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DYNAMIC PROPERTY EVALUATIONS OF FULL-SCALE 4-STORY STEEL FRAME USING PARALLEL FE-ANALYSIS

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ABSTRACT

The project of E-Simulator is under way at Hyogo Earthquake Engineering Research Center (E-Defense) of National Research Institute of Earth Science and Disaster Prevention (NIED), Japan, which facilitates the world's largest shaking table. The E-Simulator uses the parallel finite element (FE) analysis software package called ADVENTYRECluster (ADVC) as a platform. In this study, we report the results of high-precision FE-analysis for simulation of collapse behavior of the 4-story steel building frame that is the specimen of the full-scale total collapse shaking-table test conducted in September 2007 at E-Defense. It is shown that elastoplastic dynamic responses can be estimated with good accuracy using a high-precision FE-analysis without resort to macro models such as plastic hinge and composite beam effect.

Introduction

In the conventional process of seismic response evaluation of a low-rise steel building frame, static pushover analysis is carried out for the frames using an empirically defined plastic hinge or fiber model. Macro models are also used for representing the properties of column base and composite beam effects. Therefore, the seismic responses obtained by the static pushover analysis strongly depend on the assumption incorporated in the building code and the intuition made by an engineer.

The project of E-Simulator is under way at Hyogo Earthquake Engineering Research Center (E-Defense) of National Research Institute of Earth Science and Disaster Prevention

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(NIED), Japan, which facilitates the world's largest shaking table (Hori *et al*. 2007, E-Defense 2009). The E-Simulator uses ADVENTYRECluster (ADVC) as a platform (Akiba *et al*. 2006, Ogino *et al*. 2005). ADVC is a commercial software package of parallel finite element (FE) analysis, which uses domain decomposition technique for parallel implementation. It can solve dynamic nonlinear problems with more than 10 million DOFs for a structure discretized by three-dimensional solid elements. The authors carried out elastoplastic dynamic analysis of a 31-story high-rise steel building model using ADVC (Ohsaki *et al*. 2009). The E-Simulator is conceived as a virtual shaking table, and its final form is a software environment to simulate global and local seismic responses of a city, as assemblage of buildings and infrastructures, by fully taking advantage of recent development of computer science and high-performance computing in computational mechanics.

As a part of this project, the purpose of this study is to show that the global and local elastoplastic behaviors of a steel frame under severe seismic motions can be simultaneously simulated by a high-precision FE-analysis software, ADVC. Elastoplastic dynamic analysis is carried out for the 4-story frame model as the specimen of full-scale shaking-table test (Suita *et al*. 2007) conducted in September 2007 at E-Defense shaking-table facility. The test is one of the series of experimental studies on moment-resisting frames, innovative methods for new or existing buildings, protective systems, and nonstructural elements (Kasai *et al*. 2007). In this study, it is shown that the local and global collapse behaviors of a steel frame consisting of thin plates can be accurately simulated by discretizing the whole structure using hexagonal solid elements without resort to macro models such as plastic hinge and composite beam effect.

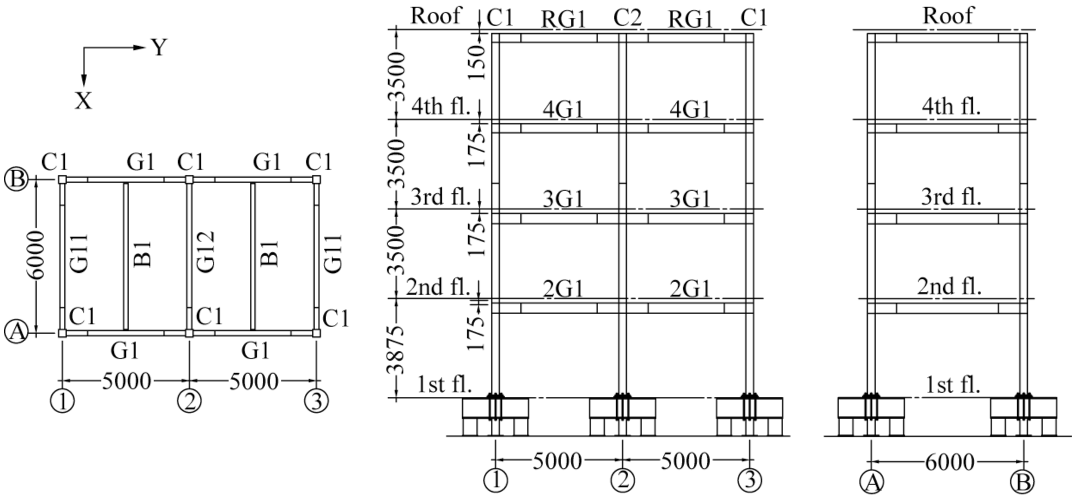
Four-Story Steel Frame Model

The FE-model of the 4-story frame, as shown in Fig. 1 (Tada *et al*. 2007), is generated using the data and documents distributed for the blind analysis contest (Ohsaki *et al*. 2008, Hikino *et al*. 2009). All the members as well as the floor slabs are modeled by 8-node hexahedral solid elements; i.e., the DOFs of each node are three translational displacements, and the displacements in the element are interpolated by conventional first-order shape functions.

The FE-mesh generated by Noguchi Laboratory at Keio University, Japan, is used as the prototype, where the total numbers of elements, nodes, and DOFs are 651,662, 1,207,902, and 3,623,706, respectively. In order to improve the accuracy, each element is divided twice in the three directions into eight elements, using the conversion program *uvmesh*, to result in 5,181,880 elements, 523,295 nodes, and 22,569,885 DOFs. Figs. 2(a) and (b) show the meshes around the connections before and after subdivision, respectively. Consequently, the plates such as flanges and webs of beams are divided into two layers of solid elements. The slab of each floor is also divided into the solid elements with two layers. The studs connecting the flange and the slab are omitted in the model, and the lower surface along the boundary of the slab is directly connected to the upper layer of the flange.

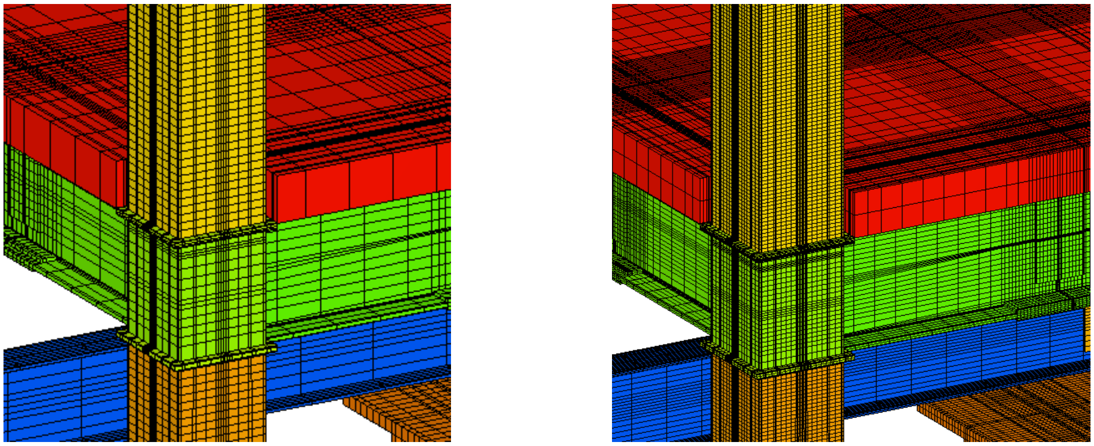
A piecewise linear isotropic hardening is used for the constitutive model of the steel material, and its parameters are identified from the uniaxial test results, which were distributed for the blind analysis contest. A bilinear relation is used for that of the concrete of the floor slab. The self weight of the steel is computed from the mass density 7.86×10^3 kg/m^3. By contrast, the mass density 2.3×10^3 kg/m^3 of the slab is increased appropriately to include the weights of the nonstructural components and the anti-collapse frames used in the experimental model, etc.

Elastoplastic dynamic collapse analysis is carried out for Cases 1, 2a, and 2b, which are defined as shown in Table 1. Fig. 3 depicts FE-models of these three cases. Case 1 ignores the stiffness of the exterior wall, whereas it is modeled by a shear spring connecting the flanges of the beams in the upper and lower floors. The three types of column bases are considered; i.e., fixed, rotational spring, and solid model. In Case 2a, the rotational stiffness around Z-axis of the column base is 10 times as large as those around X- and Y-axes. Since most of the damping of a steel frame is related to the friction and plastification of the nonstructural components, the ambiguous equivalent linear damping is expected to be replaced by more accurate model of nonstructural components.



(a) Plan (1st Floor) (b) Y-elevation (longitudinal) (c) X-elevation (transverse)

Figure 1. 4-story steel frame model (Tada *et al*. 2007).



(a) Before subdivision (b) After subdivision

Figure 2. FE-meshes near the connections.

Table 1. Model types of column bases and exterior walls.

Case	Column base	Stiffness of exterior wall
Case 1	Fixed.	Ignored.
Case 2a	Rotational spring based on the recommendation by Architectural Institute of Japan (1990).	Shear spring (truss element) connecting the flanges of the beams in the upper and lower floors. Parameters are identified from the experimental results (Matsuoka *et al.* 2007).
Case 2b	Solid model. Beam element for the anchor bolt with pretension. Contact with small friction between the lower face of base plate and the upper face of base.	

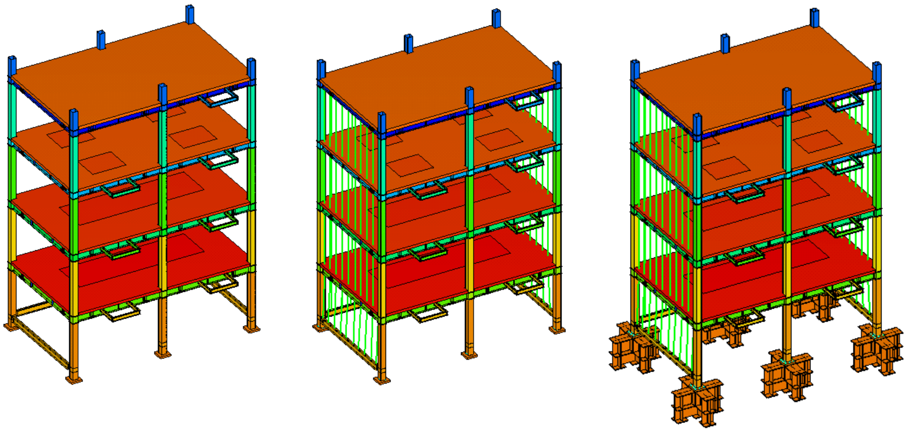

(a) Case 1 (b) Case 2a (c) Case 2b

Figure 3. FE-models of the three cases (drawn without mesh).

Results of Numerical Analysis

Eigenvalue analysis

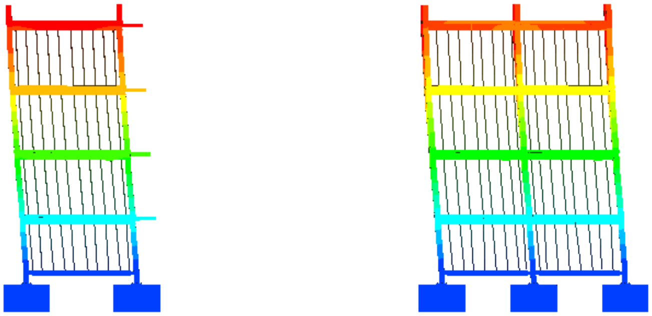
The four lowest natural periods obtained by eigenvalue analysis for Cases 1, 2a, and 2b are listed in Table 2. The 1st and 4th modes correspond to translation in X-direction defined in Fig. 1; the 2nd mode is in Y-direction; and the 3rd mode is a torsional mode. Note that Case 2a with stiffness of exterior walls does not always have smaller periods than Case 1 because Case 2a has smaller stiffness at the column bases. The contact state is maintained at the column base in the process of eigenvalue analysis of Case 2b, which leads to the smaller periods than Case 1 or 2a. The shapes of the first and second modes of Case 2b are shown in Fig. 4. Note that the 1st and

2nd periods identified in experiments are 0.82 s and 0.74 s, respectively; i.e., the 2nd period by analysis is larger than that obtained by the experiment. The CPU time for eigenvalue analysis is 5,471.6 s using 16 cores of HP ProLiant BL465 2.6 GHz Dual Core Cluster.

Table 2. Four lowest natural periods for Cases 1, 2a, and 2b.

Case	**Natural period**			
	1st	**2nd**	**3rd**	**4th**
Case 1	0.8389	0.8144	0.5700	0.2702
Case 2a	0.8303	0.8203	0.5555	0.2700
Case 2b	0.7947	0.7833	0.5372	0.2578

Unit: second



(a) 1st mode

(b) 2nd mode

Figure 4. Two lowest eigenmodes of Case 2b.

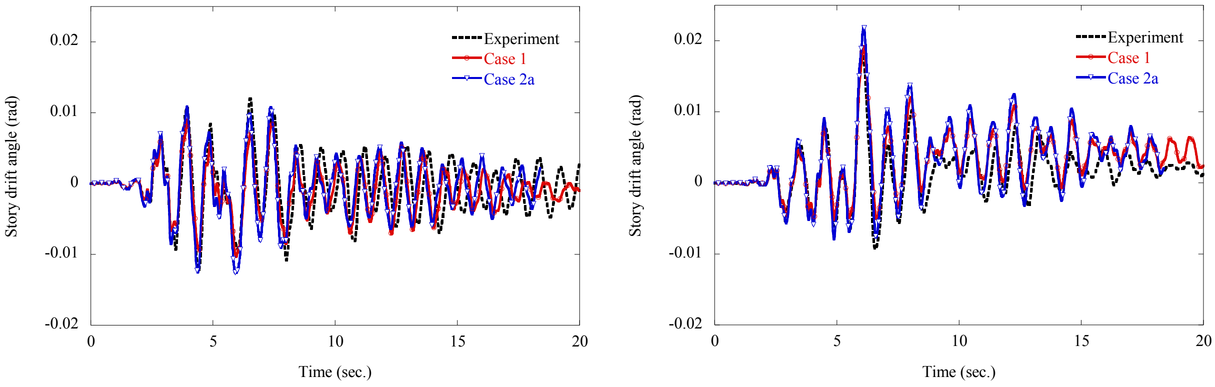
Time-history analysis

Next, time-history analysis is carried out for Cases 1 and 2a for the three dimensional input motions of the JR-Takatori wave of the 1995 Hyogo-ken Nanbu Earthquake that is scale by 0.6. The acceleration record measured on the shaking table of the full-scale test is used rather than the numerically scaled ground motion record of the earthquake. Note that EW, NS, and UD components correspond to X-, Y-, and Z-directions, respectively. The duration of the motion is 20 s. The Rayleigh damping is used, where the damping factors are 0.02 for the 1st and 4th modes, which are the two lowest modes in X-direction. The Hilber-Hughes-Taylor method is used for time integration with parameters $\alpha = -0.05$, $\beta = (1 - \alpha)^2/4 = 0.275625$. In this analysis, the 256 cores of one-node of SGI Altix 4700 with Intel Itanium 1.66 GHz processors, 1 node × 256 core, in NIED was used for computation. The elapsed computation time is 2,414 s for static analysis for self-weight, and average of the elapsed times for one step ($\Delta t = 0.01$ s) of the time-history analysis is 1,106 s.

The time histories of interstory drift angles and shear forces of the 1st story are plotted in Figs. 5 and 6, respectively. In Case 2a, better correlation with the experiment result is observed than in Case 1. The maximum and minimum values of the interstory drift angles are 0.01089 rad and –0.01357 rad in X-direction, and 0.02300 rad and –0.007942 rad in Y-direction, whereas the experimental results are 0.0121 rad and –0.0122 rad in X-direction, and 0.0190 rad and –0.00933 rad in Y-direction. Therefore, moderately accurate values are obtained by numerical analysis. Note that a residual deformation exists in Y-direction.

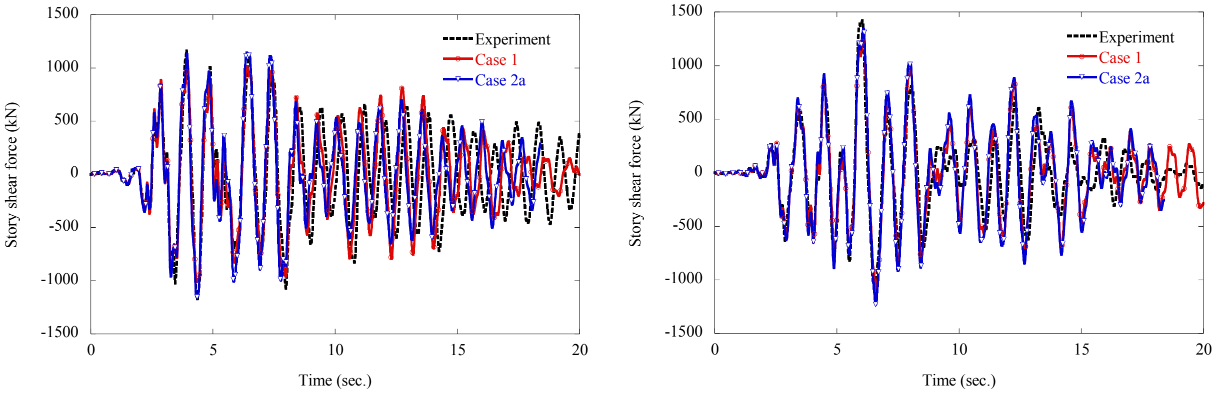
The story shear forces are calculated by the summation of the products of concentrated mass of each layer and the acceleration at the center of gravity of each layer. The maximum and minimum values of the shear forces in X-direction are 1142 kN and –1153 kN, respectively, and those in Y-direction are 1385 kN and –1229 kN, respectively. The measured values in the experiment are 1169 kN and –1173 kN in X-direction, and 1423 kN and –1058 kN in Y-direction. Therefore, the shear forces are estimated with good accuracy.

Figs. 7 and 8 respectively depict deformation of Cases 1 and 2a at 6 second, at which the input motion causes nearly the maximum deformation of the specimen. The deformation is magnified 10 times and the colors stand for the distribution of equivalent stress. In Case 2a, rotational response around Z-axis is observed and this is because the model of Case 2a considers exterior walls, which leads to the uniaxial eccentricity. The distribution of equivalent stress at the maximum deformation in Case 1 is shown in Fig. 9. As is seen, large stress is observed around the column base and beam-to-column connections.



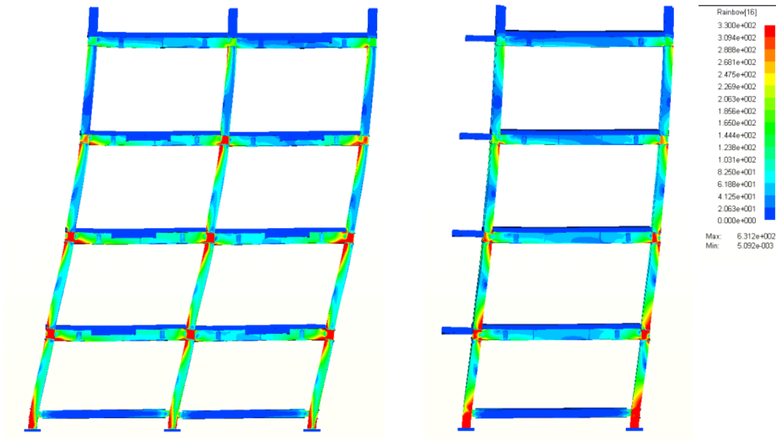
(a) X-direction (b) Y-direction

Figure 5. Time-history of interstory drift angle of the 1st story.



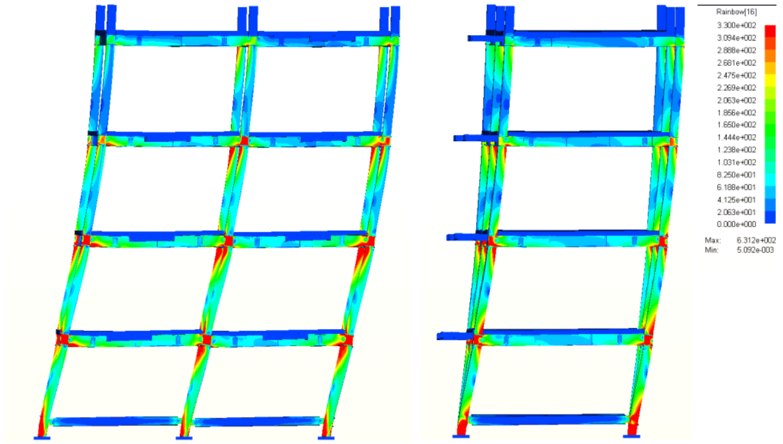
(a) X-direction (b) Y-direction

Figure 6. Time-history of shear force of the 1st story.



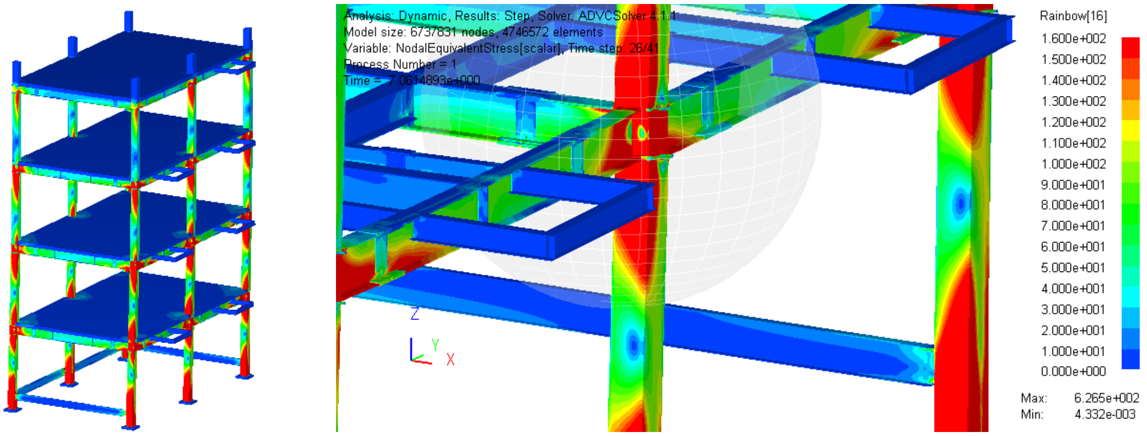
(a) X-axis (b) X-axis

Figure 7. Case 1: deformation (magnified 10 times) with distribution of equivalent stress at 6 s.



(a) X-axis (b) X-axis

Figure 8. Case 2a: deformation (magnified 10 times) with distribution of equivalent stress at 6 s.



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Analysis: Dynamic, Results: Step, Solver: ADVCSolver 4.1.1
Model size: 6737831 nodes, 4746572 elements
Variable: NodalEquivalentStress[scalar], Time step: 26/41
Process Number = 1
Time = 7.0614893e+000
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(a) Whole frame (b) Close view around the 2nd floor and the 1st story

Figure 9. Distribution of equivalent stress at the maximum deformation (Case 1).

Conclusions

A virtual shaking-table test has been carried out using the prototype of the E-Simulator for investigation of elastoplastic dynamic behavior of the 4-story frame model as the specimen of full-scale shaking-table test conducted in September 2007 at E-Defense. It has been shown that the large-strain elastoplastic dynamic behaviors can be estimated with good accuracy by using the fine mesh with the solid elements and the constitutive relations of the steel material without resort to macro models and empirical parameters such as plastic hinge and stiffness amplification factor of the composite beam.

A shear spring that is applicable to large-deformation analysis has been implemented to the ADVC, which is the platform of the E-Simulator, to incorporate the stiffness and strength of the exterior walls. Hence, the use of ambiguous equivalent damping factor due to the friction and plastic deformation of the nonstructural components will be avoided by elaborating the model. This spring model will be further replaced by a solid model that is under development. This way, the local collapse behavior at the column base can be accurately simulated using the contact with small friction between the plate and the base.

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