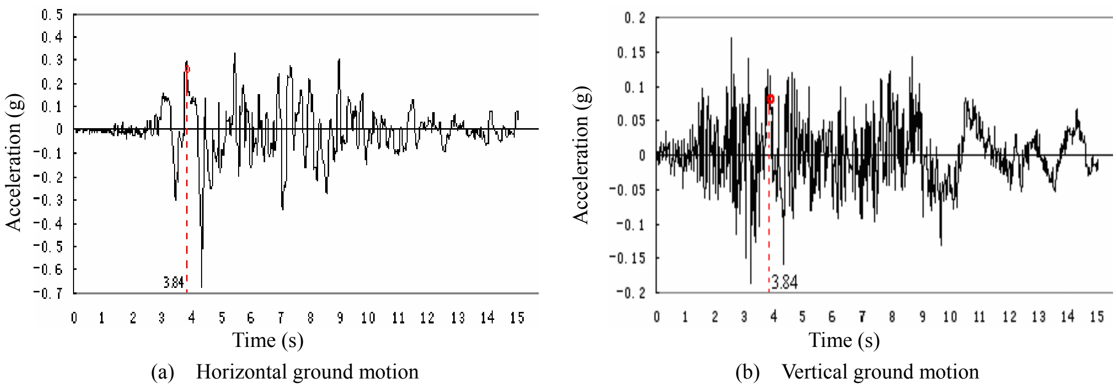

Figure 12 The positions of ground motion corresponding to crushing of concrete

Table 4.1 shows the time of the concrete compression failure and the steel tensile yield occur in middle column, lateral wall and roof. In order to analyze the influence of the vertical ground motion, this paper compares and analyses the results in two calculation cases of the bidirectional loading and uniaxial loading. The results indicate that (1) on the two conditions, steel tensile yield is earlier than concrete compression failure, and the steel tensile yield does not firstly occurred in the middle column; (2) The concrete compression failure firstly occurred in the middle column; (3)The tension-destroying in the lateral wall and roof is relatively serious, namely the concrete crack will appear in these positions; (4) The earthquake damage in the upper end and lower end of the middle column is most serious in the whole underground structure, the whole column section is crushed, but the partial concrete is crushed in other parts (see figure 13), the results are similar to the real earthquake damage; (5) We find that the vertical ground motion accelerates the structure failure by comparison of two calculation cases.

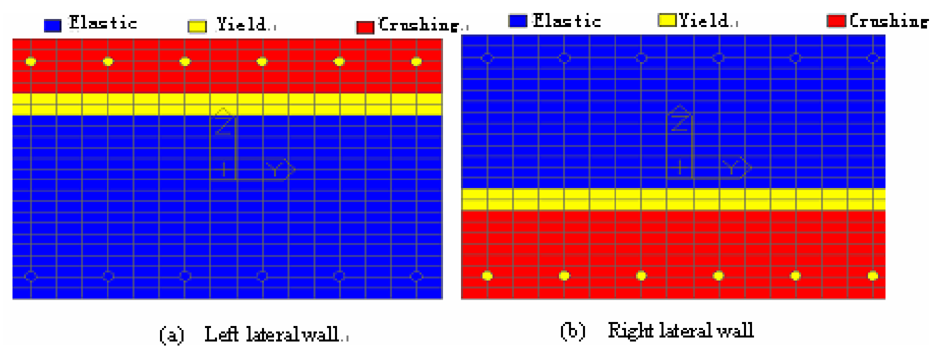

Figure 13 The failure condition of the fiber element section in lateral wall

The failure of the middle column is the most serious part in the whole underground structure, so it is necessary to analyze the column failure mode. We know that the axial force design value is 1804 KN by calculating. The maximum axial force that middle column bears in KOBE earthquake is 1354 KN, so the pute axial force doesn't cause the failure of middle column, the failure of concrete fiber element of middle column is the result of concurrent effects of axial force and bending moment.

Table 4.1 The failure time of fibber element

position	Vertical and horizontal loading		Horizontal loading	
	Crushing of concrete	Tensile yield of steel	Crushing of concrete	Tensile yield of steel
Upper end of column	3.82 (4.20)	3.76	3.84 (4.50)	3.76
Lower end of column	3.82 (4.16)	3.76	3.82 (4.20)	3.76
Upper end of left sidewall	5.68	3.36 (3.82)	5.68	3.34 (3.80)
Upper end of right sidewall	4.90	3.72 (4.22)	4.90	3.72 (4.24)
Lower end of left sidewall	4.80	3.70 (4.30)	4.82	3.70 (4.34)
Lower end of right sidewall	5.60	3.28 (4.80)	5.60	3.28 (4.78)
Left end of left roof	—	3.78 (5.64)	—	3.78 (5.66)
right end of right roof	—	4.22 (4.86)	—	4.22 (4.86)

Note: the front time expresses the time when the failure of fiber element first occur; the time in the bracket expresses the time when the failure of the whole section of fiber element occur.

Formula 4.1 expresses the relation of design shearing bearing capacity and axial force for the reinforced concrete members [7], figure 14 shows the time-history curve of shear force and the design shearing bearing capacity under the action of varying axial force for middle column. It will be seen from the figure that the maximum shear force exceed the design shearing bearing capacity, although it can not entirely illuminate that shearing-destroy occurred for middle column, the shear force should have a destructive action for the middle column.

$$V \le V_u = \frac{1.75}{\lambda+1} f_t b h_0 + f_{yv} \frac{A_{sv}}{s} h_0 + 0.07N \tag{4.1}$$

Where:

V_u： The maximum shearing bearing capacity design value of diagonal section

f_t： Concrete axial tensile strength design value

b： The width of rectangular section

h_0： The effective height of section

f_{yv}： The tensile strength design value of stirrup

A_{sv}： The total section area of stirrups in a cross-section

s： The spacing of stirrups

N： axial compression force design value，when $N \ge 0.3 f_c bh$，$N = 0.3 f_c bh$

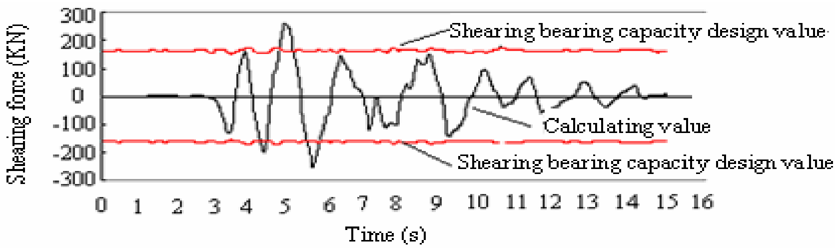

Figure 14 The time-history curve of shearing force of middle column

5. CONCLUSIONS

In this paper, based on section fiber model theory, the finite element model of DAKAI subway station is built in full accordance with the actual structure size and the dynamical response analysis of subway station is made. The results show that （1）The middle column is firstly damaged in earthquake，which is the weakest part in the entire underground structure（2）The horizontal earthquake is the main factor for underground structure destruction and the vertical earthquake accelerates the destroy of reinforced concrete column（3）The column damage resulted in structure internal force redistribution and final collapse of the entire structure（4）The shear damage and bending damage coexist in the column and the failure type of the lining is mainly the bending damage.

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