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Detailed Finite Element Analysis of Full-scale Four-story Steel Frame Structure subjected to Consecutive Ground Motions

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Abstract

Detailed finite element (FE) analyses of a full-scale four-story steel frame structure, subjected to consecutive 60% and 100% excitations from the JR Takatori records during the 1995 Hyogoken-Nanbu earthquake, are conducted using E-Simulator. The four-story frame was tested at the largest shake-table facility in the world, E-Defense, in 2007. E-Simulator is a parallel FE analysis software package developed to accurately simulate structural behavior up to collapse by using a fine mesh of solid elements. To reduce computational time in consecutive dynamic time history analyses, static analysis with gravity force is introduced to terminate the vibration of the structure during the analysis of 60% excitation. An overall sway mechanism when subjected to 60% excitation and a story mechanism resulting from local buckling of the first-story columns when subjected to 100% excitation are simulated by using E-Simulator. The story drift response to the consecutive 60% and 100% excitations is slightly smaller than that for the single 100% excitation.

Keywords: Finite element analysis, Seismic response, Collapse, Consecutive excitation, E-simulator

1. Introduction

The world's largest three-dimensional (3D) shake-table test facility, E-Defense, was constructed at the Hyogo Earthquake Engineering Research Center of the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan, in 2005 (Ohtani et al., 2004; Hyogo Earthquake Engineering Research Center, 2015). A full-scale four-story steel frame structure, which is the object of simulation in this study, was tested at E-Defense in 2007 (Yamada et al., 2008; Suita et al., 2008). Simultaneously, at NIED, a parallel finite element (FE) analysis software package, E-Simulator, was developed to accurately simulate the seismic behavior of building, bridge, and underground structures up to collapse (Hori et al., 2007). The platform of E-Simulator is a general purpose parallel FE analysis code, ADVENTURECluster (Allied Engineering Corporation, 2015), and E-Simulator allows large-scale parallel computation for simultaneous simulation of both global and local behavior, including buckling and fracture, by using a fine mesh of solid elements. Dynamic

FE analyses of the four-story steel frame structure using a very fine mesh of solid elements were conducted by using E-Simulator (Miyamura et al., 2011; Miyamura et al., 2015). In these analyses, local buckling behavior at the top and bottom ends of the first-story columns and story mechanism were successfully simulated for a single excitation. However, the influence of the consecutive strong ground motions used for the E-Defense shake-table test was not investigated.

Several researchers have investigated residual stress effects on the seismic performance of structures (Lu et al., 2001; Okazaki et al., 2009; Mathur et al., 2011). Lu and MacRae (2011) conducted pushover and push-pull analyses and incremental dynamic analyses on a single cantilever column with nonlinear beam-column fiber sections under moderate compressive axial load. The results showed that whereas the initial residual stresses do have some effect on structural behavior at the first yielding, the postyielding behavior is not affected. Okazaki et al. (2009) conducted monotonic pushover and cyclic push-pull analyses on steel frame structures modeled by fiber elements to compare the structural responses with and without the initial residual stresses and initial imperfections. They concluded that the initial residual stresses and imperfections accelerate frame collapse for cases in which

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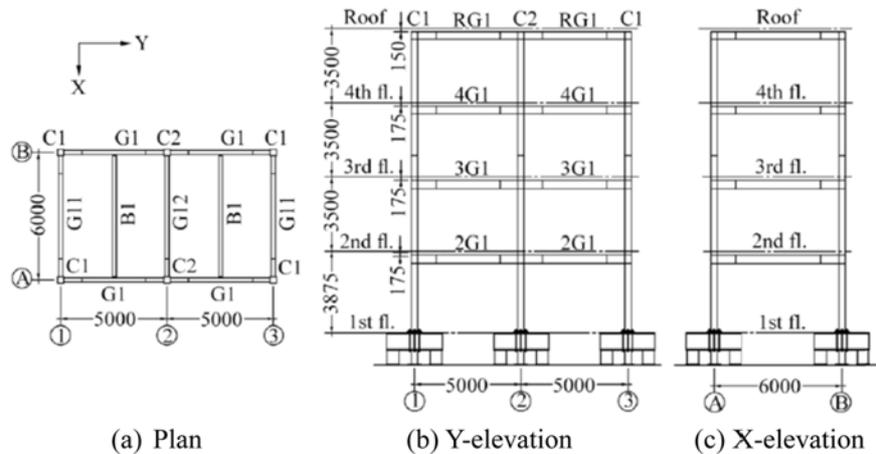
Figure 1. Framing and elevation of four-story steel frame specimen.

deformation is concentrated in a small number of stories. Additionally, several researchers have investigated the effects of accumulated damage induced by multiple strong ground motions (Takeda et al., 2011; Mizushima et al., 2014). Mizushima et al. (2014) conducted detailed FE analyses on a three-story steel frame, which was tested at E-Defense in 2014 (Namba et al., 2014), for single and consecutive ground motions. The steel frame was modeled by shell elements and the concrete slab was modeled by solid elements. An analysis found that the drift response for consecutive excitations was smaller than that for single excitation. They stated that one possible reason for this result is strain hardening.

In this study, dynamic FE analyses are conducted by using E-Simulator for consecutive 60% and 100% excitations of the JR Takatori records of the 1995 Hyogoken-Nanbu earthquake. Simulation results are compared with those for the single 100% excitation to evaluate the effects of consecutive excitations on structural responses.

2. Finite Element Modeling

The specimen was a four-story, two-bay by one-bay steel moment-resisting frame structure, as shown in Fig. 1. Each story is 3.5 m high, making the overall specimen height equal to approximately 14 m. This is a typical steel building designed and constructed according to the current design specifications and practice in Japan (Yamada et al., 2008; Suita et al., 2008). The columns are made of

cold-formed square-tube, beams are made of hot-rolled wide-flange, and through diaphragm connection details are adopted, in which short brackets are shop-welded to the columns. Table 1 provides a list of member sections.
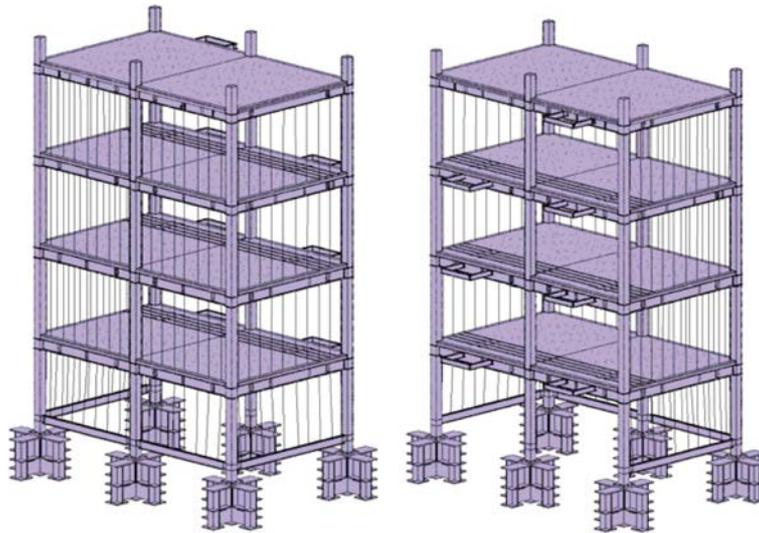
An FE model for the four-story steel frame structure, which primarily consists of hexahedral solid elements, as shown in Fig. 2, has 4,543,243 elements, 6,330,752 nodes, and 18,992,256 degrees of freedom. This analysis utilizes a hexahedral element using linear functions enhanced by incompatible modes (Simo and Rifai, 1990; Simo and Armero, 1992). The element is fully integrated using eight integration points. The modeling details are described in previous studies (Miyamura et al., 2011; Miyamura et al., 2015). The FE models of column, beam, deck plate, and wire mesh are shown in Fig. 3. The results of composite beam tests conducted by Yamada et al. (2009) indicated that the contact of a column to a slab influences the response of the beam during cyclic loading. However, because it is computationally expensive to simulate dynamic contact in the current version of E-Simulator based on ADVENTURECluster, no contact condition is considered in this study. Accordingly, the two surfaces of the column and slab are always separated and not in contact.

## 3. Material Properties, Constitutive Model, and Natural Periods

The self-weight of the steel is computed based on a mass density of 7.86×10^3 kg/m^3. The mass density of 2.3×10^3

Table 1. List of member sections

	Beam			Column	
Floor	G1	G11	G12	Story	C1, C2
R	H-346×174×6×9	H-346×174×6×9	H-346×174×6×9	4	SHS-300×300×9
4	H-350×175×7×11	H-350×175×7×11	H-340×175×9×14	3	SHS-300×300×9
3	H-396×199×7×11	H-400×200×8×13	H-400×200×8×13	2	SHS-300×300×9
2	H-400×200×8×13	H-400×200×8×13	H-390×200×10×16	1	SHS-300×300×9

Figure 2. FE model for four-story steel moment-resisting frame structure.
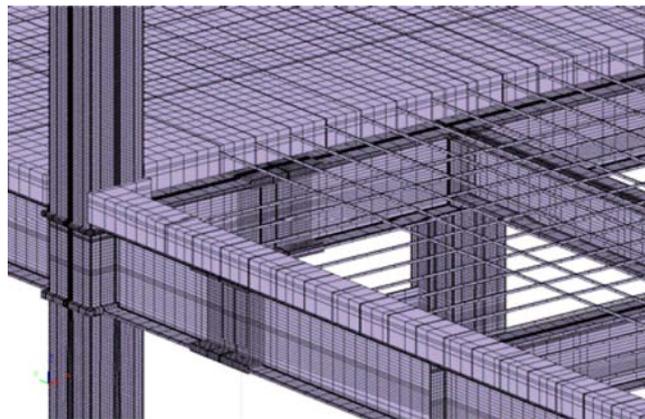
Figure 3. FE models of column, beam, deck plate and wire mesh.

Table 2. Material properties

Member	Steel	Section	Element	Measured properties (N/mm^2)	
				Yield strength	Tensile strength
Beam	SN400B	H-340×175×9×14	flange	309	443
			web	355	468
		H-346×174×6×9	flange	333	461
			web	382	483
		H-350×175×7×11	flange	302	441
			web	357	466
		H-390×200×10×16	flange	297	451
			web	317	458
		H-396×199×7×11	flange	311	460
			web	369	486
		H-400×200×8×13	flange	326	454
			web	373	482
Column	BCR295	SHS-300×300×9	first story	330	426
			second-fourth story	332	419

Table 3. Five lowest natural periods obtained by analysis and experiment

Model	Natural Period				
	First	Second	Third	Fourth	Fifth
Analysis	0.826	0.808	0.542	0.266	0.261
Experiment	0.82	0.74-0.78			

kg/m^3 of the slab is increased appropriately to include the weights of nonstructural components, safe-guard system to protect shaking-table, and stair landings attached to the specimen.

Table 2 lists the material properties of steel beam and column members. In the constitutive modeling, the piecewise-linear combined isotropic-kinematic hardening model (Ohsaki et al., 2012) is used for the rolled mild steel material. This material model is based on the von Mises yield criterion using a combined isotropic-kinematic hardening rule with a number of piecewise smooth hardening curves. Its parameters are determined from the results of the uniaxial tests under monotonic and cyclic loading conducted by Yamada et al. (2002). These monotonic uniaxial tests were conducted for all members. Therefore, different stress-strain curves are used for different members.

The extended Drucker-Prager yield criterion (Abaqus Analysis User's Manual, 2015) is utilized for the constitutive law of concrete material used in the slabs.

$$F = \sqrt{l_0^2 + q^2} - p\tan\beta - d' = 0 \qquad (1)$$

where q is the equivalent stress, p is the hydrostatic stress, β is the internal frictional angle, and l_0 and d' are the parameters to determine the shape of yield function. In this analysis, β is set to be 67.14 degree, l_0 is 1.297 N/mm^2, and d' is 33.71 N/mm^2 according to the material test results on slab concrete.

The natural periods of the steel frame obtained by the analysis are shown and compared with experimental ones in Table 3. The Rayleigh damping is applied and the coefficients for the Rayleigh damping are calculated so that damping factors of the first and fourth modes, which are the two lowest eigenmodes in the X-direction, are equal to 0.02.

4. Analysis Procedures for Consecutive Shaking

In the simulation for the consecutive 60% and 100% excitations from the JR Takatori records, the static analysis for the application of gravity force is first conducted, and then the dynamic analysis for 60% excitation is conducted. The JR Takatori records used for the E-Defense shake-table test have a duration of approximately 160 s (ASEBI, 2015), although the main excitation that causes large amplitude vibration to the frame structure continues for only approximately 10 s. To reduce the computational time, the analysis for the first 60% excitation is termina-

ted at 20.0 s and the following distinctive measures are introduced in order to compute the unloaded state and conduct the consecutive analysis for 100% excitation:

1. Dynamic analysis is terminated at 20.0 s, and static analysis with only gravity force is conducted to stop the vibration. The displacements, stresses, and elastic-plastic state at 20.0 s of the dynamic analysis are successively used as the initial values for the static analysis. On the other hand, the accelerations and velocities are set to zero; that is, the inertia and damping forces are abruptly eliminated at 20.0 s. Therefore, the out-of-balance force is released by conducting the Newton-Raphson method, and unloaded status with residual displacements and stresses due to elastic-plastic behavior in the dynamic analysis are obtained.

2. The consecutive analysis for 100% excitation is conducted using the residual displacements, stresses and elastic-plastic state as the initial values.
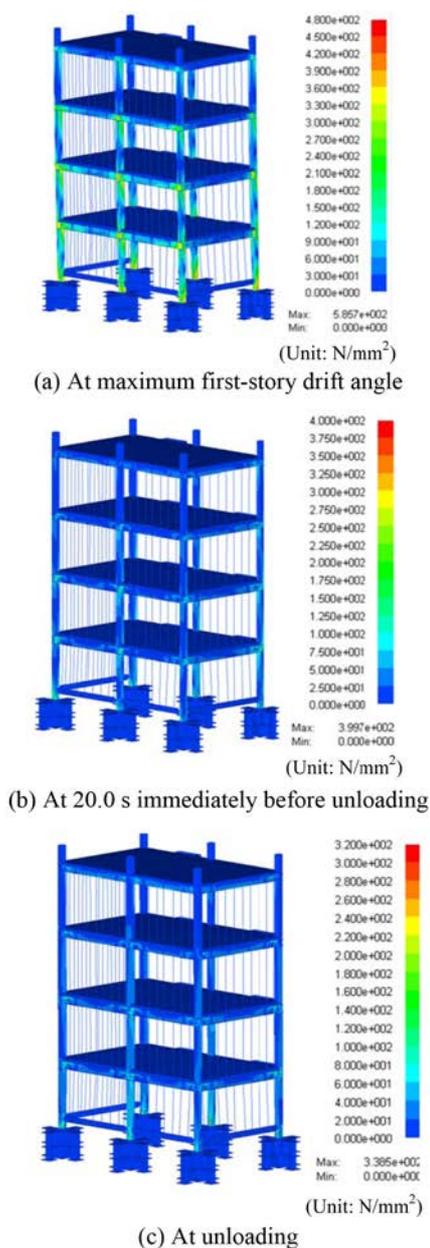
Using this method, the computational time is significantly reduced compared to the method in which a free vibration analysis with damping is conducted after 20.0 s until the vibration is reasonably reduced.

5. Results of Numerical Simulation

5.1. 60% Excitation and Unloading

For 60% excitation of the JR Takatori records that were measured on the shaking table during the test (ASEBI, 2015), an overall sway mechanism, which was observed in the E-Defense shake-table test, is successfully simulated by the analysis. The maximum first-story drift angles obtained by the analysis are 0.011 rad in the X-direction and 0.019 rad in the Y-direction, which are similar to those obtained by the E-Defense shake-table test: 0.012 rad and 0.019 rad in the X- and Y-directions, respectively. Residual drift angles of the first story at 20.0 s of 60% excitation, which were obtained by the static analysis with only gravity to release the out-of-balance force, as explained in the previous section, are 0.00081 rad in the X-direction and 0.00193 rad in the Y-direction. These results correspond well with the residual drifts obtained by the E-Defense shake-table test, which are almost zero after 60% excitation.

The contour plots of the von Mises equivalent stress and equivalent plastic strain at the maximum first-story drift angle, which corresponds to 6.08 s, 20.0 s, and unloading after 20.0 s, are shown in Figs. 4 and 5, respectively. The maximum values of the von Mises equivalent stress are 585.7 N/mm^2 at 6.08 s and 399.7 N/mm^2 at 20.0
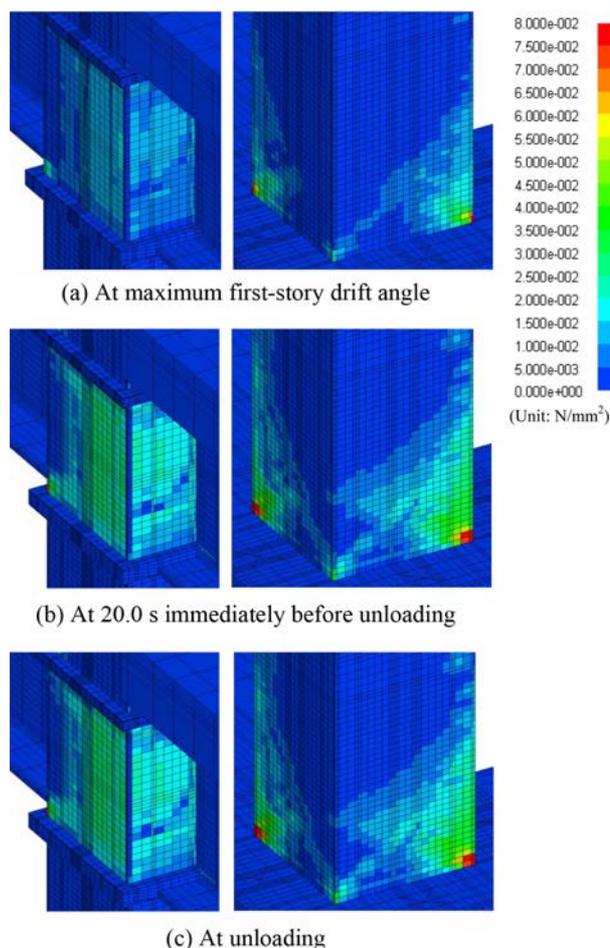
(Unit: N/mm²)

(a) At maximum first-story drift angle

(Unit: N/mm²)

(b) At 20.0 s immediately before unloading

(Unit: N/mm²)

(c) At unloading

Figure 4. Contours of von Mises equivalent stress during 60% excitation.

(a) At maximum first-story drift angle

(b) At 20.0 s immediately before unloading

(Unit: N/mm²)

(c) At unloading

Figure 5. Contours of equivalent plastic strain during 60% excitation (left: beam-column joint panel, right: column basement).

s, and the maximum value of residual stress is 338.5 N/mm², as shown in Fig. 4. Additionally, the maximum value of the equivalent plastic strain is 0.1385 at 6.08 s, which is accumulated to 0.2617 at 20.0 s and at unloading, as shown in Fig. 5. Therefore, the initial value of the equivalent plastic strain for 100% excitation in the consecutive analyses is 0.2617, which enlarges the von Mises yield surface at the initial state.

5.2. Consecutive 100% Shaking after 60% Shaking

The acceleration measured on the shaking table during the test (ASEBI, 2015) is also used in this section. In the
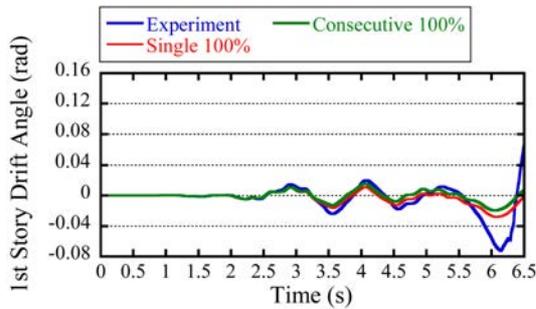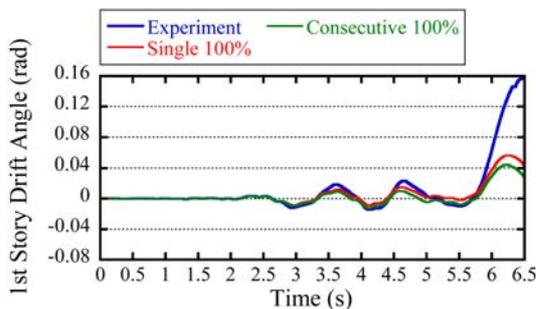
E-Defense shake-table test, the specimen collapsed completely, as shown in Fig. 6, during 100% excitation after 40% and 60% excitations of the JR Takatori records, in which plastic deformations are observed. A story mechanism was caused by local buckling at the top and bottom of the first-story columns (Yamada et al., 2008; Suita et al., 2008). The local buckling at the top and bottom of the first-story columns and story mechanism are also simulated successfully in the analyses for both single 100% excitation and consecutive 60% and 100% excitations, as shown in Fig. 6. However, the complete collapse observed in the E-Defense shake-table test is not reproduced in either of the two analyses. The time histories of the first-story drift angle in the X- and Y-directions are shown in Figs. 7 and 8, respectively. The orbit for the first-story drift angles in the X- and Y-directions is shown in Fig. 9. In these figures, the results for the single 100% excitation and those obtained by the E-Defense shake-table tests are also shown. It is found that the maximum values of the first-story drift angle for the consecutive 60% and 100% excitations are 0.019 rad in the X-direction and 0.044 rad in the Y-direction. These values are slightly smaller than

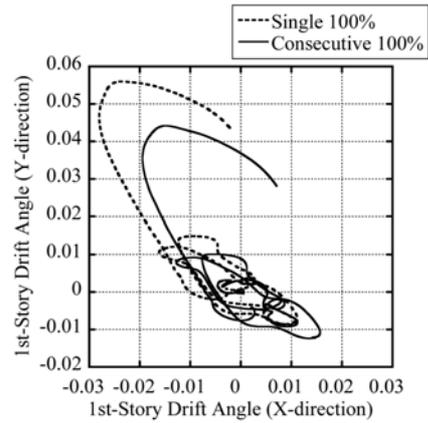**Figure 6.** Story collapse mechanism caused by local buckling in the first-story column observed by experiment.

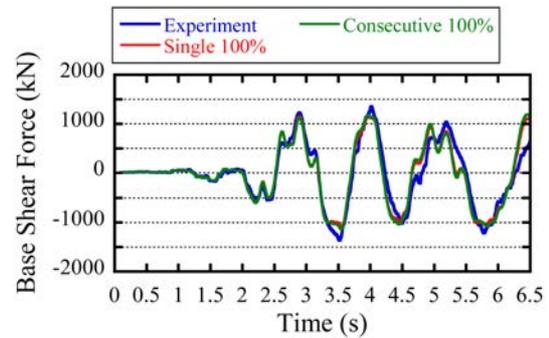**Figure 9.** Interaction diagram of first-story drift angles in X- and Y-directions.

Figure 7. Time-history of first-story drift angle in X-direction.

Figure 10. Time-history of first-story shear forces in X-direction.

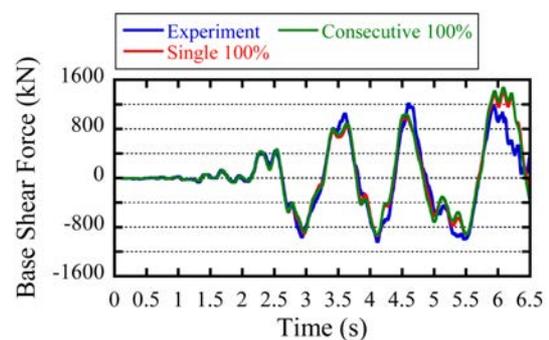**Figure 8.** Time-history of first-story drift angle in Y-direction.

Figure 11. Time-history of first-story shear forces in Y-direction.

0.028 rad and 0.055 rad in the X- and Y-directions, respectively, for the single 100% excitation. These maximum values of the first-story drift angle obtained by the analyses are much smaller than those obtained by the test in which the collapse occurred. The time histories of the first-story shear force in the X- and Y-directions are shown in Figs. 10 and 11, respectively. Base shear forces obtained

by the analyses for the single 100% excitation and consecutive 60% and 100% excitations are similar to those obtained by the E-Defense shake-table test.

The contour plots of the von Mises equivalent stress and equivalent plastic strain at the maximum first-story drift angle for the consecutive 100% and single 100%
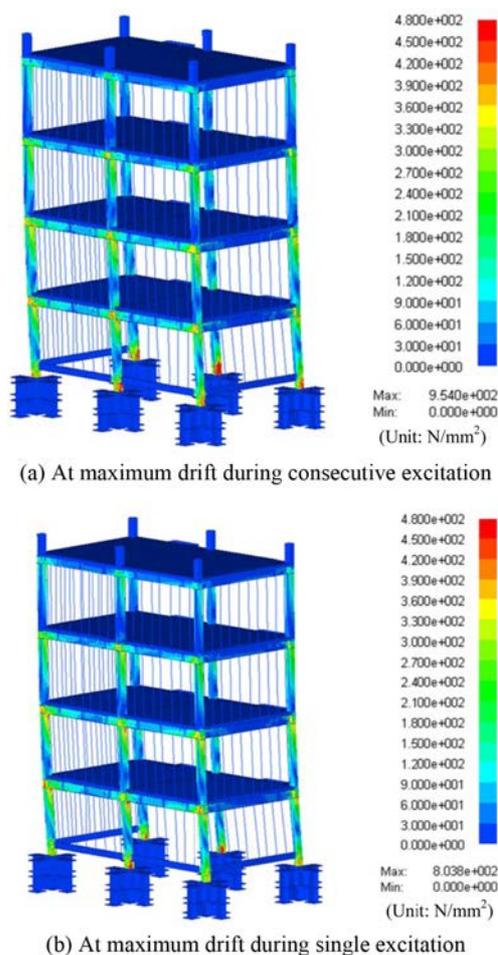
(a) At maximum drift during consecutive excitation

(b) At maximum drift during single excitation

Figure 12. Contours of von Mises equivalent stress during 100% excitation.

(a) At maximum drift during consecutive excitation

(b) At maximum drift during single excitation

Figure 13. Contours of equivalent plastic strain during 100% excitation (left: beam-column joint panel, right: column basement).

Figure 14. Time-hostory of equivalent stress during single and consecutive excitations.

excitations are shown in Figs. 12 and 13, respectively. The maximum value of the von Mises equivalent stress is 954.0 N/mm^2 for the consecutive 100% excitation and 803.8 N/mm^2 for the single 100% excitation, as shown in Fig. 12. The von Mises equivalent stress of one element for the consecutive 100% excitation is always larger than that for the single 100% excitation as shown in Fig. 14. Additionally, the maximum values of the equivalent plastic strain are 0.3979 and 0.3625 for the consecutive and single 100% excitations, respectively. According to these observations, strain hardening progresses more for consecutive excitation, which causes larger equivalent plastic strain and von Mises equivalent stress, and then a possibly smaller first-story drift angle.

6. Conclusions

Dynamic finite element analyses of a four-story steel frame structure, which was tested by the world's largest shake-table facility, E-Defense, in 2007, were conducted by using a parallel finite element analysis code, E-Simulator. The steel fr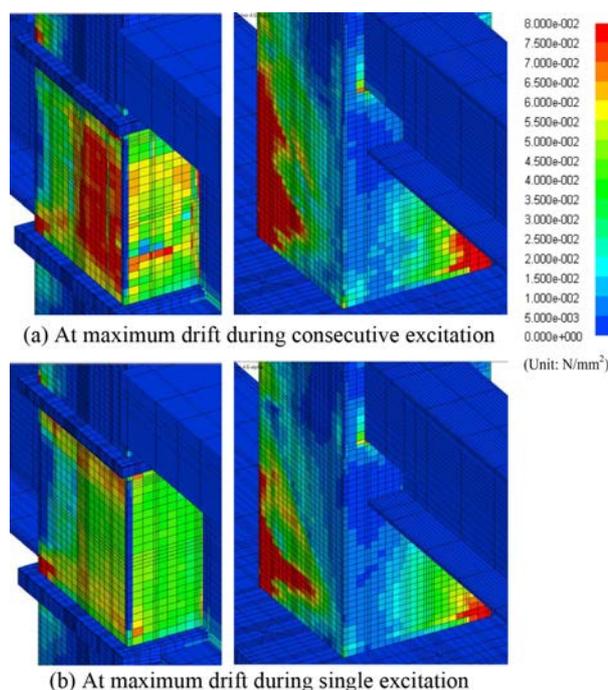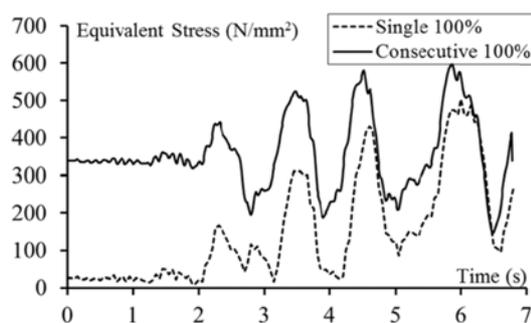ame structure, modeled by a fine mesh of solid elements, was analyzed for single 100% and consecutive 60% and 100% excitations of the JR Takatori records of the 1995 Hyogoken-Nanbu earthquake. Major findings are summarized as follows:

1. To conduct the two consecutive excitations, the dynamic analysis was stopped after major response vibration terminated, then the accelerations and velocities were set at zero. After that, the out-of-balance force was released by conducting the static analysis with the Newton-Raphson method and residual deformation and stresses were obtained. This method can reduce the computational time compared to the method in which free vibration analysis with damping is conducted until the vibration is reason-

ably reduced.

2. Local buckling behavior at the top and bottom of the columns in the first story and a story mechanism were simulated. Analysis results indicated that the first-story drift response for the consecutive 100% excitation after 60% excitation was slightly smaller than that for single 100% excitation.

3. Complete collapse, which occurred in the E-Defense shake-table test, was not observed by the analysis for the consecutive 60% and 100% excitations or for the single 100% excitation.

Acknowledgements

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