THE USE OF NONLINEAR STATIC AND DYNAMIC METHODS IN HIGH-RISE BUILDINGS UNDER RARE EARTHQUAKE

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ABSTRACT : This paper discussed the use of nonlinear static and dynamic methods in high-rise buildings under rare earthquake in China these years. These nonlinear static and dynamic analysis methods were based on the independency software PUSH&EPDA of PKPM serial structure design software. This paper gave out the main methods and processes of nonlinear static and dynamic analysis, such as the steel and concrete stress-strain model in structure components, finite element models of beam, column, brace and concrete shear wall, the processes of nonlinear static and dynamic methods in EPDA software. Some analysis examples of test model and high-rise building using the nonlinear static and dynamic methods are gave out. This paper discussed how to use the nonlinear static and dynamic methods in engineering applications, what can the numerical simulation tell us under rare earthquake and how to improve the design of buildings based on the nonlinear static and dynamic analysis.

KEYWORDS : nonlinear static analysis, nonlinear dynamic analysis, high-rise buildings, rare earthquake

1. Introduction

In Wenchuan earthquake on May 12, 2008, many lives and belongings are lost, include many young students. This earthquake told us, that the last and the most important responsibility of building structures is ‘not collapse in rare earthquake’. The most direct method to get the performance of building structures is to do nonlinear static or dynamic analysis of structures. Though there are many parts need more deeply research, the harvest in this field can give us many useful and satisfying results based on nonlinear static or dynamic analysis of building stuctures.

This paper discussed some methods in nonlinear static or dynamic analysis such as stress-stain model , nonlinear finite element of beam, column, brace and shear wall. These models and methods had been used in the software PUSH&EPDA, the nonlinear static and dynamic analysis program in the serial software PKPM.

2. Stress-Strain Model of Steel and Concrete

The material stress-strain model is very important in nonlinear static and dynamic analysis, include the stress-strain model of concrete and steel, and how to use this models in beam,

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column, brace and shear wall elements.

In this paper, we use 2-line cycled stress-strain model in steel material, shown in Fig.1. Use Saenz Curve and 3-line cycled stress-strain model in concrete material, shown in Fig. 2.

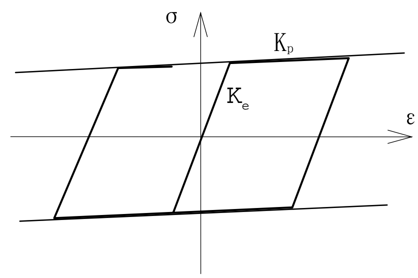


Fig.1 Stress-Strain Model of Steel

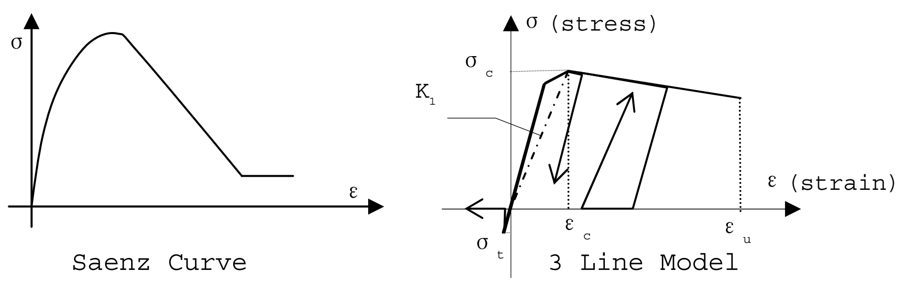


Fig. 2. Stress-Strain Model of Concrete

In the nonlinear fiber finite element of beam, column and brace, the stress-strain model can be used directly. In finite element of shell wall, this paper is based on nonlinear shell element, the main rebar in shear wall can use the material model directly, the D matrix of distributed rebar is separate, so the material model can be use directly, shown in expression (1).

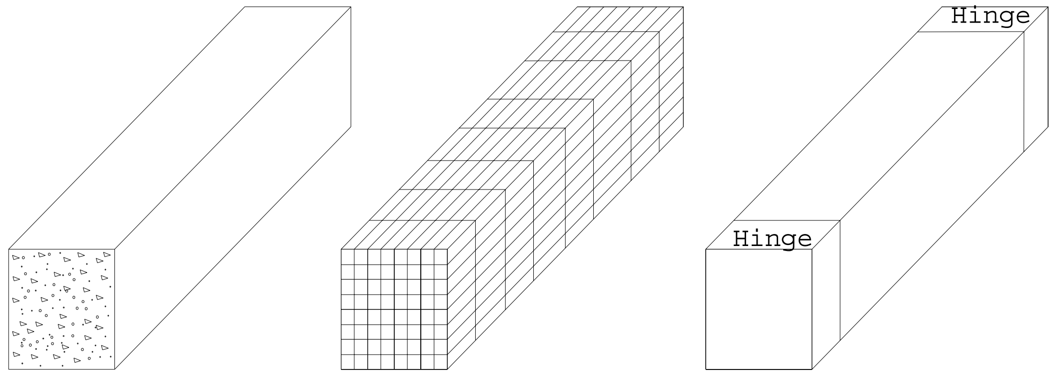
$$\begin{Bmatrix} d\sigma_x \\ d\sigma_y \\ 0 \end{Bmatrix} = \begin{bmatrix} E_x & & \\ & E_y & \\ & & 0 \end{bmatrix} \begin{Bmatrix} d\varepsilon_x \\ d\varepsilon_y \\ d\gamma_{xy} \end{Bmatrix} \tag{1}$$

Because of the complex stress-strain state, the nonlinear elastic Darwin-Pecknold model were used in the concrete part of shear wall, shown in expression (2). In the main stress direction, the stress-equivalent strain model were used.

$$\begin{Bmatrix} d\sigma_1 \\ d\sigma_2 \\ d\tau_{12} \end{Bmatrix} = \frac{1}{1-\mu^2} \begin{bmatrix} E_1 & \mu\sqrt{E_1 E_2} & 0 \\ \mu\sqrt{E_1 E_2} & E_2 & 0 \\ 0 & 0 & \frac{1}{4}(E_1 + E_2 - 2\mu\sqrt{E_1 E_2}) \end{bmatrix} \begin{Bmatrix} d\varepsilon_1 \\ d\varepsilon_2 \\ d\gamma_{12} \end{Bmatrix} \tag{2}$$

3. Nonlinear 'Fiber Element' and 'Plastic Hinge Element' of Beam, Column and Brace

The most popular nonlinear finite elements of beam, column and brace are 'plastic hinge element' and 'fiber element'. This paper gave these two model, shown in Fig. 3. In 'fiber element' ,use trice Hermit function, the displacement is shown in expression (3)



Concrete Component Fiber Element Model Plastic Hinge Model

Fig. 3. Nonlinear Element Model of Beam, Column and Brace

$$\begin{cases} \Delta_x(x) = h_i(x)\delta_x^i + h_j(x)\delta_x^j \\ \Delta_y(x) = H_i^1(x)\delta_y^i + H_i^2(x)\theta_z^i + H_j^1(x)\delta_y^j + H_j^2(x)\theta_z^j \\ \Delta_z(x) = H_i^1(x)\delta_z^i - H_i^2\theta_y^i + H_j^1(x)\delta_z^j - H_j^2(x)\theta_y^j \end{cases} \tag{3}$$

If fixed in two end, the shape function is shown in expression (4).

$$\begin{cases} h_i(\mathrm{x}) = 1 - \dfrac{\mathrm{x}}{\ell}, & h_j(\mathrm{x}) = \dfrac{\mathrm{x}}{\ell} \\ \mathrm{H}_i^1(\mathrm{x}) = 1 - 3\left(\dfrac{\mathrm{x}}{\ell}\right)^2 + 2\left(\dfrac{\mathrm{x}}{\ell}\right)^3, & \mathrm{H}_j^1(\mathrm{x}) = 3\left(\dfrac{\mathrm{x}}{\ell}\right)^2 - 2\left(\dfrac{\mathrm{x}}{\ell}\right)^3 \\ \mathrm{H}_i^2(\mathrm{x}) = \mathrm{x}\left(1 - \dfrac{\mathrm{x}}{\ell}\right)^2, & \mathrm{H}_j^2(\mathrm{x}) = \dfrac{\mathrm{x}^2}{\ell}\left(\dfrac{\mathrm{x}}{\ell} - 1\right) \end{cases} \tag{4}$$

The 'plastic hinge element' include one elastic beam and two 'plastic hinge' at the end. The parameter of 'plastic hinge' consulted FEMA273(274).

4. Nonlinear Concrete Shear Wall Element

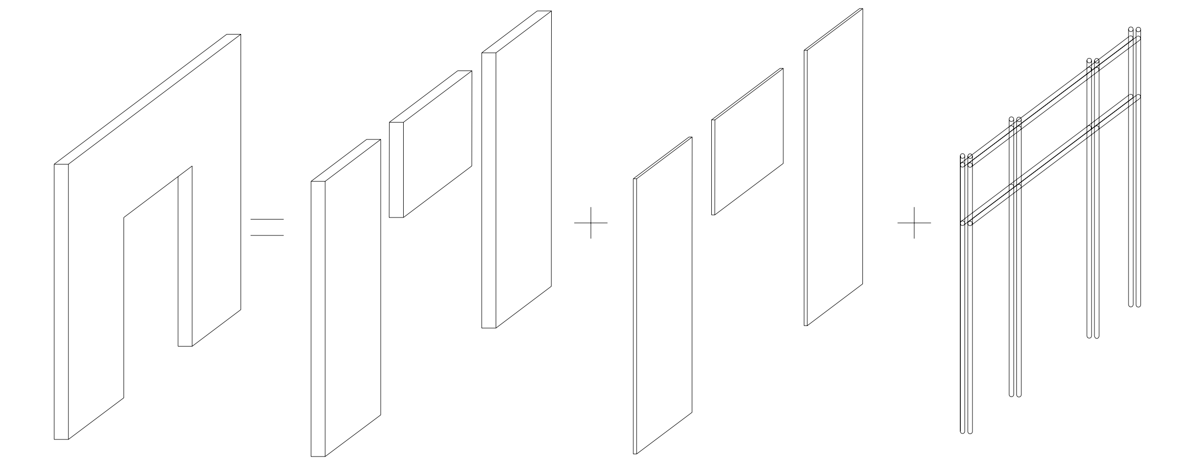
This paper gave out a 'macro-shear wall element' to Simulate reinforced shear wall. In this element, the shear wall was decomposed to concrete shell blocks, distributed rebar shell blocks, main rebar fibers, shown in Fig. 4. This shear wall element was based on Allman shell element, the shape function is shown in expression(5)~(8).

$$U = N \times \{\delta\} \tag{5}$$

$$N = \begin{bmatrix} N_1 & 0 & (N_8\delta y_4 - N_5\delta y_1) & N_2 & 0 & (N_5\delta y_1 - N_6\delta y_2) & N_3 & 0 & (N_6\delta y_2 - N_7\delta y_3) & N_4 & 0 & (N_7\delta y_3 - N_8\delta y_4) \\ 0 & N_1 & (N_5\delta x_1 - N_8\delta x_4) & 0 & N_2 & (N_6\delta x_2 - N_5\delta x_1) & 0 & N_3 & (N_7\delta x_3 - N_6\delta x_2) & 0 & N_4 & (N_8\delta x_4 - N_7\delta x_3) \end{bmatrix} \tag{6}$$

$$N_i = \frac{1}{4}(1+\xi_i\xi)(1+\eta_i\eta) \qquad (i = 1,2,3,4) \tag{7}$$

$$[N_5 \quad N_6 \quad N_7 \quad N_8] = \frac{1}{16}\left[(1-\xi^2)(1-\eta), (1+\xi)(1-\eta^2), (1-\xi^2)(1+\eta), (1-\xi)(1-\eta^2)\right] \tag{8}$$



Concrete Shear Wall Concrete Shell Distributed Rebar Shell Main Rebar Shell

Fig. 4. Nonlinear Element Model of Concrete Shear Wall

The research object of this 'macro-shear wall element' was the shear wall with hole, so this paper gave some methods to deal with it. This paper use 'block integral' shown in expression (9), and reduce shell stiffness shown in Fig. 5, expression (10)

$$\begin{cases} [K_e] = t\sum_{i=1}^{n}\int_{-1}^{1}\int_{-1}^{1}[B]^T([D_h]+[D_s])[B]J|d\xi d\eta \\ \{dF_e\} = t\sum_{i=1}^{n}\int_{-1}^{1}\int_{-1}^{1}[B]^T(\{d\sigma_h\}+\{d\sigma_s\})|J|d\xi d\eta \end{cases} \tag{9}$$

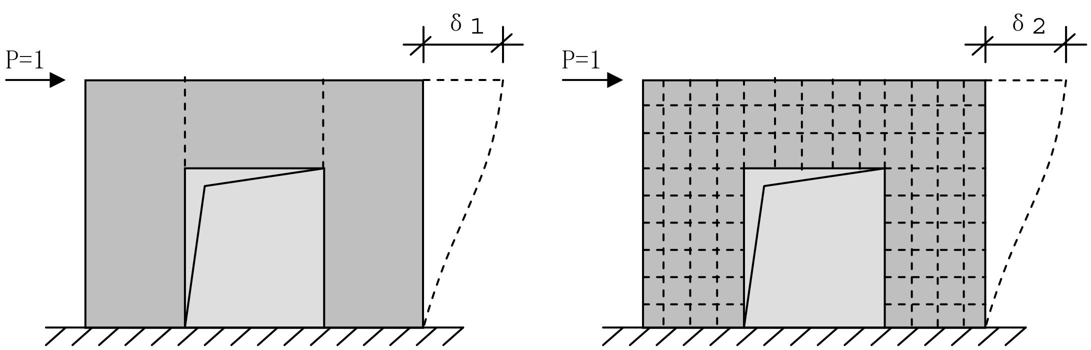


Fig. 5. Shear Wall Stiffness Reduce

Shear wall stiffness reduce factor：

$$\xi = \frac{K_2}{K_1} = \frac{1/\delta_2}{1/\delta_1} = \frac{\delta_1}{\delta_2} \tag{10}$$

The main rebar in shear wall is integrated directly to the whole shear wall element shown in Fig. 6 and expression(11).

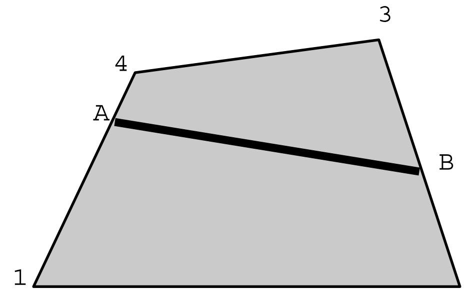


Fig. 5.   Shear Wall Stiffness Reduce

Main rebar stiffness:

$$[K_s]=\frac{EA}{L}\begin{bmatrix} c^2 & cs & -c^2 & -cs \\ cs & s^2 & -cs & -s^2 \\ -c^2 & -cs & c^2 & cs \\ -cs & -s^2 & cs & s^2 \end{bmatrix} \tag{11}$$

$$c=\cos\theta \quad s=\sin\theta \tag{12}$$

If some nodes in shear wall element was not harmonized, this paper gave a method to deal with the transition matrix of shear wall element shown in Fig. 6 and expression (13).

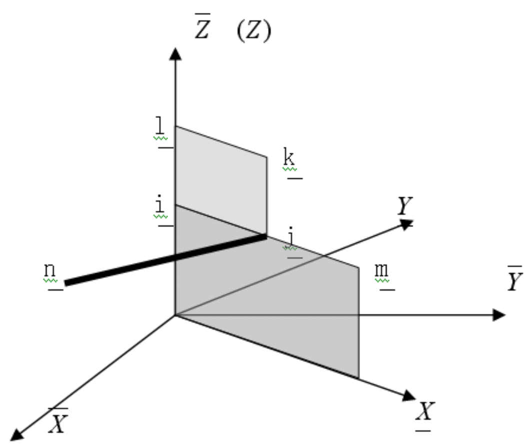


Fig. 6.   Shear Wall Stiffness Reduce

$$\{\delta_j\}=[H_a]\{\delta_i\}+[H_b]\{\delta_m\} \tag{13}$$

5.   Test Examples

The theories and methods in this paper were realized in software PUSH&EPDA. We have done many test examples with ANSYS, ABAQUS, SAP2000 from frame structures to shear wall structures, This paper gave some result of them.

The first example is a 9 layers steel frame. This example test the nonlinear alternate program, the cycled stress-strain model of steel material, nonlinear fiber beam element, nonlinear dynamic and static processes. The structure model is shown in Fig.7, the static and dynamic results of PUSH&EPDA with ABAQUS is shown in Fig. 8, 9.

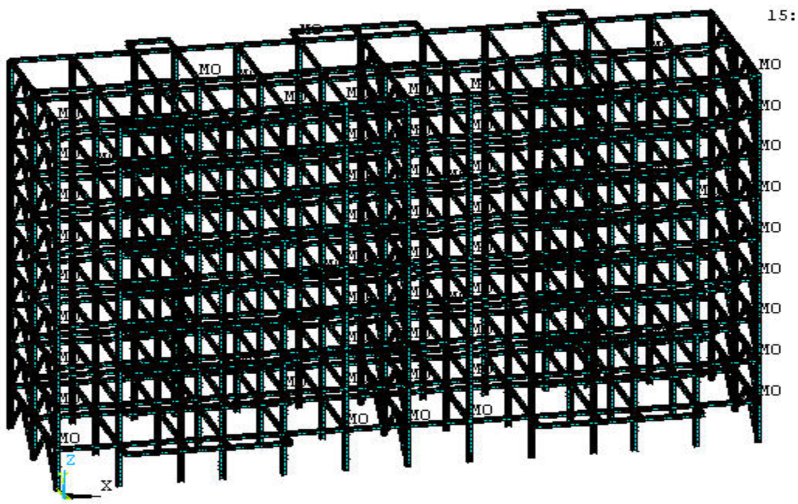


Fig. 7. 9 layers steel frame model

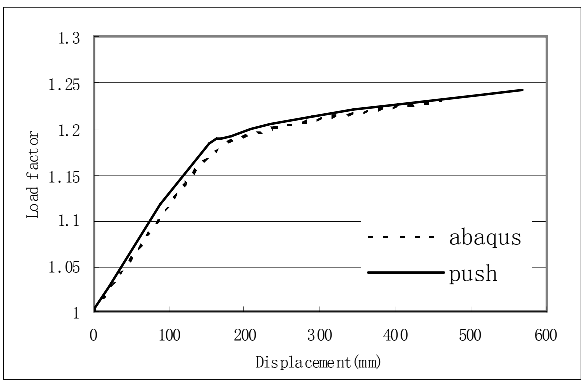


Fig. 8. Nonlinear static result

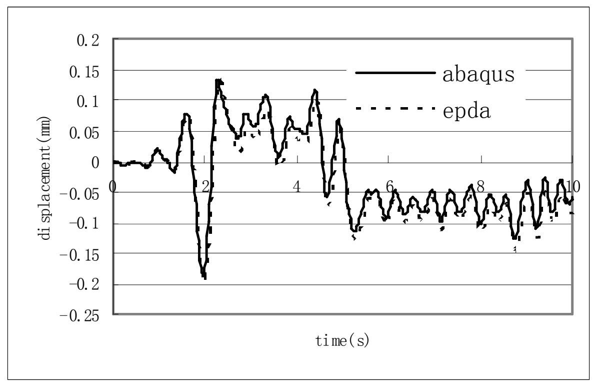


Fig. 9. Nonlinear dynamic result

The second example is a 10 layers concrete shear wall structure. The displacement time history is shown in Fig. 10, the plastic region of ABAQUS and EPDA is shown in Fig. 11.

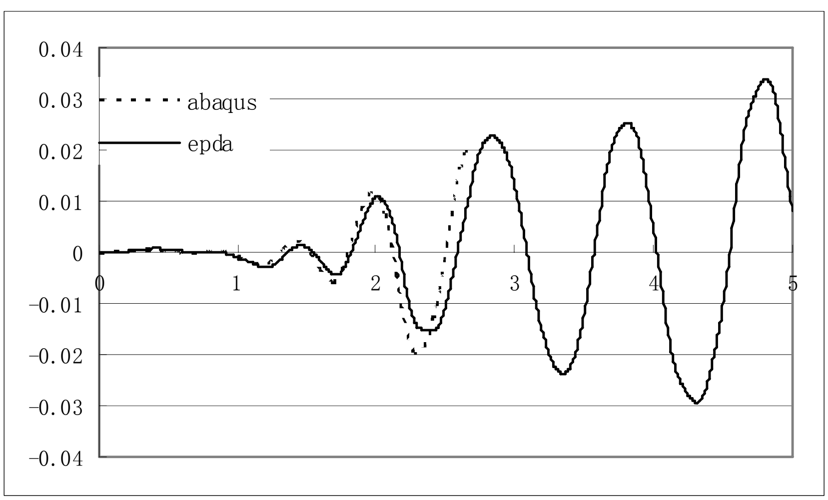


Fig. 10. Displacement time history of 10 layer concrete shear wall

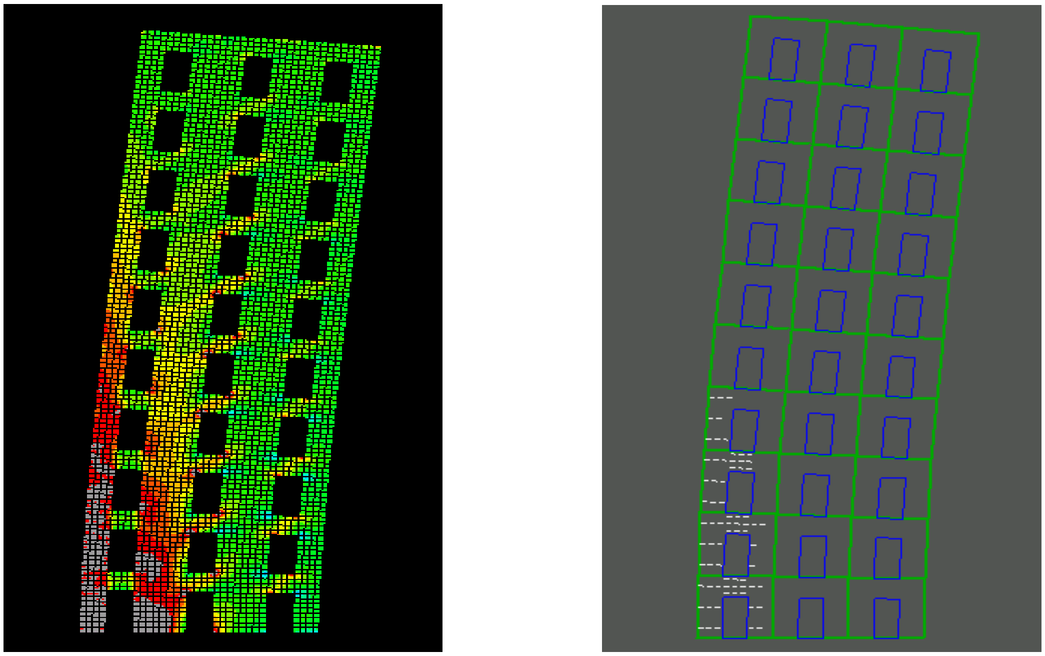


Fig. 11. Plastic region of ABAQUS and EPDA

6. Building Structures using Nonlinear Static and Dynamic Method

More than 100 high-rise buildings of China had been analysis with PUSH&EPDA software using nonlinear static and dynamic methods from year 2004. The following structures are some of them.

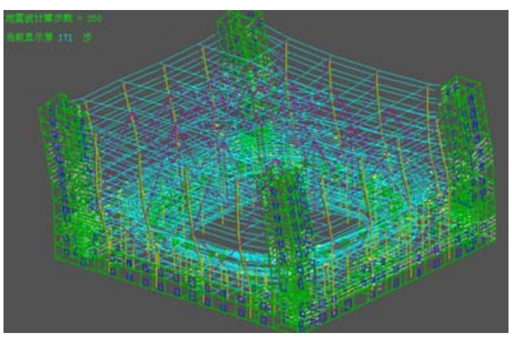


Fig.12 Beijing Olympic Basketball Gymnasium

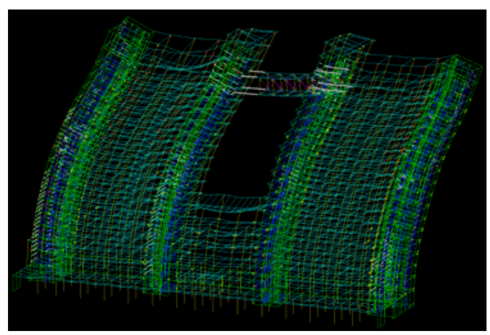


Fig. 13 Building with Isolators in corridor

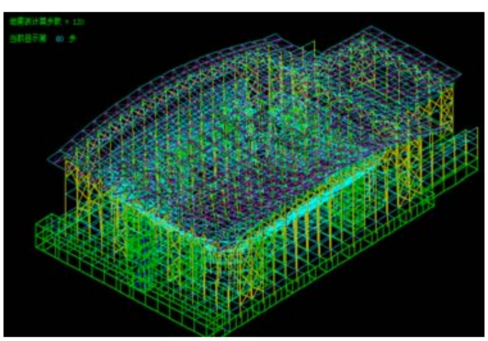


Fig.14 Beijing Olympic National Indoor Stadium

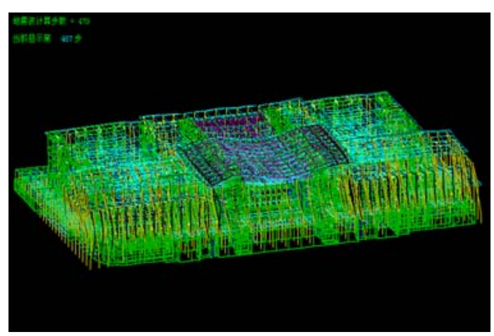


Fig.15 National Museum of China

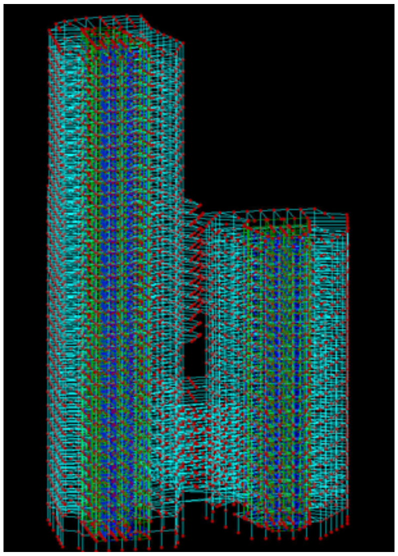


Fig.16 Two tower building

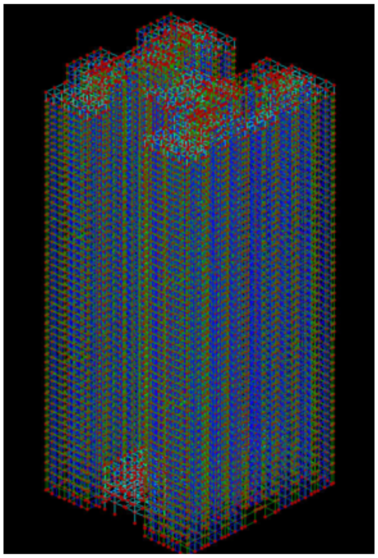


Fig.17 64 layers Large Volume building

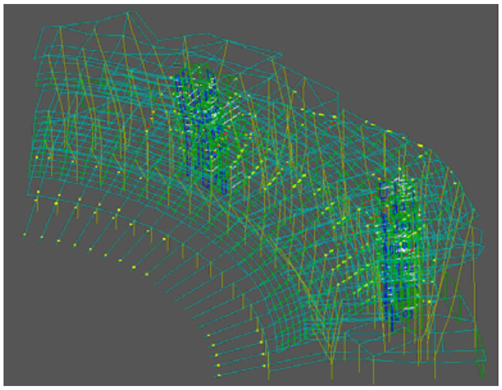


Fig.18 Stand of Beijing Olympic ‘Bird Nest’

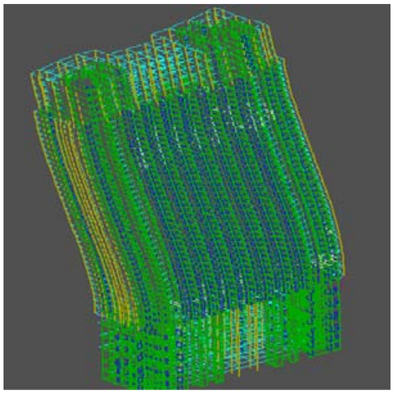


Fig.19 100,000 DOF shear wall building

7. Conclusions

This paper gave out some methods and examples of nonlinear static and dynamic analysis, the most important thing to do these analysis in high-rise buildings is to get balance between veracity and efficiency. From the analysis of test models and high-rise buildings, we can see the nonlinear static and dynamic analysis is seething in China.

8. References

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[2] Technical specification for concrete structures of tall building, JGJ 3-2002, 2002, Beijing.

[3] User Guide of ElastoPlastic Static and Dynamic Analysis Software PUSH&EPDA, Institute of Building Engineering Software, China Academy of Building Research, 2008, Beijing.