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Elastic-plastic study on high building with SRC transferring story*

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Abstract: A new type of transferring structure for steel reinforced concrete (SRC) beams is used in high building. The pushover analysis method was used to study the failure mechanism and ductility of SRC transferring structure through consulting pseudo-static test results for the structure. And, the occurrence order and position of the plastic hinge, the weak story and seismic capacity of high building with SRC transferring story were also studied through consulting shaking table test results for the high building, showing that the seismic behavior of high building with SRC transferring story is good.

Keywords: Steel reinforced concrete (SRC), Transferring structure for SRC beams, Static pushover analysis, High building, Pseudo-static test, Shaking table test

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INTRODUCTION

Due to the increasing number of building story braced by transferring member during development of high or superhigh rise buildings, and the many demands and restrictions on floor height and space in architecture, it is necessary to use steel reinforced concrete (SRC) materials in transferring structure. SRC has high bearing capacity, good stiffness and relatively less section dimension, and ductility, durability and aseismic behavior better than that of reinforced concrete.

Transferring structure for SRC beams has been used in engineering projects as a new type of transferring structure. Based on studies on common small span (≤12 m) and single bay SRC transferring beams (Fu *et al.*, 2000), this study on large span (16.2 m) and continuous beams is still insufficient in the aspect of kinetic elasto-plasticity. The connection between the transferring story composed of several SRC transferring beams and common reinforced concrete (RC) frame is a problem that needs to be studied by kinetic tests and relevant elasto-plastic analysis method, so the influence on the whole building under the action of earthquake can be determined.

In this work, inelastic static pushover analysis was used to study the failure mechanism and ductility of SRC transferring structure. And, the occurrence order and position of plastic hinge, the weak story and seismic capacity of high building with SRC transferring story were also studied.

PUSHOVER ANALYSIS

Inelastic static pushover analysis is a simple option for estimating the strength capacity in the post-elastic range. The technique may also be used to highlight potentially weak area in the structure. Static pushover analysis has no rigorous theoretical foundation, and is based on the assumption that the structure response is directly related to the response of an equivalent single degree-of-freedom (SDOF) system. Static pushover analysis is aimed at discovering some structure response properties not obtainable by elastic dynamic response analysis methods from the structure's elastic response spectrum. These response properties include the member's internal force, the whole and local deformation of the structure during the action of earthquake (Tso and Moghadam, 1998; Vidic *et al.*, 1994; Li *et al.*, 2001).

Type and location of plastic hinge in the structure

This is the most crucial step of pushover analysis. Generally there are five types of plastic hinges, such as moment hinge, axial hinge, torsion hinge, shear hinge and P-M2-M3 hinge. A combination of plastic hinges can be used for one member. However, the types of plastic hinge combined are not the same for different location or function in the member.

Generally, the P-M2-M3 hinge can appropriately be used for the common frame columns whose interaction between two-way moment curves and axial loads must be considered. As the frame beam's contribution of stiffness to the frame plane is only considered, the frame beam often adopts the moment hinge. The shear hinge and P-M2-M3 hinge can be used for short columns. Combinations of the shear hinge and moment hinge are used for deep beams.

For equivalent columns transferred from shear-wall or tube, combinations of P-M2-M3 hinge and shear hinge are often used.

When there are sufficient numbers of moment hinges on the column and beam ends, a static structure can be transferred to a collapse mechanism. The potential locations of moment hinge and P-M2-M3 hinge in every beam and column member often appear at the position αL and $(1-\alpha)L$ away from the member end (L is the member length after subtracting the stiffness areas length and α is proposed to be 0.05) to meet the hypothesis that the joint between column and beam is stiffness areas and is unable to be collapsed. But the other three hinges are supposed to appear at the mid-span of the member.

Establish hysteretic model

The plastic hinge is described by hysteretic model. Degrading Tri-Linear (D-TRI) of stiffness degeneration describes the whole process of the members under bearing force. In this work, D-TRI hysteretic model is used to analysis the structural elasto-plastic performance. The results showed that the RC frame's columns and beams can often adopt the moment hinge or the P-M2-M3 hinge.

The moment (M) and curvature (ϕ) relative curve of tension failure of the member sections (the sections of bearing moment and large eccentric pressure) can be simplified into the D-TRI model considering the stiffness degeneration presented in Fig.1, where M_{cr}, M_y, M_u and M_d are the moments at the crack point, the yield point, the limit point and failure point respectively, and ϕ_{cr}, ϕ_y, ϕ_u and ϕ_d are the curvatures at the crack point, the yield point, the limit point and failure point respectively.

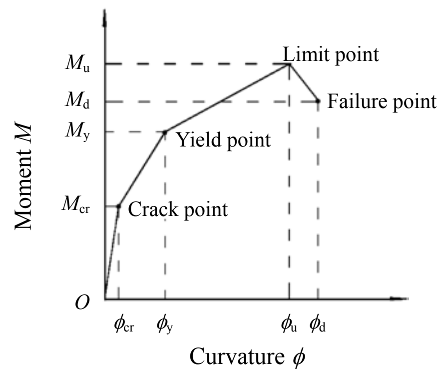

Fig.1 Relation curve between the moment and curvature of RC member

The methods for calculating SRC member's moment and curvature (or section corner) at every characteristic point can be referred to (Liu, 2004), where the moment and limit corner were calculated including the bond-slip effect between steel and concrete.

Lateral load patterns

For performance evaluation, load pattern selection is likely to be more critical than the accurate determination of the target displacement. The load patterns are intended to represent and bound the distribution of inertia forces in an earthquake design. It is clear that the distribution of inertia forces varies with earthquake severity (extent of inelastic deformations) and duration. If an invariant load pattern is used, the basic assumptions are that the distribution of inertia forces will be reasonably constant throughout the earthquake and that the maximum deformations obtained from this invariant load pattern will be comparable to those expected in earthquake design. These assumptions may be close to the truth in some cases, but not in others. They are likely to be reasonable if:

(1) the structural response is not severely affected by higher mode effects; or (2) the structure has only a single load yielding mechanism that can be detected from an invariant load pattern.

Currently, there are six invariant types of lateral patterns in this regard. Comparatively, the load pattern of the response spectrum analysis reasonably represents the distribution of the earthquake. Thus, we will adopt the pattern to calculate the following examples of SRC transferring structure.

PUSHOVER ANALYSIS ON TRANSFERRING STRUCTURE FOR SRC BEAMS

Static pushover analysis is an effective elasto-plastic analysis method. In this work, a high building with SRC transferring structure (the high building for production management at Zhejiang Province Electric Company, China), was taken as engineering background. The pushover analysis method was used to study the failure mechanism and ductility of the SRC transferring structure by consulting the results of the pseudo-static test of the structure.

In order to examine whether or not pushover analysis of SRC transferring structure is feasible, the results of the analysis were compared with those of the pseudo-static test.

Introduce the pseudo-static test model

The pseudo-static test model was a two-story-and-three-bays SRC structure with transferring beam, whose section representation is shown in Fig.2. The pseudo-static test is described as follows:

(1) A hydraulic jack was installed at the place between the SRC column top and the reacting prop. Vertical load is imposed on the column top by the jack to simulate the effect of axial pressure over the column. The axial loads imposed on MZ1 column and MZ3 column were 600 kN and 340 kN. The MZ2 column axial load was 300 kN imposed by means of tensioning-prestressing bar.

(2) Roller bearings were installed between the

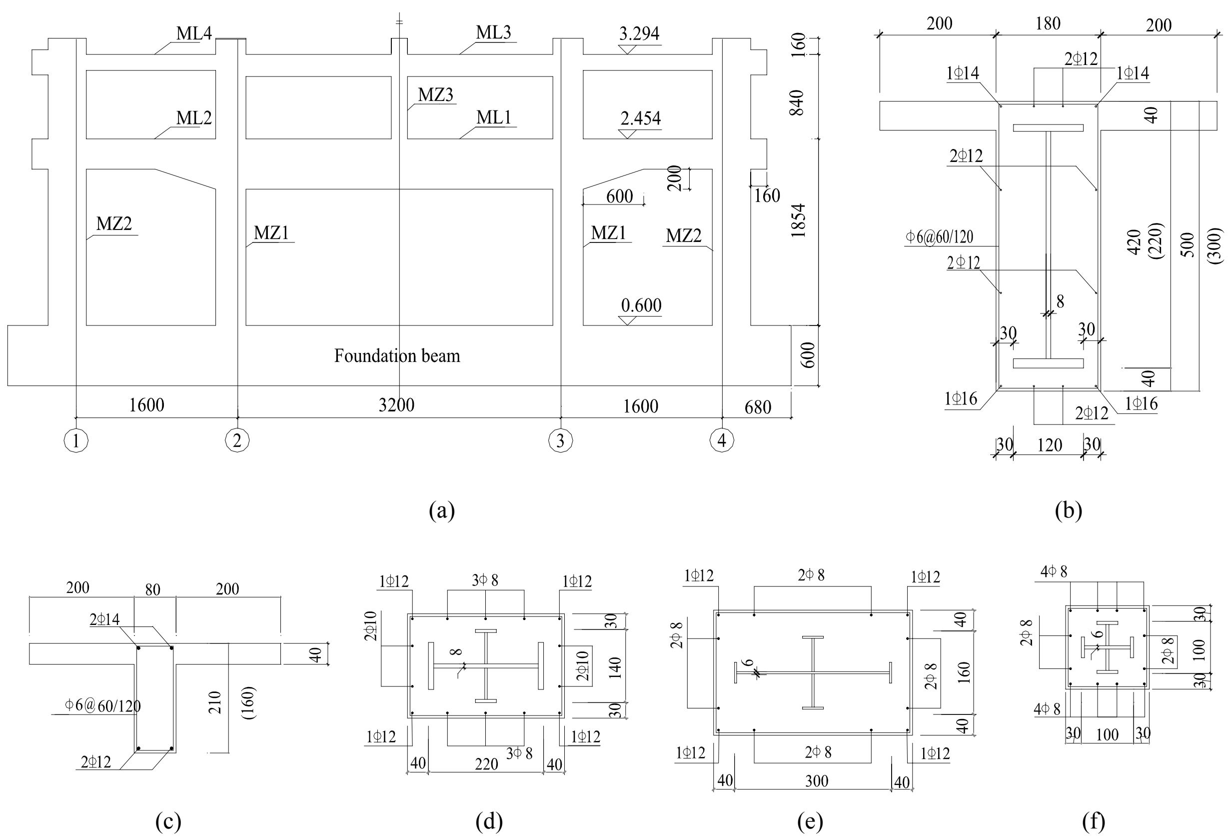

Fig.2 The model of SRC transferring structure (Units: mm)
(a) SRC transferring structure; (b) ML1 (ML2); (c) ML3 (ML4); (d) MZ1; (e) MZ2; (f) MZ3

column top and the reacting prop to satisfy the structural freedom of lateral motion during pseudo-static test.

(3) The column height exceeded by 50 mm the top of the section of RC beam on the second story in order to lessen the structural restrain caused by the hydraulic jack at work.

(4) Lateral reciprocating loads were imposed on the ends of the first and second story continuous beam by the hydraulic jack.

Introduce the pushover analysis model

Before using SAP2000 software with the pushover analysis to assess seismic damage, the model must be established considering:

(1) The SRC beam and column adopt spar element with user-defined cross-section, which include combination of profiled steel and concrete. It is assumed that the plastic deformations are all concentrated on the possible plastic location of the member, and other parts of the member are only in elastic stage during the action of earthquake.

(2) The actual dimension and number of reinforcing steel bar and profiled steel of the member are used to calculate the hysteretic model curves.

(3) In the pseudo-static tests, the jacks restrict the rotation of the column tops. The rotation degree of freedom of the column tops in the model of the pushover analysis should be restrained in accord with the pseudo-static test.

(4) The second-order effect (P-Δ).

(5) Lateral loads were imposed on the left ends of two beams (Fig.2).

Comparison of results of pushover analysis and pseudo-static test

The P in the relation between the level push force P and top target displacement δ can be obtained by the pseudo-static test. But the Q in the relation between the base shear and top target displacement δ can only be obtained by pushover analysis. The distinction between the level force P and base shear Q is that P consists of two parts of the shear Q and friction f of the response of the sliding displacement between the roller and the reacting prop.

1. Establishment of friction f

In order to find the seismic properties of the transferring structure under the level force, it is necessary to subtract the friction f from the level push force P. Some relevant tests revealed that the coefficients of friction at pressure of 340 kN and 600 kN are 0.0838 and 0.0853 (Liu *et al.*, 2002). The level friction f can be written as

$$f=2\times600\times0.0853+340\times0.0838=131\text{ kN} \tag{1}$$

The friction f subtracted from the level push force P gives the modified level force, which is equal to base shear Q.

2. Comparison and analysis

The lateral load pattern of the pushover analysis was

$$P_2:P_1=15:1 \tag{2}$$

where, P_2 and P_1 were the level push forces of the second and first story of SRC transferring structure respectively (presented in Fig.2). When the top target displacement was 15.5 mm, the yield phenomenon was not apparent in the skeleton curves of SRC transferring structure during pseudo-static test. Particularly, in the pushover analysis, the target displacement was enlarged to 35 mm in order to get the inelastic skeleton curves of the SRC transferring structure. The target displacement of the control method can be used to analyze the structure and obtain the relation between the base shear Q and top displacement δ. Fig.3 gave the result comparison of the pushover analysis with the pseudo-static test.

Fig.3 shows that the simulated result was feasible by pushover analysis of the structure and reflected the good ductility of the SRC transferring structure. The whole ductility of the SRC transferring structure was fully represented. When the lateral displacement

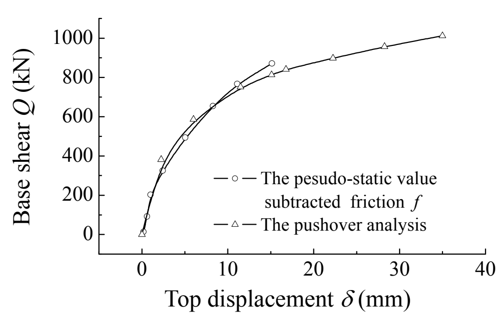

Fig.3 Relation curve between base shear and top displacement

reached 15.2 mm, the level force of pushover analysis and pseudo-static test were 813 kN and 871 kN, so they were almost equal.

3. Failure mechanism

After the pushover analysis, the occurrence order of the plastic hinge for the beam and column of the SRC transferring structure can be obtained for all the steps of the lateral loads. In Fig.4, the occurrence plastic hinge of the pseudo-static test and the pushover analysis were given at target displacement.

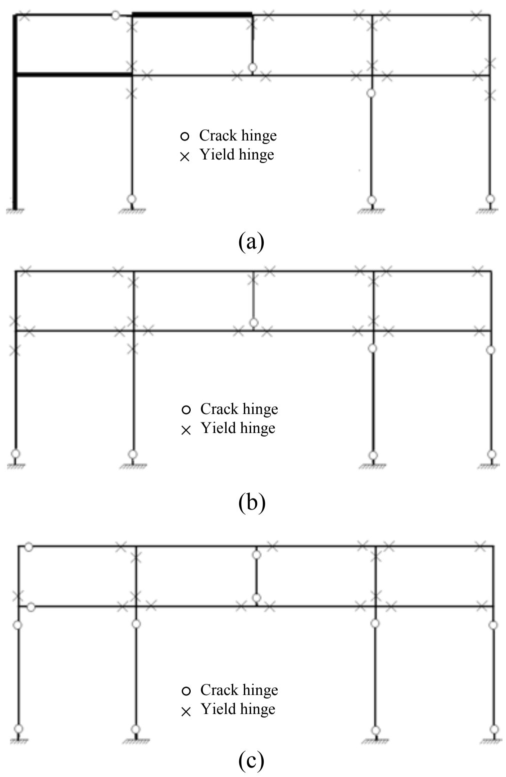

Fig.4 Produced plastic hinge under level loads. (a) Pseudo-static test (δ=15.15 mm), bold solid lines are the beams and columns without the measurement points at test; (b) Pushover analysis (δ_1=16.26 mm); (c) Pushover analysis (δ_2=35 mm)

If the tolerance of the occurrence plastic hinge of the SRC column top brought by the vertical loading installation (the jack) and the indefinite influence on the structure are all neglected during the construction, it is almost considered that the mechanism of occurrence plastic hinge on the SRC transferring structure in the pseudo-static test and that of the pushover analysis are the same at the lateral displacement of δ =15.15 mm. They are all mechanisms of the plastic hinge occurring on the column. However, the common SRC frame is the mechanism of the plastic hinge occurring on the beams. These hinges of SRC transferring structure often appear on the two ends of MZ1 column beneath the SRC transferring beam and two ends of the SRC transferring MZ3 column in Fig.2.

In the second story of the structure in Fig.4, the plastic hinges did not appear on the two ends of the MZ1 column, so the lateral rigidity of the second story was comparatively large. In Fig.4, because the SRC transferring beam had only crack “hinges”, not the yield plastic hinges in the three types of analysis, the SRC transferring structure can meet the demands of the structure design for “strong-transferring beam and weak-frame column”.

PUSHOVER ANALYSIS ON HIGH BUILDING WITH SRC TRANSFERRING STRUCTURE

We took the high building of production management at Zhejiang Province Electric Company, China, as engineering background. The pushover analysis method was used to study the occurrence order and position of plastic hinge; the weak story and seismic capacity of high building with SRC transferring story were also studied through consulting the results of shaking table test for high building (SICABR, 2003).

Establish the model of analysis

The construction prototype of the high building for production management at Zhejiang Province Electric Company (Fig.5) adopted non-linear finite element procedure SAP2000 to establish a 3D finite element model of the static pushover analysis. The building was a frame-shearwall structure with 14 floors, with the fifteenth floor of the building being the framework. A transferring story consisting of four SRC transferring beams with span of 16.2 m was set on the second floor at Axial 1~4/Axial *C*~*E*. Pushover analysis was implemented as follows (Saiidi and Sozen, 1981; Moghadam and Tso, 2000; Wang and Zhou, 2002):

(1) As the high building had the irregular shape, the 3D whole computing model for pushover analysis was established.

(2) As the SAP2000 procedure does not involve

shell element plastic hinge, the shear wall's post-elastic behavior was only presented by equivalent change methods. The common method is that the shear wall is changed to equivalent column and the connecting beam is changed to beam with stiffness areas at two ends.

(3) From the actual dimension and number of reinforcing steel bars and profiled steel on the member cross-section, the hysteretic model curves were calculated.

(4) The hysteretic model consisting of elastic stage, hardening stage, unloading stage and plastic stage was adopted. The relation between moment M_{cr} and section corner θ_{cr} at crack point was neglected.

(5) Shaking table test showed that the largest displacement of the top story in *Y* direction was 0.23 m under intensity 7 seldom-occurred earthquake level. Double lateral displacement of 0.46 m was selected as the target displacement for the pushover analysis.

(6) Considering second-order effect (P-Δ).

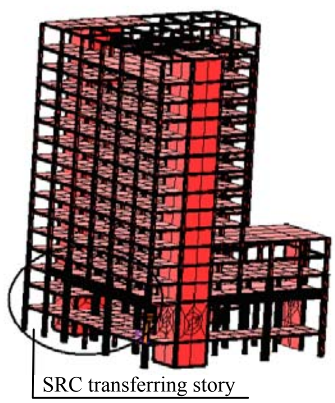

Fig.5 The whole model of high building

The response spectrum was selected to calculate the level push force with data listed in Table 1.

Y direction pushover analysis on the whole structure indicated that the moment hinges mostly appeared on the RC frame beams of the high building, that the P-M2-M3 hinges appeared on the two ends of the columns located at Axial 2/*D* and Axial 3/*D* on the seventh to the tenth story. A few shear hinges also appeared on the tube wall. The *Y* direction final plastic hinges were distributed as shown in Fig.6.

At target displacement of δ=0.23 m, the base shear of the whole structure was 54600 kN, equivalent to 0.994 times that of the structure under intensity 7 seldom-occurred earthquake simulated in the shaking table test. At target displacement of δ=0.276 m, pushover analysis was implemented to completion. The base shear was 59642 kN, which was equivalent to 1.085 times that of the structure under simulated intensity 7 seldom-occurred earthquake.

In view of the plastic hinge position distribution, the equivalent column of the tube wall from Axial 2 to Axial 3 was easily liable to early yield to the shear and

Table 1 The distribution of level force at every story

Level force	Relative rate	Level force	Relative rate
P_1	0.0035	P_9	0.0732
P_2	0.0174	P_{10}	0.0902
P_3	0.0240	P_{11}	0.0957
P_4	0.0315	P_{12}	0.1070
P_5	0.0399	P_{13}	0.1537
P_6	0.0455	P_{14}	0.1233
P_7	0.0573	P_{15}	0.0782
P_8	0.0595	ΣP_i	1.0000

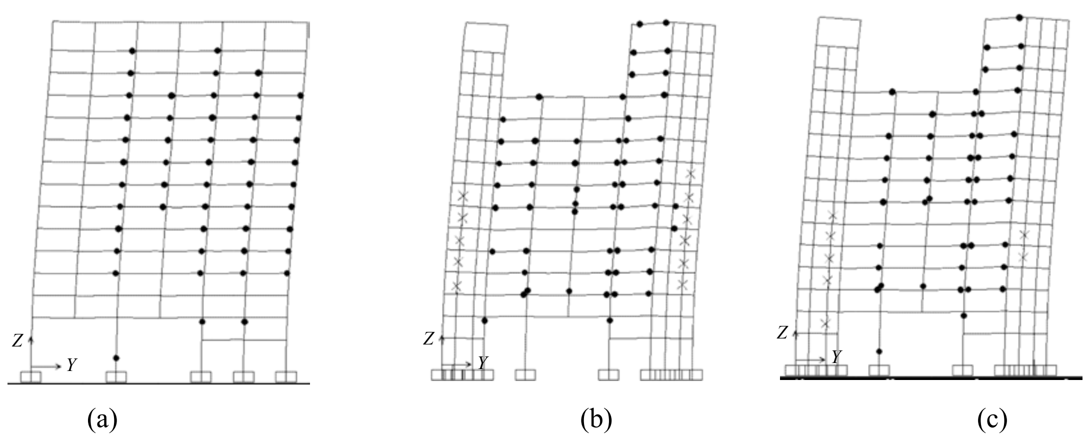

Fig.6 Failure mechanism of *Y* direction lateral force resisting member (δ=0.276 m)
(a) Axial 1-1; (b) Axial 2-2; (c) Axial 3-3. • represents Moment hinge and P-M2-M3 hinge; × represents shear hinge

was wrecked seriously. The phenomenon of many crevasses appearing on tube wall was observed during shaking table test. Most of the plastic hinge concentrated on the middle part of the frame. Sudden change of lateral rigidity of the frame led to occurrence of weak story in RC frame. P-M2-M3 hinges appeared on the RC column of the fourth story, but the small number of the hinges did not weaken the story.

At target displacement δ=0.276 m, no hinges appeared on the SRC transferring beam. Appearing on the local position of the SRC column beneath the two ends of the SRC transferring beam, several P-M2-M3 hinges indicated the frame columns were relatively weaker than the transferring beam in the transferring structure. The phenomenon characterized the performance of transferring beam with concentrated mass and high rigidity under the action of earthquake.

Appearing on the bottom of the fourth story RC columns connected with SRC transferring story, the P-M2-M3 hinges showed the connection between the transferring story (higher rigidity) and RC frame easily formed weak points. Commonly, the transition story between the transferring story and the upper RC frame is proposed in structure design to solve the difficulty of the lateral rigidity sudden change. But in Fig.6, the plane frame of Axial 2 only had two P-M2-M3 hinges on the fourth story of the high building, and had no weak story subjected to the action of earthquake.

Assessment of seismic capacity of the whole structure by capacity spectrum method

In order to assess the seismic capacity of the whole structure, multiple degree of freedom (MDOF) system must be changed to an equivalent SDOF system. It was assumed that the structure only has first order mode vibration under the action of earthquake (Fajfar, 1999). The mode shape vector of frame in pushover analysis can use that of frame at shaking table test, which can be obtained as defined in Eq.(3):

$$\{\phi\}=\{0.0124,0.0248,0.0641,0.1034,0.1510, 0.1985,0.2543,0.3060,0.4094,0.5087, 0.5902,0.6716,0.7494,0.8271,1.0\}^{T} \quad (3)$$

The relation curve between spectrum displacement (or period) and spectrum acceleration can be obtained from relevant equations. Fig.7 gave the relation curve between the period and spectrum acceleration plotted with the demand spectrum curve. In Fig.7, the capacity spectrum curve crossed the demand spectrum under seldom occurring intensity 6 (α_{max}=0.35), 7 (α_{max}=0.5) and 8 (α_{max}=0.9) earthquake, which showed that the building with SRC transferring structure has strong seismic resistance. But the ductility of the whole structure was not presented fully. It is reasonable that when plastic hinges appear increasingly on the member, the convergence of the 3D frame-shearwall model gets more difficult than the plane frame model by the current pushover analysis procedure, which leads to the result of elasto-plastic analysis be still insufficient. In Fig.7, the ductility of common frame-shearwall was good, but the ductility of the frame-shearwall with SRC transferring story at the bottom of high building was decreased.

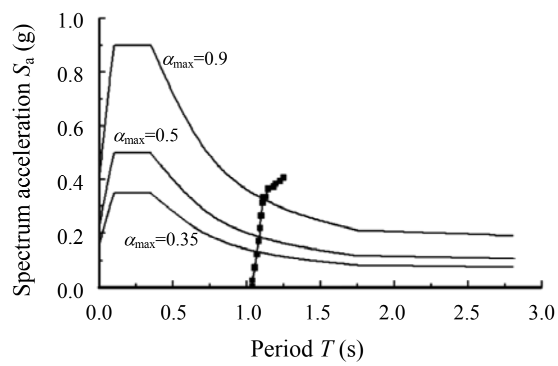

Fig.7 The capacity spectrum curve and the demand spectrum curve

CONCLUSION

The elasto-plastic properties of SRC transferring beams were studied by pushover analysis, and the following conclusion were drawn:

(1) The simulated result of the structure is feasible by the pushover analysis, which reflects the good ductility of SRC transferring structure.

(2) The SRC transferring structure involves all the mechanisms of occurrence of column plastic hinge. These hinges often appear on the two ends of MZ1 columns beneath the SRC transferring beam and SRC transferring MZ3 column.

(3) The SRC frame columns are relatively

weaker than the SRC transferring beam in the structure, which characterizes the performance of transferring beam with concentrated mass and high rigidity during the action of earthquake.

(4) The connection between the transferring story with higher rigidity and RC frame easily forms weak points. Commonly, the transition story between the transferring story and the upper RC frame is proposed in structure design to resolve the problem of sudden change in the lateral rigidity of frame.

(5) Building with SRC transferring structure can withstand the action of seldom occurring intensity 7 and 8 earthquake.

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