Seismic failure mode control of tall steel buildings by strengthening the weaker-members

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ABSTRACT: This paper mainly studies seismic failure mode analysis and seismic failure mode controlling of steel tall buildings. Firstly, the structural nonlinear calculation model and the criterion of failure mode are given. Secondly, tall steel buildings' seismic failure mode control method that based on simultaneous failure principle strengthening weaker- members in the weakest failure mode time after time is presented. Thirdly, the analysis methods of structural integral seismic capacity and capacity storages respectively corresponding to design capacity and yield capacity are presented. Finally, the failure mode, integral seismic capacity and capacity storage corresponding to weakest failure mode are obtained by employing a 15-story steel frame building for limit time history analysis under typical earthquake ground motion and limit Pushover analysis. And controlling method of seismic failure mode of tall steel buildings in this paper is verified practicable. The research in the paper show that tall steel buildings' seismic failure mode can be control effectively by strengthening weak-members in the weakest failure mode time after time.

1. Abstract

Large-scale complex structures have many kinds of failure modes. So it is difficult commonly to enumerate all kinds of these failure modes. But only several failure modes work mostly for structural failure. They are called mainly failure mode [1]. The concept of the weakest failure mode is put forward foremost by Ou Jinping etc. The weakest failure mode is defined as the failure mode corresponding to most large event set under singe random source load. The practical meaning of the weakest failure mode is that the weakest failure mode alone appears or any other failure modes appear inevitable conjoint the weakest failure mode [2]. According to practical meaning of the weakest failure mode, the failure mode with minimum structural integral seismic capacity (appear foremost) is structural weakest failure mode. So practical meaning of failure mode control is that searching and controlling the weakest failure mode and accordingly improving structural integral seismic capacity.

Design method of simultaneous failure [3] is used of reference in the paper. Strengthen structural weaker-members by making members of the weakest story in the weakest failure mode and referenced story fail synchronously. We expect to achieve objective of controlling structural weakest failure mode by strengthening structural weaker-members repeatedly such-and-such and to improve structural integral seismic capacity.

In the paper, failure modes of tall steel buildings are analyzed by employing a 15-story steel frame structure for limit time history analysis under typical earthquake ground motion and limit Pushover analysis. Then tall steel buildings' seismic failure mode control method that based on simultaneous failure principle strengthening weaker-members in the weakest failure mode time after time is presented. And original frame and controlled frame are all carried out integral seismic capacity analysis.

2. Seismic failure mode analysis method of tall steel buildings

2.1Seismic failures mode analysis method

2.1.1Analysis model

Frame plastic hinge model is used in the paper. Plastic hinges use steel hinge property in FEMA356. Beams are intercalated bend hinge and shear hinge. Columns are intercalated coupled axial force-bend hinge and shear hinge. Geometry nonlinearity induced by P-delta effect and large deformation effect is considered.

2.1.2Limit time history analysis

Limit time history analysis method is defined that time history analysis is made step by step by increasing acceleration peak value of input earthquake wave until reaching structural limit state.

(1)Damp model

Relay damp model is used in time history analysis. Relay damp model is denoted as:

$$\boldsymbol{C}=\alpha_0\boldsymbol{M}+\alpha_1\boldsymbol{K} \tag{1}$$

Here, $\boldsymbol{M}$ is structural mass matrix. $\boldsymbol{K}$ is structural stiffness matrix. $\boldsymbol{K_0}$is structural initial stiffness matrix can be used.

$$\alpha_0=\frac{2(\frac{\xi_j}{\varpi_j}-\frac{\xi_{j+1}}{\varpi_{j+1}})}{\frac{1}{\varpi_j^2}-\frac{1}{\varpi_{j+1}^2}},\qquad \alpha_1=\frac{2(\xi_{j+1}\varpi_{j+1}-\xi_j\varpi_j)}{\varpi_{j+1}^2-\varpi_j^2} \tag{2}$$

Here, ϖ_j , ϖ_{j+1} (ξ_j , ξ_{j+1})structural random two border upon self-vibration circular frequency. The first circular frequency ϖ_1 and the second circular frequency ϖ_2 corresponding to structural initial stiffness can be used. Damp ratio of steel ξ_1 and ξ_2 is 0.02 under 'small earthquake' action and 0.05 under 'large earthquake' action [4].

(2)Numerical integral method

Newmark method is used because of accuracy and stability. Newmark method is denoted by the following formulas.

$$\{\dot{u}\}_{t+\Delta t}=\{\dot{u}\}_t+(1-\gamma)\{\ddot{u}\}_t\cdot\Delta t+\gamma\{\ddot{u}\}_{t+\Delta t}\cdot\Delta t \tag{3}$$

$$\{u\}_{t+\Delta t}=\{u\}_t+\{\dot{u}\}_t\cdot\Delta t+(\frac{1}{2}-\beta)\{\ddot{u}\}_t\cdot\Delta t^2+\beta\{\ddot{u}\}_{t+\Delta t}\cdot\Delta t^2 \tag{4}$$

Here, γ and β are parameters. In the paper, γ equal to 1/2 and β equal 1/4.

2.1.3 Limit Pushover analysis

Pushover analysis method is a kind of static elastic-plastic analysis method. Pushover analysis method is defined that loading to structures with monotone incremental horizontal load until reach target displacement of reference point or buildings collapse. In Pushover analysis horizontal load is monotone increased until structures reach limit state. Control method of Pushover analysis includes displacement control and load control. Displacement control is used in the paper [11].

2.2Criterion of seismic failure mode

Failures of tall steel buildings mainly include joints failure, members' failure and structural collapse. The assume that joints don't fail is made in the paper. Members' failure caused by material yield is considered in the paper. Structural collapse is that structures lose whole stability. When too many plastic hinges in members appear, structures would become mechanisms and collapse [5~6].

2.2.1Failure criterion of members

When material intensity of members reaches yield limit state, members would fail. Yield limit state include three kinds. They are separate coupled axial force-bend limit state, shear stress limit state and torsion shear stress limit state. The three limit state of material are not separate correlative and should be respectively checked [7].

2.2.1Failure criterion of structures

Structural failure is defined that structures lost load-carrying capacity or can not work for use normally. The two failure criterions used for distinguishing structural limit states. When anyone of two failure criterions is satisfied, structures would be determined having reached structural limit state [7].

（1）Structural total stiffness matrix singularity. When whole structure system or local structure becomes mechanism, structural total stiffness matrix singular appears. It can be denoted by the following formula.

$$\boldsymbol{K}=0 \tag{5}$$

Here structures have reached structural limit state.

（2）Structural total displacement or local displacement overrun. Displacement control condition is denoted by the following formula.

$$\Delta\leq[\Delta] \tag{6}$$

When above inequation is not fitted, structures would be determined having reached structural limit state. Here $[\Delta]$ is structural control displacement limit value. Code for seismic design of buildings in china [8] control structural deformation by restricting story drift.

3. Seismic failure mode control method of tall steel buildings

Seismic failure mode control of tall steel buildings is achieved by strengthening structural weaker-members in the weakest failure mode time after time. The strengthening method is that members of the weakest story in the weakest failure mode and consulted story are required to start fail(yield) simultaneously by strengthening members of both of the two stories or anyone of the two stories, that columns of the weakest story in the weakest failure mode is first considered for being strengthened and columns of consulted story may be strengthened or not be strengthened and that only beams of the story failing earlier between the two stories may be strengthened. The consulted story is a story selected from the two conjoint stories of the weakest story in the weakest failure mode. Selection method is that the story below the weakest is first selected and that the story above the weakest story is selected if members of the story below the weakest story and members the weakest story start fail simultaneously before strengthened. If members of the two conjoint stories of the weakest story and members of the weakest story start fail simultaneously before strengthened. The consulted story will be selected from the two stories separated by a story with the weakest story according to above selection method. If floor i is the weakest story in the weakest failure mode and floor j is consulted story, the following formulas should be fitted.

When θ_i equals θ_{yi}, then

$$\theta_j = \theta_{yj} \tag{7}$$

$$\theta_i = \frac{Q_i}{k_i \cdot h_i}, \quad \theta_j = \frac{Q_j}{k_j \cdot h_j} \tag{8}$$

Formula(7) can be denoted by formula(9).

$$\frac{k_i}{k_j} = \frac{Q_i}{Q_j} \cdot \frac{h_j}{h_i} \cdot \frac{\theta_{yj}}{\theta_{yi}} \tag{9}$$

Here k_i is lateral story stiffness of floor i and should be calculated through story shear being divided by story drift. Q_i is story shear of floor i. h_i is height of floor i. θ_{yi} is story yield drift rotation of floor i.

Whether columns or beams, when strengthened, same kind of member of same floor should be strengthened all together. When columns strengthened, cross sections of columns should are bigger than cross sections of columns of below conjoint story. When beams strengthened, smaller cross sections should be used.

When members of floor 2 is required to be strengthened, columns of both bottom floor and floor2 should be first considered if need to be strengthened. When beams of floor2 need to be strengthened, beams of both bottom floor and floor2 should be strengthened with same cross sections all together except special demand.

Whether the weakest failure mode determined by limit time history analysis method or the failure mode determined by limit Pushover analysis method (only one failure mode) can be controlled or can be improved by using above strengthening method time after time until the weakest failure mode determined by limit time history analysis method is eliminated or the failure mode determined by limit Pushover analysis method is improved for obtaining expected structural integral seismic capacity. Corresponding analysis method of structural integral seismic capacity will be discussed thereinafter.

4. Integral seismic capacity analysis of seismic failure mode of tall steel buildings

4.1Analysis method

Structural integral seismic capacity is defined as earthquake action endured by the structure before the structure reach limit state. For limit time history analysis structural limit integral seismic capacity can be represented by acceleration peak value of input ground motion. For limit Pushover analysis structural limit integral seismic capacity can be represented by structural base shear.

Structural safety can be evaluated by using capacity storage. Structural capacity storage coefficient is defined as ratio of limit integral seismic capacity to yield capacity or of limit integral seismic capacity to ‘large earthquake’ design capacity. Structural capacity storage coefficient may be calculated respectively by formula (10) or formula (11).

$$R_s = \frac{a_u}{a_y}, \qquad R_s = \frac{F_u}{F_y} \tag{10}$$

$$R_s = \frac{a_u}{a_m}, \qquad R_s = \frac{F_u}{F_m} \tag{11}$$

Here a_u, a_y and a_m are separate acceleration peak value of input earthquake wave when structures reach structural limit state, structures start yield and 'large earthquake' design demand. F_u, F_y and F_m are separate structural base shear when structures reach structural limit state, structures start yield and designed according to 'large earthquake'.

4.2Failure mode control can improve integral seismic capacity

Structural seismic failure mode is controlled in order to eliminate the weakest failure mode determined by limit time history analysis method and improve failure mode determined by limit Pushover analysis method for improving structural integral seismic capacity. So feasibility of control method of seismic failure mode should be verified by judging if structural integral seismic capacity can be improved.

5. Example

5.1Analysis parameters

The employed structure is a 15-story steel frame building with 3 bays. The structure is regular. Each span is 6.6m. The height of bottom story is 4.2m and height of other stories is all 3.3m. Structural calculating diagram is showed by figure 1. Vertical distributed dead load on beams is 21.0kN/m. Vertical distributed live load on beams is15.0kN/m [9]. Seismic fortification is intensity 8. The site-class is Ⅱ.Design earthquake group is the second group. Elastic modular of steel is E =2.06×10^5N/mm^2. Material property of steel is Q235.

The finite program SAP2000 is used for structure design and nonlinear finite element analysis. Three typical ground motions fitting site Ⅱ is selected for time history analysis. They are Elcentro(NS) wave, Sgs_00_w wave and Tangshan wave.

The structure is designed according codes [8~10]. Structural member section types are listed in table1.

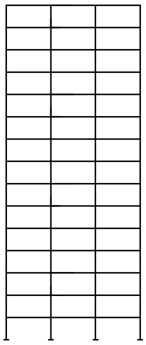


Fig.1 Structural calculating diagram

Table 1 Member sections

Members	*Sections*
Columns of floor 1,2	□500×500×40×40
Columns of floor 3,4	□500×500×35×35
Columns of floor 5~8	□500×500×30×30
Columns of floor 9~10	□500×500×25×25
Columns of floor 11~15	□500×500×20×20

Beams of floor 1~15	$H500\times300\times12\times25$

5.2Failure mode analysis

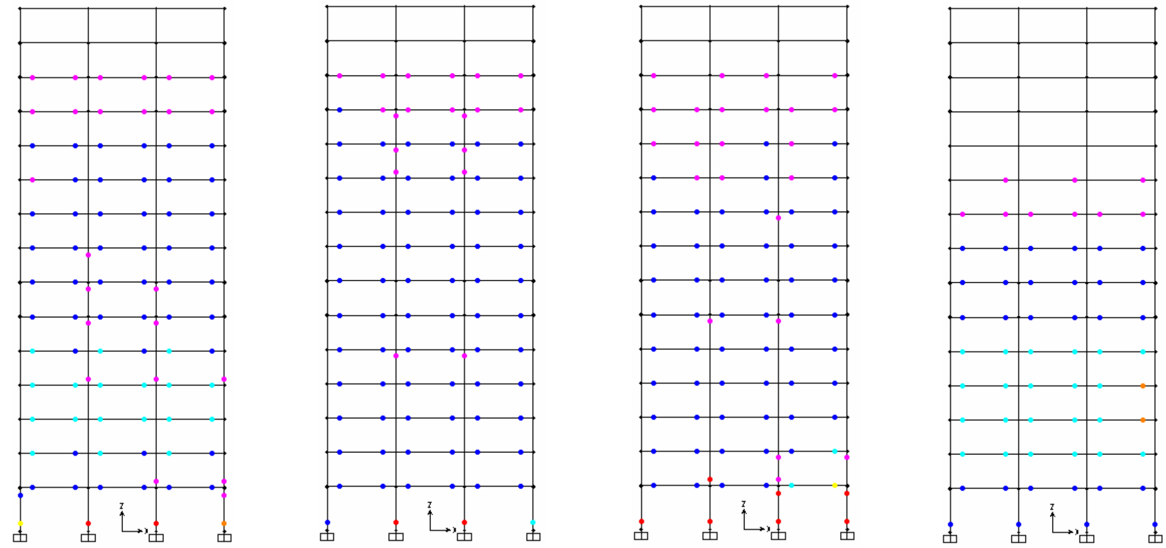
The structure is carried out limit time history analysis under typical earthquake ground motion and limit Pushover analysis respectively according to each of above two failure criterions. In limit Pushover analysis the structure is loaded by using inverse triangle distribution pattern.

(1) Structural whole failure mode

When whole structure system or local structural part becomes mechanism, the structure whole failure mode appears. Criterion of structural whole failure mode is that structural whole stiffness matrix singular appears.

In limit time history analysis, when acceleration peak values of Elcentro(NS) wave, Sgs_00_w wave and Tangshan wave reach respectively 2100gal, 2500gal and 1450gal, the structure becomes geometrical unstable system. Corresponding failure mode is showed in figure 2.

In limit Pushover analysis, when structural base shear force is 2516.0kN before the structure becomes geometrical unstable system. Corresponding failure mode is showed in figure 2.



(a)Elcentro wave input (b) Sgs_00_w wave input (c) Tangshan wave input (d) Pushover analysis

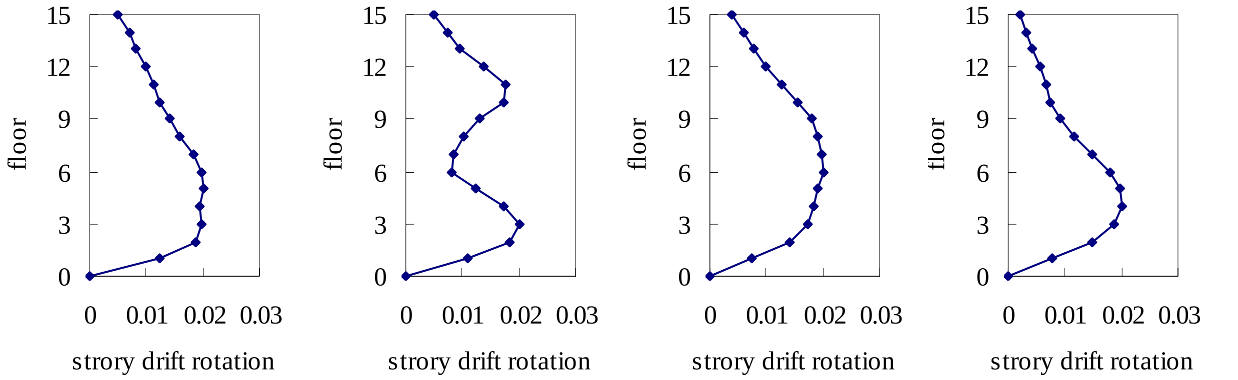
Fig.2 Mode of overall failure

(2) Structural displacement overrun failure mode

Code for seismic design of buildings in china control structural deformation under 'large earthquake' by restricting elastic-plastic story drift of weak story. For steel buildings limit elastic-plastic story drift rotation is $[\theta_p]$=1/50.

In critical time history analysis, when acceleration peak values of Elcentro(NS) wave, Sgs_00_w wave and Tangshan wave reach separate 1015gal, 1150gal and 550gal, the structure failure all because of displacement overrun. Corresponding elastic-plastic story drift rotations of weak story are separate 0.0202, 0.0200 and 0.0200. Structural story drift rotations are showed by Figure3.

In limit Pushover analysis, when structural base shear is 2324.4kN, elastic-plastic story drift rotations of weak story reach 0.02. Structural story drift rotations are showed by Figure3.



(a) Input Elcentro wave (b) Input Sgs_00_w wave (c) Input Tangshan wave (d) Pushover analysis

Fig.3 Story drifts rotations

According to above analysis, we find that structural limit load-carrying capacities corresponding to displacement overrun are smaller than structural limit load-carrying capacity corresponding to structural whole failure in both limit time history analysis and limit Pushover analysis. This shows that displacement overrun failure criterion is stricter than whole failure criterion.

（3）Structural weakest failure mode

In limit time history analysis the structure has three different seismic failure modes when acted by three different earthquake waves. Failure mode corresponding to minimum acceleration peak value is the weakest failure mode. So the structural weakest failure mode is failure mode under Tangshan wave action. Structural integral seismic capacity corresponding to the weakest failure mode under Tangshan wave action is 1450gal（whole failure criterion）or 550gal(displacement overrun failure criterion).

For limit Pushover analysis only one failure mode can be obtained corresponding to each failure criterion, so weakest failure mode can't be determined.

5.3Failure mode control

From above analysis we can find that the weakest failure mode corresponding to smaller structural integral capacity is displacement overrun failure under Tangshan wave action (see table2). So displacement overrun failure under Tangshan wave action is object for failure mode control. In the weakest failure mode the weakest story is floor 6（see table3）. The consulted story selected is floor5. Columns of floor6 should be first considered for being strengthened. But columns of floor 6 have same sections type with columns of below floor 5. Furthermore lateral story stiffness break is not great. And columns of floor6 will not be strengthened here for making less members being strengthened. Columns of floor 5 are not very impartment for being strengthened. So columns of floor 5 will not be strengthened here. Beams of floor 5 will be strengthened because they fail before beams of floor 6 fail. Members should be strengthened with less section when ensuring members of floor 5 and members of floor 6 starts fail simultaneously. The strengthened member section types are listed in table 4.

The strengthened frame is carried out limit time history analysis under typical earthquake ground motion and limit Pushover analysis. The strengthened frame is made to respectively reach structural limit state corresponding to minimum limit load-carrying capacity. In limit time history analysis the weakest failure mode is displacement overrun failure under Tangshan action. Structural integral seismic capacity is 580gal. In limit Pushover analysis structural failure mode is also displacement overrun failure when structural base shear reach 2376.8kN. Structural story drift rotations are showed by figure4.

Above analysis shows that structural weakest failure mode isn't eliminated. According to the method strengthening the structure after strengthened time after time until the weakest failure mode is eliminated. Structural integral seismic capacities and the weakest stories after every time strengthened are showed respectively in table2 and table3. Members strengthened every time are showed in table 4. Members of the frame after controlled (the frame after 11^{th} time strengthened) are showed in table 5.

The frame after controled fails first because of story displacement overrun in both limit time history analysis under typical earthquake ground motion and limit Pushover analysis. In limit time history analysis the weakest failure mode of controlled is story displacement overrun failure under Sgs_00_w wave action. Corresponding structural integral seismic capacity is 710gal. In limit Pushover analysis structural integral seismic capacity is 2880.6kN. Structural story drift rotations are showed by figure 5.

Above analysis shows that structural weakest failure mode of has been eliminated and structural integral seismic capacity has been improved by carried out failure mode control.

Table 3 Structural integral seismic capacity

Structures	*Limit time history analysis /gal*			*Limit Pushover analysis /kN*
	Input Elcentro wave	*Input Sgs_00_w wave*	*Input Tangshan wave*	
Original frame	*1015*	*1160*	*550*	*2324.4*
1st strengthened frame	*1010*	*1150*	*580*	*2376.8*
2nd strengthened frame	*1010*	*1150*	*600*	*2403.9*
3rd strengthened frame	*1040*	*1190*	*620*	*2450.3*
4th strengthened frame	*1050*	*1161*	*630*	*2523.9*
5th strengthened frame	*1060*	*1120*	*630*	*2546.7*
6th strengthened frame	*1090*	*1119*	*650*	*2584.8*
7th strengthened frame	*1115*	*1050*	*660*	*2637.6*
8th strengthened frame	*1150*	*9910*	*690*	*2689.5*
9th strengthened frame	*1135*	*8000*	*700*	*2712.9*
10th strengthened frame	*1155*	*740*	*720*	*2771.7*
11th strengthened frame	*1170*	*710*	*730*	*2880.6*

Table2 the Weakest floor

Structures	*Limit time history analysis*			*Limit Pushover analysis*
	Input Elcentro wave	*Input Sgs_00_w wave*	*Input Tangshan wave*	
Original frame	*5*	*3*	*6*	*4*
1st strengthened frame	*3*	*3*	*7*	*4*
2nd strengthened frame	*3*	*3*	*3,4*	*4*
3rd strengthened frame	*3*	*3*	*4,8*	*4*
4th strengthened frame	*3*	*10,11*	*3*	*4*
5th strengthened frame	*3*	*10,11*	*3,4*	*4*
6th strengthened frame	*3,4*	*10,11*	*3*	*4*
7th strengthened frame	*4*	*11*	*4*	*4*
8th strengthened frame	*4*	*10,11*	*3*	*4*
9th strengthened frame	*4*	*11*	*4,9*	*4*
10th strengthened frame	*4*	*11*	*4,7*	*5*
11th strengthened frame	*4*	*11*	*4,7*	*5*

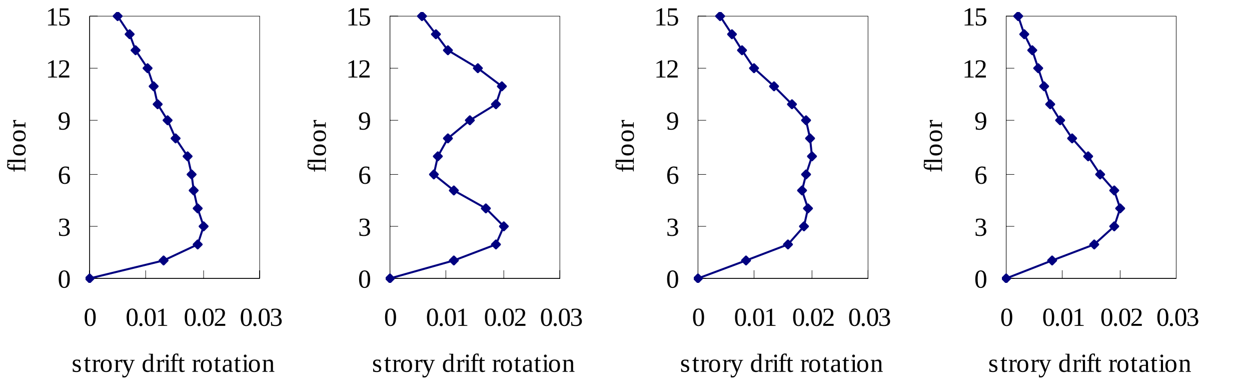
Table4 Every time strengthened frame Members

Strengthened members	*Members and sections*
1st strengthened Members	*Beam of floor 5:* $H500\times350\times15\times25$
2nd strengthened Members	*Beam of floor 6:* $H500\times300\times15\times28$
3rd strengthened Members	*Column of floor 1,2:* $\square 510\times510\times40\times40$
	Column of floor 3: $\square 500\times500\times40\times40$
	Column of floor 4: $\square 500\times500\times40\times40$
	Beam of floor 3: $H500\times300\times15\times26$
4th strengthened Members	*Beam of floor 4:* $H500\times300\times15\times28$
	Beam of floor 7: $H500\times350\times15\times26$
5th strengthened Members	*Column of floor 1,2:* $\square 520\times520\times40\times40$
	Column of floor 3: $\square 510\times510\times40\times40$
6th strengthened Members	*Column of floor 4:* $\square 510\times510\times40\times40$
	Beam of floor 3: $H500\times350\times15\times25$
7th strengthened Members	*Beam of floor 1,2:* $H500\times300\times12\times28$
8th strengthened Members	*Column of floor 5:* $\square 500\times500\times40\times40$
	Beam of floor 4: $H500\times350\times15\times28$
9th strengthened Members	*Beam of floor 1,2:* $H500\times300\times16\times28$
10th strengthened Members	*Column of floor 9:* $\square 500\times500\times30\times30$
	Beam of floor 3: $H500\times400\times15\times25$

11th strengthened frame	*Beam of floor 8:* $H500\times300\times15\times28$ *Column of floor 5:* □ $500\times500\times40\times40$ *Column of floor 7:* □ $500\times500\times35\times35$ *Beam of floor 1,2:* $H500\times350\times15\times28$ *Beam of floor 6:* $H500\times350\times15\times28$

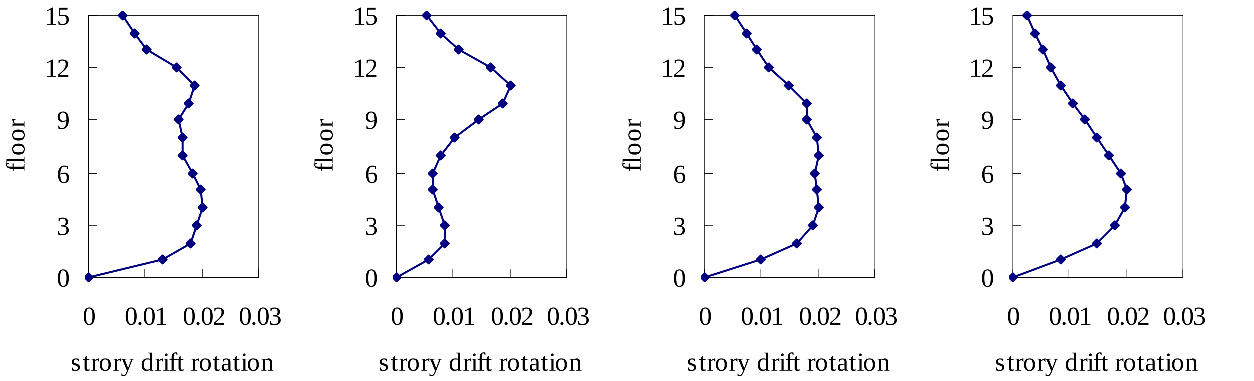
Table 4 Member sections of frame after controlled

Members	*Sections*
Columns of floor 1,2	□ $520\times520\times40\times40$
Columns of floor 3,4	□ $510\times510\times40\times40$
Columns of floor 5,6	□ $500\times500\times40\times40$
Column of floor 7	□ $500\times500\times35\times35$
Columns of floor 8,9	□ $500\times500\times30\times30$
Column of floor 10	□ $500\times500\times25\times25$
Columns of floor 11~15	□ $500\times500\times20\times20$
Beam of floors 1,2	$H500\times350\times15\times25$
Beam of floor 3	$H500\times400\times15\times25$
Beam of floor 4	$H500\times350\times15\times28$
Beam of floor 5	$H500\times350\times15\times25$
Beam of floor 6	$H500\times350\times15\times28$
Beam of floor 7	$H600\times400\times15\times26$
Beam of floor 8	$H500\times300\times15\times28$
Beam of floors 9~15	$H500\times300\times12\times25$



(a) Input Elcentro wave (b) Input Sgs_00_w wave (c) Input Tangshan wave (d) Pushover analysis

Fig.4 Story drift rotations of frame by strengthened firstly



(a) Input Elcentro wave (b) Input Sgs_00_w wave (c) Input Tangshan wave (d) Pushover analysis

Fig.5 Story drifts rotations of controlled frame

5.4Integral seismic capacity analysis

Structural limit integral seismic capacity is earthquake action endured by the structure before the structure reaches structural limit state. Structural limit integral seismic capacities of original frame and controlled frame are listed in table 6. Structural limit integral seismic capacities of control frame have been improved.

Table 6 Limit seismic resistance capacity

Structures	*Limit time history analysis /gal*	*Limit Pushover analysis /kN*
Original frame	*550*	*2324.4*
Controlled frame	*710*	*2880.6*

Structural yield capacity is earthquake action endured by the structure when structural member yielding appear firstly. Structural yield capacity can be expressed by peak value of acceleration of inputted ground motion or by total basic shear force. By nonlinear time history analysis under typical earthquake ground motion and Pushover analysis Structural yield capacity may be calculated. Structural yield capacity of original frame and controlled frame are listed in table 7. Structural yield capacities of control frame have been improved.

For seismic fortification 8 intensity, peak value of ‘large earthquake’ design acceleration of ground motion is 400gal. In Pushover analysis, structural total basic shear force corresponding to performance point obtained by design response spectrum and demand spectrum of ‘large earthquake’ is ‘large earthquake’ design earthquake action. ‘Large earthquake’ design earthquake actions of original frame and controlled frame are separate 1467.5kN and 1589.9kN.

Structural capacity storage coefficients corresponding to yield (listed in table7) and corresponding to ‘large earthquake’ design (listed in table8) have been calculated by formula (10) and (11). Minimum capacity storage coefficients corresponding to yield of original frame and controlled frame are separate 1.34 and 1.26. The cause that minimum capacity storage coefficients corresponding to yield of controlled frame diminish is that extent increased of yield capacity is bigger than extent increased of integral seismic capacity. Minimum capacity storage coefficients corresponding to ‘large earthquake’ design of original frame and controlled frame are separate 1.38 and 1.78. Minimum capacity storage coefficients corresponding to ‘large earthquake’ design of controlled frame are increased.

Table 7 Yield capacity

Structures	*Limit time history analysis /gal*	*Limit Pushover analysis /kN*
Original frame	*167*	*1738.6*
Controlled frame	*177*	*2281.7*

Table 8 Capacity storage coefficient corresponding to yield

Structures	*Limit time history analysis*	*Limit Pushover analysis*
Original frame	*3.29*	*1.34*
Controlled frame	*4.01*	*1.26*

Table9 Capacity storage coefficient corresponding to ‘large earthquake’ design

Structures	*Limit time history analysis*	*Limit Pushover analysis*
Original frame	*1.38*	*1.58*
Controlled frame	*1.78*	*1.81*

6. Conclusions

The paper mainly studied analysis and controlling method of seismic failure mode of steel tall buildings. The following conclusions are made.

1) In nonlinear time history analysis, by inputting more ground motions more structural failure modes can be obtained. Sequent the weakest failure mode can be determined. In Pushover analysis, only one structural failure mode can be obtained, so the weakest failure mode can’t be determined.

2) Structural integral seismic capacity may be determined according to structural failure mode. When time history analysis method is used, acceleration peak value of input ground motion represents structural integral seismic capacity. When Pushover analysis method is used, structural base shear represents structural integral seismic capacity. Structural integral seismic capacity storage coefficient corresponding to yielding capacity or corresponding to ‘large earthquake’ design is important for estimating structural safety storage.

3) Structural whole failure and story displacement overrun of structural weak story are two kinds failure criterions used in the paper. By analyzing structural failure mode and structural integral seismic capacity, we find the structure usually story displacement of structural weak story breaks bound before the structural becomes mechanisms and collapse.

4) The weakest failure mode in time history analysis can be eliminated, or the failure mode in Pushover analysis can be improved, and structural integral seismic capacity is improved by based on simultaneous failure principle strengthening weak members in the weakest failure mode time after time.

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