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SIMULATION OF STRUCTURAL NONLINEAR SEISMIC RESPONSES BASED ON SIMULINK

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SUMMARY

Since the existing programs of structural nonlinear seismic analysis have shortage of capability of visualization and exploration, simulation of nonlinear seismic response for the multi-stories shear-type model and the member model based on the SIMULINK are established in the paper, the results of two examples show that the simulation of structural nonlinear seismic responses based on SIMULINK is available and reliable.

INTRODUCTION

As the main method of analysis of structural nonlinear seismic responses, time-history analysis has been applied for many years. A lot of effort has been made by the researchers to correct and improve the method, that is, to improve the accuracy and strengthen the manipulation. But, the serious deficiencies of the present time history analysis program, such as visible operation, further development, are not concerned. Actually, such deficiencies have been the obstacles of the method on application. Even if most of engineers have adequate specialized knowledge and have been familiar with the using software, they are hard to control the calculating progress of the program and know nothing about it how to run. Even the reliability of the results is suspected by people sometimes. At the same time, in the aspects of the adjustment of structure design, structural control and so on, the structural parameter is need to be modified real-timely during the simulation of structural responses to meet presetting target. Consequently, It is very important that the visible operation and further development function is in a time history analysis program in the application of the engineering [1,2].

Dynamic system simulation software SIMULINK based on the platform of Matlab have the characteristics of strong visual function, powerful ability of further development, unimaginable ability of digital calculation and simply visualized operation [3]. Based on the dynamic system simulation software SIMULINK, the analysis method for the structural nonlinear seismic responses is proposed in this paper.

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METHOD FOR SIMULATION OF STRUCTRAL SEISMIC RESPONSES BASED ON SIMULINK

Simulation technique based on computer includes three basic elements, which are system, model and computer. The relationship among the three basic elements is shown in Fig. 1. An ordinary simulation process can be described as follow steps, (1) Mathematic model establishment, (2) Simulation model establishment, (3) test of simulation. When the simulation technique based on computer is applied to structural seismic responses analysis, the system is described using the structural dynamic parameters. The process of Simulation of structural seismic response analysis based on SIMULINK can be established based on the differential equation of motion.

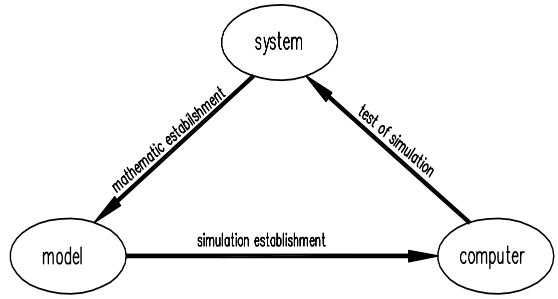


Fig.1 Three elements of simulation

Differential equation of Motion

Member model as the example, the differential equation of motion t is established based on simulation of structural nonlinear seismic responses by SIMULINK in the paper.

There are some basic assumption about the plane member model, that is, the stiffness of the floor in plane is infinitely, the mass of every member can be concentrated in the node, the horizontal displacement of every node is same, and every node has three degrees of freedom that are horizontal, vertical, and rotational [4]. The differential equation of motion under the action of horizontal seismic is shown in equation (1),

$$[M]\begin{Bmatrix}\ddot{u}\\ \ddot{v}\\ \ddot{\theta}\end{Bmatrix}+[C]\begin{Bmatrix}\dot{u}\\ \dot{v}\\ \dot{\theta}\end{Bmatrix}+[K]\begin{Bmatrix}u\\ v\\ \theta\end{Bmatrix}=-[M]\begin{Bmatrix}\ddot{u}_g\\ 0\\ 0\end{Bmatrix} \tag{1}$$

Where u , v and θ represent the horizontal displacement, the vertical displacement and the angle of rotation of the mass point respectively. $[M],[K]\, and [C]$ represent the mass matrix, stiffness matrix and damping matrix of the structure respectively. The damping model adopts the Rayleigh Assumption. $\ddot{u}_g$ represents the horizontal acceleration of the ground motion. Because the node resists only the acceleration action of the ground motion in the horizontal direction, horizontal displacement is named main displacement, and the vertical displacement and angle of rotation are named vice displacement. In this way, node freedom is divided into main freedom vector $\{\delta\}_r$ and vice freedom vector $\{\delta\}_s$. The differential equation of motion is shown as,

$$\begin{bmatrix}[M]_r & 0\\ 0 & [M]_s\end{bmatrix}\begin{Bmatrix}\{\ddot{\delta}\}_r\\ \{\ddot{\delta}\}_s\end{Bmatrix}+\begin{bmatrix}[C]_{rr} & [C]_{rs}\\ [C]_{sr} & [C]_{ss}\end{bmatrix}\begin{Bmatrix}\{\dot{\delta}\}_r\\ \{\dot{\delta}\}_s\end{Bmatrix}+\begin{bmatrix}[K]_{rr} & [K]_{rs}\\ [K]_{sr} & [K]_{ss}\end{bmatrix}\begin{Bmatrix}\{\delta\}_r\\ \{\delta\}_s\end{Bmatrix}=\begin{bmatrix}[M]_r & 0\\ 0 & [M]_s\end{bmatrix}\begin{Bmatrix}\{\ddot{u}_g\}\\ 0\end{Bmatrix} \tag{2}$$

Neglecting the inertia force and damping force in the vice displacement direction, and assuming $[M]_s = 0, [C]_{sr} = [C]_{rs} = 0$. And then, the equation (2) can be written as,

$$[M]_r\{\ddot{\delta}\}_r+[C]_{rr}\{\dot{\delta}\}_r+[K]_{rr}\{\delta\}_r+[K]_{rs}\{\delta\}_s=-[M][I]\ddot{u}_g \tag{3}$$

$$[K]_{sr}\{\delta\}_r+[K]_{ss}\{\delta\}_s=\{0\} \tag{4}$$

Combine the equation (3) and (4),

$$[M]_r\{\ddot{\delta}\}_r+[C]_{rr}\{\dot{\delta}\}_r+[K^*]\{\delta\}_s=-[M][I]\ddot{u}_g \tag{5}$$

Where,

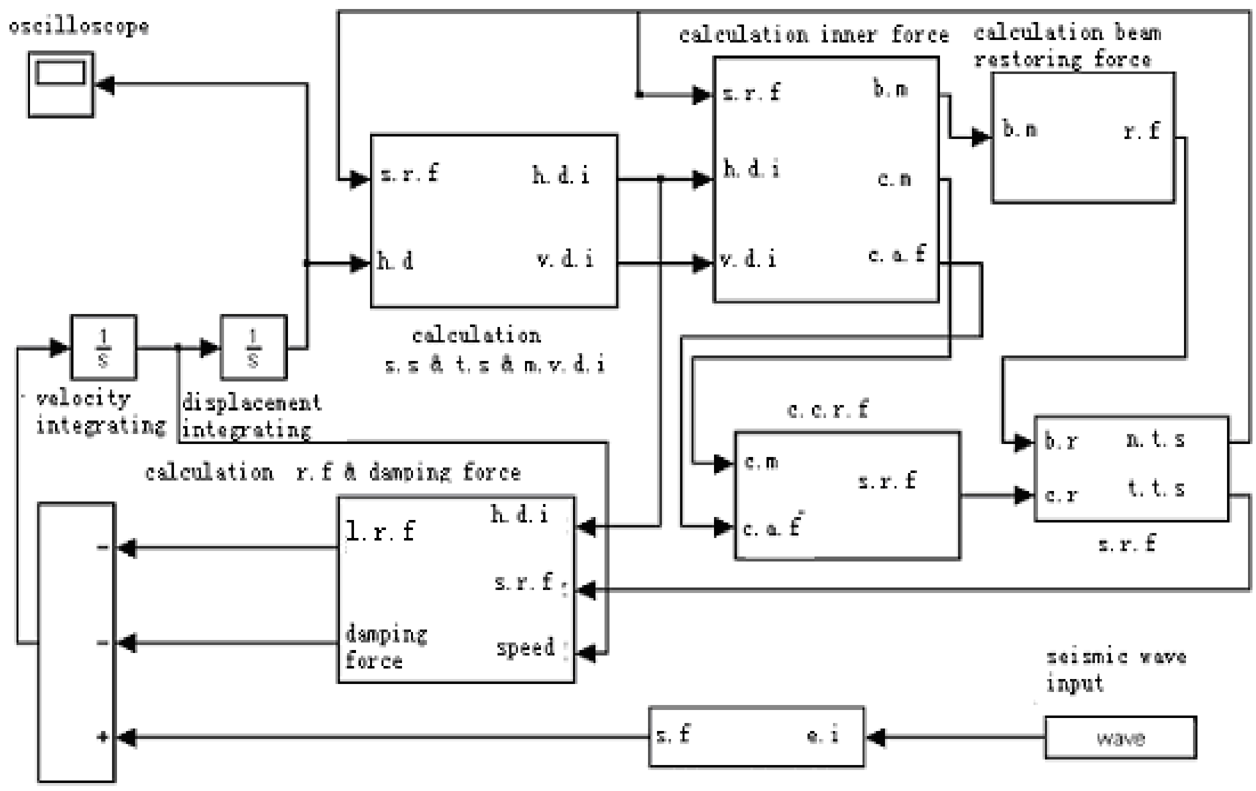
$$\left[K^*\right] = \left[K\right]_{rr} - \left[K\right]_{rs}\left[K\right]_{ss}^{-1}\left[K\right]_{sr} \quad (6)$$

$\left[K^*\right]$ is called equivalent stiffness matrix of lateral resistance, it reflects the displacement effect under horizon, bending and vertical action.

Two kinds of common used hysteretic model of structural member, non-degenerated two-line-type and degenerated three-line-type, are employed in this paper. Hereinto, the single component model is selected for the unit mechanic model of the plane member model [5]. Assuming that any nonlinear deformation of the member concentrated in the region where the member length is zero, using the feature that two equivalent elastic-plastic rotational spring in the rod ending to simulate elastic-plasticity of the member, the middle of the member is idealized into member element that has elastic deformation only and has no mass. In the course of simulation of structural nonlinear responses, the modification of unit stiffness matrix is embodied by the stiffness reduction factor that changes independently in the two ends of the member.

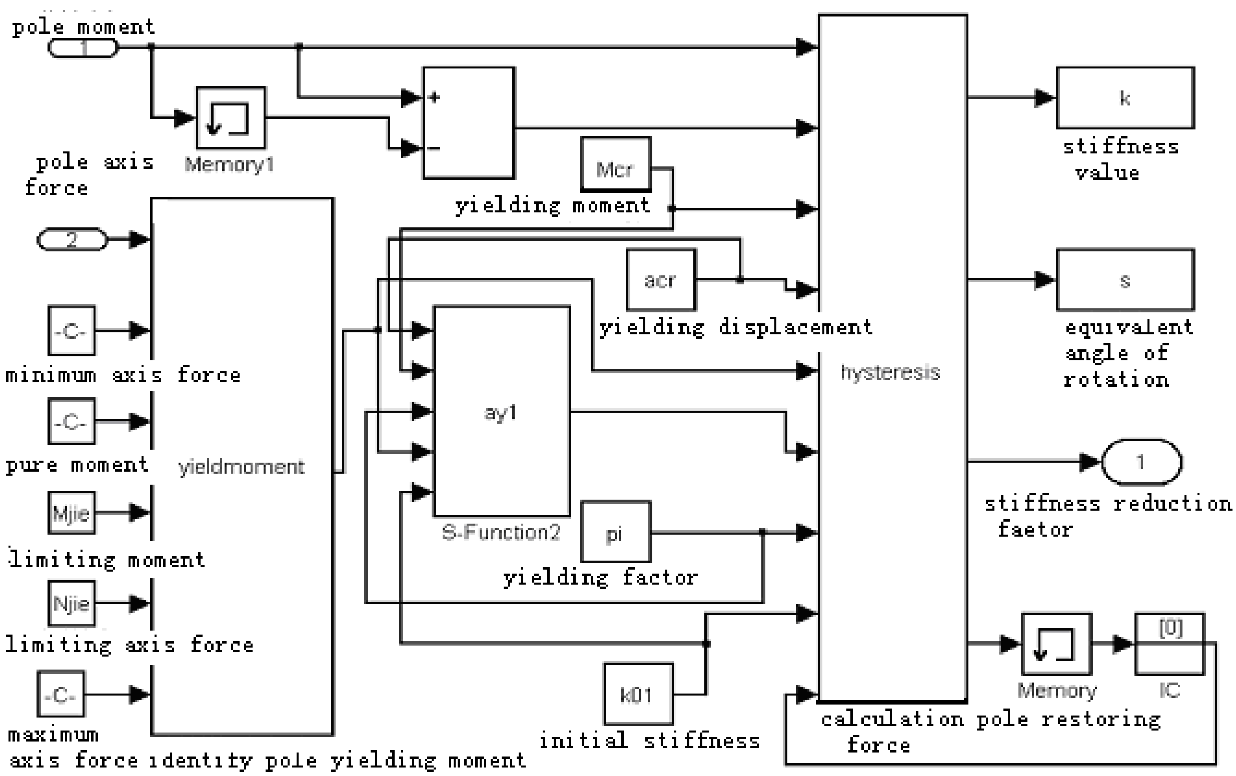
Modeling of the structural system

Regarded the plane member model as an example, the schemes of main system based on SIMULINK for dynamic simulation (calculate the horizontal displacement and acceleration of the structure), subsystem for hysteretic force and subsystem for damping force are given in Fig.2.

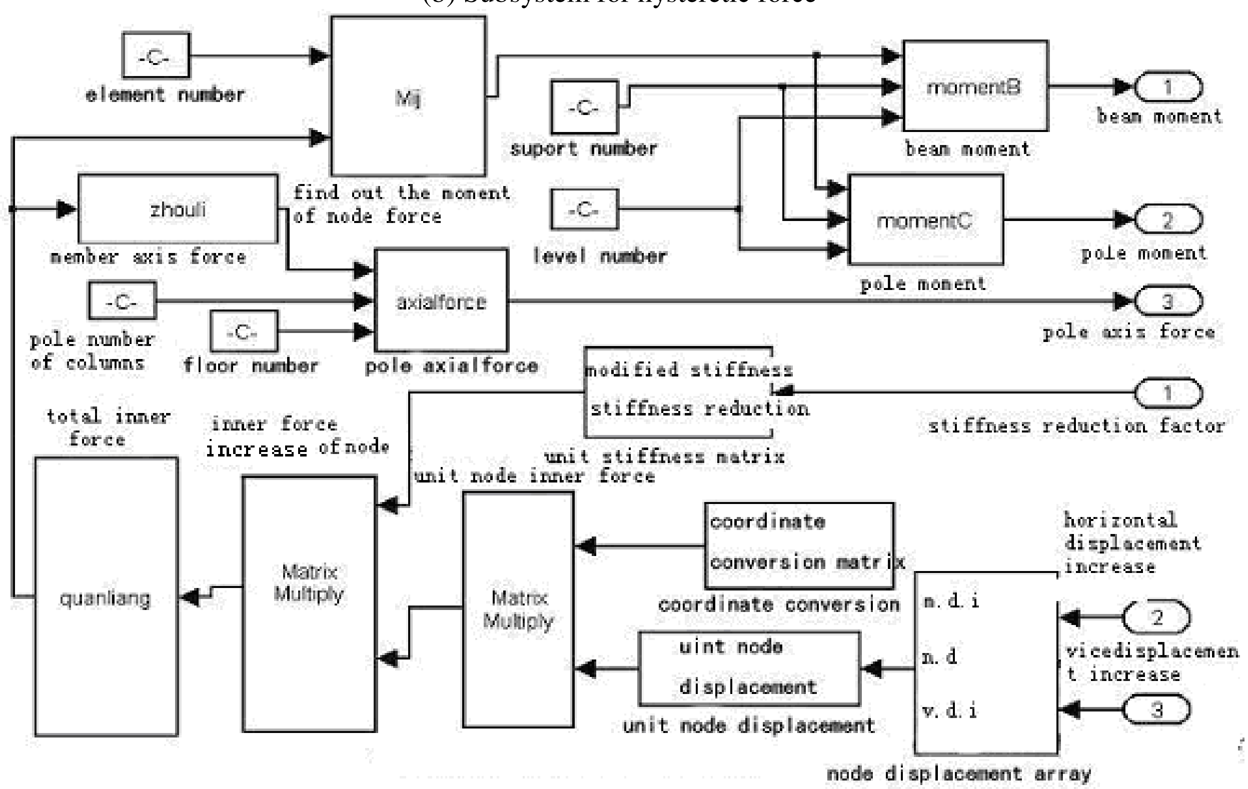


(a) Main system

Note: s.f---seismic force, e.i---earthquake input, s.s---element stiffness, t.s---total stiffness, m.v.d.i---main vice displacement increment, h.d---horizontal displacement, v.d.i---vice displacement increment, l.r.f---lateral resistant force, h.d.i---horizontal displacement increment, s.r.f---stiffness reduction factor, v.d.i---vice displacement increment, b.m---beam moment, c.m---column moment, c.a.f---column axis force, r.f--- hysteretic force, c.c.r.f---calculation column hysteretic force, b.r---beam reduction, c.r---column reduction, n.t.s---next time step, t.t.s---current time step



(b) Subsystem for hysteretic force



(c) Subsystem for inner force

Note: m.d.i---main displacement increase, n.d---node displacement, v.d.i---vice displacement increase

Fig. 2 Main system and subsystem based on SIMULINK for plane member model

The performance progress of the model is, at the beginning of simulation, the original stage of the velocity integrating module and the displacement-integrating module is read by SIMULINK. At the time of zero, the instant acceleration is calculated according to the initial values of velocity and displacement, and restoring force, damping force and seismic action are calculated by subsystem. In the next time step, the velocity integrating module and displacement integrating module is called by SIMULINK firstly, then the displacement, speed and acceleration of the system is obtained by numerical integrating. The structural responses of the whole time history can be calculated by repeating above steps continuously. This process is consistent with traditional time history analysis.

Algorithm of numerical integration and hysteretic force model

The commonly used numerical integration methods applied in the existing time history analysis include linear acceleration, Newmark-β, Wilson-θ, Runge-Kutta and so on. All of the numerical integrating algorithms above-mentioned for dynamic simulation are provided by SIMULINK. Runge-Kutta has the outstanding advantage for accuracy, convergence property and stability. So, variant step size four to five order Runge-Kutta method is employed to solve the differential equation of motion in this paper.

The concept of zero crossing detection is to find out the zero crossing point of the signal. In SIMULINK, the main function of zero crossing detection is to find out the discontinuity point of system state variation [6]. The mathematic principle of Zero crossing detection is based on the zero theorem of infinitesimal calculus, that is, as to a continuous signal, there must be at least a zero point between two points if the sign of the two points is different. The yielding point, crack point and maximum displacement point are the discontinuity points of system state variation [7]. The zero-crossing detection function of SIMULINK is employed to find the boundary point in this paper [8].

ANALYSES OF TWO EXAMPLES

Multi-storey shear-type model

A reinforced concrete frame located at the Secondary Wool Spinning Factory in Tianjin is selected as a sample in this paper [9]. Its structural parameters are shown in table 1. The input earthquake wave is Tianjin Record, which is gotten from Ninghe earthquake nearby the Tianjin Hospital. Its maximum acceleration is $1.347 m/s^2$ and lasting time is 6s. The damping ratio of structure is supposed as0.05.The seismic responses are obtained by SIMULINK simulation and SAP2000, respectively. The time history displacements on 3^{rd} layer calculated by the above two methods are shown in Fig.3. The comparisons of the maximum displacement and the maximum inter-story displacement rotation are given in Table 2. The results show,

(1) The results obtained by SIMULINK simulation are compatible well with SAP2000 results. It is easy to find that the maximum relative error of displacement between SIMULINK and SAP2000 is 1.7%, and the maximum relative error of maximum inter-story displacement rotation is 4.6%.

(2) The calculation results show that yielding of bottom and rather large story draft caused the collapse of building, and the other two layers yield almost at the same time with the bottom. The calculation result is corresponding well with actual damage.

Table 1 Structural parameters of the example

Layer	Mass (kg)	Stiffness (N/m)		Yielding displacement (m)
		K1	K2	
1	91840	6870000	0	0.0373
2	93540	7412300	0	0.0228
3	84620	6563000	0	0.0142

Table 2 The maximum displacement and maximum inter-story displacement rotation

Layer	Maximum displacement (m)			Maximum inter-story displacement rotation		
	SIMULINK	SAP2000	Relative error	SIMULINK	SAP2000	Relative error
1	0.0431	0.0419	2.80%	1/115	1/119	2.86%
2	0.1160	0.1152	0.69%	1/56	1/56.5	0.28%
3	0.1487	0.1462	1.71%	1/67	1/70	4.59%

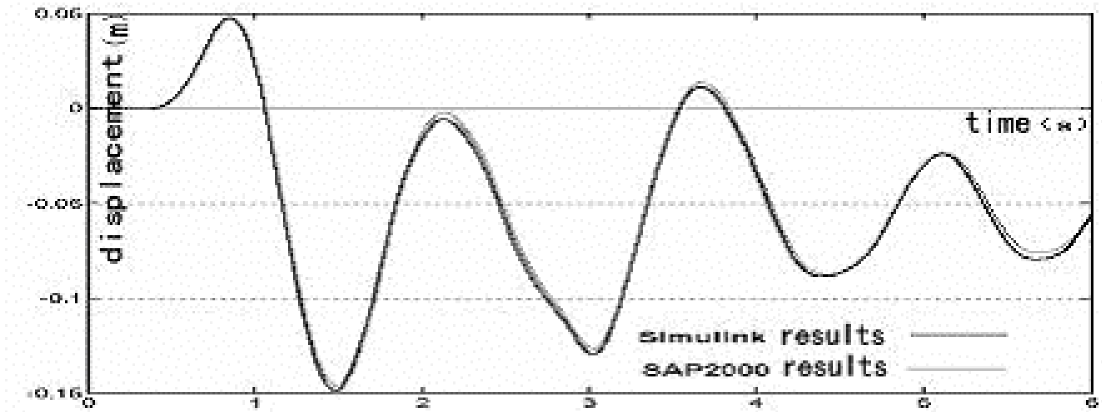


Fig. 3 Comparison between storey displacements evaluated by SIMULINK and SAP2000 for the 3rd layer

Plane member model

The model of Example analysis based on plane member model is come from documentation [4], and structural calculation sketch is shown in Fig.4. Relational parameters are, Axis compressive strength of concrete is 12N/mm^2, bending compressive strength is 13N/mm^2, Young's modular of concrete is 27kN/mm^2, the strength of secondary layer bearing bar is 310N/mm^2, stiffness reduction factor of the beam and column after yielding is 0.05, and damping ratio of the first and the second mode shape of the frame is 0.05. The distributed steel is marked in the Fig.4. Additional mass is considered as 20kN/m on the beam. EL Centro wave is selected as the input earthquake wave, and the amplitude of the maximum acceleration is adjusted to 3.969m/s^2.

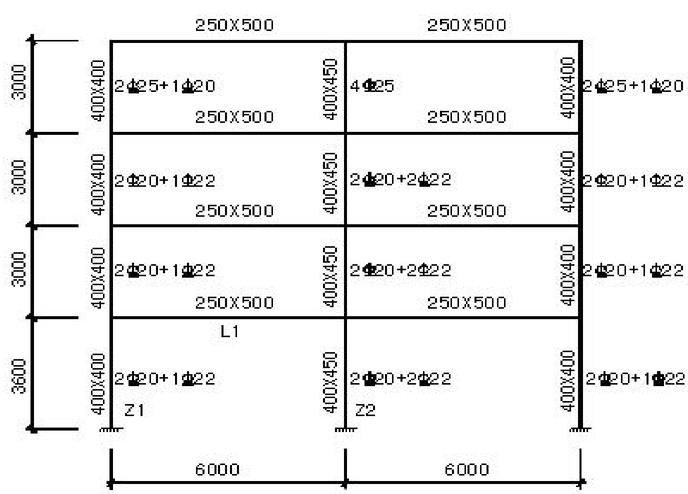


Fig.4 Sketch of structural calculation model

Note: reinforcing bars of the beams (1st and 2nd layer):
upper part:2d16+2d20, under part:3d16
reinforcing bars of the beams (3rd and 4th layer):
upper part: 4d16, under part: 3d16
yielding strength : 235MPa

The displacement time histories obtained by the SIMULINK simulation and the program PFEP are shown in Fig.5. The curve of moment to equivalent angle of the middle column in the bottom calculated by SIMULINK is shown in Fig.6. Table 3 gives the results of the structural maximum displacement and maximum inter-story displacement rotation calculated by SIMULINK simulation and PFEP, respectively.

All these show that, (1) The results of SIMULINK simulation compatible well with PFEP; (2) The maximum response of the structure occurs at the bottom, and the Maximum inter-story displacement rotation is 0.0096. The first layer is structural stiffness mutation layer (structural layer height excesses from 3.6m to 3m), which results in nonlinear elastic deforming concentration; (3) The inflection point of hysteretic model is disposed quite correctly by SIMULINK, so the results is ensured the adequate accuracy.

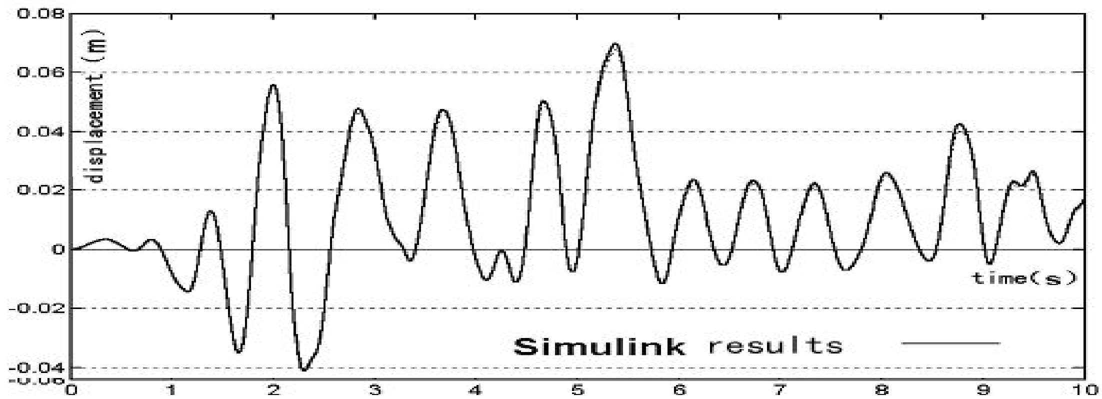


Fig.5 Comparison between storey displacements evaluated by SIMULINK and PEEP for the displacement time history

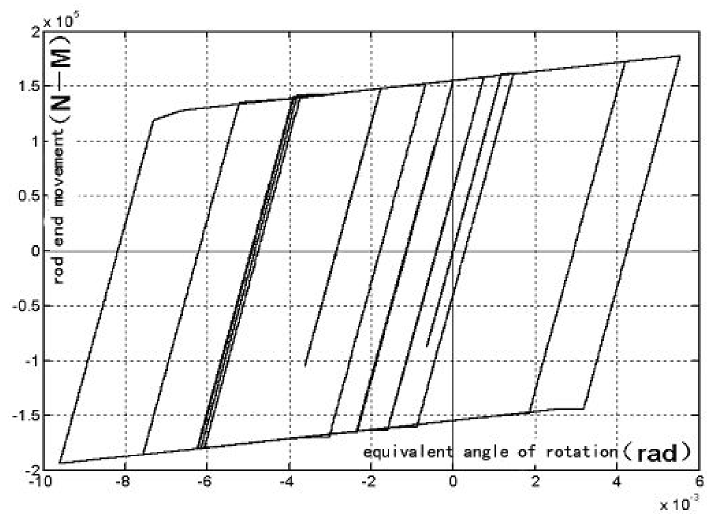
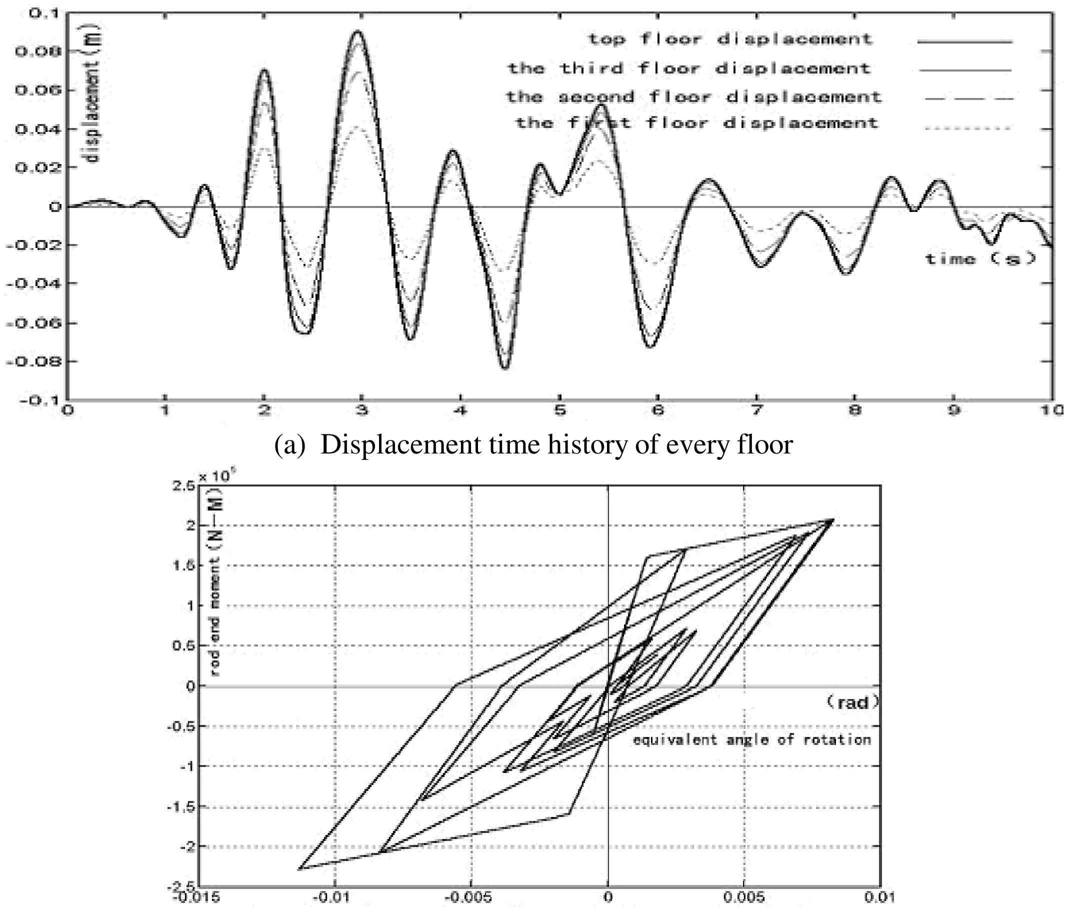


Fig. 6 Hysteretic curve of bottom end of middle column in bottom layer calculated by SIMULINK

Table 3 Comparison of the maximum displacement and inter-story displacement rotation

Layer	Maximum displacement (m)		Maximum inter-story displacement rotation (rad)	
	SIMULINK	PFEP	SIMULINK	PFEP
1	0.0348	0.0345	0.0096	0.0091
2	0.0547	0.0536	0.0068	0.0062
3	0.0638	0.0625	0.0032	0.0029
4	0.0682	0.0673	0.0019	0.0016



(a) Displacement time history of every floor

(b) Restoring force curve of bottom end of middle column in bottom floor

Fig.7 Displacement time history and hysteretic force curve based on model Takeda

Fig.7 gives out the calculated results using the degenerate three-line-type hysteretic model (Takeda model). Compared Fig.5 with Fig.7, it is obviously that there are a lot of differences, such as the time of peak value, waveform etc. The main reasons led to the above results are the difference of the hysteretic model [10]. In the non-degenerated two-line-type hysteric model, the factor of member crack is not taken into account, and unload stiffness keeps constant; In Takeda model, stiffness will be reduce after member crack, then as the deepening of the layer of nonlinear, the reduce amplitude of stiffness becomes extreme.

CONCLUSIONS

(1) While using the advantages of the digital simulation of SIMULINK, the elastic-plastic simulation of multi-stories shear-type structure and member model is realized, and has been compared with the result gained from other analytic software, which shows that SIMULINK has adequate engineering accuracy.

(2) From the established model in this paper, it can be learned that simulation SIMULINK have the outstanding advantages as follows, establishment of the model is visual, simple, visual function is powerful, and complicated dynamic analysis program can be embodied by the simplest means in simulation SIMULINK. The development of the model has high succession and powerful further development function. Every module established in the paper stores in self-defining module warehouse, which can be used directly when the new model is established.

(3) The realization of structural elastic-plastic dynamic analysis based on SIMULINK is completely executive and predominant. The simulation of structural nonlinear seismic responses is elementarily established. With the deepening of the research, the advantages of structural nonlinear analysis and

structural vibration control of SIMULINK will become outstanding gradually, and this topic will become an attractive research direction of hazard resistant and reductive engineering and protective engineering.

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