Dynamic Experiment and Numerical Simulation of a Full Scale Steel Frame with Viscous Dampers

Chen Xuewei
Tall Building Structure Research Institute, South China University of Technology, Guangzhou, China

KEYWORDS

Nonlinear time history analysis, parameter analysis, full-scale steel frame, viscous damper

ABSTRACT

This paper presents a dynamic nonlinear numerical simulation of a 5-story full-scale steel frame structure based on Perform-3D. Flexibility-based fiber element and Maxwell model are adopted for structure member simulation after a post analysis of the shaking table test of a 4-story full-scale steel frame. The author simulates the low cyclic reciprocating load test for the steel members with fiber element and plastic hinge element, and also analyzes the fiber division and length of plastic hinge. Analytical results of the seismic responses under medium and severe ground motions are compared with the experiments, indicating a good simulation of the nonlinear behaviour of the steel frame with viscous dampers by using flexibility-based fiber element and Maxwell model when structural nonlinearity is limited by dampers.

FOREWORD

A shaking table test of a full-scale 5-story steel frame with viscous dampers on E-Defense as well as the 2009 Blind Analysis Contest was conducted by National Research Institute for Earth Science and Disaster Prevention (NIED) of Japan in 2009[1], which was the follow-up of the 2007 Blind Analysis Contest for a full-scale 4-story conventional steel frame that was shaken to collapse[2]. The contest required the participants to predict the response of the shaking table test and submit the results of the analysis, including responses of the structure under different ground motions. The accuracy of the analysis was judged by the comparison with the shaking table test data. The paper will focus on the shaking table test and the inelastic numerical simulation method. The nonlinear parameters of the steel frame are studied based on the post analysis of the 2007 Blind Analysis Contest and applied in the 2009's contest to estimate the dynamic response of the steel frame with viscous dampers

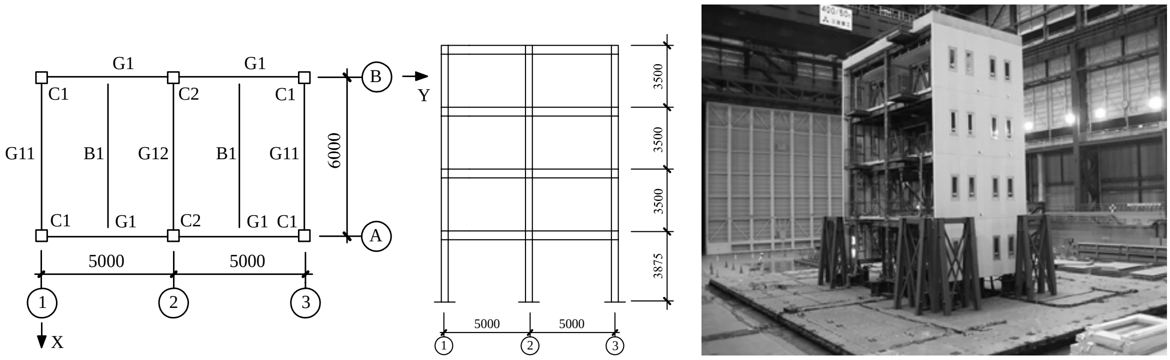
1 FULL SCALE MODEL

1.1 *E-Defense shaking table*

The world's largest earthquake simulator, E-Defense shaking table[3], was built by the National Research Institute for Earth Science and Disaster Prevention of Japan (hereinafter NIED) on January 15th 2005. E-Defense is composed of experiment building, operation building, hydraulic unit building, preparation building and three-dimensional shaking table. The size of E-Defense is 20m×15m. The max capacity of the shaking table in vertical direction is 12000kN and the max acceleration in X&Y direction is 900 cm/s2, while 1500 cm/s2 in Z direction.

1.2 *Full scale frame*

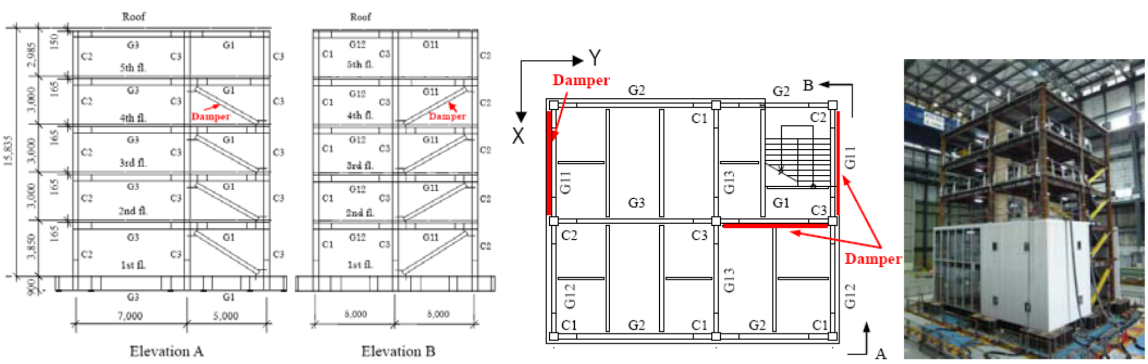
The specimen of the test in 2007 is a full-scale 4-story steel moment frame structure with profiled steel sheet and concrete composite floor[2]. The plane dimension of the frame is 10m×6m with two bays in Y direction and one span in X direction. The structure is mainly loaded in Y direction. The foundation elevation is 1.5m. The height of the first story is 3.875m, while 3.5m for 2nd-4th story. The height of the parapet is 0.6m. The total height of the structure is 16.475m. The plane layout is shown in Figure.1



(a)Plane (b) Elevation of axis A (c) Overall structure before test

Figure.1 Framing Plan and Elevation of the Specimen 2007

The specimen of the test in 2009 is a full-scale 5-story steel moment frame structure with profiled steel sheet and concrete composite floor[1], supplemented with 12 viscous dampers. The plane dimension is 12m×10m with 2 bays in each direction. Column spacing is 2×5m in X direction, 7m and 5m in Y direction. The structure is mainly loaded in Y direction. The foundation elevation is 0.9m. The height of the first story is 3.85m, while 3 m for 2nd-4th story. The total height of the structure is 15.835m. The plane layout is shown in Figure.2



(a) Elevation (b) Plan (c) Overall structure before test

Figure.2 Framing Plan and Elevation of the Specimen 2009

1.3 *Ground motion input*

The ground motion recorded in Takatori recording station in south of Hyogo in Japan on January 27th 1995 is taken as the input ground motion in the shaking table test. The magnitude of the ground motion is Ms=7.2 while the epicenter located under the sea between Kobe city and Awaji Island and the focal depth is 17,27 kilometers beneath the earth. The ground motion, which lasts for 41 seconds, can be classified as shallow earthquake according to the records. The max acceleration recorded in N-S and E-W direction is 0.606g and 0.657g respectively while that of the vertical direction is 0.279g. During the input process, the ground motion in N-S, E-W and vertical direction are taken as the X, Y, Z direction respectively.

2 INTRODUCTION OF ANALYSIS SOFTWARE AND MODEL

2.1 *Introduction to OpenSEES*

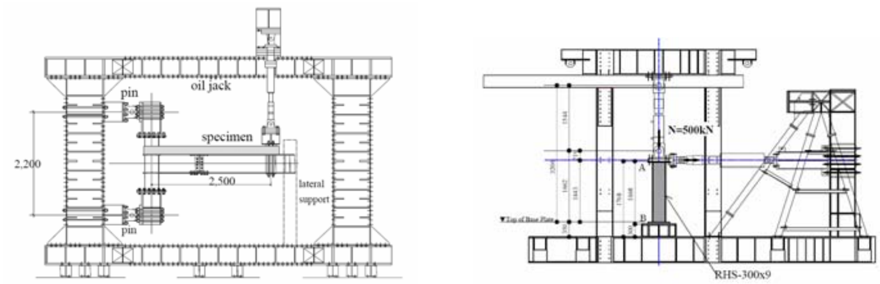
OpenSEES stands for Open System For Earthquake Engineering Simulation[4]. It is an open-source system of earthquake simulation and allows the customers add new material constitutions and new types of elements to the system by means of programming. OpenSEES is mainly applied to analysis the responses of the structure in earthquake and it can carry out the linear, static and dynamic nonlinear analysis and the eigen-value calculation, etc. The program has a large library of finite elements and the element employed for nonlinear analysis in this paper is identified as dispbeam-column, which is a displacement-based fiber model and could take the P-Delta effect into consideration. The Kent-Scott-Park constitutive model[5] is adopted as the constitution of the concrete which accounts for a higher strength and ductility under the transverse confinement, while the Giuffré-Menegotto-Pinto[6] constitutive model is adopted as the constitution of steel to simulate the behavior of stiffness degradation and buckling of steel.

2.2 *Introduction to Perform-3D*

Perform-3D is a commercial program of CSI dealing with performance-based nonlinear analysis[7]. It has a large library of material constitutive and elements. Flexibility-based fiber element and plastic hinge element are employed for nonlinear analysis and viscous dampers are simulated by Maxwell model in this paper. A large number of parameters of the element and material model can be adjusted which have influence on the accuracy of the analysis significantly. A series of parameter study are based on the 2007 Blind Analysis Contest including overall structure and component tests, and the parameters are applied in the numerical model of the 2009 Blind Analysis Contest.

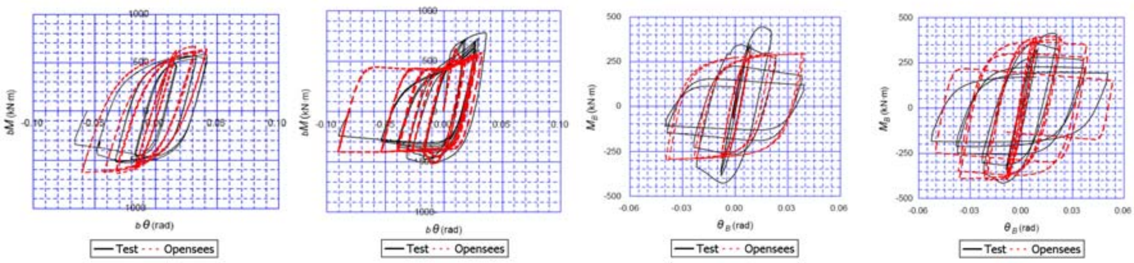
3 MODEL PARAMETER STUDY

Before the dynamic test of the structure in 2007, the low cyclic reciprocating loading experiments for the steel members, including steel beams, composite beams and square box columns were carried out by NIDE in order to reveal the seismic performance of the steel members, as shown in Figure.3. The steel members are well simulated by displacement-based fiber element in OpensSEES with a good agreement between the hysteretic curves and the tests shown in Figure.4[8], and also by plastic hinge element in Perform-3D after adjusting the parameters of strength and stiffness degradation that the skeleton curve of element is computed by “XTRACT” software with steel constitutive. Bad estimation by fiber element in Perform-3D because of the flexibility-based element can not simulate the lateral bulking of the component, as shown in Figure.5. But when nonlinear deformation is limited, fiber element in Perform-3D gains a good estimation of the tests. The more nonlinearity developed, the more deviation occurred. Considering the frame with viscous dampers would develop only slightly into nonlinear range even under the excitation of severe earthquakes, fiber element is adopted to simulate the overall structure behavior.



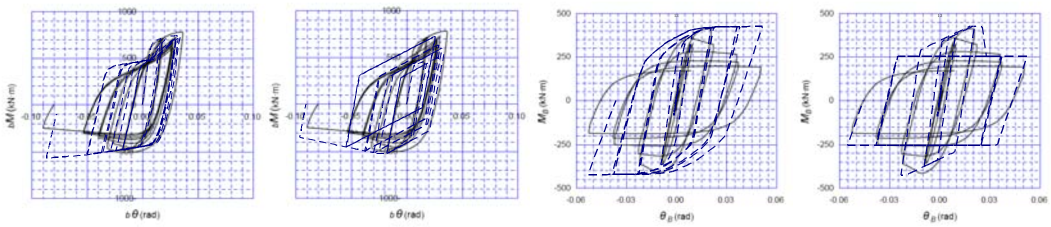
（a）Steel beam test (b) Steel column test

Figure.3 Test equipments and specimens



(a)Steel beam (b)Composite beam (c)Steel column 0° (d) Steel column 45°

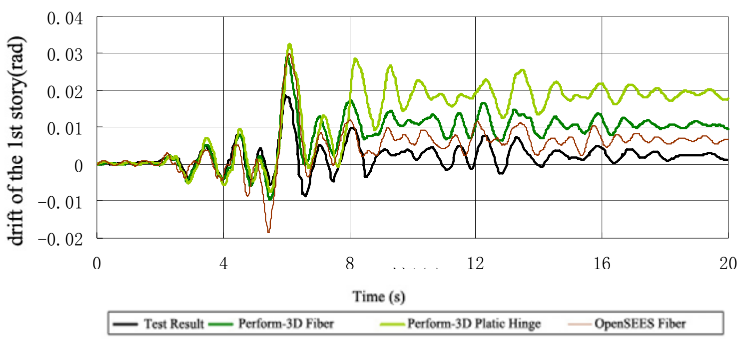
Figure.4 Comparison between hysteretic curves in OpenSEES and tests



(a)Fiber model for composite beam (b) Plastic model for composite beam (c) Fiber model for Steel column 45° (d) Plastic model for Steel column 45°

Figure.5 Comparison between hysteretic curves in Perform-3D and tests

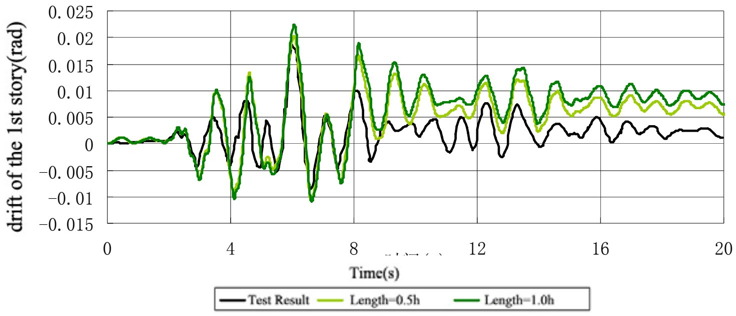
Based on the results of the shake-table test in 2007, the author compares the accuracy between fiber element in OpenSEES, fiber element and plastic hinge element in Perform-3D. As shown in Figure.6, best simulation is made by fiber element in OpenSEES, followed by fiber element in Perform-3D. For viscous damper can be well simulated in Perform-3D, the numerical model of the specimen in 2009 adopts the fiber element in Perform-3D and Maxwell model.



*Time history of drift of the 1st story in Y direction under 60%-Takatori earthquake

Figure.7 Figure.4 Comparison between different analysis element models

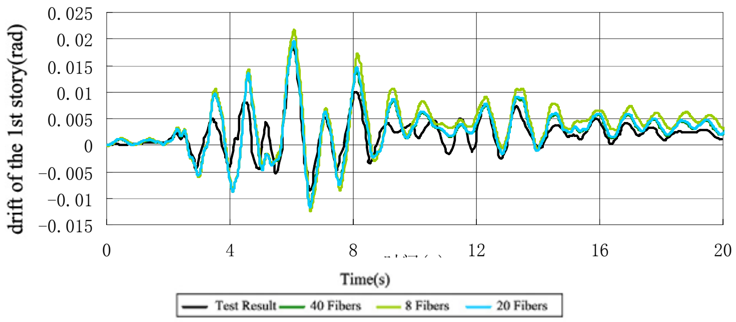
Fiber division and length of plastic hinge of the fiber element in Perform-3D determine the computing accuracy significantly, so the two parameters are studied based on the test in 2007. Length of plastic hinge for a steel column is about 0.5~1.0h, then both 0.5h and 1.0h are analyzed as shown in Figure.7. Finally it is chosen to 0.5h for a better estimation.



*Time history of drift of the 1st story in Y direction under 60%-Takatori earthquake

Figure.7 Figure.4 Comparison between different lengths of plastic

Different number of fiber divisions is analyzed and compared in Figure.8. It illustrates that analysis trends to stable when divisions are over 20, that satisfied in the analysis model in perform-3D.

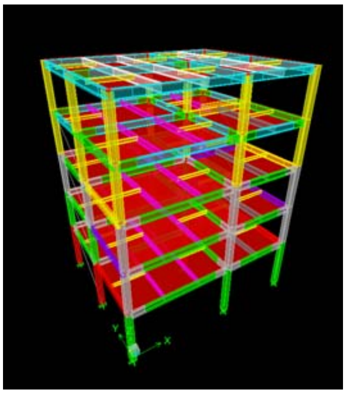


*Time history of drift of the 1st story in Y direction under 60%-Takatori earthquake

Figure.8 Figure.4 Comparison between different fiber divisions

4 INELASTIC ANALYSIS OF A STEEL FRAME WITH VISCOUS DAMPERS

The overall structure is modelled with specific mass data given by NIDE after a reasonable selection of material parameters and component model, shown in Figure. 9. To ensure the accuracy of the model, the frame is both simulated in Perform-3D and Etabs. Modal analysis is carried out and listed as follows: T1=0.7435s, T2=0.7142s, T3=0.5330s in Etabs, while T1=0.74976s, T2=0.7214s, T3=0.5355s in Perform-3D. Under the excitation of 0.05*Takatori in one direction, structure keeps elastic in Perform-3D and comparison of the story drift history is made to the elastic model in Etabs, shown in Figure.10. Both modal and elastic time history analysis agree well to ensure a reasonable model that is built in Perform-3D.



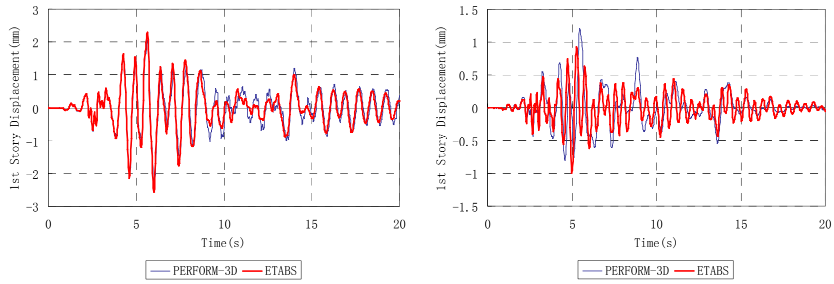


Figure.9 Steel Frame Model in ETABS (a) No dampers (b) With dampers

Figure.10 Comparison between Elastic Time-History Analysis by PERFORM-3D and by ETABS

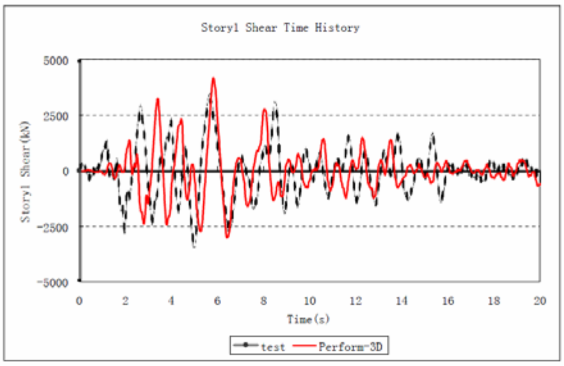
4.1 *Dynamic inelastic analysis*

The test is composed of two procedures: 50%Takatori and 100%Takatori. Ground motions in the test are given by NIED. Rayleigh damping is adopted in the numerical model and the damping coefficient for 1st and 2nd modal are set as 0.02. The step size for seismic analysis is 0.02s. The ground motions for time history analysis are input in three directions.

4.2 *Analysis results*

Under the excitation of 100%Takatori , the 1st story drift responses in time history analysis in X direction is shown in Figure.11. Both peak value and phase agree well between analysis and test. Shear against drift of the 1st story shown in Figure.12 illustrates a good estimation of the structure which slighted developed into nonlinear range.

The relative story displacement as well as the absolute story acceleration under the excitation of 50% and 100%Takatori is obtained from the experiment[9]. The corresponding story shear force is calculated. The comparisons between the results form Perform-3D and experiment are shown in Figure.13. The prediction under 50%Takatori matches well with the experiment while prediction under 100%Takatori matches in Y direction. In X direction, base shear result of anlaysis is greater than experiment result. Both experiment and numerical analysis indicate that lateral deformation is mainly concentrated on the 1st and 2nd story.



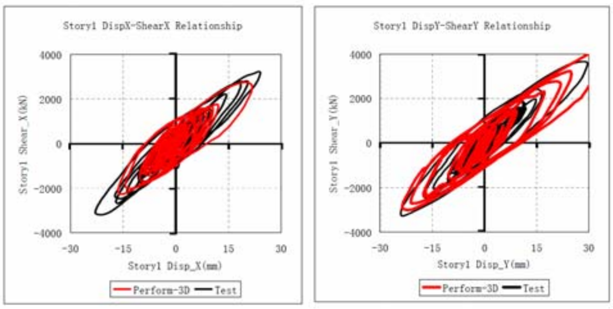
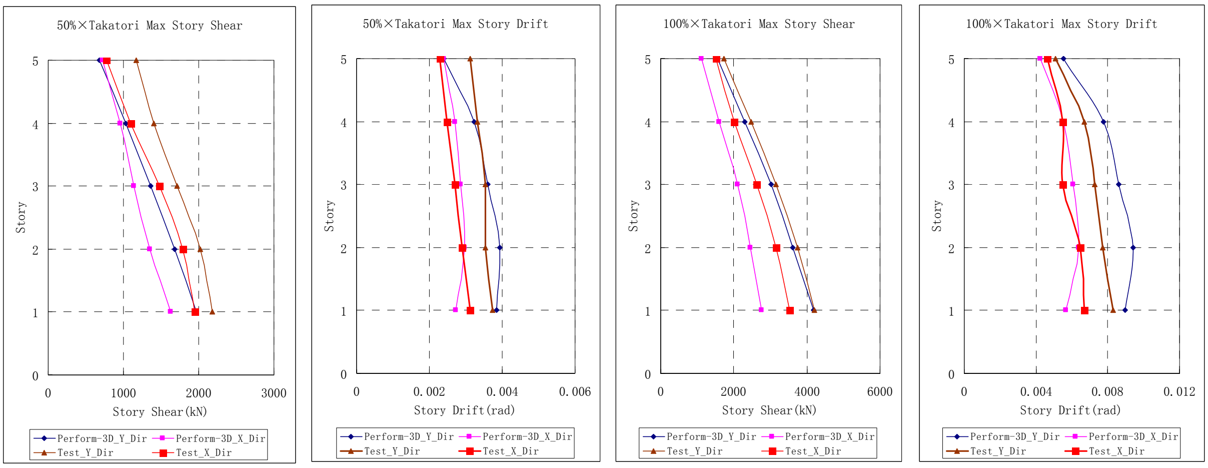


Figure.11 Time-History of Drift in 1st story

（a） X direction （b） Y direction

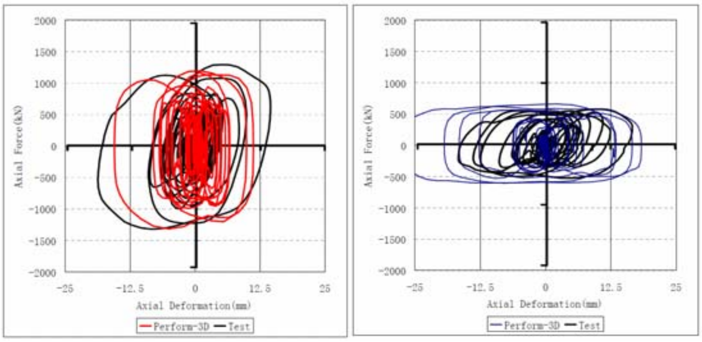
Figure.12 Drift against story shear in 1st story



(a)50%Takatori Story Shear (b)50%Takatori Story Drift (c)100%Takatori Story Shear (d)100%Takatori Story Drift

Figure.13 Comparison of the structural main properties

Axial force against deformation of the viscous dampers in the 1st story under the excitation of 100%Takatori is shown in Figure.14. By using Maxwell model, the analysis matches well with the test. Comparisons illustrate that finite analysis program Perform-3D based on fiber element can accurately simulate the frame with viscous dampers under severe ground motions.



(a) Y direction (b) X direction

Figure.14 Axial forces against axial deformation of the viscous dampers of 1st story

Processes of beam column rotation analyzed by Perform-3D are shown in Figure.15. It can be seen that rotation of column in 1st story is more than 0.005 while rotation of steel beams is only about 0.002. Rotation of steel beams in X direction in 1st story is evident. In general, the structure is slightly in nonlinear range for the installation of viscous dampers.

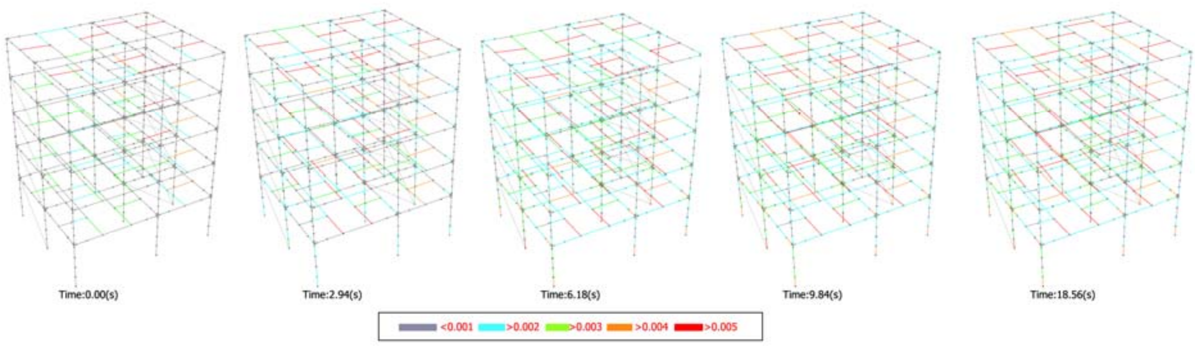


Figure.15 maximum of rotation of components in Perform-3D

5 CONCLUSIONS

A nonlinear analysis of a full scale steel frame with viscous dampers is carried out with finite element program Perform-3D to estimate the response of shaking table test. Nonlinear parameters of steel frame are studied by reviewing the 2007 Blind Analysis Contest before the analysis. The author simulates the low cyclic reciprocating load test for the steel beams and steel columns with displacement-based fiber beam-column element in OpenSEES, flexibility-based fiber element and plastic hinge element in Perform-3D, and then compares the analytical results with the data provided by NIED. Good agreement between the analysis results and experimental data indicates that nonlinear behaviors of steel members can be simulated accurately by these elements. Fiber element in Perform-3D and Maxwell damper element are adopt to the whole structure analysis after a comparison of response analysis under excitation of 60%Takatori by using the three elements. A proper selection for the fiber division and length of the plastic hinge is made.

The modal analysis and elastic time history analysis are also carried out and the results are compared with the data from Etabs so as to verifying the reasonableness of the model. Then nonlinear dynamic analysis is carried out under the excitation of 50%Takatori and 100%Takatori to compare the story drift, story shear and hysteretic curve of viscous damper with experiment. Results shows that the structure is slightly in the nonlinear range under severe ground motion by installation of the dampers and the lateral deformation is mainly concentrates on the 1st and 2nd story. The study indicates that fiber element based nonlinear analysis program Perform-3D can evaluate the inelastic behavior of he structures with dampers accurately.

References

[1]K. Kasai, Y. Ooki and M. Ishii et al, "Value-added 5-story steel frame and its components: part1-full-scale damper tests and analysis", Proceedings of 14th World Conference on Earthquake Engineering, Beijing, China, 2008, CD-ROM.

[2]Motohide Tada, Makoto Ohsaki, Satoshi Yamada. "E-Defense tests on full-scale steel building". Structural Engineering Research Frontiers, ASCE,2007.

[3]Masayoshi SATO, Takahito INOUE. "General frame work of research topics utilizing the 3D full scale earthquake testing facility". Journal of Japan Association for Earthquake Engineering, 2004,4(3),pp449-456.

[4]Mazzoni S, Mckenna F, Scott M H et al. "Opensees Command Languqage Manual" .http://Opensees. Berkeley.edu/OPENSEES/manuals/usermanual/Opensees Command Languaeg Manual June 2006. pdf. 2006-6-19.

[5] Kent D C, Park R. "Flexural Members with Confined Concrete". ASCE,1971,97(ST7).pp1969-1990.

[6] Menegotto, M. and Pinto, P.E. "Method of analysis of cyclically loaded RC plane frames including changes in geometry and non-elastic behavior of elements under normal force and bendin", Preliminary Report, IABSE, 1973,vol.13, pp:15–22.

[7] Graham H. Powell. "A State of the Art Educational Event Performance Based Design Using Nonlinear Analysis". Computers and Structures Inc.,2007.

[8] Han Xiaolei1,Chen Xuewei, Jack CHEANG et al. "Dynamic experiment and numerical simulation of a full scale steel frame", Journal Of Earthquake Engineering And Engineering Vibration,2008,28(6), pp.134-141(in Chinese).

[9] Yonetani Morio, Kasai Kazuhiko, Ooki Yoji et al, "Result of Shaking Table Test of 5-Story Steel Frame with Viscous Damper",Report, E-Defense Experimental Projects for Steel Buildings – Part 45,2009,pp.743-744.