HIGH-PRECISION FE-ANALYSIS OF STEEL FRAMES

Collapse Simulation Considering Composite Beam Effect

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INTRODUCTION

Modeling method and numerical simulation approach are presented for high-precision finite element (FE) analysis of steel frames considering composite beam effects. We use E-Simulator [1], which is under developement at Hyogo Earthquake Engineering Research Center (E-Defense) of National Research Institute for Earth Science and Disaster Prevention (NIED), Japan. The E-Simulater utilizes the parallel FE-analysis software package called ADVENTURECluster [2]. It has been shown that the collapse behavior of a highrise steel building with more than 70 million degrees of freedom (DOFs) can be simulated using ADVENTURECluster [3].

A piecewise linear isotropic-kinematic hardening rule is used for the steel material. Heuristic and implicit rules are incorporated to simulate the complex cyclic elastoplastic behavior of the material. The constitutive model for steel is first verified using a cantilever subjected to cyclic forced displacement. It is shown that the responses under asymmetric deformation can be simulated accurately using this constitutive model.

A detailed analysis is next carried out for a composite beam supported by a column. The beam is subjected to a static cyclic loading. The steel beam and column as well as the RC-slab are discretezed into linear hexahedral elements. The Drucker-Prager model is used for concrete material, and the wire-meshes (steel bars) are modeled using solid elements. Rigid beams are used for the stud bolts. It is demonstrated that the experimental results, which show asymmetric behaviors due to contact of the slab to the column, can be simulated accurately using the high-precision FE-analysis.

Finally, we simulate collapse behavior of a 4-story building frame, which is a specimen of the full-scale shake-table test carried out by E-Defense, to demonstrate effectiveness of high-precision FE-analysis for investigation of dynamic elastoplastic behaviors of building frames under severe seismic motions.

1 CONSTITUTIVE MODEL OF STEEL

We use a piecewise linear isotropic-kinematic hardening model for steel material, which can simulate the yield plateau and the Bauschinger effect. The material parameters, including hardening coefficients and ratios between isotropic hardening and kinematic hardening, are determined using an optimization algorithm to fit the stress-strain curve of the cyclic uniaxial coupon test in Ref [4]. The uniaxial cyclic behaviour can be simulated accurately using this model as shown in *Fig. 1*. Although the details are not shown here, the constitutive model is a simple extension of the conventional linear hardening model. Different rules are used for the first and subsequent loading states based on a phenomenological implicit rule.

Cyclic static analyses are carried out for the cantilever that is also tested in Ref. [4]. *Fig. 2* shows the three loading protocols RH1, RH2, and RH3, which represent symmetric, one-sided, and random deformations. The relations between bending moment at the fixed end and the average deflection angle of the cantilever for RH1, RH2, and RH3 are shown in *Figs. 3*(a), (b), and (c), respectively. We can see from these results that the elastoplastic responses of a cantilever under complex asymmetric loading conditions can be simulated accurately using this constitutive model.

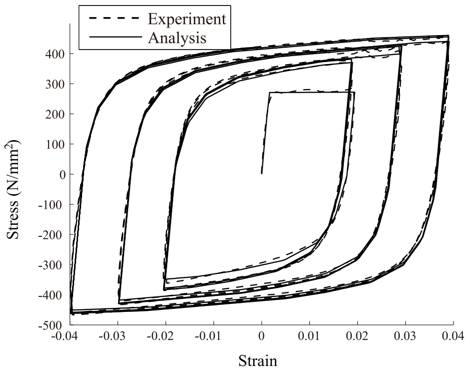


Fig. 1. Verification of constitutive model of steel material

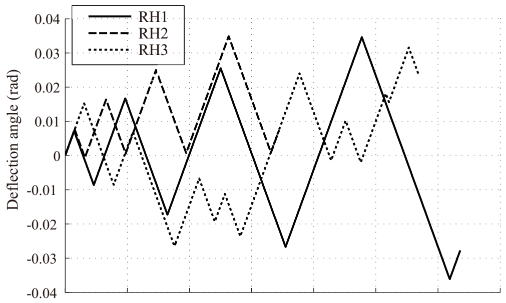
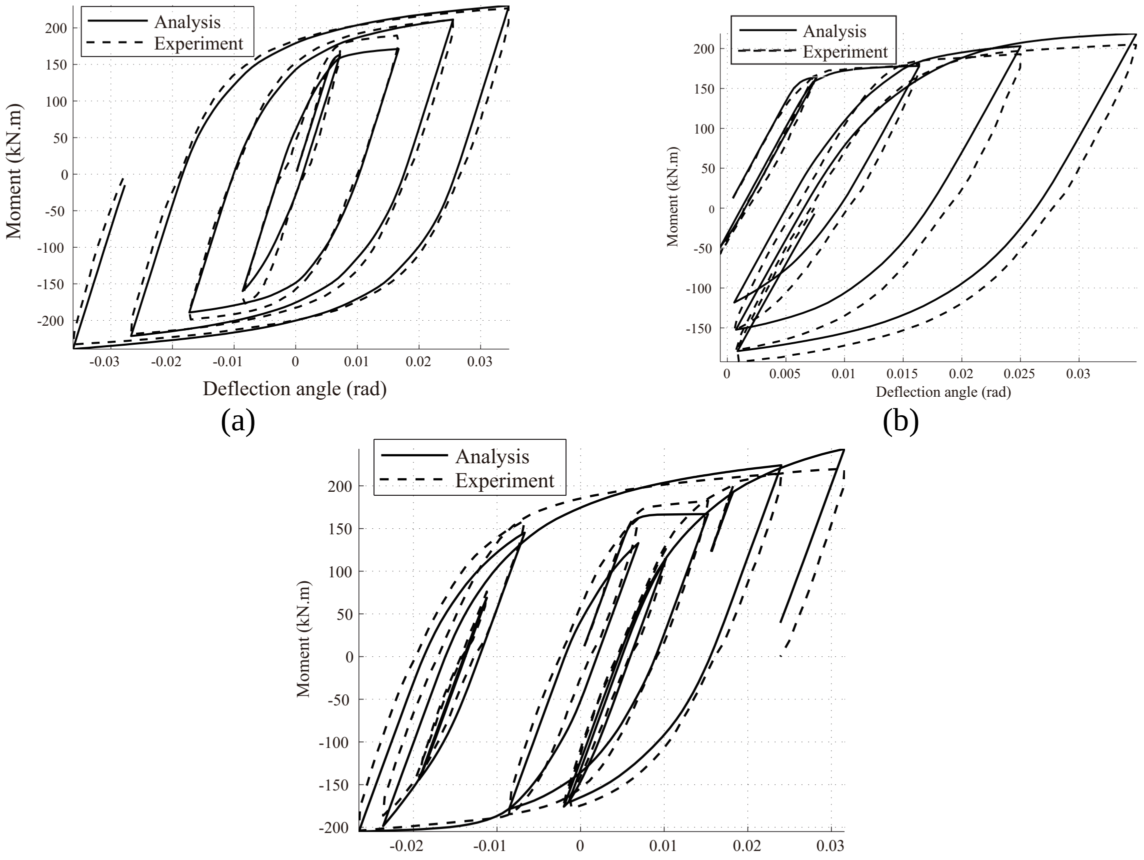


Fig. 2. Three loading protocols of cantilever; RH1, RH2, RH3



(a) (b)

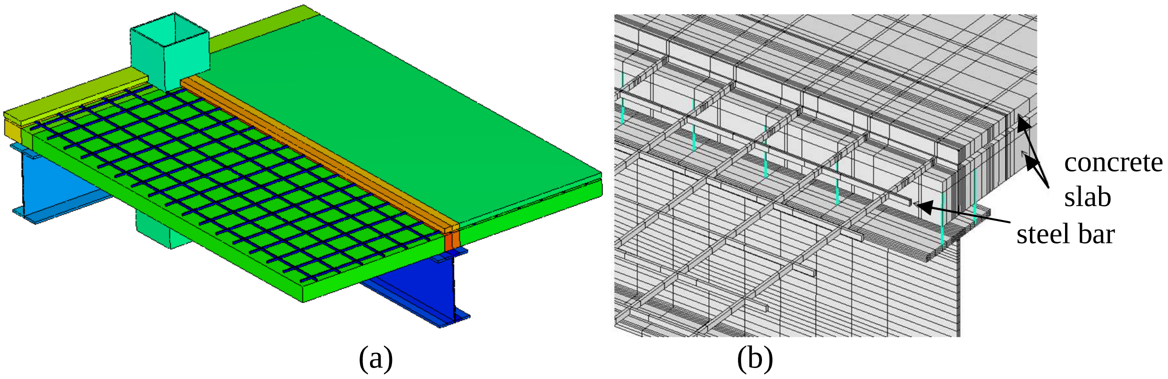
(c)

Fig. 3. Relations between moment and deflection angle of cantilever; (a) RH1, (b) RH2, (c) RH3

2 CYCLIC STATIC ANALYSIS OF COMPOSITE BEAM MODEL

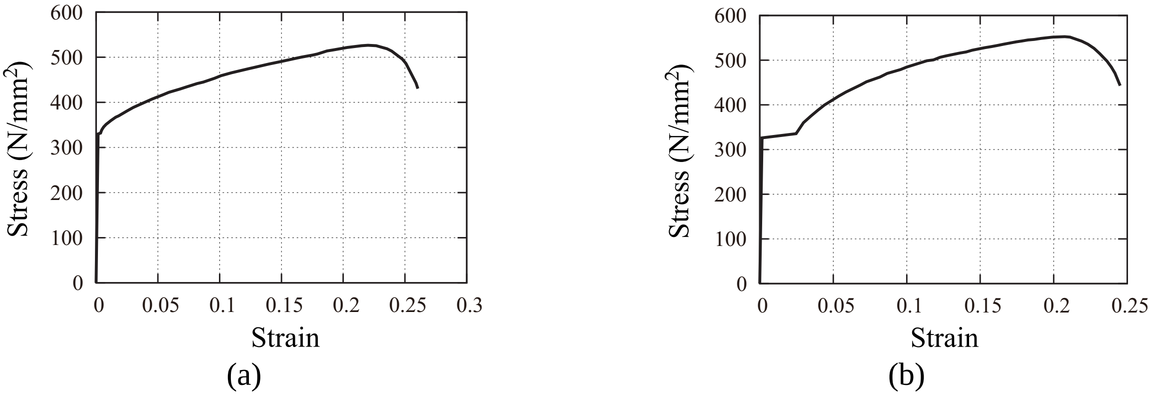
We next carry out cyclic static analysis for a composite cantilever supported by a column, which was investigated in Ref. [5]. The CAD model is shown in *Fig. 4*(a). The sections of beam and column are RH-400×200×8×13 and RHS-300×9, respectively. Young's modulus is 205.0 kN/mm^2, and Poisson's ratio is 0.3. The piecewise linear combined isotropic-kinematic hardening in the previous section is also used here for the steel material. The hardening coefficients in initial loading are identified from the result of tensile uniaxial coupon test as shown in *Figs. 5*(a) and (b) for column and beam flange, respectively. Although material parameters for flange and web of the beam are different, those for flange are used also for web. Note that only the hardening coefficients for first loading can be obtained from the tensile uniaxial test. The parameters for the hardening after reloading is estimated based on the properties observed in the cyclic test in the previous section.

The extended hyperbolic Drucker-Prager model is used for the concrete material to simulate the asymmetric behavior in tension and compression, and to prevent singularity at yielding in pure compression. Young's modulus is 25.61 kN/mm^2, Poisson's ratio is 0.2, compressive yield stress is 25.1 N/mm^2, tensile and shear yield stresses are 2.18 N/mm^2, and the hardening coefficient is 1/1000 of Young's modulus. The three parameters for the extended Drucker-Prager model are determined from the yield stresses.



(a) (b)

Fig. 4. A composite beam supported by a column; (a) CAD model, (b) FE-mesh



(a) (b)

Fig. 5. Relations between true stress and logarithmic strain of tensile uniaxial tests; (a) column, (b) beam flange

Fig. 4(b) shows the FE-meshes of the composite beam. The beams and column as well as the steel bars (wire-meshes) are discretized into hexahedral elements with linear displacement interpolation; therefore, the number of DOFs at each node is three. The stud bolt is modeled using a rigid beam that connects the middle of slab, upper surface of flange, and middle of flange. Note that the rigid beam should be connected to three nodes to transmit bending moment, because each node does not have rotational degree of freedom. There is a clearance between the flange and slab, because we ignore the concrete in the level of deck plate. The model has 124,420 nodes, 93,284 hexahedral elements, and 1,844 rigid beams. The total number of DOFs is 373,326.

The upper and lower ends of column are supported by rigid beams that are connected to pin supports as shown in *Fig. 6*. A forced cyclic vertical displacement is applied at the end of the cantilever, which is stiffened using rigid beams to prevent stress concentration. The frictionless contact condition with infinitesimal sliding dislocation is assigned between the surfaces of column and slab.

The cyclic forced rotation is given for the cantilever, where a positive rotation indicates upward displacement of the beam with compressive deformation of the slab. The relation between the bending moment at the beam-to-column connection and the average deflection angle for the pure steel beam without concrete slab is plotted in *Fig. 7*(a). Note that the rotation of the connection is removed when computing the deflection angle. Although the initial stiffness of the computational result is different from that by experiment, the maximum bending moment at each cycle can be estimated with good accuracy. Note that we confirmed the initial stiffness using the simple formula of the cantilever.

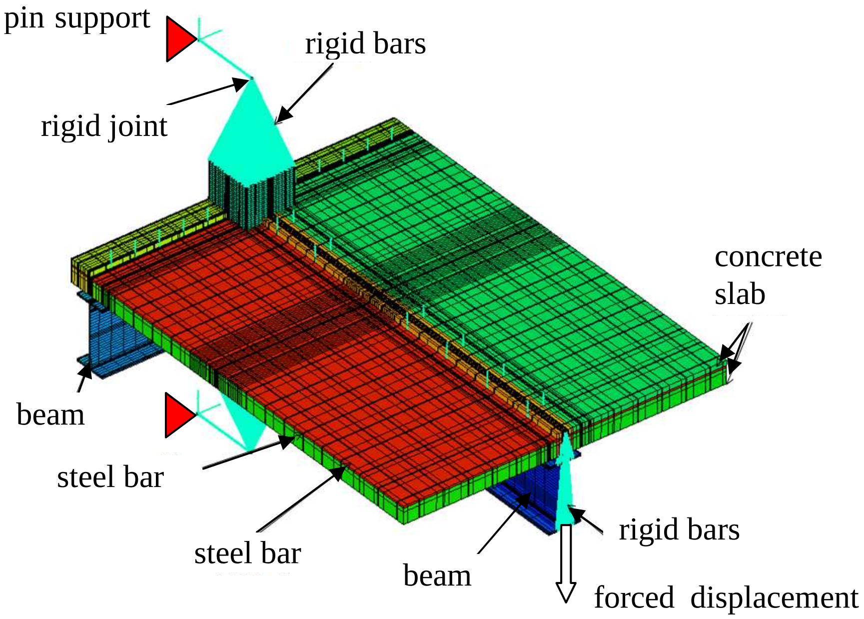
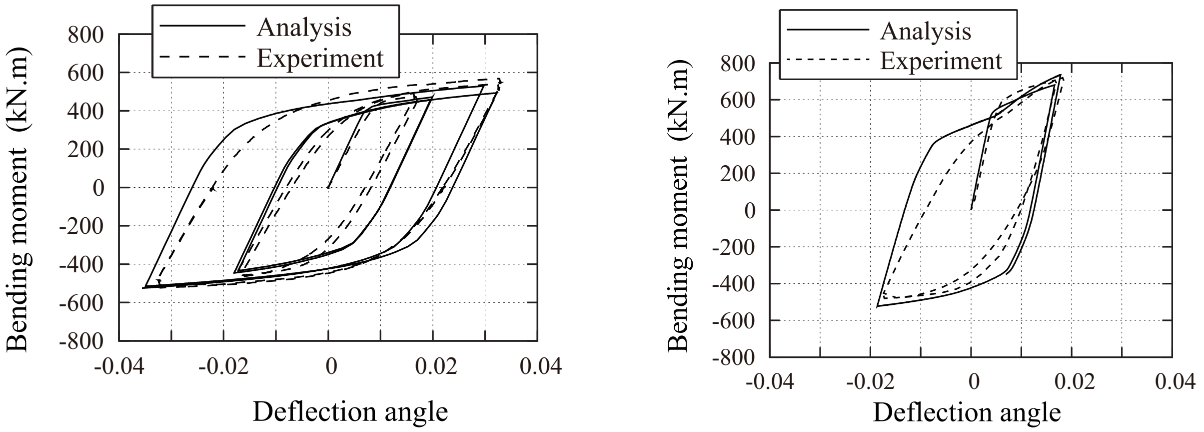


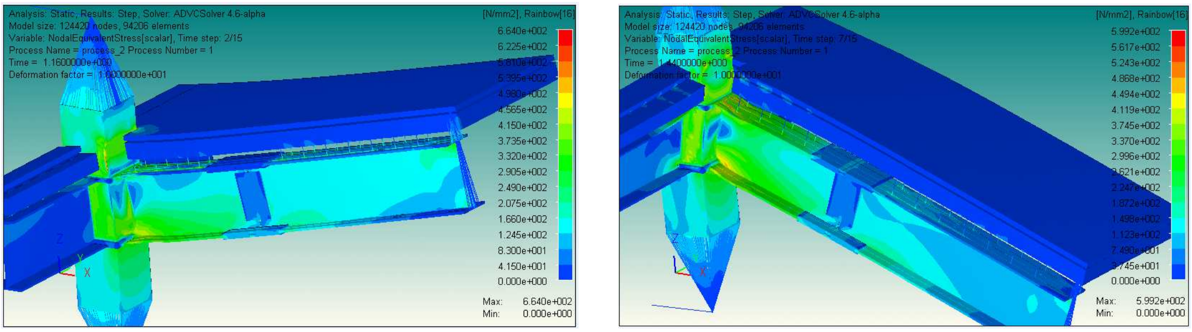
Fig. 6. Support conditions of composite cantilever beam



(a) (b)

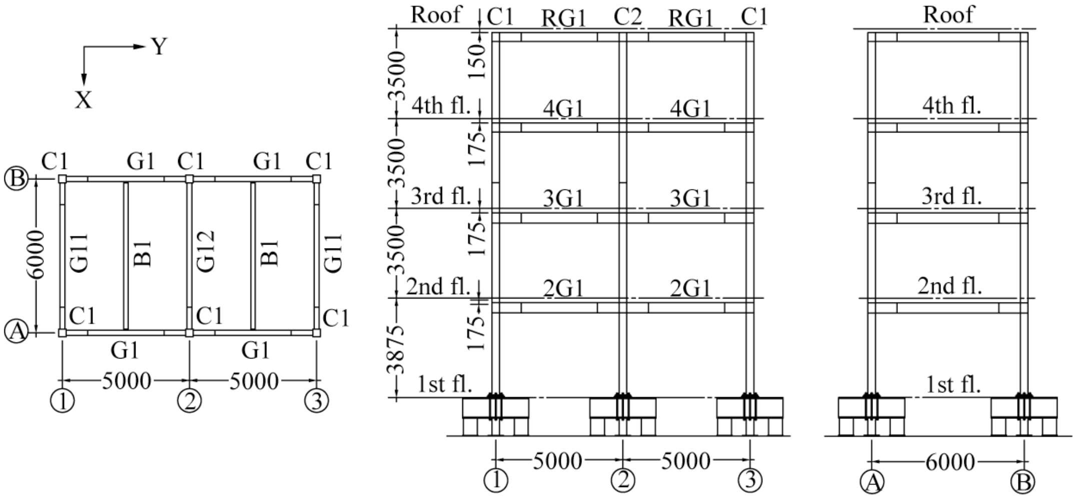
Fig.7. Relation between deflection angle and bending moment;
(a) steel beam, (b) composite beam.

Fig. 7(b) shows the relation between the bending moment at the beam-to-column connection and the average deflection angle for the composite beam. As is seen, the strengths for the positive and negative bending states can be estimated accurately by numerical simulation. However, we overestimate the stiffness in unloading state, because the crack and compressive fracture in concrete are not appropriately incorporated. *Figs. 8*(a) and (b) show the distributions of von Mises equivalent stress at the rotation 0.0178 and –0.0174 in the second cycle, where the deformation is scaled by 10. The stresses in the slab near the stud bolts are clearly observed in both figures. The effect of the beams that are orthogonal to the cantilever is very small as discussed in Ref. [5].



(a) (b)

Fig. 8. Distributions of von Mises equivalent stress at the rotation (a) 0.0178 and (b) –0.0174

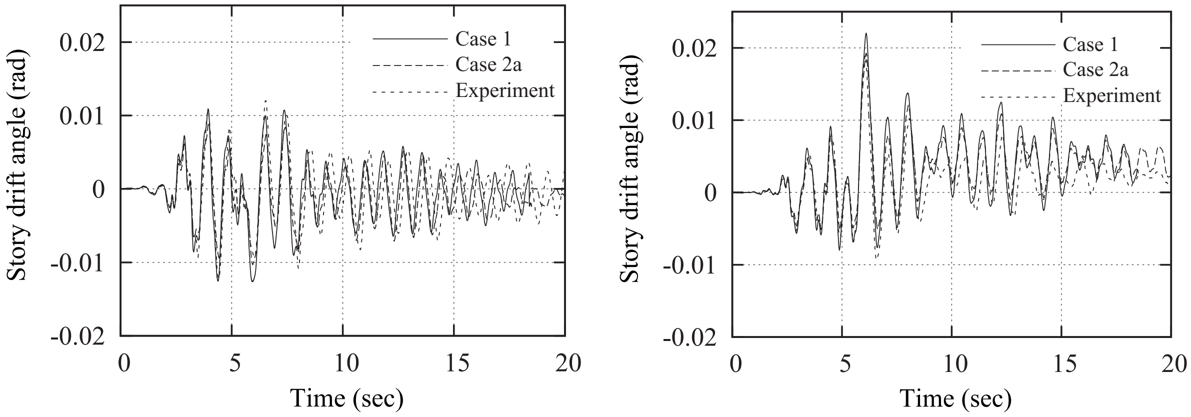


(a) (b) (c)

Fig. 9. 4-story steel frame model; (a) plan, (b), Y-elevation, (c) X-elevation [6].

3 SEISMIC RESPONSE ANALYSIS OF 4-STORY STEEL FRAME

Seismic response analysis is carried out for a steel frame as shown in *Fig. 9*, which is the specimen of the full-scale collapse test in E-Defense in 2007. See Ref. [6] for details of the model. Here only the results using a simple isotropic hardening for steel material are presented. The slabs are connected rigidly to the beam flanges.



(a) (b)

Fig. 10. Time-history of interstory drift angle of the 1st story;
(a) X-direction, (b) Y-direction

The details of the simulation model and analysis parameters are shown in Ref. [7]. Case 1 has fixed bases, and does not include the exterior ALC panel. Case 2a incorporates the stiffness and plastic energy dissipation of the panel using shear elements between the floors, and has springs representing the stiffnesses of the anchor bolts. The JR-Takatori wave of the 1995 Hyogo-ken Nanbu Earthquake is applied in three directions after scaling by 0.6. The time histories of inter-story drift angles of the first story are plotted in *Fig. 10*. As is seen, a moderately accurate agreement with the experiment results is observed for Case 2a.

4 CONCLUSIONS

A high-precision FE-analysis has been carried out for simulating the responses of composite cantilever beam under static cyclic loading. Accuracy of the piecewise linear combined isotropic-kinematic hardening rule for steel material has been first verified using the experimental results of a beam subjected to complex asymmetric deformation.

Computational results show that the strength of the composite beam under positive and negative bending states can be estimated accurately with extended Drucker-Prager model for concrete, rigid beam for stud bolt, and the piecewise linear combined hardening for steel, and contact condition between slab and column. However, crack in concrete should be appropriately modeled for accurate estimation of stiffness in unloading states.

It has also been shown that the elastoplastic dynamic responses of a 4-story steel frame, which was tested in E-Defense, can be simulated within a moderate accuracy using only the constitutive and structural models without resort to a macro model such as plastic hinges and fiber models.

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REFERENCES

[1] Allied Engineering Corporation, http://www.alde.co.jp/english/advc/index.html, as of 2011/2/13.

[2] Hori, M, Noguchi, H, Ine, T, "Project report of development of numerical shaking table coping with E-Defense", *Journal of Earthquake Engineering* (JSCE), Vol. 29, pp. 1420–1425, 2007 (in Japanese).

[3] Ohsaki, M, Miyamura, T, Kohiyama, M, Hori, M, Noguchi, H, Akiba, H, Kajiwara K, Ine, T, "High-precision finite element analysis of elastoplastic dynamic responses of super-highrise steel frames," *Earthquake Engineering and Structural Dynamics*, Vol. 38, No. 5, pp. 635-654, 2009.

[4] Yamada, S, Imaeda, T, Okada, K, "Simple hysteresis model of structural steel considering the Bauschinger effect," *J. Struct. Constr. Eng., Architectural Inst. of Japan*, No. 559, pp. 225-232, 2002. (in Japanese)

[5] Yamada, S, Satsukawa, K, Kishiki, S, Shimada, Y, Matsuoka, Y, Suita, K, "Elasto-plastic behavior of panel zone in beam-to external column connection with concrete slab," *J. Struct. Constr. Eng., Architectural Inst. of Japan*, No. 644, pp. 1841-1849, 2009. (in Japanese)

[6] Tada, M, Ohsaki, M, Yamada, S, Motoyui, S, Kasai, K, "E-Defense tests on full-scale steel buildings: Part 3 – Analytical simulation of collapse," *Proc. Structures Congress 2007*, ASCE, Long Beach, 2007.

[7] Kohiyama, M, Ohsaki, M, Miyamura, T, Onda, K, Isobe, D, Akiba, H, Hori, M, Kajiwara, K, Ine, T, "Dynamic property evaluations of full-scale 4-story steel frame using parallel FE-analysis," *Proc. 9th US National and 10th Canadian Conf. on Earthquake Engineering*, Toronto, Canada, Paper No. 1740, 2010.