SEISMIC BEHAVIOR ANALYSIS OF SUPER HIGH-RISE STRUCTURE BASED ON THREE SOFTWARE PROGRAMS

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Abstract

The main building of China Communications Construction Company Limited South Regional Headquarter, located in district Zhuhai of Guangzhou City, is a hybrid structure of concrete filled steel tubular laminated columns and reinforced concrete core tube, in which ring beams are adopted to connect concrete filled steel tubular laminated columns with reinforced concrete frame beams. At the same time, the height of this building is 198.m that exceeds the Chinese specification limit, with 3 underground floors and 43 above-ground floors. In order to explore the seismic behavior of the super high-rise structure, and verify the reliability of numerical simulation analysis, three finite element models (FEMs) are built in the three software programs i.e. NosaCAD, Perform-3D, and ABAQUS simultaneously. Then, the first six vibration modes of the three FEMs and the mass of each model are calculated and compared. Thirdly, according to the site soil, seismic design groups, natural vibration properties, and design response spectrum based on the Chinese Code for Seismic Design of Buildings (CSDB, GB50011-2010), three different earthquake waves AW, NW, and EI-Centro are chosen to nonlinear time history analyses. Lastly, time history analyses of roof displacement, story displacement, interstory drift, base shear, and damage patterns are performed under rare earthquake waves AW, NW, and EI-Centro. Results showed that (i) in the three models, the sequences of vibration modes are identical, the natural vibration periods are uniform, and the masses of models are similar; (ii) the numerical results of the three FEMs meet well. Although numerical values in ABAQUS is a little different form those in NosaCAD and Perform-3D, the trends of envelope curves of roof displacement, story displacement, interstory drift and base shear are nearly the same in the three software programs, which means the analysis results are credible; (iii) in the three FEMs, maximum values of roof displacement, interstory drift and maximum base shear under AW and NW are all bigger than that under El-Centro; (iv) under rare earthquake, the interstory drift of numerical analyses in the three software programs all can meet the limitation stipulated in Chinese Design Codes. The structural destruction process can meet the seismic designing principles of “strong column and weak beam” well. The seismic energy mainly dissipated through coupling beams and frame beams, and the damage of vertical load-bearing components is slight. The above means the structure meets the requirement stipulated in Chinese Design Codes of “no collapse under rare earthquake”; (v) under rare earthquake, the reinforcement and steel tubes in ring beams, frame beams and laminated columns keep elastic all the time, while the concrete shows different degrees of compressive damage, which is not severe. Beyond that, the damage of ring beams is relatively small, which is mainly concentrated at the bottom of the cross section of the ring beam and a certain frame beam. What’s more, the damage of the ring beam does not affect its performance.

Keywords: super high-rise structure; finite element model; nonlinear time history analyses; rare earthquake waves

1. Introduction

In recent years, a number of high-rise buildings have been built, in which many structures are ultra-limited and many structural shapes are complex to meet the architectural design requirements [1-3]. Therefore, this requires structural engineers to understand the seismic behaviors of these high-rise buildings to ensure the safety under earthquakes.

Many researchers have explored the seismic behaviors of different ultra-limit structures by shaking table tests [4-6]. It is noted that some tests are expensive, and the majority of experimental models are scaled. As a result, numerical simulation analysis is widely used increasingly. It can not only show the experimental process of full-scale structure repeatedly and continuously, but also explore the detailed physical phenomenon which cannot be observed by actual tests. NosaCAD, Perform-3D and ABAQUS are widely used in structural analysis [7-10]. Numbers of researchers have conducted numerical simulation experiments to analyze the seismic behaviors of various ultra-limit structures. Nonlinear time history analysis with NosaCAD on National Hall of China Pavilion for Expo 2010 Shanghai was performed by Wu et al. [11] to investigate the seismic behavior of the peculiar structural system. Zhou et al [12] conducted seismic analysis on a hybrid structure of steel frame and reinforced concrete core tube using Perform-3D. Using ABAQUS, elasto-plastic behavior was analyzed on tall buildings to obtain seismic deformation and mechanical behavior [13-14].

In this paper, one building called CCCC South Regional Headquarter is focused on, with main part totally 198.9 m high. In order to explore the seismic behavior of the super high-rise structure, and verify the reliability of numerical simulation analysis, three kinds of software NosaCAD, Perform-3D, and ABAQUS are adopted simultaneously to perform time history analyses. Firstly, finite element models are built in the three software programs. Secondly, dynamic properties are compared. Lastly, roof displacement, story displacement, interstory drift, base shear, and damage patterns are analyzed in NosaCAD, Perform-3D, and ABAQUS, respectively.

2. Structural overview

2.1 Building structure

CCCC South Regional Headquarter is located in district Zhuhai of Guangzhou City, Guangzhou Province. The building mainly consists of two parts: the main structure and annex structure. The main part is an office building, totally 198.9 m high, which exceeds the Chinese specification limit, with 3 underground floors and 43 above-ground floors. It is a hybrid structure of concrete filled steel tubular laminated columns and reinforced concrete core tube, in which ring beams are adopted to connect concrete filled steel tubular laminated columns with reinforced concrete frame beams. The standard floor plane layout of main building is shown in Fig. 1.

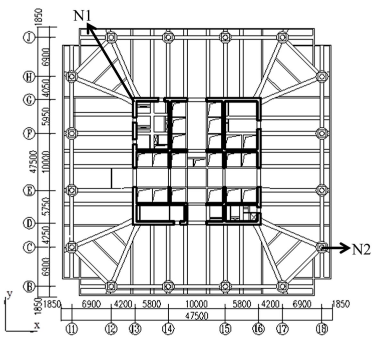


Fig. 1 – Plane layout of standard floor (unit: mm)

2.2 Structural design and material parameters

The design parameters of main building are shown in Table 1. The concrete compressive strength is 25 MPa, 35 MPa, 40 MPa, 50 MPa, 60 Mpa and 80 MPa, respectively. The yielding strength in longitudinal reinforcement is 400MPa, and in shear walls of core tube, coupling beams, and concrete filled steel tubular laminated columns is 345MPa.

Table 1 – Design parameters of main building

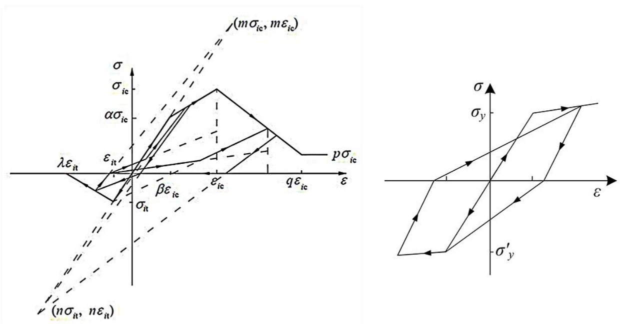
Project name	South regional headquarter of CCCC				
Site classification	II	Seismic fortification intensity	7	Safety classes of building structure	II
Number of structural layers	46	Classification of design earthquake	The first group	Height	208m
Classification of seismic protection of buildings	Key project(II)		Structural system	Concrete filled steel tubular laminated column-reinforced concrete core wall system	

3. Analysis of models

3.1 Finite element model

3.1.1 NosaCAD

In NosaCAD, beam and column are modeled by bar element, shell element is used in modeling the shear wall, and structural slab is simulated by elastic slab element. Fig. 2 (a) shows the concrete constitutive law of beam, which is trilinear model based on user material subroutines called TJFiber developed by Tongji University. Fig. 2 (b) shows the steel constitutive law of the spring model in column, which is ideal elastic-plastic, and the stiffness value after yielding is 1% of the initial one.



(a) Concrete (b) Steel

Fig. 2 – Material constitutive law

3.1.2 Perform-3D

In Perform-3D, beam and column are also simulated by bar element. Shear wall is simulated by the macroscopic wall element called General Wall. General hysteretic model is used to simulate the restoring force curve of components and the constitutive relationship of material, as shown in Fig. 3. It is seen that five key points (Y, U, L, R, X) are defined to describe different stages including elasticity, yield strengthening, and strength degradation.

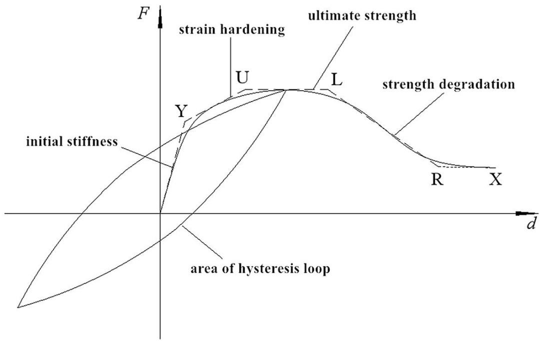
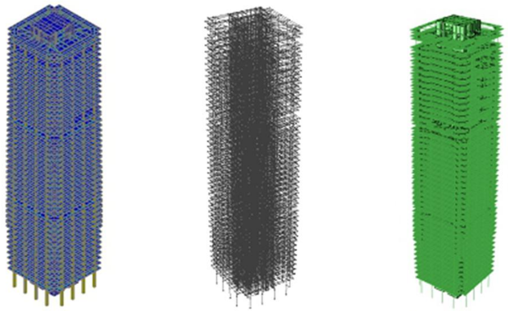


Fig. 3 – General hysteretic model in Perform-3D

3.1.3 ABAQUS

The first-order 3D Timoshenko beam element (B31) is used to simulate the reinforced concrete frame beam and concrete filled steel tubular laminated column. The shear wall is modeled by the reduced-integration shell element of quadrangle (S4R), while the structural slab is simulated by the reduced-integration shell element of quadrangle or triangle (S4R or S3R). In ABAQUS, the constitutive relation of concrete and steel of beam element is based on TJFiber developed by Tongji University. For the shear wall, the steel constitutive law is ideal elastic-plastic model, and the concrete constitutive law is plastic-damage model based on ABAQUS.

Different macroscopic models in Nosa CAD, Perform-3D, ABAQUS are shown in Fig. 4.



(a) NosaCAD (b) Perform-3D (c) ABAQUS

Fig. 4 – Three models in NosaCAD, Perform-3D and ABAQUS

3.2 Comparison of dynamic properties

In order to realize the natural vibration properties and verify the reliability of finite element models, model analysis is carried out. Table 2 shows the mass of each model. The first six vibration modes of the three macroscopic models in NosaCAD, Perform-3D and ABAQUS are shown in Table 3.

As shown in Table 2 and Table 3, the first two order periods in Perfom-3D are similar to that in NosaCAD. The third order period in NosaCAD is close to that in ABAQUS, and in Perform-3D is the smallest. In the three models, distribution of structural lateral stiffness has little difference, as the sequences of vibration mode are identical, the natural vibration periods are uniform, and the masses of model are similar.

Table 2 – The mass of macroscopic models

Software	NosaCAD	Perform-3D	ABAQUS
Mass(t)	160810	161040	164433.8

Table 3 – Natural vibration properties

Order	Period (s)			Description
	NosaCAD	Perform-3D	ABAQUS	
1	4.891	4.891	4.766	Translation in X
2	4.754	4.751	4.713	Translation in Y
3	3.690	3.488	3.625	Torsion
4	1.489	1.467	1.463	Second translation in X
5	1.393	1.373	1.372	Second translation in Y
6	1.370	1.304	1.350	Second torsion

3.3 Earthquake waves instruction

The characteristic period of the structure is 0.35s, and its seismic characteristics under rare earthquake waves of seven-degree are studied.

Three different earthquake waves are used in nonlinear time history analyses: (a) the natural wave NW; (b) the natural wave El-Centro; (c) the artificial wave AW. According to modal analysis, the structural lateral stiffness in direction X is smaller than that in direction Y. The NW, El-Centro and AW waves are inputted simultaneously in horizontal direction X (principal direction) and Y (secondary direction). Specific information of the three earthquake waves are shown in Table 4. Taking AW as an example, acceleration time history and corresponding response spectrum curves are shown in Fig. 5.

Table 4 – Earthquake waves

Earthquake waves		Component properties		Time Information	
		PGA(cm/s^2)	Directions	Intervals	Duration
AW	AW_1	100	X	0.02s	50s
	AW_2	100	Y		
NW	NW_1	220（standardization）	X	0.02s	55s
	NW_2	220（standardization）	Y		
El-Centro	El-Centro_NS	126.4	X	0.01s	40s
	El-Centro_EW	290.8	Y		

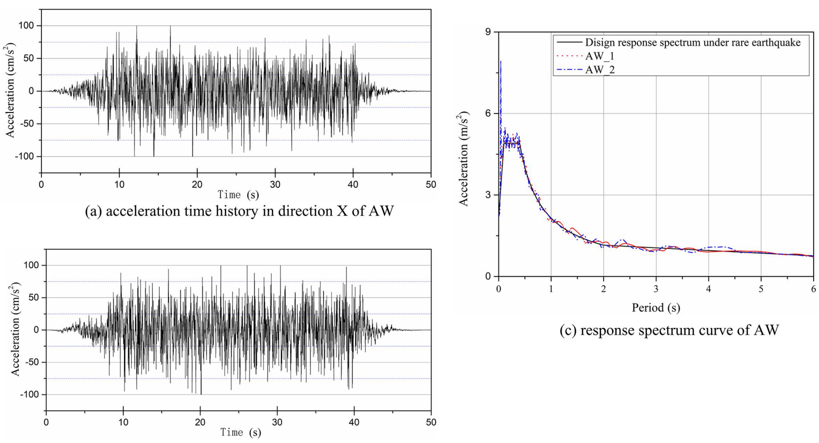


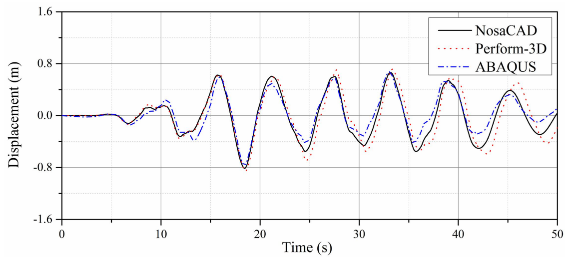
Fig. 5 – Time history and response spectrum curve of AW

3.4 Analysis results of models

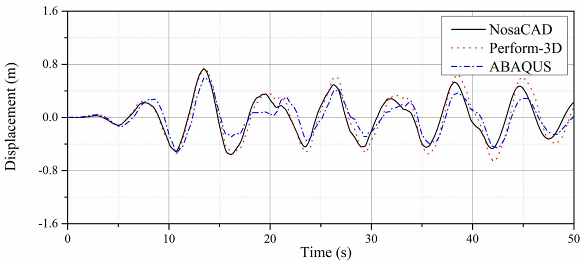
Nodes N1 and N2, located on the edge of shear wall and the corner of laminated column respectively, are chosen to explore the seismic performance of the overall structure (as seen in Fig. 1). Roof displacement of N1 and N2, story displacement and interstory drift of the string of nodes along vertical direction at N1 (SN1s) are discussed.

3.4.1 Roof displacement

By analyzing the roof displacement of nodes N1 and N2 under rare earthquakes of AW, NW, and El-Centro, it is concluded that all the structures come into nonlinear state, resulting in longer vibration period. The results show the simulating data in NosaCAD and Perform-3D are nearly the same, while in ABAQUS is a little bit different from NosaCAD and Perform-3D. In the same software, maximum values of roof displacement under AW and NW are bigger than that under El-Centro. Roof displacement of node N1 under AW of rare intensity is shown in Fig. 6. Roof displacement of node N2 under El-Centro of rare intensity is shown in Fig. 7.

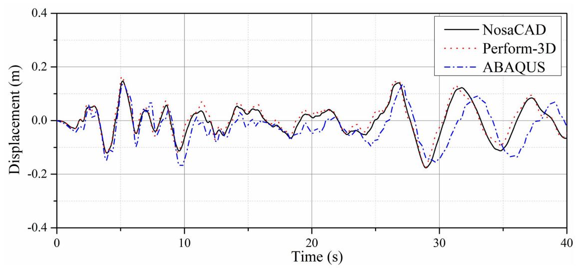


(a) displacement time history in direction X

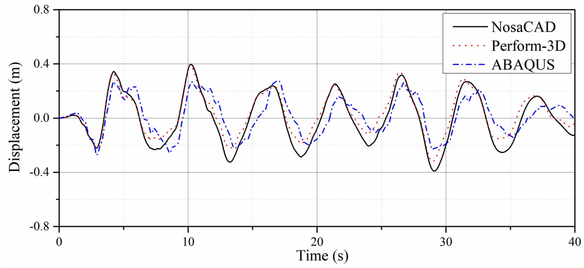


(b) displacement time history in direction Y

Fig. 6 – Roof displacement of node N1 under AW



(a) displacement time history in direction X



(b) displacement time history in direction Y

Fig. 7 – Roof displacement of node N2 under El-Centro

3.4.2 Story displacement

The SN1s are chosen to investigate the structural deformation. Taking AW as an example, Fig. 8 shows the story displacement envelopes of SN1 under rare intensity. By analyzing the story displacement envelopes under rare earthquakes of AW, NW and El-Centro, it is found that there is no obvious weak story in the structure. The lateral story displacement curves in NosaCAD and Perform-3D are nearly identical, while in ABAQUS is a little bit different from the others. In direction X, the average story displacement in NosaCAD, Perform-3D, and ABAQUS is respectively 500.53mm, 494.02mm and 515.06mm, and the maximum deviation rate is 4.08%. In direction Y, the average story displacement is 658.05mm, 640.28mm, 552.62mm, respectively, and the maximum deviation rate is 16.02%.

3.4.3 Interstory drift

Interstory drift envelopes of SN1s under three earthquake waves AW, NW and EI-Centro are analyzed. In direction X, the maximum interstory drift in NosaCAD, Perform-3D, and ABAQUS is 1/185, 1/162 and 1/173 respectively, which all appeares under wave AW. In direction Y, the maximum interstory drift in NosaCAD, Perform-3D, and ABAQUS is 1/195, 1/204 and 1/197, respectively, which all appearesunder wave NW. The interstory drift of numerical analyses in the three software programs all is less than 1/100 that is required in the code. In general, in the same software, the interstory drift under wave AW and NW is bigger than that under wave El-Centro. The interstory drift envelopes of SN1 under El-Centro of rare intensity is shown in Fig. 9.

The trends of envelope curves in the three software programs are nearly the same, but there is a little difference among numerical values, which in Perform-3D show an agreement with those in NosaCAD, and in ABAQUS are quite not the same. For the three software programs, the maximum interstory drift exists in the same story and has little difference. The maximum rate of deviation is 12.43% in direction X, and 4.41% in direction Y.

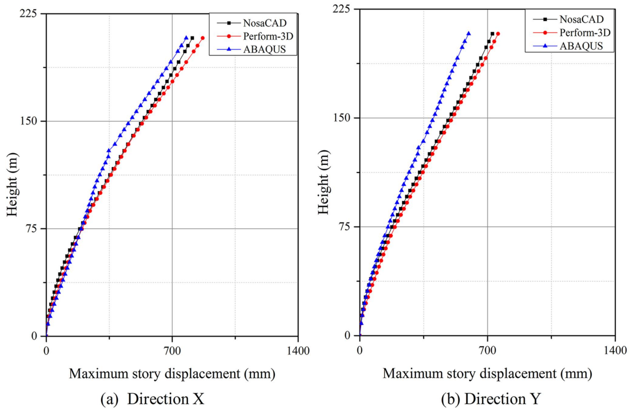


Fig. 8 – Story displacement envelopes of SN1 under AW

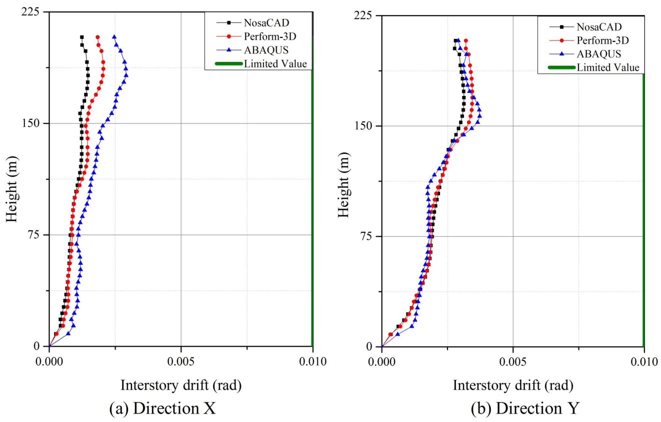
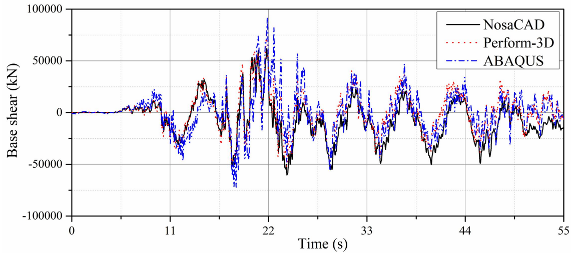


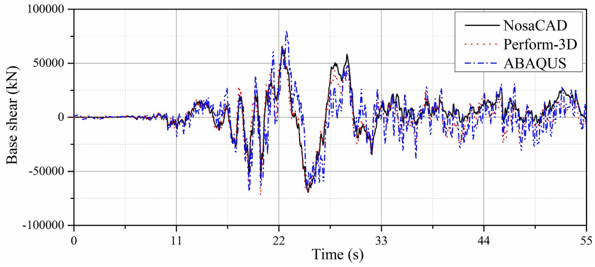
Fig. 9 – Interstory drift envelopes of SN1 under El-Centro of rare intensity

3.4.4 Base shear

The time history curves of base shear under three rare earthquakes are analyzed. The trends of time history curves in the three software programs are nearly the same, except for numerical values showing a little difference. In direction X, the maximum base shear in NosaCAD and Perorm-3D exists under earthquake wave AW, while in ABAQUS, the maximum base shear exists under earthquake wave NW. In direction Y, the maximum base shear in the three software programs all exists under earthquake wave AW. In direction X, maximum base shear is 7.56×104, 8.95×104 and 9.18×104 kN, respectively, and the maximum rate of deviation was 17.65%. In direction Y, maximum base shear is 7.18×104, 8.09×104 and 7.66×104 kN, respectively, and the maximum rate of deviation is 11.25%. In addition, in the same software, maximum base shear under waves AW and NW is bigger than that under wave EI-Centro. The time history curves of base shear under NW of rare intensity is shown in Fig. 10.



(a) time history curve of base shear in direction X



(b) time history curve of base shear in direction Y

Fig. 10 – Time history curves of base shear under NW of rare intensity

3.4.5 Damage patterns

Under earthquake waves of rare intensity, the structural damage caused by AW is the most severe, then is NW and El-Centro is the last one. As a result, the structural response under AW is used to illustrate structural damage in NosaCAD, Perform-3D and ABAQUS.

1. Damage in NosaCAD

Fig. 11(a), 11(b) and 11(c) show the damage patterns of shear walls, laminated columns and beams of the global structure. Fig. 11(d) and 11(e) show the damage patterns of shear walls, coupling beams, and frame beams of the second floor structure. As can be seen from Fig. 11(a), (b) and (c), cracks occur in most shear walls, damage mainly appears at the corner of core tube, and concrete in seldom shear walls is crushed. Only tensile cracks exist in laminated columns, which have no plastic hinges. Plastic hinges appear in several frame beams that located in bottom or middle floors. Most coupling beams come into plastic state, and concrete is crushed in parts of coupling beams which reach the ultimate state, attributing to the stiffness of the overall structure is decreased and the earthquake action is weakened. In the second floor structure, Fig. 11(d) and 11(e) show that only tensile cracks appear in shear walls and frame beams. More than half of coupling beams come into plastic state, including two beams reaching ultimate state, showing seismic energy is dissipated well.

Considering the destruction process of global structure, firstly, plastic hinges appear in coupling beams. Secondly, plastic hinges appear in frame beams connecting laminated columns and core tube. Lastly, concrete of seldom shear walls in the bottom floor are crushed. Basically, the vertical load-bearing capacity of global structure is unaffected, because the laminated columns and core tube only have tensile cracks, with little damage, except for seldom shear walls in the bottom floor reaching ultimate state.

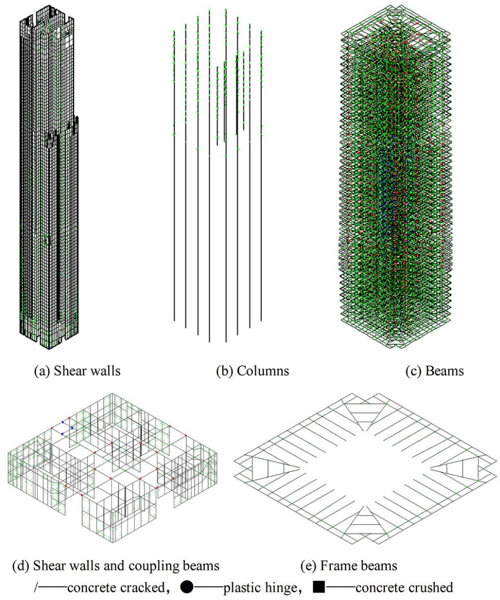


Fig. 11 – Damage patterns under rare earthquakes (NosaCAD)

2. Damage in Perform-3D

Fig. 12- Fig. 14 show the damage patterns of different components under earthquake wave AW in Perform-3D. Plastic development of coupling beams can be seen from Fig. 12. Under rare intensity earthquakes, plastic hinges appear in most coupling beams, and several coupling beams located in the middle and top floors reach their ultimate state. Fig. 13 shows the damage patterns of frame beams. Rebars in most frame beams come into yielding state, and the concrete of seldom frame beams located in the middle floor is crushed. As shown in Fig. 14, the concrete in few shear walls located at the bottom of core tube is crushed, and there is little damage in laminated columns, which have no plastic hinge and crushed concrete. In addition, there is still long time for laminated columns coming into yielding state.

Considering the destruction process of global structure, the plastic hinges appear in coupling beams firstly, appear on the edge of frame beams secondly, and appear in the concrete of shear walls lastly.

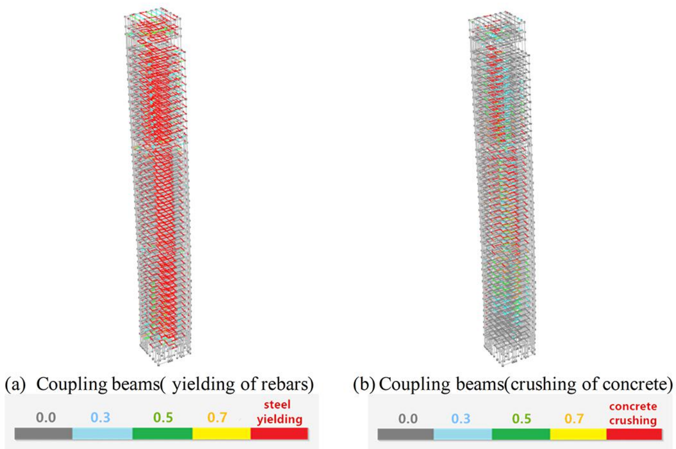


Fig. 12 – Damage patterns of coupling beams under rare earthquakes (Perform-3D)

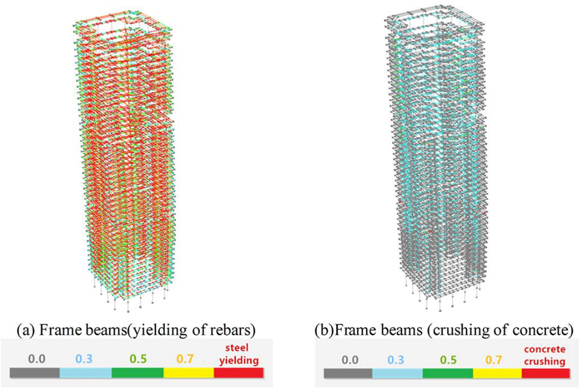


Fig. 13 – Damage patterns of frame beams under rare earthquakes (Perform-3D)

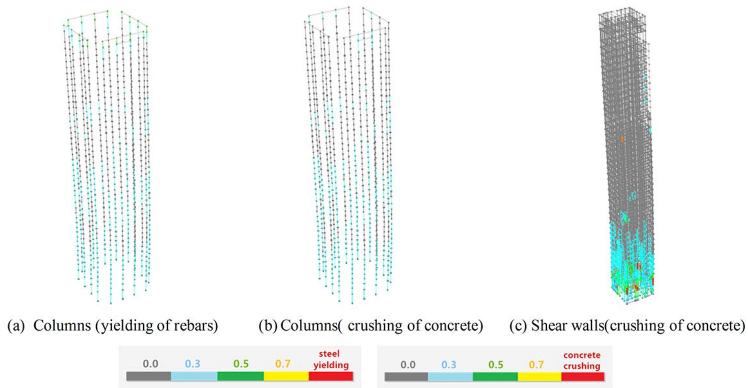
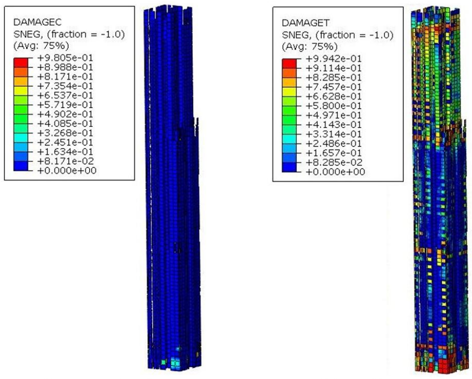


Fig. 14 – Damage patterns of vertical load-bearing members under rare earthquakes (Perform-3D)

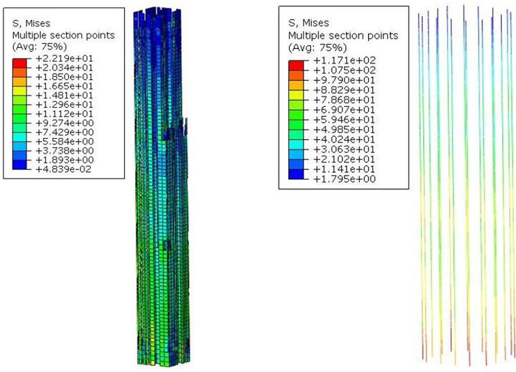
3. Damage in ABAQUS

Fig. 15(a) and 15(b) show the damage of core walls in ABAQUS. Fig. 16(a) and 16(b), respectively, show the Mises stress of rebars in shear walls and steel tubes in laminated columns. The following can be concluded from Fig. 15. For the shear walls in core tube, the maximum compressive damage factor and maximum tensile damage factor, respectively, is 0.9805 and 0.9942, and both compressive damage and tensile damage occur at the bottom of structure. Concrete is brittle material whose tensile strength is much lower than compressive strength, resulting in the tensile damage is more likely to occur, and the area of tensile damage is bigger than that of compressive damage. Basically, the compressive damage of core tube is slight, existing at the bottom of the structure. While the bottom, middle and top floors of core tube have different degrees of tensile damage, and the damage in the bottom and top floors is greater than that in the middle floors. As shown in Fig. 16, the rebars in shear walls and the steel tubes in laminated columns both not come into yielding state. The maximum stress of rebars in shear walls is 22.19MPa and the maximum stress of steel tubes in laminated columns is 117.1 MPa that both values are much smaller than the yielding stress.



(a) Compressive damage (b) Tensile damage

Fig. 15 – Damage patterns of concrete in the shear walls under rare earthquakes (ABAQUS)



(a) rebars in shear walls (b) steel tubes in laminated columns

Fig. 16 – Mises stress under rare earthquakes (ABAQUS)

4. Conclusions

Aiming at the super high-rise office building of CCCC South Regional Headquarter(zone A), nonlinear analysis is conducted to obtain seismic behaviors by establishing three finite element models in NosaCAD, Perform-3D and ABAQUS, respectively, which can verify the correctness of results each other. Conclusions are summarized as follows:

(1) In the three models, the sequences of vibration modes are identical, the natural vibration periods are uniform, and the masses of models are similar.

(2) Generally, the numerical results of the three FEMs meet well. Although numerical values in ABAQUS is a little different form those in NosaCAD and Perform-3D, the trends of envelope curves of roof displacement, story displacement, interstory drift and base shear are nearly the same in the three software programs. This means the analysis results are credible.

(3) Under rare earthquake, the interstory drift of numerical analyses in the three software programs all can meet the limitation stipulated in Chinese Design Codes. The structural destruction process can meet the seismic designing principles of “strong column and weak beam” well. The seismic energy mainly dissipated through coupling beams and frame beams, and the damage of vertical load-bearing components is slight. Therefore, the structure meets the requirement stipulated in Chinese Design Codes of “no collapse under rare earthquake”.

(4) Under rare earthquake, the reinforcement and steel tubes in ring beams, frame beams and laminated columns keep elastic all the time, while the concrete shows different degrees of compressive

damage, which is not severe. And the damage of ring beams is relatively small that does not affect its performance. The damage is most severe at the bottom of the structure, where should be reinforced.

5. References

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